Lessons and conclusions from elastic optical networks

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Author(s):	Name	Partner
	Marco Quagliotti (editor)	TI
	Andrew Lord	BT
	Paul Wright	BT
	António Eira	Coriant PT
	João Pedro	Coriant PT
	Matthias Gunkel	DT
	Michael Parker	LEXDEN
	Juan Fernandez Palacios	Telefónica
	Kostas Christodoulopoulos	University of Patras
	Loris Corazza	University of Patras
	Panagiotis Kokkinos	University of Patras
	Manos Varvarigos	University of Patras
	Chris Matrakidis	University of Peloponnese
	Theofanis Orphanoudakis	University of Peloponnese
	Alexandros Stavdas	University of Peloponnese
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	Gabriel Junyent	UPC
	Marc Ruiz	UPC
	Luis Velasco	UPC
	Mirosław Klinkowski	WUT
	Michał Pióro	WUT
	Artur Tomaszewski	WUT
	Mateusz Żotkiewicz	WUT
Checked by:	Andrew Lord	BT
	Emilio Riccardi	TI

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1 Executive summary

1.1 Benefits of Elastic Optical Networks

This is the final WP1 deliverable in IDEALIST and its intention is to summarize the field of Elastic Optical Networking, reviewing the technology, its benefits and applications. It also looks at likely evolution scenarios. This final report seeks to set the entire project into context, summarizing the main findings and charting a path forwards. It begins by defining Elastic Optical Networks (EONs) and summarizing the main benefits and advantages in using them.

EONs are characterized by several features:

(i) Flexrate – Bandwidth Variable Transponders (BVTs) with the ability to dynamically adjust their modulation format from DP-QPSK to DP-16QAM and others. Flexrate might also include the availability of different FEC options to aid interoperability or provide options to reduce latency when needed. Another future aspect of flexrate might include the potential for changing the baudrate. This is currently fixed at 25 Gbaud for the data payload plus whatever overhead is required for FEC – typically giving baudrates of 28-32 Gbaud.

The ability of the transceiver to optimize its modulation format to fit the channel unlocks significant network bandwidth and enables the maximum data to be carried through the transceiver. For example a transceiver operating at DP-16QAM carries twice the capacity compared to DP-QPSK operation. In this case the costs are approximately halved. In general, flexrate can reduce network costs by around a factor of 2 and also release significant spectrum for future demands, delaying the need for new build.

(ii) Flexgrid – the optical spectrum can now be used more flexibly and not be restricted to operating within approximately 90 50 GHz slots. The new ITU standard allows for 12.5 GHz resolution, allowing, for example, a new 37.5 GHz slot size. Two distinct benefits emerge: one is the direct spectrum saving available by squeezing channels together more tightly, freeing up spectrum for future demands. This doesn’t give a direct cost saving, but it does allow the network to support more traffic before new build is required. The second benefit comes from the new ability to concatenate spectrum to create larger spectral chunks. These can now be used to hold so-called super-channels, which comprise multiple sub-channels transmitted together tightly and with high spectral efficiency.

The reduced slot size allows approximately 1/3 more spectrum to be available – having a significant effect on network capacity and delaying the need for new build, something of high importance to carriers. Taking flexrate and flexgrid together can unlock between two and three times as much capacity on the network.

(iii) Sliceability – the spectrum concatenation enables the possibility of a new range of transceivers – capable of creating super-channels within one device – called a sliceable bandwidth variable transponder or S-BVT. These highly flexible devices have multiple laser sources and modulators, and can produce a high aggregate bandwidth, made up of multiple individual carriers. These carriers can either all go to separate destinations as separate entities, or all go to the same destination as one giant super-channel– or some combination of these.

Sliceable Bandwidth Variable Transponders allow a reprovisioning of existing bandwidth in the network as traffic changes and grows, making them more cost effective than their single channel BVT counterparts. They also allow advantage to be taken of the concatenated spectrum to enable highly efficient superchannels and save spectrum for future demands.

These high level benefits hide the fact that networks are too complex for the improvement to be summarized in a single figure of merit. Therefore, this deliverable unpacks these more detailed benefits, progressing from nearer term, more static networks to longer term with more dynamicity.

In the shorter term, we focus on this key discussion above – i.e. whether we wish to optimize cost or spectrum. As already explained, EONs give the capability to do both of these things: for example a flexrate transceiver can save cost by transporting twice as much data (DP-16QAM vs DP-QPSK) for shorter paths, but it can also save spectrum by removing the need for a second (DP-QPSK) transceiver. How valuable are these two benefits for service providers? The discussion in section 3.2.1 shows how to minimize a function with a parameter *w* which is the weight used in the optimization function that considers both the spectrum utilization and the transponder's cost. Defining *C,* the cost of the transponders and *S,* the maximum number of frequency slots used, the algorithm optimizes a weighted combination of these metrics. Changing parameter *w* determines whether cost or spectrum saving is prioritized. The conclusion shows a trade-off reproduced below: Figure 1 explains how more expensive transponders will be required if spectrum saving is the main objective – and vice versa.

Spectrum saving is a longer term objective as it serves to delay the requirement for new network build. Therefore this modelling provides direct and highly useful advice to operators when it comes to how they choose to operate their networks and make use of their transponder and spectrum resources.

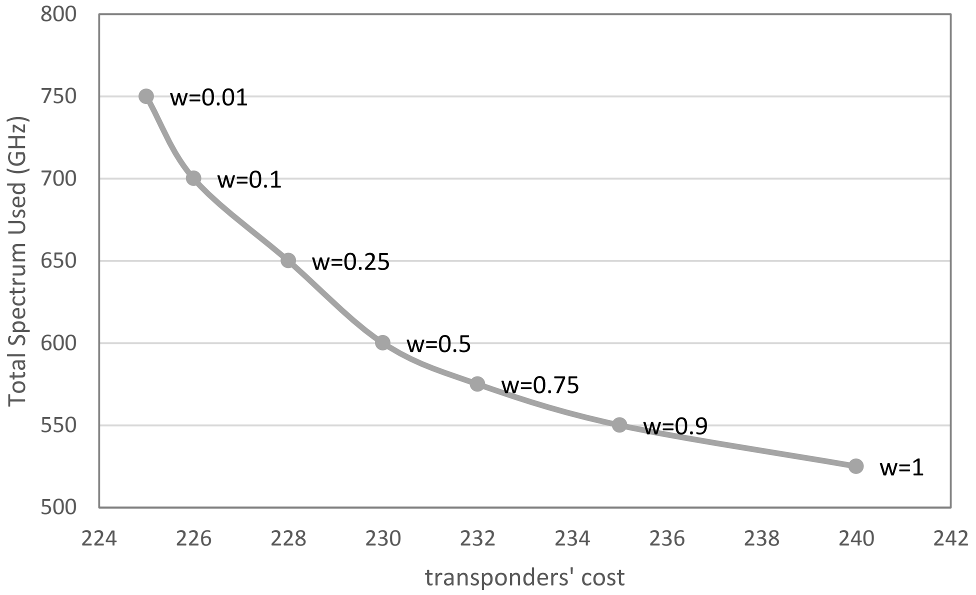

Figure 1: Trade-off between spectrum and transponder cost in the DT network.

Following a description of significant progress made in how to model and optimize huge network data, this then leads to a discussion on how to plan network evolution over many years of static traffic growth. This inevitably brings into play the third of our EON benefits – sliceability – which is a significant IDEALIST contribution to EON research. The topic is known as multi-period planning and it acknowledges the fact that in the future, EONs will be added to as traffic grows, and existing resources will be redeployed as required. The work in 3.2.3 shows in detail how S-BVTs provide this new level of redeployment flexibility, resulting in equipment savings over a longer time period.

One critical element here, and a key part of the joint work between WP1 and WP2, relates to the need for more flexible switching between the client and line side – essential if we are to release the full S-BVT capabilities.

Finally the static traffic considerations extend to looking at how to grow networks when multiple fibres are required between nodes, and the work in 3.2.4 shows that it is far better to over-load fibres around the network 'centre' than simply double up fibres across the network.

The first instance of traffic dynamics is likely to come from the need for resilient EONs. For example, if fibres are cut, then large amounts of traffic need to be redirected – often very quickly. This is essentially a kind of network dynamics and it puts both a stress on EONs but also gives them the chance to demonstrate benefits – IDEALIST believes that EONs operate successfully and advantageously in dynamic scenarios.

The graph below (Figure 2), described more fully in 3.3.1, shows how a BVT-based EON can perform very beneficially in a network suffering fibre breaks. In this work, a historical fibre break figure was used from the BT network. The graph plots the cumulative blocking probability in function of the number demands for three different options which entail different combinations of transponders (one option uses fixed and the other two bandwidth variable transponders) and design margins.

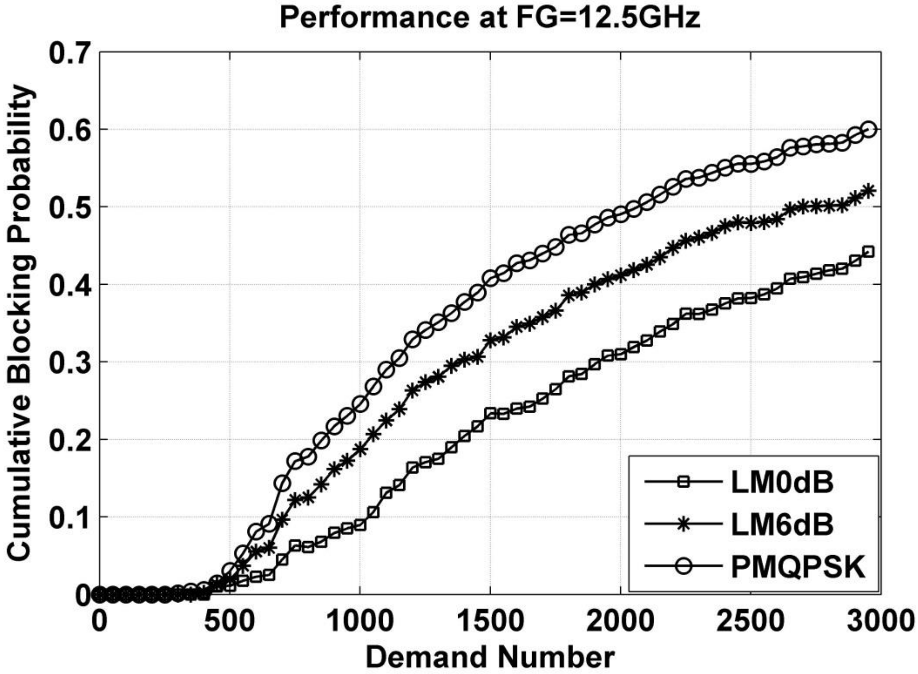

Figure 2: Network blocking as traffic grows and fibres break - for different margin settings.

Here we utilize the fact that BVTs can adjust their modulation format to meet the channel requirements. Therefore, we can choose to operate right on the zero dB margin point – and adjust the modulation if the fibre loss degrades after a cut. The line plotted with circles shows a fixed transceiver solution (QPSK). Simply moving to BVTs (line with asterisks) improves network capacity – but the improvement is significantly larger if we dynamically reduce the margin – over 50% more capacity can be supported for 0.1 blocking probability (squares).

The following discussion goes further – it introduces new ways to actually implement restoration by taking full advantage of EON resources (in section 3.3.2). The benefits of IDEALIST's new Multi Path Protection scheme are both large, but also give a trade-off with restoration time, to allow different options.

So far the discussion has been limited to Layer One protection, but the Control Plane developments in WP3 enable EONs to help the IP layer capitalize on these new optical resources, discussed in 3.4.4 which summarizes the key developments in this area. Detailed modelling on the DT network is showing up to 78% benefit for this Use Case, see 3.3.3. Of course, IP over Optical highlights the growing mismatch between layers one and three especially now that EONs can produce multi-Tb/s super-channels. IDEALIST has studied the logical use of OTN to bridge this gap as discussed in 3.4.1 Here, OTN can serve to groom smaller flows into large ones suitable for super-channel transport. The key architectures to enable this are provided in the report.

Section 3.4.3 shows how, with EONs, the entire network can become more dynamic, and that it is possible to now redesign the metro and core domains to minimize the amount of electrical switching and routing. This has been a large theme in IDEALIST, in which flatter networks with larger numbers of nodes become feasible through the EON capability of setting up flexible optical paths.

IDEALIST believes that the need for traffic dynamics will increase beyond that induced by restoration events. For example inter-datacenter traffic already is exhibiting dynamic behavior. This introduces a new traffic feature – it can be regularly removed as well as added. For EONs, this means that spectrum demands can grow and shrink in real time. In handling this elasticity, we distinguish between three modes of operation: (i) fixed – in which the central frequency (CF) and width are fixed, (ii) semi-elastic – in which the CF is still fixed but spectral widths can grow and shrink and (iii) elastic – where both spectral widths and CF can move. We show in 3.5.1 how full elastic provisioning is required to get all of the benefits and we also describe how the Control Plane architecture developed in IDEALIST can organize resource requests.

One issue that can reduce the effectiveness of elastic bandwidth provisioning is fragmentation, in which irregular and hard-to-use chunks of spectrum are left around, reducing the overall efficiency. There is a detailed discussion on this, showing the IDEALIST approach to traffic management to reduce the impact of fragmentation.

There then follows in 3.6 a summary of the work done on energy aware network algorithms. Analyses and modelling are provided using realistic power consumption figures and the general principle is that layer 3 processing should be avoided where possible. OTN grooming is also shown to be an efficient way to save power – by carrying out the grooming functions at layer one rather than layer 3.

The final section here (3.7) looks closely at the benefits of sliceability. This has required a deeper study of traffic and network growth including static but growing traffic with some uncertainty on device cost and which mix of traffic rates would be required in the future. We also looked at the use of sliceability to improve resilience schemes and also explored the multicast traffic use case.

The following figure shows the basic S-BVT principle whereby an original component can be redeployed as traffic grows.

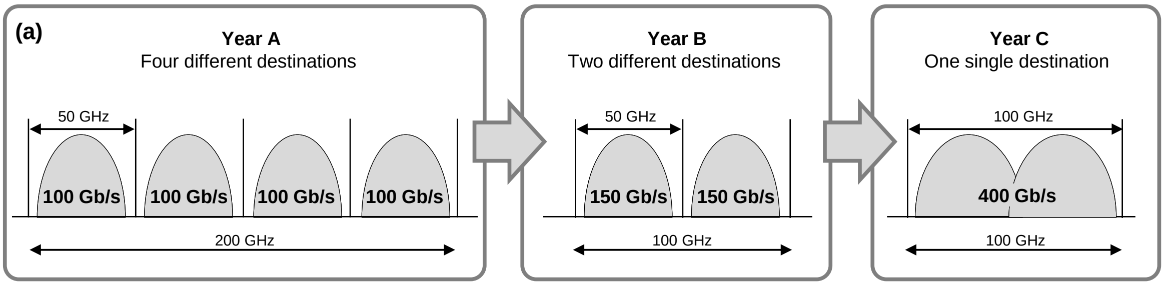

Figure 3: Different deployment scenarios for an S-BVT transceiver.

In the figure it is straight forward to see how a single 400 Gb/s S-BVT device with 4 lasers + modulators initially generates 4 x 100 Gb/s headed to different destinations. Then later as the traffic grows it can be used to send more traffic to two destinations – and then finally the entire S-BVT resources can be used to send a super-channel to one destination. This flexibility of deployment gives the device a great advantage, reducing the overall number of devices required.

1.2 IDEALIST solutions

Based on this thorough study and analysis of the merits of EON, IDEALIST has developed solutions to allow implementation of these concepts. Section 4 of this deliverable summarizes the main building blocks, which are reported in Table 13 together with the situations (e. g. use cases considered in WP1, corresponding to the ones described in detail in subsections of Section 3) that require them. These building blocks include physical layer components, but also softer elements such as algorithms, methods, planning tools, GMPLS and SDN control software and orchestrators.

Much of the contents of this section is highlighting results from WP2 and WP3, bringing all the key results together so that all the building blocks are described at a high level in the same place. So for example, we show an S-BVT architecture including coupling from client to line side. Also shown is an important table of example S-BVT modules for short term implementation, with up to 400 Gb/s capability. Examples of optical switch architectures are also provided.

These physical layer blocks are then followed with cost estimates for them all – as far as is possible for components that don't yet exist in the market. Just as important, but often neglected, is a table highlighting potential OPEX costs, associated with rental of fibre, space for equipment and energy consumption. A specific energy consumption model is included and used for the energy based optimization in section three.

Section 4.3 describes the Adaptive Network Manager (ANM) that is the key output of WP3 and provides the IDEALIST Control Plane Architecture, showing how all of the concepts and Use Cases in IDEALIST could be carried out and orchestrated in practice. The figure below reproduces this architecture.

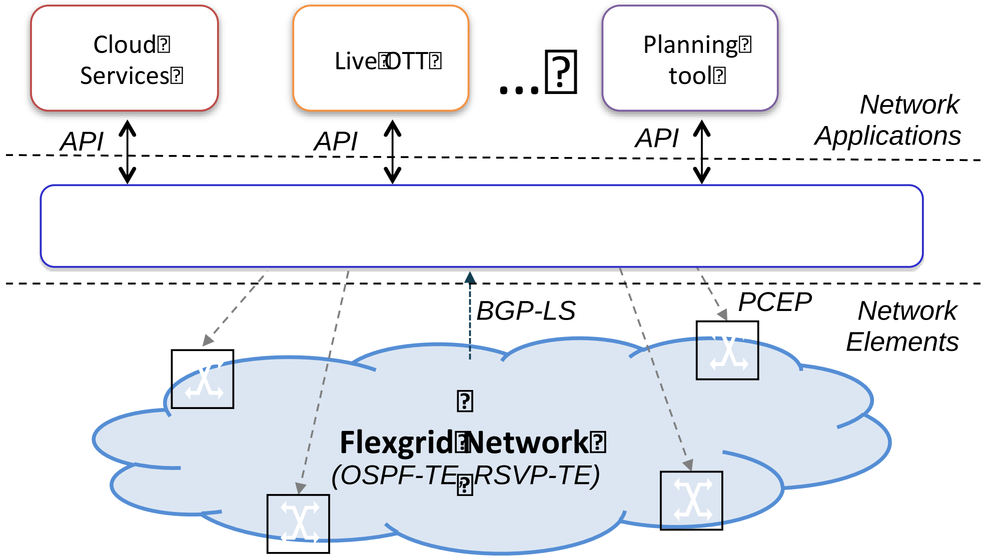

Figure 4: IDEALIST Control Plane Architecture.

1.3 Migration strategies

Section 5 of this deliverable asks the question – when will these new technologies be introduced into service provider networks? Currently optical transport networks use WSS based ROADMs and often these WSS are flexgrid-ready – requiring only software changes to take advantage of the enhanced spectrum control. Already there is deployment of early coherent transceiver technology – not flexrate – but usually 40Gb/s and 100Gb/s coherent fixed rate transceivers and some early 200Gb/s.

The following figure summarizes how IDEALIST expects the new technologies to be implemented and the evolutionary process involved. The deployment roadmap presented hereafter is a general scheme summarizing a potential strategy and it does not reflect any specific operator deployment plan. The final deliverable of WP6 committed to project exploitation, includes specific sections illustrating the EON deployment roadmaps as they are in the individual view of each operator participating to the consortium.

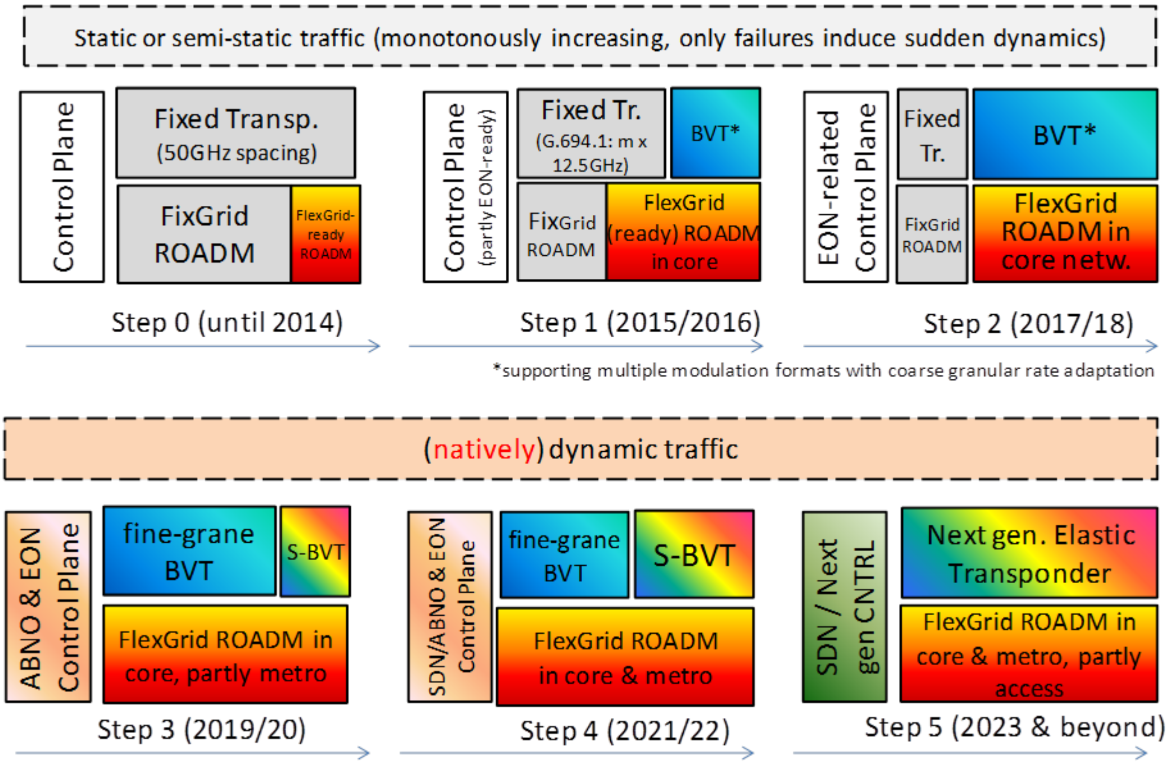

Figure 5: Evolutionary deployment roadmap for a gradually smooth migration.

Summarizing these steps very briefly:

Step 0: 50 GHz spaced networks and Fixed Grid ROADMs but with potential for new flexgrid-ready WSS technology to be installed by early adopters. Fixed transceivers with 40/100 Gb/s coherent technology.

Step 1: It is more likely now that service providers will install flexgrid-ready WSS. Also, the transceivers might still be predominantly fixed, but higher QAM capability starting to emerge such as 200G DP-16QAM. Even some early BVT adopters are foreseen, i.e. transceivers that enable both 100G DP-QPSK and 200G DP-16QAM in the same device.

Step 2: Large scale introduction of BVTs in which the transceiver can be dynamically tuned to use different modulation formats – ensuring each path uses the most data per transceiver that is possible given by the path OSNR. Also seeing actual use of flexgrid in the core – to give more spectrally efficient operation. Introduction of EON-related control plane that allows full management of both flexrate and flexgrid functions in isolated domains.

Step 3: Some early S-BVTs are introduced. The ABNO architecture is the chosen framework for orchestration of the control planes active in different network domains, i.e.

an "ABNO compliant" orchestrator coordinates a set of EON-aware control planes, potentially comprising "flexgrid enhanced" GMPLS control planes (CP), but also early SDN / Openflow CPs. In any case the EON control planes are expected to be predominantly vendor-specific and serve to shield the optical transport complexity from the orchestrator.

Step 4: Evolution of control planes with the introduction of open interfaces between the EON controllers and the ABNO-based orchestrator following the SDN paradigm. This allows enhanced multilayer functions such as IP over EON. Potentially, EON SDN CPs will be in the majority but still need to coexist with residual GMPLS-based CPs. At this step we will have the full flexgrid implementation.

Step 5: Full next generation data plane and control plane.

One of the other key developments will be the move of this technology from core towards metro as it becomes more cost effective.

Finally, the report discusses the longer term view which hasn't been included in the roadmap above as it is more speculative. We anticipate that when traffic demands begin to require many fibres per link that advanced concepts such as Architecture on Demand and SERANO will become useful.

In conclusion, this final WP1 deliverable for IDEALIST completes a full review of EONs, including details on technologies, implementations, use cases and timescales. The resounding conclusion is the EONs will inevitably be the next direction for core transport and will support huge traffic growth in European countries for the next decade.

2 Introduction

2.1 Purpose and scope

This is the sixth deliverable from Work Package 1 of IDEALIST and the last of the project dealing with general aspects about network architectures, optimization issues and techno economics associated with the introduction of EON in next generation networks. The motivation and an overview of this deliverable have been provided in the Executive summary. The core part of the document is organized into three sections (Section 3, 4 and 5) which report on the conclusions of the project in the form of answers to the questions "why", "how" and "when" Elastic Optical Networks should be, and we believe they will be, industrialized by equipment vendors and deployed by operators and service providers.

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2.2.2 Acronyms

ABNO	Application-based Network Operations
AFRO	After Failures Repair Optimization
AoD	Architecture on Demand
API	Application Programming Interface
ARPA	ARea Partitioning
ASO	Application Service Orchestrator
BB	Branch and Bound
BGP-LS	Border Gateway Protocol – Link State
BP	Branch and Price
BPSK	Binary Phase Shift Keying
BV-OXC	Bandwidth Variable - Optical Cross Connect
BVT	Bandwidth Variable Transponder
BV-WSS	Bandwidth Variable Wavelength Selective Switch
CAPEX	Capital Expenditures
CF	Central Frequency
CG	Column Generator
CMOS	Complementary Metal-Oxide Semiconductor

DC	Data Center
DC2DC	Data Center to Data Center
DP	Dual Polarization
DPP	Dedicated Path Protection
DP-16QAM	Dual Polarization - 16 state Quadrature Amplitude Modulation
DP-8QAM	Dual Polarization - 8 state Quadrature Amplitude Modulation
DP-BPSK	Dual Polarization - Binary Phase Shift Keying
DP-QPSK	Dual Polarization - Quadrature Phase Shift Keying
D-RSA	Dynamic - Routing and Spectrum Allocation
EC2	Elastic Compute Cloud
EON	Elastic Optical Network
FEC	Forward Error Correcion
GA	Genetic Algorithm
GMPLS	Generalized Multi Protocol Label Switching
HD-FEC	Hard Decision - Forward Error Correcion
ICT	Information and Communication Technologies
ILP	Integer Linear Programming
IP	Internet Protocol
LSP	Label Switched Path
MCS	Multi Cast Switch
MEMS	Micro Electro-Mechanical Systems
MFOM	Multi Flow Optical Module
MIMO	Multiple Input Multiple Output
MIP	Mixed Integer Programming
MLR	Mixed Line Rate
MPLS	Multi Protocol Label Switching
MPR	Multi Path Recovery
NMS	Network Management System
NMS	Network management System
OFDM	Orthogonal Frequency Division Multiplexing
OFP	OpenFlow Protocol
OPEX	Operational Expenditures
OSNR	Optical Signal to Noise Ratio
OSS	Operations Support System
OTN	Optical Transport Network

OXC	Optical Cross Connect
P2MP	Point to Multi Point
PG	Path Generation
QAM	Quadrature Amplitude Modulation
QoT	Quality of Transmission
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RSA	Routing and Spectrum Allocation
RWA	Routing and Wavelength Assignment
S-BVT	Sliceable Bandwidth Variable Transponders
SD-FEC	Soft Decision - Forward Error Correcion
SDM	Spatial Division Multiplexing
SDN	Software Defined Network
SERANO	Switchless Elastic Rate Node
SPP	Shared Path Protection
U2DC	User to Data Center
U2U	User to User
WDM	Wavelength Division Multiplexing
WP	Work Package
WSS	Wavelength Selective Switch

2.2.1 Definitions

CPLEX	Mathematical programming solver for linear programming, mixed integer programming, and quadratic programming commercialized by IBM.

2.3 Document history

Version	Date	authors	Comment
DRAFT1	31.08.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	First version with agreed ToC, placeholders and incorporating a first set of contributions from UPC, TID, DT, WUT, UoP, TI.
DRAFT 2	09.09.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Second version with contributions from Coriant and University of Patras added.
DRAFT 3	05.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Third version with additional contributions on Planning tool (UPC), performance metrics (TI) and data plane solutions (TI). Reorganization of Sec. 3. Change of position of performance metrics (from Sec. 3 to Sec. 4). Upgrade of Sec. 5.
DRAFT 4	09.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Version of the document after Madrid meeting. In particular Section 3.1 reports the discussion on EON attributes. Updates (3.3.2, 3.4.3 and 3.5.1) and new contributions (3.5.3, 3.5.4 and ext. of 4.4.1) are provided by UPC during the meeting.
DRAFT 5	19.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Table on uses cases-building blocks introduced in sec. 1. Contributions from BT added, (sec. 3.1, 3.3.1 and 5.1). Contribution from LEXDEN added (sec. 3.3.4). Acronyms

			completed. Other minor changes.
DRAFT 6	22.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Updated contributions from DT (5.1.2, 5.2.2), WUT (3.2.2), UPatras (4.2.2), BT (Executive Summary). Other editorial work on references and figure and table captioning.
DRAFT 7	26.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Reviews from DT and WUT, updates from Upatras (Figure 1), moving and modification of previous Table 1 , now Table 13 (Use Case-bulding blocks), to align it with the same table in D4.4. Some preliminary additional reviews based on the feedback of the internal reviewer.
DRAFT 8	29.10.2015	All people in the list of authors. Edited and distributed by Marco Quagliotti.	Reviews from some contributors feedbacks. Update of table 13.
Version 9	06.11.2015	Andrew Lord	Complete version reviewed by WP1 leader (Andrew Lord).
Version 10	11.11.2015	Emilio Riccardi	Review with comments.
Version 11	12.11.2015	Marco Quagliotti	Reviews and comments processed and version ready for the 3rd year project review completed.

2.4 Document overview

The document starts with two introductory sections: the Executive summary (Section 1), which offers a concise and effective summary of the content of the core part of the document, and the Introduction (Section 2), which includes all the general information relevant for the deliverable (i.e. the scope of the document, the list of acronyms, the quoted references and the editorial history).

The core of the document is structured in the three sections, namely from Section 3 to Section 5.

Section 3 includes the project results organized to answer the question ***why*** EON should be developed and deployed. The Section is structured with an introduction with the description of EON attributes that have been compiled according to an agreed vision of the project partners, and a list of Use cases which demonstrate, by means of quantitative and qualitative studies targeted to specific scopes, the benefits of introducing EONs.

Section 4 explains ***how*** IDEALIST proposes to proceed towards the optical network of the future. The section summarizes the IDEALIST solutions in terms of building blocks developed within the project that, combined together or even only in part, could constitute the solutions for the forthcoming EONs. Building blocks include data plane solutions (from WP2), control plane architectures (from WP3) as well as tools, models and methods which make possible the overall implementation of an EON.

Section 5 tries to answer the question ***when*** EONs will be a reality in the field, beyond successful proofs of concept and lab trials, as networks actually operated by service providers and operators to cope with challenging high capacity and high dynamic network scenarios. After an overview of the state of the art of optical networks as they are today and of the migration strategies towards flexgrid proposed so far in the literature, the section presents some realistic network deployment roadmaps targeted to the short and mid-term, which are consistent with the data plane roadmaps of WP2. The Section proposes also some indications about possible evolutions in the long term when an accurate and reliable prediction has not been possible, but whose solutions have been considered in many studies during the project.

The conclusions are exposed in Section 6. As D1.6 is the final deliverable dealing with general architectural and techno economic subjects about EONs, conclusions are written taking into account the work done by all the work packages in the whole lifetime of the project.

3 Why - Benefits of Elastic Optical Networks

In this section the benefits of elasticity in optical networks are illustrated with the support of a selection of results achieved with the defined Use Cases during the project. The section starts with the definition of the attributes of EON, as they were agreed within the project, and afterwards it includes subsections focused on an overview of specific use cases which demonstrate, by means of quantitative studies, the benefits of EONs.

