IDEALIST: Exploitation Plan

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1 Introduction

1.1 Purpose and Scope

This report provides an overview of the exploitation and commercialization routes for the work emerging from the IDEALIST project over its three years duration. The resulting technology solutions are assigned into five categories: Planning Tools, the Control Plane and SDN, Advanced Transmission techniques, the Metro Border Node, and the Data Plane. Start-of-the-art commercial solutions are proposed to exploit the resulting IDEALIST technologies in the short term, whilst pre-commercial products are also identified. Individual exploitation plans of the industrial partners are presented, and the socio-economic impact of the IDEALIST technologies discussed.

1.2 Acronyms

ABNO	Application-based network operations
ANM	Adaptive Network Manager
API	Application programming interface
ASIC	Application specific integrated circuit
ASON	Automatically Switched Optical Network
BGP-LS	Border gateway protocol – link state
BVT	Bandwidth variable transponder
CAGR	Compound annual growth rate
CapEx	Capital Expenditure
CMOS	Complementary metal oxide semiconductor
DBA	Dynamic bandwidth allocation
DC	Data Centre
DDoS	Distributed denial of service
DSP	Digital signal processing
DWDM	Dense wavelength division multiplexing
E2E	End-to-end
EBL	Elastic Black Link
EDFA	Erbium doped fibre amplifier
EON	Elastic Optical Networking
EVM	Error vector magnitude
FT	Fixed transponder
FLC	First Level Controller
FPGA	Field Programmable Gate Array
FSC	Fibre switch capable
GMPLS	Generalized multiprotocol label switching
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet protocol
ITU	International Telecommunications Union
JIT	Just-in-time
MPLS	Multi-protocol label switching

NMS	Network management system
NPCM	Network Planning and Configuration Management
LCoS	Liquid Crystal on Silicon
LDPC	Low-density parity-check
LSC	Lambda Switch Capable
LSP	Label switched path
MLR	Multi-layer resilience
NIC	Network interface card
NPT	Network Planning Tool
OAM	Operations, administration, and maintenance
OF	OpenFlow
OIF	Optical Internetworking Forum
ONF	Open Network Foundation
OpEx	Operational Expenditure
OSNR	Optical signal-to-noise ratio
OSPF-TE	Open shortest path first – traffic engineering
OSS	Operational support system
OTN	Optical transport network
OTU	Optical Transport Unit
PCE	Path computation element
PCEP	Path computation element protocol
PDM	Polarisation division multiplexing
PIC	Photonic integrated circuits
PLL	Physical and Link Layer
PMD	Polarisation Mode Dispersion
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RWA	Routing and Wavelength Assignment
S-BVT	Sliceable bandwidth variable transponder
SDH	Synchronous digital hierarchy
SDM	Space Division Multiplexing
SDN	Software defined networking
SDO	Standards development organization
SLA	Service level agreement
SONET	Synchronous optical networking
SP	Service provider
SSMF	Standard single-mode fibre
TFP	Time Frequency Packing
TMF	Telemanagement Forum
TLV	Type length value
TP	Transport profile
TSDN	Transport SDN
VOA	Variable Optical Amplitude
WDM	Wavelength division multiplexing

WSON	Wavelength Switching Optical Networking
WSS	Wavelength selective switch

1.3 Document History

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1.4 Executive Summary

This report describes a detailed overview of the exploitation and commercialisation plans for the industry partners taking part in the IDEALIST project. Five categories of technology for exploitation are described: Planning Tools, the Control Plane and SDN, Advanced Transmission techniques, the Metro Border Node, and the Data Plane.

Planning Tools

With regard to the Planning Tools developed during the IDEALIST project and their proposed exploitation, Alcatel-Lucent (with its Service aware manager SAM, and network planning tool, NPT), and Coriant (via its TransNet solution) already offer planning tools for optical network design. Currently, the commercial planning tools only allow one to take the results of the upper layer as inputs to the lower layer, but not as a joint design approach. A commercial tool that supports a multi-layer network planning approach and also includes multi-layer optimization algorithms is not yet available. However, the Mantis tool developed by the University of Patras can now be used to create a base-line setup for multilayer network optimization planning and operation. The Mantis tool has also been developed to deal with SDN-based networks emerging in core, metro and datacentre networks. Mantis performs multilayer optimization, multilayer protection and restoration, accounting for physical-layer impairments and energy consumption, and can also be extended to consider evolution over time.

The industry partners in IDEALIST have developed an architecture tool to support both on-demand incremental capacity planning and in-operation planning. The resulting planning algorithm has access both operational and inventory databases, and the centralized management element, i.e. application-based network operations (ABNO), therefore has a global view of the resources and network topology, as well as the established connections. The central element of the planning tool receives planning requests from the network management system (NMS) and the path computation element (PCE) inside ABNO. To access data stored in the operational databases, the planning tool can be implemented as a back-end PCE and uses border gateway protocol – link state (BGP-LS) and PCEP protocols.

Control Plane and SDN

Current commercially available control plane solution packages do not include the main control functionalities required for elastic optical networking (EON) design, while commercial SDN solutions are based on proprietary implementations, which are only applicable in single vendor domains. In addition, current SDN implementations are also focused on packet-based technologies, mainly IP and Ethernet. This is in contrast to most operator networks that comprise many more technologies and elements than just IP and Ethernet.

IDEALIST has addressed these deficiencies by implementing the control plane as a set of cooperating entities (control plane controllers) that execute processes to facilitate resource management and service set-up and teardown. Control plane functions included are: topology management, and the distribution of path computation or signalling via a set of routing and signalling protocols. The protocols ensure the autonomous coordination and synchronization of functions and recovery from failures. The IDEALIST reference architecture was defined by the ITU-T, specifically around a framework called "Automatically Switched Optical Network" or ASON. Control plane standardization has been a key objective for the IDEALIST project, and the research effort has yielded multiple international standards, and significant success and leadership at multiple standards development organizations (SDOs), and across multiple work areas. SDO control plane and SDN achievements include:

ITU-T

- Leading technical clarifications for the standardization of data plane technologies related to flexgrid.

IETF

- Multiple RFCs related to Control Plane signalling and resource management;
- Multiple RFCs related to the Path Computation Element (PCE).

There are three core flexgrid documents:

- Framework and Requirements for GMPLS-based control of flexgrid DWDM;
- Generalized Labels for the flexgrid in Lambda Switch Capable (LSC) Label Switching;
- RSVP-TE Signalling Extensions in support of flexgrid.

These are either currently an RFC (principal standards setting technical publication) or a few weeks from publication as RFCs, with a fourth document:

- GMPLS OSPF-TE Extensions in support of flexgrid DWDM.

IDEALSIT has developed a proposal for an SDN controller framework into an IETF-based framework, architecture, and use-case document entitled:

- A PCE-Based Architecture for Application-Based Network Operations.

Advanced Transmission Techniques

Existing data plane technologies can be divided into three broad categories: bandwidth-variable transponders (BVTs), optical switching, and fibre/amplifiers, all of which have needed development in order to satisfy IDEALIST aspirations.

BVTs

A pre-product BVT solution was deployed in a field trial conducted by Coriant and TeliaSonera International Carrier (TSIC), where the trial was implemented on TSIC's existing Coriant® hiT 7300 Multi-Haul Transport Platforms[17]. In this case, the 400G flexi-rate trial used a new Coriant CloudWave™ Optics [18]prototype, which incorporates a versatile suite of software-programmable photonic layer technologies. The field trial featured the successful transmission of different software-programmable modulation formats at variable symbol rates over deployed fibres. The modulation formats were: quadrature phase shift keying (QPSK), 8 quadrature amplitude modulation (8QAM), and 16QAM. All of them were successful propagated over a distance of 1634 kilometres. Moreover, a variety of line-side transmission speeds (100G, 200G, 300G, 400G) in a mix of capacity and reach application test scenarios were demonstrated. In order to provide the flexibility of using arbitrary modulation formats within the same BVT, data-aided channel estimation and equalization techniques were also investigated within IDEALIST. The performance of different kinds of training symbols and their arrangements within the data stream were analysed, and promising types of training sequences that are suitable for use in a BVT were identified. Due to their flexibility and their system performance, the use of these training symbols in future products is likely to occur.

Metro Border Node

Simulations and experiments of new modulation formats such 8QAM including different bit-to-symbol mappings has helped drive the final choice of Alcatel-Lucent’s new transponder card, which now includes the 8QAM format that is well-suited for long-haul 200G applications. Several 1-Tb/s record experiments were conducted during the project lifetime testing different techniques of transmission - spectrally-efficient superchannels for 1-Tb/s transmission are highly likely to be the next step for Alcatel-Lucent’s 1-Tb/s product. The line interface container OTU has been made flexible by interleaving *N* subframes of 10-Gb/s, which aligns this with a proposed contribution of the OTN standards called “beyond 100G”; but the bit-rate has been scaled down due to the FPGA-based prototype whose best evaluation board is capable of running at ~30 Gbaud, hence ~100 Gb/s for a PDM-QPSK signal. SDN-control of ALU’s elastic interface FPGA prototype has been developed, with appropriate OpenFlow commands designed to support the functionalities of the elastic board. This has been showcased during Bell Labs FutureX days in 2015 and is feeding to ALU’s SDN strategy.

Data Plane

Ericsson, in collaboration with CNIT, has validated a sliceable bandwidth variable transponder (S-BVT) architecture supporting up to 1-Tb/s super-channel transmission, and including advanced programmability and adaptation functionalities. Transmission based on the time frequency packing (TFP) concept has been designed and demonstrated, with high spectral efficiency (e.g., 6 b/s/Hz with low-order PM-QPSK modulation format) proved, showing 1-Tb/s super-channel transmission conveyed in a 150-200 GHz frequency slot range. Thanks to the results achieved within the IDEALIST project, the LDPC-based TFP technique represents a relevant candidate technology for the development of the next-generation 1-Tb/s Ericsson transponder. Distance adaptation with code rate selection, and restoration with code rate adaptation represent two relevant examples of functionalities experimentally tested during IDEALIST, which is also expected to be included in the next-generation 1-Tb/s Ericsson transponder. Both PCE/GMPLS and SDN control plane solutions have been considered and investigated. For example, routing-spectrum-code assignment for provisioning and re-optimization, control-driven hitless shifting, hitless code adaptation procedures, differentiated filtering and super-filter techniques have been validated with properly designed extended control messages.

The larger industrial partners in the IDEALIST consortium have described their various exploitation routes, to feed the successful results of the project into their respective business plans, and further research and development roadmaps.

Telefonica have described multivendor SDN interoperability field trials set to take place in 2016, which will feature technologies developed during the IDEALIST project, as well as their migration estimation for 400G technologies into their network, and the anticipated cost savings by introducing 400-Gb/s and 1-Tb/s S-BVTs into their network.

Telecom Italia has described roadmaps towards the introduction of EON technologies into their optical transport backbone network, and also into the Pan-European backbone photonic network, as well as the introduction of S-BVT and flexgrid ROADM technologies with accompanying techno-economic analyses.

Deutsche Telekom expects the IDEALIST project results to increase its network efficiency, and ensure the flexibility and scalability of DT's network infrastructure in coming years. The superiority of next-generation flex-rate transceivers has been demonstrated, and their application potential in the various network segments that DT operates. The large cost advantages caused by multi-layer resilience (MLR) is one of the important outcomes of the project or DT. In addition, one of the key strategic outcomes emphasizes the need for an appropriate ABNO-based control plane as part of an integrated Transport-SDN solution, and Deutsche Telekom is now introducing this paradigm change. DT is planning several field trials on elastic interfaces and control plane implementations, with the first one planned together with an IDEALIST system vendor and further project-external suppliers in Q4 2015.

British Telecom's network is continuing to evolve to higher and higher capacities, with IDEALIST concepts anticipated to be deployed as required. BT expects to see flexrate BVT technology first, and flexgrid coming later. There will be some targeted early use of 400-Gb/s 'superchannels' (2 sub-channels) for key links that are filling up quickly. Full EON embodiment is further away, and will require continued bandwidth growth and perhaps an increased need for network dynamics at the optical layer. As part of its involvement in IDEALIST, BT has run field trials with vendors to assess the capability of EONs. BT has shown various capabilities including: (i) superchannels of up to 3 Tb/s constructed by bringing 200-Gb/s DP-16QAM sub-channels as close together as possible (around 32GHz); (ii) flexrate tunability – changing from DP-QPSK to DP-16QAM; (iii) superchannel protection; and (iv) coexistence of superchannels with legacy channels without interference. BT has also focused on alien waves, and is already making use of alien wave technology in strategic places in its network – both to reduce costs and also where there is no space to build the additional terminal equipment required (or power available to run the equipment in some cases.)

Ericsson in collaboration with CNIT and Coriant has experimentally validated an integrated multi-domain, multi-vendor, flexgrid, control and data plane network. Protocol extensions have been evaluated in a distributed multi-partner control plane test-bed. The carried research activity gives the possibility to define the applicability and feasibility of a fully end-to end interoperable EON network at the control and data plane levels. Over the next three years, complementary metal oxide semiconductor (CMOS) based electronics is expected to scale industrially down to 14 nm and complex processing functions will be designed by Ericsson into dedicated ASICs for superchannel generation to significantly enhance system margins with respect to current 100 Gb/s installed transmission systems. Silicon photonic integrated chips (PICs) will also help with the introduction of PIC modules encompassing electrical drivers, optical modulators filters, and laser sources. Interoperability of several implementations of S-BVTs by different system vendors for network flexibility and adaptability is now also being better understood by Ericsson.

Coriant now has a better understanding of how existing planning tools (and planning processes) need to evolve to take advantage of the new degrees of freedom enabled by the adoption of a flexible DWDM grid, and the deployment of transponder equipment characterized by being modulation format adaptive and supporting super-channel configurations. Coriant and TU/e have conducted an extended series of experiments within IDEALIST that will have a significant impact on next-generation Coriant transponders, with the research also contributing to the definition of the roadmap of upcoming Coriant products. Coriant has been involved ourselves in two field trials, plus a third under preparation (planned at the end of Nov. 2015). In particular, Coriant has been able to report on the performance of a first prototype of their upcoming BVT product, used over a real customer network. In this experiment, all the main features of a BVT, widely investigated within IDEALIST, have been tested and verified in the field. Moreover, the lessons learned, the developed algorithms, and the expertise acquired in system optimization will help Coriant to define the new engineering rules for the next-generation of Coriant systems.

