Assessing the Scalability of Next-Generation Wavelength Switched Optical Networks

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I. Introduction

ULTRA-HIGH definition video, 3-D Internet, 3-D multimedia, multimedia-supported social networks are some of the new broadband services responsible for the current growth of traffic demand. In the next 10 years, yearly traffic growth-rate is expected to be within 25% and 50% [1]. Therefore, optical transport of per-channel bit-rates beyond 100 Gb/s is under active research. As a matter of fact, 100 Gb/s technologies have been already standardized in 2010 for both Ethernet and optical transport network (OTN), and 400 Gb/s and 1 Tb/s interfaces are candidates to become the transmission systems for next-generation photonic networks [2].

During the last decade, not only transmission systems but also network architectures have faced tremendous changes. While current optical networks are static, wavelength switched optical networks (WSONs) represent the next step towards fully flexible and dynamic networking to cope with the increasing demand of emerging dynamic applications. In order to "operationalize" dynamicity in optical networking a suite of control plane protocols and a reconfigurable optical layer are needed. As for the former, new software defined networking and OpenFlow-based control planes are gaining momentum. However, for carrier-core long distance network applications, generalized multiprotocol label switching still represents the primary solution. As for the latter, colorless-directionless-contentionless (CD&C) reconfigurable optical add/drop multiplexers (ROADMs) enable the high level of automation and efficiency requested by WSONs [3].

For current and future ROADMs, the wavelength selective switches (WSS) represent the core switching elements. The port number of WSS is a critical parameter for WSS-based ROADMs, since this is the number of WSS ports that must be at least equal to the number of adjacent dense wavelength division multiplexing (DWDM) links plus the number of add/drop modules. We refer to it as the *feasibility* constraint of WSONs. The feasibility constraint limits the nodal degree and the number of added/dropped lightpaths or in other words the maximum traffic that optical nodes can manage (i.e., the *scalability* of the node) [4]. The deployment of a WSON represents a huge investment for telecom operators. Thus, the network design phase has to be carefully addressed in order to prevent cost and energy waste.

II. Prior Works

Recent developments in planning approaches for impairment aware optical networks are reviewed in [5]. Most of the cited papers propose a quality of transmission (QoT) estimator and perform impairment aware routing, by fibre and wavelength assignment with regenerator placement (IA RFWA-RP) algorithm to carry out network design. However, the features of coherent transmission systems and WSS-based ROADMs are not addressed. In [6] authors deal with Impairments Awareness versus Impairment Unawareness when designing the network accounting also for ROADM-like flexible network nodes. Comprehensive studies on modelling transmission impairments in future WSON have been proposed in [7] and in [8]. In the former, no network design phase has been carried out, while in the latter authors focused only on the number of optoelectronic (OE) interfaces. In [9], the author performs network design addressing both coherent systems and WSS-based ROADMs but focusing only on the number of OE devices. A novel WSON planning procedure has been illustrated in [10], where some preliminary results have been reported.

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Despite the importance of evaluating the impact of traffic growth on network architecture, none of the cited works propose a method for assessing the scalability of future WSONs. In [11] authors performed a photonic-layer scalability analysis considering different evolution scenarios. With respect to [11]: a) we have developed an ad-hoc scalability analysis algorithm, b) we consider a more realistic QoT estimator for coherent systems instead of a reach-based approach, c) we address all the features of WSS-based ROADMs instead of neglecting the add/drop contention constraints in the routing process, d) we perform a cost and energy consumption analysis in order to envision for the first time to our knowledge the future roadmap of network upgrades of a real WSON.

The rest of this paper is organized as follows. Section III describes the network model. Section IV shows our novel approach to assess WSON scalability and our procedure to outline the roadmap for technological upgrades. Section V presents the case-study network Kaleidon, including: traffic assumptions, growth-rate projections, technology scenarios, CAPEX and power consumption models. In Section VI, we report the results of our investigation and Section VII highlights the concluding remarks.

III. Network Model

The aim of a network designer is planning the network to satisfy a client traffic demand given a topology, under constraints regarding budget, technology, power consumption, etc. In the specific case of translucent WSONs the data plane has to be dimensioned in terms of: a) number of DWDM systems, b) number of channels per fibre, c) amplifiers and transmission technology, d) ROADMs' input/out (I/O) and add/drop (A/D) sections, e) OE devices (i.e., Transponders (TXPs) and 3R regenerators).

Fig. 1 shows the devices involved in our design phase, considering a "broadcast-and-select" ROADM architecture [3]. Particularly, for any connection request, one or more WDM channels (for each crossed link), TXPs, 3Rs and A/D ROADM module ports (i.e., WSS and splitter/coupler (S/C) ports) may be needed to satisfy the demanded traffic.

In this study we assume that all DWDM systems have the same maximum number of WDM channels W; thus if more channels are needed, parallel systems can be installed. Furthermore, we consider that at each A/D module, cascading of WSS and S/C takes place, so that W ports are available (i.e., at most W TXPs can be connected at each A/D side). In fact, as was the case with DWDM systems, parallel A/D modules can be deployed if more than W ports are needed or the same wavelength is added/dropped more than once in the same node (i.e., contentionless [3]).

It is worth mentioning that WSS ports on the A/D side may also saturate by increasing the number of DWDM systems. However, the feasibility is driven by the I/O WSS ports, since they have as input both A/D modules and DWDM systems (see Fig. 1).

