Migration Strategies towards All Optical Metropolitan Access Rings

Jorge Finochietto*, Javier Aracil†, Ángel Ferreiro‡, Juan P. Fernández-Palacios‡, Óscar González‡

* Politecnico di Torino, C.so Duca degli Abruzzi, 24,10129 Torino (Italy) e-mail: jorge.finochietto@polito.it

† Universidad Autónoma de Madrid, Campus de Cantoblanco, 28049 Madrid, Spain e-mail: javier.aracil@uam.es

‡ Telefónica I+D, Emilio Vargas, 6, 28043-Madrid (Spain) e-mail: {olivo, jpfpg, ogondio}@tid.es

Abstract

Nowadays, network operators are steadily deploying Optical Circuit Switching (OCS) equipment in their metropolitan networks, in order to cope with the traffic increase and, most importantly, in order to reduce the CAPEX and OPEX of existing active technologies. On the other hand, Optical Burst Switching (OBS) technology is expected to become mature in the medium term, and it may be used as an alternative to current OCS networks, due to its potential advantages in terms of bandwidth allocation granularity. While OBS is being extensively studied in the literature, little attention has been paid to comparative analysis of OBS versus OCS, specially concerning cost analysis. In this paper, we provide a comparative analysis of OBS versus OCS as an evolutionary technology for all-optical rings in the metropolitan access network. This study is specifically targeted towards optimizing the number of optoelectronic (O/E) receivers and wavelengths, with real traffic matrices from the metropolitan rings in the city of Madrid, Spain. Such matrices also include traffic projections of foreseeable broadband services, based on a market analysis from the largest operator in Spain. Our findings show that OCS might be more efficient than OBS in the metro access segment, which is characterized by a highly centralized traffic pattern. However, the more distributed the traffic is the more efficient OBS is. Consequently, OBS might be better suited to metro-core networks, which show a more distributed and dynamic traffic pattern.

I. Introduction and problem statement

The present fast development of new broadband services calls for an upgrade of the metropolitan infrastructure. In fact, traffic characteristics are radically changing, in terms of volume, burstiness and geographical distribution. As a result, metropolitan networks are becoming a bottleneck in the network operators' infrastructure. Thus, the availability of efficient transport solutions for the metro area is the key for smooth deployment of new broadband services.

As of today, network operators are increasingly adopting OCS as the transport solution to upgrade their metropolitan networks. OCS serves to tackle the ever-increasing metro traffic demand, also reducing the CAPEX and OPEX of existing active technologies based on SDH/SONET rings and Ethernet star or ring topologies. However, OCS turns out to be inefficient in terms of the number of wavelengths and O/E transceivers for bursty

Internet traffic, because the OCS granularity is very coarse (i.e., lightpaths). Such lightpaths are set up at the connection establishment phase and their capacity remains unchanged for the whole duration of the connection, regardless of the traffic burstiness.

On the other hand, more advanced technologies such as Optical Packet Switching (OPS) [1] and Optical Burst Switching (OBS) [2] provide a higher granularity compared to OCS. OPS is based on the statistical multiplexing of optical packets at intermediate nodes. The optical packet headers suffer O/E conversion while the payload is switched and possibly buffered in the optical domain. This requires header detection and fast switching techniques that are well beyond the current state of the art for large-scale deployment.

In OBS [2], a Burst Control Packet (BCP) is sent an offset time before the optical burst in order to book resources in advance. Thus, OBS inherits part of the OCS functionality in terms of in-advance resource reservation. Interestingly, such reservation is typically unconfirmed and optical bursts can be dropped, the same way packets can be dropped in OPS. Contention resolution techniques serve to avoid burst dropping, and can be broadly classified into time or space techniques. In the former, contending bursts are temporarily stored in a Fiber Delay Lines (FDLs), on attempts to re-schedule them again once the contention period is over. In the latter, burst are redirected to another wavelength or fiber, depending on the wavelength conversion capabilities of the switch and on the availability of alternate routes (deflection). On the other hand, the process of making up optical bursts from packets is called ”burstification” and it has an impact on the performance of higher layer protocols. More specifically, if several TCP segments or acknowledgments are bundled together in the same burst and the burst is lost, this is interpreted by TCP as loss of consecutive segments. On the contrary, if several acknowledgments are received in the same burst they trigger a sudden increase in the transmission window. The issue of how to adecuately tune the burstification parameters to maximize the TCP throughput has been addressed in [3].

Concerning the evolutionary path of optical technology, OBS requires a switching granularity which is coarser than that of OPS, since bursts and not packets are switched in the optical domain. Furthermore, a lower processing speed is required for the switch control unit, because a single header is transmitted per burst, which comprises several packets. As a result, the technological requirements imposed by OBS are less stringent and several OBS testbeds have already been developed [4], [5], [6]. In conclusion, OBS solutions are expected to become commercially available in the medium term and before OPS.

There is a large literature for both OCS and OBS networks. However, since OBS is a relatively new technology the research effort has been focused on single link issues, such as scheduling, switch architectures, TCP over OBS, etc [7]. Nevertheless, network-scale aspects have not been considered in-depth. With regard to the state of the art in the comparison of OBS versus other technologies, Sheeshia et al. [8] and Zapata et al. [9] address the issue of SDH/SONET versus OBS but they do not consider the case of OCS. The study by Comellas et al. [10] provides comparison between an OCS and OBS optical node, i.e. the analysis is restricted to a single switch. Xue et al. [11] compare the performance of OCS and OBS using the same traffic matrix and resources for a meshed backbone network, finding that OBS obtains better throughput. The topic of OBS versus OCS is also addressed by the study of Coutelen et al. [12], where it is pointed out that there is a need for further studies and experiments. Surprisingly, a comparative analysis in terms of resource consumption of both techniques is lacking in the literature. More specifically, to the best of our knowledge, there is no concluding analysis that serves to determine what is the optimum technique, OCS versus OBS, in terms of number of wavelengths and O/E transceivers. Note that such analysis should not only be limited to capacity planning issues, i.e. number of wavelengths/transceivers, but it should also encompass techno-economical aspects such as overall network cost. For example, the cost of the OBS O/E receivers is expected to be higher than the cost of OCS receivers, because the OBS receiver is required to recover synchronization every time a new burst is received.

In this paper, we provide a comparative analysis of OCS versus OBS networks in the metro-access scenario, a subset of the metropolitan network. Our goal is to assess the feasibility of newly introduced optical switching techniques (OCS and OBS) in the migration from existing SDH/SONET and Ethernet backbones to all-optical metropolitan rings. Generally speaking, OCS proves more efficient as the traffic burstiness decreases and the contrary applies to OBS. Namely, the suitability of OCS or OBS for the metro scenario is strongly dependent on the traffic pattern. Precisely, a distinguishing feature of this work is the availability of real traffic traces from a working SDH/SONET ring in the city of Madrid. To further assess the strengths and drawbacks of OBS versus OCS we introduce traffic forecasts to the matrices, i.e. video-on-demand and other interactive services that are expected to be offered in the near term. By doing so, not only the case study of a working SDH/SONET ring is considered, but also the broader case of ring networks providing broadband services to be deployed in the close future. This prospective analysis is based on current market trends for telecommunication services, as perceived by the largest operator in Spain. On the other hand, hybrid alternatives are also considered, that encompass OBS for intra-ring traffic and OCS for inbound and/or outbound traffic to the ring. Furthermore, we also propose a grooming technique, called Last-Hop Grooming (LHG), that aims at minimizing the number of O/E receivers in OBS networks.

The paper is structured as follows, section II provides a description of our reference scenario while section III presents the node architecture. Next, section IV is devoted to the traffic model. An analytical model for performance evaluation is presented in section V, followed by the results and discussion in section VI and the conclusions in section VII.

II. Metropolitan reference scenario

The current metropolitan network in the city of Madrid consists of SDH/SONET rings arranged in two levels of hierarchy, namely metro-core and metro-access (see Figure 1). In the present study, the focus is on the *metro-access level*. The metro-access rings are dual-homed to the metro-core rings for protection purposes. A traffic concentrator (i.e. a DSLAM) is usually attached to each of the metro-access nodes. Then, a SDH/SONET virtual container is used to transport traffic over the metro-access ring and to the metro-core ring.

