Next Generation Elastic Optical Networks: The Vision of the European Research Project IDEALIST

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ABSTRACT

In this work we detail the strategies adopted in the European research project IDEALIST to overcome the predicted data plane capacity crunch in optical networks. In order for core and metropolitan telecommunication systems to be able to catch up with Internet traffic, which keeps growing exponentially, we exploit the elastic optical networks paradigm for its astounding characteristics: flexible bandwidth allocation and reach tailoring through adaptive line rate, modulation formats, and spectral efficiency. We emphasize the novelties stemming from the flexgrid concept and report on the corresponding proposed target network scenarios. Fundamental building blocks, like the bandwidth-variable transponder and complementary node architectures ushering those systems, are detailed focusing on physical layer, monitoring aspects, and node architecture design.

INTRODUCTION

In the last decade we have witnessed significantly increased utilization of web-based applications such as streaming, sharing, and downloading of multimedia contents that are saturating the capacity of transnational backbones. Globally, consumer mobile devices and network connections grew to 7 billion in 2013, up from 6.5 billion in 2012. Simultaneously, the Internet of Things is envisioned to be practical in the short term. Moreover, the dynamic nature of Internet traffic sets further requirements on the flexibility of next generation optical communication systems.

Based on data obtained from backbone reference networks, operators within the Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks (IDEALIST) project estimate a compound annual growth rate (CAGR) of Internet traffic around 35 percent; therefore, a substantial redesign of current networks is required. At the moment, three strategies are possible to postpone the imminent capacity crunch:

1. The development of ultra-low-loss and low-nonlinear optical fibers, in conjunction with hybrid amplification schemes (i.e., lumped and distributed)
2. The utilization of spatial division multiplexing transmission
3. The implementation of elastic optical networks (EONs)

All combinations of the three options are possible. However, the two first alternatives necessitate massive infrastructure rollout, leading to substantial network cost overheads. Conversely, IDEALIST expressly focuses on short- to medium-term industrial outcomes; consequently, we have opted for the latter alternative.

The realization of EONs [1] is considered a realistic perspective because:

1. It can be seamlessly deployed.
2. It optimizes the required optical spectrum.
3. It provides flexibility with minimum disruption to the existing infrastructures since they can support the innovative concepts of sliceable bandwidth-variable transponder (S-BVT) and flexible optical cross-connect (Flex-OXC) at competitive costs.

The concept of bandwidth on demand stems from mobile communications and recently has been proposed for optics to efficiently utilize the available spectrum, thus increasing the spectral efficiency (SE), defined as the channel information rate over the utilized frequency slot. Within optical networks, flexibility is obtained by redesigning and adding features to the aforementioned blocks. The S-BVT, for example, must be able to transparently transmit signals with selectable modulation formats at adaptive rates [2] and allocating the capacity into one or several independent optical flows that are transmitted toward one or multiple destinations [3]. The Flex-OXC implements dynamic optical functions in a modular and flexible manner by employing the architecture-on-