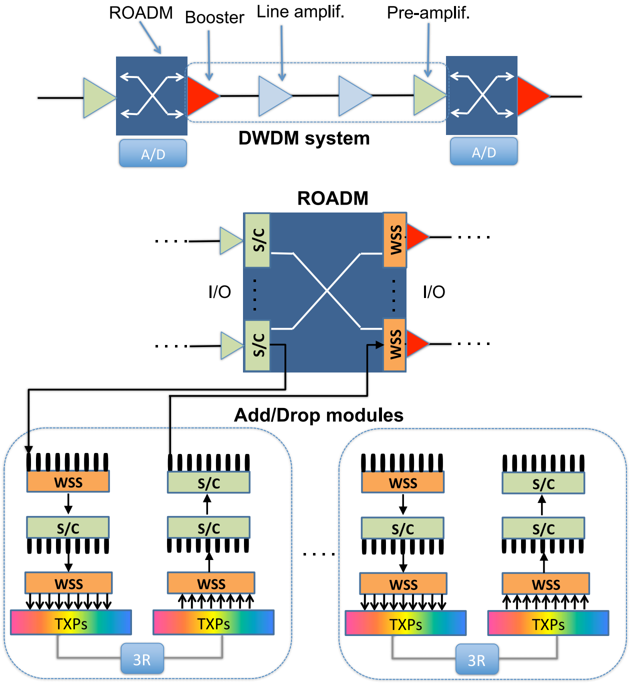


Fig. 1. Devices involved in the WSON design phase.

IV. Scalability Analysis and Efficiency Assessment

Our novel approach to assess WSON scalability is composed by three main functions: 1) traffic modelling, 2) IA RFWA-RP and 3) feasibility check. In the following we refer to "technology" as a case-study scenario given by a certain combination of a) amplification type, b) fibre type, c) transmission systems and d) WSS port size. Details on the scenarios investigated in this paper are reported in Section V-B.

The output of the scalability analysis for each technology is used as the input to the efficiency assessment procedure which evaluates the CAPEX and power consumption in order to draw an evolutionary path of network upgrades. In this section, we report the details of each building block; then we summarize the algorithmic procedures.

A. *Traffic Modelling*

The traffic generation process is also of paramount importance to contain the amount of simulations for network scalability evaluation.

The first step involves a benchmark traffic matrix whose total aggregated traffic value T [Gb/s] is composed by j traffic types (e.g., IP, OTN, etc.) that are given a certain value α_j as the portion of the total traffic T which comes from the traffic type j.

Second, starting from the benchmark matrix, we create the traffic matrices for our investigation by iteratively scaling traffic values with a given traffic growth-rate G_r, which may be considered as the annual projected traffic increase. A realistic value of yearly traffic increase is $G_r = 25\%$ or a very optimistic value is $G_r = 50\%$ [1]. A maximum traffic value $T_{\max}$ [Gb/s] is set, which corresponds to the limit of the scalability investigation.

We define the set of the investigation points as I, such that $i = \{1, \ldots, N\}$ where $T_{i=1} = T$ and $T_N = T_{\max}$. The value of α_{ji} for each ith investigated traffic matrix can be either kept fixed (i.e., the same as for the benchmark matrix) or allowed to vary according to a suitable function $f(i)$. For example, the IP contribution to the total traffic is projected to increase over the years, whereas the portion of OTN decreases, and so on.

In order to obtain more accurate results, the scalability analysis might be required to be intensified around some specific traffic values T_i. This is achieved by an algorithmic procedure reported in Section IV-D.

B. The IA RFWA-RP Algorithm

Our heuristic network planning procedure makes use of the RFWA-RP approach described in [12] and extended to be applicable to ROADMs and coherent WDM transmission systems. In order to model the switching features of WSS-based CD&C ROADMs [4], we exploit the logical graph modelling technique called *Variable Detailed Graph* (VDG), patented in 2004 by PIRELLI SPA and TELECOM ITALIA SPA [13]. Details of the VDG and the comparison with another common modelling technique (i.e., the layered graph) can be found in [14]. The description of the ROADM Arc-based model we have implemented is beyond the scope of this paper.

By dealing with IA RFWA-RP in a ROADM-based network, the routing algorithm must be carefully designed in order to address the issues arising particularly when intermediate regenerations are needed. Since end-to-end connection provisioning is typically bidirectional, operators expect a certain symmetry of assigned resources between *upstream* and *downstream* flows for practical reasons of resources management (e.g., failure restoration and localization, etc.) and cost. Therefore, some constraints have to be enforced: 1) upstream and downstream lightpaths must traverse the same set of network nodes and ducts; 2) the assigned wavelengths must coincide in each transparent segment in both directions; 3) regeneration must occur at the same network nodes. Particularly, 2 and 3 are crucial in WSS-based ROADMs since regeneration is a two-step process which requires a cross availability at the drop and at the add side (see Fig. 1).

The implemented impairment awareness is based on the optical signal to noise ration (OSNR) calculation as in [7] and the estimated OSNR thresholds required to achieve a bit error rate (BER) of 10^{-3} at the receiver (before forward error correction (FEC)) can be taken from [15] for a variety of transmission technologies. For each simulated traffic matrix, we route every connection request and we compute the overall amount of needed resources, though maximizing the use of those already deployed.

C. WSON Feasibility

By increasing the traffic, an increasing number of DWDM systems and A/D modules has to be installed to accommodate all the requested connections, as well as WSS, S/Cs, TXPs and 3Rs. As mentioned above, WSS port size introduces the so-called feasibility constraint: a given I/O WSS (and S/Cs) can saturate if its port size is less than the nodal degree (number of incoming/outgoing fibres) plus the number of A/D modules (see [4]). If this limit is exceeded even at just one single node, larger port size WSS (and S/Cs) have to be installed in the network; thus, we define the network *unfeasible*, i.e., being unable to support a specific traffic when provided with WSS of that size. In fact, we have assumed that the same type of WSS is deployed in the network for practical reasons of resources management and control plane operations.

