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Quantifying Bypass Traffic in Partially Meshed Transparent Optical Networks

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Abstract

This work investigates the transparent bypassing capacity requirements of elastic backbone optical networks to determine the all-optical cross-connection capacity needed at network nodes. Topological parameters have been used to develop a random network generator, and the generated topologies are evaluated. Reference values are obtained and applied to well-known topologies, and extensive simulations are conducted to obtain network nodes' bypassing traffic under realistic traffic profiles. The study reveals that although bypassing traffic varies by topology, it never exceeds 9% of total network traffic per node degree. These findings can help properly dimension network nodes by determining the necessary quantity of transceivers and cross-connection capacity based on the network topology and expected traffic.

Keywords Transparent optical network · Flex-grid network · Routing and spectrum allocation · Network topology · Network performance

1 Introduction

The always increasing bandwidth demanded by end-user applications has made the end-to-end transparent optical switched network as the de facto standard for high capacity transport networks. Successive evolutions from the original wavelength

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division multiplexing (WDM) optical networks have led to the elastic optical network (EON, [1, 2]) concept, where the optical fiber spectrum is discretized into finer spectral slots which can be contiguously reserved to form transparent optical connections tailored to any signal bandwidth. Further evolution brought the introduction of space division multiplexed (SDM, [3, 4]) networks where the end to end optical connections are not just based on efficient spectrum assignment but an extra degree of freedom is achieved by allowing to spatially switch channels (e.g. routing the generated connections through the different parallel cores multi-core optical fiber). A common characteristic is shared in any kind of transparent optical network, which obviously corresponds to the existence of bypass traffic at the intermediate nodes of the connection paths. Once information is converted to the optical domain at the source node, it keeps optical until it reaches the destination node. All the nodes included in the path (except the origin and destination ones) are just optically cross-connecting (OXC, [5]) any incoming optical connection to the appropriate output port according to the previously selected network path. Therefore, the network nodes are supposed to encompass some OXC capacity, usually consisting in N-by-M wavelength selective switches (WSS, [6]) where N and M correspond respectively to the number of input and output fibers linking the node to its neighbors. It is usual to consider N = M = ND (nodal degree of each node) in optical networks traffic engineering works when partial mesh topologies are studied. Depending on the network technology assumed this WSS can typically switch wavelengths, elastic optical connections of variable bandwidth, and even space switched channels [7]. The common characteristic to any of these technologies is that traffic is transparently transiting the intermediate nodes, so some kind of cross-connection capacity is needed at each one of them. Therefore, although this work has been focused on a typical flex-grid EON scenario, it could be leveraged to any kind of all-optical network technology.

In this study, the topological properties of optical networks are used as the basis to extract information about the necessary OXC capacity in their nodes. The OXC capacity of nodes in this study is defined as the total number of optical connections that the OXC can switch. In an EON network, the maximum number of optical connections that can be allocated in an optical fiber depends on the available spectrum and number of spectral slots used per connection. Therefore, we quantify OXC capacity in optical slots or channels throughout this work, as specifically defined in Sect. 3. To provide an example, a node with ND input/output fibers, where each fiber can transport up to W channels, would have a maximum OXC capacity of ND·W channels. This allows for a straightforward calculation of OXC capacity based on the number of input/output fibers and the number of channels transported per fiber.

Some previous works have dealt with obtaining information about the necessary network resources as a function of the network topology. Reference [8] obtained indication about the necessary number of wavelengths in traditional WDM wavelength-routed optical networks. Taking into consideration different topological parameters such as *physical connectivity* which relates the number of nodes with the number of links, *network diameter* or *average number of hops per connection*, they were able to figure out a value of the minimum number of wavelengths required to perform appropriately under some pre-determined traffic conditions. Further research on the effect of network topology on required number of wavelengths was carried out in [9]. A random network generation algorithm which takes into consideration the properties of real WAN networks was presented in that work. Statistical correlations between network topology properties and wavelength usage in WDM networks were found. More recently [10] studied relationship between topology and network throughput of arbitrarily-connected mesh networks, specifically analyzing the lengths distribution of the network paths and their influence in the connections' capacity.

A similar approach is followed in this work but the focus is now on the OXC capacity needed by the network nodes as a function of the topological characteristics. Having insight on the required OXC capacity per node can be useful at the networks design phase. Specifically, the number of devices required at each one of the network nodes can be better adjusted to the network requirements thus resulting in huge savings. The work is divided into two main blocks: (1) a generator of random networks, whose parameters are similar to those of the networks typically used in this area, and, (2) the evaluation through simulation of realistic flex-grid networks considering the results about nodes required OXC capacity previously obtained. The remaining of the paper is organized as follows. In Sect. 2, a study of the OXC required capacity in randomly generated networks (with some specific topology characteristics) is carried out. The results obtained in Sect. 2 are then applied to realistic dynamic flex-grid optical network scenarios, where typical transport network topologies are considered. The effects of limiting the OXC capacity on the network performance are evaluated by simulation under different conditions. Finally, the main conclusions of the work are summarized in Sect. 4.

