**WSS requirements in Next-Generation Wavelength Switched Optical Networks**

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**Abstract:** We investigate how the WSS port-count requirement scales with traffic, transmission technologies, fiber types and amplification schemes in future WSONs. The highest benefits come with the Hybrid-EDFA implementation.

**OCIS codes:** 060.4256 Networks, network optimization, 060.4251 Networks, assignment and routing algorithms.

1. Introduction
Optical communication networks are experiencing an increasing penetration of Reconfigurable Optical Add/Drop Multiplexers (ROADMs) into the core and metro segments as all optical switching fabric enabling the high level of automation and efficiency required by Wavelength Switched Optical Networks (WSONs) [1]. According to Infonetics Research, the optical networking equipment market has been growing by an annual rate of 8% since 2002 while ROADDM market has grown by 46% annually between 2005 and 2009 [2]. For current and future ROADMs, the Wavelength Selective Switches (WSS) represent the core switching elements. We recall that a 1xN WSS is a device switching one or more selected wavelengths from the input port to anyone of the N output ports; the device is reciprocal (input and output can be reversed).

The port size of WSS is a critical parameter for WSS-based ROADMs since the number of WSS ports must be at least equal to the number of adjacent DWDM links plus the number of Add/Drop modules. This limits the nodal degree and the number of added/dropped lightpaths, thus the scalability of the node [1]. 1x9 and recently 1x20 WSS are commercially available and some attempts to provide very high port-count WSS (e.g., 1x43) are underway [3]. In this study we want to investigate the impact of a) capacity of the transmission systems, b) optical reach, c) amplification scheme and d) type of fiber, on the WSS port-count requirements in a real WSON. We address the WSS port-count scalability by performing network design on the recently deployed Telecom Italia’s national WSON with realistic traffic values and traffic growth-rate projections.

2. Problem Formulation

**Network Architecture and Design**

The network under study is shown in Fig. 1. It is a state of the art WSON with 44 nodes and 71 DWDM links covering the whole Italian territory. The average nodal degree is 3.2 and network diameter is 2100 km [4].

We have developed a WSON planning tool which performs the Impairment Aware Routing, Fiber and Wavelength Assignment with Regenerator Placement (IA RFWA-RP) addressing colorless/directionless/contentionless ROADMs and coherent systems’ features. The impairment awareness is based on the OSNR calculation as in [5] and the estimated OSNR thresholds required to achieve a BER of $10^{-3}$ at the receiver (before FEC) are taken from [6]. Each traffic demand is routed and the amount of resources is evaluated. Particularly, resources for each connection comprise: WDM channels (one for each crossed link), Transponders (TXPs), Regenerators (3Rs) and Add/Drop ROADM module ports (i.e., WSS and splitter/coupler ports). All DWDM systems have the same maximum number of WDM channels $W$, thus if more channels are needed, parallel systems can be deployed. Similarly, more Add/Drop modules can be installed in the node if necessary. We assume that at each Add/Drop module, cascading of WSS and splitters takes place, such that a number of Add/Drop ports equal to $W$ is available. Further details are omitted.

**Traffic scenarios**

In order to evaluate WSS port-count scalability, a benchmark traffic matrix is considered reflecting the current traffic requirement, taken from [4]. Its composition is shown in Table I. A scale factor from 2 to 128 has been applied to the total traffic volume though assuming that IP and wholesale traffic increase more than OTN traffic. Approximately 12 years (2024) are estimated to achieve the maximum traffic growth (x128) with a very optimistic annual traffic-rate.
increment of 50%. Assuming a more realistic 25% increase per year [7], more than 20 years (2032) are needed to achieve the final traffic volume. In the following we will refer to the 50% yearly growth-rate as “GR-50” and to the 25% yearly growth-rate as “GR-25”.

<table>
<thead>
<tr>
<th>Traffic Source</th>
<th>Values</th>
<th>IP backbone</th>
<th>4.7 Tb/s</th>
<th>OTN</th>
<th>5.1 Tb/s</th>
<th>λ-wholesale</th>
<th>0.2 Tb/s</th>
<th>TOTAL</th>
<th>10 Tb/s</th>
</tr>
</thead>
</table>

Table I. Benchmark traffic matrix structure.

| Baud-rate | Upto 250 Tb/s with 1x20 WSS. | A good compromise is represented by the 200G technology, which shows the best performance in terms of scalability. | PDM-16 QAM 400G transmission systems. We have set an overhead of about 8% corresponding to an hard FEC and the baud rate of each system is 56 Gbaud (thus compatible with a 33.3 GHz grid). As for the 400G, we have chosen a 40 Gbaud transmission [9] occupying 75 GHz. In this case, the number of channels in each DWDM systems is reduced: W=53 with EDFA and W=126 with HRA. Table II reports the estimated reach values for G.655 and G.652 fibers. The OSNR threshold values are derived from Fig. 4 of [6] and the reach values are obtained by considering a maximum span length of 80 km at optimal launch power.

Table II. Optical reach values for each technology. Baud-rate, spacing and net bit-rate are reported on the left.

<table>
<thead>
<tr>
<th>Technology</th>
<th>G.652 Reach</th>
<th>G.655 Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDFA</td>
<td>3271 km</td>
<td>1907 km</td>
</tr>
<tr>
<td>HRA</td>
<td>6268 km</td>
<td>3633 km</td>
</tr>
<tr>
<td>G.652</td>
<td>3633 km</td>
<td>1446 km</td>
</tr>
<tr>
<td>G.655</td>
<td>1446 km</td>
<td>742 km</td>
</tr>
</tbody>
</table>

Technology scenarios
We have addressed two main scenarios: EDFA and hybrid Raman/EDFA (HRA) amplification-based WSONs. The EDFA scheme has a total amplification optical bandwidth of 4 THz (32 nm) whereas in the HRA case we can exploit a 8 THz (65 nm) bandwidth [8]. We have modeled the superior noise performance of Raman-based optical amplifiers by decreasing the OSNR required thresholds reported in [6] of 3 dB. In the EDFA case each transmission system can support W=120 channels 33.3 GHz spaced apart, whereas W=240 channels at 33.3 GHz spacing can be supported by HRA. We have chosen 33.3 GHz since it provides the maximum transmission reach-spectral efficiency product for many practical modulation formats [6]. We assume that any WSS in the node is capable of switching 33.3 GHz spaced signals.

