Optical Transport Networks with Flexi-Grid Planning (June 2019)

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Abstract— **In an exponentially growing traffic environment that characterizes the first decades of the 21st century, the search for innovative technological solutions, compliant with dynamic client's traffic demands, is pushed to its new limits. Fixed grid bandwidth management is being gradually combined with the flexible one that introduces the new paradigm of elastic optical networks. This technological leap was possible with the development of new equipment, with a highlight to the coherent detection solutions, and introduction of new modulation formats. Also, the implementation of high capacity traffic channels, the Super Channels (SC), with capacities that can reach up to 1 Tbps, required new approaches of the routing strategies. In static simulation scenarios, generally applicable at the dimensioning of new optical networks, it is possible to derive best strategies that may be adopted at specific scenarios. In the present investigation, there were compared different combinations of routing strategies, client traffic profiles, demand orderings and optical networks. Heuristic approach was implemented, and the results compared. It was concluded that demand orderings by the most congested link first and routing criteria that considers the minimum number of regenerators as the first criteria and the minimum spectrum as an untie criteria lead to best results. Thus, demand ordering and routing criteria algorithms have direct influence at the performance networks, being be an important tool in the planning process. However, networks with different topologies will react differently to client's demands, therefore it is important to consider network's and client's specificities before implementation of extensive modifications.**

Index Terms— **Demand Ordering, DWDM, Elastic Optical Networks, Fixed and Flexible Optical Networks, Optical Transport Network, Routing Strategies, Super Channels**

I. INTRODUCTION

AN OTN is a fundamental component of the telecommunication networks that supports a wide variety of different client signals, like IP/MPLS, Ethernet, SDH/SONET and other protocols. Typically, OTN is a long-distance telecommunication transport network (up to 1200-3500 km) where the communication is performed at transparent optical domain through optical fibres and it is supported by Dense Wave Division Multiplexing (DWDM) technology (multichannel system). Thus, OTN is a digital wrapper technology, defined by an Optical Transport Hierarchy (OTH), performed under ITU-T normalization, and destinated to provide high capability channels. Total network capacity enabled by traditional optical technology is typically upper-bounded to 96 channels of 100 Gbps [1] per each optical fiber, where each channel occupies a fixed spacing of 50 GHz, which is called a fixed-grid solution. It is foreseen that fixed-grid based optical networks won't have the capability to sustain the exponential traffic growth [2] [3] [4]. To obviate this limitation, ITU-T G.694.1 has redefined the frequency grid enabling the capability of supporting a variety of fixed and flexible (or flexi-grid) channel spacings, ranging from 12.5 GHz up to 100 GHz [1]. This innovation allowed Super-channels, technique that combines multiple optical signals into a single spectral window, to have variable and adjustable dimensions and to improve the spectral efficiency and reduce the penalties caused by filtering in the traversed nodes.

Independently of using Super-channels and flexi-grid, higher transmission capabilities typically result in the additional accumulation of impairments from the optical fiber that, in turn, limit the maximum distance that is possible to be achieved without complete signal regeneration, thus requiring higher number of optical interfaces. Hence, and considering that the Super-channels can be tuned to different configurations (number of optical carriers, bit rate per carrier, spectrum occupied), it should be possible to efficiently manage the relationship between the capacity of the established connections and the respective regeneration usage. Flexi-grid and Super-channels are two examples of disruptive techniques that are being introduced in OTN with the purpose of, in a short time, increase the transmission capacity over optical fiber. Specifically, it is foreseen that the maximum channel capacity will increase up to 400 Gbps and beyond at single wavelength [5].

Considering this engineering problematic, there is a need to make readjustments to the processes followed in OTN planning. To promote the best practices, it becomes important to analyze the impact of different factors in the usage of the available network resources for a large set of scenarios. The start point of the network planning generally consists in the analysis of the physical network topology and the characterization of the traffic model. Generally, networks have measuring points at the nodes that allow to determine precisely the traffic at each node and, subsequently, perform statistical modelling of the obtained data. In static scenarios, the traffic compilation for all possible pairs of sources and destinations, and for a certain period, results in a traffic matrix (in dynamic scenarios, it is not feasible to perform this type of analysis due to data unpredictability). Then, there are evaluated different strategies concerning routing, wavelength assignment and traffic grooming, among other specific aspects (such as static or dynamic traffic). Finally, planning also depends on the time horizon and the amount of resources that are available to be allocated at each period along the life cycle of the network.

In this context, routing is an optimization process, based on some specific criteria, that calculates the best feasible paths (set of links), that will be crossed by lightpaths, aiming such way to solve all traffic requests that exists in a studied network. In the other hand, traffic is the amount of data that is being exchanges through the network at a given period. This traffic is wrapped (or encapsulated) and is groomed accordingly established by OTN standardization, providing high bandwidth efficiency. Each demand (or request) is a source-destination pair that will be transmitted through the network accordingly some established algorithms. Wavelength assignment consists on the assignment of the wavelength to each lightpath in the network.

Present investigation is centered only at physical layer characteristics and specifically at the optical frequency plan, contextualized at DWDM frequency grid (centered at 193.1 THz) and formulated according specifications defined at ITU-T G.694.1 [1]. It is focused specifically in evaluating three factors: traffic distribution, demand ordering algorithms, and demand routing algorithms. Whereas the first factor defines how the nodes exchanging demands are selected, the second one stipulates the order by which those demands are served, and the third one specifies the criteria employed to determine the optical path for each of those demands. Uniform and gravitational traffic distribution models will be used to compare how the limited network resources are consumed when the demands are geographically concentrated. Different ways to define the sequence by which demands are ordered are investigated to determine if any a-priori knowledge of the network is useful to increase the number of satisfied demands. A similar approach is used regarding the routing strategies. The scenarios investigated are characterized by different properties, such as 1) network topology; 2) spectral grid format; 3) types of available Super-channels; 4) client traffic rates. The planning algorithms can be characterized by the 1) demand ordering algorithms; 2) and routing and spectrum assignment algorithms. To evaluate network performance, both blocked demands and installed regenerators will be used as measurable results. The former measurement is useful to identify how much of the offered load was eventually satisfied by the planning procedures employed, whereas the latter quantifies how much additional cost (in regenerators) will this performance be dependent on. It is important to underline that both Capital Expenditures (CapEx) and Operational Expenditures (OpEx) represent the decisive factors when building telecommunication networks. In this context, satisfied demands and required regenerators can be somewhat viewed as OpEx and CapEx figures. Single period planning was considered since the investigation is focused essentially on an end-of-life (EOL) planning where it is not considered the reuse of equipment.