3.1 Attributes of EON

Elastic Optical Networks have been researched now for a number of years and various attributes have emerged as being crucial to an understanding of them. The main three of these are flexrate, flexgrid and sliceability (or multi-flow):

- Flexrate. This is a transponder property and refers to the new capability of transponders whereby the data through-put can be adjusted – even dynamically. The general term for these transponders is BVT (bandwidth variable transponder). There are different flavours – all introduced here:

  (i) Flex Modulation Format. This relates to changing the modulation format – e.g. from DP-QPSK to DP-16QAM and other formats. In these cases, the baud rate is maintained relatively constant (apart from small changes coming from different Forward Error Correction (FEC) overheads). This implies that approximately the same optical spectrum is used despite flexrate changes. The main benefits relate to a tighter matching of the transponder reach to the required optical path and consequently a more efficient use of spectrum, wherever possible and especially for shorter optical paths. This means that the same transponder can be used to carry more traffic where possible, leading to network dependent gains. For example, moving from DP-QPSK to DP-16QAM gives 100% gain in capacity but won't work on very long paths. The feature can be useful for protection, where the protection path is likely to be longer than the working path and so may require a different modulation format. The main benefit of flexrate is CAPEX (only a single transponder required to do up to 200Gb/s and beyond). Sparing is a related benefit, allowing just one type of transponder to fulfil the various reaches. Additionally there is a spectrum-saving benefit where the use of higher modulation formats makes full use of a given spectrum, before moving on to use more.

  (ii) Flex-FEC. As introduced above, different FEC rates are added to the data rate (typically 25 Gbaud) to produce the overall baud rate of data plus overhead. Different FECs are provided to give service providers more flexibility – e.g. to achieve different reaches or optimize latency, or transponder power, or perhaps to achieve compatibility with transponders from other vendors when alien waves are required.

  (iii) There is some discussion in the industry about providing a transponder capability that allows for a flexible baud rate. In this application, a transponder with a high baud rate capability could be operated at a rate lower than its maximum. Changing the baud rate is challenging and hasn't been included in the short term transponder options considered in WP2. Changing the baud rate leads to a change of spectrum which requires flexgrid to manage, whereas flexible modulation formats don't necessarily need flexgrid (though see comments below related to cascaded ROADMs). Situations where we might want to reduce the baudrate below the maximum might include reducing the spectrum to fit in a restricted optical path, management of impairments, defragmentation (i.e. fitting into a small optical spectrum) and energy management.

Overall it is not the view of IDEALIST that flex-baud rate is as important as flex-modulation format, and the Use Cases haven't been convincing so far.

- Flexgrid. This refers to the ability of the optical switching in the network nodes, usually carried out by ROADMs. The ROADMs are used to control the adding, dropping and switching of chunks of spectrum and with flexgrid capability; they have two distinct improvements: an improved resolution of 12.5 GHz (instead of 50 GHz), and the ability to concatenate slots together to define arbitrarily large chunks of spectrum. This implies two benefits:

  (i) 37.5 GHz is a potential new minimum slot size compared to the conventional fixed-grid DWDM spacing of 50 GHz, which leads directly to a saving of 33% in spectrum for a point to point link. Network based modelling has shown similar benefits on a network scale, though these can be reduced if traffic becomes very dynamic, due to increased fragmentation. Note that this is a spectrum saving rather than a reduction in cost. However this is still a great benefit to service providers as it allows the network to support higher capacity before additional network build is required (e.g. overlay fibres). Operation on a new fixed-grid of 37.5 GHz would be possible but this might be too restrictive, especially for long optical paths comprising many cascaded ROADMs, where the net optical path will be reduced to the point where it starts to filter out some of the signal spectrum. The flexgrid option of widening the channel to 50 GHz would be highly useful in these situations, with the proviso that this could produce fragmentation (i.e. random, unusable spectral gaps of 12.5 GHz arising because some slots are 37.5GHz and some are 50GHz). We don't expect this to be a big issue unless the traffic becomes very dynamic.

  (ii) Larger spectral slots to carry super-channels. These are collections of multiple sub-channels that together comprise a large overall demand between two nodes. For example 5 x 200 Gb/s (DP-16QAM) sub-channels would make a 1Tb/s super-channel. It would be entirely possible to carry the 5 sub-channels as individual channels – effectively inverse-multiplexing them. The main advantage of combining them into a super-channel is that the entire spectrum can be transported as a single entity, with the appropriate flexgrid spectrum made available by the intermediate ROADMs. This is more spectrally efficient than treating them as separate channels, which would all require guard bands to allow for ROADM filtering effects. We might also expect simpler management from a combined super-channel. Additionally, inverse multiplexing (e.g. transporting a single 1Tb/s client demand from a large IP Router as 5 separate 200G transport channels) involves additional cost compared to having a line side super-channel able to match the client rate interface. Although super-channels require flexgrid for operation, their true benefits emerge when we consider the novel transponder approaches (applying electronic and optical integration) for generating them.

- Sliceable or multi-flow transponders (S-BVT) are novel transponders that are capable of multiple, separate modulated outputs for a single device. They have emerged as key components in the EON paradigm for two basic reasons: (i) super-channel operation requires the generation of multiple sub-channels and the most economic way to do this is within a single device, (ii) traffic growth can be efficiently handled if the multiple sub-channels can be dynamically re-provisioned, making full use of resources during the whole lifetime of the network. For example, an S-BVT with 5 modulators can initially use each of the 5 sub-channels to create paths to 5 other nodes, whereas later on, the sub-channels could be combined to make larger super-channels to connect fewer nodes. This represents a new dimension for EONs which IDEALIST believes to be highly useful in all long term growth or dynamic scenarios. The flexrate alternatives already discussed above are single channel BVTs, and IDEALIST believe the novel S-BVTs to be more cost effective. One issue that could moderate this conclusion is the problem of providing enough client-line side flexibility to enable clients to be routed through to the appropriate line side modulator. This could introduce a cost that undermines the S-BVT innate benefit. Advances in device technology could significantly benefit the development of S-BVTs. This includes the extensive use of integration to make the multiple parallel lines involved.

The extent to which the optical layer of future networks remains static or becomes more dynamic holds the key to the extent to which some of these technologies become relevant. IDEALIST is of the view that the core network is unlikely to require full dynamicity, in which large optical circuits will be set up and turn down regularly. On the other hand, unpredictable traffic growth, time-of-day fluctuations, inter data center traffic and protection-based dynamicity will give rise to a moderate degree of traffic matrix dynamicity.

In this environment, we expect that:

- Flexgrid will give a moderate spectrum saving which is not in itself sufficient to have a large network impact – although worthwhile in conjunction with other benefits. Flexgrid is also an essential prerequisite for super-channels, which are expected to be highly used in future networks.
- Flexrate will be even more directly relevant in the short to medium term through the use of BVTs with the capability of dynamically varying modulation format. These will, in a single device, provide the means to extract the most capacity from the various required optical channels in the network.
- Sliceability of multiple-line S-BVTs provides a medium term cost effective alternative to single line BVTs, especially when taking advantage of super-channel operation.

3.2 Static high capacity networks planning: algorithms and best simulation results

This section reports on the algorithms and best simulation results in the field of static planning of high capacity elastic optical networks. Apart from the use of the flexgrid switches, EONs utilize flexible transponders (bandwidth variable transponders – BVT) that can be configured tuning a number of transmission parameters. Thus network planning, in addition to calculating routes and assigning spectrum to connections, has to decide on configurations of the elastic transponders. This, however, makes the optimization problem quite complicated, since the rate the spectrum and the reach of the lightpaths are not constant but constitute variables of the problem. Thus the resource assignment problem (usually referred to as the routing and spectrum allocation – RSA) is substantially more complicated than the related problem in fixed-grid and fixed-transponder traditional networks. In this subsection, there is first a presentation of the general problem of static off-line resource allocation in EON, followed by further dedicated sub-subsections dealing with specific aspects of static off-line planning. One sub-subsection has a special focus on how to solve the hard optimization challenge of large scale networks. Another sub-subsection presents the approach for planning in a multi-period perspective and benefits of EON assessed in this scope. The last sub-subsection present an approach based on maximum entropy (MaxEnt) allocation strategies that can optimally upgrade the number of fibers on the topology edges when traffic grows and more capacity is required in the network. Other contributions related to static planning are also presented together with subsections having specific focuses on resilience (subsection 3.3), multi-layer (subsection 3.4) and energy aware planning (subsection 3.6).

3.2.1 Resource allocation in elastic optical networks

In this section we outline an algorithmic solution and basic findings for a baseline planning problem in an elastic optical network. The baseline planning problem under consideration is for an optical network of known topology (fibers and flexgrid switches are already in place) and traffic that uses flexgrid switches and tunable transponders BVTs. Given the traffic, the network is planned by deciding the placement of transponders and regenerators and their configuration to connections. Using developed algorithms (an ILP formulation and a heuristic) [1] we compare the cost and spectrum utilization of a network planed following the elastic optical network concept to that of a traditional mixed-line-rate (MLR) fixed-grid WDM network.

Several algorithms that range from integer linear programming (ILP) formulations to heuristics to solve variations of the RSA problem have been proposed in the literature [1], [2], [3], [5], while multi-layer planning, protection/restoration and dynamic network algorithms are also directions that have received attention and are also discussed in the following sections of this deliverable.

To formulate the problem, we start by describing a way to model the physical layer effects and the tunability of the BVT in an elastic network. We assume a BVT transponder having certain configured parameters (modulation format, and/or baud-rate, and/or FEC, etc.). The transmission reach depends not only on the specific configuration of the BVT, but also on the presence of adjacent interfering lightpaths, their transmission configurations and guardbands used. The number of combinations is huge. So, in what follows we define the transmission reach assuming that a lightpath suffers worst case interference (four-wave-mixing, cross-phase modulation, crosstalk) from the adjacent lightpaths for a given transmission configuration and guardband. For a BVT transponder we define (*reach-rate-spectrum-guardband-cost*) transmission *tuples*, corresponding to feasible configurations. The term “feasible” is used to signify that the tuple definition incorporates physical layer impairment limitations which can be found in published experiments or analytical modelling [6], [7], while the cost parameter enables the modelling of transponders of different capabilities and costs. The above definition is very general and can describe any type of flexible or even fixed transponders.

The problem of planning an elastic optical network is thus described by the network topology, the traffic matrix and the transmission tuples that describe the capabilities of the transponders. To solve such a planning problem we used the algorithms presented in [1] and also in D1.3 of IDEALIST [7]. In particular, an ILP formulation and a heuristic algorithm for solving such problems were proposed. Both proposed algorithms use a pre-processing phase, which calculate *k-shortest paths* and then combine those with the feasible transmission tuples of the transponders (placing also regenerators) to form what are called path-transmission tuple pairs. The algorithm (ILP or heuristic) selects from the candidate path-transmission pairs for each demand and performs the spectrum allocation. Let *C* be the cost of the transponders and *S* the maximum number of slots used. The objective is to find a solution that serves the traffic and optimizes both these metrics. We scalarize this multi-objective problem and optimize a weighted combination of these metrics, using the coefficient *w*: Minimize $w \cdot S + (1-w) \cdot C$.

Our results showed that the proposed heuristic had very good performance with affordable run times when compared to the ILP for small size networks where the ILP solution was tractable. Using the heuristic algorithm, we also compared the performance of an elastic optical network to that of a fixed-grid mixed-line-rate (MLR) WDM network. We assumed a MLR system that utilized 3 types of transponders with the following (reach-rate-spectrum-guardband-cost) tuples: (2500 km, 40 Gb/s, 50 GHz, 0, 0.48), (2000km, 100 Gb/s, 50 GHz, 0, 1), and (450 km, 400 Gb/s, 50 GHz, 0, 1.36). The unit cost is taken as the cost of a 100 Gb/s transponder. We assumed that the elastic network has a single type of tunable transponder. For a fair comparison, we assumed that the flexible transponder has the same maximum spectral efficiency and maximum rate as the fixed 400 Gb/s transponder, but with higher cost equal to 1.5 to account for its tunability.

For the comparison we used the DT topology and the traffic matrices provided in D1.1 of IDEALIST [9]. Figure 6 and Figure 7 present the results obtained for the two types of networks, elastic (flex) and fixed-grid MLR, and for two different optimization choices, namely *w*=1 (spectrum minimization) and *w*=0.01 (transponders' cost – TR minimization). In Figure 6 we see that the flexible network uses much lower spectrum than the MLR network when optimizing the spectrum (*w*=1). When optimizing the TR cost (*w*=0.01) some spectrum is sacrificed to obtain lower cost. With respect to the TR cost (Figure 7), the MLR-optimize TR cost case achieves the best performance for light load, but after year 2020 the elastic network becomes more cost efficient. At light load, all demands are served by single and transparent connections, utilizing in MLR network low rate and cheap transponders. As load increases and high rate demands appear, higher rate transponders (MLR) or higher rate configuration tuples (in elastic) are utilized. But also some demands are broken into multiple connections and regenerators are employed to enable the use of higher spectral efficiency connections. The finer granularity and the increased transmission options of the BVTs lead to gains in the cost at heavy loads in Figure 7.

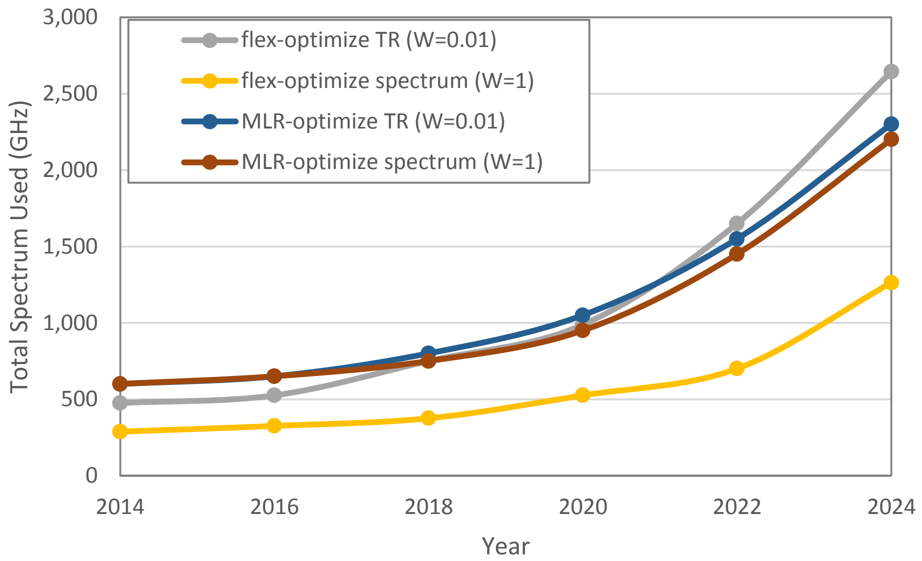


Figure 6: Maximum spectrum used (GHz) for the elastic and the MLR network, for optimizing the spectrum used (*w*=1) and the transponders' cost (*w*=0.01) on the DT network.

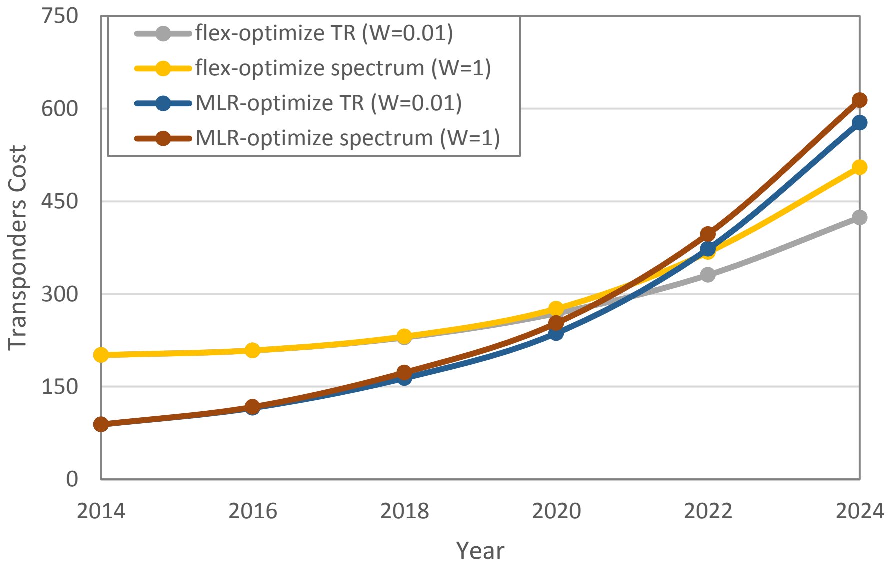


Figure 7: Transponders' cost for the elastic and the MLR network, for optimizing the spectrum used (*w*=1) and the transponders' cost (*w*=0.01) on the DT network.

An interesting property, the tradeoff between the spectrum and cost, was observed in the previous figures. Figure 8 presents the spectrum usage and transponders cost of the solutions obtained by ranging the optimization coefficients *w* for the elastic network and traffic of year 2018, that is, these solutions are calculated for the same input but different values of the optimization coefficient *w*. The solutions found (points in the figure) form the so-called Pareto front. To reduce the used spectrum ($w \rightarrow 1$) a higher cost is encountered, indicating that some transponders use transmission tuples with high modulation format (more bits/symbol) but low reach and low rate. On the other hand, minimizing the transponders' cost ($w \rightarrow 0$) selects tuples with the maximum total rate that might not use the highest possible modulation format. Depending on the actual market prices of the spectrum and TR, a specific solution from the Pareto front would achieve the minimum overall cost and would be picked as the optimum.

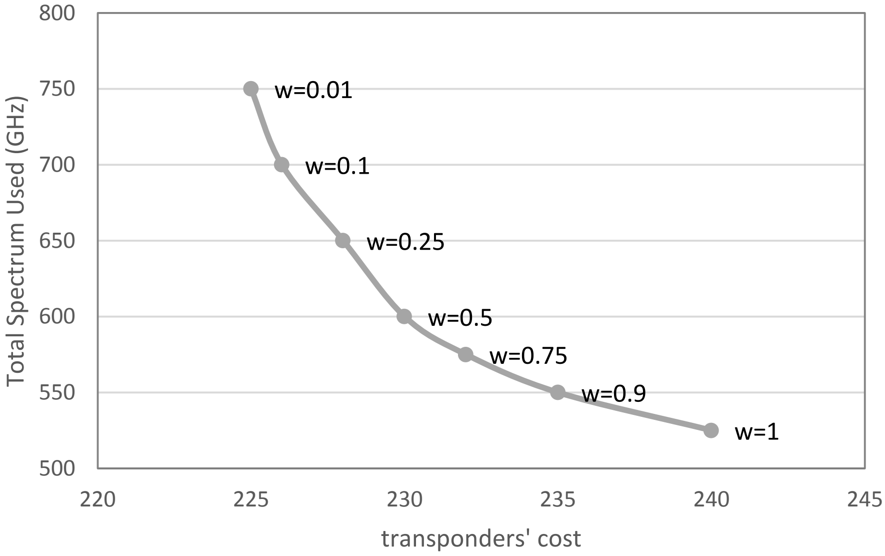


Figure 8: Tradeoff between maximum spectrum used and transponders' cost.

3.2.2 Large scale optimization

A basic optimization issue in the design and operation of flexgrid elastic optical networks (EONs) is the problem of routing and spectrum allocation (RSA). RSA consists in establishing optical path (lightpath) connections, tailored to the actual bandwidth of the transmitted signal, for a set of end-to-end demands that compete for spectrum resources. The RSA optimization problem is *NP*-hard. Several alternative mixed-integer programming (MIP) formulations of the RSA problem can be found in the literature (see [2] for a review of such MIP models). MIP formulations can be optimally solved and a common approach to achieve this is to use a standard branch-and-bound (BB) method implemented in the MIP solvers, for instance in the commercial CPLEX solver. The resolution of MIP using BB can be still difficult and time-consuming due to a large set of involved integer variables. To make large instances of RSA tractable by MIP formulations, large-scale optimization methods (involving problem decomposition) must be applied. Such methods usually involve dynamic addition of variables (columns) and/or constraints (valid inequalities = cuts) to the MIP model. A column generation (CG) algorithm – also referred to as path generation (PG) – for dynamic generation of lightpaths was developed in Section 4.3.2 of Deliverable 1.3 [7]. Additionally, a kind of clique cuts for strengthening MIP formulations of RSA was proposed in Section 5.1.1 of Deliverable 1.5 [10]. Still, in both cases, RSA solutions were generated using a heuristic approach.

As a natural next step we have developed an effective optimization procedure that involves PG, is able to produce optimal RSA solutions, and is competitive to CPLEX. We applied several optimization approaches that were built into a branch-and-price (BP) framework – a combination of BB and CG methods. The algorithm components include a linear relaxation of the basic MIP problem (referred to as restricted master problem, RMP) solved by the PG technique and extended with valid inequalities aiming at improving lower bounds of the relaxation, as well as a search for upper bound solutions by means of a hybrid greedy RSA and simulated annealing algorithm. As in similar works on that topic (e.g., see [1]), our focus was on optimizing the spectrum width required to allocate a certain set of traffic demands. The algorithm is applicable to distance-adaptive EONs, in which the format of an optical signal depends on the quality of the routing path. A block diagram of the algorithm is presented in Figure 9. For further details on the implementation of BP and CG, refer to [3] and [5].

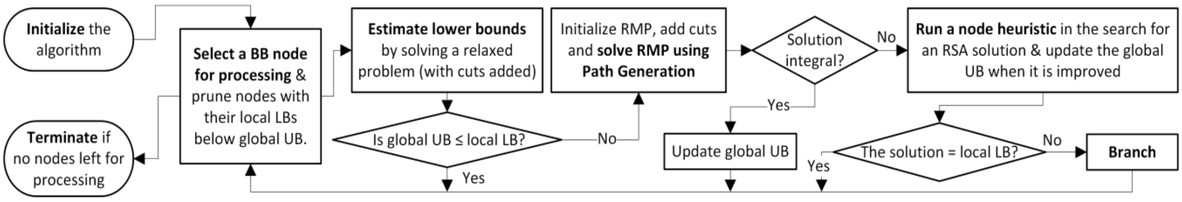


Figure 9: A branch-and-price optimization algorithm.

The performance of the BP algorithm was evaluated for different network topologies and traffic demand sets. In Figure 10, we present exemplary results which demonstrate effectiveness of the BP optimization procedure in producing optimal and near-optimal solutions for large instances of the RSA problem. Here, we have assumed a generic British Telecom (BT) network of 22 nodes and 35 links, 12.5 GHz flexgrid granularity, number of demands $|D|\in\{50,100,150, 200\}$, and 10 randomly generated demand sets for each |D|. As a reference, we have used a standard BB method of CPLEX (v.12.5.1). We have set a 1-hour run-time limit for the algorithms. In Figure 10, we show the percentage of the RSA problem instances with either *optimal* (dark blue) or *feasible* (blue) or *unknown* (light blue) solution status obtained. We can see that BP has been able to solve 92.5% (37 out of 40) of all analyzed problem instances (*optimal* solution status) and it required between 112 sec. (for |D|=50) and 1316 sec. (for |D|=200) of computation time in average. We would like to mention that the spectrum width required to allocate all lightpath demands has been between 857 GHz (for |D|=50) and 3371 GHz (for |D|=200) on the average. Eventually, BB has not found any feasible solution in 85% of problem instances (*unknown* solution status).

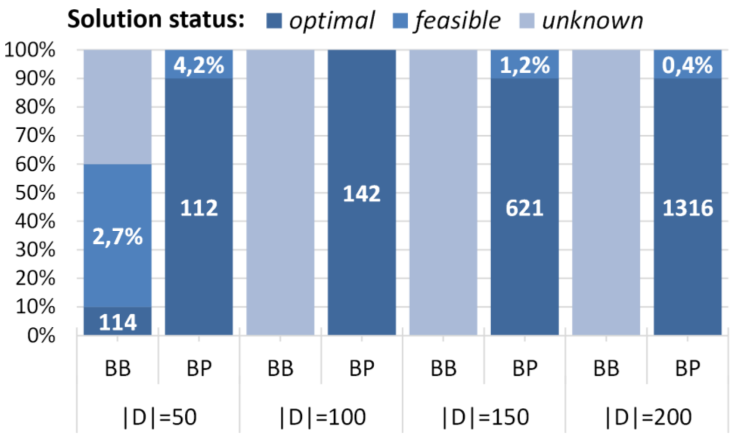


Figure 10: Status of RSA solutions obtained with BB (CPLEX) and BP in a 22-node BT network in a function of the number of demands (|D|); the value on bars corresponds either to the average computation time (for *optimal* solutions, in seconds) or optimality gap (for *feasible* solutions).

3.2.3 Multi period planning

The main value proposition of the elastic-based architectures in IDEALIST is network flexibility, be it in the physical design of all the building blocks (e.g. flexrate capabilities in (S)-BVTs, flexgrid capable ROADMs), or in the conceptual control plane design (ubiquitous software configurability).

In terms of pure network capacity planning, the main advantages of (S)-BVT architectures coupled with flexgrid capabilities lie in the ability to efficiently respond to dynamic network scenarios, by reconfiguring hardware on demand according to changing traffic conditions [12], [13]. The evolving networking paradigms brought by (among others) the commoditization of cloud resources and the associated requirements on data center connectivity may create the levels of traffic dynamicity at the transport layer that justify the adoption of flexible hardware for optical backbones. However, in the short and mid-term, even if traffic volumes are expected to increase considerably, service provisioning and the associated planning at the WDM layer for more traditional network operator services is still relatively static in comparison with higher layers or specific use cases like data center interconnection.

In these fairly static scenarios (over smaller time scales), more complex hardware architectures that increase flexibility cannot be expected to be as cost-effective as simpler fixed-rate designs from day one. Rather, their efficiency must be evaluated over an entire network lifecycle, where the competitive advantages of flexible-rate hardware and the modularity of the S-BVT concept emerge in the form of increased operational efficiency for handling different traffic conditions. Thus, multi-period planning optimization models are required to assess the trade-offs between deployments based on S-BVTs with flexrate capabilities and fixed-rate transponders. This also enables the validation of the proposed S-BVT architectures (e.g. rate-adjustable sub-carriers) in a simulation scenario featuring actual routing of traffic demands over the network.

Within IDEALIST, a multi-period planning framework was developed to assess the network-wide efficiency of S-BVT-based deployments in what-if scenarios featuring multiple network topologies, traffic forecasts, equipment upgrade and reuse policies, survivability schemes, etc.

The results of this analysis suggest that flexrate S-BVTs are, in the long run, more cost-effective on CAPEX alone than traditional fixed-rate designs in small/medium sized networks where higher bitrates are easily deployed without need for regeneration. This is particularly evident when traffic assumptions feature yearly growth rates over 30% [12].

In larger long-haul networks, even in the cases where the initial CAPEX investment in flexible modules is not entirely offset over the network life cycle, the operational benefits provide a compelling case for deploying these solutions. Concretely, a roughly 10% decrease in network footprint is observable, with spectrum reduced by the same amount. Thus, not only is OPEX expected to be significantly reduced, but network capacity is also extended, delaying the need for further network investments.

Figure 9 summarizes the equipment requirements of network deployments where the sub-carrier ports in each S-BVT had either fixed or flexible-rates (i.e. were modulation format adjustable) for selected metro/regional and long-haul topologies, as well as different yearly traffic growth estimates. The impact of using flex-rate subcarriers on the line-side equipment footprint is visible over multiple network planning cycles.

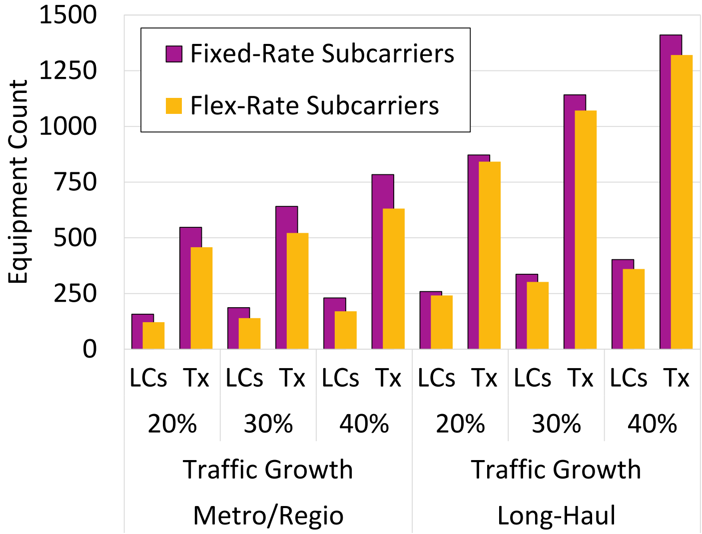


Figure 11: Line-side equipment requirements with fixed and flex-rate subcarriers for S-BVT-enabled networks (LC – line card, Tx – transceiver).

Beyond the advantages at the level of line-side equipment, the multi-carrier nature of the S-BVT also changes the way in which networks are planned over multiple periods considering the underlying client layers. The dimensioning of switching fabrics supporting the S-BVTs, as well as the provisioning of the client-card interfaces for the tributary signals must be able to exploit the grooming flexibility provided by the S-BVT module for maximum cost efficiency.

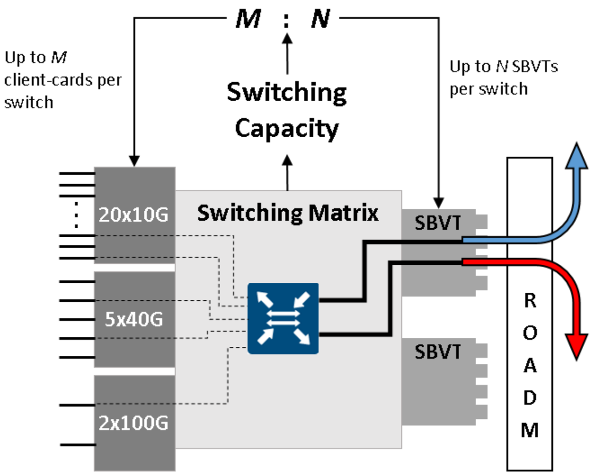


Figure 12: Client-to-line-side switching model for multi-period optimization.

The multi-period planning framework developed in IDEALIST was extended to consider switching fabrics and client-cards, as schematized in Figure 12. This framework allowed us to demonstrate that, for optimal cost, switching capacity must be carefully balanced between very large switches that overprovision capacity relative to existing traffic, and smaller independent modules which tend to cause either client or line-side blocking over multiple periods due to the reduced grooming flexibility of smaller switches acting as stand-alone modules [13].

3.2.4 Multi-fiber, flexgrid EON design using maximum entropy optimization

During the IDEALIST project we have demonstrated how maximum entropy (MaxEnt) allocation strategies can optimally determine links within a flexgrid elastic optical network (EON) [14] requiring multiple (up to x4) fiber-pairs to support 100% capacity growth with 34.3% improvement in the uniformity of spectrum allocations [15], [16], [17]. We have shown how adding additional fiber to those links featuring the highest number of demands in a link allows optimum allocation of network capacity resource to all source-destination demand pairs, and maximizes available spectral capacity to each demand.

Shannon entropy underpins our approach [17], and is used to measure the spectral fragmentation of links, and forms the basis of the metric that is maximized when maximizing the fragmentation entropy. The Shannon entropy fragmentation metric uses the well-known $H = -\sum_{i=1}^{N} p_i \ln p_i$ formula (where $\sum_{i=1}^{N} p_i = 1$) and can be calculated on the unused spectrum, the used spectrum or both. To calculate the metric, the optical spectrum is first considered as a number of slots representing the individual flexgrid quanta, e.g. 6.25 GHz, or indeed 10 GHz which is the resolution adopted (for convenience) in the following simulations. These can then be grouped into blocks consisting of contiguous slots of either used (irrespective of the individual super-channel signals that make up that block) or unused spectrum. The Shannon entropy metric of a spectrum can then be calculated as:

$$H_{frag} = -\sum_{i=1}^{N} \frac{D_i}{D} \ln \frac{D_i}{D} \qquad \text{(Eq. 3.1)}$$

where D is the total number of slots (quanta) across the entire spectrum band and D_i is the number of slots used in the current block of contiguous unused (and/or used) spectrum. Large values for H_{frag} indicate higher levels of fragmentation. MaxEnt routing and spectral assignment (RSA) optimization spreads the presented load as uniformly across the network as possible, so maximizing overall bandwidth capacity utilization and bandwidth availabilities across all fibers. Whenever additional fiber is added to the network, the MaxEnt RSA is re-calculated (using a genetic algorithm (GA) for non-deterministic optimization) to optimally exploit all the additional spectrum and associated network flexibility afforded by the new fiber. MaxEnt operation has the advantage of making guardbands between different spectral demands much less critical, so that overall network management complexity is reduced, due to:

i) Defragmentation-less operation (both real-time, and off-line);
ii) A simplified RSA table (i.e. only a single entry for each S-D pair);
iii) Resulting lower complexity of flexgrid (de)muxing technologies, e.g. sliceable bandwidth-variable transponders (S-BVTs), wavelength selective switches (WSSs), and wavelength converters etc.;
iv) Greater concatenation potential of such devices due to the more relaxed guardband tolerances;
v) Minimal spectral negotiation and RSA re-calculation for growing or dynamic bandwidth demands;
vi) Lower CAPEX (i.e. due to the reduced-complexity of equipment) and OPEX (i.e. simplified management and reduced energy consumption of simpler equipment).