Alcatel-Lucent's exploition of IDEALIST results is based on the following main items: (i) the technical options designed and prototyped for elastic optical communications, to allow (ii) networking applications with (centralized) controller enhancements. (iii) Together, these two enhanced elements have been integrated in the final demonstrations, with the expectation that this integration phase will lead to good future business opportunities. Alcatel-Lucent has been actively involved in standardization activities related to the IDEALIST context, particularly in ITU-T Q6 that is treating the flexible grid definition, G.698.1 and G.698.2. In the ITU, ALU is heavily involved in the definition of the "beyond-100G-OTUflex" work, in Q11 and G.709 extension in Q9. Following this activity ALU has used the related concept to provide a FPGA in the project to enable multiplexing/demultiplexing of 1 to 10 OTU2 lines to simulate OTUflex implementation. In the IETF Alcatel-Lucent has actively contributed to the framework draft for GMPLS-based control of a flexible-grid WDM network (draft-ietf-ccamp-flexi-grid-fwk-07) that recently passed LC to become a RFC. ALU is also involved heavily in the SDN context in both the ONF and IETF. In the ONF, Alcatel-Lucent is co-author of the requirements for Transport API, SDN Architecture and Common Information Model, and in IETF ALU is also the co-author of a draft composing the overarching work, called Abstraction and Control of Transport Networks (ACTN). Alcatel-Lucent's key achievements in IDEALIST have been focused around transponder technology and control for software-defined hardware reconfigurations. Feasibility studies for integrating into commercial equipment (related to the 1830PSS family, mainly) has been under discussion, and will most likely be planned for the others. Alcatel-Lucent can also now offer a very flexible transponder card with a wide-range of modulation formats, such as QPSK, 8QAM, 16QAM, and a CDC-flexgrid node is now commercially available. ALU has introduced a new paradigm of 'just-enough recovery' for the leveraging of elastic optical devices capable of adjusting their modulation format (and hence data rate) when restoration of an optical path is needed. Simulation results show ~35% cost reduction with 30% gold traffic. ALU has also studied the impact of asymmetrical bidirectional traffic routing in the case of elastic devices. The newly introduced routing paradigm saves up to 25% overall (add/drop and regeneration) optoelectronic devices. Finally, Alcatel-Lucent has also studied the impact of flexgrid networks based on a just-enough bandwidth allocation, to support the exact traffic demand in the case of tight filtering impairments. The ideal extra capacity of 33% brought about by 37.5 GHz channel spacing (compared to 50 GHz) may be significantly reduced under the physical constraints of fully transparent meshed networks.

Naudit's exploitation of the skills and knowledge acquired during its participation in IDEALIST is considered in three categories: (i) High-speed monitoring probes, (ii) algorithms for bandwidth estimation and link dimensioning, and (iii) a new product line for operators based on dynamic bandwidth allocation. Naudit has plans to create a 40 Gb/s Kinnic board, and to develop a series of algorithms for bandwidth estimation based on the output of monitoring probes, with the aim to characterize links beyond transient situations. Naudit plans to exploit these algorithms for two purposes: 1) Bandwidth estimation algorithms will be used to evaluate the dimensioning of links; 2) The bandwidth estimation algorithms will be helpful in order to detect anomalous situations, such as distributed denial of service (DDoS) attacks.

Finally, the positioning of the IDEALIST project in the overall European socio-economic context is discussed in this report, with particular regard to the energy-efficiency (carbon footprint) characteristics of core networking and its relative importance in the overall telecommunications networking situation. The drivers pushing increasing data-rates are discussed, as is the issue of where future research into energy-efficient photonic networking may best be focussed.

2 State of the Art of Commercial solutions

2.1 Planning Tools

Software-based network planning tools assist Operators in their operational ability to perform network planning. Different network planning tools are already to be found in the market, spanning a broad range of platforms, systems, languages, functionalities and applications. In particular, third-party suites and vendor-specific tools currently dominate the market in commercial planning tools of IP/MPLS and optical networks, with very little availability for non-commercial tools. The third-party suites include Riverbed SteelCentral Network Planning and Configuration Management (NPCM) (formerly OPNET) [1], Cariden MATE Design (acquired by Cisco in 2011) [2], VPI OnePlan [3], and WANDL IP/MPLSView (acquired by Juniper) [4]. RSoft MetroWAND was another commercial tool, but this has recently been discontinued. All the commercial tools provide a more or less complete set of features to design and analyse networks, without relying on a specific vendor. These features include simulations of several configuration scenarios, routing schemes, network recovery tests, or traffic load analysis. Most of the tools provide capabilities to automate the configuration of network equipment for different brand manufacturers (mostly Cisco and Juniper) from the network plan. Apart from this, some vendors also offer planning tools specialized for their own equipment. For example, Alcatel-Lucent [5], Coriant (via its TransNet solution) [6] as well as Huawei all offer planning tools for the optical networks.

At the present, there is no commercial tool that truly supports a multi-layer network planning approach and also includes multi-layer optimization algorithms. Currently, the commercial planning tools only allow one to take the results of the upper layer as inputs to the lower layer, but not as a joint design approach.

There is only one tool that comes out of an academic open-source context, Net2Plan [7], that considers multi-layer planning. However, due to its academic approach it lacks some of the capabilities available from the more commercial tools.

A multi-layer tool should include the following objectives:

- Support to the architecture and optimization of network – including network design and analysis of Transmission/IP network topology, and recovery analysis (inc. network configuration, and analysis of critical points that are more vulnerable to failures and how these can be mitigated);
- Optimized design of the network topology using advanced multilayer algorithms;
- Support to gaining knowledge of topology optimization for future planning;
- Network engineering and traffic engineering;
- Capacities associated with network recovery, and failure analysis;
- Solutions to support capacity planning and engineering, and traffic engineering (e.g. when and where the Transmission/IP network is likely to be without appropriate capacity, and/or what will be the impact on the network due to the addition of a new service or client etc.);
- Growth forecasting;
- Analysis of upgrade paths;
- Impact of new services on the network;
- Planning of SLAs;
- E2E view of the Transmission/IP network (inc. optical fibre, optical transmission, IP/MPLS core, metro Ethernet, backhaul, MW…);
- Unique appearance for all types of elements of the managed Transmission/IP network, independent of the actual supplier (multi-supplier and multi-technology);
- Provide configuration functionalities of the Transmission/IP network, and connectivity capacities;
- Consultation of the performance measures of Transmission/IP network.

Product	Planning / Operation	Company	Layers/protocol	Multi-vendor / optical vendor
Mate Design	Planning & Operation	Cisco, USA	IP/MPLS	Multi-vendor
SteelCentral Network Planning and Configuration Management (NPCM)	Planning & Operation	Riverbed, USA	SONET/SDH, WDM FIBRE, IP/MPLS	Multi-vendor

IP/MPLS View (former WANDL)	Planning & Operation	Juniper, NJ, USA	IP/MPLS	Multi-vendor
OnePlan (Transport & IP/MPLS)	Planning	VPI Systems, NJ, USA	Optical Transport Networks: SONET,SDH,WDM. IP/MPLS	Multi-vendor
9500 NPT (Network Planning Tool)	Planning	Xtera (formerly Meriton) TX, USA	RWA in optical network	(optical vendor software)
5620 Alcatel-Lucent SAM (Service aware manager)	Planning & operation	Alcatel-Lucent	Optical Network Management SDH, SONET, DWDM and all IP networks	(optical vendor software)
1390 Alcatel-Lucent NPT (Network planning tool)	Planning and commissioning	Alcatel-Lucent	Optical network, multi-technology OTN/WDM networks	(optical vendor software)
Coriant® TransNet Network Planning Tool	Planning	Coriant	DWDM networks, RWA, Optical Performance Optimization	(optical vendor software)

Table 1 Commercial Planning tools

2.2 Control Plane

The current commercially available control plane solution packages do not include the main control functionalities required for elastic optical networking (EON) design.

Flexgrid GMPLS support

Currently deployed control plane-enabled optical transport networks (OTNs), like that of Telefonica's Spanish transport network, are based on the GMPLS architecture with WSON (wavelength switched optical network) extensions. In GMPLS, the entity that is managed is the LSP (label switched path), which is a representation in the control plane of the physical resources. Thus, the main resource to be managed in current deployed optical networks is the "lambda" LSP (lightpath), which includes both the optical signal and the spectrum used, and represents the optical channel between two transponders. Note that as the grid is fixed in current networks, there is no flexibility in the choice of spectrum, and thus this is a part of the LSP. From a practical perspective, the control plane LSP begins and ends at transponders.

Given the level of maturity, the GMPLS architecture is the straightforward choice for an elastic core control plane. However, a set of modifications needs to be applied to the GMPLS architecture in order to support flexgrid along with the necessary protocol extensions.

In a flexgrid network, there is a separation of concerns in terms of the spectrum and optical signalling. Thus, there will be spectrum-only LSPs (media LSPs), which represent a set of cross-connections and filter configurations, and optical signal LSPs, that use media LSPs.

In GMPLS-based systems, the label indicates the physical switching resource. For example, in a WSON network the label value represents the wavelength, characterized by its central frequency. In the case of flexgrid, the label value indicates the slot, which includes both central frequency ('n', as in the WSON case) and the slot width ('m'). Thus the 'm' parameter is both a property of the label (i.e., it helps define exactly what is being switched) and of the end-to-end LSP.

It is important to note that the label is local to the nodes. Thus, an LSP may have different 'm' values (slot widths) along the path, due to the different granularities of the equipment. There is a 'm' parameter, which is carried end-to-end, and represents the slot width of the channel needed.

Multidomain and Multilayer SDN Orchestrator

Existing networks relay on the traditional design of deploying separated layers. Optical networks are commonly used in a static fashion for providing high capacity circuits to the upper layers, mainly IP/MPLS, operating in a packet-based mode. The service provisioning in this kind of architecture involves a number of manual interventions directly on the actual devices or by means of a management system.

From a functional point of view, new uses of the network, including data centre-centric services, are showing a trend to require higher responsiveness from the network side through programmatic interfaces. The dynamic re-allocation of resources accompanying the traffic demand guarantees in-time service delivery. From a financial perspective, the decoupling of income from traffic demand (the former is decreasing while the latter still increasing) imposes the need for a better utilization of existing network resources while slowing down the need for new investment. The joint optimization of application performance and network utilization is therefore the driver for this point, as a way of minimizing service costs whilst leveraging the deployed infrastructure.

The SDN concept of separating the control plane from the nodes and logically centralizing it onto powerful platforms with a whole vision of the network can facilitate the above-mentioned targets. Furthermore, the introduction of SDN allows us to expect some extra benefits through the high automation of service provisioning, and network node simplification (leading to cheaper devices).

Commercial SDN solutions are based on proprietary implementations, which are only applicable in single vendor domains (e.g. Cisco, Huawei, Cyan…).

Current SDN implementations are focused on packet-based technologies, mainly IP and Ethernet. Nevertheless, an operator's network typically comprises many more technologies and elements that just IP and Ethernet. A typical transport network consists of a variety of optical and packet links and nodes, and could contain, for example, Ethernet, MPLS-TP and/or OTN technologies, as the means for data delivery. The extension of the SDN concept to transport networking facilitates an easier integration of such a variety of technologies and their corresponding network layer capabilities for dynamic, multilayer, and multi-domain end-to-end networking. However, the control plane considerations in the optical field are more complex than the ones in the packet-switched domain: physical impairments, light path routing, protection and restoration etc., all need to be taken into account. Thus the idea behind Transport SDN (TSDN) is to support the evolution of current transport networks for a seamless integration into SDN architectures. This includes not only extensions to existing protocols (e.g., OpenFlow) for supporting the control of optical parameters by (logical) central entities, but also the development of orchestration capabilities for enabling, e.g. multilayer or multi-domain capabilities. TSDN control can therefore effectively optimize the use of both packet (i.e. electrical) and circuit (i.e. optical) domains.

There are two main topics where vendors are positioning their work within SDN. The first one is the controller itself. Each vendor is presenting their controller to operate in single controller scenarios, where there is a domain that can be configured using their solution. Some vendors are proposing some standard interfaces that would enable configuration with other vendor's equipment. The second topic where vendors are working is the support of the OpenFlow protocol to support optical devices. There is already a definition to support rules at the packet level but, at the moment of writing this document, there is no standard extension to OpenFlow for optical circuits. Finally, there exists a third topic where vendors are positioning their work in the SDN context, and this is multi-layer coordination. Figure 1 presents a summary highlighting where various vendors are currently positioned in these three topics: SDN controllers, OF extensions for optical networks, and IP+Optical Integration.

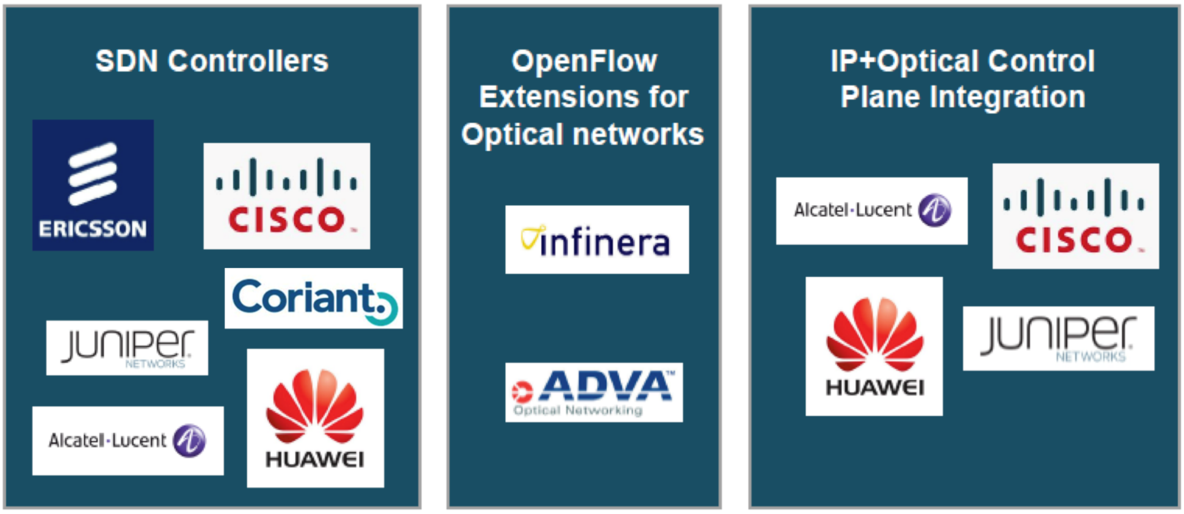

Figure 1: Models to support Transport SDN

2.3 Data Plane

The existing data plane technologies can be divided into three broad categories: transponders, optical switching, and fibre/amplifiers. Here we examine the existing state-of-the-art available in these three areas, and show how they currently fall short of IDEALIST aspirations.