II. FLEXI-GRID AND SUPER-CHANNELS

Multi-carrier modulations (MCM) allowed to increase spectral efficiencies, replacing the traditional digital modulation methods (PSK, FSK, ASK and QAM), and it was complemented by coherent optical communication systems and digital signal processing, to obtain reach advantages. Since MCM requires large channel spacing, requiring this way a flexible partitioning of the optical spectrum. For the same spectrum occupation, flexi-grid support more channels (narrower positioned) and allows it’s grouping to obtain high capacity channels (super-channels), that may be carried as single entities through the OTN. The implementation of smaller granularities of 12.5 GHz, allowed to obtain more precise dimensioning of the channels slots, with 12.5 GHz, 37.5 GHz and 50 GHz spacings, resulting, consequently, in a more efficient and adjusted to real necessities channels. Elastic Optical Networks (EON) and associated elastic structure brought the “fitted for the need” concept, where the traffic management can be made through an allocation of frequency slots that are effectively needed, instead of being limited to predefined traffic channels. In this concept, several number of contiguous frequency slots can be assigned through the route, being characterized by some specific spectrum width and effective filter bandwidth and not by fixed boundaries (as in fixed-grid WDM). Introduction of flexibility in the grid allows mixed bit rates or mixed modulation formats, optimizing this way the bandwidth management.

Super-channels (SC) allow to aggregate or groom at transport level of OTN different client’s signals with different bit rates in the same lightpath, enabling this way EONs and support to next-generation high-speed services. Grooming operations are performed at electronic layer, where client’s signals are mapped successively from Low Order ODU, High Order ODU, OTU, and finally converted to the optical signal. Thus, SC is a combined signal with desired capacity provisioned for specific operational cycle that packs multiple optical signals into a single spectral window with variable and adjustable dimension to improve the spectral efficiency and/or reduce the penalties caused by Reconfigurable Optical Add/Drop Multiplexers (ROADM) [3]. SC technology is supported by sliceable bandwidth variable transponders (SBVT), that allow several optical interfaces that may be configured and operated separately or jointly. However, SBVT are still a matter of study and are not a completely matured technology.

During present investigation there were considered different optical transmission format structures for SC that were used by (Santos, 2014) [3] in previous evaluation of OPS based investigation associated to analysis of Spectrally-Efficient Super-channel Formats in Brownfield Networks with Legacy Services accordingly Table I, where it was considered 12.5 GHz granularity to obtain the total occupied spectrum of the

TABLE I
SC OPTICAL TRANSMISSION FORMATS [a]

Client (Gbps)	Modulation	Optical Carriers	Grid (GHz)	Spectrum (GHz)	Maximum Reach (km)
100	CP-QPSK	1	50	50	2500
100	CP-QPSK	1	37.5	37.5	2000
200	CP-QPSK	2	50	100	3000
200	CP-QPSK	2	37.5	75	2400
200	16-QAM	1	50	50	600
200	16-QAM	1	37.5	37.5	500
300	CP-QPSK	3	50	150	3100
300	CP-QPSK	3	37.5	112.5	2500
300	8-QAM	2	50	100	1200
300	8-QAM	2	37.5	75	1000
400	CP-QPSK	4	50	200	3200
400	CP-QPSK	4	37.5	150	1600
400	16-QAM	2	50	100	750
400	16-QAM	2	37.5	75	625
100	CP-QPSK	1	50	50	2500

[a] SC that were implemented in present investigation [3]

client signals. Table I reflects the relationship that exists between different modulation formats and the maximum reach. Note that modulations with higher efficiency of the spectrum (e.g. 16-QAM vs CP-QPSK) are associated to lower maximum reach. Also, for the same modulation format, higher occupied spectrum (and grid) of different SC is associated respectively to higher maximum reach, which is related with lower efficiency of higher grid formats (e.g. 50 GHz vs 37.5 GHz). It was also only considered a gridless scenario in the demand routing process, i.e., there were considered 50 GHz, 37.5 GHz, and 50 / 37.5 GHz grid partitions simultaneously. This option was motivated by the results obtained by investigation developed by (Santos, 2015, page B128, Figure 10), that shows that the consequences of using gridless approach when deploying the Super-channel services, and independently of the legacy bandwidth values, are almost negligible. As explained by Santos, this important result means that predefined frequency grids could be an adequate solution to support Super-channel signals without incurring in heavy performance penalties, which is particularly important if the applied transmission formats are based on mixed (37.5/50 GHz) grids, which are harder to manage.

III. OPTICAL TRANSPORT NETWORK PLANNING

A. *Routing in Optical Networks*

A routing strategy refers to computation mechanism of the routes (paths) from source node to destination node, where the network topology can be represented by a graph $G=(V,E)$, where V represents a set of nodes and E the set of links that connect them. The main purpose of the routing algorithms is to find a set of paths that satisfy the requests and simultaneously determine the capacity of all links/connections of the network. It is also responsible for mapping the logical topology over the physical one. In context of OTN, nodes are materialized by in Network Elements (NE) such as ROADM and Optical Terminal Multiplexer (OTM). In the optical transparent and translucent networks, routing is a key control and operational feature at the optical layer. It is directly related to the path selection and wavelength assignment process designated Routing and Wavelength Assignment (RWA) or Routing and Spectrum Assignment (RSA). The RWA/RSA problem refers to process of designating lightpaths to connect the source node to the destination node and assigning it wavelengths/spectrum slots and it is typically formulated in two separate steps: routing and wavelength/spectrum assignment. Generally, the problem consists in minimizing the set of lightpaths while maximizing the number of established connections and consequently minimize the blocked connections. In addition to the amount of lightpaths (which materialize into a given number of O/E/O interfaces), there is also a need to consider some specific blocking ratio, i.e., the percentage of the traffic that won't be routed through the network. Here, traffic can be represented by a traffic matrix D containing several demands ($d \epsilon D$), where each demand is represented by a source node s_d, target node t_d and bit rate r_d (data transmitted by the demands). Traffic blocking can occur due to several reasons, but it is mostly impacted by the limited link capacity and the wavelength/spectrum continuity constraint.