The network architecture presented in Figure 1 is not all-optical because packets undergo O/E/O conversion at each of the nodes. As the rings migrate to all-optical architectures the SDH nodes will be replaced by Reconfigurable Add-Drop Multiplexers (ROADMs). However, the network topology will remain the same, i. e. a two-level hierarchy of metro-access rings linked to a metro-core network. As previously mentioned, a DSLAM will be usually attached to each ROADM and, as a result, ROADMs will concentrate traffic from a large number of users. The metro-access ring specification is as follows:

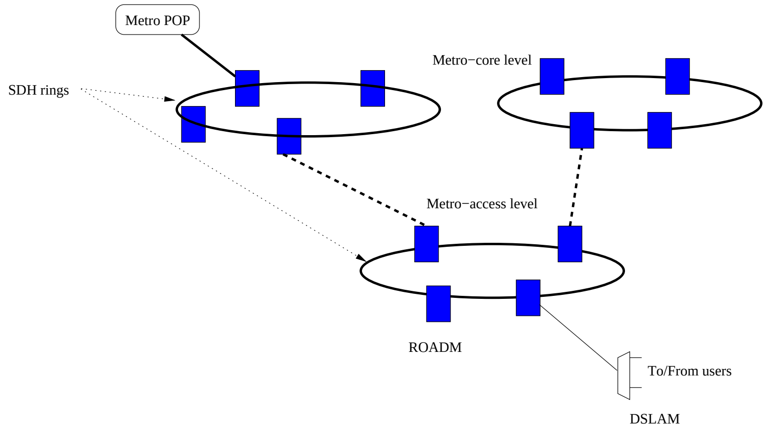

Fig. 1. Present architecture of metro network based on SDH technology

- Support of up to 21 access nodes (total maximum length of 80 Km). The minimum number of nodes per ring is five.
- The ring is bidirectional (traffic can be sent through the shortest path either clockwise or counterclockwise). This specification may be relaxed if the number of nodes per ring is reduced by segmenting the ring into smaller stacked rings.
- A 1+1 protection scheme is provided. There is a single working fiber and a backup fiber for redundancy. (MS-SPRING mechanism).
- Out-of-band signaling.
- Dual homing of metro-access ring to metro-core ring.

From a logical topology standpoint, *this ring architecture allows virtual mesh or star topologies* depending on how the network is configured. Concerning the latter, a node in the ring may be configured as a hub, that relays traffic from/to the access nodes. Actually, two nodes may serve to this purpose in order to preserve the dual-homing requirement.

III. Metro node architecture

In this section the different node architectures are presented, both for OCS and OBS rings.

A. OCS node architecture

In the OCS ring, lightpaths are established according to the traffic matrix demand. Hence, incoming traffic is classified by destination, and assigned to an established lightpath. Each lightpath has a dedicated transceiver and three transceiver speeds are considered, e.g. 1 Gbps, 2.5 Gbps and 10 Gbps.

Needless to say, peak-rate capacity planning is not adopted for economical reasons, and, thus, it may well happen that the incoming traffic rate exceeds the wavelength capacity. Consequently, electronic buffers are used to absorb traffic peaks. It is assumed that the traffic matrix is stationary and circuits are established at the network boot time. An increase in the offered traffic requires either an upgrade in the lighpath capacity or the establishment of a new lightpath. Consequently, a new transceiver will be physically added to the node, either to upgrade the lightpath capacity or to provide a new lightpath.

An OCS node is composed of an OCS Control unit and a ROADM (mux/demux, switch matrix, transceivers). The OCS Control unit classifies packets according to destination, and assigns them to a certain lightpath (which has to be already established). It also features several queues to electronically store the packets pending transmission before optical conversion, in order to absorb the traffic peaks.

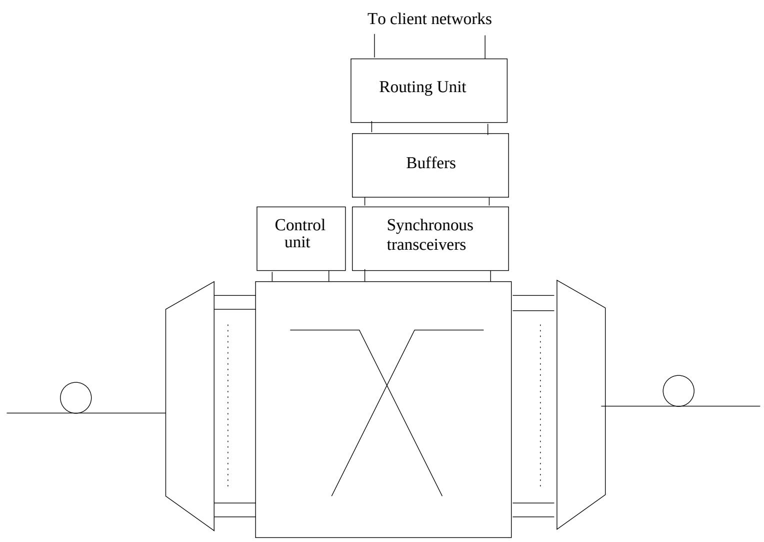

Fig. 2. OCS Node architecture

The ROADM is a symmetric device with W wavelengths and O O/E transceivers, such that the switching fabric is a symmetric $(W + O)x(W + O)$ matrix with full wavelength conversion capabilities. Although not depicted in the figures, we will assume that there is an Automatic Protection Switch (APS) device that provides automatic failover switching to the spare fiber in the ring. Importantly, not only a ROADM relays traffic from the neighboring ROADMs but it is also a traffic source and sink itself, i.e. it adds and drops lightpaths.

B. OBS node architecture

Assuming full wavelength conversion capabilities also at OBS nodes, bursts can be transmitted using any of the available wavelengths. If no wavelengths are available, the burst is dropped. Since the OBS node itself is also a traffic sink and bursts can potentially arrive from any wavelength, many O/E transceivers are needed (i.e., one per wavelength). It can be easily seen that this issue leads to an unacceptable number of O/E transceivers. Actually, OBS is originally envisioned as a core network technology, and no O/E transceivers are necessary at the intermediate switches, because all the incoming traffic will pass through the switch. For ring networks, however, O/E conversion is needed for all incoming wavelengths, which implies an unacceptable implementation cost.

In order to minimize the number of O/E receivers we propose the following algorithm, which will be called *Last-Hop Grooming* (LHG) algorithm. If the number of nodes is equal to N, the traffic to node i is groomed at the upstream node $i-1 \bmod N$ (clockwise) and $i+1 \bmod N$ (counterclockwise), such that it can only be transmitted through a subset of predefined wavelengths. Hence, O/E receivers are only needed for such subset of wavelengths at node i. By doing so, significant savings can be achieved in comparison to having the incoming traffic to node i arrive from any of the incoming wavelengths. Figure 3 illustrates the LHG concept. In this example, clockwise traffic to node 2 comes from wavelength 1 and 2 only. As a result only 2 O/E receivers are needed at node 2.

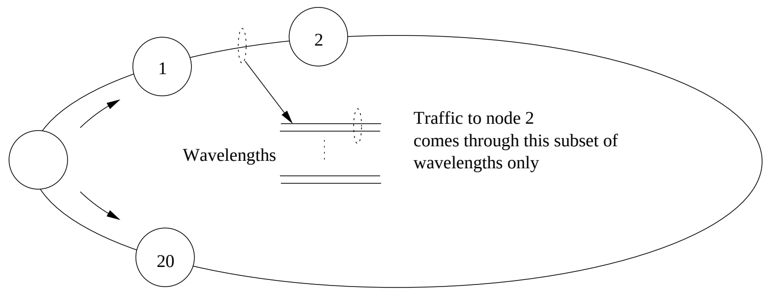

Fig. 3. Last Hop Grooming (LHG) algorithm

Note that the OBS nodes include both edge and core node functionality. They are composed of an OBS Control unit and a ROADM, which has the same functionality than the OCS one. The OBS Control unit includes the following features:

- Ingress interfaces with client networks (typically gigabit Ethernet interfaces).
- Routing module: it classifies incoming packets according to destination.
- Burstifier: it aggregates packets to a given destination. It features several electronic queues, one per each destination. Packets could also be classified according to QoS, but this is not considered in this paper.
- Burst scheduler: it is in charge of burst scheduling and ROADM control. It implements the LHG algorithm and decides which wavelength should a given burst be switched to.
- Deburstifier: it performs burst disassembly into packets, which are sent to the routing model, which in turn forwards them to the ingress interfaces.