We have considered coherent PDM-BPSK 50G, PDM-QPSK 100G, PDM-8QAM 150G, PDM-16QAM 200G and PDM-16 QAM 400G transmission systems. We have set an overhead of about 8% corresponding to an hard FEC and the baud rate of each system is 28 Gbaud (thus compatible with a 33.3 GHz grid). As for the 400G, we have chosen a 56 Gbaud transmission [9] occupying 75 GHz. In this case, the number of channels in each DWD system is reduced: W=53 with EDFA and W=126 with HRA. Table II reports the estimated reach values for G.655 and G.652 fibers. The OSNR threshold values are derived from Fig. 4 of [6] and the reach values are obtained by considering a maximum span length of 80 km at optimal launch power.

3. Illustrative Numerical Results

The maximum values of WSS port size required in a certain network node for each transmission technology are reported in Fig. 2. Results for Double Star and Mesh traffic with both EDFA (dotted) and HRA (continuous) and G.655 fibers are presented. Figures 2a,b show in detail a limited range of traffic values, though simulations have been carried out up to a traffic scale of 128.

The first remarkable result from Fig. 2a is that 1x9 WSS are no longer sufficient for traffic beyond 70 Tb/s if the EDFA scheme is used. The recently standardized 100G technology along with EDFA scheme needs a WSS port size larger than 1x20 to support traffic values beyond 100 Tb/s. 400G allows increasing the data-rate at the cost of reducing the optical reach and the number of wavelengths per fiber: with EDFA and 1x20 WSS, up to 150 Tb/s can be sustained. A good compromise is represented by the 200G technology, which shows the best performance in terms of scalability (up to 250 Tb/s with 1x20 WSS).

In the Mesh traffic, much more lightpaths are set up with respect to the Double Star case but the “meshed” nature of the traffic has the beneficial effect of “spreading” more uniformly the WSS port occupancy over the network nodes. On the downside, as longer connections are requested, short reach transmission technologies suffer from the need of frequent 3R regenerations. This has an impact on the WSS port saturation since more Add/Drop modules may be required. Particularly, if the EDFA scheme is used, Fig. 2b shows that 1x9 WSS do not support traffic beyond 60 Tb/s
and 400G cannot be used with WSS port size less than 1x14, thus supporting up to 120 Tb/s with 1x20 WSS. However, the overall performance is increased though: in any case, lower WSS port size than Double Star are needed.

<table>
<thead>
<tr>
<th>Traffic [x10 Tb/s]</th>
<th>Double Star logical topology</th>
<th>Mesh logical topology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EDFA</td>
<td>HRA</td>
</tr>
<tr>
<td>100G</td>
<td>1.4058</td>
<td>0.6953</td>
</tr>
<tr>
<td>150G</td>
<td>0.9333</td>
<td>0.4677</td>
</tr>
<tr>
<td>200G</td>
<td>0.6953</td>
<td>0.3477</td>
</tr>
<tr>
<td>400G</td>
<td>0.7864</td>
<td>0.3941</td>
</tr>
</tbody>
</table>

Table III. Slope values of the WSS port-count requirement functions [Wss port size]/(10 Tb/s)].

An important result is that the WSS port-count requirement scales linearly with traffic for values above 150 Tb/s, independently on traffic type, technology, fiber and amplification scheme. Table III reports the slope values of the WSS port size requirement functions for all the simulation scenarios. Very high values can be therefore attained over the years (traffic): e.g., at the highest simulated traffic value (x128, within 10 years in the worst case), 200G and 400G would require 1x95 and 1x107 WSS respectively in the Double Star with G.655 fibers. However, the introduction of HRA can be highly beneficial in reducing the slope of each function (see Table III). In fact, we can save up to about 50% beyond 150 Tb/s in terms of WSS port-count in all cases. We reported that up to 500 Tb/s can be supported with 1x20 WSS and reasonable values of WSS port size can therefore be achieved even at the highest simulated traffic. As an example, in order to support 1280 Tb/s, WSS 1x42 (200G) and 1x48 (400G) are requested with Mesh traffic while 1x49 (200G) and 1x55 (400G) are required for the Double Star with G.655 fibers.

Finally, the enhanced transmission performance of G.652 fibers result in very low savings in terms of WSS port-count requirement. Table III shows that the slope of the WSS port-count functions can be reduced of up to almost the 1% in the Double Star and 8% in the Mesh with respect to G.655 case, due to traffic distribution.

Summarizing the previous results, in this work we have estimated the WSS port-count requirements in a real WSON with realistic traffic value: we have showed that 1x9 WSS can resist up to 60-70 Tb/s (year 2017 GR-50 or 2021 GR-25) along with the EDFA scheme and up to 500 Tb/s (year 2022 GR-50 or 2030 GR-25) can be supported by 1x20 WSS with HRA scheme. We reported that WSS port-count increases linearly with traffic but we can achieve about 50% of WSS port savings by employing HRA in all simulated scenarios. Fiber type is slightly relevant only in the Mesh traffic case.

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References
2. Infonetics research, ROADM Components, March 2010.