2.3.1 Transponders

Current core transport networks are generally operating with full coherent transponders at 40 Gb/s and (increasingly) 100 Gb/s data rates. These transponders have stabilized on DP-QPSK modulation format, and currently are being used on a 50-GHz wavelength grid. The current generation is fixed – i.e. not BVTs - and can only operate at QPSK.

Recent trials, within the past year or two have heralded 200-Gb/s transponder capability from the leading equipment vendors. 200 Gb/s is achieved via DP-16QAM modulation with the same electrical bandwidth – hence the same spectrum. These cards are beginning to become available for operators who already need capacities like this on their busiest links. These cards can generally also be operated at 100 Gb/s – as might be required for some of the longer spans – hence they are effectively 100G/200G line cards and the first transponders to qualify as BVTs. There is a lack of dynamic agility between 100G and 200G, and currently, use cases have not yet been sufficiently focused to understand and start capitalizing on this type of functionality.

Vendors have also begun to couple two of these cards together to produce what they describe as a 400G card – with output consisting of two 200G carriers. In principle, these carriers can be squeezed together closer than the 50-GHz fixed grid restriction and this implies that they are already "flexgrid ready".

Currently, the industry debate is centering on the use cases for flexrate, and vendors will want to find ways of using these new functions that enable them to recoup development costs.

2.3.2 Optical Switching

Current wavelength selective switches (WSSs) are flexgrid ready, meaning they have LCoS (liquid crystal on silicon) technology that is capable of much finer optical filter resolution than micro-electro-mechanical systems (MEMS). Many service providers (SPs) are still using them in 50GHz fixed-grid mode, partly due to the lack of current need for more than this, and partly due to lack of mature flexgrid control software – although this situation is changing.

Once demand for flexgrid increases, SPs will either discover that they need to replace all their optical switches, or they will (more easily) need to implement a software change to access the fine WSS features.

WSS technology continues to improve, with GHz resolution available, as well as the ability to apply subtle intensity profiling on signals. Indeed, this fine-grained variable optical amplitude (VOA) capability of the WSS is highly useful for maintaining balanced optical networks.

Other ideas entering the market include multicast switches – which enable cost effective contentionless operation without having to use lots of WSSs on the add/drop side of the switch.

Finally, the concept of filterless metro networks is emerging, in which there are no WSSs, but just passive couplers. Here, the filtering is effectively done by the local oscillator in the coherent receiver as it selects the required signal from the rest.

In principle the flexgrid requirements laid out in IDEALIST are available once a suitable control is implemented on a network scale. Further developments in switching will require architectural developments, once the existing 1x9, and 1x20 (and higher) WSSs reach their performance limits.

2.3.3 Fibre and Amplification

Transmission innovations over recent years have generally assumed that SPs will remain loyal to their G652 fibre infrastructure. There are some exceptions: for example, part of the TI network has other fibre types, and there was a period when operators installed newer types that had different dispersion zeros and/or different effective areas. It has turned out however, that G652 fibre has continued to perform extremely well and competitively as compared to its newer rivals – something that is unusual for technology in general. One area that caused great concern was the poor polarisation mode dispersion (PMD) of the older G652 fibres. Not only has this issue been significantly reduced in modern fibres (of all types – and through careful manufacturing process improvements), but the recent advent of coherent transmission has largely removed the issue for core networks, where DSP (digital signal processing) is able to compensate for the pulse distortions caused by this effect.

Consequently, old fibres have received a new lease of life and continue to be used for 100-Gb/s transmission and beyond. The main issue relates to loss – which can be higher for older fibres. Fibre loss requires amplification, which causes noise and reduces the optical signal-to-noise ratio (OSNR) available. This OSNR limit prevents the use of higher modulation formats such as 32- and perhaps 64-QAM. Also responsible are optical switch losses and the noise figures of the amplifiers themselves.

Solutions are available to help with all of this – operators could make use of new, ultra low loss fibres, WSSs with low loss (perhaps mid-stage amplifiers) and even Raman gain (which has a lower noise figure than EDFAs.)

3 Idealist pre-commercial products

3.1 Planning Tools

Dynamicity at the optical layer has been kept rather limited so far, as a result of the large traffic aggregation performed in the upper network layers. Hence, optical transport networks are currently statically configured and managed. In fact, long planning cycles to upgrade and prepare optical transport networks for the next planning period, means that spare capacity is usually installed to ensure that traffic forecast and failure scenarios can be supported. Nevertheless, forecasts predict huge yearly global growth due to the introduction of new services such as live-TV distribution, datacentre interconnection, etc.

In addition, changes in traffic will affect not only its volume but also its distribution. Periodical planning needs as exact as possible predictions for expected traffic volumes and distributions, which, although feasible for static traffic scenarios, becomes somewhat unrealistic when dynamic traffic is considered. Hence, new efficient planning methods are now needed to increment the capacity of optical networks whilst reducing overprovisioning costs.

Aiming at reducing network expenditures, a pay-as-you-grow approach can be implemented to add capacity to the network according with traffic growth. Let us assume that a periodical planning cycle is in charge of the design of the network; as a result, new network nodes can be installed, and a reduced number of spare equipment (e.g. line-cards and transponders) can be purchased and made available in some warehouses distributed over the geography or even placed on-site. In addition, just-in-time (JIT) techniques can be used to keep enough spare cards always available. Spare equipment availability is often stored in an inventory database, together with information about optical cables, optical amplifiers, fibre usage, etc. When the capacity of the optical backbone network becomes exhausted in some parts, new capacity will need to be installed.

Dealing with traffic dynamicity requires automating connection provisioning, which explains the development of centralized architectures based on the software-defined networking (SDN) concept, such as application-based network operations (ABNO) one [RFC.7491]. Operating the network dynamically might bring cost savings, but it also might cause nonoptimal network resource utilization. To solve that, network resources can be made available by applying *in-operation network planning*.

It is clear from the above that the classical network life-cycle has to be extended to support both on-demand incremental capacity planning and in-operation planning. Figure 2(a), below, presents the proposed augmented network life-cycle. Once the network is in operation, its performance can be monitored so that either incremental capacity planning or in-operation planning can be triggered when a threshold has been exceeded.

To add a new link, the planning algorithm needs to know the current state of the network including the state of the resources and established connections. Furthermore, it needs information about physical resources, even those not yet installed. A planning tool can decide the equipment and connectivity to be installed at the minimum cost; the planning tool needs access to both the inventory database and the current state of the network stored in operation databases, i.e., the TED and the LSP-DB. Note that those databases are also needed for in-operation planning to compute re-optimizations.

Figure 2(b) presents an architecture to support both on-demand incremental capacity planning and in-operation planning. The architecture might support any planning algorithm that needs to access both operational and inventory databases. A centralized management element, e.g. ABNO, has a global view of the resources and network topology, as well as of the established connections. The central element is the PLATON planning tool that receives planning requests from the network management system (NMS) and the path computation element (PCE) inside ABNO. To access data stored in the operational databases, the planning tool can be implemented as a back-end PCE and use BGP-LS and PCEP protocols.

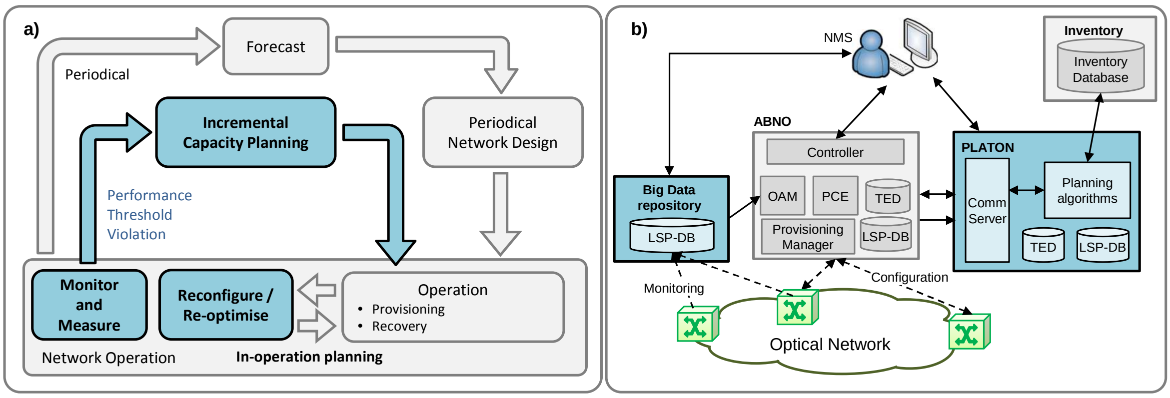

Figure 2: (a) Extended network life-cycle, and (b) Management architecture.

The Mantis tool developed by University of Patras (UPAT) can be used to create a base-line setup for multilayer network optimization planning and operation. Both these directions (planning and operation) have flexible decision points that can be explored. A challenge for the planning part is to make it vendor agnostic, but still to also include in enough details regarding the available equipment and their performance characteristics. The challenge for the operational part of the tool is to take an 'off-line' optimization process, and then to deploy it as a real-time and 'on-line' network control process. Together, the tool can be used to create and justify a business case that enables the operation of a more flexible and intelligent network than is currently the case, as well as to subsequently optimize the cost and use of these flexible resources.

The optical telecommunications market is expected to reach new heights in the coming years, as it is reflected by the projected increase in optical equipment [1]. Similarly, the Metro market growth is being driven by the rising use of WDM systems for mobile and fixed backhaul, as well as the increasing number of data centres (DCs) and the traffic being directed to them [9]. Adoption of 100G coherent technology is growing in long haul networks, and is now becoming a material part of metro networks [1]. Moreover, the global market for flexgrid technology and carrier SDN (both in terms of software, hardware and services) [10] is also expected to grow.

Today, most related offerings for planning tools usually target the core, but their most important drawbacks include: (i) they tend to be vendor specific (though, not all); (ii) they perform poorly on optimization (it is not their main focus); (iii) they do not support multilayer functionality (though this is now currently under development by many players); and finally, (iv) they miss to take into account many of the current and future optical network technology trends (e.g. flexgrid, coherent, SDM etc.).

The main advantage to the setup part of Mantis is the network logic already incorporated in the tool, in combination with its ability to deal with current networking developments: the SDN-based networks emerging in core, metro and datacentre networks. Mantis logic performs multilayer optimization, multilayer protection and restoration, accounting for physical-layer impairments and energy consumption, and can be extended to also consider the time domain.

3.2 Control plane and SDN

For IDEALIST, the control plane is implemented by a set of cooperating entities (control plane controllers) that execute processes to facilitate resource management and service set-up and teardown. Control plane functions include: topology management, and the distribution of path computation or signalling via a set of routing and signalling protocols. The protocols ensure the autonomous coordination and synchronization of functions and recovery from failures. Typically, the provisioning of a new service is done upon request from a separate system, such as an NMS or SDN Controller.

The IDEALIST reference architecture was defined by the ITU-T, specifically around a framework entitled “Automatically Switched Optical Network”, or ASON for short. ASON provides an enabling set of technologies for the dynamic control of an optical network, and automating the resource and connection management. ASON relies on the generalized multiprotocol label switching (GMPLS) set of protocols defined by the Internet Engineering Task Force (IETF).

Therefore the ASON architecture and GMPLS protocol suite has been a core technology platform for IDEALIST. Principally they needed to be extended to fully support the IDEALIST EON design objectives and formalizing flexgrid for interoperability between vendors, especially at the control plane level.

Control plane standardization has been a key objective for the IDEALIST project. When we started the project we understood that EONs and flexgrid would provide an exciting opportunity for showcasing European research, but we were also eager to demonstrate industry impact as well.

During the three years since the IDEALIST project began, we have been able to show that our research effort has yielded multiple international standards, and we have achieved significant success and leadership at multiple standards development organizations (SDOs), and across multiple work areas.

The ITU-T and IETF are two of the most important SDOs related to telecommunications and are populated with large international communities of network designers, operators, and vendors. All are concerned with the specification, development and evolution of the architecture of the Internet, and especially in the case of the IETF the smooth operation of the Internet.

Our SDO control plane and SDN achievements include:

ITU-T

- Leading technical clarifications for the standardization of data plane technologies related to flexgrid.

IETF

- Multiple RFCs related to Control Plane signalling and resource management;
- Multiple RFCs related to the Path Computation Element (PCE).

An RFC is authored by IETF participants, typically engineers from vendors or network operators, researchers or scientists in the form of a document describing methods, behaviours, research, or innovations. They take many forms: requirements, architecture, protocol specifications, and best practices. All are applicable to the working of the Internet and Internet-connected systems. Each proposal is submitted either for review by a working group tasked with a specific technology topic or challenge, or simply to convey new concepts, and information. The IETF adopts some of the proposals published as RFCs as Internet Standards.

Flexigrid Standards

There are three core flexgrid documents:

- Framework and Requirements for GMPLS-based control of Flexgrid DWDM [11];
- Generalized Labels for the Flexgrid in Lambda Switch Capable (LSC) Label Switching [12];
- RSVP-TE Signalling Extensions in support of Flexgrid [13].

These are either currently an RFC (principal standards setting technical publication) or a few weeks from publication as RFCs, with a fourth document:

- GMPLS OSPF-TE Extensions in support of Flexgrid DWDM [14].

They are currently being progressed after a recent working group last call (one of the few final steps before publication as an RFC).

In addition to the flexgrid framework, routing extensions and signalling extensions standards we have also embarked on new standards for modelling flexgrid networks. Our models are being developed in YANG, and will be used to model configuration and state data, vital functions for operating networks in commercial environments.

PCE Standards

The PCE can be used in a wide-variety of deployments and utilized by control plane nodes, NMS's, and SDN Controllers. However, a number of key questions and requirements for these varying architectural views of the PCE needed to be identified and some key questions answered. We developed an RFC that drew out those questions and discusses them in an architectural context, with reference to other architectural components, existing protocols, and recent IETF efforts.