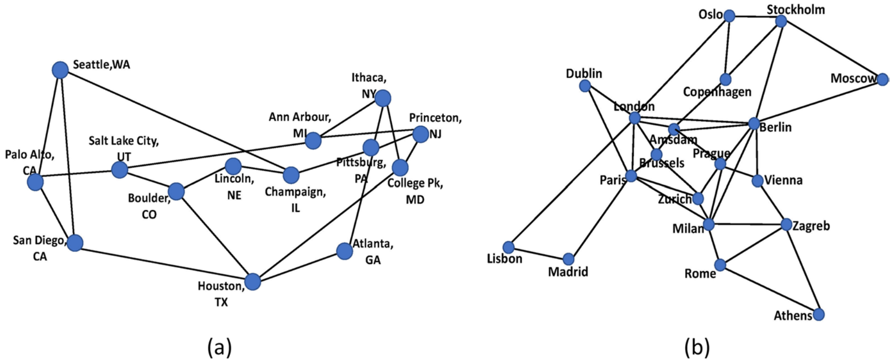
2 Random Partial Mesh Network Topologies Analysis

The main objective of this work is to give insight on the OXC capacity necessary to attain certain optical network performance. Many previous works focusing on traffic allocation in all-optical backbone networks have assumed unlimited OXC capacity in the nodes, thus being networks only limited by the spectrum available on fiber links and the number of transceivers in the nodes. In this study, a realistic estimation of the required OXC capacity necessary in all optical networks is obtained. It is quite obvious that the OXC capacity required at a node is directly related to its degree of connectivity (hereafter referred as nodal degree, ND). The higher the number of links reaching a node, the more likely this node will be an intermediate hop of different network paths. Therefore, OXC capacity is finally related to the network topology used. Different topologies have been used to study the performance of optical transport networks (a complete collection of them can be found in [11]). Transport network research works commonly utilize topologies with specific characteristics. These topologies typically consist of a moderate number of nodes, ranging from 10 to 20, and a corresponding number of links, ranging from 15 to 40. As a result, the average node degree (ND) usually falls within the range of 2.5 to 4. The design of optical backbone networks, where each node serves large geographical areas, differs slightly due to their high capacity requirements. These networks incorporate expensive, high-capacity, all-optical components capable of switching traffic streams whose bit-rates exceed 100 Gbit/s. US NSF (14 nodes, 21 links) and European EONet (19 nodes, 37 links) topologies are among the most used throughout transport networks literature [12, 13]. These partially meshed networks are shown in Fig. 1.

This study intends to obtain generic rules to calculate the expected bypass capacity necessary in these network topologies, and extend these rules to other similar topologies whose parameters, as stated previously, do not differ much from NSF and EONet (relevant networks topology characteristics were studied at [11]). To do that, a huge collection of random networks with topological characteristics similar to those of NSF and EONet are generated, and the required bypass capacity in each one of the network nodes is measured when all the possible end-to-end paths are created. When simulating a large number of connections uniformly distributed between any two network nodes (each simulation run in Sect. 3 will generate 6000 end-to-end connections), all the possible shortest paths in the network are utilized. As a result, analyzing all of the shortest paths within the network allows us to faithfully replicate the statistical patterns associated with generating uniform traffic between any source–destination pairs. The collection of random NSF and EONet similar networks is generated and studied using the following algorithm:

Random topology networks analysis algorithm

```
for 1 to number_of_networks do:
    generate random topology network algorithm (see below)
    for all the possible (N·(N-1)) source-destination pairs do:
        find the shortest path
        count for the bypassing paths at each intermediate path node
    end for
    record bypass traffic per node normalized to ND with respect to total #paths
end for
```



(a) (b)

Fig. 1 **a** NSF and **b** EONet transport network topologies

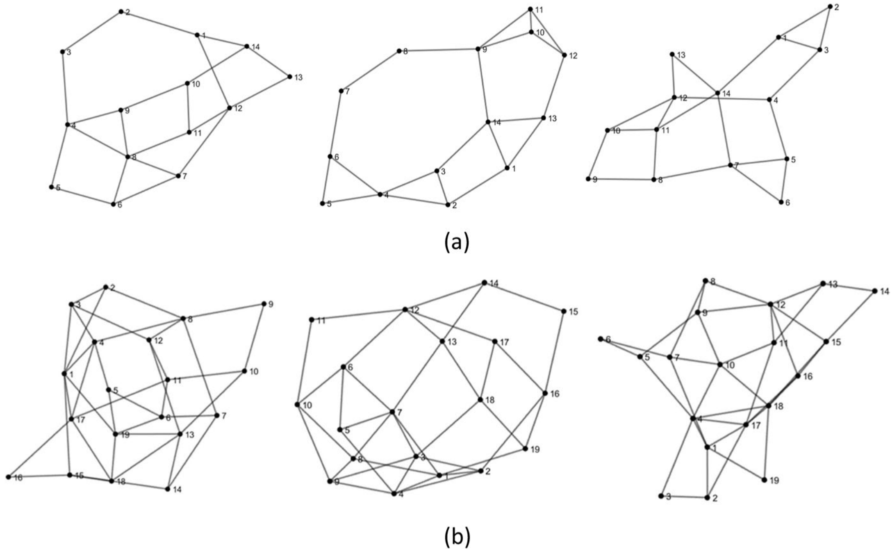
Generate random topology network algorithm

```
Set N (number of nodes), ND (average nodal degree) & max_ND (maximum nodal degree)
NLinks=round(N*ND)   % total number of links
Initialize s=d=zeros(1, Nlinks) %vectors with source & destination nodes of network links
for i=1 to N do  %an N nodes ring is generated (first N links created)
    s(i)=i
    d(i)=(i+1) MOD N
end for
for i =N+1 to NLinks do:  %remaining links are randomly added
    s(i)= random integer between 1 and N
    d(i)=s(i)
    while d(i)=s(i) OR (Frequency_of_s(i)_in_s>max_ND) OR (Frequency_of_d(i)_in_d >max_ND) do
        s(i)= random integer between 1 and N
        d(i)= random integer between 1 and N
    end while
    Add s(i) to d(i) to vectors s,d
    i=i+1
end for
generated_network=graph(s,d)
Set the network nodes locations and calculate the links lengths
```

The generated topologies have to fulfill some constraints. They require to be connected (no isolated subnetworks can be generated), so at least one path from any to any nodes always exists; the minimum ND for any node is 2 and the maximum ND has been limited to the maximum ND of NSF or EONet topologies, which are respectively 4 and 7.