In the current MaxEnt simulations approach, we remain agnostic to actual traffic patterns occurring across the network (i.e. no apriori assumptions about actual traffic statistics between S-D pairs, e.g. anticipated hot-spots and/or locations of high dynamicity) so that the network is optimized to deal with any traffic demand increase occurring between a node-pair. This makes the MaxEnt network particularly robust and agile to traffic dynamicity. It is interesting to note that although no explicit (or indeed, implicit) traffic patterns are used in the MaxEnt algorithm, the intrinsic (abstracted) topology of the simulated BT network is itself sufficient to create a S-D demands profile (and associated multi-fiber distribution across the network) which closely mirrors the actual types of traffic flows experienced in reality. For example, Figure 13 shows that the greatest traffic intensity is experienced around London in the BT network, and this is where the greatest density of multi-fiber links is also to be found following MaxEnt optimization. Thus although not explicitly considered, the BT network topology is itself a reflection of the traffic flows and intensities across the country, and the MaxEnt optimization automatically picks up on this implicit information to create a RSA table (see Figure 14) which closely matches the S-D traffic demands which are experienced in reality.

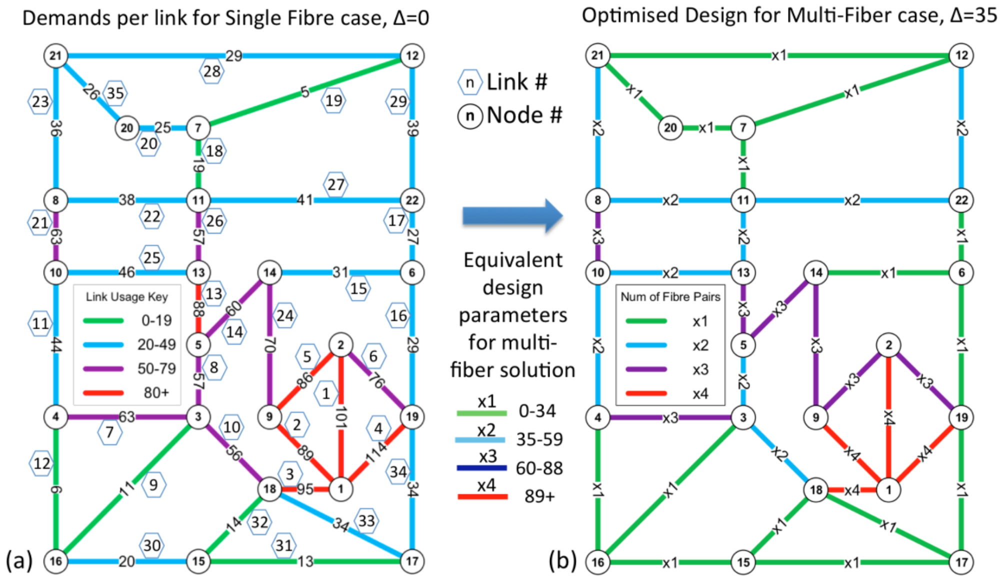


Figure 13: (a) Initial single-fiber BT Reference Network, indicating number of demands per link before multi-fiber evolution; (b) Final multi-fiber network configuration after 35 additional fibers and MaxEnt optimisation.

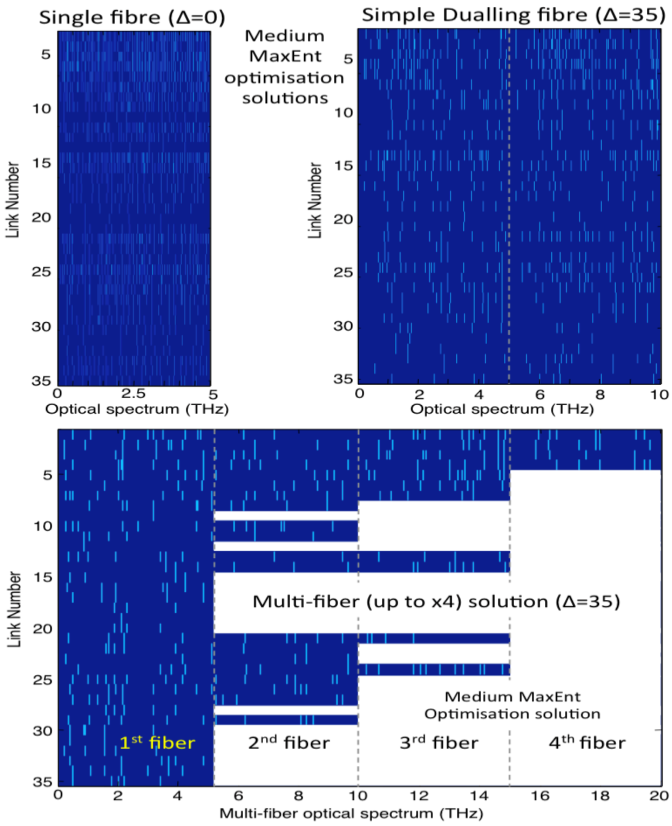


Figure 14: Representations of the RSA central frequency allocations for the single-fiber, simple-dualling of all links, & the MaxEnt optimized multi-fiber (up to x4) cases.

We have shown how a jointly-optimized (multi-fiber and MaxEnt) flexgrid EON operating in a defragmentation-less mode can be designed to evolve over time to provide ever-increasing bandwidth capacities to all S-D demands. MaxEnt GA optimization also ensures the tightest possible range of available channel bandwidths, centered around 160 GHz, to uniformly distribute traffic (i.e. attempting to avoid hot-spots) across the network and maximize the alignment of available capacities to dynamically-varying S-D demands and future traffic growth. Overall, multi-fiber implementation of a MaxEnt RSA network potentially offers a convenient and practical approach to providing the appropriate S-D channel bandwidths required for dynamic flexgrid EON networking.

3.3 Resilience and restoration in EON

It is essential to study the impact of resilience in the context of EONs because not only do all networks require resilience in some form, but also it is through specific implementations of resilience that some of the benefits of EONs emerge clearly. As a simple example, following a fibre cut, BVTs can adjust their characteristics to fit the new protection path, enabling higher resource utilization and reducing cost. This section takes these simple ideas much further and with some detailed modelling.

3.3.1 Optical restoration after fiber breaks

This work looks at the impact of BVTs in a very realistic network environment in which the traffic is steadily growing, but there are also occasional random fibre failures [18]. The modelling considers the UK reference network and assumes historical figures for fibre cuts

(133 FITs/km). It also assumes an EON solution with restoration so that failed demands are re-assigned (if possible) following a fibre cut.

An additional highly promising benefit of BVTs is related to the scope for operation with very low levels of margin. Margin is traditionally applied to optical networks by both the operator (to account for ageing and breaks in the fibre plant) and equipment vendors (to account for equipment degradation, tolerances and ageing). A major benefit for BVTs is that they could operate close to the actual operating limit of the link, rather than a theoretical one determined by offline calculations. High margins were always necessary when there was only one kind of fixed transponder, but the BVT has flexibility which allows it to take advantage of excess margin, wherever it exists. For example, all links with higher margin could be operated with higher order QAM. If any given links deteriorate for whatever reason, then the QAM order could be reduced to allow for the reduced OSNR. This low-margin operating paradigm releases lots of dBs of margin to be used by BVTs and these in turn can extract a great deal more capacity from the network. Figure 15 shows some of the results of this modelling work.

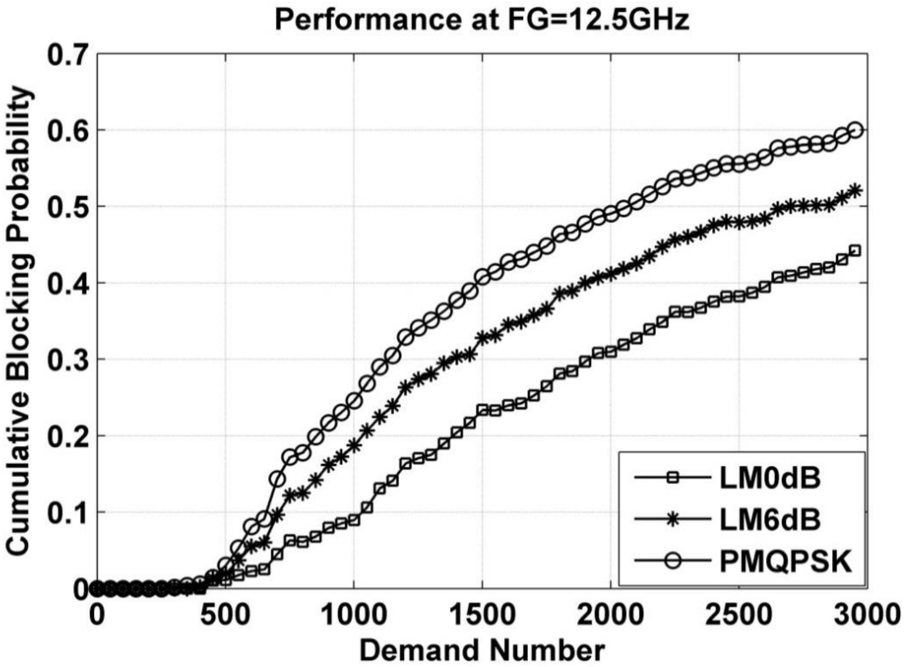


Figure 15: Cumulative Blocking Probability vs. increasing traffic demands for both fixed DP-QPSK transponders and BVTs – where the BVT case is studied for high and low margin operation.

Figure 15 shows that the fixed transponder (DP-QPSK) performs the worst. This is because it can't provide any additional bandwidth for a potential restoration circuit. The BVT performs better – but now we study the low margin case, where the BVT performs better still. This is because it has often access to free bandwidth slots in higher QAM modulation modes. This remains true even when fibre cuts cause the margin to erode on certain links and lower QAM modes to be used than might be expected. Additionally more restoration bandwidth was available for the 0dB margin case due to the higher number of higher order QAM transponders.

3.3.2 Multi-path recovery

Owing to the huge bitrate associated to each established lightpath, *recovery* schemes need to be used to guarantee that the associated client connection demands continue being served even in case of failures. Recovery can be provided by either *protection*, where the failed working path is substituted by the pre-assigned backup one, or *restoration*, which is based on rerouting the working path. Backup paths use resources, i.e. each of the wavelengths in a fiber link, that are *dedicated* to protect a single working path, or they can be *shared* to provide protection to multiple working paths. The former scheme is known as dedicated path protection (DPP) and the latter as shared path protection (SPP).

Although protection schemes reserve resources to guarantee that all the protected paths are recovered in case of any single failure, SPP provides better resource utilization than DPP because spare resources are shared among several working paths. Even higher efficiency can be achieved with path restoration since resources are only allocated after a failure impacts a working path. Notwithstanding, recovery times are usually much shorter when protection is used; in the case of DPP, since spare resources are already being used, recovery times are really short, being slightly longer for SPP because spare resources are reserved beforehand and activated in case of failure.

In flexgrid optical networks, lightpaths can use a variable slot width depending on the requested bitrate and the modulation format. As a consequence, new recovery schemes can be devised exploiting variation in the amount of resources assigned to each lightpath. In fact, bitrate squeezing can be applied so as to only recover part of the bitrate of demands.

In this context, a new recovery scheme, called multi-path recovery (MPR), specifically designed for flexgrid-based optical networks was proposed. It combines protection and restoration schemes to jointly recover, in part or totally, the bitrate requested by client demands in case of failure.

For illustrative purposes, Figure 16 shows how MPR works. In Figure 16a one client demand is requesting 400Gb/s that translates into a 100GHz frequency slot. The working path serves all the requested bitrate and there is another frequency slot reserved along the backup route to protect some minimum bitrate (e.g., 75Gb/s). After a failure has impacted the working path, the +protection path is activated and a restoration path is computed and established in Figure 16b. Note that the two recovery paths jointly serve 225Gb/s in that failure scenario.

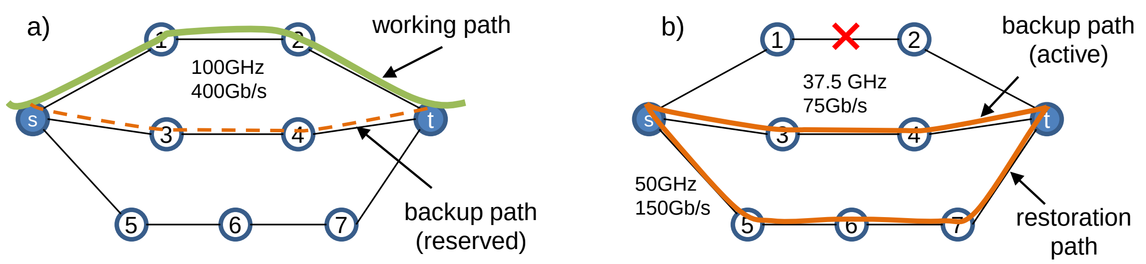


Figure 16: MPR in action. In a) the working path of a demand is established and resources for the protection path are reserved. After a failure (b) the protection path is activated and a restoration path is also established.

Figure 17 presents the evolution of the bitrate actually served for a demand as a function of time when only restoration (Figure 17a), only protection (Figure 17b) and a mixed of protection and restoration (Figure 17c) is used for recovery. In the period $t<t_1$ all the requested bitrate is served. In $t=t_1$ a failure impacts the working path and in $t=t_3$ the failure is repaired. When only restoration is used for recovery in Figure 17a, no bitrate is served until a restoration path is established for the demand in $t=t_2$. On the contrary, when only protection is used, the recovered bitrate is served in a short time (few ms) after the failure is detected in $t=t_1$, as shown in Figure 17b. Since the outage inherent in restoration might not be desirable for some clients and lower efficiency might not be desirable for the network operator, the proposed MPR scheme serves a minimum bitrate just after the failure is detected in $t=t_1$ using protection, while complementing some bitrate using restoration later in $t=t_2$, as shown in Figure 17c. In $t=t_3$ the failure is eventually repaired and all the requested bitrate is served again in all the three schemes.

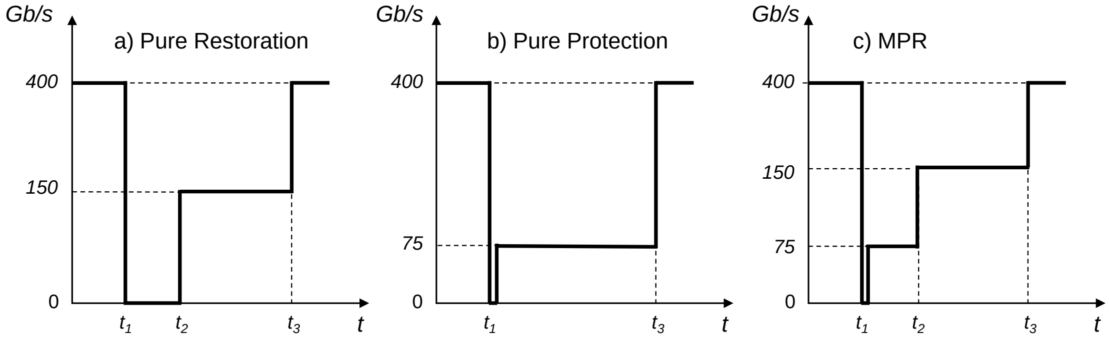


Figure 17: Evolution of the served bitrate for a demand vs time when a failure impacts the working path in t_1. Path restoration (a), Path protection (b), and MPR (c) schemes are considered.

The performance of all recovery schemes was analyzed through intensive numerical experiments under different traffic profiles. Comparing mixed schemes against pure protection schemes, we observed a clear gain in the amount of unrecovered bitrate when restoration is added in MPR-based schemes. Table 1 summarizes the gains obtained by MPR-based with respect to pure protection schemes. In addition, time to recovery in milliseconds is also included in Table 1.

Table 1: Bitrate gain and recovery time when MPR-based schemes are used.

TP	Avg. bitrate (Gb/s)	Bitrate gain		Mean recovery time (ms)	
		DPP + PR	SPP + PR	DPP + PR	SPP + PR
1	24.1	39.1%	37.5%	100	100
2	52.0	51.0%	24.8%	147	168
3	80.0	37.4%	30.5%	793	809

The results clearly show the benefits of the proposed MPR recovery scheme when compared to pure protection ones. Therefore, MPR provides a good trade-off between efficiency and recovery times.

3.3.3 Optical restoration in IP networks

Elastic optical networks are expected to feature not only a flexible channel grid, but also to provide rate-adaptive transceivers [19]. One important use case for such kind of flexrate transceiver technology is the coordinated recovery from optical network failures comprising optical restoration together with packet layer recovery mechanisms [20].

In order to evaluate the application potential of optical rate-adaptive transmission technology in IP-based networks, we consider an aggregation network with a fiber ring topology. It might be equipped with elastic ROADMs, at least at the sites of the two core routers R2 / R2', see Figure 18, in order to disable any multiple wavelength round-trips and prevent the ring from laser behaviour. Regional nodes might be equipped with passive splitter/coupler technology according to the TeraStream concept [21], as long as all physical effects are not large. Otherwise, flexgrid ROADMs with their inherent filtering capabilities are recommended there as well.

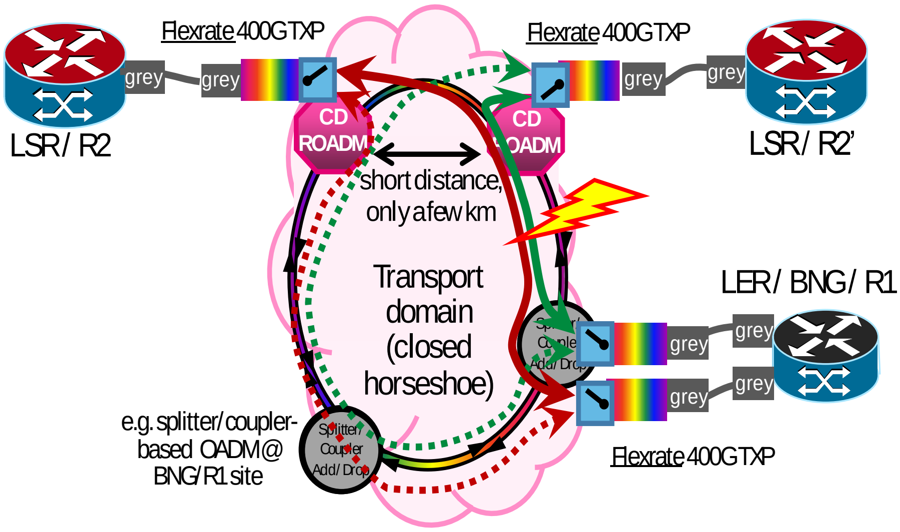


Figure 18: Parallel guidance of dual-homed lightpaths (R1-R2 in red and R1-R2' in green) between aggregation node and two core nodes (solid and dashed lines for working and backup paths, respectively).

Logically, the aggregation router R1 is connected to both its two label-switched core routers R2 / R2' (dual homing). Physically, the two associated working lightpaths are guided in parallel through the ring network, see Figure 18. Even though both working connections are then subject to the same failure risk, a parallel guidance offers two main advantages over a traditionally disjoint guidance:

- In the failure-free case, both lightpaths follow the shortest path and provide the maximum possible flexrate capacity making obsolete any kind of packet load-balancing between the two IP links.
- Both lightpaths could be quasi-immediately recovered by an optical tail-end protection switching as long as the backup lightpath is already in hot-standby even before the failure. In this sense, 1+1 protection prevents the optical amplifiers down the link from showing any dynamic power excursions due to front-end switching.

At the receiver side, the optical switching from working to backup path is to be accomplished as fast as possible. However, in case the backup length exceeds the actually required OSNR for a given data rate, the reception of this signal would lead to unacceptable error-rates of the connection. Thus, the affected remote transmitter has to reduce its transmit speed. Afterwards, the local receiver has to re-synchronize to the new signal speed. This needs to be done together with the re-synchronization of chromatic and polarization mode dispersion compensation of the backup path.

Complete recovery is expected to be accomplished within <50ms making IP resilience mechanisms obsolete. This is not practically feasible today, but should be pursued as a mid-term technology goal.

In order to prove the techno-economic benefit of this approach, we investigated DT's existing aggregation network assuming closed WDM rings and calculated the relevant working and backup lightpath lengths. Instead of taking real traffic volumes into account, we assumed for simplicity one transceiver pair per logical IP link.

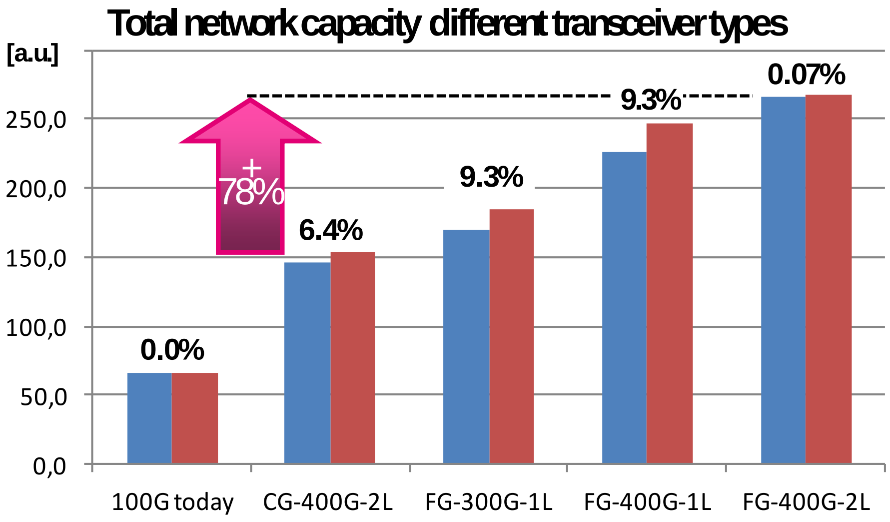


Figure 19: Network capacity scaling for various flexrate transceivers. Blue: disjoint lightpath guidance; red: parallel lightpath guidance. Relative gain by fine-granular over coarse-granular rate adaptability in percent for a load of one transceiver pair per IP link.

Figure 19 shows how the total network capacity scales for several realistic transceiver configurations (for a definition see [22]). Fine-granular rate adaptability achieves more than 75% higher network capacity over coarse-granular, e.g. compare CG-400G-2λ to FG-400G-2λ. Additionally, we identify a capacity improvement of up to 9.3% due to parallel lightpath guidance compared to disjoint guidance. It should be noted that this improvement basically depends on three main ingredients: (i) the ratio between backup and working path lengths, (ii) the corresponding capacity ratio of the involved flexrate interfaces and (iii) the operator's specific interface loading policy (for more details see [20]).

From an operator's perspective the presented capacity improvement induced by flexrate transceivers is highly attractive, as multi-layer recovery is accomplished without further IP protocol modifications. Only a fast receiver-sided switch-over of lightpaths in reaction to an optical failure is necessary accompanied by the fast adaption of the optical modulation format at the flexrate transmitter and a fast resynchronization at the flexrate receiver.

3.4 Multi-layer and grooming

This section presents concepts and studies in which EON is seen as a part of a multi-layer network. The grooming opportunity at the OTN level is presented according to two different declinations: a first relying on OTN switches only (electronic grooming) and a second with the extension to switching in the optical domain (optical grooming), the second being the one that relies on the full functionalities of EONs. Then special subsections are dedicated to IP over optical networks with specific focuses on planning and control.

3.4.1 OTN grooming

In wavelength switched optical networks several techniques have been proposed to increase resource utilization by means of traffic grooming [23], [24]. Traffic grooming aims at maximizing switch port and link capacity utilization by appropriately routing traffic flows to pre-selected points in the network and aggregating them so that they can share common paths. These approaches may assume flat, mesh-based topologies or hierarchal network organizations based on node clustering (Figure 20).

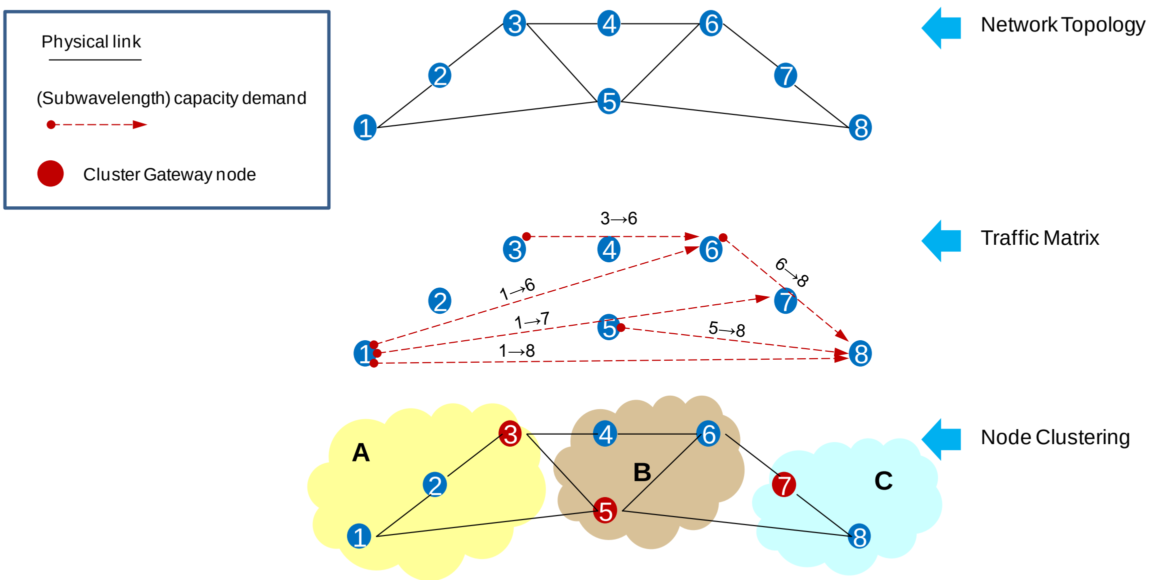


Figure 20: Example network topology, traffic matrix (demands) and hierarchical topology creation based on node clustering.

Recently, new advanced optical transmission technologies have emerged, trying to address the same objective i.e. increased resource utilization. Flexgrid and elastic systems [25] aim to improve spectral efficiency and allow dynamic adaptation to line-rate changes exploiting S-BVTs and flexible spectrum allocation, overcoming the limitations imposed by the fixed ITU grid. However, efficiency gains are strongly dependent on the traffic distribution, which in turn is determined by the routing and traffic aggregation techniques used. Hence, appropriate network planning techniques are needed in order to maximize the benefits of flexgrid.

A schematic illustration of the OTN grooming operation is given in Figure 21 (and is also applicable to any other L2 grooming approach). In Figure 21a two traffic demands T_{AE} (red), T_{BF} (blue) are shown and their corresponding routing over the network. Obviously since the two paths share the link between nodes C and D, given the specific capacity requirements, the same virtual connection between C and D could serve both demands.

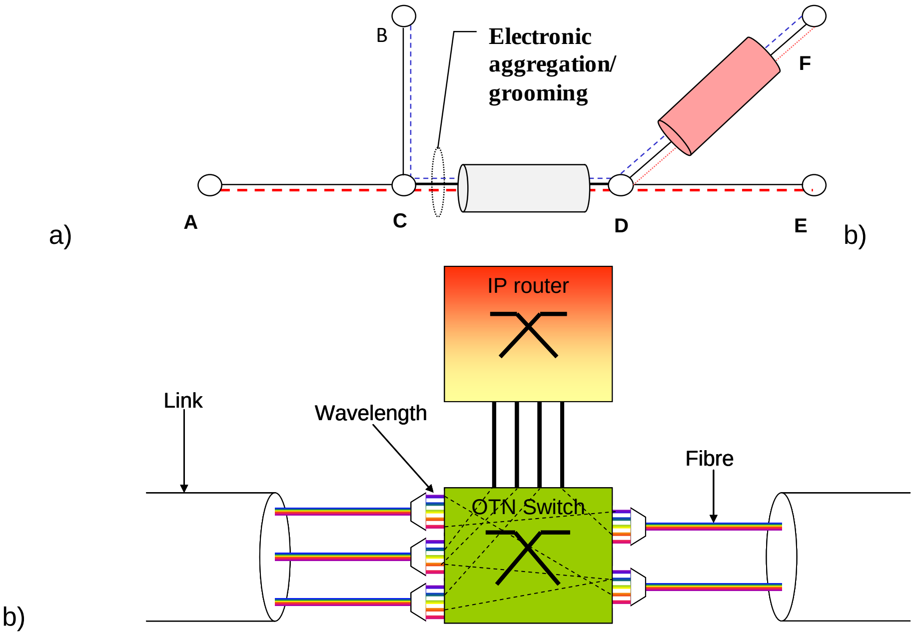


Figure 21: a) Electronic aggregation (e.g. OTN) b) typical electronic grooming node.

Figure 21b shows the architecture and operation of a typical OTN electronic grooming node, where:

- The transportation network consists of an IP over OTN over WDM network.
- For the OTN-over-WDM segment, there is an o-e-o conversion in every node followed by OTN grooming and traffic is forwarded to the next node.

All links, potentially consisting of multiple fibres, are connected to the OTN switch. The OTN switch moves traffic to the next link, grooming appropriately, with only the local traffic terminating at the IP router.

3.4.2 OTN over optical grooming

For OTN over optical grooming, the typical node architecture shown in Figure 21b is modified with the addition of WBV-WSS for transparent routing of lightpaths, as shown in Figure 22.

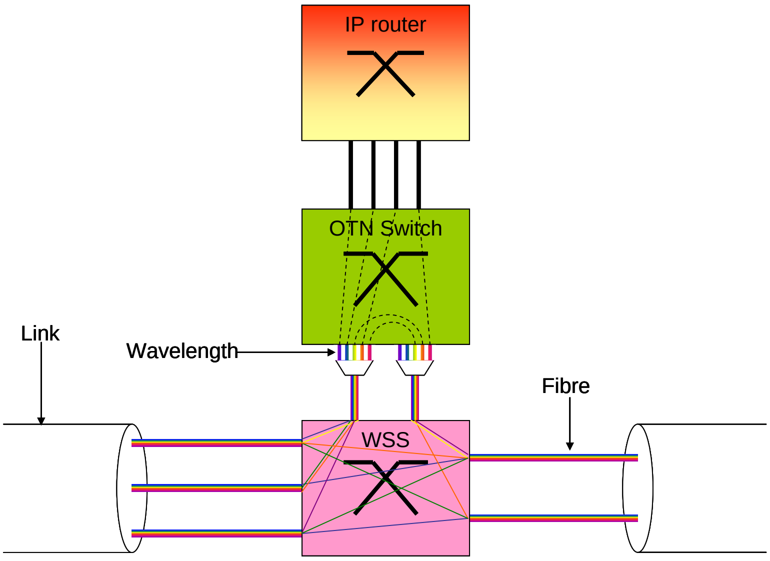


Figure 22: OTN over optical grooming node architecture.

In Figure 22, all fibres are connected to the WSS and the lightpaths are routed transparently. The OTN switch grooms traffic as specified by the grooming algorithm and only the local traffic reaches the IP router.