In optical fiber DWDM networks, each lightpath represents an optical signal, transmitted at a specific wavelength/spectrum, carrying information across the network. Since the lightpath is only converted to the electrical domain at its boundary points, it is constrained to wavelength/spectrum-continuity over the links used. This constraint imposes that two different optical signals that are routed through common paths (even partially) can't be assigned the same wavelength (frequency). In elastic optical networks, the routing problem is also related with spectrum assignment (RSA), since in flexible grid the channels are designated according the required and available spectrum. In fact, RWA is a subcase of RSA. Whereas the latter requires selecting a set of contiguous frequency slots of 12.5 GHz, the former is limited to selecting only one slot corresponding to a fixed 50 GHz occupation.

The RSA studied in the present investigation consists of three steps, for a given network topology and traffic profile, and with the final purpose of maximizing the efficiency of the whole routing process: 1) demand ordering taking into account the generated client traffic and the network topology; 2) demand routing, i.e., select the most favorable path(s) accordingly specified criteria for the traffic requests; 3) wavelength assignment to the calculated routes. Specifically, there are used Dijkstra and Yen algorithms to compute the shortest path and *k*-shortest paths.

B. *Static routing*

Since the main emphasis of the present investigation was to analyze the influence of the demand ordering/routing and traffic distribution at the behavior of the network, a static scenario was considered. It was considered a high average input traffic of 130 Tbps and no exit bandwidth (i.e., the connections are cumulatively occupied without no release of any capacity) since the purpose was to obtain the maximum outflow of the traffic, by analyzing the total blocked traffic and total regenerator count, i.e., the number of regenerators that were needed to implement the studied combination.

Static routing (or non-dynamic routing) of the demands generally refers to routing that is performed considering a stationary scenario, not affected by operational flows that may affect real circumstances. Generally, it applies to permanent or long-term connections or to planning of future networks, where the purpose is generally to minimize some pre-defined cost parameters like the number of wavelengths (or spectrum) or networks resources (regenerators, ROADM, etc.).

C. Client Traffic Generation

There were considered traffic profiles for client rate distributions according Table II, implemented by Santos (2015) [7] and it was considered an extensive use of Super-channels to reach higher bandwidths that characterize EONs. The main considered demands are 100, 200, 300 and 400 Gbps (SC) in different proportions and different bandwidths ratio for different profiles (A, B, C, D, E, F and G). The A profile represents an evenly distributed traffic, whereas profiles B, C, D and E, polarizes the traffic to one specific client types. Profiles F and G polarizes the traffic evenly in two different client rates.

The generation of traffic was performed accordingly two traffic distribution models: uniform and gravitational model. Uniform model (UM) considers an equitable distribution of the traffic along different nodes, i.e., the probability of some traffic demand being attributed during the simulation process to some specific node is equitable or uniformly distributed. Gravitation model (GM) intends to reflect the non-equal distribution of traffic that is verified at some cities' nodes. The expected traffic (E_{ij}) at each connection / link (i,j) (link is established from node i to node j) is calculated accordingly the generic expression of GM accordingly expression (1), where pop_i is the population of the city i, pop_j is the population of city j and d_{ij} is the distance between the cities i,j [8].

$$E_{ij} \sim \frac{pop_i \cdot pop_j}{{d_{ij}}^2} \qquad (1)$$

D. Demand Ordering

Demand ordering refers to a process that sorts the traffic demands that will be processed first and occurs before the RWA/RSA process. Present investigation focuses in the influence of the ordering policies in the efficiency of the routing algorithms and its effect on the maximum exploitation of the available resources (bandwidth) at the optical network. Thus, it is possible to consider some specific priority-based rules that will influence the order of the demand processing.

There were considered and evaluated different demand orderings as described in Table III. Thus, Highest Client Rate First means that the client demands with the highest data rate will be ordered before remaining demands (i.e., these demands will have lower index). Largest Distance orders first the demands associated to the paths with higher distance (km). Most congested link ordering considers first the demands that are associated to the most occupied links which involves pre-routing calculations.

TABLE II
CLIENT RATE DISTRIBUTION PER TRAFFIC PROFILE [a]

Traffic Profile	100 Gbps	200 Gbps	300 Gbps	400 Gbps
A	25%	25%	25%	25%
B	85%	5%	5%	5%
C	5%	85%	5%	5%
D	5%	5%	85%	5%
E	5%	5%	5%	85%
F	45%	45%	5%	5%
G	5%	5%	45%	45%

[a] Client Rate Distributions implemented in present investigation [7]

TABLE III
DEMAND ORDERING POLICIES [3]

Traffic Profile	Main demand ordering policy	Untie policy
0	Highest Rate First	Largest Distance
1	Largest Distance	Highest Rate First
2	Most Congested Link	Random
3	Most Congested Link	Highest Rate First
4	Most Congested Link	Largest Distance First

E. Demand Routing

The routing of the demands is based on previously computed *k*-shortest paths for each node pair based in Yen algorithm. There are also calculated initially, for each path, total costs associated to each identified path, the number of regenerators, the number of interfaces and the total occupied spectrum. Then, demand routing uses the three shortest paths and selects the one that minimizes some designated criteria. Essentially, the implemented demand routing algorithm consists in the following steps:1) search for the best path, i.e., it is identified the one that minimizes some specific criteria, accordingly Table IV; 2) if solution is found, deploy the best path while doing the wavelength assignment; 3) update link occupation (both directions); 4) if no feasible path found, the demand is blocked. In first criteria, the routing algorithm uses the shortest path that minimizes the number of regenerators (3R) along the path and in case of tie, uses the path with lower occupied spectrum. Again, if tie occurs, the demand routing algorithm will select the path that has the lowest cost, that is, the path that has the lower number of interfaces which in present investigation corresponds to the number of hops or lightpaths (product of number of interfaces per modulation and the number of the required regenerators per path). Following routing criteria (2,3,4) use the same criteria of first one, but implemented with reversed orderings. The criteria 5 refers to a routing performed firstly by the lowest number of

TABLE IV
ROUTING CRITERIA

ID	1sr criteria	2nd criteria	Untie criteria
1	Lowest 3R	Lowest spectrum	Lowest cost
2	Lowest spectrum	Lowest 3R	Lowest cost
3	Lowest 3R	Lowest cost[a]	Lowest spectrum
4	Lowest spectrum	Lowest cost[a]	Lowest 3R
A	Lowest 3R	Maximum spectral availability [b]	First-fit
B	Lowest 3R	Maximum mean spectral availability [b]	First-fit
C	Lowest 3R	Shortest number of lightpaths at the path	First-fit

[a] Lowest cost refers to lowest number of interfaces

[b] Per lightpath of the path

regenerators (3R) among the available shortest paths and then, in case of tie, choses the path that has the highest available spectrum per lightpath. Criteria 6 refers to the routing algorithm that uses as untie criteria the path with the highest average value of the available spectrum. Criteria 7 uses as untie criteria the path with lowest number of lightpaths.