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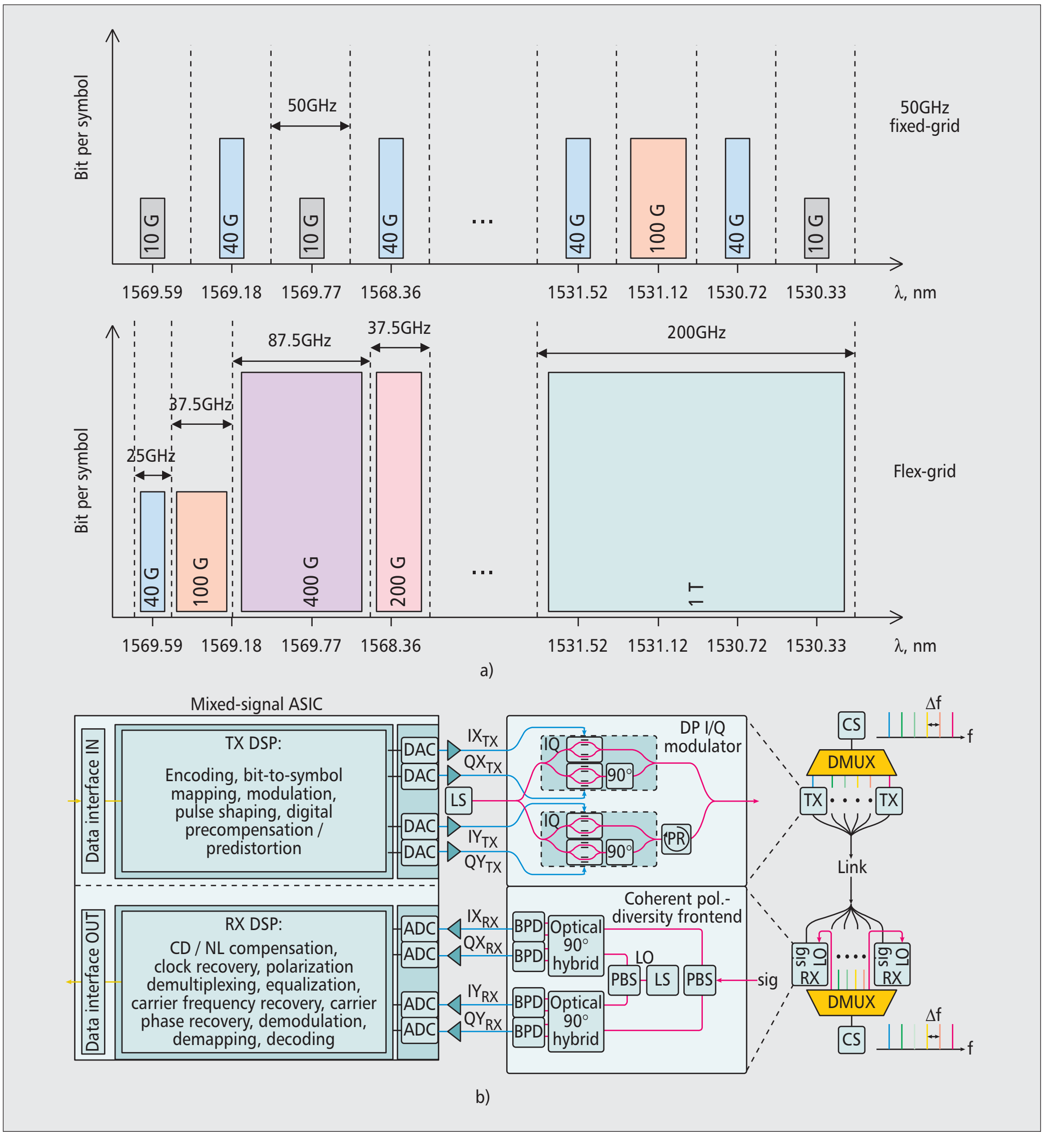

Figure 1. a) Fixed (50-GHz granularity) vs. Flex-grid optical systems (12.5-GHz granularity); b) block diagram of a Flex subcarrier module. ASIC: application-specific integrated circuit (ASIC); TX: transmitter; DP: dual-polarization; DMUX: demultiplexer; RX: receiver; LS: light amplication by stimulated emission of radiation (LASER) source; LO: local oscillator; BPD: balanced photo-detectors; CS: comb source; NL: nonlinearity.

EONs present the benefit of providing customized spectral grids whenever new lightpaths are established. The allocation of several channels to form super-channel configurations is performed according to user requests in a highly spectrum-efficient and scalable manner.

demand (AoD) paradigm [4] and utilizing the switchless elastic rate node (SERANO) [5] as one of the key functional elements for signal processing and routing. These innovations must be delivered by simultaneously decreasing the transmission costs and reducing the energy consumption, paying particular attention to the operation, administration, and maintenance (OAM) issues to enable flexibility and awareness of the dynamical traffic during the whole migration process.

The article is structured as follows. We introduce the migration from state-of-the-art systems toward EONs. Next, we describe the most relevant characteristics of the S-BVT and Flex-OXC. We compare EONs and commercial fixed-grid networks, providing the motivations for the envisioned migration. Finally, the last section draws the conclusions.