The routing is a combination of OTN grooming assisted by optical bypassing. The grooming algorithm specifies all grooming of traffic and the resulting traffic matrix is routed using transparent lightpaths from end to end. For the grooming, there are two prevailing approaches: 1) multi-hop traffic grooming algorithm, (eg. [23]); 2) hierarchical traffic grooming (e.g. based on node clustering as in [24]).

In [23] grooming is potentially performed at every node (for non-transparent paths). A heuristic algorithm establishes direct shortest paths for all demands until link capacity is exhausted. Whenever grooming of multiple demands over a single wavelength resource is performed, the respective traffic flows are electronically processed and multiplexed and then forwarded over the allocated optical channel. Grooming and RWA are performed simultaneously employing shortest path routing and first fit wavelength assignment. The approach of [23] can be modified to operate under EON conditions using a different request order. Since the higher bit rate transceivers have limited reach, the requests that would be served by them are searched in increasing path length order, ensuring that as many requests as possible are served by the high rate transponders. Figure 23a illustrates this approach using the Traffic Matrix shown in Figure 20. After allocating wavelengths and paths for demands 3->6, 6->8, 5->8), it then routes the remaining traffic to the next node where grooming facilities have been allocated during planning over spare capacity of established lightpaths (e.g. in Figure 23a grooming of lower capacity demands 1->6, 1->7 and 1->8 over the established paths and establishment of additional lightpaths across the remaining links when required).

In [24] grooming is performed at preselected cluster hubs/gateways only. Direct paths are also possible (only for “large” demands). Routing is performed after grooming of requests (as an independent process). In Figure 23b a potential result of [24], under the Traffic Matrix and a potential resulting clustered network topology of Figure 20 is shown. In Figure 23b the demands of clusters A, B and C are served by establishing direct optical paths from each cluster node to its corresponding gateway i.e. 3, 5 and 7 apart from demand 1->8, which justifies a direct lightpath (i.e. achieves near 100% utilization of the allocated wavelength/spectral slot) to be established between nodes 1 and 8. Each gateway node then establishes in the same manner, direct lightpaths to distant cluster gateways and recipient nodes.

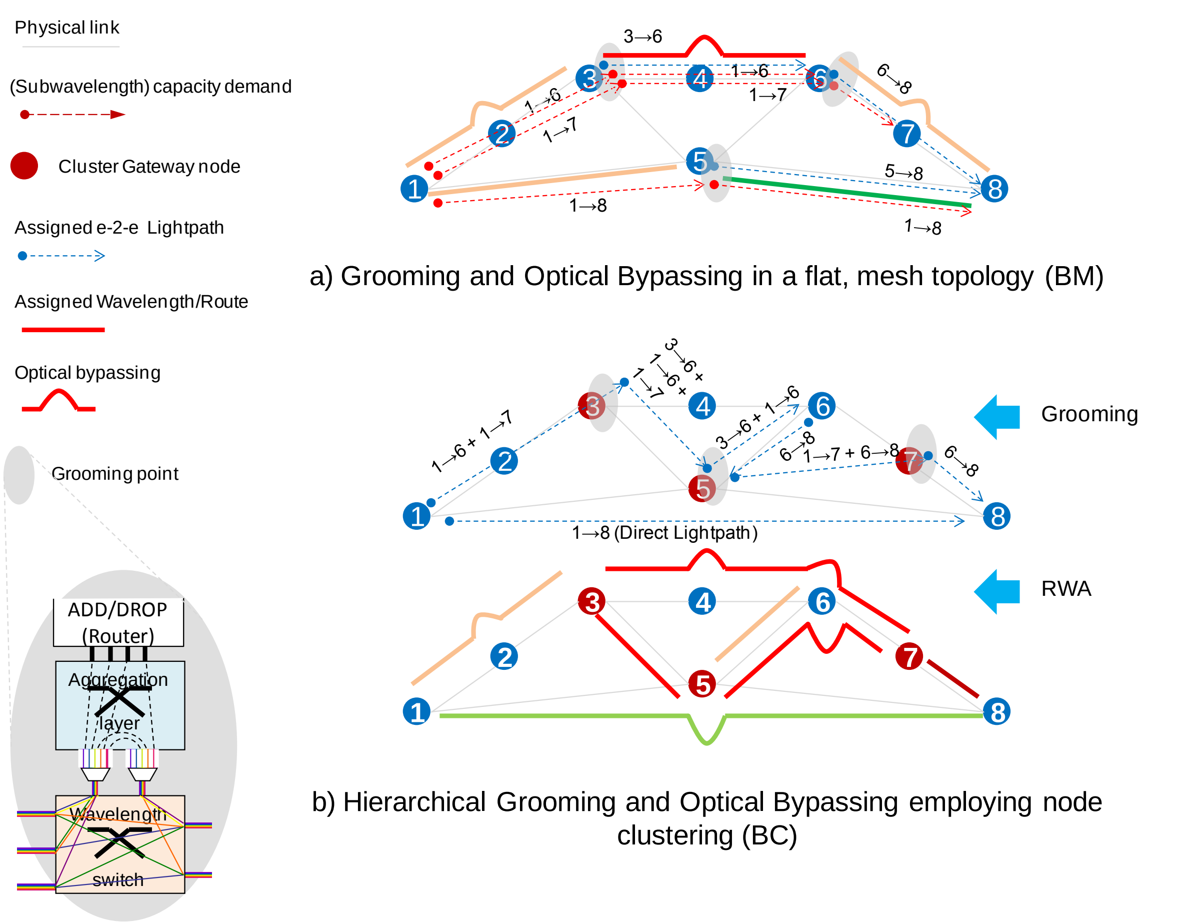


Figure 23: Example of traffic grooming based on multi-granular IP/L2/WDM employing WBV-WSS for optical bypassing.

3.4.3 IP over Optical planning

As a consequence of link lengths, national IP/MPLS networks have been built on the top of optical networks, and thus the design problem has been typically addressed through a multi-layer IP/MPLS-over-optical approach where IP/MPLS routers are placed adjacent to optical cross-connects (OXC). Besides, due to the coarse granularity of the fixed-grid wavelength division multiplexing technology used at the optical layer, aggregation networks were deployed between clients and core networks to groom client flows thus increasing the spectral utilisation of the optical layer.

However, flexgrid technology, providing a finer optical spectrum granularity, allows a new flatter multi-layer approach: IP/MPLS routers equipped with Sliceable bandwidth-variable Transponders (S-BVT) are connected to BV-OXC, transforming the multi-layer approach into a single-layer approach where a number of IP/MPLS metro area networks performing aggregation are connected through a flexgrid-based core network (Figure 24).

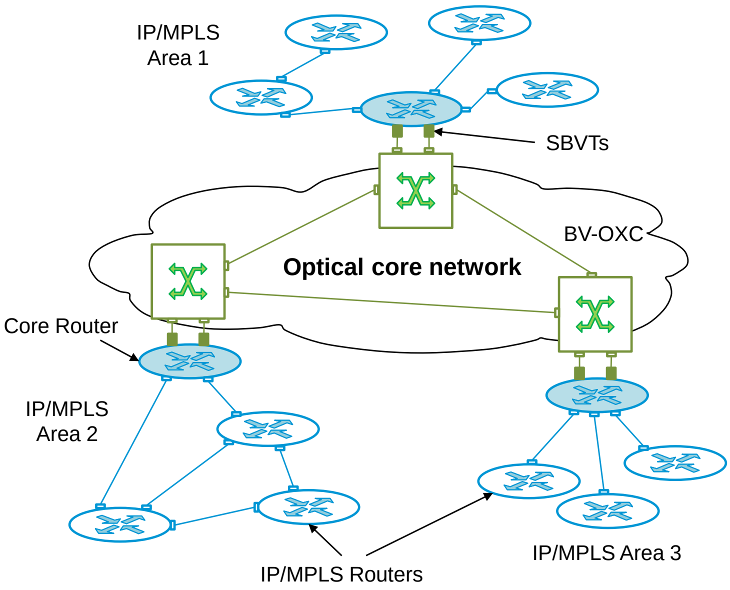


Figure 24: Flatten multi-layer network architecture.

Given a national network, with over 1100 Central Offices, a full, single step network optimization is clearly impossible. Hence, a two-step procedure is proposed to design such IP/MPLS national networks and investigate its optimal size so as to minimize CAPEX: 1) area partitioning and 2) networks design.

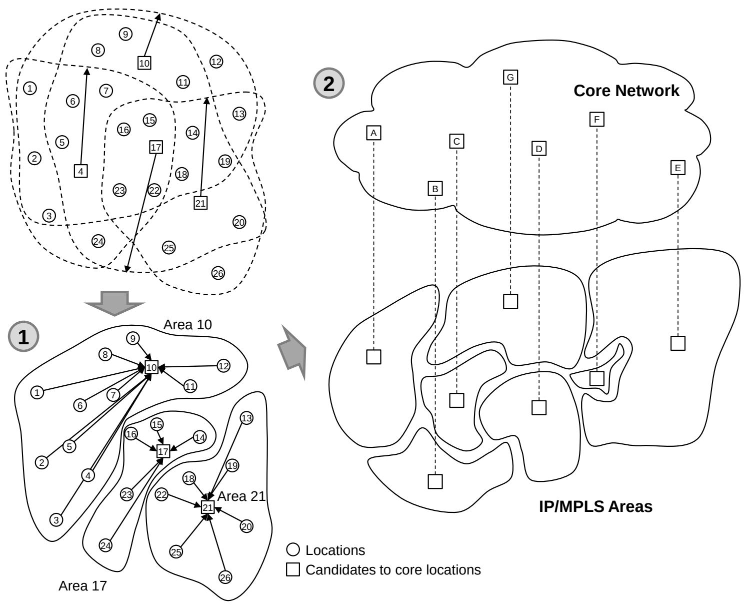


Figure 25: Two-step procedure for network design: 1) Locations are grouped into areas. 2) IP/MPLS areas and to the core network are designed.

Starting from a given set of locations, where some of them are also candidate core locations (based on location and good node connectivity), and from a traffic matrix for the entire network, the first step, the ARea PArtitioning (ARPA) problem, finds the optimal set of areas, each consisting of a subset of locations, one of them belonging to both that area and the core network. Figure 25 illustrates the proposed design procedure where some data needs to be pre-computed: a) candidates for core nodes can be limited to those nodes with sufficient connectivity degree and b) the limited subset of potential core nodes (e.g. based on distance) each location can belong to.

The ARPA problem aims to maximise the total aggregated traffic to be conveyed by the optical core network. Note that by maximizing the aggregated traffic we are indirectly minimizing the internal traffic of the resulting areas. That is important since the cost per bit of the optical switching technology is generally cheaper than that of the IP/MPLS layer and the aggregated flows in the optical core network occupy many spectral resources, so are most cost effectively groomed and routed optically.

Results showed that simpler and smaller areas containing 10-15 locations are enough to obtain good spectral efficiency in the flexgrid-base core network with 12.5 GHz granularity. Table 2 shows the characteristics of the solutions for different number of considered areas.

Table 2 Solutions details

	# IP/MPLS Areas			
	116	**165**	**216**	**295**
Areas size (Max / Avg)	19.66 9.94	15.04 6.97	15.04 5.46	9.77 3.83
Core Router Capacity (Max / Avg (Tb/s))	58.0 28.5	45.1 20.1	35.3 15.7	28.5 11.1
Area flows (Max / Avg (Gb/s)	72.33 32.68	56.06 23.84	50.52 21.12	37.92 14.60
Aggregated flows (Max / Avg (Gb/s) / #)	989.06 264.95 13,884	602.16 129.47 28,335	404.51 82.73 48,684	229.91 38.83 87,990

Significant savings from the flexgrid core network (31%) as well as the IP/MPLS area networks (23%) can be obtained when the core network extends towards the edges increasing the number of areas that are connected. Both the capacity and the number of IP/MPLS routers and ports can be reduced.

3.4.4 IP over Optical control

Elastic data plane solutions proposed in IDEALIST (S-BVTs, elastic OTN/Flexgrid grooming, etc) can be configured by software enabling the following use cases.

Dynamic Multiflow and Bandwidth Allocation. Existing optical transponders are designed to support single flows at a fixed bit rate (e.g 10 Gb/s, 40 Gb/s, 100Gb/s). However, both bitrate and number of flows can be dynamically configured according to control plane commands in new S-BVTs proposed in IDEALIST.

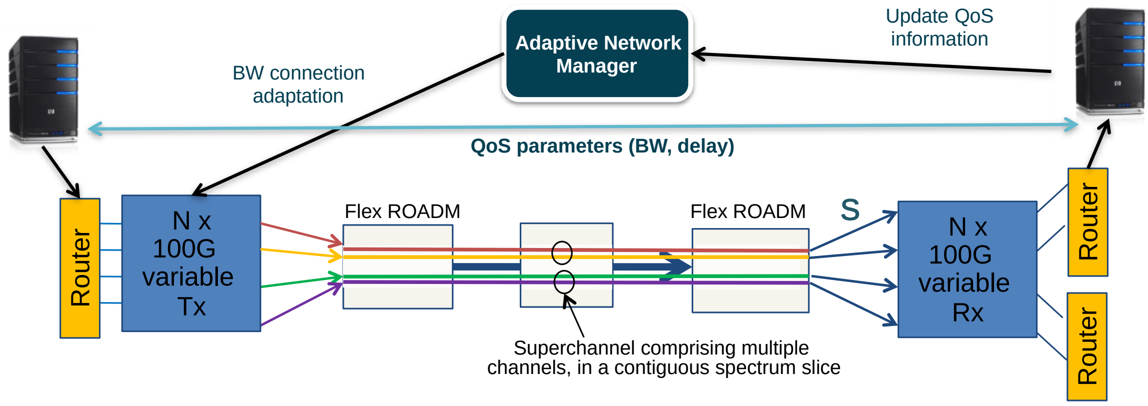


Figure 26: Example scenario for dynamic bandwidth allocation use case.

S-BVT benefits in terms of network optimization and operation simplification are reported in multiple publications, such as [26], [27], [28] and [29].

Automatic IP_Link provisioning. This refers to coordinated IP and optical network control plane reconfiguration according to the new physical topology after a lightpath establishment (e.g IP routing tables). Traditional carriers' networks operation is very complex and is not adaptable to flexible traffic requirements. Hundreds of thousands of node configurations per year are needed by network operators such as Telefonica in Spain. Furthermore, network solutions typically use vendor-specific Network Management System (NMS) implementations. Such complex architecture results in complex and long workflows for network provisioning (e.g. more than six weeks for core routers connectivity services over photonic mesh). By coordinating both the IP and optical planes, this process may take minutes, mainly because of equalization of optical channels, power monitoring and channel calibration times within the (elastic) ROADMs. For current network operator requirements this reduction in IP link and service turn-up time, would significantly reduce operational expenditures in the network provisioning process.

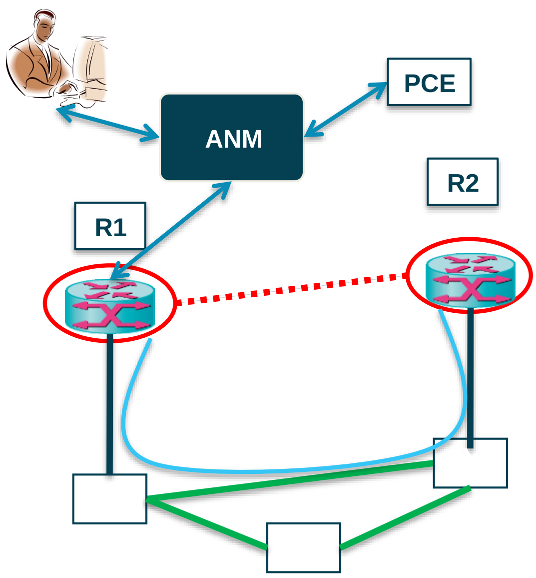


Figure 27: ANM automatic IP link configuration.

Flexible Router Interface. Another scenario is the case of the creation of a by-pass link when all the existing bandwidth on some intermediate link between two routers has already been used up (i.e. crosses a pre-defined threshold). Instead of using additional interfaces on both routers, an alternative solution could be to have a “flexible router interface” able to be partitioned and channelized using a S-BVT. In this case, it would be possible to split the interface maximum bandwidth in two (or more) fragments, reducing the bandwidth of the original connection (the one to the next IP hop) to create a new direct connection towards the destination router.

Multi-layer restoration. This refers to the coordination of IP and optical restoration mechanisms enabling increased survivability and optimized CAPEX and OPEX.

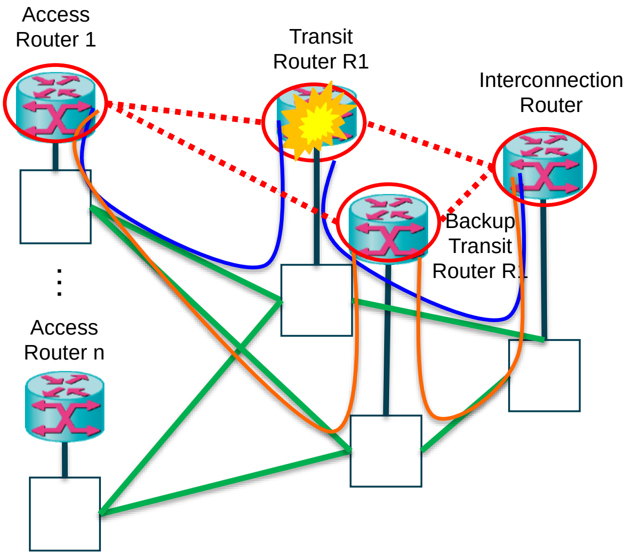


Figure 28: Multi-layer restoration using a remote backup transit router.

However, the above use cases would not be feasible in real transport networks unless a standard control architecture enabling multi-vendor and multi-technology interoperability, such as the one proposed in IDEALIST, is implemented. Otherwise, network elasticity would only be achieved in single vendor networks.

3.5 Full dynamic optical networks

Inter-data center (DC) traffic highly varies over time as a result of performing elastic DC operations, i.e., performing virtual machine migration and database synchronization among federated DCs (DC2DC traffic). Figure 29 shows an example of the traffic profile in dual data center hubs in Latin America, where DCs synchronize data during night time and periodically during the day.

However, current DC connections are configured as static *big fat pipes*, which entail large bitrate over-provisioning and thus high operational costs, since network operators cannot share such connections between customers.

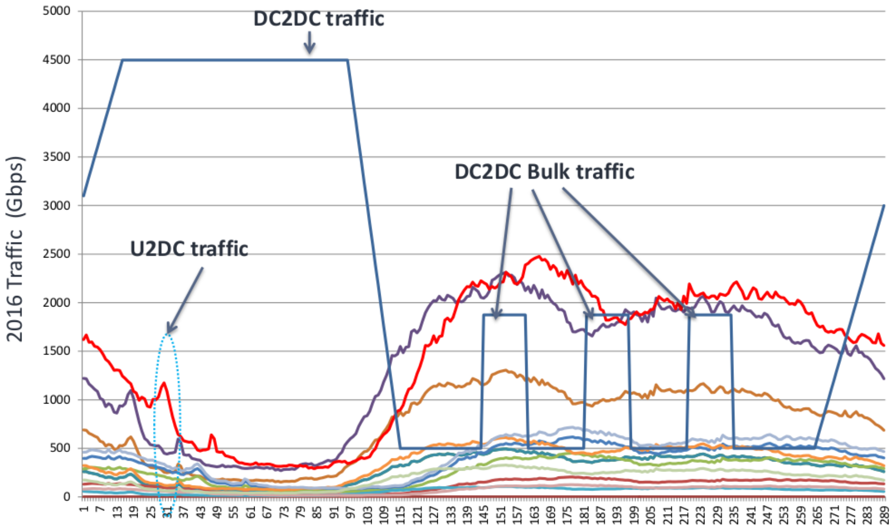


Figure 29: Traffic Profile in Dual Data center Hubs in Latin America (reproduced from C. Liou, O. Turkcu, V. Lopez, J. Fernandez-Palacios, in PTC 2013).

Another source of time-varying traffic comes from expanding the core network towards the edges to connect a number of IP/MPLS aggregation networks. It was shown that by increasing the number of metro areas, significant CAPEX savings can be obtained. However, it also entails having a larger number of relatively small metro areas, which leads to a reduction in the traffic aggregation at the IP/MPLS layer, thus resulting in higher variability of the traffic flows offered to the optical layer during the day (Figure 30), since user to user (U2U) and user to DC (U2DC) traffic variations are transferred to the optical core network.

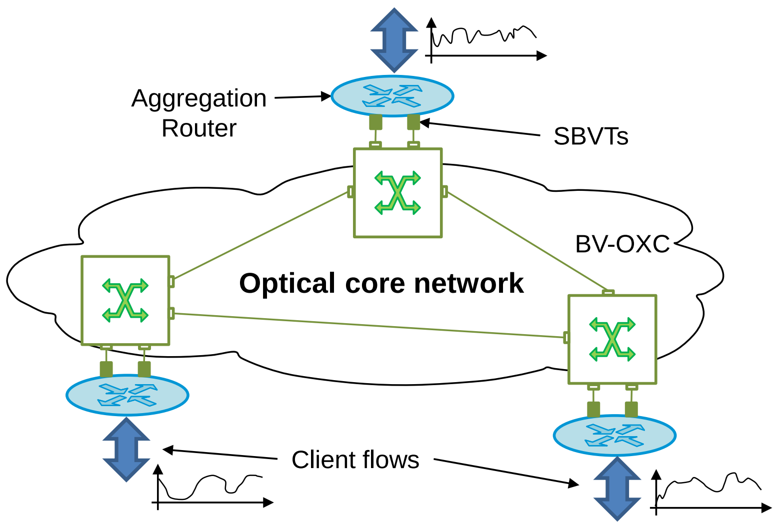


Figure 30: A flexgrid-based optical core network connecting aggregation IP/MPLS networks.

To improve resource utilization and save costs, dynamic and elastic connectivity is clearly needed and as such, it has been the focus of research and standardization.

One of the main advantages of flexgrid is the capability to allocate spectrum in a flexible way to fit bandwidth demands. Routing and Spectrum Allocation (RSA) algorithms are needed to find a feasible route and spectrum allocation for a given connection request. In addition, elasticity, i.e., increasing/decreasing the slot width of an existing lightpath e.g., by adding or releasing sub-carriers, according to traffic demands, is also required. Indeed, the resources may be used efficiently, firstly, because of the finer granularity of flexgrid which allows fitting closely the allocated spectrum and the signal bandwidth, and secondly, due to the elastic (adaptive) spectrum allocation (SA) in response to traffic variations.

3.5.1 Dynamic provisioning including DC interconnection

In dynamic scenarios, the RSA problem consists of finding a feasible route and spectrum allocation for an incoming connection request. In flexgrid, the spectrum allocation is represented by a frequency slot and thus, in the absence of spectrum converters, the same slot must be used along the links of a given routing path (*spectrum continuity constraint*). Besides, the allocated spectrum must be contiguous (*spectrum contiguity constraint*). Due to the spectrum contiguity constraint, algorithms for the Routing and Wavelength Assignment (RWA) problem developed for WDM networks are not applicable for RSA in flexgrid optical networks and they need to be adapted to include that constraint.

The RSA problem was proved to be *NP*-complete, so it is crucial that efficient methods are available to allow solving the problem in practical times so as to not introduce additional delay to the provisioning process.

Shortest paths algorithms, e.g. *k*-shortest paths, can be adapted to include spectrum availability during route computation, given that the complexity of the proposed spectrum availability extension is negligible. In a second step, spectrum allocation can be realized using any heuristic, e.g. first fit, random selection, etc.

Regarding spectrum allocation for time-varying traffic demands, three alternative policies (reproduced in Figure 31) were studied. The spectrum allocation policies put the following restrictions on the assigned central frequency (CF) and the allocated spectrum width, in particular:

- *Fixed* (Figure 31a): both the assigned CF and spectrum width do not change in time. At each time period, demands may utilize either whole or only a fraction of the allocated spectrum to convey the bitrate requested for that period.
- *Semi-Elastic* (Figure 31b): the assigned CF is fixed but the allocated spectrum may vary. Here, spectrum increments/decrements are achieved by allocating/releasing frequency slices symmetrically, i.e., at each end of the already allocated spectrum while keeping invariant the CF. The frequency slices can be shared between neighbouring demands, but used by, at most, one demand in a time interval.
- *Elastic* (Figure 31c): asymmetric spectrum expansion/ reduction (with respect to the already allocated spectrum) is allowed and it can lead to small shifting of the CF. Still, the relative position of the lightpaths in the spectrum remains invariable, i.e. no reallocation in the spectrum is performed.

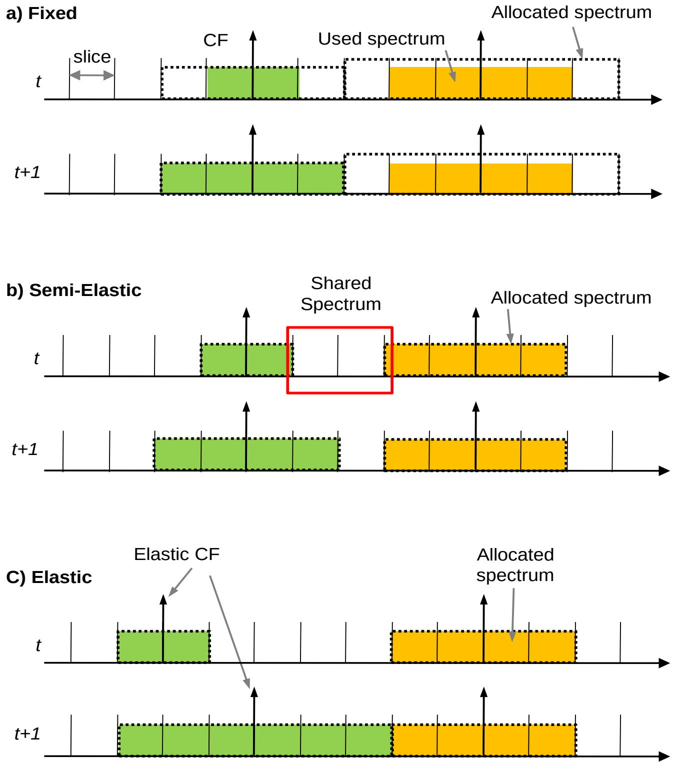


Figure 31: Three spectrum allocation policies for time-varying traffic in a flexgrid network. Two time intervals are observed: *t* before and *t*+1 after spectrum adaptation has been performed.

In Table 3, the gain of elastic spectrum allocation policies with respect to the fixed one is reported in detail. In all the analyzed scenarios the Elastic policy outperforms the Semi-Elastic policy which, on the other hand, performs better than Fixed spectrum allocation policy.

Table 3: Gain of Adaptive spectrum allocation policies vs. Fixed one.

Spectrum Allocation Policy	
Elastic	20.99%
Semi-Elastic	9.34%

Finally, evolution towards cloud-ready transport networks entails dynamically controlling network resources, considering cloud requests in the network configuration process. Hence, that evolution is based on elastic data and control planes, which can interact with multiple network technologies and cloud services. An Applications Service Orchestrator (ASO) between the cloud and the interconnection network is eventually required to coordinate resources in both strata in a coherent manner. When considering a cloud-ready transport network, where the control plane can dynamically set up and tear down connections, the entry point from applications to the network is ABNO.

Dynamic connectivity allows DCs to manage optical connections to remote DCs, requesting connections as they are really needed to perform data transfers and releasing them when all data has been transferred. Nonetheless, the availability of resources is not guaranteed, and the lack of network resources at request time may result in long transfer times.

To alleviate to some extent the dependency between cloud management and network connectivity, we proposed a novel network-driven connectivity model. ASO implements a northbound interface to request transfer operations Figure 32. Those applications' operations are transformed into network connection requests. The northbound interface uses an application-oriented semantic, liberating application developers from understanding and dealing with network specifics and complexity.

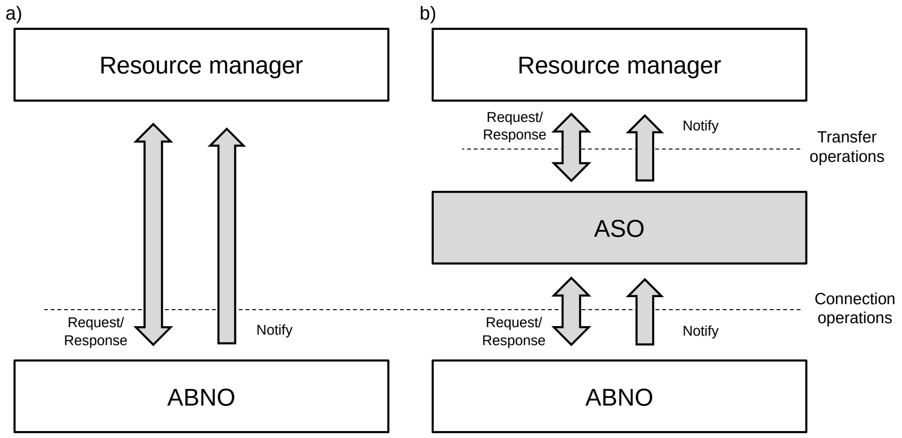


Figure 32: Control architectures supporting dynamic connections (a) and transfer mode (b) requests.

ASO is in charge of managing inter-DC connectivity; if insufficient resources are available at requesting time, notifications (similar to interruptions in computers) are sent from the ABNO to ASO each time specific resources are released. Upon receiving a notification, ASO can take decisions on whether to increase the bitrate associated with a transfer, applying elasticity on optical connections. Therefore, we have effectively moved from polling to a network-driven transfer mode.

3.5.2 Defragmentation and re-optimization

We consider an elastic network in which during its operations new connections are established and torn down dynamically. In contrast to traditional WDM networks, where spectrum assignment is uniform (in the form of wavelengths), in elastic networks the spectrum eventually becomes fragmented [30], a problem that becomes more severe as time progresses, leading to inefficient spectrum utilization. To address this problem we have developed a Dynamic RSA (D-RSA) algorithm for serving new demands in an elastic optical network that (reactively) de-fragments the spectrum and re-optimizes the network when a new connection cannot be served. The goal is to re-optimize the network, provision the new demand and minimize the changes made in the network.

To address the fragmentation problem in elastic optical networks, two types of defragmentation methods have appeared: proactive and reactive methods. Reactive defragmentation is triggered when a new demand cannot be served, while proactive defragmentation is performed in a periodic or in an event-driven manner (e.g. at connection release). The latter method aims at maintaining the network in a good shape without a priori knowing if the changes made will be needed. The former method is triggered only when needed, meaning that spectrum fragmentation has reached a critical point, and thus it has to be fast. Rearranging as few connections as possible (achieve little disruption) and low running time are the most relevant performance metrics.

In the following we outline a Dynamic RSA (D-RSA) algorithm for serving demands in an elastic optical network that reactively defragments the network when deemed appropriate [31]. We assume an optical network that encompasses flexgrid switches and tunable transponders. Serving a demand requires the establishment of one or several connections, depending on the requested rate, the distance between the end-points and the capabilities of the transponders. If a demand cannot be served at the current network configuration state, we re-optimize and defragment the network [32]. In particular we examined two solutions: (i) push-pull or (ii) rerouting. Note that the push-pull technique [33] is hitless, while for rerouting we assumed a Make-before-Break technique that utilizes additional transponders (and regenerators, when used) to re-establish an existing connection before tearing it down. Figure 33 presents an example of how these two techniques can solve the fragmentation problem.

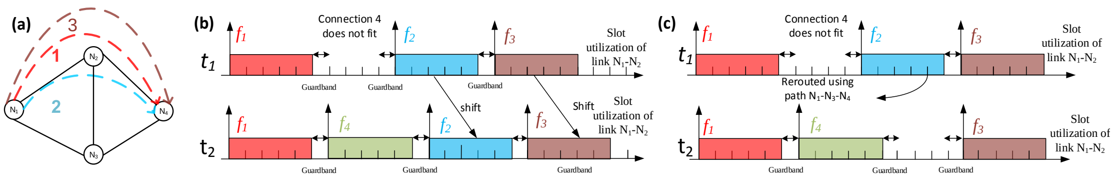


Figure 33. (a) An elastic network where 3 connections exists at time t1. (b) The spectrum slot allocation on link N1-N2 at two different time instants t1 and t2. Initially at time t1, connections 1, 2 and 3 exist and a new connection 4 arrives. Not finding sufficient space to serve it, we shift (push-pull) connections 2 and 3 by two slots each, and the new connection 4 is established at time t2. (c) Same scenario but using the rerouting technique.