F. Wavelength Spectrum Assignment

(D)WDM technology allows to carry several signals at the same fiber, but at different wavelengths. Therefore, after the lightpaths are routed they must be assigned to a specific wavelength or spectrum (taking into account the wavelength continuity constraint). Different methods may be used. Due to its simplicity and efficiency, the spectrum assignment is performed using the First-Fit criteria, as it was implemented by (Santos, 2015) [7].

G. Optical Planner Software

Optical Planner Software (OPS) used to perform all simulations was developed by Coriant®. The flowchart of the planning tool is illustrated in Figure 1 and Figure 2 [3] - at the first one it is illustrated the general flowchart of the OPS framework and at the second one it is illustrated the RSA algorithm. The implemented methods, that lead to modifications in the RSA algorithm, were evaluated considering three reference network topologies (Figure 4 and Table V), seven client rate distributions, two traffic distributions, three types of frequency grids, five demand ordering algorithms and seven demand routing algorithms. It was considered a greenfield scenario, i.e., it was considered an absence of the legacy bandwidth (LB=0). There were used two important measuring parameters that correspond to OPS platform outputs and that have a purpose to measure the performance of the network planning and associated ordering and routing algorithms, namely the total blocked traffic (TBT) and the total regenerator count (TRC). TBT refers to metric that calculates the amount of traffic that wasn't routed due to filled (overloaded) network capacity for considered paths, where network capacity refers to the capacity of the three shortest paths calculated for corresponding demand. Total regenerator count (TRC) refers to the required number of regenerators that were employed in the routing (and assigning) of the fulfilled demands. The analysed networks were COST 239, GBN and Portuguese Backbone Network (PRT). Since it was considered static scenario, only one period per network scenario was implemented. The input maximum legacy bandwidth was considered as zero since it was simulated greenfield scenario. The average entry load (bandwidth) was fixed at 130 Tbps in order to evaluate the performance of the algorithms under heavy load conditions. The average exit load (bandwidth) parameter refers to dropped bandwidth, a set of demands that exit the network. Since it was only considered a single period and the purpose of the simulation process was to compare the efficacy of different implemented algorithms the maximum exit bandwidth per period was fixed in 0 Tbps (it was supposed that all input load was completely distributed). There were also performed by OPS platform some pre-defined initializations, such as optical transmission format structures for SC. There were performed 50 trials per each network scenario, where each trial by itself represents mean value of the results obtained from 50 cycles per each trial.

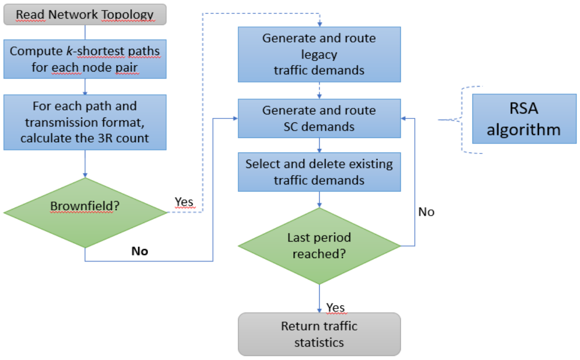

Fig. 1. Flowchart of the OPS tool – general framework [7].

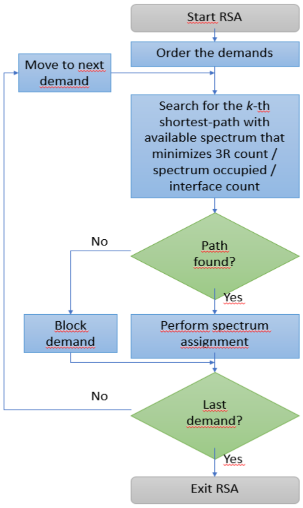

Fig. 2. OPS framework - RSA algorithm [ ].

After input network topology processing (COST, GBN or PRT), which corresponds to "Read Network Topology" block as illustrated in Figure 1, OPS tool calculates, based in Yen algorithm, the k-shortest paths for all node pairs associated to the network with the purpose of minimizing the total path distance, considering a maximum of 3 paths (k=3). Next follows the computation of the minimum number of regenerators (3R) required per each path (previously calculated k-paths) and each modulation format, considering the maximum reach of the client signals as shown in Table I. Paths whose individual links surpass the maximum reach of the client signals are considered unfeasible and there are calculated alternative paths [7]. Client traffic demands are randomly generated with discrete distributions of traffic patterns/profiles indicated in Table II and node pairs are randomly selected accordingly it was selected UM or GM. During this computational process, it is also calculated the number of hops / interfaces for each path and each modulation format.

Then, RSA algorithm performs the ordering and routing of the created demands and spectrum assignment, selecting this way, for each demand, the transmission format and respective path. Each transmission format is carried over one single path being treated as a single entity in the network. Thus, some of implemented transmission formats may be or not available for selection depending on the adopted frequency grid. The path assignment and selection are only performed if among calculated shortest paths there exist available spectrum for a given modulation format and it manages to minimize the selected (at some specific cycle) routing. Then, first-fit policy is used to assign the demands to the free spectrum slots in each lightpath, starting from the lowest free indexes. If the demand is blocked, i.e., it wasn't found path with available spectrum resources for the specific demand, TBT will be updated. If the demand is successfully assigned, TRC count will be updated accordingly the characteristics of the assigned path. This closes the cycle and the demand is assigned as treated and RSA moves to the next request [7]. Summary of important topological data is described in Table V.