From Fixed-Grid-Based Optical Networks toward EONs

In the category of emerging telecommunication technologies, EONs have gained momentum in relation to optical transport networks (OTNs). The EON architecture efficiently utilizes the optical spectrum through a network infrastructure that implements flexible channel allocation using frequency slots with reduced sizes (e.g., from current fixed-grid 50 GHz wavelength-division multiplexing, WDM, systems to configurable slots of 12.5 GHz granularity). In addition, EONs present the benefit of providing customized spectral grids whenever new lightpaths are established. The allocation of several channels to form super-channel configurations is performed according to user requests in a highly spectrum-efficient and scalable manner

Feature	2018	Goal (2025)
Maximum optical switching capacity	60 Tb/s	500 Tb/s
Maximum electrical switching capacity	18 Tb/s	150 Tb/s
Type and number of client interface (typical node)	10G-100G-1T, IEEE 803.1/3, number: 150	100G-1T, IEEE 803.1/3, number: 150
Number of fiber pairs attached to the node (largest node)	About 4–6 where ND = 6	About 30 fibers pairs, ≫ topological ND (maximum ND = 6). This implies several parallel WDM links.
Minimum super-channel rate	10 Gb/s	100 Gb/s
Maximum super-channel rate	1 Tb/s	10 Tb/s
Typical super-channel rate	100 Gb/s	1 Tb/s
Minimum transparency reach	700 km	700 km

Table 1. Node and network target requirements.

[1]. Figure 1a illustrates an example of allocation of different data rates from 40 Gb/s up to 1 Tb/s for both fixed- and flex-grid.

With this in mind, the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) adapted recommendations G.694.1 and G.872 to include flexibility within ITU standards. A novel WDM concept was defined by ITU-T Study Group 15, starting with Recommendation G.694.1, with the formalization of the nominal central frequencies (6.25 GHz granularity), the channel width (multiples of 12.5 GHz), and the concept of frequency slots. In such a scheme, a data plane connection is switched, based on allocated and variable size frequency ranges within the optical spectrum (media channels), providing a first brick for EONs. This technology can be exploited by multicarrier WDM transmission through a super-channel approach as well as by optical-orthogonal frequency-division multiplexing (O-OFDM). Once the ITU grid has been adapted to the flexible scheme, current transponders and reconfigurable optical add-drop multiplexers (ROADMs) will follow the same path. The transponder has to move from fixed-grid architecture toward flexible transmission with the possibility of adjusting the spectrum by expanding or contracting the bandwidth on demand. This is possible by varying the number of sub-carriers, the symbol rate, or the employed modulation format based on a dynamic trade-off between reach and capacity. However, when BVTs need to transmit at low bit rates, part of its capacity remains unused. To address this issue, the concept of S-BVT was introduced [3], which further increases the level of elasticity and efficiency inside the network. S-BVTs enable transmission from one point to multiple destinations, changing the traffic rate to each destination and the number of destinations on demand (e.g., multi-flow transmission). Concerning Flex-OXC, the latest spectral selective switch (SSS) technology enables channel routing with the aforementioned finer granularity, and the embedded flexibility in the node architecture [4] helps follow dynamic traffic variation.

Finally, the two aforementioned main blocks of the EON data plane architecture proposed in IDEALIST are supposed to be fully programmable so that they can be dynamically controlled by external software agents implementing online service network optimization mechanisms. In that respect, IDEALIST follows a software defined network (SDN) approach based on the application based network operation (ABNO) architecture proposed in [6].

Target Networks

Within IDEALIST the target reference application scenario is a backbone transport network with a CAGR of ~ 35 percent and target reach of ~ 1500 km (the typical size of a large national European network). System design parameters are estimated on deployed topologies, realistic traffic matrices, and evolution predicted until 2018 when the first rollout should begin. Scalability, flexibility, end-to-end performance, low cost, and limited energy consumption are the most critical issues to be addressed. A possible solution is to integrate OTN or IP with the optical layer to share flexibility of the network, thus increasing node agility and scalability. Concerning energy consumption and costs, photonic integration jointly with S-BVTs represents a key technology to simultaneously reduce both cost and energy consumption.