D. Scalability Algorithmic Procedure

A simplified scheme of the complete procedure to assess WSON scalability is reported in Fig. 2(a). First of all, the network topology is given as input along with the technology scenario. The procedure starts by setting the input traffic parameters (i.e., benchmark traffic matrix, $T_{\max}$, G_r, and α_{ji}). Then, the traffic generation block iteratively generates the traffic matrix corresponding to a given T_i value as explained in Section IV-A.

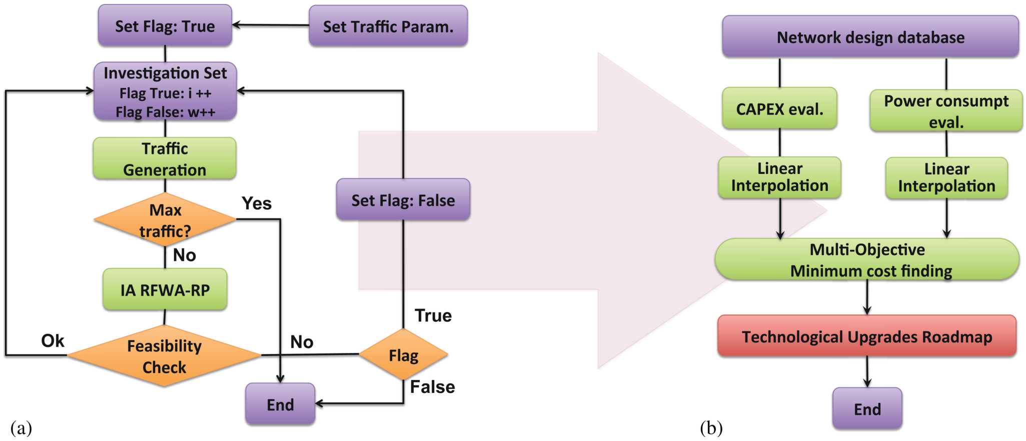
Before running the IA RFWA-RP design phase, a check is performed to test whether $T_{\max}$ has been reached. Starting from $i = 1$ (i.e., the benchmark traffic matrix), the design is accomplished and then the WSON feasibility is evaluated for the given WSS port size under investigation. Then, the procedure continues by investigating the traffic matrices corresponding to the investigation points $i > 1$ until the feasibility check is violated at the $\bar{i}th$ point. In this case, a deeper analysis on the discontinuity point (i.e., between $\bar{i} - 1$ and $\bar{i}$) is required. Flag value is now set to false to go back into the design procedure and to iteratively generate traffic matrices equal to $T_{\bar{i}-1} + w \cdot \Delta T$, where ΔT [Gb/s] is preset as detail level of the analysis, w is integer $w \geq 1$ and $\bar{i}-1$ was the investigated point before the feasibility check was violated. Also, the flag value set to false will enforce that when the feasibility check fails for the second time at a certain $\bar{w}$ counter value, the procedure ends thus returning $T_{\bar{i}-1} + (\bar{w} - 1) \cdot \Delta T$ as the maximum scalability value for the simulated scenario.

This procedure allows us to reduce the investigation points and thus the number of design simulations. It has been successfully applied to a variety of case studies as we will show in Section VI. The output of the scalability analysis procedure is the input to the network efficiency assessment.

E. Network Efficiency Assessment

Fig. 2(b) shows the flowchart of the proposed efficiency assessment procedure. This is a heuristic procedure which aims at finding the technology solution which gives the lowest network cost for each investigated traffic value.

After the scalability analysis is performed for each investigated scenario, the results of the design phase for each simulated traffic value are stored in a dedicated network design database. We then carry out a CAPEX and power consumption evaluation by using appropriate cost models, such as those presented in the next section. Since with different technology scenarios we may obtain different final scalability values, we deduce a common set S of simulated traffic values T_s. If a given traffic T_s was not formerly simulated for a given technology, we linearly



(a) (b)

Fig. 2. Flowchart of the proposed (a) scalability analysis procedure, (b) network efficiency assessment.

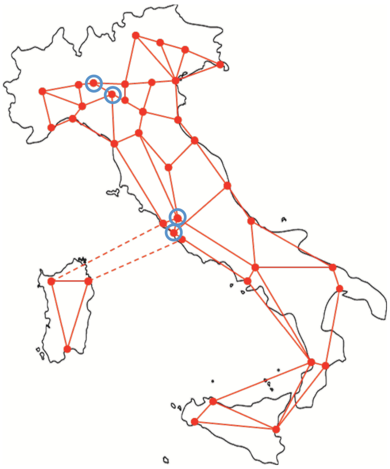


Fig. 3. Italian backbone WSON Kaleidon.

interpolate both the CAPEX and power consumption. Next, for each sth point and for each technology scenario we calculate a global cost given by

$$G_s = \beta \cdot C_s + \gamma \cdot P_s \tag{1}$$

where C_s and P_s are respectively the CAPEX and power consumption values at the s-th simulation point for a given technology scenario. Two different objectives are defined: (i) CAPEX minimization and (ii) power consumption minimization. The coefficients β and γ allow us to select one of the two as the primary objective, while the other serves as the secondary objective. If multiple solutions satisfy the primary objective, then the solution performing better in terms of the secondary objective is selected. Finally, the roadmap for technological upgrades can be drawn by reporting the technology scenario which returns the lowest network cost C_s for each simulation point s.