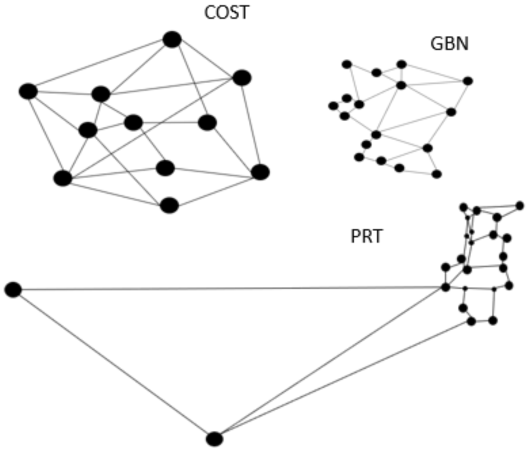

Fig. 3. Optical Backbone Networks – a) COST 239; b) GBN; c) Portuguese Network (PRT)

IV. RESULTS AND DISCUSSION

A. *Demand Ordering Strategies*

Results obtained for the five-demand ordering (DO) algorithms and uniform distribution are described in Table VI. It is possible to verify that, in average, the TBT (Gbps) is higher for GBN and COST networks than for PRT network which can be explained by the fact that GBN and COST are smaller networks, with 13 and 11 nodes, respectively, if compared to PRT network, with 26 nodes . Additionally, the results are worse for GBN since this network has the smallest number of links (38), if compared to COST (52) and PRT (72) networks. Since the generated input client traffic is equal for all simulated scenarios / networks (130 Tbps), when it is featured the uniform distribution model to distribute the same amount traffic the smaller networks will have higher ratio of number of demands per each node and link.

Relatively to the DO, it is possible to conclude that for GBN and COST networks, DO 0 and 1 have in average worse performance, meaning that in these networks the most congested link first is the best ordering criteria. Results obtained for PRT for different DO don't have very significant variations, meaning that the injected traffic have lower impact at PRT that has higher number of nodes and links, distributing this way better the injected traffic.

Relatively to results obtained for TRC, the highest values were obtained for COST and GBN networks, which may be explained by the fact that the average distance between nodes associated to these networks is higher, if compared to PRT. The number of TRC at PRT network is not affected significantly by the DO, reinforcing the conclusion that this network is not proportionally affected by the same input traffic (130 Tbps) due to topological reasons. Both for COST and GBN networks, the DO 0 a 1 lead to the worst results (TRC and TBT), supporting the conclusion that at highly saturated networks, the most efficient DO is associated to the most congested link first algorithm (DO 2,3,4).

TBT results with GM are higher if compared to the UM, meaning that gravitational formulation of a problem, generally more alike to the real scenarios, accelerates the saturation of

TABLE V

SUMMARY OF IMPORTANT DATA RELATIVE TO STUDIED NETWORKS

Net [a]	nº nodes	nº links	Ratio[a]	MD[c] (km)	MD / n[d] (km)	MD / l[e] (km)	MP[f] ($x10^3$)
COST	11	55	0.2	462	42.0	8.9	2062
GBN	13	38	0.3	216	16.6	5.7	776
PRT	26	72	0.4	203	7.8	2.8	816

[a] Net - networks
[b] Ratio - total number of nodes / total number of links
[c] MD - Mean distance between links
[d] MD/n – ratio MD / number of nodes
[e] MD/l – ratio MD / number of links
[f] MP – Mean Population

TABLE VI

DEMAND ORDERING STRATEGIES

MEAN VALUES OF TBT (GBPS) AND TRC – UNIFORM MODEL

	Network / DO [a]	0	1	2	3	4
TBT	COST	$2.7x10^3$	$3.1x10^3$	$1.8x10^3$	$2.0x10^3$	$1.8 x10^3$
	GBN	$3.3x10^4$	$3.1x10^4$	$2.4x10^4$	$2.6x10^4$	$2.7 x10^4$
	PRT	$8.4x10^2$	$9.2x10^2$	$9.9x10^2$	$9.4x10^2$	$8.9x10^2$
TRC	COST	50	53	47	47	47
	GBN	34	35	26	27	29
	PRT	3	3	3	3	3

[a] DO – Demand Ordering

TABLE VII

DEMAND ORDERING STRATEGIES

RATIO BETWEEN MEAN VALUES AND THE MINIMUM VALUE

UNIFORM MODEL

	Network / Demand Ordering	0	1	2	3	4
TBT	COST	1.5	1.7	1.0	1.1	1.0
	GBN	1.3	1.2	1.0	1.1	1.1
	PRT	1.0	1.1	1.2	1.1	1.1
TRC	COST	1.1	1.1	1.0	1.0	1.0
	GBN	1.3	1.4	1.0	1.0	1.1
	PRT	1.0	1.0	1.0	1.0	1.0

TABLE VIII
DEMAND ORDERING STRATEGIES
MEAN VALUES OF TBT (GBPS) AND TRC – GRAVITATIONAL MODEL

	Network / DO[a]	0	1	2	3	4
TBT	COST	$3.5\text{x}10^4$	$3.4\text{x}10^4$	$3.0\ \text{x}10^4$	$3.2\ \text{x}10^4$	$2.9\ \text{x}10^4$
	GBN	$7.5\text{x}10^4$	$6.9\text{x}10^4$	$6.7\ \text{x}10^4$	$7.1\ \text{x}10^4$	$6.7\ \text{x}10^4$
	PRT	$4.5\text{x}10^4$	$4.0\text{x}10^4$	$3.7\ \text{x}10^4$	$4.0\ \text{x}10^4$	$3.9\ \text{x}10^4$
TRC	COST	40	43	24	24	25
	GBN	39	42	40	40	39
	PRT	2	2	1	2	2

[a] DO – Demand Ordering

the network and reveals the importance of consider carefully different factors associated to specific characteristics of the analyzed networks (such as the traffic origins and terminations) during the planning process of optical networks. Demand orderings 0 and 1, for all networks, lead in average to worse results of TBT (Table VIII). Thus, when networks need to work under heavy load conditions (130 Tbps) concentrated at specific nodes of the network, the scarcest resource becomes the number of the available links, leading to preferable DO option be the most congested link first (DO 2, 3 and 4). However, since the differences are not very significant, it is important to analyze, *a priori*, the cost-benefit of its implementation due to additional computational processes that are required at DO 2,3,4. TRC results are in average higher for UM. Thus in GM, associated to higher TBT, the most congested nodes aren't capable to distribute all the traffic in the same proportion as in UM (where the traffic is more equally distributed), generating this way higher values of TBT and, in its turn, proportional lower levels of TRC.