From a functional point of view, IDEALIST identifies two types of network nodes: border and core. The first is suitable for metro regional traffic grooming, while the second is used in long-haul networks for direction switching. Both nodes need enhanced modularity and programmability to enable smooth upgrades and variable traffic conditions. It is generally agreed that the differences in terms of size among nodes located in different parts of the same network will probably not imply the complete redesign of the architecture. Border and core nodes are essentially different flavors of the same structure, varying only in size and equipment. Nevertheless, a modular design is envisaged, following the *pay-as-you-grow* approach. In particular, node design requirements should take into account that a node has a 10-year lifetime, and its maximum capacity should refer to the estimated traffic conditions at the end of life (a factor of 10 from 2018 is assumed with a yearly traffic growth of ~35 percent). In Table 1 we summarize the most relevant specifications for the identified target network elements. These values are extrapolated from a set of backbone reference networks, provided by the operators within our project, with the aim of roughly identifying the size and needs of a future network element. The maximum size of the optical switching fabric by 2025 is estimated to be around 500 Tb/s, scalable in a hitless way from 25 Tb/s minimum capacity. Similar figures apply to the electrical crossconnect with a maximum size of 150 Tb/s derived from a typical 30 percent add/drop capacity.

Operators' forecasts identify 100 Gb/s (optionally 40 Gb/s) as the most common bit rate for client interfaces. 10 Gb/s should still be considered for 2018 deployment. The add/drop capacity, divided by the *most common bit rate interface*, roughly defines the number of client interfaces to be equipped in a single node. The maximum topological nodal degree (ND) provides the information about the maximum number of directions (at the line side) exiting from a site. This information alone does not identify the correct number of WDM systems linked to that particular network element, since parallel WDM systems might sometimes be required. Nevertheless, it is still possible to derive the number of fiber pairs directly connected to the network element. By 2025 we conjecture that 30 fiber pairs over C-band could be a reasonable value.

The super-channel bandwidth can be calculated using the minimum, typical, and maximum traffic. Considering that the figures of *minimum traffic per demand* range from 2 to 40 Gb/s by 2018 and the minimum frequency slot is 12.5 GHz as reported earlier, it is realistic to specify a minimum super-channel rate of 10 Gb/s. The maximum super channel rate will be 1 Tb/s by 2018 and possibly up to 10 Tb/s by 2025.

The Sliceable Bandwidth-Variable Transponder

From the optical perspective, the key component inside the S-BVT is the optical front-end, which is called the multi-flow optical module. The module distributes different traffic demands over several media channels, which are then grouped into super-channels. It contains a set of Flex subcarrier modules (where each subcarrier is modulated by a specific traffic portion) and a number of subcarrier generation modules, each generating non-modulated subcarriers.

The most important elements within the multi-flow optical module based on spectrally efficient super-channels are: flexible comb sources, coherent receiver, rate-adaptive coded modulation, and modulation format transparent digital signal processing (DSP). At the transmitter, a flexible comb source, as the one described later, generates an optical frequency comb with a variable carrier spacing Δf. After demultiplexing, each optical carrier is individually modulated by a Flex subcarrier module. The modulated wavelength channels are then combined and transmitted over a link. The local oscillators for the coherent receivers are also derived from a comb source, creating a scenario in which joint DSP of all subcarriers (e.g., for intra super-channel fiber nonlinearity compensation) is possible.

General Concept

Figure 1b illustrates the block diagram of a possible Flex subcarrier module realization, which comprises a pool of coherent front-ends (light sources, I/Q modulators, and drivers) associated with the processing electronics (digital-to-analog converter [DAC], analog-to-digital converter [ADC], transmitter, receiver, DSP at the transmitter and receiver, and forward error correction [FEC] coding and decoding). The transmitter DSP consists of encoding and mapping blocks supporting various modulation formats and optionally variable FEC code rates for rate-adaptive coded modulation. An optional pre-compensation stage at the transmitter allows for chromatic dispersion (CD) and/or component limitations and/or fiber nonlinearity precompensation [2, 7]. The DSP-based receiver digitally corrects the optical front-end characteristics, CD and/or fiber nonlinearity compensation, clock and carrier recovery, as well as polarization demultiplexing and linear equalization [2, 7]. The requested bandwidth can be tuned by changing the modulation format, symbol rate, spectral shaping, and coding. For cost-efficient realization of Flex subcarrier modules, modulation format transparent solutions for all mentioned functions are required [2]. Ideally, Flex subcarrier module functionalities, and more generally S-BVT parameters, can be controlled, for example, by SDN that has access to the physical layer parameters and can adjust S-BVT configurations, as discussed later.