V. NETWORK CASE STUDY

The network under study, Kaleidon, is a state of the art WSON with 44 nodes and 71 DWDM links covering the whole Italian territory. The network graph is shown in Fig. 3. The average nodal degree is 3.2 and network diameter is 2100 Km.

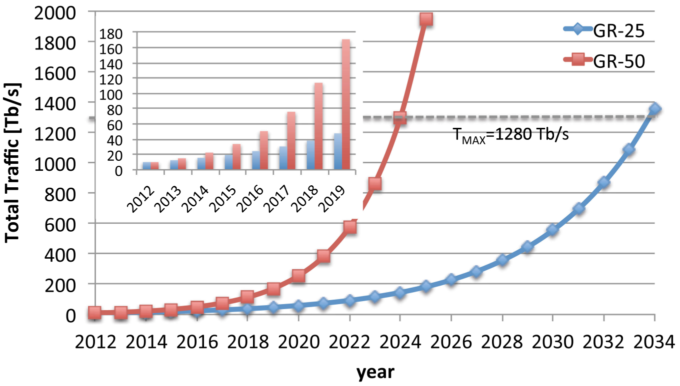


Fig. 4. Yearly traffic growth-rate projections: GR-50 and GR-25.

A. Traffic Assumptions

We have set the maximum investigation value $T_{\max} = 1280$ Tb/s, the accuracy step $\Delta T = 10$ Tb/s and we have used two growth-rate projections G_r, 25% and 50%, whose reference values are reported in Fig. 4. In the following we will refer to $G_r = 25\%$ and $G_r = 50\%$ as GR-25 and GR-50, respectively.

The traffic matrix considered as benchmark encompasses demands coming from three sources: the IP backbone network ($j = 1$), the overlay OTN network ($j = 2$) and a number of OCh dedicated to the lambda wholesale (WHL) customers ($j = 3$). The total traffic is 10 Tb/s of which 4.7 Tb/s come from IP, 5.1 Tb/s is OTN and 0.2 Tb/s is WHL [11]. These figures correspond to the traffic transported by Telecom Italia's Kaleidon through year 2012. Thus $T_1 = 10$ Tb/s is the starting point of our analysis, $i = 1$.

In order to determine the total amount of traffic at the ith investigation point generated by each traffic source j, we have chosen the $f_j(i)$ as logarithmic functions based on realistic traffic-growth projections, such that, while at the benchmark traffic $\alpha_{1j} = [47\%, 51\%, 2\%]$, when approaching 200 Tb/s (i.e., approx. year 2020 with GR-50, year 2026 with GR-25) then the traffic contributions tend to 80%, 12% and 8% for the IP, the OTN and the WHL, respectively. These values do not reflect Telecom Italia's official traffic projections but have been chosen to provide a realistic-like analysis.

TABLE I
$OSNR_{\text{req}}$ AND CORRESPONDING REACH VALUES FOR EDFA AND HRA

	EDFA			HRA	
	OSNR_{req}	G.652 Reach	G.655 Reach	G.652 Reach	G.655 Reach
50G	9.6 dB	6834 km	3895 km		
100G	12.2 dB	3271 km	1907 km	6268 km	3633 km
150G	16.2 dB	1302 km	750 km	2495 km	1446 km
200G	19.1 dB	668 km	389 km	1280 km	742 km
400G	22.1 dB	675 km	394 km	1279 km	741 km

In the current Telecom Italia's infrastructure, all IP traffic from the north and south part of the country is aggregated in two sites: Milan and Rome. Therefore, we have modelled this condition by considering a *Double Star* logical topology in which flows to/from peripheral nodes are aggregated by two couples of hub nodes (circled in blue, Fig. 3) which are mutually interconnected by a full mesh of backbone logical links. We have also considered the *Mesh* case as an evolution of current needs of IP connectivity, in which there is a direct logical link between most of the pairs of nodes. OTN and WHL traffic is the same in both the considered cases. For each investigation point, 30% of the overall traffic requests are protected with dedicated link-disjoint path protection. In the Double Star case, 50% of connections use path distance equal to or less than 400 Km. This value increases to 520 Km in the Mesh traffic matrix. In both cases, all the connections are requested for source-destination distances equal or less than 2100 Km.

B. Technology Scenarios

Any WSON scenario we have simulated in this study is a combination of four technological solutions, one from each of the following groups: A) amplification type, B) fibre type, C) transmission system, and D) WSS port size.

A) We have considered two main amplification types: Erbium doped fibre amplifier (EDFA) and hybrid Raman/EDFA (HRA) amplification. The EDFA scheme has a total amplification optical bandwidth of about 4.5 THz whereas in the HRA case we can extend the bandwidth to almost 9 THz by using both C and L bands [16]. We have modelled the superior OSNR performance of HRA by decreasing the noise figure (NF) of the amplifiers so that the optical reach is doubled.

B) G.655 and G.652 fibres are addressed in this study: the main difference is related to the dispersion coefficient D and the effective area A_{eff}, while the attenuation is almost the same. Typical values for G.652 are $D = 17$ [ps/(nm km)] and $A_{\text{eff}} = 86$ [μm^2], whereas for G.655, $D = 4$ [ps/(nm km)] and $A_{\text{eff}} = 72$ [μm^2]. Regarding coherent transmission, the average reach allowed by G.655 fibres is about 55% of the average reach of the G.652 fibres. The main reasons for this gap are smaller noise accumulation, reduced nonlinear effects and high local dispersion [7].