To serve a demand, the D-RSA establishes one or more parallel (when the demanded rate is not supported at the respective distance by a single transponder) connections. The D-RSA algorithm examines a number of candidate paths between the source and destination, and combines them with the transmission tuples, to form what are called path-tuple pairs. For each path-tuple pair, it calculates the number of transponders and regenerators needed for serving the demand. Given the path-tuple pairs for a demand, the algorithm tries to serve the demand at the current network state. If this is not feasible it re-optimizes the network by defragmenting it, using the push-pull, rerouting, or a combination of these techniques. The objective in this case is to minimize the changes made in the network.

We devised both an optimal ILP and a heuristic algorithm to solve the dynamic demand serving problem. The ILP algorithm takes as input the current state of the network and searches to serve the demand as is and if this is not feasible it searches for the solution that minimizes the changes made in the network. The heuristic algorithm we devised selects the biggest void and makes space around that void, by applying the shifting and/or rerouting techniques, or a combination of those in a recursive manner. The shifting can be done towards the upper and bottom direction by certain slots. To achieve the lowest possible cost, the heuristic algorithm considers all possible combinations of slots freed in the two directions. A similar approach is followed when rerouting connections. The heuristic can also examine cases where some connections are rerouted and others are push-pulled to create the appropriate space. Note that shifting a connection might result in shifting some other connection, and this process is recursive and can go deep. We used a recursion threshold *H* to control the running time of the heuristic.

We implemented the proposed D-RSA algorithms used them to evaluate the performance of the proposed re-optimization techniques. In particular we compare four network scenarios: (i) D-RSA/no re-optimization, (ii) D-RSA/rerouting, (iii) D-RSA/push-pull, (iv) D-RSA/push-pull and rerouting.

In small scale experiments the performance of the heuristic was shown to be close to the ILP algorithm. In the following we report on results obtained using the heuristic algorithm for the Telefonica network topology, assuming spectrum slots of 12.5 GHz and 320 slots supported in the network. We also assumed the use of a single type of flexible transponder that transmits up to 400 Gb/s. The (reach-rate-spectrum-guardband) tuples used as input to these experiments were according to IDEALIST D1.1. Demands at each node are generated according to a Poisson process with arrival rate λ and an exponentially distributed duration with mean $1/\mu=1$ time unit and destination uniformly chosen among all network nodes. The demanded rate is drawn from a uniform distribution on the closed interval [0,400] Gb/s, rounded with a 10 Gb/s step, so as to cover scenarios where the network is quite dynamic and adaptable to edge traffic changes. Experiments were performed for 50,000 connections.

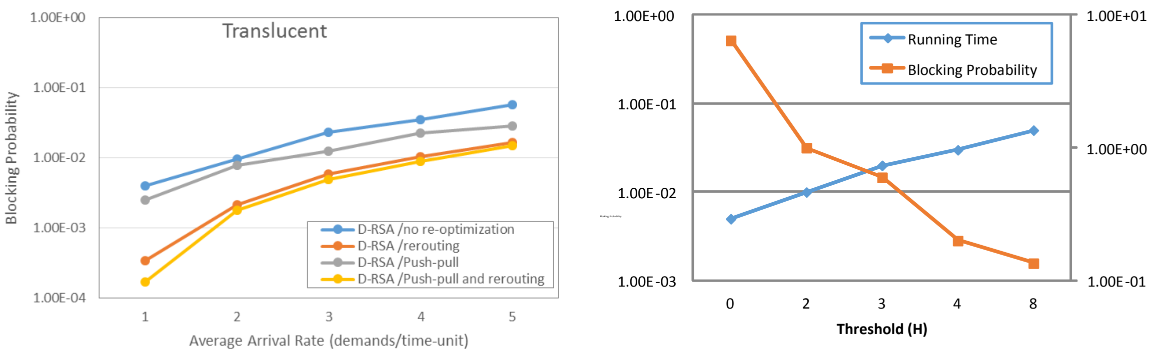


Figure 34. (a) blocking probability and (b) blocking probability and average running time of the D-RSA/push-pull and rerouting algorithm for λ=3 demands/time unit as a function of the recursion threshold.

Figure 34(a) shows the blocking probabilities of the D-RSA algorithm. As expected, serving the demands without re-optimization (D-RSA/no re-optimization) has the worst performance. Push-pull and rerouting techniques improve the performance, rerouting being better, since it exploits the solution space of different paths. Using both techniques in the joint algorithm improves the performance slightly more than the rerouting algorithm. Figure 34(b) shows the effect of the recursion threshold *H* on the performance of the D-RSA/push-pull and rerouting algorithm (note that in previous experiments *H* was set to infinite) for average arrival rate λ=3 demands/time-unit. We see that lowering *H* increases the blocking probability but reduces the average and maximum running time, introducing a trade-off between these two metrics. The blocking and running time performance for *H*>8 is similar to that where *H* was set to infinite. On the other end, when *H* is set to 0, the performance of the D-RSA/push-pull & rerouting emulates that of the D-RSA/no re-optimization. Thus, *H* can be chosen so as to meet the response time requirements for serving the demands.

A version of the D-RSA/push-pull algorithm, named as Spectrum Shifting (SPRING), was selected to be implemented in the PLATON planning tool (see section 4.4.1).

3.5.3 Dynamic re-optimization after failure repairs (AFRO)

In dynamic flexgrid optical networks, the usage of capacity may not be optimal due to the permanent process of setting up and tearing down connections, which, if not controlled, leads to spectrum fragmentation and, as a result, to increase of connection blocking. On top of this, a restoration mechanism that is launched in reaction to a link failure (cable cut) restores the affected lightpaths. Eventually, when the cable is repaired and its capacity becomes available for new connections, the imbalance between lightly and heavily loaded links increases, thus further decreasing the probability of finding optical paths with continuous and contiguous spectrum for future connection requests.

We studied the effects of re-optimizing the lightpath connections after a link failure has been repaired (namely, the AFRO problem) as an effective way for both reducing and balancing capacity usage and, by these means, for improving network performance.

Figure 35 shows an illustrative example of the network states at different time instants. Here, we consider a dynamic network that serves a set of lightpaths under normal operation (denoted as state t0). After a link failure event, the restoration mechanism finds an alternative route for each of the lightpaths affected by the fiber cut (state t1). Specifically, Figure 35a) shows a network with three lightpaths, namely p1, p2, and p3, just before the event of a fiber cut in link 2-7. After that, lightpaths p1 and p2 are rerouted by the restoration algorithm (Figure 35b)).

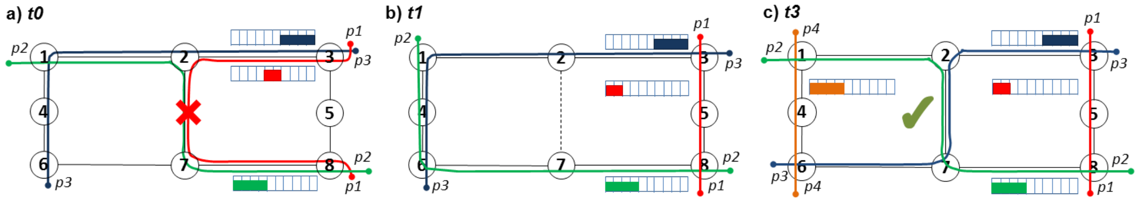


Figure 35: An example of link occupancy in different network states.

Once the solution of the restoration algorithm is implemented, the network operates without the failed link until it is restored (6-12 hours are usually needed to repair a fiber link), which is denoted as state t2. For the ease of presentation, in Figure 35 we assume that t1=t2, i.e., neither setups nor tear-downs of lightpaths occur during the period of link restoration. At this point, we can see that after the link is repaired, the network capacity increases, however, its performance is not necessarily improved. Namely, in Figure 35(b) a new connection requesting 4 slices between nodes 1 and 6 can be established neither when the link is broken nor when the capacity of the repaired link is available again.

Illustrative numerical results show that AFRO allows to significantly decrease the request blocking probability in realistic dynamic network scenarios. Besides, traffic disruptions resulting from lightpath rerouting are practically negligible.

This algorithm was selected to be implemented in PLATON planning tool (see section 4.4.2).

3.6 Energy aware planning

Despite the undisputed energy efficiency benefits brought about through the use of ICT, the ICT industry itself has recently been identified as a major contributing factor to the emission of Green House Gases. It is a common knowledge that the number of end users and their demanded network speeds exhibit a very rapid growth, while ISPs keep on deploying and continuously upgrading their network infrastructures. This in turn results in a consequent continuous increase in the telecommunications networks' energy consumption. It is estimated [34] that the energy consumption of fixed broadband devices will rise from 3% in 2002 to 14% in 2020. Similarly, the energy consumption of telecom devices will rise from 12% in 2002 to 20% in 2020. Summing these two yields 10% of the total ICT energy consumption in 2020 (total ICT consumption includes the energy consumption of mobile devices, pcs, laptops, printers, and whole data centers). Thus, many concerns have been raised regarding the limitations that energy consumption may put on Internet growth. So, energy aware planning of telecom networks, and in particular the metro and core parts of the networks that contribute a substantial amount, seems to be more imperative than ever.

This subsection includes two contributions on the topic of energy saving in EON: an approach for achieving the energy saving in static off-line planning and a specific study which demonstrates that, under realistic network and traffic assumptions, OTN grooming gives important savings both in cost and in energy consumption.

3.6.1 Energy aware planning algorithm

To address this problem we focus on the energy minimized design of a multi-layer IP over elastic optical networks. At the IP layer, we consider the IP/MPLS routers located at the edges of the optical network that aggregate the traffic to be forwarded over the optical network. Since packets are forwarded transparently over lightpaths, there is no packet/header processing in the optical network, and the majority of the energy is consumed at the electronic edges or the intermediate IP/MPLS routers of the network that process the packets. Thus, accounting for the electronic edges and jointly planning the multi-layer network is of paramount importance. Although our study assumes IP/MPLS routers, the proposed solution is generic and can be applied for other types of edge routers (such as MPLS-TE or OTN).

Network model

We assume a multi-layer optical network that consists of optical ROADM switches and fiber links that form the optical network and IP/MPLS routers connected to the optical switches that form the edges of the optical network.

In the elastic optical network under study we assume that the transponders are flexible and can be tuned at several transmission configurations described by the so called *feasible transmission tuples* [1], which take into account the physical layer impairments. This model is quite generic and can express fixed transponders (expressed by a single tuple) and different types of flexible transponders.

Concerning the Energy model this study refers to the Energy model developed by IDEALIST and briefly presented in subsection 4.2.2.

Problem formulation and proposed solution

The multi-layer network planning problem takes as input the given IP over flexible network topology, the model of the routers, the feasible configurations of the transponders, and the traffic matrix that corresponds to the IP traffic to be forwarded over the optical network. Its goal is to decide on the IP/MPLS modules and the optical transponders required to install and establish lightpaths, and route the traffic over these lightpaths and through possibly intermediate IP/MPLS routers to the end IP/MPLS router destinations, so as to minimize the total network's energy consumption. So, to solve (a) the "IPR" sub-problem, we have to decide on the modules to install at the IP/MPLS routers, how to map traffic onto the lightpaths, and which intermediate IP/MPLS routers will be used to reach the domain destination, (b) the "RML" sub-problem, we have to decide how to route the lightpaths, where to place the transponders, and also to select the transmission configurations of those flexible transponders, and (c) the "SA" sub-problem, we have to allocate spectrum slots to the lightpaths, avoiding slot overlapping.

The proposed energy-aware multi-layer network planning algorithm is an extension of the algorithm of [35] so as to account for energy consumption. It uses a single demand serving algorithm so it serves demands one-by-one in some particular order, and is executed until it serves all demands in the traffic matrix. Since the results depend on the ordering, we used a simulated annealing meta-heuristic to search among different orderings and select the best one. The devised single demand serving algorithm follows a multi-cost routing approach. The algorithm runs on the network graph consisting of both virtual (IP routers) and optical nodes, and three types of links: (i) inter-layer links corresponding to transponders that connect a virtual and an optical node, (ii) optical links corresponding to fibers that connect two optical nodes, and (iii) virtual links corresponding to previously established lightpaths with residual capacity that connect two virtual nodes. Links are assigned cost vectors that incorporate information regarding both layers, the optical and the IP. To calculate the cost vector of a path we define appropriate associative operators to combine the cost vectors of the different links. The devised multicost algorithm for serving a single demand is a generalization of Dijkstra's algorithm (which considers only scalar link costs). Instead of scalar addition it uses the associative operator to add the cost vector or paths and links. Note that as opposed to Dijkstra and the related scalar routing problem, there is no single candidate path but a set of non-dominated paths calculated between the source and the destination. Once this set is obtained the algorithm applies an optimization function to the cost vectors of the found candidate paths which transforms the vectors into scalars and selects the optimum path. In our proposed algorithm the optimum is defined as the one with the minimum transponders and routers energy consumption.

Performance Results

To quantify the energy consumption benefits that can be obtained when planning a multi-layer optical network, we conducted a number of studies. In particular we examined the following network scenarios:

(a) flexible (elastic) network with joint multi-layer network planning (*flex-JML-NP*),
(b) fixed-grid MLR network with joint multi-layer network planning (*fixed-JML-NP*),
(c) flexible (elastic) network with sequential multi-layer network planning (*flex-SML-NP*),
(d) fixed-grid MLR network with sequential multi-layer network planning (*fixed-SML-NP*).

For the following study we used the Deutsche Telekom (DT) topology and traffic matrices provided in D1.1 of IDEALIST where traffic was projected for 2016, 2020 and 2024 assuming 35% increase per year. The transmission tuples (reach, rate, spectrum, energy consumption) of the used flexible and fixed transponders are shown in Table 9 and Table 10, respectively (located in subsection 4.2.2). The energy consumptions of the various IP/MPLS router modules are listed in Table 12 (subsection 4.2.2) and are computed as 90% of the maximum values given in [36], while the energy consumption of the whole modular router is computed according to Eq. 1.

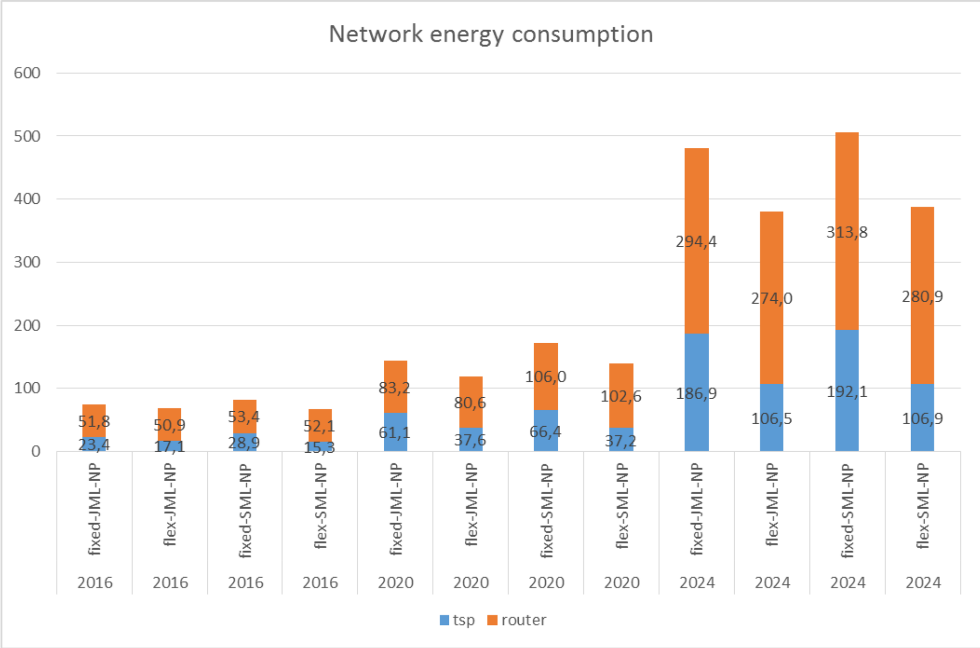


Figure 36: Transponder's, router's and total energy consumption (in kW) for the 4 network cases.

Figure 36 presents the energy consumption (in kW) for the 4 network cases. Concerning the transponders' energy consumption of the jointly planned networks, we observe that the flexible (*flex-JMP-NP*) case outperforms the fixed (*fixed-JML-NP*) case over time, and as the traffic increases, the difference between the transponder's energy consumption of the two aforementioned networks increases. This was expected as the flexible transponders are better utilized than fixed transponders, especially at high loads, and consequently become more energy efficient. Concerning the network's total energy consumption, the *flex-JMP-NP* network has smaller energy consumption during all the examined period. By comparing the two networks planned sequentially, we observe that the *flex-SML-NP* network outperforms the *fixed-SML-NP* network, in terms of total network energy consumption, their difference increases as load increases. Moreover, we observe that for both flexible and fixed grid network the total network energy consumption of the joint planning scenarios is less than the equivalent sequential planning. Finally, we observe that in all cases, the energy consumption of routers is the main contributor to the total network energy consumption.

Table 4: Network energy consumption (in kW) for different network scenarios with *min-energy* and *min-cost* objective.

Year	***min-cost***				***min-energy***			
	fixed-JML-NP	*flex-JML-NP*	*fixed-SML-NP*	*flex-SML-NP*	*fixed-JML-NP*	*flex-JML-NP*	*fixed-SML-NP*	*flex-SML-NP*
2016	74.60	71.87	89.25	71.87	75.16	68.01	82.30	67.43
2020	158.15	140.35	191.35	152.36	144.29	118.20	172.42	139.79
2024	488.27	414.02	520.54	416.00	481.26	380.44	505.85	387.83

Table 4 depicts network energy consumption for two optimization objectives: min-energy and min-cost. As expected, we observe that in all cases the network energy consumption is smaller when using min-energy as opposed to min-cost. We also observe that the related difference between the energy consumption of *flex-JML-NP* and *flex-SML-NP* is bigger when compared to the difference of the same scenarios for the fixed-grid cases (*fixed-JML-NP* and *fixed-SML-NP)*.

Concluding we observed that savings in energy consumption can be achieved both at the IP and optical layers of a multi-layer optical network when they are planned through a joint process, and the savings are more pronounced when the underlying optical network is based on elastic as opposed to fixed-grid MLR technology.

3.6.2 Energy saving from OTN grooming optimization

To show the potential for energy saving from OTN grooming optimization we present the results of planning on the BT network with 1,113 nodes. These results show that efficient hierarchical topologies can be constructed that can exploit the bandwidth granularity of the allocated transponders reducing overall network cost and power consumption. The network planning methodology, efficiently exploiting traffic grooming over flexgrid and elastic rate systems, and the power consumption model, are presented in D1.5 [10], section 8.2.4.

The network consists of 1,113-nodes, partitioned into two categories: 103 are Metro/Core nodes forming a mesh topology using 164 links, while the rest operate as Aggregation nodes. To obtain a traffic matrix, it was assumed that aggregation nodes groom and then forward incoming traffic from the given number of residential and business customers to their topologically nearest metro/core nodes using the shortest available path. 30% of this traffic is evenly distributed between metro/core nodes. The remaining 70% is routed from each metro/core node directly to the topologically nearest of 7 Internet exchanges. A 7.8 Tb/s total traffic matrix was thus obtained with year 2010 traffic figures, a figure consistent with the one presented in [37] This was then scaled 40 fold to a 312 Tb/s total traffic matrix for the year 2020, which is used in the results shown here.

The six scenarios investigated are electronic grooming in an opaque network (O-fixed and O-flex), optical bypassing in cluster (BC-fixed and BC-flex) and mesh based (BM-fixed and BM-flex) topologies. The -fixed scenarios employ fixed grid wavelength allocation and the -flex scenarios use EON. The use of S-BVT was considered only in the –flex scenarios.

Using the 2020 traffic matrix we calculated the equipment required across all nodes of the network and obtained the total power consumption by accounting for the contribution of each sub-system (optical amplifiers, wavelength cross connects, line cards, transceivers and S-BVTs) as detailed in D1.5, section 8.2.4. In Table 5 we report the main components that need to be deployed throughout the network and in Figure 37 we show the corresponding total power consumption numbers.

Table 5: Network and node dimensioning for the six scenarios

	Line Cards	400 Gb/s S-BVT	100 Gb/s MXP	40 Gb/s MXP	Max n.d.
O-fixed	8566		27738	52	18
O-flex	8648	7138	50	22	12
BM-fixed	3680		6992	3076	26
BC-fixed	3754		7880	1570	24
BM-flex	3839	1721	1024	2416	18
BC-flex	3824	1952	516	1246	15

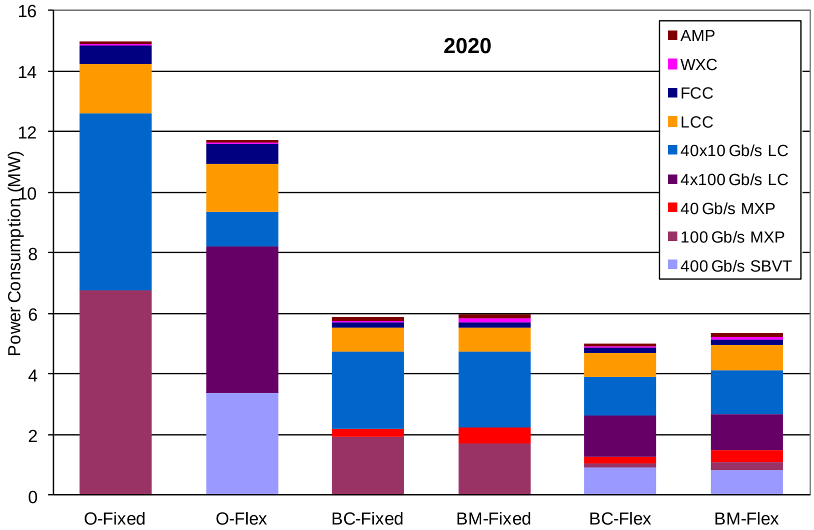


Figure 37: Total power consumption per scenario.

In Figure 37 we observe that optical bypassing solutions achieve significant gains compared to the opaque network, up to about 60%. Moreover, the –flex scenarios show the additional gains that are possible when employing S-BVTs in the network. As an example, the power consumption figure is improved by 22% for the opaque network (O-Fixed vs. O-Flex) as observed in Figure 37.

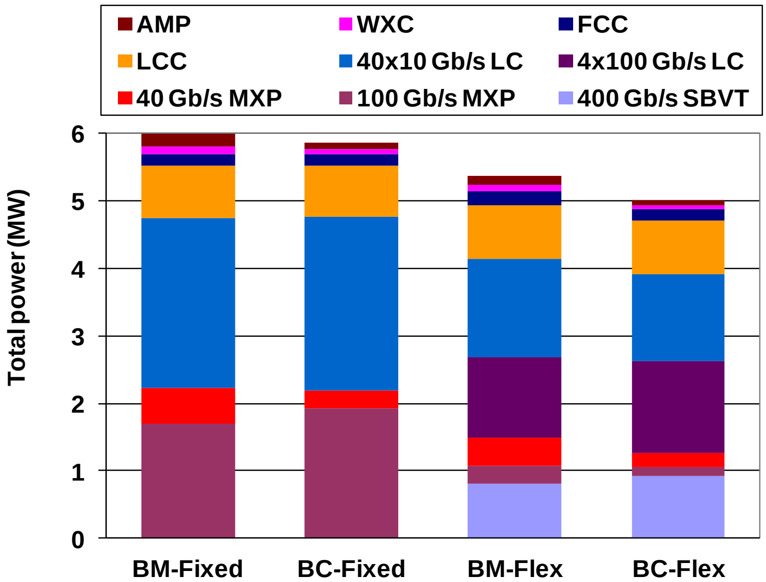


Figure 38: Optical bypassing scenarios total power consumption.

In Figure 38 only the optical bypassing scenarios are shown for clarity. Here, the introduction of S-BVTs improves the power consumption of the clustered solutions by 14% and mesh-based solutions by 10%.

3.7 Benefits of sliceability

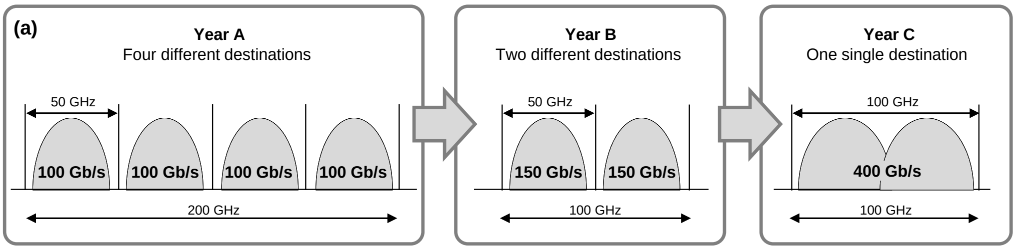
This subsection presents some specific use cases in which advantages achievable by adding the sliceability property to a BVT have been proven. In particular, the next subsections analyze the advantages of deploying S-BVTs under the static traffic assumption in some simple scenarios: *i*) incremental traffic, *ii*) uncertainty in traffic pattern and rate mix, *iii)* failure recovery, *iv)* multicast traffic (in this case also in case of dynamic traffic).

3.7.1 S-BVT to cope with incremental static traffic

Traffic is growing year on year as a result of the introduction of new services and consequently, core transport networks need to be periodically (e.g., yearly) planned. The result of the planning process might include upgrading the network adding more optical nodes as well as more transponders to cope with the traffic forecast. In this context, deploying S-BVTs in the network helps operators to cope with traffic increments by adding new transponders and reconfiguring existing ones. Figure 39(a) shows an example where a 400Gb/s S-BVT is configured to source four 100Gb/s optical connections to four different destinations in year A. As soon as the traffic increases, the configuration is changed so as to source two 150Gb/s optical connections in year B and one single 400Gb/s connection in year C. Note that new S-BVTs are needed to support the remaining connections.

It is interesting to compare several transponder types, from fixed transponders (FT) to S-BVTs, and analyze the amount of them and their total cost in an operator network. The study was done on the Spanish Telefonica 14-node transit network, assuming an initial traffic matrix of 2.9Tb/s and 25% annual increment applied to every source-destination pair (i.e., no changes in traffic direction). The table embedded in Figure 39(b) presents the evolution of the connection's bitrate distribution with time.

The results, plotted in Figure 39(c) and (d), show that the number of 100Gb/s FTs follows the traffic increment, while for 400Gb/s FTs and 400Gb/s and 1Tb/s S-BVTs the number of transponders scales better. From the cost viewpoint, the present cost was computed assuming 3% interest rate and the cost figures presented in Figure 39(d). 1Tb/s S-BVTs show the best scalability and cost among the studied options, while 400Gb/s S-BVTs provides cost reduction during the first years until there is a significant proportion of connections larger than 300Gb/s, enough to fill a single transponder each; that happens around year 7 in our study.



(b)

Gb/s	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
<=100	85.7%	61.9%	47.6%	33.3%	19.0%	19.0%	4.8%	4.8%	4.8%	4.8%
(100-200]	14.3%	33.3%	42.9%	52.4%	61.9%	42.9%	28.6%	14.3%	14.3%	0.0%
(200-300]	0.0%	4.8%	9.5%	9.5%	9.5%	23.8%	28.6%	28.6%	9.5%	14.3%
(300-400]	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	23.8%	33.3%	33.3%	14.3%
>400	0.0%	0.0%	0.0%	0.0%	4.8%	9.5%	14.3%	19.0%	38.1%	66.7%

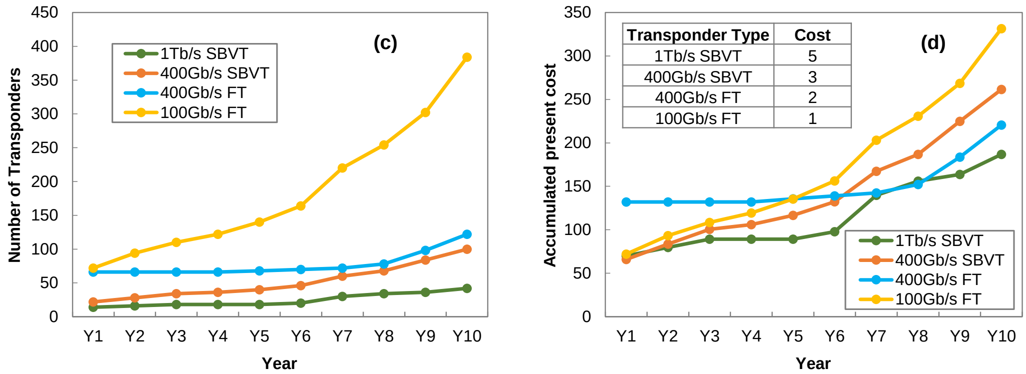


Figure 39: Different configurations of a 400 S-BVT to cope with incremental traffic (a). Evolution of the connection's bitrate distribution (b). Accumulated number of transponders (c) and present cost (d).

3.7.2 S-BVT to face uncertainty in client rate mix and traffic pattern

A study on an evolving multi period traffic scenario in a Pan European network is performed to compare the cost of a network using transponders of different types. Three types of transponder have been considered: Fixed, Bandwidth variable (BV) and Sliceable (S-BVT). Traffic is supposed to evolve not only in volume but also in client rate mix. It has been demonstrated that S-BVT, for a wide range of cost projections, gives better results in term of cost (with up to 27% of cost of transponders saving) not only in the case of traffic increasing with a steady pattern, but also in case of uncertainty in the knowledge of the mix of client rates and in the traffic pattern evolution.

In more detail the hypotheses of this use case are that the reference pan European backbone defined in D1.1 [9] evolves towards the future following five subsequent time period steps in which the traffic doubles from one period to the next. In this evolution framework, the assortment of interfaces required by the clients are assumed to change from dominant lower rates (100G and 200G) in short term to dominant higher rates in the long term (1T and 2T).

Assuming that flexgrid ROADMs are installed for the whole analysis period and for all transponder alternatives, the difference between the compared scenarios is in the way the client traffic requirements are accommodated by the available devices: with dedicated transponders in case of FT (many models of FT are required, one for each client rate required); with a reduced set of devices in case of BVT (to avoid wasting electronic capacity BVTs cover a limited range of rates); by a portion of the capacity of a single very high capacity device (1.2T or 2T) in case of S-BVT. In the case of S-BVT a client demand uses not only a part of the electronic capacity but also a subset of the total optical sub-carriers of the S-BVT.

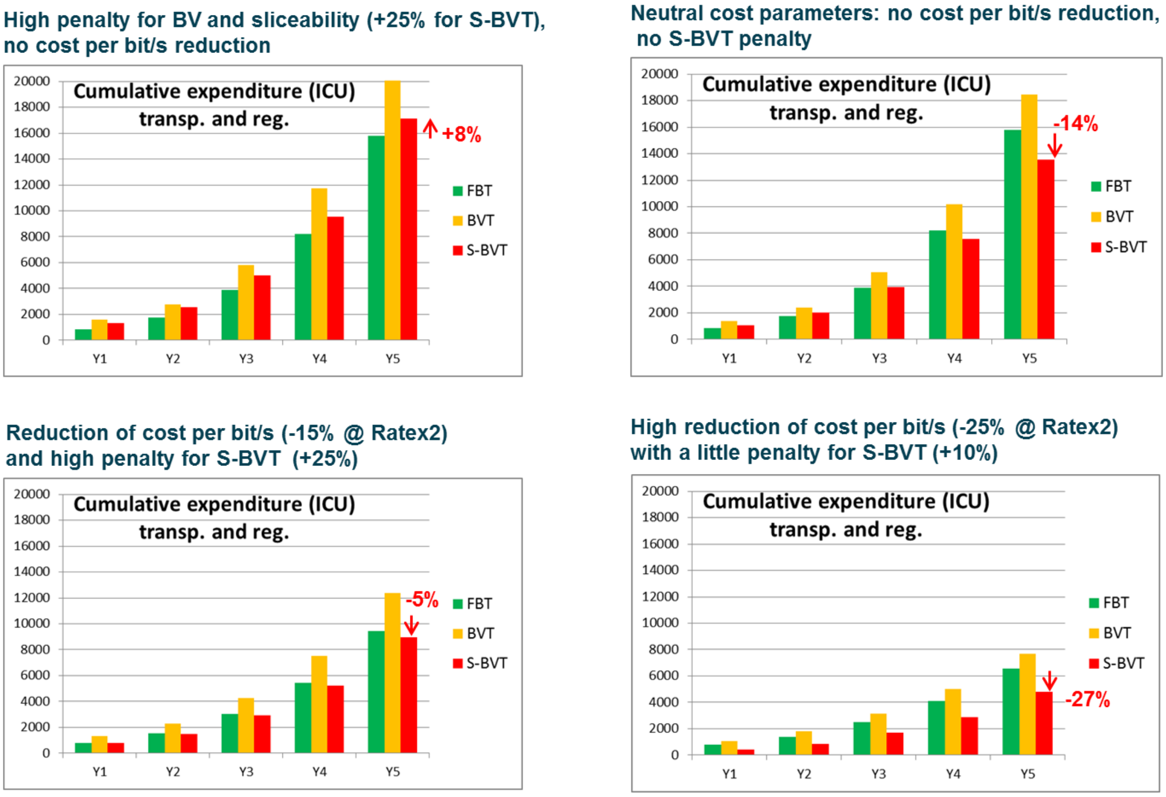


Figure 40: Transponder cost for different device alternatives and cost parameters trends of EON devices.