Subcarrier Generation Module

The comb generator is a fundamental block of the multi-flow optical module. Two solutions can be adopted for subcarrier generation: an array of LASER sources or a multi-wavelength source able to generate several subcarriers from a single LASER. In the first case particular attention has to be paid to frequency locking and stabilization, because they are independently generated, and as a consequence, the modulated spectra may overlap.

On the contrary, a frequency comb generator produces a spectrum that consists of a series of equally spaced frequency- and phase-locked sharp lines. In order to generate a comb signal, one may employ super-continuum LASER source techniques, such as mode-locked LASERs (MLLs). Based on MLLs, simultaneous tones are generated due to the LASER emission of a train of periodic ultra-short optical pulses establishing a fixed phase relationship across a broad spectrum of frequencies. The periodic pulses naturally generate a comb of discrete, regularly spaced series of sharp lines. In addition, by pass-

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Transmission scheme	Pros	Cons	Application scenarios
NWDM	• Suitable for long distances • Cost-effective • DSP-enabled adaptive capabilities • Self-performance	• DAC/ADC bandwidth limitation • Nonlinear limitations	• National, long-haul, and ultra long-haul
O-OFDM	• Sub-wavelength granularity • DSP-enabled adaptive capabilities • Electrical subcarrier control/manipulation (BL/PL) • Self-performance monitoring • 1-tap equalizer • Ease of bandwidth/bit rate scalability	• DSP complexity • DAC/ADC bandwidth limitation • Electrical/optoelectronic components linearity • High peak-to-average power ratio • Nonlinear limitations	• Metro, regional, national, and long-haul
TFP	• Highest SE • Self-performance monitoring • No DAC/ADC limitation	• High DSP complexity at the Rx (sequence detector instead of a less complex symbol-by-symbol detector) • Nonlinear limitations	• Data center, national, and long-haul

Table 2. Comparison of transmission schemes.

ing the ultra-short pulses from the MLL to a highly nonlinear fiber (HNLF), a self-phase modulation effect is created, affecting the signal by widening its spectrum and shortening the pulse duration. Within IDEALIST a novel comb generator, based on an MLL and an HNLF, was undertaken, where optical components were optimized. The proposed approach can generate, with a relatively simple setup, a 555 Gb/s super-channel consisting of 52 subcarriers carrying 10.675 Gb/s each, from a single 10 GHz MLL and an HNLF, as displayed in Fig. 2 [8].

Transmission Schemes

In IDEALIST we considered optical transmission schemes addressing the network specifications listed earlier. These also include spectrum allocation techniques, DSP algorithms, and power consumption considerations.

We examined three different transmission methods: Nyquist WDM (NWDM) [2], O-OFDM [9], and time-frequency packing (TFP) [10]. Table 2 reports their main differences.

NWDM uses digital spectral pulse shaping to reduce the spectral width of the signals, allowing for channel spacing equal to the symbol rate, providing higher SE. As mentioned earlier, one of the most innovative features of S-BVTs is to provide data rate on request by varying, for example, the symbol rate. Nevertheless, such a transponder should be engineered for a limited ensemble of modulation schemes, thus keeping costs acceptable. Consequently, starting from the criteria mentioned earlier, we determined the minimum ensemble of needed modulation schemes for an S-BVT to transmit from 100 Gb/s to 1 Tb/s. The selected modulation formats are: pulse modulated quadrature phase shift keying (PM-QPSK), pulse modulated 8-quadrature amplitude modulation (PM-8QAM), and PM-16-QAM [2].

O-OFDM offers unique spectral domain manipulation with super- and sub-wavelength granularity. The former is considered for building super-channels, while the latter includes the electrical subcarrier level, which is ideal for accurately adapting the spectrum to instantaneous needs at the expense of increased DSP complexity. The bit and power per subcarrier can be finely adapted and reconfigured at the S-BVT DSP according to the bandwidth demand and channel profile for a flexible rate/distance adaptive transmission. Furthermore, the S-BVT based on OFDM technology can be sliceable in both time and frequency, thus supporting multiple variable capacity data flows. A key issue for an actual implementation of the OFDM-based S-BVT is DSP optimization for reducing its complexity (e.g., employing alternative fast transforms [9]).