TABLE II
CAPEX AND POWER CONSUMPTION VALUES FOR WSON DESIGN

	CAPEX [SCU]	Power Cons. [W]
EDFA band C Amplifier 2 ways	1.9	100
HRA band C+L Amplifier 2 ways	3.8	300
Pre-Amplifier/Booster	0.8	20
WSS 1x9 (including splitter)	4	100
ROADM control (WSS 1x9)		100
WSS 1x20 (including splitter)	6	200
ROADM control (WSS 1x20)		200
TXP 50G	6	150
TXP 100G	15	350
TXP 150G	16.5	525
TXP 200G	18	700
TXP 400G	22	723
3R 50G	9.6	180
3R 100G	24	420
3R 150G	26	630
3R 200G	28	840
3R 400G	35	867

C) Two main categories for single carrier transmission systems: DWDM systems at 28 Gbaud transmission occupying 37.5 GHz including guardbands; 56 Gbaud transmission occupying 87.5 GHz including guardbands, both with an overhead of about 8% corresponding to an hard FEC. For the first case, coherent polarization-division-multiplexing binary phase shift keying (PDM-BPSK) at 50 Gb/s (50G), PDM-Quadrature PSK (PDM-QPSK) at 100 Gb/s (100G), PDM-8 Quadrature Amplitude Modulation (PDM-8 QAM) at 150 Gb/s (150G), PDM-16 QAM 200 Gb/s (200G) are considered. As for the second case, PDM-16 QAM 400 Gb/s (400G) [17] is simulated in this study. We assume that with 37.5 GHz spacing, we can fit $W = 120$ wavelengths per fibre by using the EDFA amplification scheme and $W = 240$ by the HRA while $W = 51$ (EDFA) and $W = 102$ (HRA) for 87.5 GHz spacing. Note that we assumed 50G to be end-of-life by the time HRA systems will be widely implemented in core networks, thus we do not investigate that particular scenario.

D) WSS are here available in two configurations: 1 × 9 and 1 × 20. The former is well consolidated while the latter is starting to appear on the market [21].

Table I reports the estimated reach values for G.655 and G.652 fibres and the OSNR threshold values to achieve a BER of 10^{-3} derived from [15, Fig. 4]. Optical reach values in ideal network state are obtained at the optimal launch power considering a maximum span length of 80 Km. Note that 400G optical reach is within that of 150G and 200G. In fact, given the modulation format and bandwidth assumptions, a) the spectral efficiency [bit/s/Hz] for 400G is higher than that of 150G but lower than 200G and b) due to larger bandwidth requirements of 400G transmission less channels are supported in the C band when using 87.5 GHz spacing, thus resulting in lower impairments.

C. CAPEX and Power Consumption Models

Most of the values used for our capital expenditure (CAPEX) and power-consumption analysis reported in Table II come from [18], [19] where all the cost values are normalized to the cost in the year 2012 of a 10 Gb/s TXP with a transparent reach of 750 Km. This value is named STRONGEST Cost Unit (SCU) [19].

In order to model all the technology scenarios under investigation, we made the following assumptions:

1) the HRA amplifier costs two times the EDFA as it manages both band C+L, whereas EDFA gives amplification only to band C;

TABLE III
SCALABILITY LIMITS IN THE EDFA SCENARIO FOR DOUBLE STAR AND MESH LOGICAL TRAFFIC TOPOLOGIES

	Double Star				***Mesh***			
	G.652		**G.655**		**G.652**		**G.655**	
	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20
EDFA	*Max. Traffic*		*Max. Traffic*		*Max. Traffic*		*Max. Traffic*	
50G	20 Tb/s	50 Tb/s	20 Tb/s	50 Tb/s	20 Tb/s	60 Tb/s	20 Tb/s	60 Tb/s
100G	30 Tb/s	100 Tb/s	30 Tb/s	100 Tb/s	30 Tb/s	120 Tb/s	30 Tb/s	120 Tb/s
150G	50 Tb/s	150 Tb/s	50 Tb/s	150 Tb/s	50 Tb/s	180 Tb/s	50 Tb/s	180 Tb/s
200G	60 Tb/s	200 Tb/s	60 Tb/s	200 Tb/s	50 Tb/s	200 Tb/s	50 Tb/s	200 Tb/s
400G	40 Tb/s	140 Tb/s	40 Tb/s	140 Tb/s		120 Tb/s		120 Tb/s

TABLE IV
SCALABILITY LIMITS IN THE HRA SCENARIO FOR DOUBLE STAR AND MESH LOGICAL TRAFFIC TOPOLOGIES

	Double Star				***Mesh***			
	G.652		**G.655**		**G.652**		**G.655**	
	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20	WSS 1x9	WSS 1x20
HRA	*Max. Traffic*		*Max. Traffic*		*Max. Traffic*		*Max. Traffic*	
100G	70 Tb/s	220 Tb/s	70 Tb/s	220 Tb/s	60 Tb/s	250 Tb/s	60 Tb/s	250 Tb/s
150G	110 Tb/s	340 Tb/s	100 Tb/s	330 Tb/s	100 Tb/s	390 Tb/s	100 Tb/s	390 Tb/s
200G	140 Tb/s	460 Tb/s	130 Tb/s	460 Tb/s	150 Tb/s	520 Tb/s	150 Tb/s	510 Tb/s
400G	100 Tb/s	360 Tb/s	100 Tb/s	360 Tb/s	70 Tb/s	420 Tb/s	60 Tb/s	410 Tb/s

2) the power consumption of the HRA scheme can be obtained by considering that the power supplied to a typical unidirectional C-band only RAMAN amplifier is about 100 W [20]. Then, to amplify both C+L with EDFA and RAMAN we would need 2 × EDFA and 2 × RAMAN which takes the consumption up to 400 W. Finally we can estimate a 25% cost drop due to integration on the same board which results in 300 W;
3) CAPEX and power consumption of WSS and ROADM control systems are multiplied by two in those simulation scenarios where HRA is used. This is to consider the effect of doubled number of WDM channels over control and filtering;
4) we used CAPEX and power consumption values for 50 G and 100 G TXPs from [18], [19] and we linearly interpolated 150 G, 200 G and 400 G values;
5) for the power consumption of regenerating devices, the rule of 3R = 1.2 × TXP has been applied.