With the aim of having statistically significant results, 100 different topologies with the same topological characteristics than NSF or EONet ($N = 14/19$, $L = 21/37$), $2 \leq ND \leq 4/7$) are generated. Some of the actual obtained network topologies are shown in Fig. 2.

As has been commented previously, the higher the ND (high nodal degree is usually referred as *degree centrality* in graph theory [14]) of a node is, the greater the probability that this node is traversed by different network routes. Although this statement is absolutely true at first glance, there is another factor to determine the amount of nodes' bypass traffic, which is related to the geographical position of the node in the network. Nodes located in geographically central areas will be much more visited by shortest paths than those located on the periphery. When nodes are placed at specific locations, and links reflect distances between nodes, geographical centrality is directly related to *closeness centrality* [14] because the distance from central nodes to the rest of nodes is smaller. This shorter distance allows central nodes to have higher *closeness centrality* values, as they can reach other nodes more efficiently compared to nodes located farther away. This is quite obvious from simple observation of Fig. 1. It is found that, for example in the NSF topology, Princeton node has a low amount of bypass traffic while Ann Arbor node (even having $ND = 3$ as Princeton) is one



(a)

(b)

Fig. 2 Examples of randomly generated network topologies. **a** NSF-like. **b** EONet-like

of the most transited nodes. Similar behavior is observed when analyzing the EONet topology. When all the N·(N – 1) = 342 possible shortest paths are generated, it has been found that Amsterdam node is much more used as intermediate hop than the Prague node, even considering that both of them are in relatively close locations and both have ND = 5. It is then concluded that other topological characteristics have some effect on the bypassing traffic in addition to nodes connectivity. Nevertheless, there is a clear correlation between ND and bypassing shortest paths, which is even stronger when traffic balancing strategies are applied, because the excessive node repetition would be avoided in that case. Therefore, the bypassing paths per node results obtained from the random topologies generation algorithm have been normalized to the respective ND value of each node. Results shown in Fig. 3 represent the statistical distribution of the percentage of shortest paths that cross by the generated nodes normalized to their respective ND values. This can be better understood by means of an example: if 20% of the network paths bypass Node X and its ND is equal to 4, the value represented in Fig. 3 is 20/4 = 5, so it will be accounted in the [5, 6) range. If its ND was 3, the value represented would be 20/3 = 6.67 and would belong to the [6, 7) range. It is observed how the *% of Node Bypassing Paths/ND* values in NSF-like topologies range from 0% (some nodes are never used as intermediate hops because they are placed at corner locations of the network) to 9% (few selected central and highly connected nodes are frequently transited by many different paths). It is noteworthy that for each one of the generated topologies the N * (N – 1) possible paths are calculated, and the number of times that every node is an intermediate hop of the paths is recorded. It is found that 95% of the nodes are intermediate path nodes (normalized to their ND) in less than 6% of

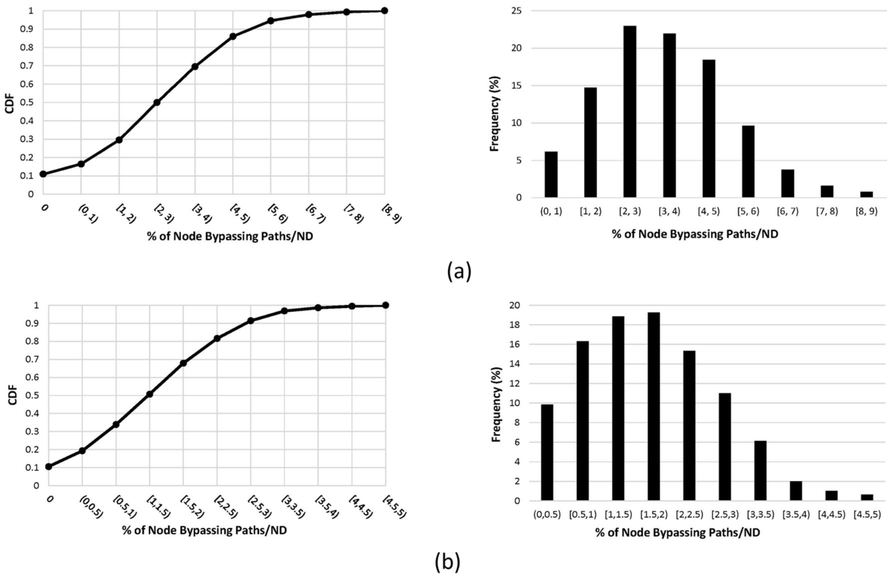


Fig. 3 Statistical distributions of the percentage of bypassing paths per node (normalized to its ND) after 100 random topologies have been generated. **a** NSF-like topologies. **b** EONet-like topologies

the total number of network paths. It has to be highlighted that this result will be very helpful at the nodes dimensioning network phase. The required number of optical cross-connecting ports can be set according to that value, so a clear and simple rule for nodes design has been obtained.