C. Hybrid OBS/OCS node architecture

Hybrid node architectures can also be considered [13], [14], in which OCS lightpaths are established for high capacity demands (inbound and outbound traffic to the ring), while OBS is used for the bursty traffic (intra-node traffic).

The hybrid OCS/OBS control unit classifies packets according to destination, and sends them to the proper unit, either OBS or OCS. Both OBS and OCS units are assigned different sets of wavelengths. To simplify the architecture, we have not considered hybrid architectures with shared wavelengths.

IV. Traffic model

Real traffic traces have been collected in order to obtain a realistic starting point for our analysis. Based on these measurements, an initial traffic matrix has been produced. Then, a traffic forecast has been performed,

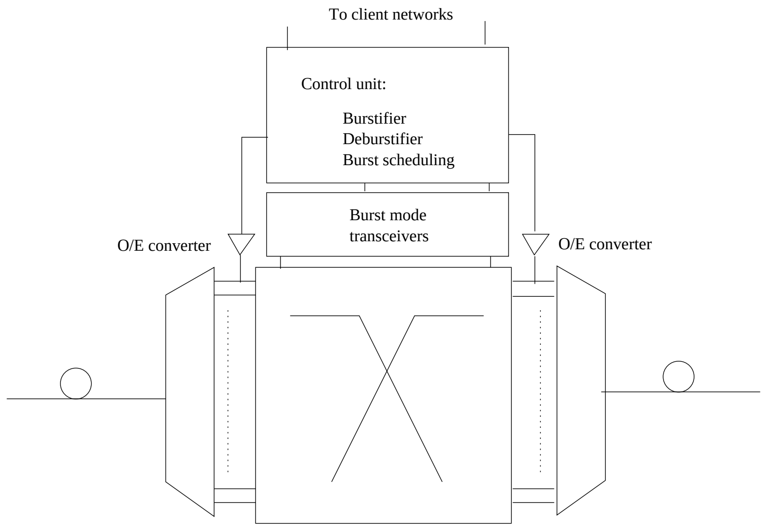

Fig. 4. OBS Node architecture

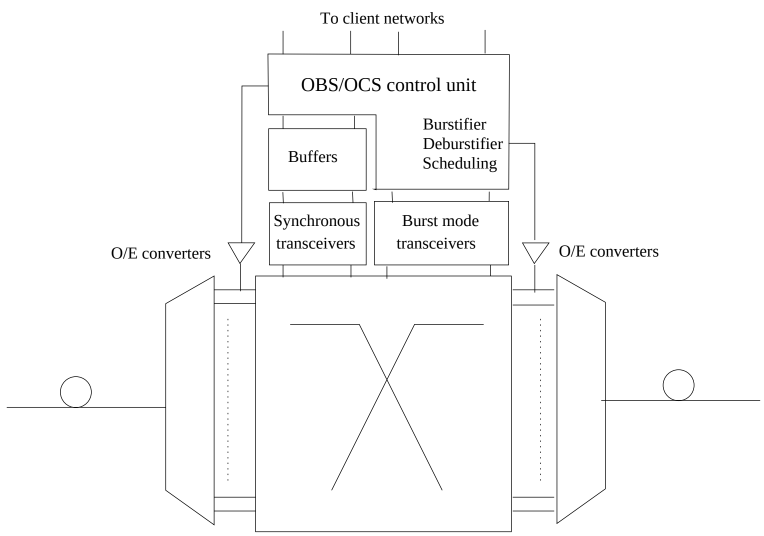

Fig. 5. Hybrid OCS&OBS Node architecture

based on market analysis, in order to come up with a number of possible traffic scenarios for the close future.

Regarding the traffic measurements, they were performed in the metro-access network of the city of Madrid during 2005. Such metro-access network has been described in section II. These metro-access nodes serve as access nodes (i.e. DSLAMs) for densely populated areas, with around 100,000 customers each. The measurements that were taken comprised a variety of end users, with an access bandwidth of around 1 Mbit/s for residential users and from 10 to 100 Mbit/s for business customers. We believe that the measurements obtained are a significant traffic sample which is representative of working SDH rings in large metropolitan scenarios. Furthermore, only the mean traffic during the rush hour was collected, which implies that our analysis is conservative.

On the other hand, a traffic forecast has been produced based on internal market analysis. For the traffic forecast, the following issues have been considered:

- Penetration of IPTV, VoD and other multimedia contents distributing applications.
- Evolution of compression and cryptography techniques.
- Development of P2P gaming applications involving video transfers.
- Performance of set top boxes (and DRM related issues).
- Demand for high definition video.
- Multicast upgrades of network equipments.
- Local caches (for local preferences, for instance) and introduction of Diffserv for transactional traffic.

On the other hand, the bandwidth requirements for residential customers in the long term (2015) have been evaluated within the EU project NOBEL[1] [15]. The results are presented in table I. According to this analysis, the individual bandwidth demand will increase by a factor of forty times compared to the present one. These reports, together with the study by VanBreda [16], constitute the basis for our traffic forecasts for metro networks.

Service	Downstream	Upstream
2 HDTV channels	16 Mbps	256 kbps
Gaming channel P2P	1 Mbps	1 Mbps
2 Voice calls	32 kbps	32 kbps
High Speed Internet	3 Mbps	512 kbps
Total	20 Mbps	2 Mbps

TABLE I

EXPECTED BANDWIDTH DEMAND FOR A TYPICAL RESIDENTIAL CONNECTION

In conclusion, three types of applications have been considered: *real time, broadcast and Internet-P2P traffic*. For real-time and broadband traffic we have considered the forecasted deployment of IPTV and VoD applications. Furthermore, three different evolution scenarios have been considered: *Optimistic, Medium and Low*, for the three types of traffic, with two access ring sizes, *5 and 21 nodes*.

V. ANALYSIS

The objective of our analysis is to come up with a *cost* comparison between OCS and OBS. First, we analyze the cost model for optical rings. It is commonly accepted that OBS demands more advanced optical components than OCS, despite its potential advantages. Furthermore, OBS needs a high performance electronic control unit to run advanced and complex control algorithms (e.g. for contention resolution, QoS, routing). Therefore, the OBS cost-effectiveness depends on whether its higher efficiency compensates for the required investment in technology.

The following cost indicators are commonly used in techno-economic studies to compare the efficiency of different network architectures:

[1] http://www.ist-nobel.org

- Node capacity: Switching capacity (e.g. in gigabits per second) required in each node. Node capacity is limited by the hardware configuration (i.e. processors for routing and control, buses, switch fabric, etc). This cost indicator is strongly related to the hardware cost.
- Fiber connectivity: The cost of a fiber between two locations is usually assumed to be the sum of two components: the cost of amplifiers and the cost per kilometer of deployed fiber.
- Transceivers: The total number and capacity of transmitter /receiver (Tx/Rx) elements has a strong impact on final CAPEX and OPEX requirements [17], [18], [19].
- Wavelengths: The cost of optical passive elements is usually determined by the number of channels they are capable of multiplexing/demultiplexing.

We focus on passive optical rings and, thus, the node capacity will only be taken into account for logical star topologies, in which the hub plays a major role aggregating and disaggregating traffic. On the other hand, fiber connectivity is not considered in our comparative analysis because we assume the same fiber connectivity in both cases (refer to section II). Consequently, our analysis will focus on two indicators: the number of wavelengths and the cost of transceivers. Furthermore, we assume that the cost of each wavelength in OCS and OBS is essentially the same, thus, our analysis focuses on the maximum number of wavelengths required for each solution.

The cost of transceivers can be divided into two costs: the cost of transmitters and the cost of receivers. Since the number of transmitters required for OCS and OBS is the same (one per wavelength) and so is their electronic complexity, we also assume that they have the same cost and do not consider them in our analysis. However, if we consider receivers, neither the number of required receivers for OCS and OBS nor the associated cost is necessarily the same. On the one hand, in OCS the number of receivers is equal to the number of lightpaths while in OBS this number is related to the blocking probability when grooming traffic at the neighboring node (LHG algorithm). On the other hand, the cost of an OCS receiver is lower since clock recovery is much simpler in OCS networks. As a result, table II shows the receiver cost values used in this study. Such values, which are expressed in relative units, have been obtained by confidential means and market survey.