The scalability analysis can be related to a time projection by using the expected traffic growth rate as mentioned in Section IV-A. We have assumed that cost drops over the years occur for each component in the same manner.

VI. ILLUSTRATIVE NUMERICAL RESULTS

In this section, we first report the results of our WSON scalability analysis of the Italian backbone network Kaleidon for each simulation scenario as per Section V-B. We show the roadmap of network upgrades resulting from our network efficiency assessment procedure.

A. WSON Scalability

1) EDFA Scenario: The scalability limits of Kaleidon network are reported in Table III as the maximum supported traffic before WSS port occupancy exceeds the WSS port size in any node of the network. We have considered both G.655 and G.652 fibres and the two types of traffic topology, double star and mesh.

In the Mesh traffic, many more lightpaths are set up than with the double star case. Nevertheless, they have similar performance in terms of scalability. In fact, the "meshed" nature of the traffic has the beneficial effect of "spreading" the WSS port occupancy more uniformly over the network nodes, whereas in the Double Star those nodes acting as hubs are usually overloaded. On the downside, longer lightpaths are set up to satisfy demands from node pairs that are further from one another. Thus, when using transmission technologies with short reach (i.e., 200G and 400G) more regenerations are needed (i.e., more add/drop modules) thus limiting the previous benefit. Particularly, Table III shows that in the case of Mesh traffic evolution, 400G cannot be supported by a 1 × 9 WSS, either with G.652 or with G.655.

Increasing the data-rate of transmission systems reduces the number of wavelengths to be routed over the network. It implies that less DWDM systems are installed, which results in the capability to support more traffic before WSS ports saturate. On the other hand, increasing the data-rate reduces the optical reach, which in turn implies more Add/Drop ports used for regeneration (i.e., more installed Add/Drop modules). According to Table III, a good compromise seems to be represented by the 200G technology: it has almost the same optical reach as 400G but it can benefit from less spectrum occupancy and thus more channels in the DWDM systems.

2) HRA Scenario: The hybrid Raman-EDFA amplification makes networks highly scalable. Very high traffic values can be supported particularly with 200G transmission. In fact, since the number of WDM channels in a DWDM system is doubled as well as their optical reaches, HRA more than doubles the limit of the EDFA case. These results suggest that Kaleidon can maintain 1 × 20 WSS until 2021/2022 (GR-50) or until 2029/2030 (GR-25). However, it should be noted that an upgrade from EDFA to HRA implies the extra cost of massively replacing current C-band WSS with those operating at C + L bandwidth. HRA boosts any system performance. Particularly, the 400G can be used even with 1 × 9 WSS and Mesh traffic, which was not possible with the EDFA scheme. Finally, similarly to what was shown for EDFA, fibre types only slightly impact the network scalability.

B. A Cost Perspective

Before moving to the network upgrade roadmap, let us add some final comments about the CAPEX and power consumption evaluation-phases shown in Fig. 2(b).

As mentioned above, G.652 does not introduce relevant benefits in terms of network scalability but it does reduce cost and power consumption. In fact, in the EDFA scenario we found average CAPEX savings of up to 28% and energy savings of 23% (i.e., Mesh traffic and 400G transmission).

As for the HRA, benefits of introducing high-performance G.652 fibres are on average very low due to the already extended reach achieved with Raman amplification.

Based on results reported in Tables III and IV, HRA increases the maximum supported traffic with respect to EDFA by a factor of 2.3 (Double Star) and of 3.3 (Mesh) averaged over all simulated scenarios. However, HRA employs more expensive devices. On the other hand, it allows a reduction of the overall amount of resources owing to larger bandwidth and extended optical reach. In fact, by comparing HRA versus EDFA at the maximum traffic value supported by the EDFA, we have obtained that HRA can achieve up to 28% of CAPEX and 24% of energy savings with respect to EDFA on G.655 fibres for 200G and 400G technology, though values three times lower are attained on G.652 fibres. As for 100G, HRA brings only extra costs whereas for 150G, the benefit are up to 2% for both CAPEX and power consumption.

C. A Roadmap for Network Upgrade

The last part of this study proposes a roadmap for network upgrades. Such a roadmap is the final result of the network efficiency assessment procedure shown in Fig. 2(b).

Fig. 5 shows the evolution roadmap of the Kaleidon network versus traffic in the Double Star scenario. The minimum cost technology is selected by taking into account that a telecom operator aims at performing “green” networking but at reasonable costs (i.e., β is greater than γ in (1)).

In the current Double Star traffic scenario, 50G with WSS 1 × 9 along with the EDFA scheme represents the lowest cost solution up to 20 Tb/s (see Figs. 5(a) and (b)). Such traffic value is expected in year 2014 (GR-25) or 2016 (GR-50). Then, HRA should be introduced along with 400G transmission in order to achieve the most cost-effective solution, though the 1 × 9 WSS can be maintained up to 100 Tb/s, which is expected around year 2023 (GR-25) or 2018 (GR-50). From 100 Tb/s on, the deployment of 1 × 20 WSS is required. Moreover, since the cost for G.652 and G.655 starts to differ significantly, fibre replacement should also be considered. Fig. 5(b) demonstrates that it is mandatory to adopt some techniques to reduce network power consumption, otherwise Kaleidon network will require almost 2.6 MW (G.652) and 2.9 MW (G.655) in 2020, in the worst case.