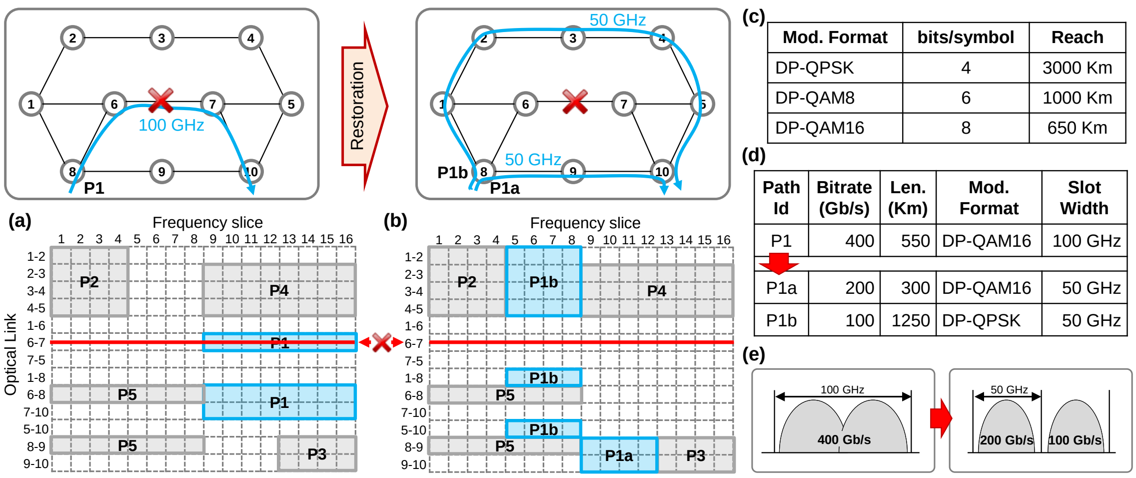
Figure 40 shows the cumulative cost for transponders only: the cost of all other network parts are the same in all the cases as the network is assumed to use flexgrid ROADM and the spectral efficiency is assumed to be the same for all the devices, whether they are fixed, or variable or even sliceable. The transponder costs for BVT and S-BVT in Figure 40 are evaluated under four different parameter trends as regard cost per bit reduction with capacity and penalties for bandwidth variability and sliceability implementation. BVT is always the worst solution because the expensive electronic capacity is sometimes not fully utilized (for instance to accommodate a 100G in a 200G BVT, which has been assumed the smallest device in that scenario, half of the potential bit rate is wasted).

S-BVT, in this traffic growing and client rate assortment changing scenario, results in the best cost solutions for a wide set of cost parameter trends. The only case in which the use of S-BVTs perform worse than employing FTs is the very pessimistic one (top left of Figure 40) characterized by a constant cost per bit/s and by a high penalty for S-BVT implementation (S-BVT costs 25% more than a FT having the same capacity). The poor cost performance of the BVT is due to its partial use of the total capacity, in other words to the intrinsic inability of BVT to share its resources among flows having diverse destinations. (This drawback of BVT could be partially obviated introducing on client side of the BVT the muxponder functionality: this would allow the flexibility to share resources between connections having the same end nodes, but this has not been done in this study). The good cost performance of S-BVT is due to the intrinsic capability of a S-BVT to reconfigure itself from more lower rate clients to fewer higher rate clients, avoiding the waste of CAPEX caused by wasted and no longer used lower rate interfaces, or to the cost of displacements of existent interfaces among nodes in case the requirement of interface types on nodes changes among periods. Cost evaluations are performed with different client rate mixes and with changing in time of the traffic distribution, namely assuming that not only the volume but also the pattern changes among different periods. For all the evaluations done the results are similar to the ones shown in Figure 40. In other word S-BVT performs well not only in case of traffic increasing but also in case of uncertainty in knowledge of the client rates assortment and traffic pattern. The previous results support the introduction of S-BVT, starting as soon as they will become available. Looking at mid and long term, we believe that such a choice will be strategic to get technical and economic advantages in next generation optical networks.

3.7.3 Multi-path restoration

A source of dynamicity, even in static networks, is that caused by network failures. When a failure occurs, a recovery mechanism, usually restoration, is activated to reroute affected connections. In the case that not enough resources are available for some of the connections, its bitrate can be squeezed so as to recover part of the connection's bitrate. In addition, S-BVTs can facilitate implementing multi-path restoration strategies, so as to increase the recovered bitrate. Note that restoration routes are usually longer than the original one and the modulation format might be reconfigured at the transponder side. This is especially important when the multi-path recovery technique is applied since every connection could need a different modulation format. After failure repair, re-optimization can be applied, targeting at reducing resource utilization.

Figure 41 shows an example on a small network. In Figure 3(a), 400Gb/s connection P1 is established using DP-QAM16, so the allocated frequency slot width is 100GHz. After a failure in link 6-7 occurs, two connections are used to restored the failed one; a 200Gb/s connection using DP-QAM16 and another 100Gb/s connection using DP-QPSK to jointly recover 300Gb/s. Figure 3(c) presents the characteristics of some modulation formats while Figure 3(d) and Figure 3(e) show the connection and S-BVT configuration before and after the failure.



Mod. Format	bits/symbol	Reach
DP-QPSK	4	3000 Km
DP-QAM8	6	1000 Km
DP-QAM16	8	650 Km

Path Id	Bitrate (Gb/s)	Len. (Km)	Mod. Format	Slot Width
P1	400	550	DP-QAM16	100 GHz
P1a	200	300	DP-QAM16	50 GHz
P1b	100	1250	DP-QPSK	50 GHz

Figure 41: Example of multi-path recovery on a small optical network.

3.7.4 Multicast traffic

New applications require conveying huge bitrates from a source node to multiple destinations (e.g. uncompressed real time 8k transmission needs 72 Gb/s connections). As a result, point-to-multipoint (P2MP) connections need to be established in the optical layer.

Figure 42 illustrates the considered routing schemes to serve multicast demands in the optical layer. Client routers/switches are connected to OXCs by means of S-BVTs. Let us assume 400 Gb/s S-BVTs that can be shared among 4 paths (S-BVT flows). In the case of unidirectional paths, S-BVTs can be shared by up to 4 incoming paths and up to 4 outgoing paths. In this scenario, the multicast demand <A, {B, C, D}, 100 Gb/s> can be served by three lightpaths or, alternatively, by a single light-tree.

Figure 42a shows the *path scheme*, where three 100 Gb/s unidirectional lightpaths (also known as *sub-paths*), are set-up. Each sub-path consumes one Tx S-BVT flow from those available in the source router and one Rx S-BVT flow in the destination router. Furthermore, one spectrum slot is allocated to each sub-path along the route. Although the path scheme requires many resources (S-BVT flows and spectrum), every sub-path can be routed independently from the other ones serving the same demand, which provides high flexibility in the case where spectral resources are scarce or fragmented.

To reduce resource utilization, the *tree scheme* can be implemented (Figure 42b) to source a single 100 Gb/s signal, which remarkably reduces the required number of Tx S-BVT flows to just one. Besides, spectral resources can be shared on some segments along the tree (e.g. from OXC-A to OXC-D), which reduces also spectral resource utilization. Notwithstanding, a single spectrum allocation is required for the whole tree, which might increase the demands blocking ratio in case no continuous spectrum allocation is available along the tree, e.g. as a result of spectrum fragmentation.

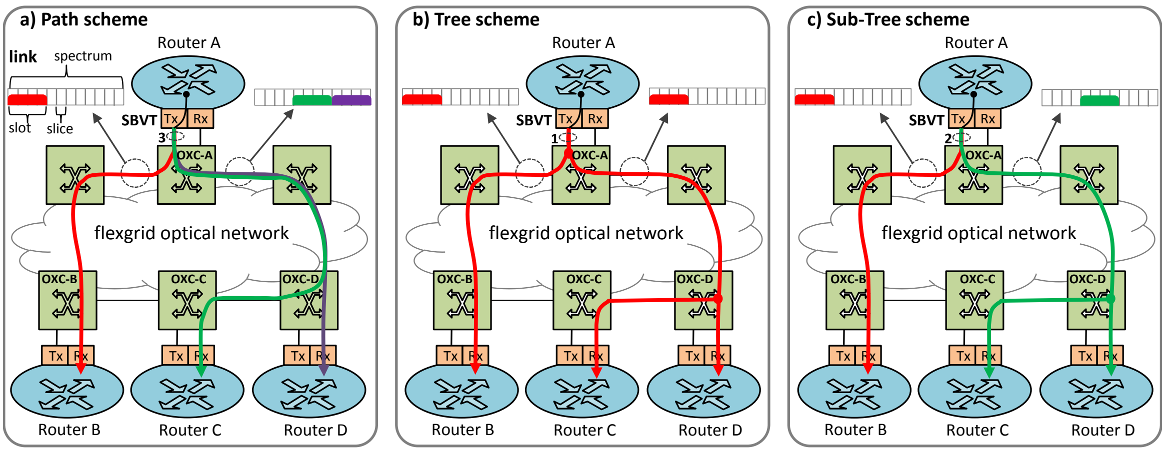


Figure 42: Routing schemes for multicast traffic.

In light of the above, we proposed the *sub-tree scheme* to combine flexibility of sub-paths with resource savings of trees (Figure 42c). Under this scheme, a multicast demand can be served as a combination of light-trees, each enforcing the spectrum continuity constraint. In the example, two light-trees are created as a result of spectrum fragmentation. Thus, two Tx S-BVT flows are needed at the source router, whereas spectral resources are shared in the segment OXC-A / OXC-D.

Numerical results showed that the sub-tree scheme outperforms the path and tree schemes, increasing the capacity of national network in the range of 17 to 30%. The worst case of the sub-tree scheme was when its performance equals that of the path scheme, as a result of the long distance of the network.

Multicast provisioning use case was selected to be implemented in PLATON (see section 4.4.3).

4 How - IDEALIST solutions

This section presents a short overview of the IDEALIST solution proposals for the data plane, the control plane and for the network planning and techno economic evaluation. These solution proposals have been organized in terms of building blocks, each one covering a specific application scope within the wide context of the EONs. The complete list of the IDEALIST building blocks and their definitions is given in subsection 4.5. In the same subsection Table 13 reports on the associations between the use cases presented in Section 3 and the building blocks which are the subject of this section.

4.1 Data plane building blocks functionalities

The building blocks for Data plane aimed at an EON implementation developed within the project are extensively described in the WP2 deliverables D2.1 [38] and D2.2 [39]. They range from BVT, S-BVT and flexible OXC (based on ROADM based on BV-WSS) for the short and mid-term, to more forward-thinking systems for the long term solutions (Architecture on Demand (AoD) for node architecture, Switchless Elastic Rate Node (SERANO) concept for opaque lambda and sub lambda switching).

In this subsection a brief overview of data plane building blocks limited to the short and mid-term solutions are presented. They are closely linked with the industrial exploitation of the project findings and they are also fundamental references for Section 5 of this deliverable.

4.1.1 BVT and S-BVT

S-BVT is an evolution of the Bandwidth Variable Transponder (BVT), a transponder able to dynamically change the transmission capacity and reach by adjusting parameters such as gross bitrate, forward error correction code and modulation format. The configuration changes in the BVT can be automatically performed by the control plane, thus making this subsystem the basic building block of an optical Software Defined Network (SDN).

S-BVTs extend BVT functionalities allowing capacity allocation into a number of independent optical flows that can be transmitted to either one or multiple destinations.

The IDEALIST project developed the S-BVT architecture, described in D2.2 [39] and published in [40] and in [41], which refer to the intermediate stage of the project. The enhanced specification of BVT and S-BVT and the potential industrial roadmap of such systems have been achieved during the last period of the project and it is reported in D2.4 [42].

The general S-BVT sub system organization and the multiplexing architectures are shown in Figure 43. The block named “configurable/sliceable flexible OTN interface” adapts service information content (e.g. IP traffic) to optical channels characteristics. The OTN framing and multiplexing standard (ITU-T G.872 and G.709) is the natural candidate for implementing this function. The blocks named Multi Flow Optical Modules (MFOM) receive properly structured bit streams from the flexible OTN interface and convert them into modulated optical sub-carriers that can be distributed among different super-channels. Each super-channel, made by one or more optical sub-carriers, can be sent to distinct destinations. An S-BVT may consist of an hosting card with several pluggable MFOM modules thus providing to operators a “pay as you grow” cost model. The outputs of MOFM are connected to the add/drop ports of a ROADM that routes super-channels towards their destinations.

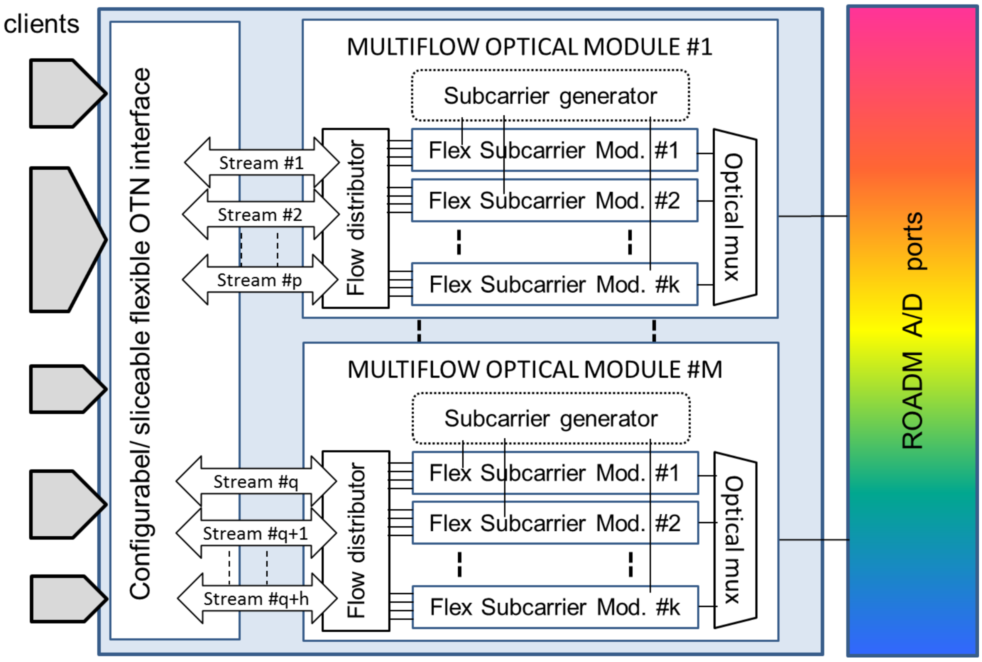


Figure 43: S-BVT architecture.

The general architecture of the S-BVT shown in Figure 43 proposed by IDEALIST comprises a configurable/sliceable flexible OTN interface module for client mapping from the OTN fabric into ODUCn/OTUCn, with a net capacity that varies from the 100G OTUC1 to the maximum rate of the transponder.

The project has identified as a particular interesting instantiation of the general model, an S-BVT with a total net capacity of 1.2 Tb/s, able to handle combinations of flows in steps of 100G from OTU-1 to OTU-C12. This device, taking the space and power constraints on racks and the expected technological evolution into account (CMOS for electronics and Hybrid or Silicon CMOS for photonics), is expected will be market ready only in the mid-term (2021).

Regarding modulation technique, the final deliverable of WP2 [42] states that in a first generation of (S)-BVTs, Nyquist WDM will be the preferred transmission technique used. In the second generation of modules, all the transmission techniques identified within IDEALIST will be probably employed, maybe by different vendors or in different network segments. Transmission techniques in the mid-term will include, in addition to Nyquist WDM, also Orthogonal Frequency Division Multiplexing (OFDM) and Time-Frequency Packing (TFP).

WP2 also identifies the preferred short term models of the (S)-BVT shown in Table 6. The name assigned to the model include type (Fixed and Bandwidth Variable, the last with the Sliceable option), total client bit rate and number of carriers. The total capacity of the transponder is limited to 400 Gb/s because in the short term, devices with higher capacity (i.e. 1Tb/s) are not expected to become commercially available, or at least not so widespread and in significant quantities. All the transponders are assumed to have an SD-FEC and a fixed symbol rate of 32 Gbaud (25 Gbaud of net symbol rate). The number of carriers ranges from 1 to 4.

Table 6: Transponder configurations identified by WP2 as interesting for industrial implementation in short term (2017/2018).

Module name	Net Capacity [Gb/s]	Modulation Format	Sub-carries Number	Clear Spectral width [GHz]	Target OSNR [dB]	Reference Reach [km]	Application
F_100G_1L	100	DP-QPSK	1	34.5	11.5	2400	R-LH
BV_200G_1L	100	DP-QPSK	1	34.5	11.5	2400	R-LH
	200	DP-16QAM	1	34.5	20.0	360	
(S)BV_400G_4L	100	DP-BPSK	2	69.0	8.5	4800	R-LH-ULH
	200	DP-BPSK	4	138.0	8.5	4800	
	100	DP-QPSK	1	34.5	11.5	2400	
	200	DP-QPSK	2	69.0	11.5	2400	
	300	DP-QPSK	3	103.5	11.5	2400	
	400	DP-QPSK	4	138.0	11.5	2400	
(S)BV_400G_2L	100	DP-BPSK	2	69.0	8.5	4800	R-LH-ULH
	100	DP-QPSK	1	34.5	11.5	2400	
	200	DP-16QAM	1	34.5	19.5	360	
	200	DP-QPSK	2	69.0	11.5	2400	
	300	DP-8QAM	2	69.0	17.2	850	
	400	DP-16QAM	2	69.0	20.0	360	

4.1.2 Optical switches for short an mid terms

The project has conducted a very extended and deep research for long term solutions in the field of optical switches developing the concept of AoD. Many publications explain the concepts of AoD and provide a variety of case studies in which the strengths of the AoD approach have been demonstrated [43]. The concept of regeneration of high bandwidth flows at every node is also studied considering a particular photonic node made according to the SERANO architecture [44]. For both AoD and SERANO, examples of node dimensioning and scalability properties are reported in Section 5 of D1.3 [8].

Concerning short and mid-term node architectures the project has concentrated the attention on WSS as the basic element in ROADMs. In this perspective increasing performances in add and drop (AD) architecture (in particular CDC) and, possibly, in filtering properties are expected in the next few years.

More specifically, regarding flexgrid ROADMs, 1x9 and 1x20 flexgrid WSSs (or more properly BV-WSSs) are provided by the majority of equipment vendors. In all cases LCoS technology is employed providing dynamic control of the channel center frequency with 6.25 GHz resolution and channel width with 12.5 GHz resolution, with minimum and maximum bandwidth width of 12.5 GHz and 500 GHz respectively. Full backwards compatibility with both the standard 100 GHz and 50 GHz ITU grids are guaranteed. A ROADM with the Route and Select structure is shown in Figure 44 where for simplicity the node is of degree 2 only. Line interface includes optical amplifiers and optical performance monitoring (OPM) functional block.

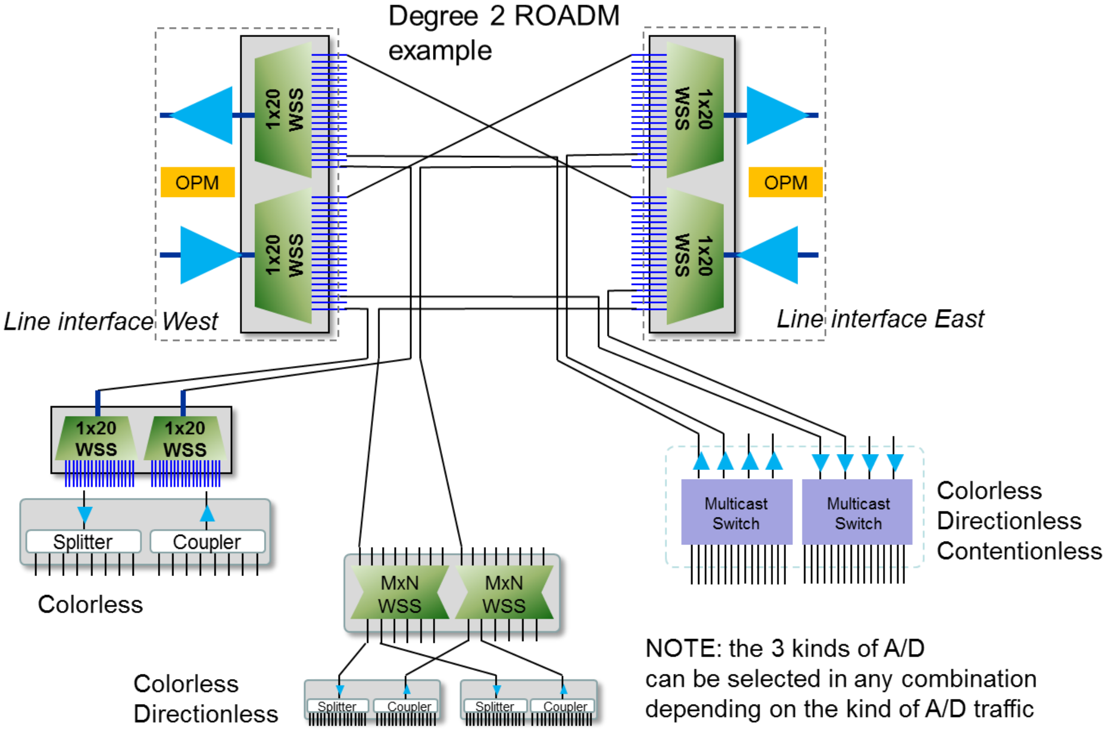


Figure 44: ROADM with Route and Select architecture with C, CD and CDC Add and Drop blocks.

Concerning AD blocks with the CD and CDC property, current Multicast Switches are expected to evolve towards less expensive and highly capable (more ports) models, while prototypes of contentionless NxM WSS are expected to become commercial products.

The use of the ROADM shown in Figure 44 in combination with S-BVT is not straightforward because the signal exiting the Multiflow Optical Module (see Figure 43) can comprise a single super-channel or can be made of many independent channels: this has to be handled by the AD chain in a proper manner, avoiding as much as possible the problem of spectrum contention within the S-BVT itself and between the S-BVTs attached to the AD block.

Within IDEALIST, a study on possible AD structures to be used in combination with S-BVT has been conducted [45]. Two add and drop architectures have been considered. The first architecture is based on coupler/splitter and therefore introduces RSA constraints. The second architecture uses MCS which is intrinsically contentionless but considering today's prices it is, and probably will be in near future, more expensive. Figure 45 shows the two AD architectures proposed.

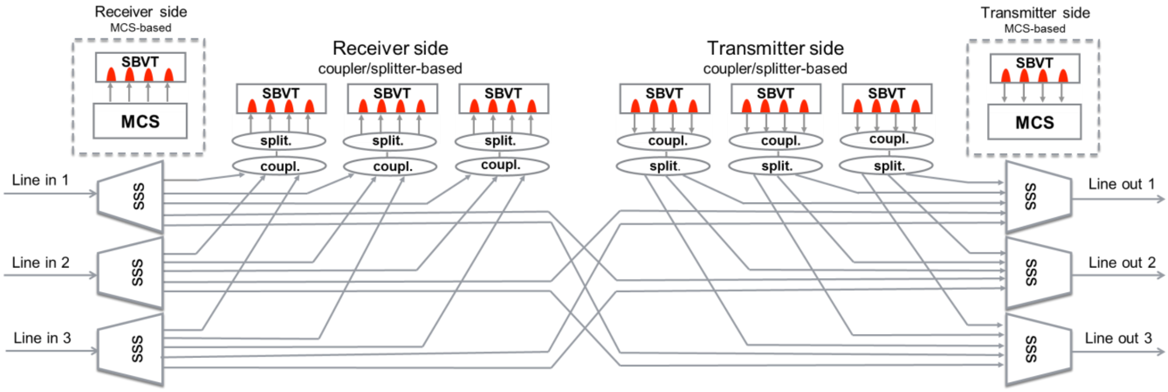


Figure 45: Proposal of two AD architectures for S-BVT.

In particular the match between the number of S-BVT sub-carriers and ROADMs per AD module port has been investigated in the above mentioned study and an evaluation of performances in term of blocking probability in the presence of dynamic traffic has been performed. Simulation results show the impact of the contentionless property on blocking probability in the case of low granularity (100Gb/s) and high granularity (1Tb/s) traffic. The MCS architecture achieves better performance than the splitter/coupler in the case of low granularity traffic. The splitter/coupler architecture achieves similar performance to the MCS architecture with 1Tb/s traffic. This suggests that, in the case of fast network migration toward high rates, splitter/coupler-based AD is an effective and cheap solution.

4.2 Performance metrics for network modelling and evaluation

In IDEALIST, network evaluation studies have been performed using two main metrics, to compare different alternatives. These metrics are the cost and the energy consumption and they are summarized in the following sub-subsections. In addition to these two metrics, performance models are used to evaluate the transmission impairments for system and network design purposes (see section 4 of D2.1 [38] and also [6], [7]). For experimental purposes other specific metrics are used for experimental tests validation (e. g. BER, OSNR, set up time): details on both metrics and experiments can be found in D4.4 [54]. All these metrics and models are considered as a unified IDEALIST Building block named "Performance metrics for network modelling and experiments" in Table 13.

4.2.1 IDEALIST cost model

At the beginning of the project a cost model has been developed with the aim of making available a common tool to perform the majority of the techno economic evaluations performed within the project.

The IDEALIST cost model reported in detail in D1.1 [9] has been developed starting from the model defined in the previous EU project STRONGEST [46].

The main concept behind the model is to refer all the costs to a single cost unit, which was chosen to be the cost of a commercially available Long Haul 100 Gb/s transponder. All network elements refer their costs to this reference value.

The transponder type taken as a reference was the state of the art best performing commercially 100 Gb/s long haul transponder at the time of the model definition (year

2013) and was characterized by a DP-QPSK modulation, a gross baud rate of 32 Gbaud allowing a Soft Decision FEC, and a resulting reach of about 2000 km on a SSMF fibre (the reach takes into account design margins). The cost of such device is assumed to be the IDEALIST COST UNIT (ICU).

A collection of information have been gathered among the partners (especially operators and vendors) in order to assign the relative costs (i. e. costs in ICU) to all the network parts considered in the model. Although this approach is far from being free of imperfections, it constitutes a useful open model that can be used quite flexibly. The model needs to be updated every time a new system is introduced to be part of the model or prices of network elements changes due to market evolution. In addition, a point in favour of the model is that it avoids to explicitly expose prices in an actual currency (€ or $), preserving confidential information.

The starting values of the IDEALIST cost model for some network elements are reported in Table 7 to Table 10 of D1.1 [9]. An extract is given below in Table 7 where, for each subsystem, the cost in ICU and the required slots in a shelf of a piece of equipment is reported. Multi shelf racks are assumed available in different configurations, from small racks with up to two half-shelves and a total capacity of 16 slots (0.2 ICU) to a standard rack with four shelves with a total capacity of 72 slots (1.6 ICU).

Table 7: Sample of cost values in ICU used in the project.

Component Type	Cost (ICU)	Required slots
Transponder 100G, 2000 km	1.00	2
100G Muxponder, 10 x 10G, 2000 km	0.87	2
OLA (bidirectional, C band, 80km span)	0.15	2
DGE functionality (one every 4 spans)	0.16	2
WSS 1x9 (unidirectional)	0.32	1
WSS 1x20 (unidirectional)	0.48	2

The method of the Target cost

As the cost of new and non-available devices is very hard to predict, in many evaluations done within the project the method of the Target cost has been applied.

According to this method, for a device which does not exist as a commercial part number, but exists as a R&D prototype or even could exist as a feasible device at a given time in the future, a parametric unknown price is assigned. Typical network elements which are subjected to this parametric pricing are BVT and S-BVT, but this also apply to flexgrid node subparts (BV-WSS) or other network subsystems.

For a given network scenario, an acceptable maximum total cost has to be assumed a-priori. For example it can be the cost of a network made by the current state of the art technologies (fixed grid nodes and fixed transponder, for which costs are well known) which fulfills assigned requirements in terms of traffic to be carried and performances to be satisfied.

The Target cost of an innovative device (a BVT or a S-BVT) is evaluated, under the same condition of traffic and performance, as giving same network cost as the one obtained with the state of the art technologies (for instance using fixed transponders). Example of works made within IDEALIST framework in which the method of the target cost has been applied are [26] and [47][48].

The cost values below the target cost found with this approach will be considered satisfactory from the economic viewpoint for the introduction of the innovative devices in replacement of established ones.

Combining CAPEX and OPEX in a single cost indicator

In addition, the IDEALIST cost model for the WDM layer has been extended to include also the OPEX. A synthetic parameter named Yearly cost is introduced for considering CAPEX and OPEX together. The Yearly cost of a network includes, in addition to the CAPEX amortization component, the following OPEX items:

- **Fiber rental cost**, i.e. the rental cost per km per year of a pair of fibers. An average single value is assumed, although in reality this cost depends significantly on the area (fiber rental costs are high in urban areas, intermediate in suburbs and low in the countryside) and the Country (Nation). Table 8 gives minimum, average and maximum values for the fiber rental cost specified in ICU per km per year.
- **Equipment hosting cost**, i.e. the cost per year for hosting a rack/subrack for OLA or ROADM. This service, in case an operator does not own the building the equipment is located in, is provided by “telehousing” companies, for instance [48]. Normally the housing service includes floor space, conditioning, power supply and communication facilities.
- **Energy consumption cost**, specified through an average cost per kW per hour. Also in this case the price depends on some factors (the Country, the hour of the day and the day of the week in which the energy is consumed), but in IDEALIST a single average value to perform cost calculation was applied.
- Maintenance cost is not modeled explicitly, but a simplified way to take this item into account is to increase the equipment investment cost by a given percentage (typical values are between 3% and 5%).

The following formula is used to compute the annual cost of the network:

Annual cost = CAPEX/amortization period + fiber rental cost +

+ equipment hosting cost + energy cost

where the amortization period is the time (in years) for which the optical layer network items can be considered active before being dismissed. An amortization period of five years has been assumed for all optical systems.

Table 8: Some OPEX cost parameters (cost in ICU).

Fiber rental (couple of G.652)	minimum	0.002 per km per year
	average	0.004 per km per year
	maximum	0.008 per km per year
Equipment hosting	Small rack / 2 half shelves / 16 slots	0.12 per year
	Full rack / 2 shelves / 38 slots	0.48 per year
	Full rack /. 4 shelves / 72 slots	0.96 per year
Energy consumption		3.00E-06 per kWh

Sources of the data reported in Table 8 concerning rental cost of fiber, equipment hosting and energy, cannot be disclosed because information is confidentially collected among the partners. In the case of the fiber rental cost, public references have been also the documents [49] and [50].