Regarding the EONet-like topologies, and due to its higher average nodal degree, the frequency of the nodes being intermediate hops of paths is reduced. In this case, the maximum observed percentage is 5%, and 95% of the nodes have a percentage of bypassing paths (again normalized to their respective ND values) smaller than 3.5%. These results are correlated with the expected percentage of bypassing traffic in this kind of partially meshed networks when uniform any-to-any nodes traffic is dynamically generated. In terms of statistical reliability, we analyzed the randomly generated networks to ensure that our results were accurate and robust. Our investigation showed that using 100 different topologies was sufficient to guarantee a deviation of less than 1% in the percentage of network paths visiting any of the network nodes. This finding supports the validity and consistency of our results, and ensures that the conclusions drawn from our analysis are statistically reliable.

Next Section is devoted to study flex-grid transparent networks performance under realistic generated traffic profiles. Optical switching network nodes will be limited taking into account the values obtained for required cross-connection capacity obtained in this section. The effects of limiting the nodes OXC capacity on the network performance will be studied and quantified, and clues about the OXC capacity needed in partially meshed all-optical networks nodes will be derived.

3 Effect of OXC Capacity Limitation on Transparent Flexgrid Optical Networks

In order to assess the results obtained in previous section, simulations for EON networks under realistic conditions have been performed. The main objective of this section is to evaluate the effect of limiting the OXC bypass capacity of network nodes on the whole network performance. To do so, a MATLAB based ad-hoc network simulator has been developed. Its main characteristics are detailed below:

- *Network nodes* are defined as a set of transceivers whose nominal capacity is established in terms of bandwidth. Concretely, each device is assumed to have capacity to send/receive the bitrate allocable to 25 GHz (which is hereafter referred as optical channel, OCh, in this study). Therefore, depending on the specific conditions of the path, allowing or not high order modulation formats, the spectral efficiency and therefore the OCh bitrate could change. For the sake of simplicity, a single value of 4 bit/(s Hz) has been considered throughout this study. It corresponds to using DP-QPSK [15] transmission, so the capacity of each transmitter (or OCh) is equal to 100 Gbit/s. It is important to note that in EON networks, the modulation format used is not fixed and can be selected based on physical constraints, such as the transparent path length. However, in this study, we have avoided addressing the modulation format selection as our primary focus is on the spectral slots transported and switched by the network elements. In addition to the transmitting/receiving capacity of nodes, the OXC capacity is the key parameter of this study. This OXC capacity is specified in terms of number of cross-connection units available per attached fiber. These cross-connection units have been defined using the same capacity as per the transceivers (OCh). The structure of the nodes considered in this work is represented in Fig. 4.

  As has been stated in previous Section, the bypass traffic supported by each node is correlated to its nodal degree; the more connected is a node the more likely it will belong to the list of intermediate nodes of the network paths. The developed simulator allows to adjust the nodes OXC capacity value. Evaluating the effect of this parameter on the network performance is a key objective of this study. It is also possible to adjust the number of transceivers per node, which is useful to understand the behavior of the network when the different types of resources are limited. Although the main focus of this work is on OXC dimensioning, comparing the effects of limiting nodes OXC capacity with those of limiting transceivers capacity is considered an added value of this work.
- *Fiber links* each fiber comprises 107 spectral slots of 37.5 GHz each. This value has been chosen considering two constraints: (1) each spectral slot has enough capacity to allocate one 25 GHz OCh plus 12.5 GHz for guard-band [2], and (2) the whole optical fiber C-band (about 4 THz) is covered by these 107 slots ($107 \cdot 37.5\ \text{GHz} = 4.01\ \text{THz}$). It is worth noting that without loss of

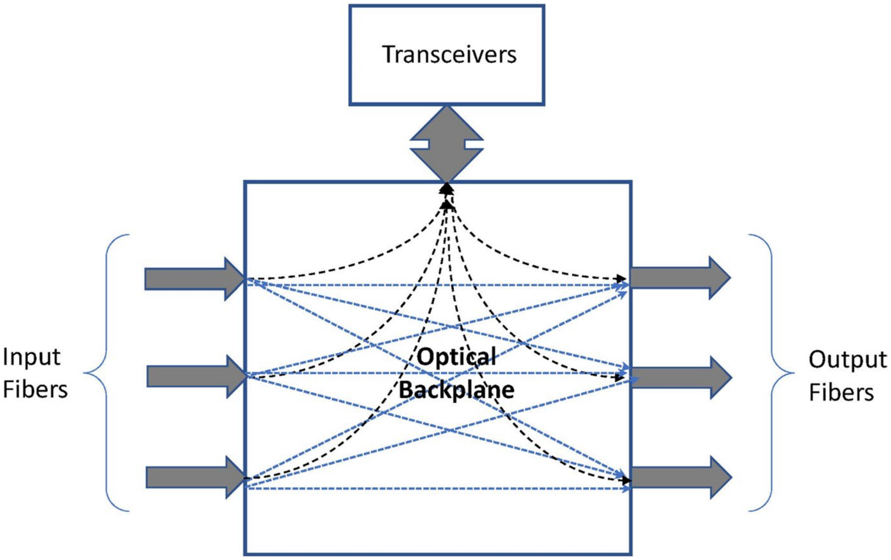


Fig. 4 Structure of the network nodes considered throughout this work. A central optical backplane connecting input and output fibers (ND = 3 in the example shown), and local transceivers where traffic is originated or destined. The granularity of the optical switch as well as the transceivers capacity is set to 1 OCh (25 GHz or 100 Gbit/s if DP-QPSK is applied)

generality the study could be extended to SDM scenarios where links are composed by parallel fibers, parallel cores of a multi-core fiber, or even independent modes in an SDM few-mode fiber [16].