- Unanswered Questions in the Path Computation Element Architecture [15].

SDN Standards

An SDN Controller framework for network operator environments must combine a number of technology components, mechanisms and procedures, including:

- Policy control of entities and applications for managing requests for network resource information and connections;
- Gathering information about the resources available in a network;
- Consideration of multi-layer resources, and how these topologies map to underlying network resource;
- Handling of path computation requests and responses;
- Provisioning and reserving network resources;
- Verification of connection and resource setup.

Our overall objective was to develop a control and management architecture of transport networks built using core IETF technologies to facilitate network operators to manage their networks using the core principles of SDN, to allow high-layer applications and clients to request, reconfigure and re-optimize the network resources in near real-time, and in response to fluid traffic changes and network failures.

We developed our proposal for an SDN controller framework into an IETF-based framework, architecture and use case document entitled Application-Based Network Operations (ABNO):

- A PCE-Based Architecture for Application-Based Network Operations [16]

The software instantiation of ABNO for the IDEALIST project has been realized with the development and deployment of an Adaptive Network Manager (ANM), which is discussed in detail in further sections of this document.

3.3 Advanced transmission

Bandwidth variable transporter for next generation elastic optical networks

A clear example of a pre-product application, carried out in the framework of the EU project IDEALIST, is the recent field trial conducted by Coriant and TeliaSonera International Carrier (TSIC).

We carried out a long-haul experiment over deployed fibre routes, which are part of a TSIC pan-European optical network. The fibre type of the link was standard single-mode fibre (SSMF) and EDFA-only amplification was in use. The trial was implemented on TSIC's existing Coriant® hiT 7300 Multi-Haul Transport Platforms [17]. The 400G flexi-rate trial used a new Coriant CloudWave™ Optics [18] prototype, a versatile suite of software-programmable photonic layer technologies that brings a new level of flexibility, efficiency, and scalability to next-generation optical transmission networks. In order to be able to engineer the trial and the bandwidth variable transponder (BVT) prototype, the research within the IDEALIST project on BVT, modulation formats and physical effects has been a key contribution.

The field trial featured the successful transmission of different software-programmable modulation formats at variable symbol rate over deployed fibres. The considered modulation formats were: quadrature phase shift keying (QPSK), 8 quadrature amplitude modulation (QAM), and 16QAM. All of them have been successful propagated over the complete distance of 1634 kilometres. Moreover, we showed a variety of line-side transmission speeds (100G, 200G, 300G, 400G) in a mix of capacity and reach application test scenarios.

This trial represents an industry-first demonstration of cutting-edge flexi-rate technology that promises to significantly advance the state of optical layer flexibility. With optical transmission speeds up to 400G, we showcased high capacity, high order modulation formats for metro, regional and long-haul optical systems with real-time BVT. Overall, this field trial demonstrates an innovative flexi-rate technology that supports the dynamic and cost-efficient provisioning of optical transmission speeds up to 400G per channel based on application-specific bit rate, reach, and modulation requirements and a proof of principle for the research done in IDEALIST.

Data-aided channel estimation and equalization

One scope of IDEALIST is the investigation of BVTs for use in EONs. Therefore many methods are being proposed, including adaptation of the modulation formats and/or code rates being used. In order to provide the flexibility of using arbitrary modulation formats within the same BVT, data-aided channel estimation and equalization techniques are also now being discussed. Within IDEALIST, we analysed the performance of different kinds of training symbols and their arrangements within the data stream (see Deliverables D2.2 and D2.3). We clearly identified promising types of training sequences which are suitable for use in a BVT. Due to their flexibility and their system performance, the use of these training symbols in future products is likely to occur. Therefore the analyses performed within IDEALIST represent one step towards the implementation of the corresponding DSP steps in future flexible transponders.

Nonlinear pre-distortion of transmitter components

In order to be able to use higher-order modulation formats within a BVT, the implementation penalty caused by these more complex signals has to be decreased. Further, in order to be able to compensate for transmission impairments, such as chromatic dispersion and fibre nonlinearities already at the transmitter side, well-defined analogue waveforms have to be launched into the fibre. One solution to both problems is the use of pre-distortion techniques within the transmitter DSP. During the IDEALIST project we investigated, both numerically and experimentally, the influence of different linear and nonlinear pre-distortion techniques on the system performance of high-order optical modulation formats (see Deliverables D4.3 and D4.4). We clearly observed large advantages in terms of signal quality by using these pre-distortion techniques. This is why we believe, that these finding's will drive the implementation of such algorithms into next-generation transponders. However, the complexity of such methods is still a concern, so that some effort has to be spent in order to be able to realize these pre-distortion techniques into today's hardware solutions.

3.4 Metro Border Node

The research carried out in IDEALIST by Alcatel-Lucent has generated numerous experimental results and prototyped subsystems. The flexibility introduced and tested has shown to be beneficial in terms of performance, i.e. lowered filtering penalties, improved the reach, and improved network capacity, etc. Therefore, these first proof-of-concepts will pave the way into a further development of these functionalities into various Alcatel-Lucent products, with new features or improvements of existing solutions. Since a node comprises multiple elements including transponders, electrical switching and optical switching, these results will find their way into multiple technology solutions.

The first part of the project gave Alcatel-Lucent the opportunity to focus on the design and specification of enhanced transmission techniques, noticeably on the transponder/muxponder evolutions with advanced DSP.

- Simulations and experiments of new modulation formats such 8QAM [19] including different bit-to-symbol mappings has helped drive the final choice of Alcatel-Lucent's new transponder card. Indeed, the new transponder card now includes the 8QAM format that is well-suited for long-haul 200G applications.
- A nonlinear compensation technique for cross-channel effects received very good feedback from the research community, and was even upgraded to invited paper status at an international conference (ECOC 2014) [20]. This may be included in the long-term in the next-generation DSP chipset, if sufficient interest from telecom operators is perceived as well.
- Several 1-Tb/s record experiments were conducted during the project lifetime [21][22] testing different techniques of transmission. Spectrally-efficient superchannels for 1-Tb/s transmission will most likely be the next step for a 1-Tb/s product, whereas single-carrier 1-Tb/s represents a longer term approach that is highly dependent on the quality and bandwidth of optical components.
- A flexible OTN mapping was designed and prototyped in real-time [23], with the idea to bring the flexibility of the OTN layer as far down as the optical transport layer (also known as out, which stands for Optical Transport Unit). The aim is to deliver just-enough capacity down to the optical signal line rate. To this end, the line interface container OTU was made flexible by interleaving *N* subframes of 10-Gb/s. This is aligned with a proposed contribution of the OTN standards called "beyond 100G", but we scaled down the bit-rate due to the FPGA-based prototype whose best evaluation board is capable of running at ~30 Gbaud, hence ~100 Gb/s for a PDM-QPSK signal.

  Elastic optical networks will become really flexible (i.e. reconfigurable or even dynamic) when the OTU container is flexible. This will be a key feature of next-generation of products.

The second part was more devoted to the integration of prototyped subsystems, effort for centralized control, and control plane extensions to be developed so as to support the new features introduced during the first part of the project. Of course, refinements of the initial proposal were also studied with, for instance, an optimization of the reconfiguration time of our elastic board prototype that has been fully characterized and decreased by a factor of two.

- We modified the first level controller (FLC) of the OTN switch to permit communication between remote Telnet connection towards Restful server and USB port connected to the FPGA-based prototype of an elastic interface.
- A RESTful server was developed to intercept REST API high-level configuration commands from the remote GMPLS controller (i.e. control plane). Consequently, it creates the correct sequence of elementary commands providing configuration to

both OTN switch and elastic interface board. It could be considered as a software-based element management level.

- We developed SDN-control of our elastic interface FPGA prototype. To this end, we designed appropriate OpenFlow commands to support the functionalities of the elastic board and implemented on another FPGA board the reception and translation of the OpenFlow packets from the ALU SDN controller into specific commands for the elastic interface. This has been showcased during Bell Labs FutureX days in 2015 and this should feed into ALU SDN strategy.

  → The Alcatel-Lucent NSP (Network Services Platform: http://www.alcatel-lucent.com/products/network-services-platform) is a carrier-grade SDN solution integrating service automation with network optimization in such a way network operators can deliver on-demand network services cost-effectively and with scalability.

3.5 Data Plane to control and monitor flexible optical networks

In the framework of the IDEALIST project, Ericsson, in collaboration with CNIT, has proposed, defined, and validated a sliceable bandwidth variable transponder (S-BVT) architecture supporting up to 1-Tb/s super-channel transmission, and including advanced programmability and adaptation functionalities. The designed architecture and experimented functionalities will pave the way for the development of next-generation transponder products, where flexibility (enabled by advanced monitoring solutions) will introduce significant improvements over existing solutions.

Within the project, Ericsson has exploited the opportunity to focus on multiple key innovation aspects, including enhanced transmission techniques, software-defined transmission adaptation, advanced monitoring, and flexgrid control plane solutions. More specifically, the following specific project activities have driven relevant innovations in the design process of the next-generation Tb/s transponder solutions.

- Transmission technique based on the time frequency packing (TFP) concept has been designed and demonstrated. High spectral efficiency (e.g., 6 b/s/Hz with low-order PM-QPSK modulation format) has been proved, showing 1-Tb/s super-channel transmission conveyed in a 150-200 GHz frequency slot range, depending on the optical reach and the number of traversed nodes. Thanks to the results achieved within the IDEALIST project, the LDPC-based TFP technique represents a relevant candidate technology for the development of the next-generation 1-Tb/s Ericsson transponder.
- Advanced adaptation functionalities have been defined and demonstrated. Distance adaptation with code rate selection, and restoration with code rate adaptation represent two relevant examples of functionalities defined and experimented in the project, which may be suitably included within the next-generation 1-Tb/s Ericsson transponder.
- Monitoring of transmission parameters enabled by a coherent detection strategy and LDPC coding has been investigated and assessed. Such advanced solutions allow the detection of even minor degradations and soft failures before the bit-error-rate actually exceeds critical thresholds, thus enabling the activation of hitless adaptation solutions and avoiding service degradation at the client network.
- Flexgrid control plane extensions have been designed and validated to support the full automatic configuration of the defined S-BVT solution. Both PCE/GMPLS and

SDN control plane solutions have been considered and investigated. For example, routing-spectrum-code assignment for provisioning and re-optimization, control-driven hitless shifting, hitless code adaptation procedures, differentiated filtering and super-filter techniques have been validated with properly designed extended control messages. Such functionalities enabled by the control plane will represent a key innovation in the design of future software-defined Ericsson transponders.

4 Idealist Industrial plan

In the following pages, the larger industry partners within the IDEALIST consortium describe how the results arising from the project are influencing their business plans, e.g. via new product roadmaps, their contributions into standards, the technical specifications for RfQs, impacting network operational efficiencies, and offering improved service availabilities and competitiveness. In addition, strategic and architectural migration guidelines, and internal company organization are also other areas where the project has had a positive impact.

4.1 Telefonica

The Telefonica evolutionary roadmap in transport networks for 2015-2018 has been strongly influenced by IDEALIST results. Main steps to be taken in that respect can be summarized as follows:

- To complete control plane standardization work (i.e Netconf/Yang modeling, ABNO) by 2016;
- To include standard GMPLS extensions for flexgrid as a technical specification in Telefonica RfQs by 2015;
- To deploy 400-Gb/s over 150 GHz with dynamic restoration by 2016-2017;
- To include ABNO standards as a technical specification in transport SDN RfQs from 2017;
- Field Trials of 1-Tb/s BVTs in 2016;
- Field trials of S-BVTs in 2017;
- To deploy BVTs and S-BVTs by 2017-2018 in the case of:
    - Commercial availability
    - Target costs fulfilment.

Control Plane

Existing ROADMs deployed in Telefonica networks are already flexgrid capable since WSSs are LCoS-based, so that flexgrid activation only requires a software update, e.g. new control plane release. First flexgrid deployments are expected by 2016, in order to enable dynamic restoration for 400 Gb/s channels (150 GHz) co-existing with 100 Gb/s on a 50-GHz grid.

Accordingly, the following control plane extensions proposed in IDEALIST are being included in the Telefonica technical specifications for 2016:

- The routing protocol (OSPF-TE) is being extended to support the dissemination of the availability of the spectrum, by modifying the available Label Set Sub-TLV;
- BGP-LS extensions to support the TE capabilities of the flexgrid network;
- Hierarchical PCE model for multi-domain services;
- PCEP as southbound interface to send the provisioning orders.

The main control functionalities to be included in Telefonica RfQs are summarized in the next table:

Protocol	Extensions
RSVP-TE	New label defined. Multi-flow transponder support. Super-filter and Differentiated Filter Configuration Support.
OSPF-TE	Flexgrid support (Available Label Set Sub-TLV extended)
BGP-LS	Flexgrid support
PCEP	Flexgrid support. Multi-domain support. ERO Format for Elastic Optical Path.
NBI (REST API)	NBI for L0 provisioning, IP Link provisioning, MPLS service provisioning, Re-optimization trigger, Dynamic Bandwidth allocation
YANG / NETCONF	Optical Network Topology Model (Optical TED Yang model + media channel Yang model)

Table 2 Control Plane Extensions

SDN

ABNO is the Telefonica reference architecture for multilayer, multi-domain and inter data-centre SDN orchestration. Telefonica is already testing multivendor SDN interoperability according to this framework [24].

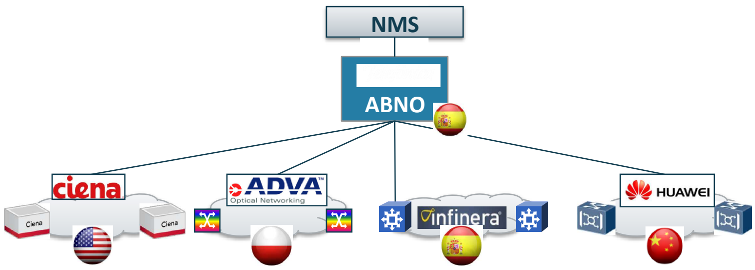

Figure 3 Multivendor tests in Telefonica

The first multivendor field trials are expected by 2016.

400G over Flexgrid

The shortest-term driver for flexgrid is the appearance of 400-Gb/s client signals and cost effective 400-Gb/s transponders. 400G transmission based on DP-QPSK over 150 GHz will enable long-haul deployments.