The first fundamental difference, with respect to NDWM or OFDM, is that TFP gives up orthogonality. In TFP, the subcarriers partially overlap in time or frequency or both, an approach that significantly increases SE at the expense of induced linear cross-talk penalty as intersymbol interference (ISI) and intercarrier-interference (ICI). Low-density parity check (LDPC) coding and detection are properly designed to account for the introduced interference. Because of the increased ISI, TFP requires a sequence detector instead of a symbol-by-symbol one. Moreover, at the transmitter a simple electrical filter is needed (DAC is not mandatory, because reach adaptation is achieved by employing variable code rate with PM-QPSK), thus reducing complexity and power consumption. The receiver negligible additional complexity (mainly to reduce the resulting ICI) is hence justified by the transmitter benefit. With particular respect to NWDM, TFP has fewer requirements in terms of LASER wavelength stability (e.g., important in the case of a super-channel) and flexibility, which is enhanced through code rate adaptation [10].

Besides the above transmission techniques, we also investigated mixed, coded, and multi-dimension modulation formats that achieve higher levels of optimization providing finer granularity [1]. Moreover, we considered the power consumption and demonstrated that (energy) sustainable development of high-speed

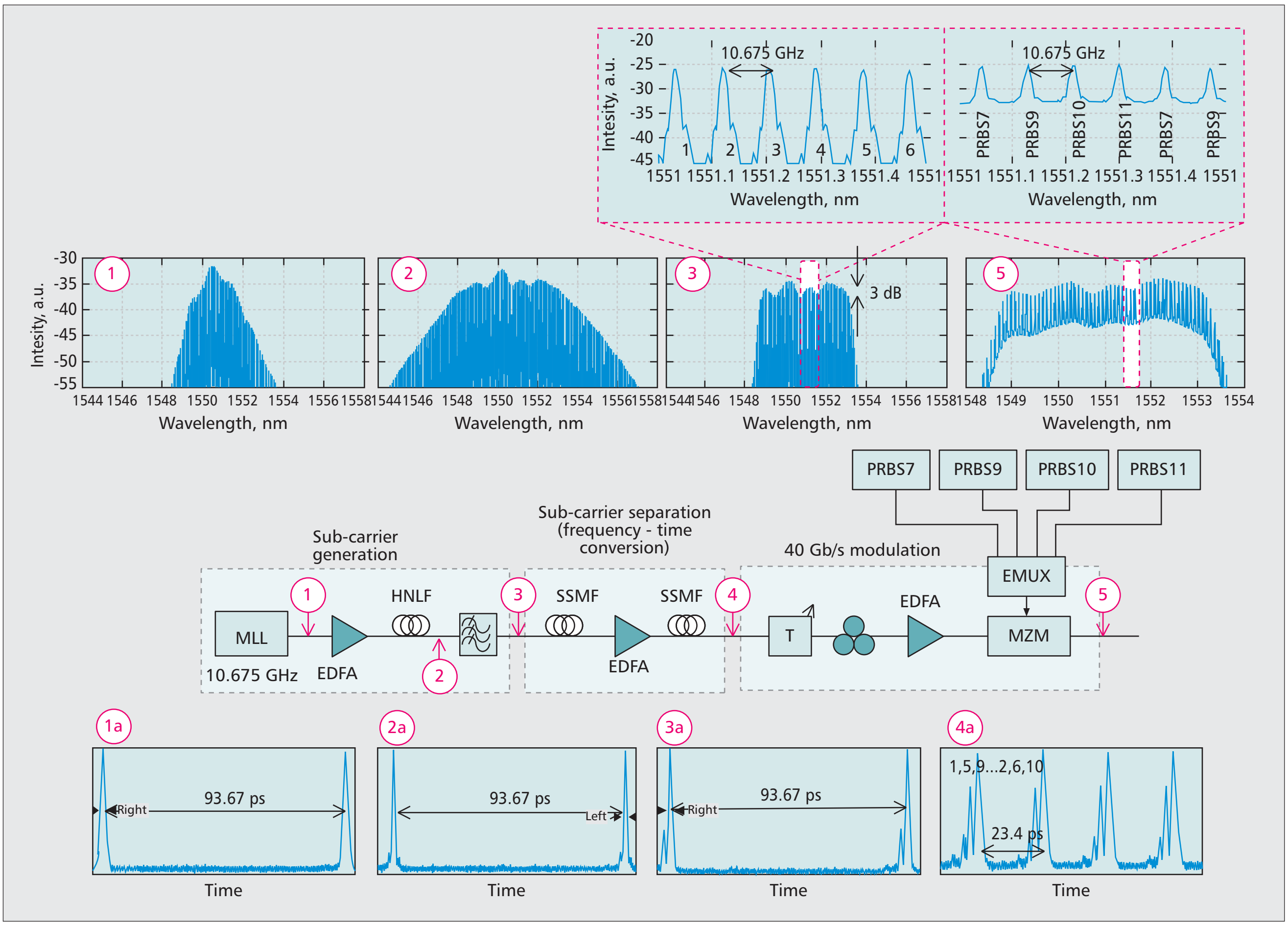

Figure 2. Experimental setup of a 555 Gb/s optical comb generator. PRBS: pseudo-random binary sequence; EDFA: Erbium-doped fiber amplifier; EMUX: electrical multiplexing; MZM: Mach-Zehnder modulator.

transponders is leveraged by SDN. In particular, flexible transponders can considerably reduce energy consumption when adapting, for example, the complexity of the CD compensation algorithm inside the DSP [1], and by evaluating the interplay of FEC and performance vs. power consumption [11]. Finally, we evaluate strategies on spectrum allocation to limit fiber nonlinear propagation impairments in dynamic flexible optical networks [12].