There is a significant reduction of TRC at COST, when DO 2,3,4 are implemented if compared to DO 1,2. Thus, in COST network, the routing by most congested links first will have higher impact at TBT and TRC counts if compared to higher rate first or largest distance first orderings, which may be explained by topological characteristics of the network (higher mean distances) and gravitational distribution of the traffic in certain cities. Results for PRT also reveal that DO 2, 3 conduced to lower number of TRC. Note that in this particular network, there are specific cities (Funchal and Ponta Delgada) are situated more than 1000 km away from the most loaded nodes (Lisbon and Porto), meaning that for this link, even with lower load at each link, there will be some traffic that need to be considered implying the existence of regenerators in case if higher modulation schemes and/or higher bit rates are used (Table I), that are associated to lower reach distances or implementation of higher number of regenerators (at least one or two, depending of the existence of traffic at these nodes). In a hole, it is possible to conclude that the demand ordering has lower impact in TRC results, in comparison to TBT. In average, COST and GBN networks lead to highest values of TRC if compared to PRT, which is again related with higher mean link distances.

TABLE IX
DEMAND ORDERING STRATEGIES
RATIO BETWEEN MEAN VALUES AND THE MINIMUM VALUE
GRAVITATIONAL MODEL

	Network / Demand Ordering	0	1	2	3	4
TBT	COST	1.2	1.1	1.0	1.1	1.0
	GBN	1.1	1.0	1.0	1.1	1.0
	PRT	1.2	1.1	1.0	1.1	1.0
TRC	COST	1.7	1.8	1.0	1.0	1.0
	GBN	1.0	1.1	1.0	1.0	1.0
	PRT	1.6	1.9	1.0	1.2	1.8

B. Demand Routing Strategies

Results obtained for different demand routing strategies for UM are presented in Tables X and XI. It is possible to observe that routing criteria (RC) has higher influence in results than DO (specially for TBT COST results, which may be explained by topological reasons, that is, lower ratio nodes/links and higher mean distances). Mean values of TRC don't vary significantly, with the exception for RC 2 and 4, for all networks. Note that RC 2, 4 are the ones that route by the lowest spectrum occupation first, while the remain RC (1,3,A,B,C) prioritize the minimum number of regenerators. Thus, at RC 2, 4, links with lower occupation will be preferred to others, independently if they are associated to higher distance or higher number of interfaces. Considering that, it is a logical consequence that the results obtained for TRC values are expressively higher. RC 2, 4 lead to better TBT results for all networks if compared to other RC and, simultaneously to induced significant increase of the TRC mean values, indicating that these RC increase traffic saturation at the cost of longer routes. Since RC 2, 4 route by the lowest spectrum occupation first, the longer paths may be preferred to the shorter ones, increasing such way the number of TRC count. This leads to a conclusion that routing algorithms that prioritize the spectrum option (2,4), instead of 3R (A, B, C, 1, 3), generally should be avoided, specially, in heavily loaded networks. The most interesting result is obtained for the PRT network for the RC C, that originated the lowest value of mean TBT, and simultaneously any TRC. It is also observed that for COST and GBN networks, RC C, 1 and 3 lead to relatively low average values of TBT and low number of TRC, indicating that minimizing by the number of regenerators or either the interface count or the number of hops are acceptable options.

Results obtained for GM are summarized in Tables XII and XIII. There is significant reduction, comparatively to the UM, of TRC counts, excluding the results obtained for COST - RC 2, 4 (routing by the lowest spectrum first). Thus, although there is a higher concentration of the requests at specific nodes (at more populated cities), the routing and the selection of paths will end up at the same links (that will be additionally loaded. In the other hand, since TBT is higher, there will be demands that will not even be able to reach the network since they will be blocked at the very beginning (before being delivered to the network), contributing this way to a reduction of TRC count.

Comparing the obtained results both for UM and GM, the best routing algorithms happens to be the routing algorithms 1,3 and C. While the routing algorithms 1 and 3 are the ones that combine the number of regenerators with lowest spectrum, the C routing algorithm combines 3R minimization with the shortest number of lightpaths. It is also important to refer that the relative results obtained for UM and GM were the same, indicating that the implementation of the GM is not significantly important to understand the influence of different demand orderings and routing algorithms in the efficiency of the network.

C. Detailed analysis with modulation scenarios

Results obtained for different modulation scenarios (MS) are summarized in Tables XIV and XV. Average TBT values obtained both for UM and GM, for different networks, are higher for MS 0 (i.e. 50 GHz grid) and are lower for MS 1 (37.5 GHz grid), leaving the MS 2 (50 GHz/37.5 GHz grid) in the middle of both. Thus, smaller granularity (37.5 GHz) and mixed granularity (50 GHz/37.5 GHz grid) have better performance if compared to the higher granularity (50 GHz). And, in its turn, the mixed granularity is slightly better than the smaller one. It is understandable that networks with flexible or smaller grids will have better (lower) TBT results, since the available spectrum is more efficiently used. TBT results for all studied networks are in line with previously discussed results. Regarding TRC results, they are generally higher for modulations 1 and 2, and lower for modulation 0. Thus, smaller and mixed grids are associated to shortest reach distances, which will induce higher number of regenerators when smaller grids are used. However, it is possible to observe that in some cases the number of regenerators is lower when smaller grid is used and the associated TBT results are also lower, if compared to the results obtained for 50 GHz grid. Since the mean traffic at each node is uniformly distributed, the total load per node is lower and the shortest paths are more frequently used (associated to higher capacity of the fiber with smaller grid), generating lower number of regenerators. Better results of TRC were obtained for PRT in GM for smaller grid may be explained by the fact that the most loaded nodes are associated to lower mean distances (that correspond to Lisbon and Porto cities) that are, in average, geographically situated closer to the remain nodes (opposingly, for example, to Porto Santo).

Comparing UM vs GM TRC results, it is possible to observe that COST and PRT results of TRC are lower for GM, whereas in GBN the TRC results are lower for UM specially for smaller and mixed grids. It is expectable to obtain lower TRC results in GM (and not in UM) since in general cases the TRC values are inversely proportional to TBT values, that is, if the TBT is higher, than the corresponding proportion of traffic that won't be introduced in the network will not require any regenerator. However, GBN results are not in line with this generalization, being higher in GM. This may be related with the fact that the obtained TBT results for GBN in GM are expressively higher if compared to other networks, resulting in also corresponding higher TRC values.