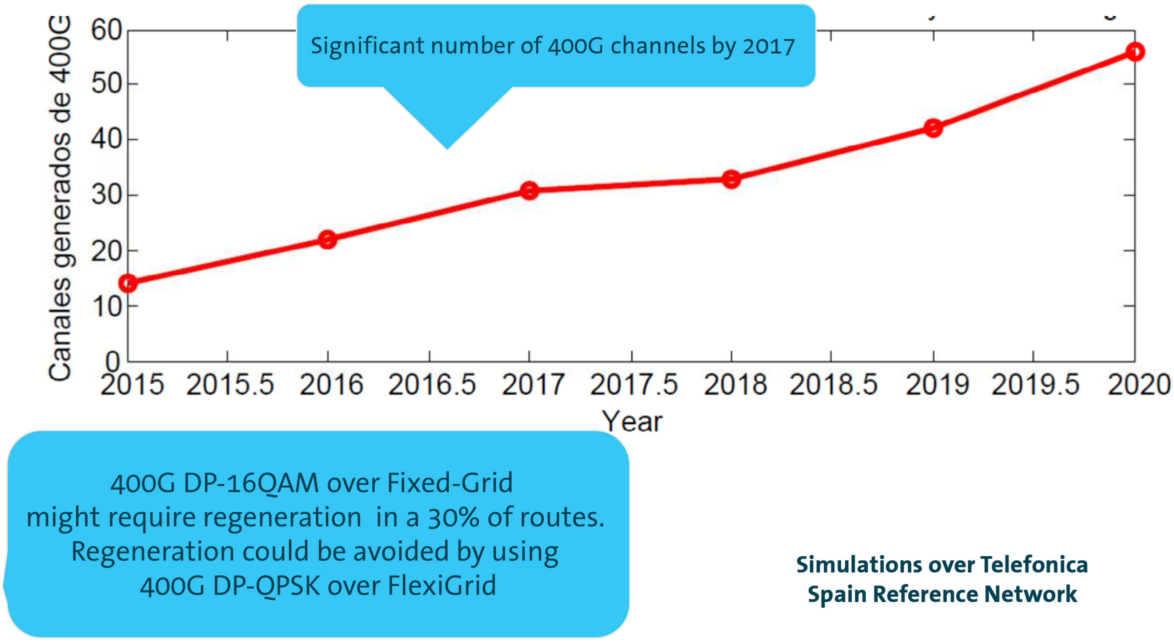

Figure 4 400G channel migration estimation on Telefonica network

The first 400G flexgrid deployments are expected by 2016-2017. These channels will coexists with existing 100-Gb/s channels over 50 GHz.

Elastic transponders

According to the simulation results done over the Telefonica core network, S-BVTs could generate significant savings in terms of the number of transponders and IP ports required. The number of cards is computed for each scenario with non-sliceable transponders and S-BVTs.

Figure 5 and Figure 6 present the percentage of total savings in the IP and optical layers. To allow for the flexibility in the S-BVT, an Ethernet switch is added in the architecture. In light of the results, we believe we can claim that the addition of S-BVTs can achieve around 30% savings in the investment for the IP/MPLS cards and optical transponders, when using 400-Gb/s S-BVTs.

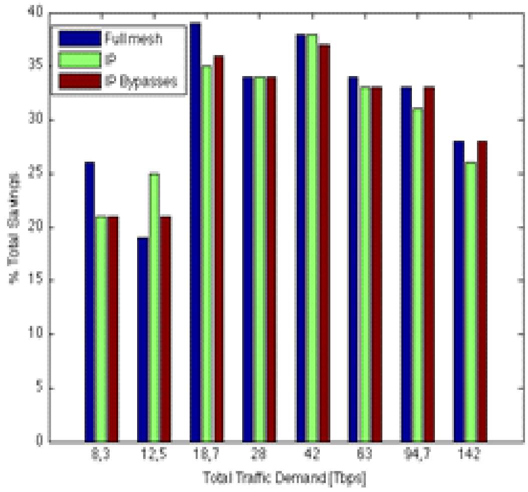

Figure 5 Percentage of total savings by using 400-Gb/s S-BVTs versus non-sliceable transponders.

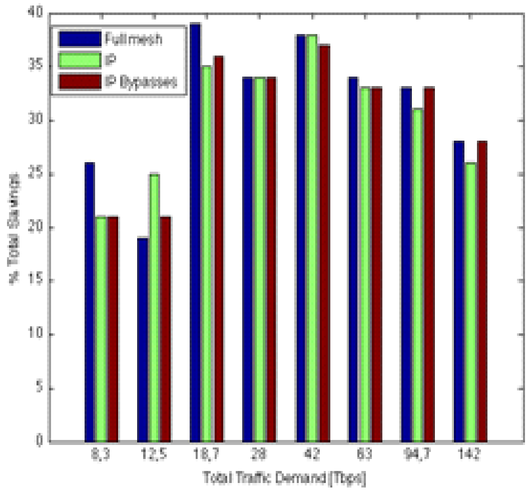

Figure 6 Percentage of total savings by using 1-Tb/s S-BVTs versus non-sliceable transponders.

Telefonica have already tested the first S-BVT implementations from different vendors. First field trials are expected by 2016-2017.

4.2 Telecom Italia

The skills acquired, and the theoretical and practical understanding of EON achieved within IDEALIST will be effectively exploited over the coming years in the planning and designing of the Telecom Italia optical transport backbone network. In particular, EON is expected to be the cornerstone of both the next-generation National Italian and Pan-European backbone photonic networks, and the introduction of S-BVT technologies is anticipated to provide a significant element in reducing operational costs.

In contrast, in the metro-core segment the cost advantages of full flexibility are not so clear cut; thus the IDEALIST concepts may, almost exclusively, find their first full place in the most challenging application scenarios, this being (at least, in the short- and mid-term) the big metropolitan areas with cloud data-centre internetworking requirements.

National Italian backbone evolution

The main evolutional driver for the Italian Backbone photonic network is the planned change in topology of the existing client IP Telecom Italia backbone network. Indeed, even if the chosen photonic technologies are client agnostic, and the network is designed to support several transport services; the main client of the optical backbone is our own IP backbone.

The topological planned changes and the transition from a 10/40G to 100G (and possibly beyond) dominant router interconnectivity, will force the introduction of a new higher capacity optical transport network. This is justified by the fact that the current optical backbone based on fixed grid optical ROADMs, originally designed for the coexistence of coherent and non-coherent wavelengths, was supposed not to have been able to be conveniently upgradable to become a full high capacity platform. Furthermore, the expected growth in IP traffic and the future availability of 400 GbE interfaces on routers (the IEEE standard is near) is creating a push towards the introduction of 400G and beyond transponders and more flexible solutions in the network.

For the aforementioned reasons the new network will be based on EON, and by exploiting flexgrid ROADM and BVT technologies, this will enable further evolution of the IP backbone and support for cloud data centre networking interconnection services not yet already planned in detail, but still expected to emerge over the next few years.

In line with this, evolution of the network control plane is needed to fully exploit the flexibility enabled by the data plane. To that end, the control plane architecture that is foreseen is in line with the IDEALIST design, based on a hierarchy of controllers/orchestrators enabling multi-domain approaches and allowing easy integration with the IP backbone and with data centres.

Pan-European backbone evolution

According to present and past trends in network renewal, a new tender for the acquisition of a next-generation optical system in the Pan-European network can be expected within the 5 years time frame. For this platform, the main driver is expected to be the increase of long distance high capacity bandwidth services together with improvements in spectral efficiency. The full capabilities of EON are not expected to be completely employed, especially flexible dynamic reconfiguration; nevertheless the flexible use of the optical spectrum and potential OPEX saving due to the inherent reduction in item numbers and stocks with the introduction of (S)-BVTs and related SDN functionalities, are anticipated to be concrete enabling opportunities.

Roadmap for evolution towards EON

According to the expected evolution of the relevant technologies and planned network deployments, a likely roadmap may include the following steps:

- By 2016, field trials of 400G BVTs (or perhaps first generation S-BVTs) from different vendors to directly test the maturity of the technology.
- By 2016, submit RFIs to major vendors to survey the state-of-the-art, the maturity and commercial availability of EON solutions, with particular focus on flexgrid ROADMs, 200G and 400G BVTs, and check the roadmap for the introduction of 1T and S-BVT devices. The survey will also focus on the maturity of control plane solutions for multi-vendor/multi-domain interoperability, with special attention to IP/optical integration (in line with the aforementioned importance of the IP backbone

as the main client of the TI optical network) and, possibly, to backbone/data centre interworking.

- By 2017, a RFQ or tender for EON equipment for the National Italian backbone.
- 2017-2018, field trials of (S)-BVTs with 1T capacity and IP/optical integration at control plane level.
- By 2018, start of deployment of EON National Italian backbone with flexgrid ROADMs and 100/200G BVTs controlled by a hierarchical SDN-based architecture able to perform IP/optical integration.
- 2019-2020, RFQ and following deployment for the Pan-European EON backbone.

Sliceable transponder saving opportunities for long-term evolution

Within the IDEALIST project, extended studies have been done to evaluate the price conditions in which EON technologies would become interesting for their actual deployment by an operator, and which will allow them to compete in the market. As the cost of next-generation flexible transponders is very hard, or even impossible, to predict, the method of the “target cost” is used as an approach to evaluate the cost that flexible devices would have to exhibit, in order to justify their introduction in place of fixed ones.

In addition to the techno-economic study performed by Telefonica and reported in subsection 4.1, Telecom Italia has also performed a techno-economic study on the Pan-European backbone, with the aim to compare the cost of a network planned with fixed transponders (FTs) only, to the cost of the same network planned with BVTs or with S-BVTs.

The hypothesis is that the Pan-European backbone evolves over time, in five successive time period steps, in which the traffic is supposed to double from one period to the next. The time between successive periods is not defined and depends on the CAGR. For instance, a CAGR of 41% implies a step period of two years: in this case the entire analysis covers a time frame of 10 years.

In this evolution framework, the assortment of interfaces required by clients are assumed to change from dominant lower rates (100G and 200G) in the short term to dominant higher rates in the long term (1T and 2T).

Assuming that flexgrid ROADMs are installed for the whole analysis period, for all the 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 the 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); or by a portion of the capacity of a single very high capacity device (1.2T or 2T) in the case of a S-BVT. In the case of a S-BVT, a client demand uses not only a part of the electronic capacity but also a subset of the total number of S-BVT optical sub-carriers.

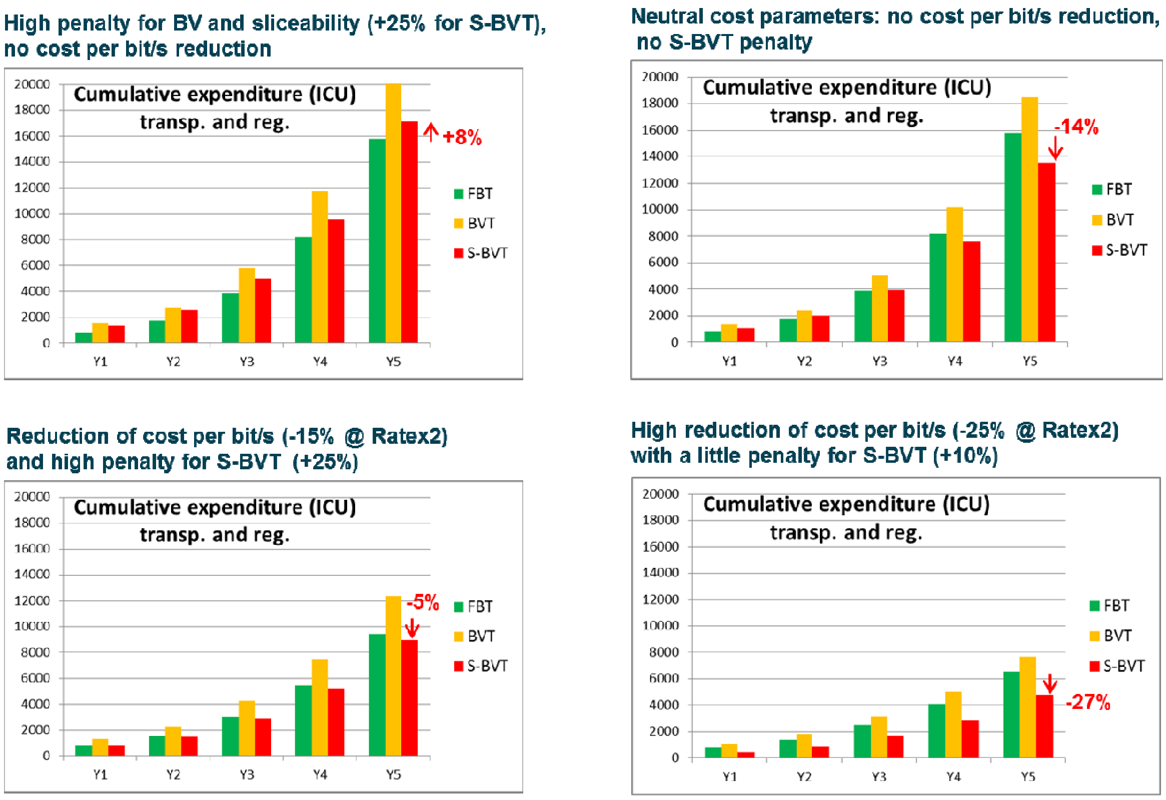

Figure 7 Transponder costs for different device alternatives and cost parameters trends of EON devices.

Going into deep detail is out of the scope of the report here, but some interesting hints can be drawn from the findings as shown in Figure 7.

Figure 7 shows the cumulative cost for transponders only: the cost of all other network parts are the same in all the cases, since the network is supposed to use flexgrid ROADM technologies, and the spectral efficiency is supposed to be the same for all the devices, whether they are fixed, variable, or even sliceable. The transponder costs for BVT and S-BVT in Figure 7 are evaluated under four different parameter trends with respect to: cost per bit reduction with capacity, and penalties for bandwidth variability and sliceability implementation. The BVT is always the worst solution because the expensive electronic capacity is sometime 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 therefore wasted.)