4.2.2 Energy model

In IDEALIST D1.1 [9], together with the cost model (discussed in the previous paragraph), an energy model for tunable transponders is also presented, while in D1.3 [8] and D1.5 [10] energy consumption models for optical switches, OTN switches and IP routers are reported. In this deliverable, D1.6, a number of studies are reported, targeting the evaluation through the comparison of the energy consumption of various IDEALIST concepts to previous approaches in both single and in multi-layer studies (IP over Optics or OTN grooming). For the purpose of these studies in the following we present the energy models used in the studies reported in D1.6, which are driven by the previous deliverables (D1.1, D1.3, and D1.5).

Flexible high bandwidth transponders require not only a high baud rate but also an additional electronic processing capacity for higher order modulation formats and multiple flows handling. Opportunity offered by the downscaling in chip fabrication integration (i. e. size of CMOS port size reduction) could not be fully exploited due to the high speed these devices have to operate. In fact, there is still a limitation in the power dissipation per unit of area, and dissipation depends on speed. For the calculation of flexible transponders' energy consumption the energy model based on D1.1 of IDEALIST has been applied. It has been demonstrated that energy consumption of a transponder is almost independent of the modulation format, but it depends on the baud-rate ([51] and IDEALIST D1.1 [9]).

In the case study on energy aware planning briefly presented in subsection 3.6.1 the adopted a tunable transponder architecture (BVT) which uses two lasers for transmitting up to 400 Gb/s with DP-16QAM as the highest modulation format. The energy consumption of a device of such characteristics is computed according to the following equation: $E_{BVT}=n\cdot(108+4.8\cdot R)\cdot 1.2$, where R is the baud-rate and n is the number of active lasers. The value *108* (in Watts) is the static energy consumption, while $4,8\cdot R$ captures the dynamic energy consumption and was calculated to fit linearly to the consumption of 40 and 100 Gb/s fixed transponders (according to D1.1). An additional 20% of consumption for energy management purposes is then included. In Table 9 we present the energy consumption of the BVT given as a function of the different transmission configuration of the BVT (these are described in the form of reach-rate-spectrum-energy consumption, also called transmission tuples). Similar information is provided for fixed (non-tunable) transponders in Table 10.

Table 9: Transmission tuples of a 400Gb/s BVT transponder.

Reach *(Km)*	**Rate *(Gb/s)***	***Required Spectrum (in GHz)***	**Energy Consumption *(W)***
2500	40	50	155
1800	40	25	155
1700	100	37.5	270
2000	100	50	270
1900	200	75	320
500	200	50	270
1800	400	125	630
450	400	75	432

Table 10: Transmission tuples of fixed transponders.

Reach *(Km)*	**Rate *(Gb/s)***	***Required Spectrum (in GHz)***	**Energy Consumption *(W)***
2500	40	50	155
2000	100	50	270
450	400	75	432

Concerning the optical switching and amplification the model applied use mainly data collected within the partners and concern commercially available equipment. Insignificant margin savings are expected in these components because they have still a good energy efficiency (the power per bit per second handled by those systems is very low and significantly lesser than the one of transponders or layer 2/3 equipment). In addition, a significant part of the power of a card hosting a WSS or an OA is associated with their control and monitoring (this is particularly true for WSS). As a consequence, saving in power consumption could be achieved reducing the consumption of those auxiliary parts, which do not involve photonic specific technologies and that are expected to follow the trends of general Telco equipment. An example of power consumption of optical equipment parts used in IDEALIST studies is given in Table 11. The equipment model is made of three levels that are, from the top to the bottom: equipment, board and sub-board. Starting from sub board components it is possible to evaluate the consumption of board and then, taking into account the capacity in term of capacity in hosting slots of the rack (which have a consumption itself due to fans, control and communications facilities), the power consumption of the overall equipment. Multi rack equipment is allowed for big systems.

Table 11: Examples of power consumptions of optical switches components.

Network element	*Description*	*Power consumption*
Equipment level	Small Rack (hosting 8 slots, for OLA)	70 W
	Half Rack (hosting 36 slots, for ROADM and transponders)	200 W
	Full Rack (hosting 72 slots, for ROADMS and transponders)	320 W
Board level	EDFA line board (board with 2 amplifiers for the two directions), req. 2 slots	110 W
	ROADM line system Board: 2 BV-WSS 1x20 plus 2 OA plus OPM, OSC, BCB, req. 2 slots	120 W
	Board of 100 Gb/s DP-QPSK SD-FEC Transponder, req. 1 slot	270 W
Sub Board level	Addition of a Raman pump (added to EDFA boards)	5 W

In multi-layer studies, in addition to the model of the optical layer, discussed above, a model for the IP layer and for the OTN layer is also required, in order to evaluate the benefits of IP offloading or OTN grooming. In a multi-layer optimized network normally the power savings made at the higher layers are greater than the additional power required at the optical layer.

An example of the power consumption model for an IP router is given below.

Router power consumption

We assume that the IP/MPLS routers follow the modular model presented in D1.1, like Cisco CRS-3 with 24-Slot Fabric-Card Chassis [36]. The routers can host multiple line-cards, each one providing a specified number of bi-directional connections. In particular, the router energy consumption is given by

$$E_R = \sum_{i=1}^{N_{LC}} E_{LC}^i + N_{LCC} \cdot E_{LCC} + \left\lceil \frac{N_{LCC}}{9} \right\rceil \cdot E_{FCC} + \left\lceil \frac{N_{LCC}}{3} \right\rceil \cdot E_{FC} \qquad \text{(Eq. 1)}$$

where, N_{LC} is the number of installed line-cards (LCs), E_{LC}^{i} is the energy consumption of *i-th* LC, N_{LCC} is the number of installed line-card chassis (LCCs), each assumed to hold 16 linecards and to consume E_{LCC}, E_{FCC} is the energy consumption of one fabric card chassis (FCC), E_{FC} is the energy consumption of one fabric card (FC). Each router line-card port is connected to a grey transceiver that is connected to a transponder of equal rate at the optical switch. Table 12 presents the reference energy consumption values for the modules (linecards, linecard chassis, fabric cards and fabric card chassis) that comprise an IP/MPLS router.

Table 12: Energy consumption of IP/MPLS routers modules.

Module	Energy consumption (W)
Linecard Chassis	2754
Fabric Card Chassis	7520
Fabric Cards	256
10x40G, 4x100G, 1x400G linecards	108

4.3 Control plane proposal overview

The IDEALIST control architecture is a combination of distributed protocols, which provide a real-time response and let the network survive against failures, and a centralized intelligence (Adaptive Network Manager) that, on the one hand, provides a point for optimization (e.g. interfacing with the planning tool) and interfaces with the applications, like Cloud or Video services, as shown in the figure below. The distributed functions are extensions of the well-known GMPLS architecture, while the centralized intelligence and interface with applications follow a SDN approach. Thus, the Adaptive Network Manager is the IDEALIST SDN Network Controller, that considers not only the Flexi-grid Network (the main focus of IDEALIST), but a wider scope, a multi-layer IP/MPLS over optical Network.

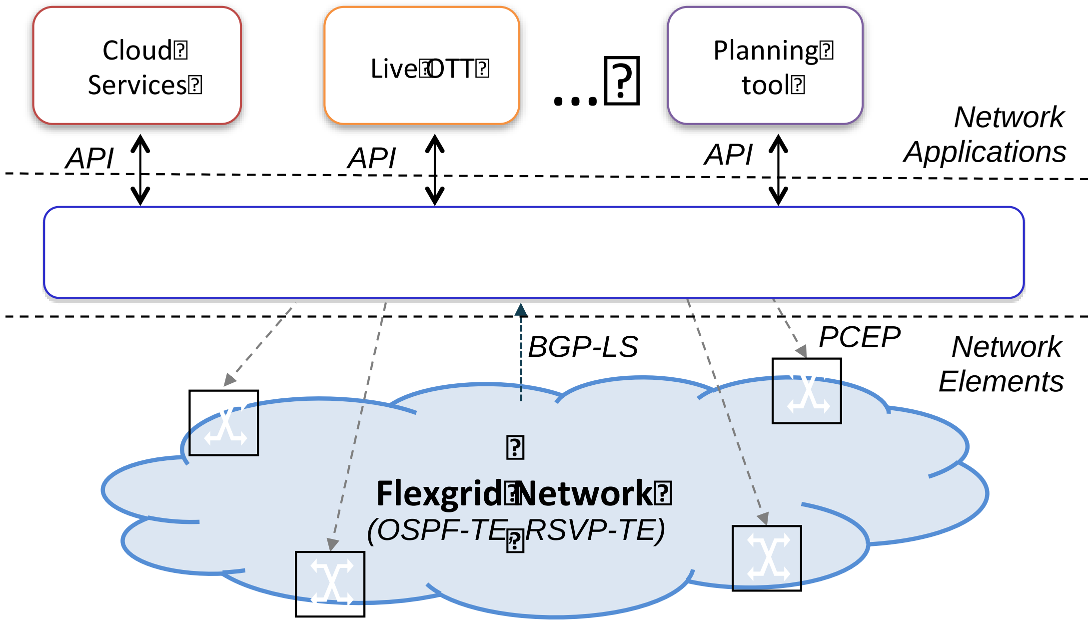


Figure 46 IDEALIST Control Plane Architecture.

The distributed control plane proposed in IDEALIST has two main functions, signaling and routing. These functions are provided by the RSVP-TE and OSPF-TE protocols, which are enhanced to support the control of advanced functionalities developed in WP2, starting from the support of the flexible grid, filters, differential filter configuration and transceiver control (including code adaptation and multi-flow transponders).

The ANM completes this architecture by providing standard network configuration interfaces, which will trigger **automated standard control plane** for **multi-domain/vendor/layer operation**. Key building block of such unified network provisioning architecture are:

- **Network Elements interface.** Multivendor nodes configuration by standard interfaces.
- **Service Layer and network coordination.** Coordinated network and service layer according to service requirements (e.g. service requirements depends on applications).
- **Network-Service interface.** Application level interface hiding details of the network. Even for NMS request, ANM requires an abstracted interface to interact with ANM. This enables having a common entry point to provision multiple services.

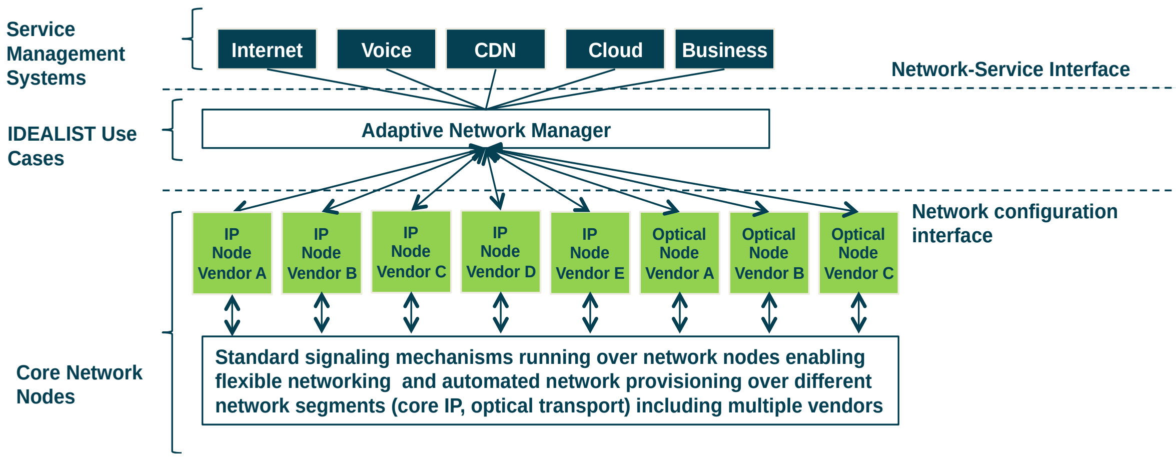


Figure 47: Network provisioning architecture based on ANM architecture.

4.4 Planning tool

This section briefly presents the UPC's in-operation PLAnning Tool for Optical Networks (PLATON), developed in WP1. Its architecture, depicted in Figure 48, is divided in five functional blocks: the communications module, the manager, the optimization algorithm framework, the databases, and the set of optimization algorithms.

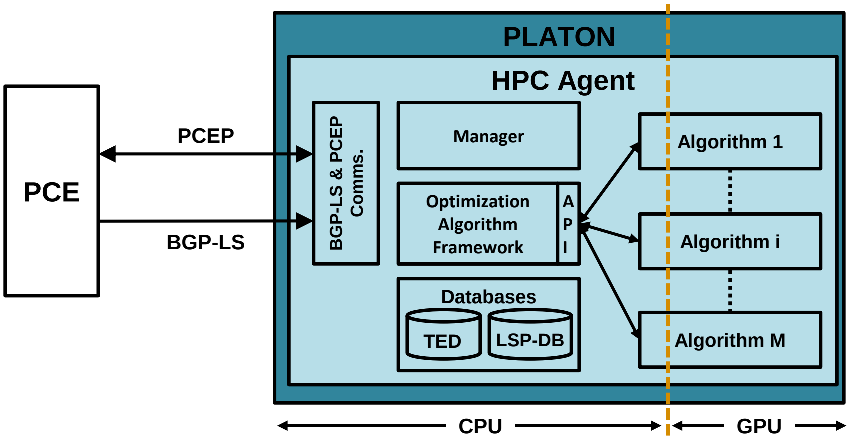


Figure 48: In-operation PLATON architecture.

The communications module implements the set of standard protocol interfaces used by PLATON to synchronize its internal databases and to handle computation requests.

The manager module schedules jobs being executed inside PLATON. Each request to be processed by PLATON is treated a job.

The optimization algorithm framework module provides a set of methods and functions common to every optimization algorithm. The set of algorithms implements the optimization algorithms executed by PLATON when a computation is requested. The methods and functions exported by PLATON are accessible through the Algorithm's API.

The databases module contains the Traffic Engineering Database (TED) and the Label Switched Path Database (LSP-DB) including appropriate methods and functions to manage them, i.e., create node, create link, connect node to link, create lightpath, allocate lightpath, etc.

PLATON provides an API for implementing new algorithms. The API is designed to be used in a C++ for Linux environment. To implement algorithms using a different language or platform, a wrapper needs to be implemented by the user. All the C++ classes composing an algorithm must be compiled and linked together into a standard Linux shared object library.

Standalone tests were reported in D1.4 [52], where BGP-LS and PCEP interfaces were tested.

Three algorithms were selected in D1.5 [10] to be implemented in PLATON. Once PLATON successfully passed those tests, integration with components from different partners, e.g. Telefonica, CNIT, and CTTC, was verified. The results, reported in D4.3 demonstrate such integration. The experimental testbeds configured to experimentally assess those algorithms are presented next.

4.4.1 Spectrum defragmentation: the SPRING algorithm

This use case assesses the SPRING algorithm in dealing with the defragmentation use case. In particular, PLATON was configured as a back-end PCE. Figure 49 describes the distributed field trial.

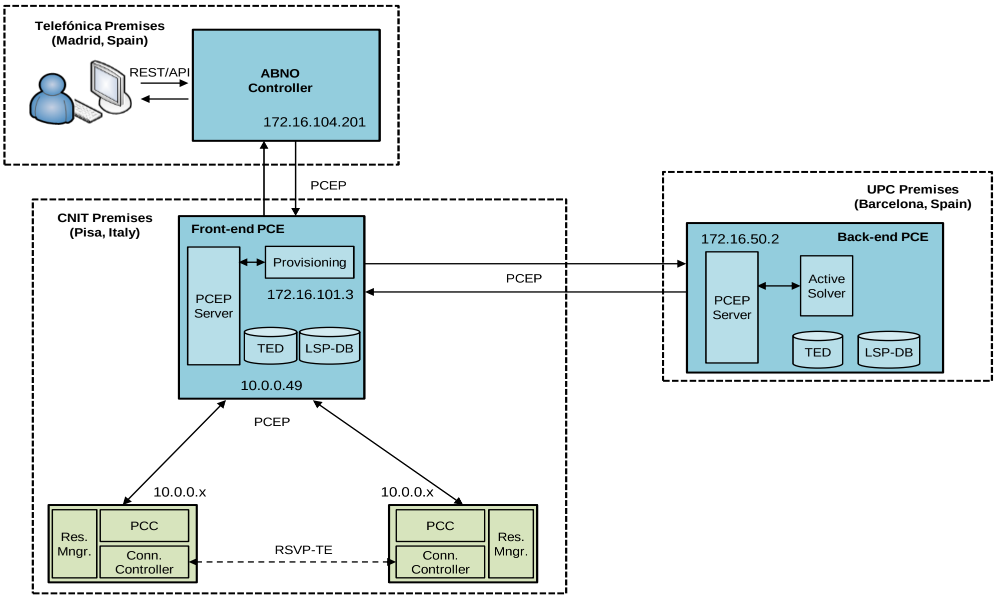


Figure 49: Distributed test-bed set-up.

4.4.2 Re optimization after link repairs of dynamic EON: AFRO algorithm

This use case evaluates the AFRO algorithm to re-optimize resource utilization after a link repair is proposed. The proposed workflow was implemented using the ABNO architecture and it was experimentally assessed in the distributed test-bed in Figure 50.

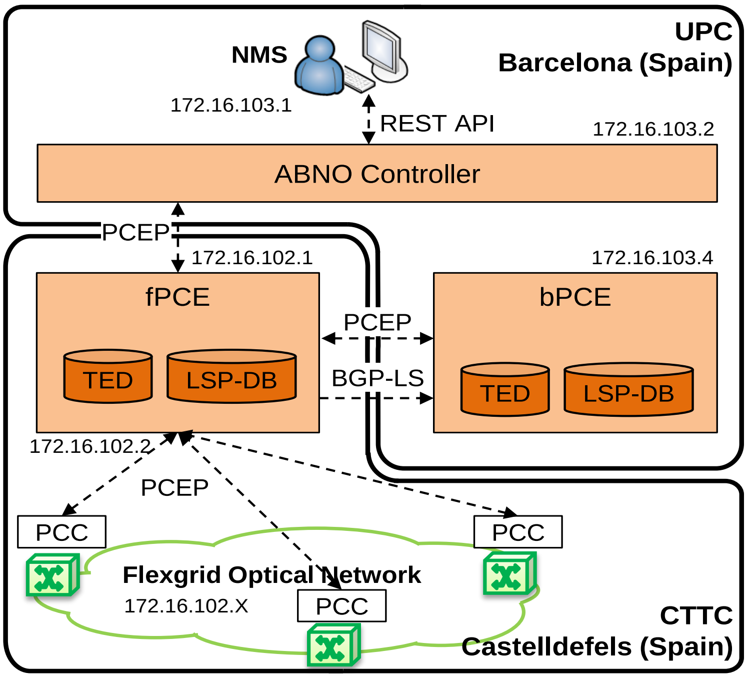


Figure 50: Control and management architecture.

4.4.3 Multicast connectivity provisioning for Ethernet services

Two approaches were proposed in D1.5 to serve large capacity (e.g. 100 Gb/s) multicast connectivity services in a multi-layer scenario where a set of federated DCs is connected through a flexgrid optical network. In the first approach, a VNT was created for each multicast request by establishing light-trees in the flexgrid network. In the second approach, multicast services are served on a multi-purpose VNT supported by 400 Gb/s lightpaths, thus favouring resource utilization. The feasibility of implementing both approaches using standardized control plane protocols was studied in WP4.

Experimental assessment was carried out in the distributed field trial set-up depicted in Figure 51.

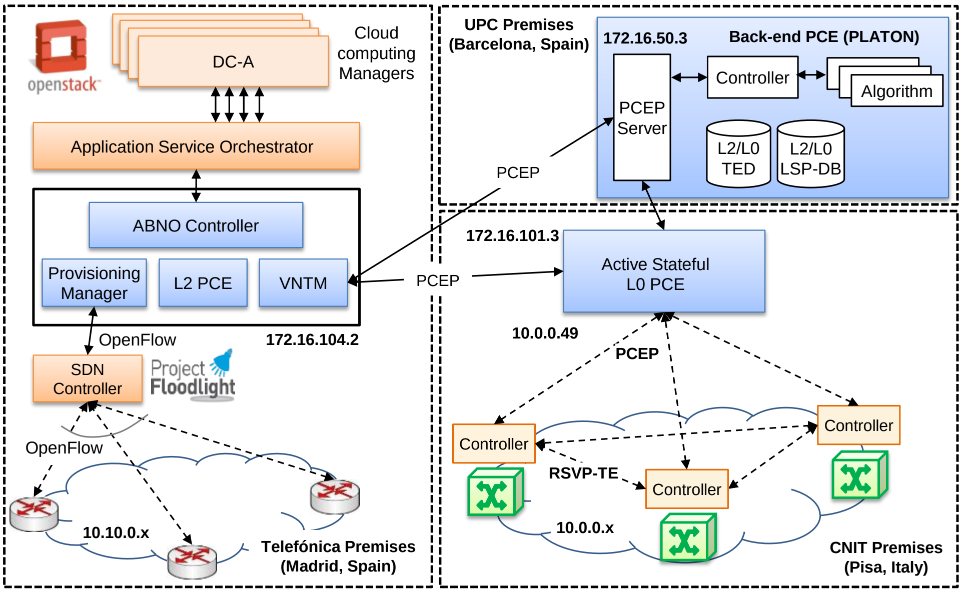


Figure 51: Distributed test-bed set-up. IP addresses are shown.

4.5 Relations between Use cases and Building blocks

Table 13 reported in this subsection points out the relations between the use cases presented in Section 3 and the set of building blocks identified as significant IDEALIST solution items. A similar table, in which only the use cases having a relevance in practical experiments performed in WP4 (called “Experimental use cases”) are present, takes also part of D4.4 [54] as Table 1.

There is a one to one correspondence between the use case descriptions reported in sub subsections of Section 3.2 and use cases present in Table 13, with only two exceptions: the first, “Resource allocation in EON including large scale problems”, which combines the cases reported in 3.2.1 and 3.2.2 and the use case named “Sliceability to cope growth and uncertainty in traffic demand”, which includes use cases reported in 3.7.1 and 3.7.2.

Concerning the **Building blocks (BB),** which are identified within the project as significant IDEALIST solutions in specific application scopes, they are briefly described here below.

Algorithm suite. The BB includes all the algorithms developed in IDEALIST, including off-line algorithms for architectural and network planning and dimensioning studies, and on-line algorithms for applications in network operation. Some of them are included in the Planning tool (e. g. SPRING and AFRO algorithms) or in control plane prototypes (e.g. the novel on-line Routing, Spectrum, and Modulation Assignment (RSMA) algorithm to dynamically configure Flex-grid paths between two remote MF-OTPs/S-BVTs, serving LSP demands). Algorithms to be put inside data plane systems are also developed in WP2, for instance algorithms used in DSP for nonlinear pre-distortion of transmitted signals with the objective of increase significantly the system performance (see experiment E9 in D4.4 [54]).

Performance metrics for network modelling and experiments. The BB includes models and methodology for cost, energy, transmission performance evaluations, merit functions (for instance the “Entropy” for multi fiber design or the figure of merit defined to measure the node complexity) and also metrics used in experiments as BER, setup time, transmission rate, spectral efficiency and others.

Planning tools. Tool developed for off-line analysis and planning of an EON network, but also usable on line as back-end PCE (aiding for example an operational networks in spectrum defragmentation or re-optimization after link repairs). They include as SW components a subset of the above mentioned Algorithm suite.

BVT and S-BVT. Transmission devices as modelled by WP2.

Elastic OTN grooming. Additional functionalities required on equipment to adapt heterogeneous clients (e. g. 10GE or 40G ODU3) to the flows handled by a BVT or a S-BVT (e. g. in the OTN framework multiples of OTU4 or OTU-Cn).

Flexgrid ROADM and BV-OXC. ROADMs and other optical switching nodes able to handle the spectrum according to the ITU-T G.694.1 recommendation for spectral flexible grid usage.

GMPLS and OFP extensions for flexgrid. Implementation of GMPLS protocol extension aimed at enabling the routing of optical connections and the resource allocation according to the ITU-T G.694.1 recommendation for spectral flexible grid usage. OpenFlow protocol (OFP) extensions are also implemented as an alternative to the use of the GMPLS control plane by using a centralized SDN controller managing several SDN agents.

Network orchestrator (ABNO). Implementation of the ABNO architecture for the multi layer and multi domain orchestration. The ABNO Controller is responsible for orchestrating and invoking the necessary components in the right order. It listens for requests from the NMS/OSS (of both types, GMPLS and SDN) and selects the appropriate workflow to satisfy each request in the right sequence.

Table 13: Associations between IDEALIST Building blocks and Use cases considered in WP1.

	IDEALIST Building Blocks							
Use cases	Algorithm suite (off-line and on-line)	Performance metrics for network modeling and experiments	Planning Tools	BVT and S-BVT	Elastic OTN grooming	flexgrid ROADM and BV-OXC	GMPLS and OFP extensions for flexgrid	Network orchestrator (ABNO)
Resource allocation in EON including large scale problems	X	X		X		X	X	X (*)
Multi period planning	X	X		X		X	X	
EON Design using Maximum Entropy Optimization	X	X		X		X	X	
Restoration after fiber breaks	X	X		X		X	X	X (*)
Multi-path recovery	X	X		X		X	X	X (*)
Optical restoration in IP networks	X			X		X	X	X (*)
OTN grooming (electrical only and over optical)	X			X	X	X		
IP over optical planning	[X]	X	X	X		X	X	X(**)
IP over optical control			X	X		X	X	X(**)
Dynamic provisioning including DC interconnection	[X]	X	X			X	X	X(*)
Dynamic defragmentation and re-optimization	[X]	X	X	X		X	X	X(*)
Dynamic re-optimization after link failure repairs	[X]	X	X	X		X	X	X(*)
Energy aware planning	X	X		X		X		
Energy saving from OTN grooming	X	X		X	X	X		
Sliceability to cope growth and uncertainty in traffic demand	[X]	X	X	X		X	X	X(*)
Sliceability in multi path restoration	[X]		X	X		X	X	X(*)
Sliceability in multicast	[X]		X	X		X	X	X(*)

(*) Multivendor optical domains

(**) Multivendor IP and optical domains

In Table 13 when a Use case can be performed with a **Planning tool**, the same Use case could also be performed by the **Algorithm suite,** if the aim is a study for evaluating the behaviour and the performances of a given algorithm in a certain network scenario. The cross put within square brackets [X] indicates that situation. It must be said that a Planning tool can operate on-line and interacting with the control plane (for instance as back-end PCE) while standalone algorithms cannot do it.

On the other hand the **Algorithm suite** includes a wider set of algorithms in comparison the set of ones included in the **Planning tools**. Some advanced research algorithms not already incorporated in a planning tool are used for specific studies (for example the algorithms for the Use cases “Multi-period planning” or “EON Design using Maximum Entropy Optimization”).

5 When - Migration strategies

This main objective of this section is to present the project vision on possible deployment roadmaps of EON technologies introduction (i. e. the IDEALIST solutions, or building blocks, presented in Section 4) having as a reference the short and mid-term time horizons. Different migration strategies starting from a known legacy will be depicted, considering both different legacies and strategies that operators could apply in upgrading their optical networks. An outlook to long term solutions, for which predictions on evolutionary steps are harder to envisage, is also attempted.

5.1 Introduction

5.1.1 State of the art of optical transport networks in core and metro-core segment

Typical core optical transport networks for the operators in Europe are today normally characterized by fixed grid ROADM based on WSS, transponders and muxponders with rate up to 100 Gb/s based on coherent reception. Links between optical nodes are made by uncompensated fibers forming a meshed topology with an average connectivity degree in the range from 2.5 to 4. Preeminent type of fiber is G.652 (SSMF) (DT, BT, TID), even G.655 (NZDF) and G.653 are also present in some contexts, with mixed cases possible (TI). A description of a sample of National and European continental networks is given in deliverable D1.1 of IDEALIST project [9].

In the field, ROADMs today are normally of the fixed grid type (based on MEMS or LCoS technologies) but there are cases in which equipment is made by BV-WSS, based on LCoS technology, are already deployed. In these cases the data plane of the network, even if it not yet used with as flexible grid network for lacking of BVTs, is ready for switching channels requiring bandwidth slices other than standard 50 GHz. In these cases a proper upgrade of the control plane will be also necessary to handle the routing and allocation according to flexgrid framework when BVTs will want to be introduced.

100 Gb/s DP-QPSK (SD-FEC) are the typical higher performance transponders in most of the situations, while 200 Gb/s DP-16QAM single carrier or DP-QPSK double carrier (the last choice implies optical channels made by two wavelengths and require BV-WSS based ROADM) have become to be deployed in few cases. Due to the reach performances of DP-QPSK (especially the last generation relying on SD FEC and 32 Gbaud symbol rate) in national European networks almost all the demands can be carried without regeneration since little or no traffic has to be routed over distances longer than 1000 km. In continental networks (e. g. pan European networks), where end to end distances are longer than 1000 km for a significant fraction of demands, regeneration is quite commonly required.

Integration with higher layers, e.g. OTN or IP, is in general not made and the optical layer acts as the serving layer of OTN or directly of IP. In this case, long-reach optical signals loaded with 100 Gb/s content are generated by transponders external to IP routers. However, there are already a few technical solutions on the market where those optical signals are generated by so-called coloured interfaces directly plugged into packet equipment. In this case, digital signal processing, e.g. FEC, is located at the router line card. The router is also responsible for e.g. tuning the interfaces' lasers to the right wavelength. Hence, a close coupling of the IP and optical control planes is mandatory. From an architectural perspective both solutions, i.e. the transponder and the coloured interface solutions, are equivalent. Even multi-layer resilience can be accomplished by both solutions.

The control plane in today's implementation is based on the GMPLS protocol suite. Optical restoration is used as a resilience mechanism for a connection after the first optical failure, or after the second and subsequent failures, in case of protected circuits. When considering potential failures on multiple layers, a coordinated multi-layer recovery is required involving reactions on all impacted layers [55].

Concerning the metro-core segment the panorama is broader than in the core. The Metro-Core ranges from networks covering wide regional areas, which have characteristics similar to a core network of a small country (wide area, medium traffic requirement), to networks covering a city or a part of a city with low requirements in terms of traffic (small area, small traffic requirements), to networks covering big highly dense populated cities in developed countries or highly demanding ITC and cloud DC areas (small areas and high traffic). Even in terms of technologies there are a broader range of cases than in the case of the core. Normally topologies are rings and WDM systems are often still of the non-coherent type with 10 Gbit/s or 40 Gbit/s as maximum rates. In some particular cases coherent 100 Gb/s is already present, for instance where high capacity connectivity is needed to interconnect DCs themselves or, towards gateways, to the core. Coexistence of non-coherent 10 and 40 Gb/s with coherent 40 Gb/s over a dispersion compensated fiber infrastructure are also an option, but it is rather uncommon. In the metro-core segment, due to the wider range of starting situations and because there is a greater uncertainty about future network requirements and structure, the paths of development and migration are more difficult to plot.

5.1.2 Target networks for short and mid term

In the two time horizons considered, short term (2018) and mid-term (2021), target networks for the Core take into account: i) the needs for traffic growth, ii) the expected increase in client interfaces rates and iii) the emerging requirements for flexibility and dynamicity.

From the Data Plane perspective the objective for the short term is to have ready in the core networks the full functionalities of flexible grid switching and a number of flexible bandwidth transponders (possibly sliceable) with up to 400 Gb/s of total capacity. The types of (S)-BVTs which have been considered by the WP2 as the most probable are presented in Table 6.

Improvement in spectrum switching between short term and mid-term will be expected in both AD modules that, to avoid spectrum contention, will be extensively installed in CDC option (lower prices than today are foreseeable) and with likely (but not certain) better filtering performances of BV-WSS. However, investment in spectrum switching (flexgrid ROADMs) must be preserved throughout the period until 2021, so later installations must be compatible with the previous ones to assure the payback of all investments made.

In the period between now and 2018, flex rate transponders (for example BV_200G_1L of Table 6), in addition to 100 Gb/s and 200 Gb/s fixed rate transponders, will be introduced. At the first milestone (2018) the BVT at 400 Gb/s (SBV_400G_4L of Table 6) will to be ready and introduced to serve 400 Gb/s client flows or multiple lower rate flows relying on client side muxponder arrangement (4x100G or 2x200G). Deployment of 400 Gb/s (S)-BVT will continue up to mid-term time avoiding as much as possible the installation of other lower rate transponders and exploiting the muxponder functionality for carrying 100 and 200 Gb/s circuits. This because a foremost part number ready to accommodate the largest number of demands allows achieving savings in spare parts and simplifies the operations of provisioning and maintenance.