Finally, it is important to highlight the significant difference in TRC results in COST network obtained for MS=0 (53 vs 25), followed by results obtained for MS=2 (57 vs 38). This difference may be explained by the fact that the mean distance between the nodes of COST network is the highest one, if compared to other networks and the associated ratio between number of nodes and links is the lower one. Thus, when GM is implemented combined with a 50 GHz grid (associated to to

TABLE X

DEMAND ROUTING STRATEGIES

MEAN VALUES OF TBT (GBPS) AND TRC – UNIFORM MODEL

	Netw[a]/ DO[b]	A	B	C	1	2	3	4
TBT	COST	3.7x10^{3}	3.6x10^{3}	3.4x10^{3}	2.1x10^{3}	4.5x10^{2}	2.1x10^{3}	4.5x10^{2}
	GBN	3.1x10^{4}	3.3x10^{4}	3.0x10^{4}	3.0x10^{4}	2.2x10^{4}	3.0x10^{4}	2.2x10^{4}
	PRT	1.0x10^{3}	9.3x10^{2}	6.7x10^{2}	1.0x10^{3}	9.2x10^{2}	9.8x10^{2}	9.1x10^{2}
TRC	COST	8	8	4	4	156	4	156
	GBN	8	9	5	4	90	4	90
	PRT	0	1	0	0	8	0	8

[a] Netw – Network

[b] DO – Demand Ordering

TABLE XI

DEMAND ROUTING STRATEGIES

RATIO BETWEEN MEAN VALUES AND THE MINIMUM VALUE

UNIFORM MODEL

	Netw/ Demand Ordering	A	B	C	1	2	3	4
TBT	COST	8.3	8.2	7.7	4.7	1.0	4.8	1.0
	GBN	1.4	1.5	1.4	1.4	1.0	1.4	1.0
	PRT	1.5	1.4	1.0	1.5	1.4	1.5	1.4
TRC	COST	2.0	2.0	1.0	1.0	41.7	1.0	41.7
	GBN	1.9	2.1	1.1	1.0	22.6	1.0	22.6
	PRT	1	2	1	1	8	0	8

TABLE XII

DEMAND ROUTING STRATEGIES

MEAN VALUES OF TBT (GBPS) AND TRC – GRAVITATIONAL MODEL

	Netw/ DO[a]	A	B	C	1	2	3	4
TBT	COST	3.3x10^{4}	3.3x10^{4}	3.3x10^{4}	3.5x10^{4}	2.8x10^{4}	3.5x10^{4}	2.8x10^{4}
	GBN	7.2x10^{4}	7.2x10^{4}	7.1x10^{4}	7.3x10^{4}	6.5x10^{4}	7.3x10^{4}	6.5x10^{4}
	PRT	4.0x10^{4}	4.0x10^{4}	4.0x10^{4}	4.1x10^{4}	4.1x10^{4}	4.1x10^{4}	4.1x10^{4}
TRC	COST	10	13	4	3	93	3	93
	GBN	6	12	4	5	124	5	124
	PRT	1	1	1	1	5	1	5

[a] Netw – Network

[b] DO – Demand Ordering

TABLE XIII

DEMAND ROUTING STRATEGIES

RATIO BETWEEN MEAN VALUES AND THE MINIMUM VALUE

GRAVITATIONAL MODEL

	Netw / DO	A	B	C	1	2	3	4
TBT	COST	1.1	1.2	1.2	1.2	1.0	1.2	1.0
	GBN	1.1	1.1	1.1	1.1	1.0	1.1	1.0
	PRT	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TRC	COST	3.3	4.3	1.3	1.0	31.0	1.0	31.0
	GBN	1.5	3.0	1.0	1.3	31.0	1.3	31.0
	PRT	1.0	1.0	1.0	1.0	5.0	1.0	5.0

TABLE XIV

MODULATION SCENARIOS (MS) - TBT (GBPS)[a]

Model[b]	Network / MS	0	1	2
UNI	COST	5.33x10^{3}	1.25 x10^{3}	2.28x10^{2}
	GBN	3.34x10^{4}	2.60 x10^{4}	2.49 x10^{4}
	PRT	2.28x10^{3}	2.56x10^{2}	2.08 x10^{2}
GM	COST	4.02x10^{4}	2.93x10^{4}	2.75x10^{4}
	GBN	7.33x10^{4}	6.85x10^{4}	6.85x10^{4}
	PRT	4.93x10^{4}	3.64x10^{4}	3.62x10^{4}

[a] Mean Values

[b] Model – Uniform (UNI) ou Graviational (GM)

TABLE XV
MODULATION SCENARIOS (MS) - TRC[a]

Model[a]	Network / MS	0	1	2
UNI	COST	53	35	57
	GBN	19	37	35
	PRT	3	1	4
GM	COST	25	30	38
	GBN	22	49	48
	PRT	2	0	3

[a] Mean Values
[b] Model – Uniform (UNI) ou Graviational (GM)

higher reach distances), the obtained relative reduction is the highest one (if compared to other grids or networks). Follows immediately the mixed grid, with associated reach distances that are situated between the 50 GHz grid and the 37.5 GHz.

Relatively to the influence of the RC at the TBT values for different MS, it is possible to conclude that for COST and GBN networks, the main tendency is that RC's 2 and 4 lead to lower (better) results. However, this is not so linear for PRT network, since despite for MS=0 maintains the trend, for MS=1 and MS=2 the results are steady, and the sequences approximately inverted. For TRC values the worst results are obtained precisely for RC 2 and 4 (COST, GBN and PRT) and there is a strong tendency for the lower (best) values being obtained with RC C,3,1. It is interesting to observe that the results for different combinations and networks are almost equal for MS=0 for, whereas they start to be different when smaller grid granularity (M=1) is introduced. It is also interesting to observe that RC C (combination of lowest 3R (1st) and shortest number of lightpaths at the path (2nd)) leads to better results in many studied scenarios.

V. CONCLUSIONS AND FUTURE WORK

The analysis of the collected results obtained via extensive computer simulations allowed to conclude that at heavily congested networks demand ordering and routing criteria algorithms denote more impact when the network is characterized by lower ratio between the number of nodes and links and higher mean link distances. Thus, highly connected networks with lower mean distances will have better behavior (in terms of average levels of TBT and TRC results) when subjected to the same input load (traffic), whereas networks with higher mean distances will require higher number of regenerators to support the traffic (e.g. COST and GBN).