- *Traffic generation* an elastic flex-grid optical network [2] scenario is considered where generated connections range (with uniform distribution) from 1 to 4 OCh (therefore corresponding to bit rates from 100 to 400 Gbit/s per connection). Hence, each generated connection will need a number of transceivers (at the end nodes) and OXC units (at every nodes in the path) in this 1 to 4 range. As for the origin and destination nodes of the generated traffic, uniform distribution from any to any nodes is assumed. This means that the N * (N – 1) possible network paths are equally probable to be set-up, so the study carried out in Sect. 2 makes sense. The inter-arrival time of connections in the network follows a Poisson distribution, with an average value of IAT (time units, t.u.). Similarly, the duration of connections is modeled by a negative exponential distribution, with an average value of HT (t.u.). As a result, adjusting the values of IAT and HT random processes allows for the adjustment of network load. Several influential research studies in the field of elastic optical backbone networks, such as [17, 18], have employed traffic models that exhibit similar statistical characteristics. The average network load after a simulation run is calculated as

$$Average\_Load = HT \ * \ Connection\_Size/IAT \ [OCh],$$

where *Connection_Size* corresponds to the average size (2.5 OCh as connection sizes are uniformly distributed between 1 and 4 OChs). The load values can be easily translated to transmission capacity as each OCh corresponds to 100 Gbit/s.

- *Network topologies* the 14 nodes, 21 links NSF topology and the 19 nodes, 37 links EONet topology have been simulated. To route each connection, a specific k-shortest path algorithm (with $k=3$) and first fit spectrum assignment is applied [19]. When no free resources are found at the shortest path, and taking into consideration that the cause of failed attempt is known (1: no continuous and contiguous fiber spectral slots, 2: lack of OXC capacity in an intermediate node, or 3: lack of transceivers at the end nodes), up to 3 successive attempts are tried if cause of blocking is 1 or 2 (when there are no available transmitters at the origin node or no receivers at the destination one, the connection is automatically blocked). In these successive attempts the failing link (in case 1) or node (in case 2) is temporarily withdrawn from the network and a new route is searched. By using this procedure, it is ensured that second and third shortest paths will not use the elements (fiber link or network node) which caused the failures in prior attempts.

Network performance is quantified in terms of blocking probability (BP), which is calculated by considering the bandwidth as well as the duration of each blocked connection. As an example, losing a connection whose bandwidth is 4 OChs and whose duration is 200 t.u. has an impact on BP 20 times higher than losing a connection whose bandwidth is 1 slot and duration 40 t.u. So, strictly speaking, the BP value corresponds to the transmission capacity lost with respect to the total capacity offered to the network. Indeed, it is well documented in flexgrid networks the unfair blocking effect [20], which implies that larger sized connections experience higher BP values as it is more difficult to find higher number of contiguous and continuous available spectral slots. Applying spectrum defragmentation mechanisms [21] to alleviate this problem is left for future study (no spectrum defragmentation is applied in this work).

Network load values shown in upcoming results figures are the average number of OCh values during the whole simulation (typically 6000 connections are generated at each run) excluding the transitory network filling phase when BP is calculated (the simulator starts calculating BP after two times the average HT t.u. have passed). The traffic alive (in number of OCh) during a complete run (NSF network) can be observed in Fig. 5.

The average duration in Fig. 5 example was set to 340 t.u., the average number of slots per connection is 2.5 (connection sizes uniformly distributed from 1 to 4 slots) and the BP was close to 1%. It is shown that even the average traffic value is close to 850 (corresponding to 340 * 2.5), there is a significant variance due to the randomness in the different parameters (duration, size and arrival rate) of the generated connections. The initial transitory network filling phase is clearly observed in Fig. 5, where an instantaneous traffic close to the average value is not reached until time is around 700 t.u. (about twice the average HT). As BP is negligible at this initial phase, it has been excluded from BP calculation in later results figures.