Synchronous 1 Gbps (OCS)	Synchronous 2,5 Gbps (OCS)	Synchronous 10 Gbps (OCS)	Burst Mode 10 Gbps (OBS)
1/3	1/6	1	1.5

TABLE II

RECEIVER COST VALUES (IN RELATIVE UNITS)

Note that the OBS receiver cost is 50% higher than the OCS receiver cost, for the same 10 Gbps capacity.

A. Analytical model

According to the previous section, only the number of wavelengths and receivers is considered in the proposed analysis. In this section we provide expressions for such cost indicators, given a certain traffic matrix.

Let us consider an access ring with N nodes, numbered clockwise, and let $[\mathbf{T}]$ be the NxN traffic matrix. Each entry $T_{ij}, i, j = 1, \ldots N$ corresponds to average traffic intensity, measured in bits per second in the rush hour, from node i to node j. It should be noted that $T_{ij} \geq 0, i, j = 1, \ldots N, i \neq j$ and $T_{ii} = 0, i = 1, \ldots, N$.

As for the node, we consider an unified OBS and OCS node model connected to a bidirectional ring, where each ring has two fibers, primary and backup. As mentioned in Section III we assume that the backup fiber is idle unless a failure occurs. In that case, traffic is automatically rerouted to the backup fiber from the primary one (i.e., a 1:1 protection scheme). For modeling purposes, we focus on a node model with a single fiber and W^i wavelengths for node $i, i = 1, \ldots, N$. Note that if $[\mathbf{T}]$ is not symmetric the clockwise and counterclockwise traffic differ. This implies that the node fabric is not necessarily symmetric. Let W^i_{cw} (W^i_{cc}) refer to the number of wavelengths clockwise (counterclockwise) for node i. In what follows we will consider shortest path routing, in the number of hops sense.

We wish to derive W^i_{cw} and W^i_{cc} with $i = 1, \ldots, N$, given $[\mathbf{T}]$ for a certain Quality of Service (QoS) objective in terms of delay or blocking probability. We use two different variables to distinguish between the traffic that goes through the node to other destination (i.e., relayed at the node) versus the traffic that is addressed to the node (i.e., dropped at the node). Firstly, let R^i_{cw} (R^i_{cc}) refer to the input traffic to node i, clockwise (counterclockwise) *that is relayed at node* i, thus, it is not addressed neither to node i nor to its neighboring node. $(i+1) \bmod N$ ($(i-1) \bmod N$). Secondly, let G^i_{cw} (G^i_{cc}) refer to the traffic *that is groomed at node* i, thus, that is addressed to node $(i+1) \bmod N$ ($(i-1) \bmod N$). Thus, note that $G^{i-1 \bmod N}_{cw} + G^{i+1 \bmod N}_{cc} = \sum_{k=1}^{N} T_{ki}$ with $i = 1, \ldots N$.

B. A unified performance metric for OCS and OBS

A QoS metric is required to evaluate OCS and OBS for a given traffic matrix $[\mathbf{T}]$. OBS networks are pure loss networks, since bursts that make it through the network will suffer a delay which is close to the theoretical minimum (propagation delay). However, delays cannot be avoided for an OCS networks providing a bandwidth smaller than the incoming traffic peak rate. Since peak-rate dimensioning is not cost-effective, buffering is allowed at the circuit source. Thus, it turns out that two different metrics, blocking probability (OBS) and delay (OCS), should be used for comparison purposes.

In order to unify both metrics we consider the blocking probability for OBS and the queueing delay probability for OCS, with constant packet size. Note that a burst that makes it through the OBS network will only suffer propagation delay and the same happens to a packet that finds an empty queue in an OCS network. Thus, blocking probability in OBS and queueing probability in OCS are related parameters. The TCP throughput is inversely proportional to the Round Trip Time (RTT), in case the window size is constraining the TCP connection. In optical networks the bandwidth-delay product is typically large and, thus, the window size becomes a limitation. In the OCS case, the RTT increases with the queueing delay. In the OBS case, the delay is constant but the TCP throughput decays approximately with the inverse of the square root of the segment loss probability [20]. Hence, there is some similarity between the delay in the OCS case and the burst loss probability in the OBS case. However, the performance comparison of TCP in OCS and OBS networks is a rather involved issue, which requires further analysis and it is left out of the scope of the paper.

In what follows, let $B_{objective}$ be the blocking probability (OBS) or queueing probability (OCS) objective.

C. Number of wavelengths

1) The OBS case: For the case of OBS, let us consider JET scheduling [7] and constant offset time. Thus, assuming burst arrivals follow a Poisson process [21], the node blocking probability is given by the Erlang-B formula [22] $\mathcal{B}(n,\rho) = (\rho^n/n!)/\sum_{i=0}^{n} \rho^j/j!$, where n is the number of wavelengths and ρ the traffic intensity in Erlangs on those wavelengths. However, this is only the blocking probability at a single node. The end-to-end blocking probability can be considered taking into account all blocking possibilities a burst may experience all over a path. On the one hand, we must then consider the probability that a burst may be blocked on an intermediate node; this is the *in-transit blocking probability*. On the other hand, a burst can be blocked on the last hop when it is groomed to be delivered to its neighboring node, this is the *grooming blocking probability*. Thus, our objective is to find the minimum number of wavelengths at node i, namely W^i_{cw} (W^i_{cc}), that guarantee that any path suffers at most a blocking probability $B_{objective}$. Due to the LHG strategy, each node i will dedicate $W^i_{G,cw}$ ($W^i_{G,cc}$) for *grooming* to its neighboring node, and $W^i_{R,cw}$ ($W^i_{R,cc}$) wavelengths for *relaying* traffic, such that $W^i_{cw} = W^i_{R,cw} + W^i_{G,cw}$ ($W^i_{cc} = W^i_{R,cc} + W^i_{G,cc}$), $i = 1, \ldots, N$.

We first consider the in-transit blocking probability. Let S^{ij}_{cw} (S^{ij}_{cc}) refer to the set of nodes in the shortest path that *relay* traffic from node i to node j clockwise (counterclockwise), with $i, j = 1, \ldots N, i \neq j$. If the shortest path between nodes i and j is counterclockwise (clockwise) then $S^{ij}_{cw} = \emptyset$ ($S^{ij}_{cc} = \emptyset$). Let B^{ij}_{cw} (B^{ij}_{cc}) refer to the blocking probability of the in-transit traffic T_{ij} if it is routed clockwise (counterclockwise). Then,

$$
\begin{aligned}
1 - B^{ij}_{cw} &= \prod_{k \in S^{ij}_{cw}} (1 - B^k_{cw}) \\
1 - B^{ij}_{cc} &= \prod_{k \in S^{ij}_{cc}} (1 - B^k_{cc})
\end{aligned}
\tag{1}
$$

for all $i, j = 1, \ldots, N, i \neq j$, where it is assumed for simplicity that node j neither belongs to S^{ij}_{cw} nor to S^{ij}_{cc}. Note that B^k_{cw} (B^k_{cc}) represents the node k in-transit blocking probability clockwise (counterclockwise). Since we are considering the case where blocking probabilities are very small, as a first approximation we can consider that $B^k_{cw} = \mathcal{B}(W^i_{R,cw}, R^i_{cw}/C)$ and $B^k_{cc} = \mathcal{B}(W^i_{R,cc}, R^i_{cc}/C)$, being C the wavelength capacity, and that the Eq. (1) can be reduced to

$$
\begin{aligned}
B^{ij}_{cw} &\approx \sum_{k \in S^{ij}_{cw}} (1 - B^k_{cw}) \\
B^{ij}_{cc} &\approx \sum_{k \in S^{ij}_{cc}} (1 - B^k_{cc})
\end{aligned}
\tag{2}
$$

since quadratic terms of the productory are negligible if probabilities are small.