With regard to different demand orderings, and for both TBT and TRC counts, analysis of the results obtained for GBN and COST with uniform traffic model allow to conclude that demand ordering strategies based on most congested links first can be an important tool to improve the performance of the routing algorithm, allowing to obtain enhancements in the efficiency up to 30-40%. When networks need to deal with high volume of traffic concentrated at specific nodes of the network, as it happens in GM, the number of the available links gains an increased importance as a lacking resource and lead, in average, to a preferable demand ordering option to be, with especial relevance for the TBT results, the most congested link first, reinforcing the results obtained in the UM, but this time, extensible to all studied networks.

Implementation of routing criteria algorithms, in comparison to the demand ordering algorithms, has higher impact in the results, being associated to higher variations in TBT and TRC average counts (with special incidence in this last ones). It was observed both for uniform and GM that routing criteria that prioritized spectrum occupation (routing criteria 2 and 4), conduced to somewhat lower TBT results, but simultaneously to expressively higher values of TRC, leading to a conclusion that these routing algorithms should be avoided if lower number of regenerators and lower total blocked traffic are the goals to achieve. Routing criteria C, 1 and 3, based on minimization of the number of regenerators and either lower number of interfaces or hops are acceptable options to consider if higher efficiencies are sought. It was also concluded that the relative results (best/medium/worst) obtained for UM and GM were the same, indicating that the implementation of the GM is not significantly important to understand the influence of different demand orderings and routing algorithms in the efficiency of the network. However, gravitational model is actually a very important tool in cases where it is important to estimate the absolute values of TBT and TRC, since it approximates the results to real scenarios.

Detailed analysis of the results for different modulation scenarios lead to a conclusion that smaller grids, especially if implemented in networks characterized by lower mean distances between the nodes, allow to obtain higher efficiencies, leading this way to lower TBT and TRC results. Networks characterized by higher mean distances between the nodes also benefit with smaller grid partitioning, however implementation of routing criteria need be analyzed more carefully. Thus, if the TBT is expressively high, the TRC count may not reflect the true number of the regenerators that is really required, since in a simulation process these demands will be blocked before being delivered to the network. It was also observer that implementation of different grids influences mainly the TRC results, being this way an important tool to consider in a planning process, which is closely related with the fact that shorted grids are associated to shortest reach distances.

Finally, it is important to refer that implementation of routing criteria is the factor that influence the most the TBT and TRC results, if compared to implementation of demand orderings and different modulation scenarios. Thus, a careful analysis of the topological elements of networks, combined with the implementation of suitable routing criteria may be the win-win solution to a problem.

VI. FUTURE WORK

The developed work can be further extended into multiple directions. Refer to the following list as a set of possible studies:

- Evaluation of the demand ordering and routing algorithms in multi-period planning with traffic churn. The use of SC implies a spectrum occupation that is not limited to single 50 GHz slot. In this sense, spectrum left vacant due to the removed traffic demands may not be enough for the demands of the next period.

- Consider different traffic loads. In this work, a fixed entry load of 130 Tbps was assumed. This was done to represent a heavy loaded network. However, the algorithms studied could have a different performance when subjected to a lighter or even heavier traffic load.
- Include high baud-rate signals into the optical signal options to carry the client traffic. The high-baud rate formats (e.g., 60 Gbaud/s, 90 Gbaud/s) can increase the bit-rate but use a single optical carrier which occupies a wider spectrum slice. There is a trade-off regarding reach with SC that could provide different conclusions regarding the most adequate demand ordering and routing algorithms.

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REFERENCES

[1] ITU-T, „SERIES G: TRANSMISSION SYSTEMS AND MEDIA, Transmission media and optical systems characteristics – Spectral grids for WDM applications: DWDM frequency grid (G.694.1), “13 02 2012. [Online]. Available: https://www.itu.int/rec/T-REC-G.694.1/en. [Zugriff am 03 10 2018].

[2] X. Yu, M. Tornatore, Y. Zhao, J. Zhang(1), X. Wang, S. Zhang, R. Wang, J. Wang, J. Zhang und B. Mukherjee, „When and How Should the Optical Network Be Upgraded to Flex Grid?,“ ECOC, p. P.6.15, 2014.

[3] J. Santos, „Evaluating the Potential for Spectrally-Efficient Super-Channel Formats in Brownfield Networks with Legacy Services (and published at OFC2015 (Optical Fibre Communication Conference)), “Optical Society of America, p. (060.4250) Networks; (060.4510) Optical communications, 2014.

[4] Coriant, „White Paper - The role of higher baud rates in evolving coherent transport (74C.0176 Rev. A), “March 2018. [Online]. Available: http://cdn.extranet.coriant.com/resources/White-Papers/WP_Role_of_Higher_Baud_Rates_74C0176.pdf?mtime=20180307013252http://cdn.extranet.coriant.com/resources/White-Papers/WP_Role_of_Higher_Baud_Rates_74C0176.pdf?mtime=20180307013252. [Zugriff am 23 July 2018].

[5] K. Roberts, Q. Zhuge, I. Monga, S. Gareau und C. Laperle, „Beyond 100 Gb/s: Capacity, Flexibility, and Network Optimization, “Optical Society of America, Bd. 9, Nr. 4, pp. C12-C24, 4 April 2017.

[6] V. Lopez and L. Velasco, Elastic Optical Networks, Switzerland: Springer, 2016.

[7] J. Santos und J. Pedro, „Support of Superchannel Formats in Optical Networks With Legacy Services and Traffic Churn [Invited], “J. OPT. COMMUN. NETW (B122) - Optical Society of America, Bd. 7, Nr. 12, 2015.

[8] D. Maniadakis und D. Varoutas, „Population Distribution Effects in Backbone Network Cost, “in IEEE Globecom - Workshop on Complex and Communication Networks, 2010.

[9] J. R. Santos, A. Eira und J. Pires, „Routing on Multi-Layer Transport Networks with OTN and Optical Flexible Grid DWDM Technologies, “IST, 15 April 2015. [Online]. Available: https://fenix.tecnico.ulisboa.pt/downloadFile/844820067124516/resumo.pdf. [Zugriff am 27 June 2018].

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