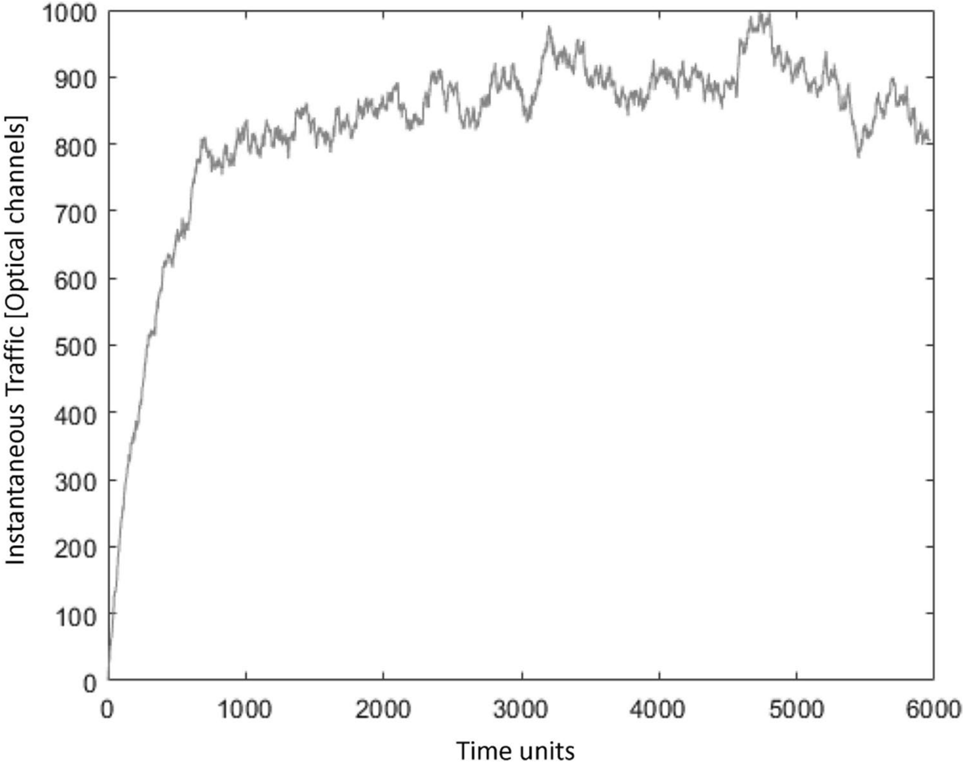
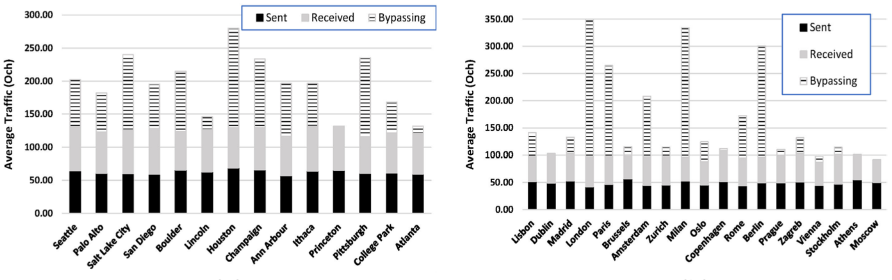


Fig. 5 Traffic alive in instantaneous number of optical channels alive during a 6000 t.u. simulation run using NSF network

A first interesting result consists in finding the values of bypass and terminating traffic for each one of the nodes of the studied topologies. To do that, uniformly distributed any-to-any nodes traffic is generated, and average values for sent, received and bypassing traffic for every nodes are recorded and averaged during a whole 6000 connections simulation run (HT and IAT have been appropriately adjusted to obtain BP = 1%). The results obtained are summarized in Fig. 6. As expected by simple observation of network topologies (represented in Fig. 1), Houston and Pittsburgh (both with ND = 4) as well as Salt Lake City and Champaign (whose ND = 3 but are centrally located from the geographical point of view) are the NSF nodes with a higher ratio of bypassing traffic, while the Sent and Received traffic is roughly similar for all nodes (uniform any-to-any nodes traffic is generated).

Similar conclusions are obtained from EONet network simulation (Fig. 6b). In this case, London and Berlin nodes (ND = 7), as well as Milan and Paris (ND = 6), are the most transparently transited ones. Again, the Sent and Received traffic is similar for all nodes because uniform all-to-all traffic is generated. When the bypassing traffic is normalized to the ND of each node, the key result of this study is found: the maximum OXC capacity used per ND never exceeds the 60% (75% for EONet topology) of the average transmitted/received traffic. This result is of capital importance in the design of the network nodes as the total number of necessary switching units per node can be easily derived from it. The fraction of bypassing traffic is greater in EONet network because the paths are longer in this topology, so the number of intermediate hops is also longer. Concretely, the average number of hops per path is 2.14 for NSF while it reaches 2.36 for EONet.

To better appreciate the arguments shown in the preceding paragraph, the following figure shows the real-time instantaneous values of the traffic sent, received and bypassing through the Lincoln and Houston nodes of the NSF network during a complete simulation run. Values in the vertical axis correspond to number of used OChs (37.5 GHz slots when considering fiber links). The load values in this simulation are IAT = 1 t.u. and HT = 350 t.u. As the connections size average value is 2.5 OCh, the average transmitted/received load per node is (350·2.5)/14 = 62.5 OCh. It is observed in Fig. 7 that the instantaneous values for sent and received traffic oscillate around this value in both nodes.



(a) (b)

Fig. 6 Average Sent, Received and Bypassing traffic at each node during a 6000 connections simulation. **a** NSF, and **b** EONet

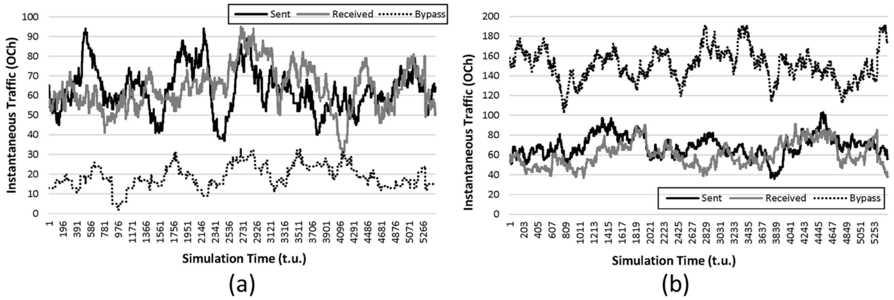


Fig. 7 Instantaneous sent, received and bypassing traffic at NSF **a** Lincoln and **b** Houston nodes during a complete simulation run (initial transitory simulation period has been omitted)

When looking at the bypassing traffic, great differences are observed between both nodes: while average bypass traffic at Lincoln is ranging around 20 OCh, it moves around 150 OCh in average at Houston, reaching values close to 190 OCh at some instants and with a minimum value over 100 OCh (at about 800 t.u. instant). Bypass traffic at Lincoln node just surpasses 30 OCh at few peaks. When the bypass traffic values of the nodes are divided by their respective ND the enormous differences are reduced and it is found that bypassing traffic (per ND) at any node is clearly below sent and received traffic. Concretely, and as can be seen in Fig. 8, the maximum reached values are somewhat below 40 OCh per node degree in both networks, which correspond respectively to 4.5% to the total NSF load, and to 3.6% in the EONet topology case.