Let B^j_{cw} (B^j_{cc}) refer to the blocking probability when grooming traffic addressed to node j for clockwise (counterclockwise) traffic. Again, if blocking probabilities are small, we can consider as a first approximation that $B^j_{cw} = \mathcal{B}(W^j_{G,cw}, G^j_{cw}/C)$ and $B^j_{cc} = \mathcal{B}(W^j_{G,cc}, G^j_{cc}/C)$. Therefore, in order to guarantee at most blocking probability $B_{objective}$ on all possible paths, we can claim that

$$\begin{aligned} B_{cw}^{ij} + B_{cw}^{j} &\leq B_{objective} \\ B_{cc}^{ij} + B_{cc}^{j} &\leq B_{objective} \end{aligned} \tag{3}$$

for $i, j = 1, \ldots N, i \neq j$.

These equations are closely related to our indicators: number of wavelengths and receivers. In fact, each node uses some wavelengths for relaying traffic and others for grooming. Hence, a decision problem arises on how many wavelengths should be allocated for relaying and how many for grooming. Wavelengths allocated for relaying will impact on the in-transit blocking probability while those allocated for grooming will impact on the grooming probability and determine the number of receivers the neighboring node must have. It is out of the scope of this paper to study this problem, which can be addressed through dynamic programming techniques; however, we propose a simple solution. Typically, we expect that traffic that is relayed would be larger than groomed one, thus, due to the exponential behavior of the blocking probability versus the number of wavelengths, we can distribute the target blocking probability such that the grooming blocking probability must be close to our target probability while the in-transit one must satisfy a more stringent requirement. Hence, our equations can be then stated as

$$\begin{aligned} B_{cw}^{ij} &\leq \epsilon B_{objective} \; ; \; B_{cw}^{j} \leq (1-\epsilon) B_{objective} \\ B_{cc}^{ij} &\leq \epsilon B_{objective} \; ; \; B_{cc}^{j} \leq (1-\epsilon) B_{objective} \end{aligned} \tag{4}$$

for $i, j = 1, \ldots, N, i \neq j$, where ϵ represents a small real number in the interval $[0, 1]$. In our analysis we have considered an $\epsilon = 0.1$. Hence, we can formulate our equations for W_{cw} and W_{cc} as

$$\begin{aligned} W_{cw} &= \min_{\substack{W \geq 1 \\ i,j \in \{1,\ldots N\}}} \{(W : B_{cw}^{ij} \leq \epsilon B_{objective}) + (W : B_{cw}^{j} \leq (1-\epsilon) B_{objective}\} \\ W_{cc} &= \min_{\substack{W \geq 1 \\ i,j \in \{1,\ldots N\}}} \{(W : B_{cc}^{ij} \leq \epsilon B_{objective}) + (W : B_{cc}^{j} \leq (1-\epsilon) B_{objective}\} \end{aligned} \tag{5}$$

for $i = 1, \ldots, N$. Finally, the maximum number of wavelengths for the OBS network is $W_{OBS} = W_{cw} + W_{cc}$.

2) The OCS case: For the case of OCS, the queueing probability is calculated using the Erlang-C formula, which assumes that the packet arrivals follow a Poisson process but it is insensitive to the packet length distribution. Let

$$\mathcal{C}(n, \rho) = \frac{n\rho^n / (n!(n-\rho))}{\sum_{k=0}^{n-1} \frac{\rho^k}{k!} + \frac{n\rho}{n!(n-\rho)}} \tag{6}$$

refer to the Erlang-C formula, where n is the number of wavelengths and ρ is the traffic intensity in Erlangs. Optical circuits are set up between any two nodes i and j such the $T_{ij} > 0$ for $i, j = 1, \ldots N$, following the shortest path in the number of hops sense. Let W_{ij} denote the number of wavelengths between node i and j, then

$$W_{ij} = \min_{W \geq 1} \{W : \mathcal{C}(W, T_{ij}/C) < B_{objective}\} \tag{7}$$

for $i, j = 1, \ldots, N, i \neq j$ such that $T_{ij} > 0$. Note that (7) only provides the number of wavelengths between two nodes, but not the number of wavelengths per node clockwise and counterclockwise. Let S^i_{cw} (S^i_{cc}) refer to the set of nodes clockwise (counterclockwise) from node i, as before, then the number of wavelengths $W^i_{O,cw}$ ($W^i_{O,cw}$) needed to set all lightpaths *originated at node* i is

$$\begin{aligned} W^i_{O,cw} &= \sum_{k \in S^i_{cw}} W_{ik} \\ W^i_{O,cc} &= \sum_{k \in S^i_{cc}} W_{ik} \end{aligned} \tag{8}$$

Next, let $S^{j^*}_{cw}$ ($S^{j^*}_{cc}$) refer to the set of nodes clockwise (counterclockwise) from node j such that $i \in S^{j^*}_{cw}$ ($i \in S^{j^*}_{cc}$). Then, the number of wavelengths $W^i_{R,cw}$ ($W^i_{R,cw}$) needed to relay all lightpaths routed clockwise (counterclockwise) through node i is

$$\begin{aligned} W^i_{R,cw} &= \sum_{k \in S^{j^*}_{cw}, k<i} W_{kj} \\ W^i_{R,cc} &= \sum_{k \in S^{j^*}_{cc}, k>i} W_{kj} \end{aligned} \tag{9}$$

for $i = 1, \ldots, N$, where the inequalities are in the $\mathrm{mod} N$ sense. Equations (5) and (10) provide the number of wavelengths per node clockwise and counterclockwise for OBS and OCS respectively.

$$\begin{aligned} W_{cw} &= \max_{i \in \{1, \ldots N\}} \{W^i_{O,cw} + W^i_{R,cw}\} \\ W_{cc} &= \max_{i \in \{1, \ldots N\}} \{W^i_{O,cc} + W^i_{R,cc}\} \end{aligned} \tag{10}$$

Finally, $W^{OCS} = W_{cw} + W_{cc}$.

D. Number of receivers

1) The OBS case: As for the number of receivers, the LHG algorithm allows, for the OBS case, to reduce the number of O/E receivers dramatically. Actually, since incoming traffic from neighboring nodes may only come from separate wavelengths, O/E converters are only needed for such wavelengths. Let O^i_{OBS} refer to the number of O/E receivers at node i for the OBS case, then, following (5),

$$O^i_{\text{OBS}} = \min_{\substack{W \geq 1 \\ j \in \{1,\ldots N\}}} \{W : B^{ji}_{cw} \leq (1-\epsilon) B_{objective}\} + \min_{\substack{W \geq 1 \\ j \in \{1,\ldots N\}}} \{W : B^{ji}_{cc} \leq (1-\epsilon) B_{objective}\} \quad (11)$$

and the total number of transceivers is given by $O_{\text{OBS}} = \sum_{i=1}^{N} O^i_{\text{OBS}}$.

2) The OCS case: On the other hand, an O/E receiver must be placed at the optical circuit destination. Thus, there is a one-to-one mapping between O/E receivers and optical circuits. Let O_{OCS} refer to the total number of O/E receivers at node i. Then,

$$O^i_{\text{OCS}} = \sum_{k \in S^i_{cw}} W_{ik} + \sum_{k \in S^i_{cc}} W_{ik} \quad (12)$$

for $i = 1, \ldots N$.

$$O_{\text{OCS}} = \sum_{i=1}^{N} O^i_{\text{OCS}} \quad (13)$$

where W^i_{cw} and W^i_{cc} are given by (8).

VI. Results and discussion

In this section, we describe different analysis that have been performed. As described in Section II, our analysis is focused on the traffic exchanged by metro-access nodes. These nodes act as traffic concentrators for the access network, while two of them are connected to the metro-core network (i.e., a dual-homed configuration) and it is assumed that these nodes perform opto-electronic conversion of inbound and outband traffic. It is out of the scope of this work to discuss which technology should be used for interconnecting the metro-access and metro-core rings. With respect to the metro-access ring, we have considered two metropolitan network scenarios: a small network with 5 nodes and a large one with 21 nodes. These scenarios illustrate network dimensions for small and large cities each scenario has been studied assuming either OCS, OBS, or hybrid OCS-OBS nodes. For hybrid nodes, we have studied the case where the network traffic is splitted in two networks: one based on OCS and the other on OBS. Our analysis consider two hybrid cases: a first one where only intra-ring traffic is handled by OBS technology and outbound/inbound ring traffic is handled by OCS; and a second one where OCS is only used for inbound traffic. Indeed, these analysis aim at identifying the advantages and disadvantages each technology offers in a metropolitan scenario.