Optical Monitoring Techniques

Optical layer monitoring is exploited by network OAM to accomplish various network functionalities:
- Fault detection
- Commissioning and provisioning
- Performance degradation monitoring
- Verification of service level agreements (SLAs)

Several parameters such as optical power (for fault detection), frequency deviation (to monitor LASER performance degradation), and delay (as verification of the SLAs) may be monitored in view of the aforementioned functionalities. OAM relies on standard monitoring techniques, both at the single subcarrier and super-channel level. Additionally, DSP creates new possibilities for monitoring, especially for the case of subcarrier frequency deviation, dispersion, and mean square error (MSE). In coherent systems, it is possible to measure the offset between the frequencies of the local oscillator and the received subcarrier, exploiting automatic frequency control inside the DSP [13]. Frequency deviation can reveal LASER instability. Differential group delay (DGD) can be monitored through equalizer parameters within the DSP [14]. MSE can be directly monitored through DSP as a subcarrier quality parameter before FEC so that effects of possible signal degradations can be observed. This information can be directly correlated with possible faults or function degradations so that in case of alarm, specific procedures can be adopted.

For example, a multi-function amplifier may generate an MSE increase detected by the receiver with a threshold comparison. In the case of SDN control, the SDN agent sends an alarm message to the SDN controller. At that point, the SDN agent can decide to reroute the connection along a disjoint path. Alternatively, provided that fiber impairments are limited, the SDN controller can increase the redundancy of the adaptive code (i.e., increase robustness to physical impairments) of the transmitted channel so that no rerouting is required.