At mid-term (2021) the market will be ready for 1 and 1.2 Tb/s S-BVT transponders and, starting from here, the deployment have to be done taking into account the flexibility of these devices in accepting demands at different rates and with different reach requirements. As for BVT in short term, in these case the S-BVT will be the dominant part numbers in the new transponder installation, and installations will have to pay attention to the choice of the model (400 Gb/s, 1.2 Gb/s or a mix of both) which maximizes the average utilization during the entire lifecycle of the system.

Multi-layer network operation done by flex-rate transponders

In the short-term horizon, flex-rate interfaces are fully under control of the optical transport network supporting the IP layer (either as coloured interface in the router or as separate transponders). In this scenario, the interfaces are utilized in a static way, i.e. adaptation induced by dynamics stemming from network failures are not considered here. The main benefit from flex-rate interfaces then comes from:

- the optimization of the line rate through the setting of the modulation constellation depending on the actual OSNR on the working path, i.e. a static lightpath [56] and
- less stockholding costs due to the application of a single device only.

At the mid-term flexrate interfaces are also used in a dynamic way. In this case, they are accessible by the IP routers or a respective instantiation of an SDN orchestrator connected to a vendor-specific network controller. Benefit comes from the dynamic adaptation of modulation constellation in case it is needed, e.g. if after an optical failure the restored backup path exceeds the limits of the previously selected modulation format [22]. The still challenging part of this use case is the dynamic adaption of the load balancing mechanisms at the IP layer.

Control Plane

As for Control plane, the innovations will be introduced gradually in order to migrate towards a fully transport SDN architecture.

In the first step (2018) the CP of vendor solutions will be opened to interact with an orchestrator for a first coordination between different vendors and among layers. The project thinks that is not realistic to assume a scenario in which ROADM and BVT of different vendors coexist in the same network domain, nevertheless within this timeframe different domains could be coordinated by a kind of orchestration, even if not yet fully compliant with the ABNO framework.

In the meanwhile the process of standardization of Control plane aspects including Application-based Network Operations (ABNO) will be completed and followed by vendors in their implementations. In this field the project worked intensively within IETF achieving some RFC publications. In particular RFCs titled “Path Computation Element Architecture” (RFC 7399), “PCE-based Architecture for Application-based Network Operations” (RFC 7491) and “Framework for GMPLS based control of Flexi-grid DWDM networks” (currently a draft, but RFC is imminent) have been published with the support of the project. Other drafts (“Generalized Labels for the Flexi-Grid in LSC Label Switching Routers”, “RSVP-TE Signalling Extensions in support of Flexible Grid”, GMPLS OSPF-TE Extensions for Flexible Grid DWDM Networks”) are under the approval process in IETF with an high probability to become RFC in next months.

In the second step (2021) a higher level of interoperability between network layers and domains is expected. WP3 and WP4 demonstrate that great achievements are possible in this field. In particular the adoption of the ABNO as a framework for coordinating the SDN controllers of IP/MPLS and the optical layers on an application base is widely supported within the project, although there is awareness that it involves further work on standardization and implementation of the subparts and their interactions to make possible to put on the field the complete general architecture. In addition the usual propensity of some players (vendors but also operators called to interoperate each other) to keep closed their systems have to be overcome.

5.2 Short and mid-term network deployment

5.2.1 Previous works on migration strategies.

The migration towards flexible grid networks has been recently addressed in some works. Among them [57] is the first work done when the EON concept was at the very beginning, and presents the problem of introduction of flexible grid network starting from existing fixed grid technology. Three strategy options are defined, ranging from a conservative approach which postpones as much as possible the introduction of the flexible technologies, to an intermediate one, which sees early flexgrid ROADM installation but delays the deployment of elastic transponders, to a most aggressive one which introduces flexibility from the beginning for both ROADMs and transponders. The conclusion of the work is that the optimum solution depends strongly on crucial factors as: traffic evolution, equipment cost evolution and potential loss of revenues in case, at the time traffic demand will come, equipment will not be ready because its deployment has been deferred.

Paper [58], extended in [60], present the problem of an optimal migration in terms of a gradual replacement of fixed-grid nodes with newer ones having flexgrid functionality. Some strategies to create flexible grid node islands (single or multiple), and extend them towards a full flexgrid network, are proposed. Strategies involve properties such as nodal degree, terminated traffic on node, transiting traffic on node (and others variants of the last two) as a ranking criterion to select the fixed grid nodes to be upgraded to flexgrid. Optimality is evaluated in terms of Bandwidth Blocking Probability (BBP, defined as the rejected bandwidth over the total bandwidth). Paper [58] considers increasing offered traffic on BBP evaluation for a limited number of strategies, while [60] extends the number of strategies and to other network scenarios, but takes the traffic volume constant. Both works evaluate the optimality (i. e. BBP) varying the flexgrid island creation strategy, the traffic profile and the traffic distribution.

Results of both works [58] end [60] show that, according to the criterion chosen for the optimality assessment, the introduction even only of a limited number of flexgrid nodes in the network can bring significant benefits if the upgrade strategy is the right one. In addition, the migration from fix to flexgrid network strongly depends on traffic profile (circuit rate mix) and traffic distribution, and therefore case by case analysis has to be performed. In the scenarios considered, the highest carried traffic first (HCTF: meaning that nodes that carry the most traffic, terminated and in transit, will be upgraded first) strategy outperforms the others and can be considered the recommended one in lack of specific and deep analysis.

In [59] the problem of the gradual process for migration from flex to fix grid is analyzed. A focus on drivers for migration and a flow chart of the migration process involving Management system, Planning requirements, Planning tool and Deployment in a closed loop process are presented. This work makes an overview on the state of the art of planning and optimization techniques that, given the complexity of the problem of hybrid fix-flex grid optical networks in an evolutionary context, are particularly challenging. Some exact methods based on tailored decomposition techniques (Column generation, Lagreangean relaxation, Bender decomposition) are mentioned together heuristics (Genetic Algorithms) which maintain a strategic role in finding fast upper bound used to provide good starting points to speed up ILP algorithms.

Works [57], [58], [59] and [60] summarized above are commendable from a general viewpoint, but they do not take into account some of the most important aspects to be considered in the deployment of real networks by operators. These aspects are the overall cost of the network, the equipment compatibility for the interworking and the impairment issue. All these aspects are strictly interrelated.

The cost issue involves a cost model (CAPEX and OPEX) for the comparison of the cost of the deployment of a flexgrid network from greenfield (beside and in parallel with the fixgrid existent network) and the cost of a network which implement the migration from fixgrid to flexgrid in a hybrid network. This is because the interworking in a hybrid network implies extra costs (for instance HW and SW upgrades on fixed grid nodes to made them compatible with newer flexgrid ones) and non-optimality implications. In addition the transparent crossing by a wavelength of fixgrid and flexgrid areas involve compatible optical parameters and can cause penalty in reach as a consequence: this can have an implication on cost as well.

The interworking issues involve the feasibility to make possible the coexistence of old fixgrid node with new flexgrid nodes from both data plane and control plane viewpoints. Data plane compatibility means avoidance of the need for an OEO conversion in fix-flex technology domain crossing. Control Plane compatibility means the possibility to maintain routing and allocation of a connection under the supervision of the same unified Control Plane.

Operator’s experience teaches that it is very difficult to make compatible and inter-networkable optical equipment from the same vendor belonging to different technology generations. In addition it is also very difficult, if not impossible, make compatible optical equipment among different vendors, even within the same technology generation. In the extremely challenging scenario of different generation (fix and flex) and different vendor (one vendor for fix and another vendor for flex) the practicability of a migration strategy in the hybrid fix and flexgrid context requires much more than a purely functional and technical evaluation. Moreover, different vendors for different technology generations equipment can be a necessity for an operator. This is because the best choice (i. e. the lower cost alternative fulfilling assigned technical requirements) has to be performed, normally by a tender, on any significant network upgrade.

Impairment issue involves the optical domain and in particular the deterioration of an optical signal in crossing many network elements as BV-WSS, MCS, Optical Amplifiers, Dynamic Gain Equalizers and fibers.

The concept of Black Link (BL), which was born to establish the full interoperability by different vendors in optical networks primarily intended in metro applications, has materialised in an ITU-T Recommendation [61] which is limited to non-coherent 10 Gb/s (standardization for 40 Gb/s is still ongoing but given the loss of interest for this interface probably it will not be finalized). It is a matter of fact that Elastic BL (EBL), which is an extended version of BL aimed to EONs for coherent 100 Gb/s and beyond, still remains a long-term goal [62].

Since there is no standardization ready for the data plane interoperability of long-haul DWDM transponders, it is very difficult to envisage in the near future the feasibility of optical transmission over an optical network made by different vendors and, to some extent, also towards technology generations.

As a consequence, also from this last point of view, the practicability of migration from fix to flexgrid in a hybrid environment is limited to the restricted and high risk case (for an operator) of a unique equipment provider committed to assure the compatibility among subsequent technology generations of equipment.

5.2.2 EON deployment strategies

Two options for handling the coexistence of fixed and flexgrid, depending on specific operator legacy and strategy, are presented in the following. The deployment roadmap options presented hereafter are two general schemes summarizing two possible strategies: they do not reflect any specific operator deployment plan. Deliverable D6.4 [63] gives an outlook of the project exploitation plans of the industrial partners and in particular the deliverable includes specific sections illustrating the EON deployment roadmaps of each operator.

A first option assumes starting from legacy in which the existing fixed grid network is implemented with equipment that can be easily integrated with newer flexgrid equipment and the operator opts for a gradual upgrade of the initial network. The typical case evolves from a deployed network made by LCoS flexgrid equipment which makes the Data Plane ready for EON. At the beginning all the installed transponders fit in the standard DWDM 50GHz grid and the Control Plane doesn't have the functionalities suitable to support EONs.

This option is depicted in Figure 52 where an evolutionary roadmap is shown. The operator expects static or semi-static traffic until 2018. In this scenario network dynamics are exclusively induced by network failures and the corresponding recovery. While some parts of the infrastructure technology, especially in the core, are already flexgrid ready today, the deployment of bandwidth-variable transponders (BVT) will last until 2016 (step1). Earliest BVT adoptions are expected to support coarse rate adaptations by selection of multiple modulation formats, such as DP-BPSK, DP-QPSK, DP-8QAM and DP-16QAM constellations.

In 2017/2018 (step 2) the share of BVTs and flexgrid ROADM technology in the network increases. A massive introduction of BVTs in which the transceiver can be dynamically tuned to use different modulation formats – ensuring each path uses the most data per transceiver that is possible given by the path OSNR is expected. We also expect to see actual use of flexgrid in the core – to give more spectrally efficient operation and also the introduction of an EON-capable control plane that allows full management of both flexrate and flexgrid functions in isolated domains.

In 2019/2020 (step 3), fueled by the tremendous traffic growth induced by cloud networking and new data center services, the optical network has to cope with natively dynamic traffic patterns. Consequently, fine-granular BVTs might be available (e.g. implemented by the application of time-domain hybrid modulation formats [19]). At the same time, sliceable BVTs might be available for addressing multiple flow destinations by a single transponder module. Furthermore, flexgrid technology extends for the first time from the core down to metro networks. Around this time, the existing, legacy fixed-grid network, will be dismantled. The ABNO architecture is the chosen framework for orchestration of the control planes active in different network domains, i.e. an "ABNO compliant" orchestrator coordinates a set of EON-aware control planes, potentially comprising "flexgrid enhanced" GMPLS control planes, but also early SDN-Open flow ones. In any case the EON control planes are expected to be predominantly vendor-specific and serve to shield the transport complexity from the orchestrator.

In step 4, the share of S-BVTs increases. Flexgrid ROADM becomes more and more the state-of-the-art commodity technology even in the metro. Evolution of control plane with the introduction of an SDN paradigm allowing enhanced multilayer functions such as IP over EON. Potentially, EON SDN control planes that will be dominant might still coexist with some residual GMPLS-based ones. At this step we will have the full flexgrid implementation.

Even though still highly speculative, a further potential migration step towards the long-term EON-everywhere goal might be the introduction of flexgrid technology even in the fiber-based access network. Finally, any new type of elastic transponder technology or next-generation network control/orchestration might appear in 2023 and beyond.

It is important to note that the evolutionary deployment roadmap option actively avoids the introduction of new fiber types, often labelled as "spatial division multiplexing" (SDM), as well any kind of "architecture-on-demand" node architecture. Those kinds of future technology can be realistically postponed until 2025 or beyond.

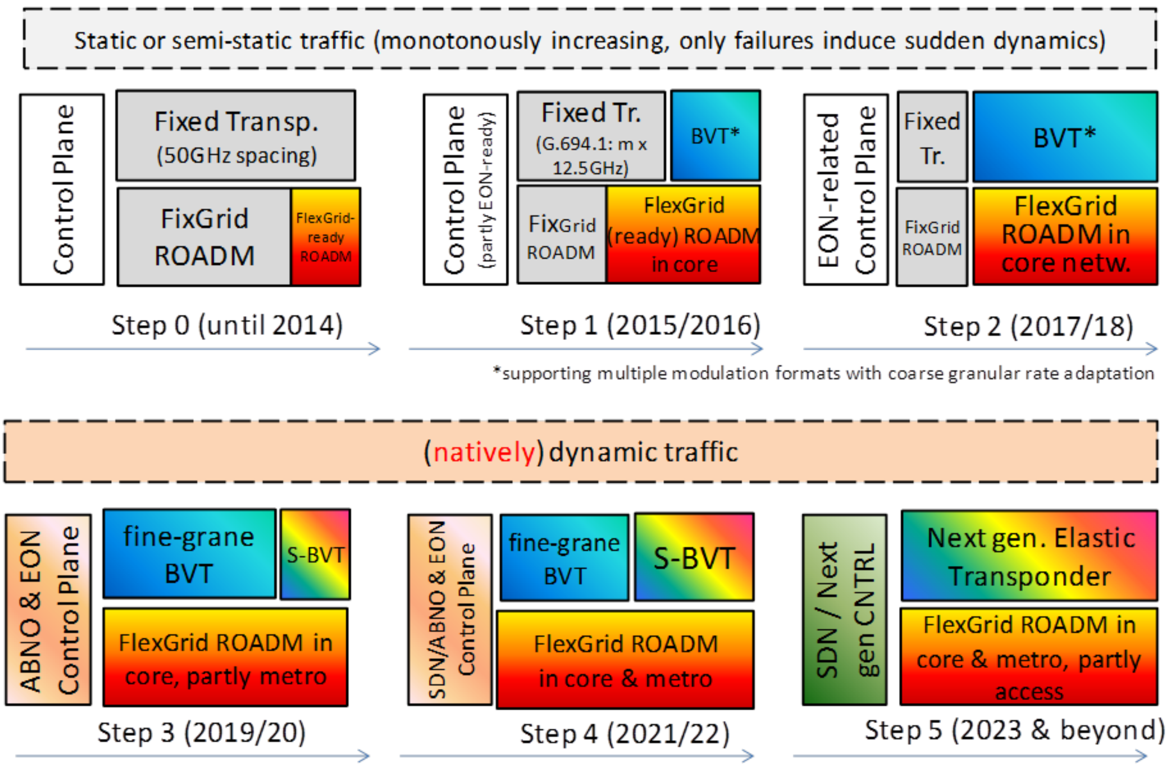


Figure 52: Evolutionary deployment roadmap for a gradually smooth migration.

The second option assumes that the operator cannot, or doesn't want to implement a gradual migration of the network. In this case the operator follows the strategy of deploying the new flexgrid network from greenfield and will operate the new network in parallel with the separate legacy fixed grid network for a certain period of time.

This option for the backbone long distance core networks is depicted in Figure 53.

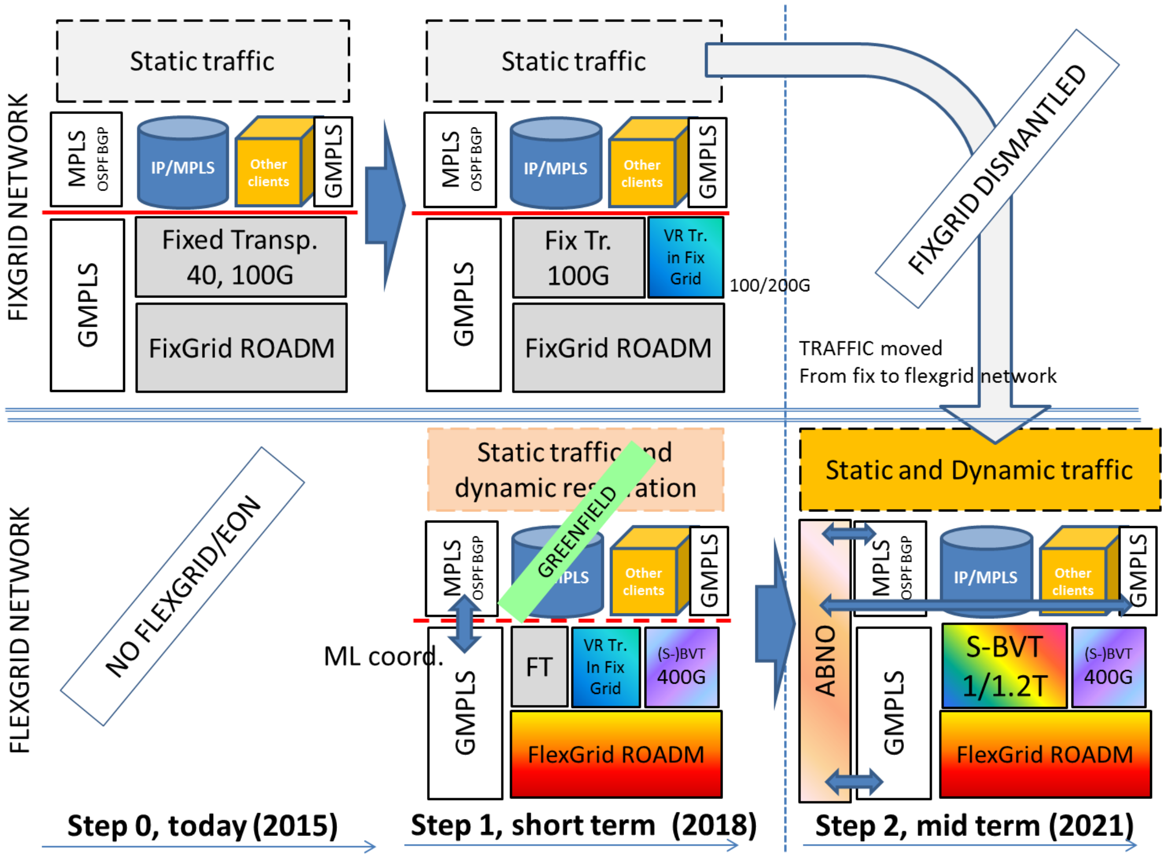


Figure 53: Evolutionary deployment roadmap for introducing flexgrid from greenfield in the backbone.

In the Backbone networks, the existing fixed grid network at step 0 (2015) will survive beyond step 1 without integration with EON technologies; it will continue to accept connections at 100 Gb/s rates (possibly 200 Gb/s in 50 GHz for short distances) up to its saturation.

In step 1 (2018) a new first release of an EON will be operated alongside the fixed grid network. The new flexgrid network will have flexgrid ROADMs using BV-WSS, bandwidth variable transponders up to 400 Gb/s (possibly sliceable) and a GMPLS control plane. Dynamicity is expected to be limited to restoration mechanisms. An interaction with IP/MPLS is expected even though it will not probably be a full coordination of the control planes (GMPLS of EON and MPLS/OSPF-BGP of IP) by an orchestrator. From step 1 new demands will be accommodated on the new EON.

Starting from step 1, there will be a transfer of traffic from the fixed grid network to the new EON network and the fixed grid network will be dismantled before step 2 (2021).

In step 2, the EON will be enhanced with new functionalities like: higher transponder rates (1 and 1.2 Tb/s of total clients' rate, sliceable), introduction of an ABNO-compliant orchestrator for a full integration of control planes of the optical layer with the IP layer and other client layer networks (OTN), enhancing the multi-layer mechanisms and enabling dynamic services at the optical layer (variable bandwidth and variable destination services). At this time the control plane could be either GMPLS or SDN (in the figure

GMPLS is represented), depending on the evolution and also on choice of vendor. The orchestrator will be able to coordinate both types, as well as in a heterogeneous scenario. At this time (or shortly after) the backbone fixed grid network will be dismantled, having completed its lifecycle (8 years at least). At step 2 all the traffic yet present on the fixed grid network will be moved to the flexible network.

A possible evolution for deployment in the metro-core segment is shown in Figure 54. The evolution starts from today's common fixed grid WDM networks characterized by ring topology, chromatic dispersion compensated fibers, and non-coherent transponders with rates up to 10 Gb/s (non-coherent 40Gb/s has also been introduced but without a significant penetration for technical and cost reasons). EON is expected to be introduced only in the mid-term and not extensively, but only in some very demanding metro areas (huge cities in developed countries or areas with a very dense presence of DC or Content Delivery Network PoPs). This hypothesis is supported by traffic predictions because, as shown in [64], in the short term (2018) the 100 Gb/s interfaces in the metro core will be enough to carry the traffic in the most demanding metro networks. In the mid-term we expect that some high demanding areas will require both interfaces with capacity higher than 100 Gb/s and flexibility, and this is the reason why EON is introduced as a separate option in the evolutionary roadmap of Figure 54. The majority of other metro-core networks will probably continue to rely on fixed grid nodes, benefiting only from the evolution of flexrate transponder features (higher rates, higher spectral efficiency).

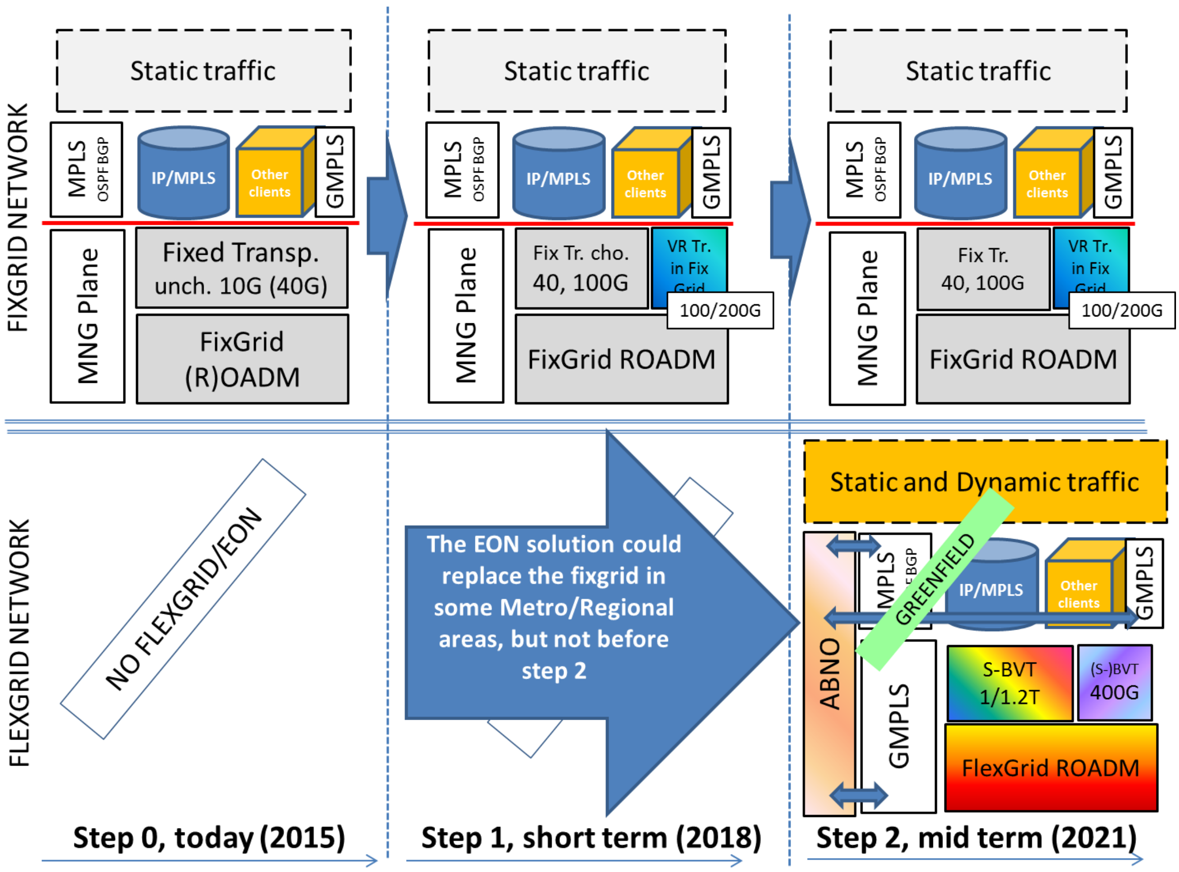


Figure 54: Evolutionary deployment roadmap for introducing flexgrid from greenfield in the metro core.

5.3 Extension to long term perspectives

The IDEALIST project, as is entirely appropriate for a large project such as this, has looked at the full range of time periods for technology deployment, from short to very long term. For shorter and medium range technologies, it is always possible to draw roadmaps as shown in the previous section and although there is no certainty that things will evolve like this, there is still a level of predictability to it.

When it comes to the much longer term, this becomes impossible to do. IDEALIST has researched very forward looking concepts – in particular the SERANO node and Architecture on Demand. Both of these approaches are predicated on huge volumes of traffic and / or large levels of dynamicity – and networks are many years away from seeing these conditions.

Therefore it isn't appropriate to include them in the same roadmap diagrams shown above. Instead we describe more qualitatively how networks might evolve in the direction of SERANO and AoD.

IDEALIST has modelled the key transition – i.e. when EONs move from being single fibre pair per link to adding multiple pairs of fibres per link. This modelling has shown the fascinating characteristic of networks – that they have hot spots nearer the centre, where much of the traffic has to transit. This implies that networks consist of links with a wide range of traffic volumes on them. Links nearer the network edge will just have traffic from the edge nodes, whereas links in the centre will carry all the transit traffic as well as that which is headed for nearby nodes. This inevitable network behaviour has important implications:

In the past, when an optical fibre link in the network centre became full, it was generally the right time to invest in a new technology – overbuilding with parallel fibres using the same technology rarely made sense because technology had moved on in the intervening years. This situation is now changing because of the IDEALIST technologies developed for EONs. With these newly proposed BVTs, we are seeing the ultimate limits of spectral efficiency being approached. Once we have done this, we then see an evolution towards super-channels, in which multiple sub-channels (which are tuned to be as closed to the spectral efficiency limit as possible for the given optical path) are added together to form a larger spectral unit. This new super-channel unit is not any more spectrally efficient – rather it is a way to efficiently pack together sub-channels.

In this new EON environment, we expect that fibre links towards the network centre, will start to fill up. Once they do, we don't expect to see a repeat of the past – in which the entire network technology is discarded as obsolete and a new technology installed in its place. Instead we expect to see these central links take advantage of parallel fibre over-build. Indeed, our modelling in IDEALIST has shown benefits in some situations for multiple fibres pairs in the central parts of the network, with only one fibre pair used for linking edge nodes.

This is a new operating paradigm and is one that emerges with high traffic volumes in EONs. How does the network continue to evolve in this situation? There are several key points to make here:

- A multiple parallel fiber paradigm is generally referred to as Spatial Division Multiplexing (SDM). This is often assumed to imply the use of multiple core fibers. It is unlikely that operators will consider installing very advanced fiber types, but many of the concepts being developed around SDM will still apply (such as multi-mode amplifiers, MIMO techniques to couple super-channels across fibres etc.)

- The conventional ROADM approach of interconnected WSS will need to be modified to allow fiber bypass. This is in essence changing the node architecture and precisely what is being proposed in IDEALIST for the AoD concept. In other words – AoD begins to become highly relevant in multi-fibre operation.
- The extension of the node beyond conventional ROADMs also brings in concepts such as SERANO. This is particularly the case as the network becomes flatter and higher numbers of nodes are optically interconnected.

It is difficult to put timescales on when these technologies will be required as it depends on year-on-year exponential traffic growth for the next 5 years and beyond.

6 Conclusions

A significant amount of research has been done in the IDEALIST project on the topic of Elastic Optical Networks as proven by the numerous publications on high impact journals, presentations at top level conferences and by contributions to standardization bodies. The complete list of the research articles and contributions to standards can be found in a specific public web page of the project [65].

The benefits of EON have been extensively demonstrated in WP1 by a rich set of use cases. In particular the three main attributes of EON, namely flexibility in bit rate (flexrate), flexibility in optical bandwidth allocation (flexgrid) and flexibility in generating different flows (sliceability), can definitely bring functional and economic advantages when they are introduced in an optical network.

These advantages, proven even in the solely optical layer, are amplified when the interworking of the optical layer with the IP layer is optimized, for instance by means of optical shortcuts of IP traffic or activating multilayer resilience mechanisms. These advantages will be even more emphasized in the foreseeable future by high dynamic and uncertain traffic patterns as expected in the coming years, where the flexibility offered by EONs will be fully exploited.

In this perspective the evolution of the control and management planes according to protocol upgrades (extensions of GMPLS for flexgrid) and the SDN paradigm makes possible an effective integration of the networks, both horizontally (among domains of the optical layer) and vertically (between IP and optical layer). The use of an orchestrator on top of optical domain controllers will enable the integration and IDEALIST believes that the ABNO model might be a suitable framework for this purpose. Significant results have been achieved by WP3 in this area, with a rich set of implementations and experimental activities, and also thanks to an active participation in the IETF with some draft proposals approved as RFCs.

The various aspects of EON implementation have been categorized as building blocks. These building blocks constitute an important output of the project and include physical layer components (i.e. BVT or S-BVT as modeled and prototyped by WP2), but also algorithms, methods, planning tools and GMPLS and SDN control software. For instance, one of these building blocks includes a planning tool named PLATON which incorporates, in addition to other SW parts, many algorithms: e.g. it can be used for off-line network analysis and planning, as well as acting as on-line back-end PCE thanks to its communication module. These building blocks are the macro elements used for defining the tests for the successful project experimentations coordinated by WP4 [66].

The roadmaps describing network migration from today's DWDM to future EON, envisage the deployment of BVT (possibly S-BVT) at 400 Gb/s soon (in short term, roughly 2018) and (S)-BVT at 1 or 1.2 Tb/s in the mid-term (roughly 2021). In this timeframe the basic architecture of optical switches are expected to remain substantially the ones available today. The ROADMs based on bandwidth-variable WSS are expected to have cheaper contentionless add and drop functionalities and to improve also in filtering performance (but this last aspect not before the mid-term). The control plane is also likely to evolve gradually with a first introduction of an intra and inter layer orchestration of management and control and then, in the mid-term, the introduction of open interfaces and common information models according to the SDN paradigm.

Depending on the specific legacies and on the strategy an operator plans to apply, deployments of networks could follow a smooth upgrade from an existent infrastructure or could follow a greenfield approach for EON implementation, with the co-existence of fixed grid and flexgrid optical infrastructures for a given period of time.

The challenge for the future involves the overcoming of the conventional paradigm which assumes the optical network to be a passive and static (or semi-static) capacity provider for upper layers. IDEALIST demonstrated that the optical networks of the future can be elastic and dynamic but, even though the enabling data plane solutions have been shown to be attainable, the potential benefits and the full success of EONs will be achieved only with a keen interworking between network domains and with a tight integration with the upper (IP) layer.

The next steps in the direction of further research in this field involve the impact of the requirements of new fixed and mobile networks, no longer seen as separate but converging to a single entity. The focus will shift from the core to the metro segment, where both changes in the network architecture and higher traffic growth rate are expected. Traffic from mobile terminals, today characterized by a rather low share of total traffic (about 20%), are expected to grow significantly with the advent of 5G and traffic distributions will become potentially more nomadic and unpredictable. At the same time higher residential fixed access rates (100 Mb/s and beyond) will enable very high definition video services, generating a huge amount of traffic. Cloud Data Centers, Content Delivery Networks and Big Data could emerge as new players driving the requirement for elastic optical networks as an attractive and cost effective communications medium.