On the other hand, two different network configurations (i.e., logical topologies) have been considered for OBS and OCS nodes: a first one referred to as mesh where all nodes can directly communicate in the optical domain with any other node, and a second one dubbed star, where all connections among nodes are switched electronically at the hub located at carrier premises. Typically, network carriers prefer this last configuration since it provides a centralized management and monitoring of all network connections; however, it requires the hub to process electronically the whole network traffic. The scope of considering both configurations is that of discussing their impact on the total network cost.

The purpose of considering different network sizes. types of nodes and network configuration aims at evaluating different migration strategies given a set of traffic scenarios that range from a quite conservative to a very optimistic one. It is worth mentioning that it is not trivial to compare all the proposed strategies. As described in Section V our goal is to provide a first-cut analysis as fair enough as possible while focusing on simple but dominant cost parameters: the maximum number of wavelengths and the cost of receivers. In fact, these parameters do not consider the cost associated to star configurations for switching all the traffic in electronics, thus, only when both parameters in the mesh configuration will be lower than in the star one, we will strictly consider more efficient the former rather than the latter. Moreover, although the cost of the control units in OBS is supposed to be higher than in OCS, this cost is not directly considered in our model. However, the results of our analysis can be usfeul to illustrate maximum costs of OBS control units, as discussed in the next sections.

A. Small Metropolitan Network: 5 nodes

We first focus our analysis on the 5 nodes' scenario and consider OBS and OCS nodes under the two possible network configurations. In Figure 6 we show results for the number of wavelengths and notice that neither the type of node nor the network configuration makes a big difference in terms of wavelengths. When considering OCS nodes the star configuration requires slightly fewer wavelengths for almost all scenarios due to benefits from aggregating links on lightpaths. Moreover, from our analysis, it results that the star configuration demands less lightpaths than the mesh one as more conservative scenarios are considered. Note that this also illustrates that aggregation benefits are always present despite the fact that intra-ring traffic in the star configuration requires traversing two lightpaths (i.e., two hops). As aggregation benefits diminish on very optimistic scenarios, the number of required lightpaths on both configurations tends to be almost the same. However, wavelength reuse benefits are more significant in the mesh configurations, thus, demanding slightly less wavelengths. Almost the same phenomenon can be appreciated for OBS nodes, where the mesh configuration helps to distribute better all traffic among nodes and less wavelengths are required to relay traffic while guaranteeing the maximum blocking probability.

In Figure 7 we consider the cost associated to receivers. At a first glance, the use of OCS nodes is the best solution, specially for conservative traffic scenarios. If we consider more optimistic scenarios with OCS nodes, then the mesh configuration overperforms the star one. As mentioned earlier, although the number of lightpaths tends to be the same on both configurations for optimistic scenarios, the mesh requires slower lightpaths, specially for intra-ring traffic, and consequently, cheaper receivers. If we now consider OBS nodes, we notice that for conservative scenarios the star configuration requires less receivers, while for optimistic ones, so does the mesh configuration. Note that for intra-ring traffic, the star configuration implies that bursts must first be received at the hub and then must be sent to nodes, thus, this configuration incurs extra cost for more receivers at the hub. On the other hand, note that these packets are sent to nodes that listen on the ring

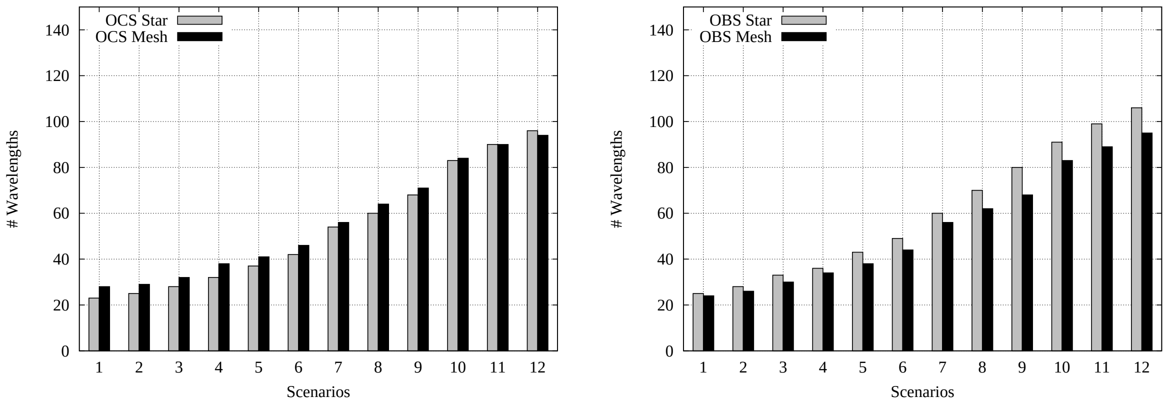

Fig. 6. Maximum number of wavelengths for 5-node network: OCS nodes (left), OBS nodes(right)

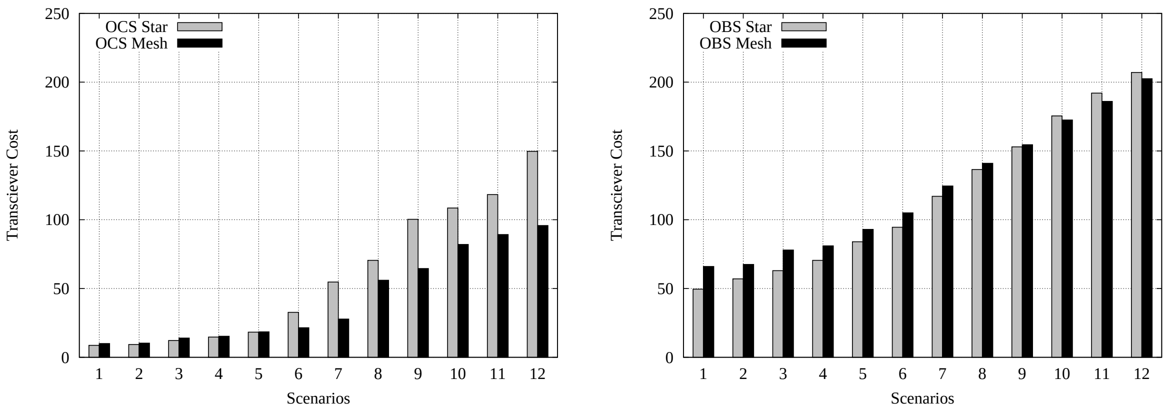

Fig. 7. Cost of receivers for 5-node network: OCS nodes (left), OBS nodes(right)

determined by the shortest path routing from the hub. Therefore, despite the extra receiver cost at the hub, all other nodes benefit from having only one set of receivers on one ring. Thus, all traffic addressed to these nodes is received aggregated on these receivers. This is not the case of the mesh configuration where each node receives traffic from both rings and each node has a set of receivers on each ring. As result, traffic addressed to these nodes is splitted in two set of receivers requiring more receivers than in the star case. Therefore, if we consider conservative scenarios the mesh configuration requires splitting low amount of intra-ring traffic on the two rings and the cost of receivers at nodes dominates the overall cost. On the contrary, if we move to more optimistic scenarios, the number of receivers on nodes is almost the same no matter the configuration except for the hub in the starconfiguration that requires more receivers for handling burst of intra-ring traffic. This is clearly illustrated in Figure 7 for OBS nodes and will be more evident in the 21-node network scenario.