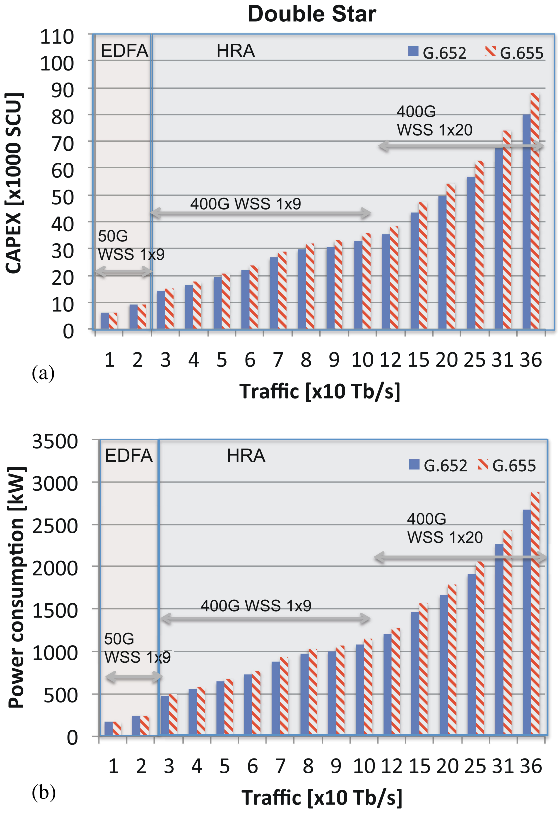


Fig. 5. Network upgrades roadmap for Double Star traffic: (a) CAPEX and (b) power consumption.

The maximum values of scalability in the network with HRA and 1 × 20 WSS has been estimated as high as 460 Tb/s with 200G technology and G.652 fibres. However, by the time such traffic volume will be achieved (i.e., year 2028/2029 (GR-25) or 2021/2022 (GR-50)), 400G or 1T transmission systems performance will be further enhanced in terms of bandwidth and reach. That could make an investment on 200G technology not sufficiently time-proof.

If traffic evolution has a Mesh trend, a possible roadmap for network upgrades is reported Fig. 6. In this case, 50G technology would be satisfactory up to 60 Tb/s with EDFA scheme (year 2020 (GR-25) or 2016/2017 (GR-50)) but an upgrade in terms of WSS ports has to be introduced at 20 Tb/s. In this scenario the introduction of HRA can be postponed at 60 Tb/s which may correspond in the worst case to year 2016/2017 (GR-50). From this point on, there may be two strategies depending on which type of fibre is used as shown in Figs. 6(a) and (b): as for the G.655 case, it consists of employing 150G up to 80 Tb/s and then moving towards 400G until 410 Tb/s (around year 2028/2029 (GR-25) or 2021 (GR-50)). On the other hand, with G.652 fibres it is recommended to deploy 400G when the traffic reaches 70 Tb/s. Finally, Fig. 6 reports the very high cost operators should expect within the next 9-17 years (i.e., when traffic reaches 420 Tb/s): more than 100 000 SCU and a power consumption higher than 3 MW with G.652 fibres.

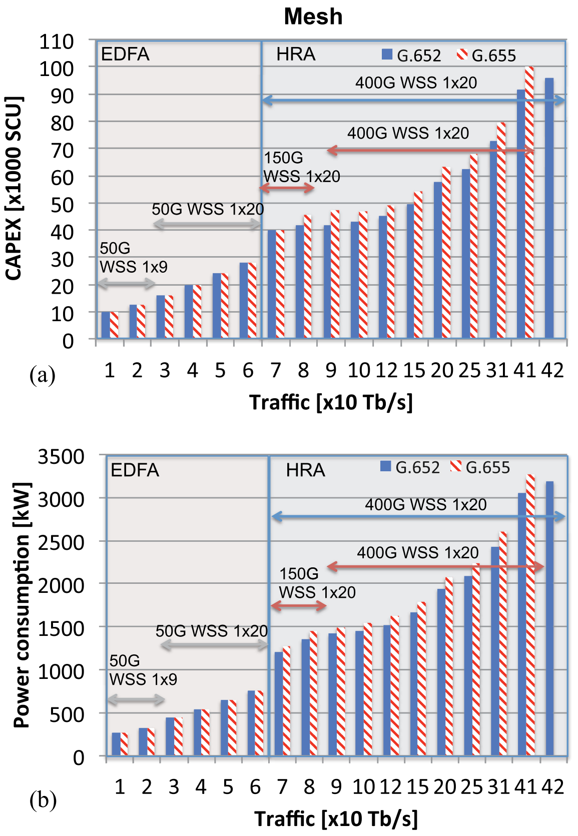


Fig. 6. Network upgrades roadmap for Mesh traffic: (a) CAPEX and (b) Power consumption.

Also in this case it is worth mentioning that the maximum traffic value supported by the WSS 1 × 20 with HRA scheme is 520 Tb/s which can be attained with 200G. Again, at that time (i.e., year 2021/2022 (GR-50), year 2029/2030 (GR-25)), 1T transmission systems with enhanced performance will be most likely commercially available.