S-BVT technology, in this scenario of traffic growth and changing of assorted client rates, results in the most cost-effective solutions for a wide set of cost parameter trends. The only case in which the use of S-BVTs performs worse than employing FTs is the very pessimistic one (top left of Figure 7) 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 good cost performance of the S-BVT is due to the intrinsic ability of a S-BVT to reconfigure itself from a higher number of lower rate clients to fewer higher rate clients, so avoiding the waste of CAPEX caused by lower rate interfaces no longer being used, or to the cost of displacements of existent interfaces among nodes in the case where the requirement of interfaces types on nodes changes. In other words, S-BVT technology performs well not only in the case of increasing traffic but also in the case of there being uncertainty in knowing what are the assorted client rates and traffic patterns. We consider the previous results as representing strong arguments in favour of the introduction of S-BVT, starting as soon as this technology becomes available. Looking at the mid- and long-term, we believe that such a choice will also be strategic as a means to gain technical and economic advantage in our network.

4.3 Deutsche Telekom

Relevance of the project as a whole on the network efficiency, architecture, operation models and networking paradigms

Deutsche Telekom will exploit the joint project results in order to increase its network efficiency. Likewise, this will ensure the flexibility and scalability of DT's network infrastructure in coming years. In particular, the installation of new fibre types (e.g. multi-core or multi-mode fibre) in the German network can potentially be avoided for nearly the next two decades - this is therefore connected to a very useful cost saving.

- Impact on service availability, competitiveness and job security

From the IDEALIST results, further improvements in service availability are expected from the introduction of flexible optical technology. Formerly hard physical range limits can now be countered by an automated adaptation of BVT capacities. From an end-customer's perspective, less time-consuming intervention can be carried out at the application level, such that the network appears to be both more secure and stable. Customers will therefore experience a higher service quality. As a result, we expect that DT's competitiveness will be strengthened and the already excellent market reputation of Deutsche Telekom further increased. In that wider sense, IDEALIST is therefore contributing to secure DT employment in Germany and Europe as a whole.

- Clarification of strategic & architectural migration guidelines

For Deutsche Telekom the project has also been of great importance, since it has demonstrated the superiority of next-generation flex-rate transceivers and their application potential in the various network segments that DT operates. The enormous cost advantage caused by multi-layer resilience (MLR) – already introduced in DT's national backbone network – can be even increased through tailor-made EON applications. Future elastic interfaces with highest data rates beyond 100 Gb/s will serve for connecting backbone and metro/regional nodes with their associated data centres, and make network connectivities even more safe, more secure and more reliable than today.

As one of the key strategic outcomes, the IDEALIST project emphasizes the need for an appropriate ABNO-based control plane as part of an integrated Transport-SDN solution. Deutsche Telekom is also introducing this paradigm change from a GMPLS-based control plane towards a comprehensive SDN approach, with its modularity both on the hardware and the software level. Consequently, DT is planning to introduce an intelligent network controller with open source software components for flexible and customized service provisioning. From today's perspective, this migration to, or the utilization of, this new platform control is considered as being essential for the economic survivability of not only start-up companies but also established incumbent network operators. SDN's modular design and function disaggregation is also expected to improve network flexibility, usability, and competitiveness against other operators and over-the-counter (OTC) providers.

- Activities related to the Elastic Black Link (EBL)

Furthermore, DT is expecting dramatic cost reductions in optical interfaces and further network infrastructure, plus avoidance of vendor lock-ins when an interoperable EBL at data rates beyond 100 Gb/s becomes standardized, or when there exists at least a joint specification of the line-side parameters with major vendors. Thus, DT's effort is based on the requirements enabling the EBL defined in IDEALIST. DT is intending to run lab experiments on the validation of the EBL concept, and isolating critical performance parameters, such as the error vector magnitude (EVM). DT further plans to drive a multi-vendor EBL specification in close cooperation with the widely recognized TeraStream project.

- Field trials and experiments

DT is planning several field trials on elastic interfaces and control plane implementations. The first one is planned together with an IDEALIST system vendor and further project-external suppliers in Q4 2015. It is targeting a vendor-interoperable transport platform controlled by a Transport-SDN hypervisor. Multi-layer use cases will also be experimentally investigated.

A further field trial on flex-rate transceivers at the transport layer embedded into packet routers at the client layer is foreseen in late 2016 or early 2017. Instead of hero results, this proof-of-concept will focus on the technical feasibility of a coordinated recovery from multiple failure patterns. In this sense, software-programmable capability of supporting multiple modulation formats and encoding schemes will be investigated. This field trial shall also demonstrate the fast adaptation of flex-rate transmitters and receivers in reaction to an optical link failure.

- Technical specifications in case of RfQs

Technical results from IDEALIST are flowing continuously into tender requirements for equipment suppliers. While DT has already included control plane standards for flexgrid technology as technical specification in RfQs for optical transport equipment in 2015, we are intending to carry on in a similar vein. In the future, ABNO standards as technical specification in RFQs for Transport-SDN equipment and solutions are also being planned, once the technology has become stable and mature.

- Contributions to standardization activities

For years now, Deutsche Telekom has actively contributed to international standardization bodies and often takes a leading role. General participation covers, e.g. the Internet Engineering Task Force (IETF), the Optical Internetworking Forum (OIF), the Open Network Foundation (ONF) with its the Optical Transport Working Group, the Institute of Electrical and Electronics Engineers (IEEE) and the ITU-T, which all significantly affect the development of telecommunication networks and architectural concepts. Particularly, the joint effort of OIF's Carrier Working Group (WG) and the Physical and Link Layer (PLL) WG on "Technology Options for 400G Implementation" deserves DT on-going support, as these groups are actively investigating the enabling technologies and implementation options for near-term 400-Gbt/s BVTs. As the whole industry moves forward towards 400G-transmission speeds, it is crucial to have operators and system vendors working together within standardization bodies. Therefore, Deutsche Telekom will continue to disseminate the key IDEALIST results within this particular organization, and will influence the design of the relevant EON standards.

- Publications and dissemination

Furthermore, Deutsche Telekom is continuing to increase the visibility of the project around the world, in that they are publishing scientific project results in a timely manner at conferences, such as the European Conference on Optical Communication (ECOC) or the

US-based Optical Fibre Conference (OFC). Key technological achievements with higher management attention are also being considered for publication in widely recognized journals such as the IEEE Communications Magazine. This demonstrates the technological leadership of European universities, scientific institutes and networking industry in the field of telecommunications and IT infrastructure.

- Intellectual property rights and patents

On the one hand, the collaborative project results that have been obtained will be made available to other network operators. On the other hand, key technological know-how, intellectual property and exploitation rights are also being protected for the benefit of the DT group. The most promising ideas and methods are therefore being continuously submitted as inventions to the European Patent Office (EPO) in Munich. In doing so, DT as an industrial partner of the IDEALIST consortium is therefore demonstrating the innovation strength of European industry as a whole. DT has exhibited a rich and successful patent history during the IDEALIST runtime. So far, four inventions have been filed at the EPO, and one further idea is likely to be submitted in the next few months.

- Impact on DT-internal organization

The IDEALIST findings are to be used in particular in internal projects in order to further promote the fusion of the optical transport department and packet router department within Deutsche Telekom. The recent past has shown very promising benefits of such a close internal cooperation. More economic benefits are now expected by an elastic optical transport infrastructure integrated into packet-based client network and a Transport-SDN orchestrator. This joint engineering of the involved competence departments will again foster collaboration and internal organization.

- Impact on the connectivity of European citizens and the related growing together of European societies

DT’s affiliates will also be involved in the exploitation of IDEALIST results. Especially for subsidiaries in South-Eastern Europe, including the incumbent Balkan operators, sharing of project results and creating new business opportunities out of that aims to sustainably influence the economic development and prospect of investments in this area. For instance, DT’s association with the Greek network operator OTE is continuing to positively contribute to economic development in the region and support the open exchange between European citizens.

4.4 British Telecom

Overall, BT’s network will continue to evolve to higher and higher capacities. As part of this evolution, the IDEALIST concepts will be deployed as they are required. BT expects to see flexrate BVT technology first, and flexgrid coming later. There will be some targeted early use of 400-Gb/s ‘superchannels’ (2 sub-channels) for key links that are filling up quickly. Full EON embodiment is further away, and will require continued bandwidth growth and perhaps an increased need for network dynamics at the optical layer – something that is still not a priority for BT.

- Field trials and experiments

As part of its involvement in IDEALIST, BT has been running field trials with vendors to assess the capability of EONs. BT has shown various capabilities including: (i) superchannels of up to 3 Tb/s constructed by bringing 200-Gb/s DP-16QAM sub-channels as close together as possible (around 32GHz); (ii) flexrate tunability – changing from DP-QPSK to DP-16QAM; (iii) superchannel protection; and (iv) coexistence of superchannels with legacy channels without interference. The purpose of all these trials was to check that the IDEALIST concepts work in practice, over real installed fibre links – often with poor fibre. The results of these demonstrations have been highly successful and proved that EON technology is not just beneficial but also very robust.

As well as demonstrating the overall capacity benefits of flexgrid, BT has also focused on alien waves. When faced with, for example, a 1-Tb/s client signal from a router, it is an expensive solution to use electrical interfaces at the router and terminal equipment – it is preferred to have the long-haul optics in the router where possible. BT has already made use of alien wave technology in strategic places in our network – both to reduce costs and also where there is no space to build the additional terminal equipment required (or power available to run the equipment in some cases.)

- Strategic network evolution

First changes towards EONs will involve DP-16QAM to access higher data rates per transponder giving an immediate cost benefit. Later developments will see deployment of flexgrid capability where needed – although the smaller spectral savings from flexgrid provide a smaller benefit as compared to flexrate.

Although the majority of the current work within BT is focused on increased cost effectiveness of data plane technologies, it has become apparent through IDEALIST, that the need for a more comprehensive spectrum control on a network-wide scale is critical. This may well not include SDN in the early years – where the optical transmission-based core network can be controlled and managed on its own without the need for multilayer or multidomain operation.

BT can imagine SDN functions being introduced steadily – firstly in off-line traffic optimization and network data gathering functions, giving real time network visualization and allowing more considered and optimized traffic engineering decisions to be made. As confidence builds with SDN, then it could begin to be used for a restricted range of functions in niche situations where a full-scale interoperability with the existing OSS is not required.

- Impact on service availability, competitiveness and job security

From the IDEALIST results, further improvements in service availability are to be expected by the introduction of flexible optical technology, which will ultimately lead to faster, more responsive provisioning as well as more pro-active planning. Formerly hard physical range limits will be countered by an automated adaptation of BVT capacities. BT's competitiveness will therefore be enhanced within the telecoms market place, with the relative commercial dynamics of such a disposition therefore encouraging overall employment stability.

- Publications and dissemination

BT is very keen to continue to publish and disseminate results – partly to demonstrate market leadership but also to ensure that the technology developed is fit for purpose. The UK is not a large country geographically, and doesn't require solutions optimized for ultra-long haul. In the new EON era, solutions meeting BT's needs should become more readily available since the required flexibility will allow technology to adjust to the specific network environment. Therefore it is critical that BT publishes and communicates the requirements of networks smaller than those in the US, for example. IDEALIST has been the "ideal" vehicle for this dissemination, coupling BT with experts able to model BT requirements on BT topologies.

- Impact within BT

Internally, BT has both a research and a networks division: these are both in the same overall organization but focus on different timescales. IDEALIST has provided high quality material that the research team has been able to use to fuel internal discussions on the direction of the BT network – for example which kind of optical filters or transceivers to use in given situations. More fundamentally, when the time comes for the next major network technology refresh, the IDEALIST work will be centre-stage in providing the key direction for vendor solutions, and indeed will arm BT with sufficient in-depth understanding to be able to effectively adjudicate solutions that meet our requirements.

4.5 Ericsson

Ericsson is designing EONs to solve the issue of having separate IP and optical transport networks, causing unnecessary resource overhead. EON represents the solution to accelerate the IP optical transport convergence and is enabled by the availability of coherent technology, flexible grid allocation, and multi-rate transmitters/receivers. The application of such technologies allows optical transmission systems to cope with increasing capacity demand without costly upgrades to the physical fibre network. Relying on the latest advances for SDN approach both in the telecom and datacom industry, EON offers a solution to attain the high levels of automation that modern networks demand for both IP and optical systems. This is also consistent with many operators who are moving toward a converged approach, with joint operation of IP and optical transport.

In this scenario, S-BVTs (as defined in Task 2.2 of the IDEALIST project) are an enabler for IP optical transport convergence. The programmability of the proposed platform, together with the monitoring features and the new capabilities to increase transmission capacity up to 1 Tb/s is paving the way for the needed network flexibility in the evolution towards 2020, at least for the back bone transport network.

S-BVTs provide flexibility to network operators through the support of variable bit rates, distance adaptation, and slice-ability (i.e., the generation/detection of multiple optical flows, aggregated or sent towards different paths/destinations according to the traffic requests.) S-BVTs may result in cost reductions by providing the functions of multiple transponders into a single card with the dynamic setting of software-driven functionalities and datacom traffic handling capabilities [25].

To define a sustainable evolutionary path, each part of the S-BVT needs to be realized with the right technology as reported in [26]. Over the next three years, complementary metal oxide semiconductor (CMOS) based electronic is expected to scale industrially down to 14 nm and complex processing functions can be designed in dedicated ASICs for superchannel generation to significantly enhance system margins with respect to current 100 Gb/s installed transmission systems. The sustainability may be obtained if photonic integrated circuits (PICs) are used. Actually, silicon photonic integration can give a great help with the introduction of PIC modules encompassing electrical drivers, optical modulators and filters, with the laser sources designed to be removed from FSC and integrated on the line card [27]. The possibility to produce silicon photonic devices in a CMOS production line leads to very low-cost photonic solutions. Really promising CMOS photonics is industrially evolving from 130 to 90 nm node dimensions, e.g. with a single lithographic process hundreds of photonic components can be integrated with millions of transistors. Substantially, CMOS technology applied to photonics allows for a high integration level between the electronic parts, providing both monitoring and signal processing functions, and the optical section with ultra-small electro-optic modulators, fast photodetectors, and low-cost in/out fibre couplers. By improving uniformity in the optical design on wafer scale, costs are strongly reduced and performance enhanced. Thanks to better node resolution, traveling-wave electrodes or silicon insulator silicon capacitor Mach-Zehnder modulators can be efficiently realized with reduced optical mode leakage and a low $V_{\pi}L$ product, compatible with standard CMOS electrical line drivers [28].

To perform network flexibility and adaptability the interoperability of several implementations of S-BVTs by different system vendors must be enabled for applications suitable for both telecom and datacom traffic handling.