In Figure 8 we consider the case when hybrid nodes are used. From Figures 6 and 7, it was clear that the OCS mesh configuration was the best one, requiring less than 100 wavelengths and a transceiver cost lower than 100. If hybrid nodes are considered, results show that handling intra-ring traffic with OBS technology and inbound/outbound traffic with OCS one is the best hybrid solution. However, despite hybrid solutions tend

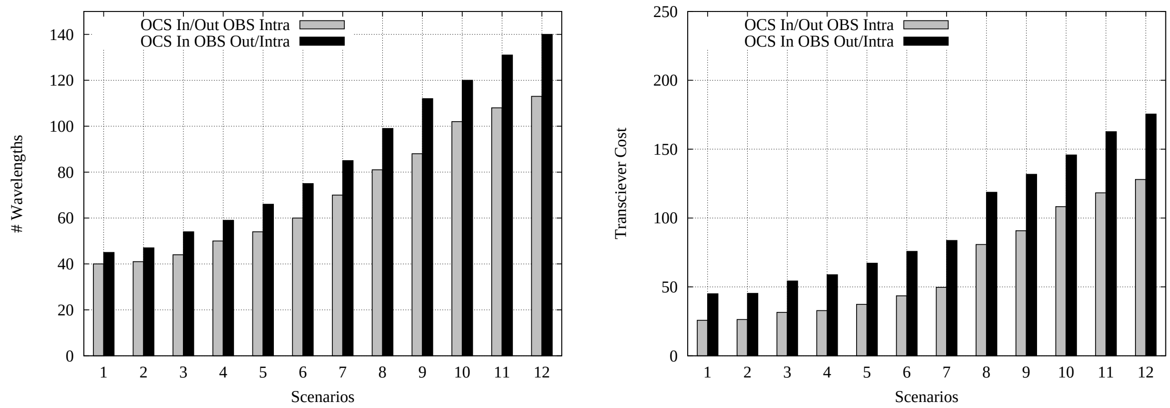

Fig. 8. Hybrid OCS/OBS for 5 nodes: Maximum number of wavelengths (left), Cost of receivers (right)

to decrease the cost of receivers near to the cost of OCS solutions, they require typically more wavelengths (i.e., more than 100) than both OBS and OCS solutions. We conclude that the OCS solution with a mesh configuration is the best strategy for small metropolitan networks as is it should be the cheapest in terms of wavelengths, transceivers and control units.

B. Large Metropolitan Network: 21 nodes

We now consider a large metropolitan network with 21 nodes. In Figure 9 we show results related to the number of wavelengths required for OCS and OBS nodes. While for the 5-node network there was little difference, for a 21-node network there is a huge difference among both solutions. Clearly, the OBS solution requires less wavelengths for all traffic scenarios. Besides, OCS and OBS exhibit different increase behavior as more optimistic scenarios are considered. While the number of wavelengths increases almost exponentially for OCS, it tends to saturate for OBS nodes. If we focus on OBS nodes, we notice that the mesh configuration overperforms the star one. Recall that the same behavior was appreciated for the 5 nodes network, but clearly for 21 nodes the difference is more significant. Thus, the mesh configuration distributes traffic among nodes minimizing the traffic that is relayed on each node's switch, resulting in less wavelengths allocated for this purpose.

In Figure 10 we consider the cost associated to receivers. Results indicate that for a large network, the difference in cost among the two solutions is quite insignificant. This was not the case for 5 nodes where OCS overperformed OBS. Besides, the mesh configuration overperforms the star one as more optimistic scenarios are taken into account as was also discussed for 5 nodes. As result, we can conclude that a mesh configuration with OBS nodes seems to be the best one among all four solutions, since it requires the least number of wavelengths while the cost of receivers is comparable to the lowest of all four solutions. However, in order to OBS be actually the best solution the additional cost associated to its control units should not exceed the cost related to the additional wavelengths required in the OCS case. In particular, we can conclude from Figure 9, that the cost of OBS control units should be lower than 100 wavelengths (Scenario 1) or even 1000 wavelengths (Scenario 12).

Finally, we consider the hybrid cases. Results shown in Figure 11 derive in the same conclusion that was discussed for 5 nodes. Although, hybrid nodes tend to minimize the cost of receivers they incur a large number of wavelengths. Indeed, hybrid solutions may require about 1200 wavelengths, while the OBS mesh solution demands only 400 wavelengths.

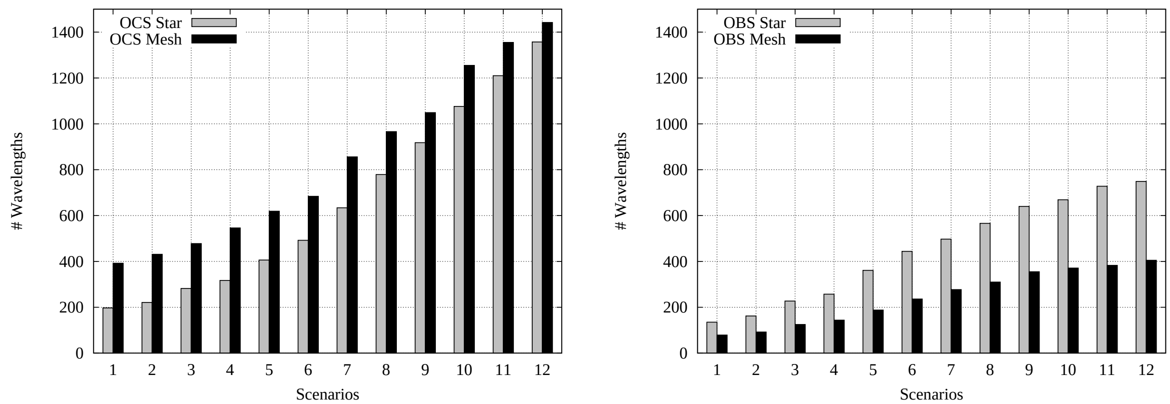

Fig. 9. Maximum number of wavelengths for a 21-node network: OCS nodes (left), OBS nodes (right)

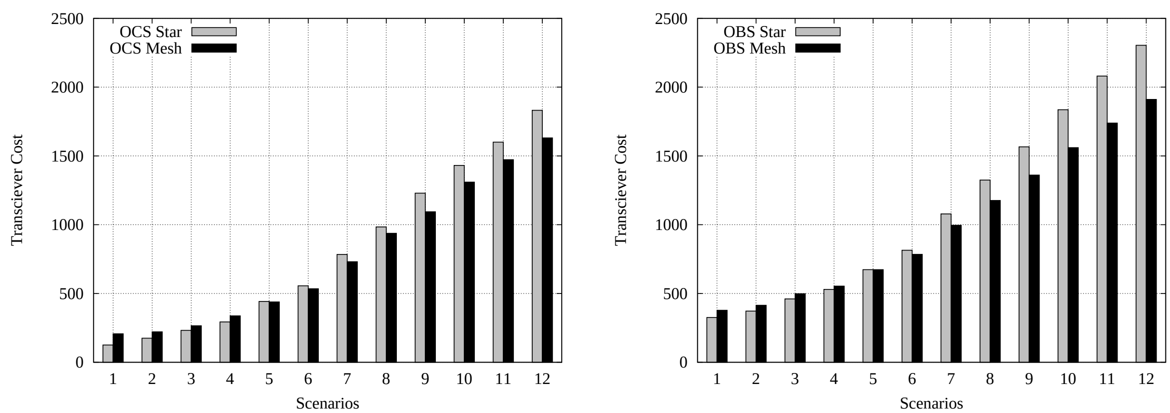

Fig. 10. Cost of receivers for 21 nodes network: OCS nodes (left), OBS nodes (right)

VII. Conclusions and future work

Currently, operators are spending lots of efforts to develop broadband access networks, but the next bottleneck in the short-term will be in metropolitan networks, which need to cope with a strong increase in traffic volume. In this paper, we have focused on the evaluation of different optical network architectures in the metro-access part. In particular, we have used Madrid's metropolitan access network as reference scenario for our study.