As explained previously, one of the main objectives of this work is to measure the impact of limiting the nodes OXC capacity in the whole network performance. The methodology followed to obtain reliable results on this question consists in carrying out a first simulation assuming unlimited number of resources (transceivers and OXC) in the nodes. This way the theoretical load supported by the network when the only limitation is the fibers capacity is obtained. It is important to highlight once again that this exercise could be extended to the SDM case [3] without loss

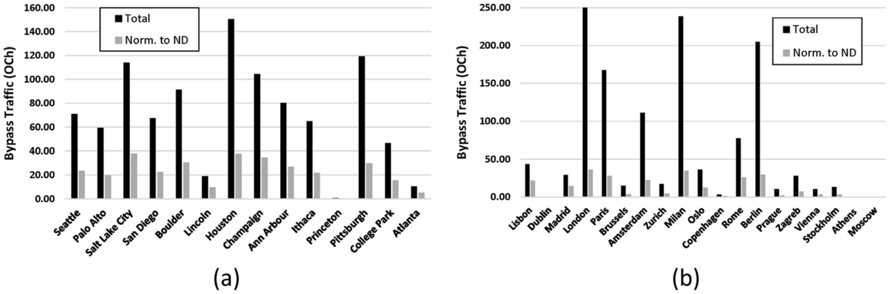


Fig. 8 Average bypassing traffic: total per node, and normalized to the respective ND values. **a** NSF topology. **b** EONet topology (dotted lines correspond to the average transmitted/received traffic per node)

of generality. Specifically, the network load is adjusted so as to reach BP = 1% for unlimited transceivers and OXC capacity. Using the obtained network load value, the number of transceivers per node as well as the number of OXC units is reduced until some effect on BP is observed. In fact, the simulator reports about the origin of each blocked connection, discriminating between "Fiber", "Transceivers" or "OXC" blocking. Once the available resources are defined, different simulations are run at different network loads and BP at each load is found. Results obtained for both tested topologies are shown in Fig. 9.

When looking at the NSF network topology graph (Fig. 9a), it is observed that BP = 1% when the average network load is about 87.5 Tbit/s. At this point, fiber is approximately causing half of the blocking (0.5%), while transceivers are responsible for 0.3% of blocking and OXC for the remaining 0.2%. For higher network load values, fiber keeps always as the main source of blocking. The number of transceivers per node in Fig. 9a has been adjusted to 105 OChs. Considering that generated connections bandwidth sizes are uniformly distributed between 1 and 4 OCh (2.5 OCh per connection in average), every node would support a maximum generated/received capacity around 42 average sized connections. In a similar way, the OXC capacity of the nodes (switches dedicated to bypassing traffic) has been set to 52 OChs multiplied by their respective ND values. Taking the results obtained in previous section, 95% of the nodes support a bypass traffic per nodal degree smaller than 6% of the total number of connections. With the traffic profile simulated, 87.5 Tbit/s correspond to:

$$350\ Connections \times 2.5\ OCh/connection \times 100\ \text{Gbit/s}/OCh = 87.5\ \text{Tbit/s}.$$

Therefore, 350 is the average number of connections during the whole simulation (as shown in Fig. 5 instantaneous traffic is changing due to the randomness in the traffic generation process). The 6% of total network load correspond to 21 connections. Assuming the average size of 2.5 OCh/connection this corresponds to 52.5 OCh, which has been set as the OXC capacity value per node degree during simulations.

As for the EONet network simulations (Fig. 9b), similar behavior is observed. In this case, fiber links are the main source of BP for low load values, but lack

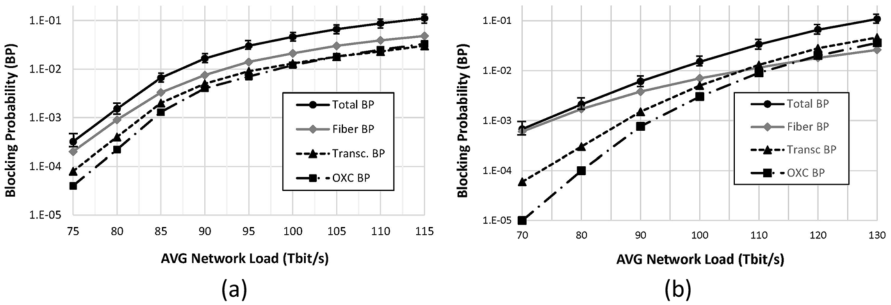


Fig. 9 Blocking probability vs. average network load. **a** NSF topology. **b** EONet topology. 95% Confidence interval bars are plotted

of transceivers and OXC capacity generate more blocking when network load is increased. This is due to the higher nodal degree of EONet topology which allow finding alternative paths when there is lack of free spectral slots on the more crowded fiber links. For the EONet network, BP = 1% is attained for a network load value equal to 95 Tbit/s. The network resources in this case have been also adjusted to ensure that the three causes (fiber, transceivers and OXC) contribute to the total BP. In this case the number of transceivers per node is 86, while the OXC capacity of network nodes has been set to 45 OChs multiplied by their respective ND values. The minimum OXC capacity per degree guaranteeing that 95% of the nodes are able to handle all the required connections bypassing them was obtained in Sect. 2 and its value is 3.5% of the total network load. The average number of connections alive during simulation in this case is 390 * 2.5 = 975 OChs, so its 3.5% is about 34 OCh. Nevertheless, it has to be taken into account that the average number of hops in EONet topology (considering the kSP path selection algorithm used) is 2.36. Therefore, every connection is transparently bypassing 1.36 nodes so the necessary OXC capacity per node degree is 34*1.36 = 46.4 OCh.