To this aim, Ericsson in collaboration with CNIT and Coriant has experimentally validated an integrated multi-domain, multi-vendor, flexgrid, control and data plane network. Protocol extensions have been evaluated in a distributed multi-partner control plane test-bed. The carried research activity gives the possibility to define the applicability and feasibility of fully end-to end interoperable EON network at control and data plane levels.

This activity has the aim to start a new open approach in the definition of a network architecture in order to efficiently distribute resources. Any resource should be available where and when it is required, in order to enhance fast responsiveness from the network. This approach enables network service differentiation and has the aim to serve any request in the shortest time possible and with the most suitable quality of transmission. These features should be maintained also in a fully end-to-end interoperable EON network.

The network architecture fashioned in this way, and the technological evolution needed for the S-BVT design will have a direct impact also on the new evolution of the Fifth Generation transport networks (5G), which corresponds not only with the network transformation in the mobile world, but also with the transport network. In this evolutionary vision, all the research activity carried out by all partners in the IDEALIST consortium will give a substantial contribution into the network design to reduce complexity and increase flexibility by abstracting network resources and functionalities, as well as managing services on-the-fly through programmatic apps [29]. These are the basis of the promise of 5G evolution.

4.6 Coriant

The knowledge acquired by Coriant during the timeframe of the IDEALIST project is of fundamental importance, and it will positively influence the next generation of our products, not only in terms of features, but also of awareness of operator needs. The positive results for Coriant also concern standardizations and recommendations. Overall, we were present in all the main activities of IDEALIST, such as network planning (WP1), data-plane solutions (WP2), control planning (WP3), and experimental verification (WP4).

Network Planning Tools

The adoption of a flexible DWDM grid along with the support of BVTs and S-BVTs not only imposes new requirements on both the data and control plane, but also demands significant changes in network planning tools, namely the ones focusing on DWDM networks. The IDEALIST project has been instrumental for Coriant to be able to better understand how existing planning tools (and planning processes) should evolve to take advantage of the new degrees of freedom enabled by the adoption of a flexible DWDM grid, and the deployment of transponder equipment characterized by being modulation format adaptive and supporting super-channel configurations. It is noteworthy, that such flexibility enables a more cost-effective use of transponder and spectrum resources.

However, it also means that network planning is becoming more complex, given the wider array of configurations available. The knowledge acquired in the IDEALIST project will therefore materialize in the form of a set of features that will improved our DWDM network planning tools, making them more advanced and robust.

Data plane solutions

The extended series of experiments that Coriant and TU/e have conducted within IDEALIST will have a significant impact on next generation Coriant transponders. Herein we investigated and developed techniques that showed their effectiveness to significantly improve the transmission performance of our transponder. This research has contributed to the definition of the roadmap of upcoming Coriant products.

As planned in the DoW, we started from numerical simulations and then moved to lab experiments. After having acquired the needed knowledge, we involved ourselves in two field trials [30][31], plus a third under preparation (planned at the end of Nov. 2015). Both trials have proven in the field the validity of our techniques. In particularly, in [31] we reported on the performance of a first prototype of our upcoming product, used to transmit over a real customer network. In this experiment, all the main features of a BVT, widely investigated within IDEALIST, have been tested and verified in the field. Moreover, the lessons learned, the developed algorithms and the expertise acquired in system optimization will help us to define the new engineering rules for the next-generation of Coriant systems.

Moreover, we have been collaborating with several partners. This has helped us to contribute to a significant number of scientific publications and to acquire expertise we were lacking in. These fruitful collaborations will hopefully also contribute in establishing future projects.

Finally, we were active in terms of standardization and recommendations. For example, we were the first, together with our partners, to deal with the topic of interoperability and elastic black link. The content of this analysis has provided important guidelines for the realization of interoperability among different operators and vendors that could be useful within the standardization institutions.

Control Plane Solutions

As Coriant further develops its own control plane related solutions – comprising both GMPLS and SDN – the outcomes of the IDEALIST project (e.g., standards extensions, architecture modifications and enhancements, field-trials) related to the control plane will be analysed internally and used to confirm or challenge the features under development related to efficiently support a flexible DWDM grid and BVTs/S-BVTs in next-generation transport networks.

Moreover, the project also presents an opportunity to know first-hand the requirements (along with their priorities and timelines) that the network operators are setting for the control and management planes, e.g. see the Telefonica roadmap above. This will be used as an input to better shape our portfolio evolution to meet their requirements.

4.7 ALU

Alcatel-Lucent already believes in the importance of EON and has already begun to support a wide range of elastic features in its Optics portfolio. The research work conducted within the IDEALIST project is a further step to pushing more flexibility into optical transmission, node architecture and software management tools.

The Alcatel-Lucent plan for exploiting IDEALIST results is based on the following main items: (i) the technical options designed and prototyped for elastic optical communications, to allow (ii) networking applications with (centralized) controller enhancements. (iii) Together, these two enhanced elements have been integrated in the final demonstrations, with such an integration phase often leading to good opportunities for business needs.

- Contributions to standards

Alcatel-Lucent is actively involved in standardization activities related to the IDEALIST context [32][33][34][35][36]. We are involved in ITU-T Q6 that, specifically, is treating the flexible grid definition, G.698.1 and G.698.2.

Moreover in the ITU we are heavily involved in the definition of the so-called “beyond-100G-OTUflex” work, in Q11 and G.709 extension in Q9. Following this activity we have in fact used the related concept to provide a FPGA in the project to enable multiplexing/demultiplexing of 1 to 10 OTU2 lines to simulate OTUflex implementation.

In the IETF Alcatel-Lucent has actively contributed to the framework draft for GMPLS-based control of a flexible-grid WDM network (draft-ietf-ccamp-flexi-grid-fwk-07) that recently passed LC to become a RFC. We are also involved heavily in the context of SDN both in the ONF and IETF. In the ONF, Alcatel-Lucent is co-author of the requirements for Transport API, SDN Architecture and Common Information Model, and in IETF we are also the co-author of a draft composing the overarching work, called Abstraction and Control of Transport Networks (ACTN), for which we have referenced only the requirements document for the summary.

- Tentative roadmap for potential commercial products identified in section 3

The overall Alcatel-Lucent strategy is to evaluate the opportunity of including research results into commercial products. In particular, the research efforts of Alcatel-Lucent in IDEALIST have been mainly directed to flexgrid optical networks. Indeed, commercial optical cross-connects were already flexgrid-ready at the project start, since the latest generation of WSS devices are LCoS-based, while further work has been required on the transmission cards to make flexgrid a reality.

As already mentioned in Section 3.4, Alcatel-Lucent’s key achievements in IDEALIST have been focused around transponder technology and control for software-defined hardware reconfigurations. Feasibility study for integrating them into commercial equipment (related to the 1830PSS family, mainly) has been under discussion for some of them, and will most likely be planned for the others. A tentative roadmap including these contributions is presented below:

	What?	Why?	Commercial availability
Static network	New modulations (e.g. 8QAM)	• Reach extension for 200G applications • Spectrum packing for beyond 100G applications	Yes
Static network	1Tbps capacity card	• Spectral efficiency	Medium/Long term
Static network	Cross-channel nonlinear compensation	• Reach extension • Spectral efficiency	Long term
Reconfigurable network	Flexible OTU container	• Bridge the gap of flexible electrical layer (ODUflex) and elastic transponder line rate • No fixed rate OTU5 for beyond 100G	Medium term (OTN standard in late 2017)
Reconfigurable network	OpenFlow commands	• SDN-controlled hardware devices	Medium term
Reconfigurable network	SDN controller	• control plane for optical portfolio	Medium term

Towards dynamic network

Figure 8 Alcatel-Lucent roadmap towards dynamic networking

Currently, Alcatel-Lucent offers a very flexible transponder card with a wide-range of modulation formats, such as QPSK, 8QAM, 16QAM, and a CDC-flexgrid node is now commercially available. This is a very good starting point for more advanced field trials with even more flexibility. This could include aspects such as higher data rates, flexgrid networking use cases, more flexible applications, and interoperability with legacy signals.

Besides this, the following actions have been already taken on the definition and implementation of configuration messaging into the standard equipment controller and on the implementation of a RESTful server to support a SDN controller on the actual commercial equipment configuration interface.

- New network operation models/paradigms, impact on network efficiencies

The techno-economics obtained during the project lifetime focused on studying the new candidate business cases for better network efficiencies and resource savings. This was obtained from dimensioning network results. A few examples are listed here below:

- We introduced a new paradigm of 'just-enough recovery' in [37] the leveraging of elastic optical devices capable of adjusting their modulation format (and hence data rate) when a restoration of an optical path is needed. The idea is to delay the delivery time of best-effort services while maintaining the service availability for gold traffic. Simulation results show ~35% cost reduction with 30% gold traffic [37].

- We also studied the impact of asymmetrical bidirectional traffic routing in the case of elastic devices. The newly introduced routing paradigm saves up to 25% overall (add/drop and regeneration) optoelectronic devices [38].

- We studied the impact of flexgrid networks based on a just-enough bandwidth allocation, to support the exact traffic demand in the case of tight filtering impairments. The ideal extra capacity of 33% brought about by 37.5 GHz channel spacing (compared to 50 GHz) may be significantly reduced under the physical constraints of fully transparent meshed networks [39]. In such a networking scenario and gain, Alcatel-Lucent is now convinced that truly dynamic flexgrid gain is not sufficient compared to the complexity of management of optical channels and spectrum defragmentation.

- Impact on internal organization and European collaboration

The IDEALIST results of all consortium members have contributed to the sharing of knowledge and enhancement of expertise of the research teams. As an illustrative example, Alcatel-Lucent Bell Labs and the University of Bristol were, for the first time, studying and implementing a proof-of-concept OTN framer; this knowledge was acquired quickly thanks to the help of Alcatel-Lucent Italy's team which is expert on OTN standards.

Second, techno-economic studies of WP1 and also discussions between telecom operators, system vendors and academics have jointly delivered some industrial guidance about the next and future generation of optical networks.

Lastly, the numerous outputs of the projects and successful (real-time) experiments of Alcatel-Lucent would most likely be integrated as new features in various products, to ensure that optical networking becomes ever more scalable and more automated. This will be only possible with flexible data plane products, and dedicated software tools for the management and control plane.

4.8 Naudit

Naudit's strategy to exploit the skills and knowledge acquired during its participation in IDEALIST is coordinated in three categories: High-speed monitoring probes, algorithms for bandwidth estimation and link dimensioning, and a new product line for operators based on dynamic bandwidth allocation.

High-speed monitoring probes

Passive monitoring probes are a key element in NAUDIT's business. A major part of NAUDIT's revenues is obtained from network analysis and monitoring services for big corporations. As the speed of network links keeps growing, monitoring traffic in the backbone of a complex network is becoming more and more challenging. Nowadays, 40 and 100 Gb/s are becoming common in corporate backbones. However, pure software approaches, based on commodity NICs, are no longer valid at those speeds.

During IDEALIST, NAUDIT has explored different FPGA-based solutions for passive network monitoring. While FPGA-only solutions have shown a very good performance, the main problem of this approach is the cost of the high-end FPGA platforms needed. As a solution, a hardware-software approach was also evaluated during the development of IDEALIST. The advantage of this solution is that it can use a lower-cost FPGA, because the programmable device is only used to accelerate the critical parts of the monitoring application. In this way, an FPGA-accelerated version of NAUDIT's monitoring tool, Detect-Pro, was developed as part of IDEALIST activities. The results were promising, determining the path to follow for future developments in network monitoring probes at NAUDIT.

Figure 9: Naudit's Kinnic board FPGA solution for passive network monitoring

Figure 9 shows the Kinnic board, developed by NAUDIT in the context of IDEALIST. The purpose of this board is to substitute a commodity NIC, offloading heavyweight tasks in the flow generation and filtering processes to the FPGA. As a result, NAUDIT plans to continue the development of the Kinnic board in order to offer it as a commercial solution in its 10 Gb/s monitoring portfolio. Additionally, there are plans to create a 40 Gb/s version of the board in order to keep NAUDIT's monitoring capabilities up-to-date.

Bandwidth estimation and link dimensioning algorithms

As part of IDEALIST's WP3 activities, NAUDIT developed a series of algorithms for bandwidth estimation based on the output of monitoring probes. The goal of these algorithms is to characterize links beyond transient situations, based on the observation of network flows. For example, Figure 10 shows the proposed bandwidth for a network link, and how this proposal follows the actual bandwidth but minimizing the number of bandwidth changes and ignoring transient changes in traffic.

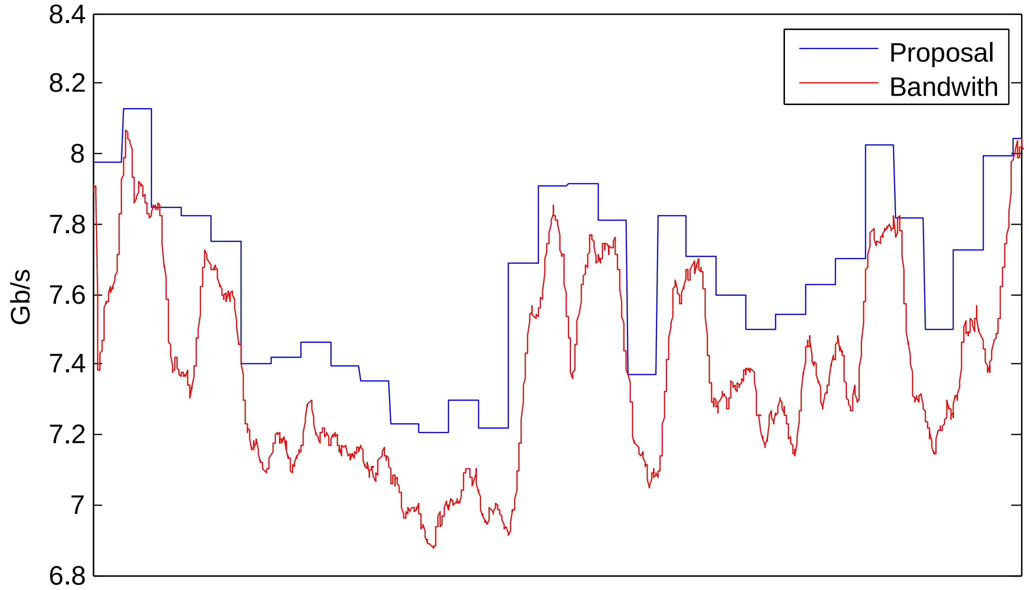

Figure 10: Naudit solution for bandwidth estimation and network flows

NAUDIT plans to exploit these algorithms for two purposes. First, bandwidth estimation algorithms will be used to evaluate the dimensioning of links. An important aspect when analysing the network of a client is being able to recommend the correct size for the different network segments. Second, and probably more important, these bandwidth estimation algorithms will be helpful in order to detect anomalous situations, such as distributed denial of service (DDoS) attacks. A sudden bandwidth increase, significantly beyond what is considered to be normal by the algorithm, could trigger a security alarm. Moreover, the basis for the bandwidth estimation algorithms is network flows. A variation in the characteristics of flows (size and/or number) will also trigger an alarm.