VII. Conclusion

In this paper, we have presented a novel method for scalability analysis and network efficiency evaluation which has been applied on the Telecom Italia's network Kaleidon. For the first time to our knowledge, we have drawn the roadmap for network upgrades and we have shown how that depends on the present and future photonic technologies. Our results show that with the current traffic topology (i.e., Double star) the deployment of hybrid Raman/EDFA amplification (HRA) scheme will be most beneficial along with 400G transmission systems after year 2014 if yearly traffic growth-rate of 50% (GR-50) is considered. Also, WSS 1 × 20 are needed to scale the network capacity up to 360 Tb/s (around year 2020/2021, GR-50) and up to 420 Tb/s (year 2021/2022, GR-50) in the Double star and the Mesh scenario respectively. However, these high traffic volumes imply a dramatic increase of the power consumption to more than 3 MW. CAPEX savings of 28% and energy savings of 23% can be achieved by employing G.652 fibre type instead of G.655 while not effectively improving network scalability. The proposed method will be applied to flexi-grid and multi line rate networks as a follow-up of this study, in order to investigate whether and when the flexi-grid solution becomes competitive in terms of cost and energy in a realistic WSON.

References

[1] S. K. Korotky, "Traffic trends: Drivers and measures of cost-effective and energy-efficient technologies and architectures for backbone optical networks," presented at the Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf., Los Angeles, CA, USA, 2012.

[2] P. J. Winzer, "Beyond 100G Ethernet," *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 26–30, Jul. 2010.

[3] S. Gringeri, B. Basch, V. Shukla, R. Egorov, and T. J. Xia, "Flexible architectures for optical transport nodes and networks," *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 40–50, Jul. 2010.

[4] G. Notarnicola, G. Rizzelli, G. Maier, and A. Pattavina, "Scalability Analysis of WSS-Based ROADM," presented at the 17th Eur. Conf. Netw. Opt. Commun., Villanova i la Geltru, Spain.

[5] J. Sole-Pareta, S. Subramaniam, D. Careglio, and S. Spadaro, "Cross-layer approaches for planning and operating impairment-aware optical networks," *Proc. IEEE*, vol. 100, no. 5, pp. 1118–1129, Mar. 2012.

[6] D. Staessens, M. Angelou, M. De Groote, S. Azodolmolky, D. Klonidis, S Verbrugge, D. Colle, M. Pickavet, and I. Tomkos, "Techno-economic analysis of a dynamic impairment-aware optical network," presented at the Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf., Los Angeles, CA, USA, 2011.

[7] A. Carena, V. Curri, G. Bosco, P. Poggiolini, and F. Forghieri, "Modeling of the impact of nonlinear propagation effects in uncompensated optical coherent transmission links," *J. Lightw. Technol.*, vol. 30, no. 10, pp. 1524–1539, May 2012.

[8] O. Rival, G. Villares, and A. Morea, "Impact of inter-channel nonlinearities on the planning of 25-100 Gb/s elastic optical networks," *J. Lightw. Technol.*, vol. 29, no. 9, pp. 1326–1334, May 2011.

[9] T. Zami, "Physical impairment aware planning of next generation WDM backbone networks," presented at the Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf., Los Angeles, CA, USA, 2012.

[10] D. Caviglia, F. Lazzeri, and G. Bottari, "WSON impact on optical network planning," presented at the Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf., Los Angeles, CA, USA, 2011.

[11] M. Schiano and M. Quagliotti, "Lambda switched future photonic network development," presented at the Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf., Los Angeles, CA, USA, 2012.

[12] G. Rizzelli, M. Tornatore, G. Maier, and A. Pattavina, "Impairment-aware design of translucent DWDM networks based on the k-path connectivity graph," *J. Opt. Commun. Network.*, vol. 4, no. 5, pp. 356-365, May 2012.

[13] G. Ferraris, G. Maier, and S. De Patre, "Method for Configuring an Optical Network," Patent WO2 007 016 942, Feb. 2, 2007.

[14] G. Maier, A. Di Giglio, G. Ferraris, M. Quagliotti, S. De Patre, and L. Savastano, "An approach for dynamic optical transport network planning and analysis," presented at the Fifth Int. Workshop Design Reliable Commun. Netw., Island of Ischia, Italy, 2005.

[15] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, "On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers," *J. Lightw. Technol.*, vol. 29, no. 1, pp. 53–61, Jan. 2011.

[16] M. O. L. Beninca, M. J. Pontes, and M. E. V. Segatto, "Design of a wide-band hybrid EDFA with a fiber Raman amplifier," presented at the Int. Microwave Optoelectron. Conf., Natal, Brazil, 2011.

[17] P. J. Winzer, A. H. Gnauck, S. Chandrasekhar, S. Draving, J. Evangelista, and B. Zhu, "Generation and 1200-km transmission of 448-Gb/s ETDM 56-Gbaud PDM 16-QAM using a single I/Q modulator," presented at the 36th Eur. Conf. Exhib. Opt. Commun., Torino, Italy, 2010.

[18] F. Rambach, B. Konrad, L. Dembeck, U. Gebhard, M. Gunkel, M. Quagliotti, L. Serra, and V. Lopez, "A multilayer cost model for metro/core networks," *J. Opt. Commun. Network.*, vol. 5, no. 3, pp. 210–225, Mar. 2013.

[19] STRONGEST European project, [Online]. Available: http://www.ict-strongest.eu/, Deliverable 2.4, 2012

[20] (2014). [Online]. Available: www.cisco.com, Raman C-Band Optical Amplifier.

[21] (2014). [Online]. Available: http://www.finisar.com/products/wss-roadms