A series of techno-economic analysis about different solutions based on OCS, OBS and hybrid OCS&OBS architectures, to afford triple-play service requirements and the bandwidth xpected growing within next decade, have been reported an their results can be summarized as follows:

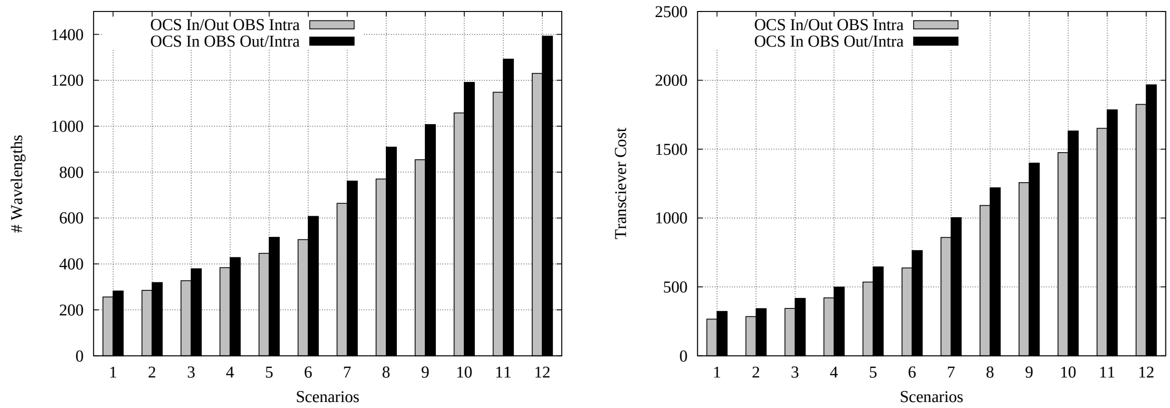

Fig. 11. Hybrid OCS/OBS for 21 nodes: Maximum number of wavelengths (left), Cost of receivers (right)

- In small metro access networks, hybrid solutions might lead to slight savings in transceiver cost, only in potential future scenarios characterized by an intensive use of VoD and P2P applications. On the other hand, these solutions always require more wavelengths than both OBS and OCS solutions.
- In large networks, hybrid solutions do not present savings neither in terms of lambdas nor transceivers. On the other hand, pure OBS solution require less lambdas for all traffic scenarios, but they typically introduce higher transceiver costs than OCS.

According to these results, we can derive that OCS might be more efficient than OBS in the metro access segment. However, we stress that this result has been obtained with the traffic mode presented in this paper, which is based on real traffic traces from working metro networks. As the traffic demand evolves with the introduction of new services further analysis will be required and the methodology presented here can be used to that end. As of today, though, we don't foresee any migration process towards OBS in the medium term, so that design aspects of current OCS deployments (switching and transceiver technology, number of lambdas, etc) might not need to consider OBS compatibility.

OBS technology seems no to be well adapted to the traffic patterns of metro access networks. Traffic in the metro access networks is characterized by a ”hub-and-spoke” topology, where a high percentage of the traffic has to pass through the Hub node in order to reach the Service PoPs located in the metro-core network. On the other hand, we have also noticed that as more distributed is the traffic as more efficient is OBS (e.g intra ring traffic). Therefore, OBS might be better adapted to metro-core networks with more distributed and dynamic traffic characteristics.

Taking into account the results of this study, we can identify several open issues for further work:

- The potential cost benefits in terms of CAPEX and OPEX of OBS in metro-core networks should still to be evaluated.
- Service oriented transport solutions might enhance the network operator's service portfolio leading to new business opportunities and improved service differentiation strategy. In that respect, different optical transport technologies might be better adapted to different types of traffic (e.g best effort, real time, streaming, etc).

References

[1] M. O'Mahony, D. Simeonidou, D. Hunter, and A. Tzanakaki, "The application of optical packet switching in future communication networks," *IEEE Communications Magazine*, vol. 39, no. 3, pp. 128–135, March 2001.

[2] C. Qiao and M. Yoo, "Optical Burst Switching OBS - A new paradigm for an optical internet," *Journal of High-Speed Networks*, vol. 8, no. 1, 1999.

[3] X. Yu, J. Li, X. Cao, Y. Chen, and C. Qiao, "Traffic statistics and performance evaluation in optical burst switched networks," *Journal of Lightwave Technology*, vol. 22, no. 12, pp. 2722–2738, Dec. 2004.

[4] Y Sun, T. Hashiguchi, V. Q. Minh, X. Wang, H. Morikawa, and T. Aoyama, "Design and implementation of an optical burst-switched network testbed," *IEEE Communications Magazine*, pp. 48–55, Nov. 2005.

[5] H. Guo, Z. Lan, J. Wu, Z. Gao, X. Li, J. Lin, and Y. Ji, "A testbed for optical burst switching network," in *Technical Digest of OFC 2005*, March 2005, vol. 5.

[6] K. Kitayama, M. Koga, H. Morikawa, S. Hara, and M Kawai, "Optical burst switching network testbed in japan," in *Technical Digest of OFC 2005*, March 2005, vol. 5.

[7] Y. Chen, C. Qiao, and X. Yu, "Optical Burst Switching: A new area in optical networking research," *IEEE Network*, vol. 18, pp. 16–23, May 2004.

[8] S. Sheeshia, Y. Chen, V. Anand, and C. Qiao, "Performance comparison of OBS and SONET in metropolitan ring networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 8, pp. 1474–1482, October 2004.

[9] A. Zapata, M. Düser, J. Spencer, P. Bayvel, I. de Miguel, D. Breuer, N. Hanik, and A. Gladisch, "Next-generation 100-Gigabit metro ethernet (100 GbME) using multiwavelength optical rings," *Journal of Lightwave Technology*, vol. 22, no. 11, pp. 2420–2434, Nov. 2004.

[10] J. Comellas, S. Sánchez, J. Conesa, S. Spadaro, and G. Junyent, "Performance evaluation of hybrid circuit/burst switching nodes," in *Proceedings of the International Conference on Transparent Optical Networks (ICTON) 2005*, 2005.

[11] F. Xue, S. J. B. Yoo, H. Yokoyama, and Y. Horiuchi, "Performance comparison of optical burst and circuit switched networks," in *Technical Digest of OFC 2005*, March 2005, vol. 6.

[12] T. Coutelen, H. Elbiaze, and B. Jaumard, "Performance comparison of OCS and OBS switching paradigms," in *Proceedings of the International Conference on Transparent Optical Networks (ICTON) 2005*, July 2005.

[13] H. L. Vu, A. Zalesky, E. Wong, Z. Rosberg, S. Murtaza, M. Zukerman, and R. Tucker, "Scalable performance evaluation of a hybrid optical switch," *IEEE Journal of Lightwave Technology*, vol. 23, no. 10, pp. 2961–2973, October 2005.

[14] E. W. M. Wong and M. Zukerman, "Analysis of an optical hybrid switch," *IEEE Communications Letters*, vol. 10, no. 2, pp. 108–110, February 2006.

[15] NOBEL, "Deliverable D30: Definition network scenarios and solutions supporting broadband services for all," Tech. Rep., IST NOBEL, 2005.

[16] M. VanBreda, "Architectures for end-to-end video delivery," Broadband World Forum, Oct. 2005.

[17] C. Develder, A. Stavdas, N. Le Sauze, P. Demeester, F. Neri, J. Fernández-Palacios, R. Van Caenegem, S. Sygletos, F. Neri, J. Solé-Pareta, M. Pickavet, A. Bianco, D. Careglio, and H. Lnsethagen, "Benchmarking and viability assessment of optical packet switching for metro networks," *Journal of Lightwave Technology*, vol. 22, no. 11, pp. 2435–2451, Nov. 2004.

[18] S. Pasqualini, S. Verbrugge, A. Kirstädter, A. Iselt, R. Chahine, D. Colle, M. Pickavet, and P. Demeester, "Influence of GMPLS on network providers operational expenditures - A quantitative study," *IEEE Communications Magazine*, vol. 43, no. 7, pp. 28–38, July 2005.

[19] S. Verbrugge, S. Pasqualini, F. Westphal, M. Jäger, A. Iselt, A. Kirstädter, R. Chahine, D. Colle, M. Pickavet, and P. Demeester, "Modeling operational expenditures for telecom operators," in *Proceedings ONDM'05*, Feb. 2005.

[20] X. Yu, C. Qiao, Y. Liu, and D. Towsley, "Performance evaluation of TCP implementations in OBS networks," Tech. Rep., Tech. Report 2003-13, CSE department, SUNY at Buffalo, 2003.

[21] M. Izal and J. Aracil, "On the influence of self similarity on optical burst switching traffic," in *Proceedings of GLOBECOM 2002*, 2002.

[22] K. Dolzer, C. Gauger, J. Späth, and S. Bodamer, "Evaluation of reservation mechanisms for optical burst switching," *International Journal of Electronics and Communications (AE)*, vol. 55, no. 1, 2001.