Once the network performance with the suitable number of resources has been evaluated, next objective is measuring the impact of limiting network nodes resources. While the primary focus of this work is on the study of the required OXC capacity, our latest simulations also compare the effects of limiting OXC resources with those of limiting the number of transceivers. It is worth noting that transceivers and the optical switch (OXC) are the primary building blocks of optical nodes, as illustrated in Fig. 4. Thus, this comparison provides a valuable addition to our work and helps to further enhance our understanding of network performance under various resource constraints. Two different simulations have been carried out to obtain these results: starting from a network with the number of resources considered in Fig. 8 (which is considered the “base case” scenario where the supported traffic is considered 100%), the network resources have been gradually reduced and the effect of this reduction on network performance is analyzed. Specifically, one of the parameters (*OXC capacity* or *transceivers per node*) is gradually reduced in 10% steps, while keeping the other with its “base case” value. For each reduction step, the average network load is adjusted to keep BP = 1%. Results obtained in this last simulation are shown in Fig. 10. It is found that the impact of reducing the number of transceivers per node is higher than that caused by the nodes OXC capacity reduction.

Concretely, it can be seen at the NSF network that for 50% of reduction in OXC capacity the network load at BP = 1% is 47 Tbit/s while for 50% of reduction in number of transceivers the load value which allows keeping BP = 1% is 39 Tbit/s. It can be then concluded that lack of transceivers has a worse impact in the network performance than lack of OXC capacity. Same trend is observed at the EONet network, although in this case the impact of resources reduction is in general higher. As an example, the load supported with 50% of reduction is in the best case below 45 Tbit/s, so the decrease in supported load is higher than in the NSF case where for 50% of OXC capacity reduction the supported load was still over 50% of its initial value.

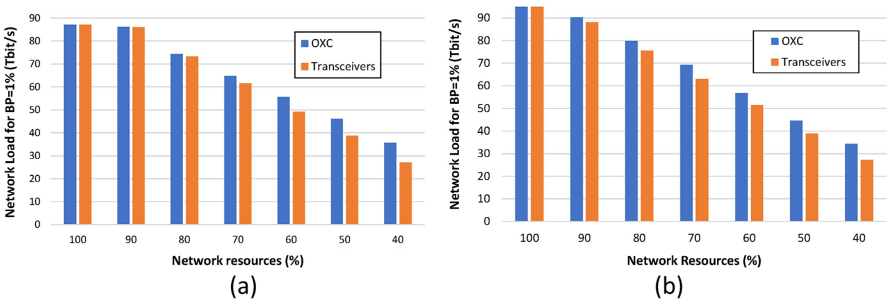


Fig. 10 Network load for BP = 1% when network resources (OXC capacity or transceivers per node) are reduced. **a** NSF. **b** EONet

All in all, the effect of OXC capacity limitation on transparent EONs has been analyzed, and some practical orientation values have been obtained by means of extensive simulations. The results found for randomly generated networks, whose topological characteristics are similar to those of NSF and EONet networks, have been tested in these existing topologies. Results obtained when realistic traffic profiles are applied to NSF and EONet networks fit quite well with the expected values. The results could be summarized in that the required OXC capacity (per node degree) is between 60 and 75% (depending on the actual network topology) of the average sent (or received) traffic per node, assuming uniformly distributed source–destination pairs. A general rule for the design of optical switching nodes is therefore obtained: the required number of optical switching units (OCh) required is under these reference values. If the network architecture under consideration is changed, for example assuming evolution to SDM networks, this reference value would hold as it is only a function of the network topology and the generated traffic profile. Therefore, the work here presented could be very helpful at the optical network nodes design stage.

4 Conclusions

In this work, we have obtained reference values for the required nodes OXC capacity in transparent EONs. To achieve this, we first evaluated the transit traffic in randomly generated networks and found a clear relation between bypassing traffic and nodal degree, which we normalized to provide generic reference values. Our main finding is that bypassing traffic (per ND) at any node is always below 10% of the total network traffic for typical transport network topologies. We have also determined that limiting the OXC capacity of network nodes to around 60% of their transmitted/received traffic ensures proper network performance under the studied traffic profiles. This value can be a simple rule of thumb to guide the design phase of real network nodes.

Moreover, we have shown that the lack of transceivers has more severe effects on network performance than the lack of OXC capacity. This is because intermediate path nodes lacking OXC capacity can be avoided by using alternative network paths, whereas there is no solution when there are no transmitters at the origin node or no available receivers at the destination node. Our findings provide valuable insights into the design and optimization of transparent optical networks and can serve as a reference for future research in this area.

Authors Contributions JC started working on the manuscript topic and proposed the main ideas. JC and FH developed the simulator and extract results from it. GJ collaborated in the analysis of the results. All authors collaborated on writing and reviewing the manuscript.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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