New product line targeted to operators

Naturally, the results of IDEALIST's dynamic bandwidth allocation (DBA) experiment are a perfect candidate to be industrially exploited. The planned strategy is to offer DBA as a supplement to NAUDIT's network analysis and monitoring services. The goal is that NAUDIT's probes will no longer be just passive elements in charge of monitoring and storing traffic: They will also provide live information to the OAM handler in order to trigger network reconfiguration, if the operator provides this service. The benefit of this approach is that is does not require more equipment, since it can be implemented on top of NAUDIT's infrastructure for traffic analysis.

Obviously, this is a long-term plan that depends on the adoption of flexgrid by operators, and the development of new business models beyond the classic SLA. For example, operators could sell network links that dynamically adapt to the bandwidth requirements of clients, which are charged according to the bandwidth provided to the client at every moment, instead of following a fixed-price model.

5 Idealist Socio-Economic Impact

The IDEALIST project has been conducted within the on-going context of exponential increase in end-user bandwidths and network data capacities. Indeed, when looking at the recent and on-going exponential increase in broadband data-rates, we see in Figure 11 that even over the 3-year duration of the IDEALIST project from 2012-2015, peak-time data rates (for the BT network) have in the least doubled, from about 600 Gb/s at the beginning of 2012, through to about 1.2 Tb/s in 2015. This behaviour is fully in line with the original IDEALIST goal, of being able to handle multi-Tb/s aggregated data streams in the core network, with typical annualised growth figures of about 60%. From this perspective, the work that has been performed during the IDEALIST project has been fully consistent with this exponential socio-economic trend, and the burgeoning digital society agenda.

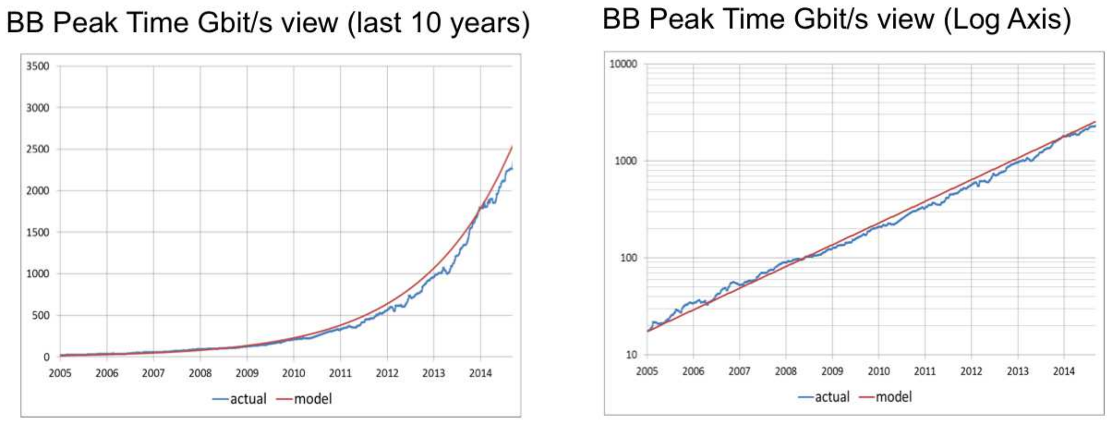

Figure 11: Exponential annual growth of peak broadband bandwidths [40]

One of the key leaders of the IDEALIST project, Prof. Andrew Lord (BT), leader of the work package WP1, recently presented a paper at the UK's Royal Society [40] on the subject "The impact of capacity growth on national telecommunications networks" where he also presented the Table 3 below, indicating the average bandwidths in core links expected over the next 10 and 20 year time-frames, again with exponential annual growth rates of low (25%), medium (45%) and high (65%). These results indicate the pressures that core networks are anticipated to experience in the coming years, in terms of raw bandwidths to be handled by individual fibres, as well as the expectation of multiple fibres required between congested nodes. All these aspects have been studied and researched in detail during the IDEALIST project, e.g. via the switchable S-BVT technologies studied in WP2, multi-fibre (maximum entropy) work of WP1, through to the SDM and AoD experimental work performed in WP4. (These being but a relatively small representation of the various research works that were successfully undertaken in the IDEALIST project to anticipate the ongoing exponential increase in data-rates consumed by end-users.)

	10 years			20 years		
Annual % growth in access usage	Ave BW on core links Tb/s	BW on major core trunks Tb/s	No. of fibres on major core trunks	Ave BW on core links Tb/s	BW on major core trunks Tb/s	No. of fibres on major core trunks
25	.23	1.9	1	2.2	18	1
45	1	8.6	1	42	350	8
65	3.7	31	1	560	4700	94

Table 3: Bandwidth and Multi-Fibre Evolution Scenarios [40]

Another critical issue that IDEALIST has been part of is the ongoing efforts to improve the intrinsic energy efficiency of telecommunications technologies. As the following Figure 12 indicates, overall power consumed by such networks on a global basis is estimated to have reached about 78.6 GW in 2013. It is important to note that the smallest component to that overall figure is that of the Core network, estimated at 0.3 GW, even though an important fraction of overall traffic will still always inevitably flow through the core. Rather, it can be seen that the key areas for targeting improving overall telecommunications power reductions are the Data Centres (DC) & Service Core, and Access & Aggregation networks, which respectively are associated with 43 GW and 20.4 GW power consumption, i.e. more than x100 larger in the case of the DC & Service Core than the Core network. From this perspective, it is apparent that Core networks have already achieved considerable success in reducing power consumption and their associated carbon footprint. Although more could no doubt be done, it is clear that the major reductions in telecommunications greenhouse gas emissions are now to be found outside of the Core network.

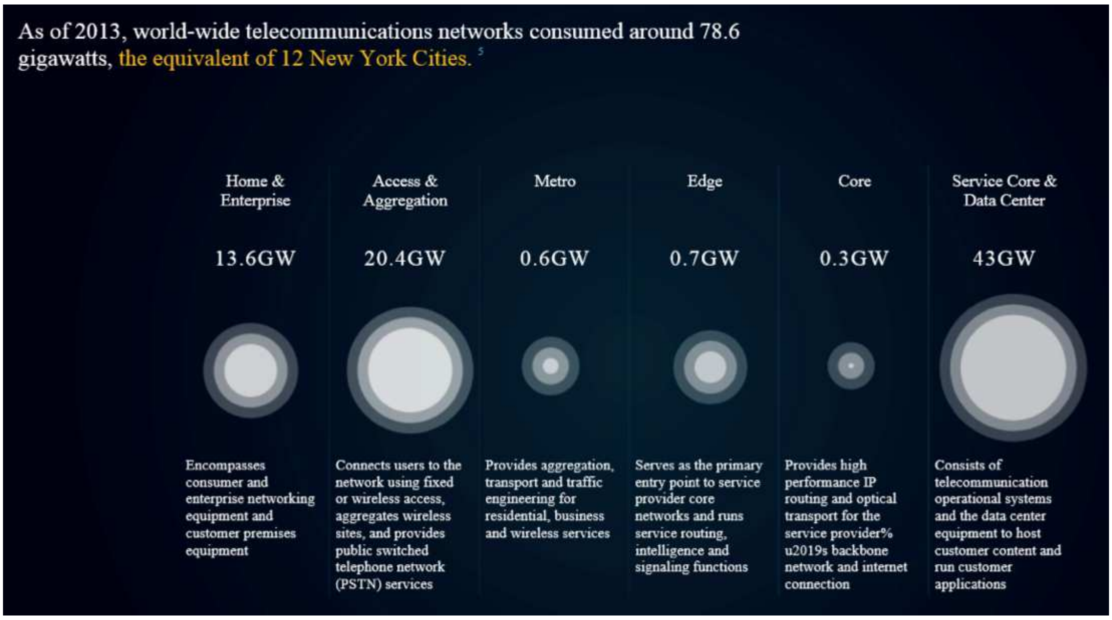

Figure 12: Power consumption figures (2013) for different segments of the telecommunications networking infrastructure [40].

We have therefore already seen that the photonic technologies comprising the core network already operate at an extremely good energy efficiency; indeed, the technologies developed in IDEALIST will continue to contribute to both a relative improvement in energy-efficiency, e.g. as measured by the number of joules per bit dissipated, even if the overall power consumed might increase slightly due to the quantity of data increasing at a faster rate; e.g. it has been estimated that energy efficiency is improving at about 1.1-1.6 dB/year [41], whereas data-rates are increasing at about 2 dB/year (i.e. analogous to Moore's Law), in which case, overall power consumption is therefore still increasing at the differential rate of 0.4-0.9 dB/year.

There are various drivers which are pushing the ever increasing data-rates being experienced in the core network. Figure 13 shows some of the drivers causing this exponential increase, from a 2013 study by the Arthur D Little consultancy [42]. These relate to the sheer number of objects now being connected in the home and office environments (e.g. Internet of Things, being an increasingly more important trend), as well as the resolution and screen sizes associated with the proliferation of smart phones and tablets, while cloudification of internet applications with on-demand interactivity and multiple video offerings etc., are also all combining to significantly increase data bandwidths.

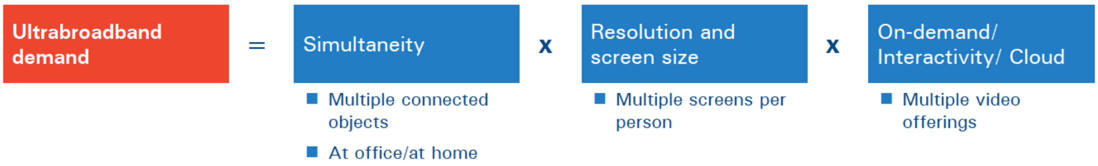

Figure 13: Drivers for growth in ultrabroadband bandwidths [42]

The same study also provides an insightful web map of all the socio-economic benefits to be accrued by increased broadband speeds, which combine with each other in a reflexive fashion to both push and pull the need for ever-increasing data-rates. This is shown below in Figure 14. Overall, the IDEALIST project has been instrumental in creating a platform for the important European incumbent telecom operators to prepare for the oncoming (and ongoing) data wave, as well as providing a basis for key European vendors and research institutes to research and develop the critical physical-layer technologies which will underpin the telecommunications networks and provide the technical capacity to provide the reliable and flexible control of such large data bandwidths.

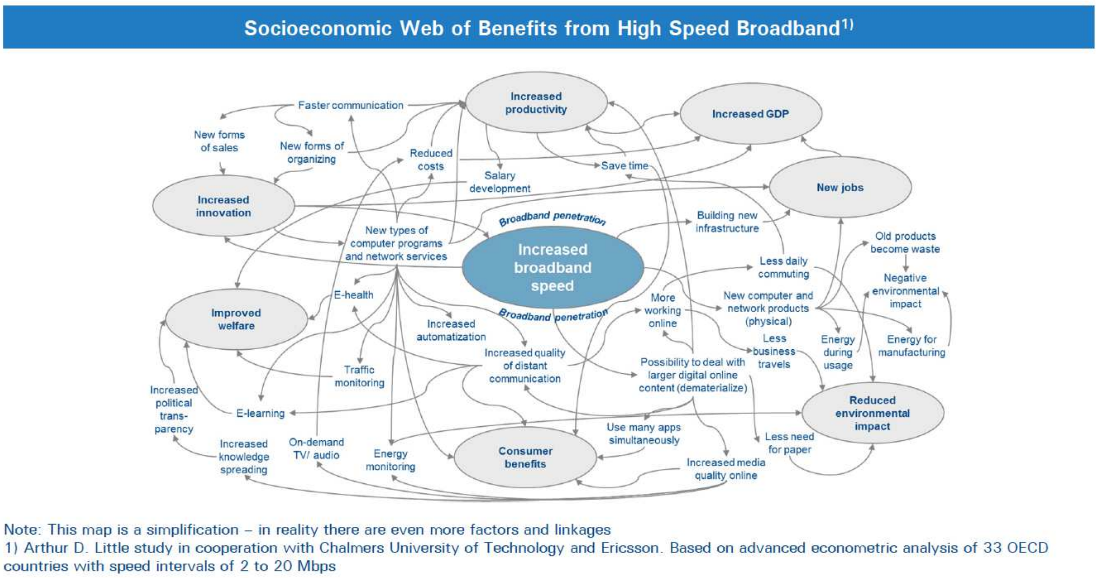

Figure 14: Socio-economic web of benefits from high speed broadband [42]

Finally, in this context, we make reference to the accompanying deliverable D6.3 on Standardisation activities in IDEALIST, where there has been a lot of effort, and here in D6.4 we can see the follow-through of these standardisation initiatives, into commercialisation activities and technology roadmaps, of where the vendor and operator partners of the projects are seeing where the technologies developed in IDEALIST will appear in their future business plans.

6 Conclusions

In this Exploitation Report at the conclusion IDEALIST we have described the numerous commercial outputs of the project that have emerged and are being pursued by the industrial partners in the consortium. We have highlighted the five technology areas of specific importance in future elastic optical networking (EON): Planning Tools, the Control Plane and SDN (software-defined networking), Advanced Transmission techniques, the Metro Border Node, and the Data Plane. In particular, we have shown how the various technologies developed in these five areas represent significant advances over the current state-of-the-art products, and we have discussed how these innovations will be exploited within future product roadmaps and business plans, and how they are feeding into future global standards in the various international standardisations organisations. The larger industry partners of the project have also given detailed indications of how the technologies emerging from IDEALIST will feed into their own commercialisation roadmaps, business plans, and on-going product development to assure future competitiveness in the global marketplace and ensure continued European excellence in engineering and innovation in the field of advanced telecommunications systems.

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