If data-aided transmission is implemented,

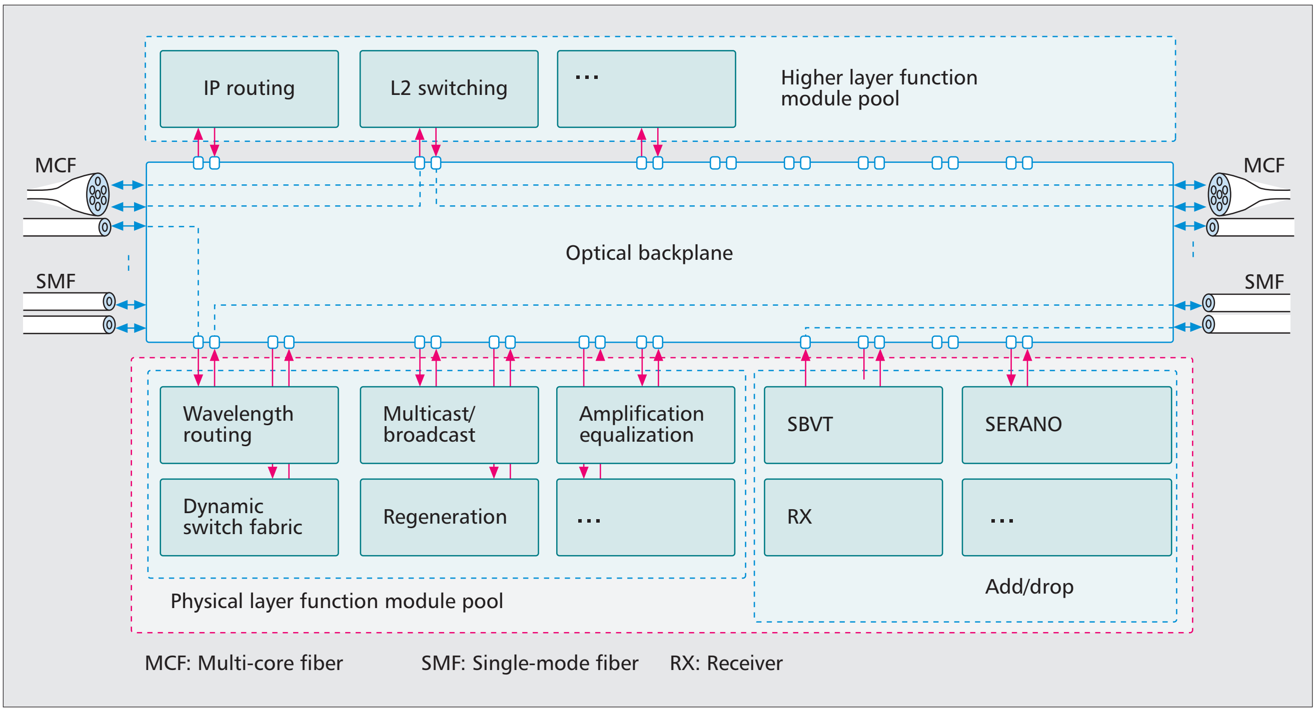

Figure 3. AoD-based NFP node.

the DSP at the S-BVT receiver enables self-performance monitoring in the electrical domain [15], as a set of system parameters required for channel estimation/equalization are acquired thanks to the overhead of information transmitted for a correct detection. Furthermore, for the case of O-OFDM, by allocating guard-bands, we are able to measure the noise by means of an optical spectrum analysis, allowing in-band non-intrusive optical signal-to-noise ratio (OSNR) monitoring that can be placed anywhere along the network [15].

Next Generation Flex-OXC

Optical transport networks continue to introduce new requirements to next generation optical nodes such as *node flexibility* in different domains (e.g., switching, bandwidth and transmission rate), node scalability to higher transmission capacities, *node reliability* and *survivability* (considering redundant components), and simple node adaptability to emerging network applications. Based on this *node adaptability*, various node subsystem architectures with different internal component distribution approaches can be depicted and supported by the proposed new Flex-OXC.

AoD-Based Network Function Programmable Node

As EONs are envisaged as the future optical network infrastructure, it is mandatory to adopt nodes with advanced features. These optical nodes consider the programmability of functions at higher layers (e.g., routing, switching) and the physical layer (e.g. amplification, regeneration) at the request of the network user, who is unaware of the available optical hardware resources (Fig. 3). This novel network function programmable (NFP) node paradigm brings to the optical network a new perspective, since the abstraction of optical (and electronic) components for network functionality is practically achieved, and node slices are enabled associated with arbitrary traffic types.

The NFP node is supported by the AoD concept [4], consisting of an optical backplane connected to the node inputs/outputs and several plug-in modules, providing the required signal processing functions, including bandwidth-variable WSS (BV-WSS), fast optical switches, power splitters, fixed-grid demultiplexers, EDFAs, SERANO, and so on. With AoD, different arrangements of inputs, modules, and outputs can be constructed by setting up appropriate cross-connections in the optical backplane. Therefore, the AoD-based NFP provides increased flexibility since the components used for optical processing are not hard-wired as in a static architecture, enabling module interconnection in an arbitrary manner. Flexibility analysis was undertaken in [4] demonstrating that the NFP node provides routing, switching, and architectural flexibility. In addition, the NFP node performance was investigated through experimental demonstration, showing dynamic composition and reconfiguration of synthetic architectures to support different sets of signals and requirements. The functional and architectural flexibility of the AoD node can provide on-demand elastic time-spectrum switching, subwavelength channel aggregation, and spectrum defragmentation. This experimental demonstration involved signals with a variety of bit rates, modulation formats, bandwidth, and signal processing requirements. Satisfactory per-

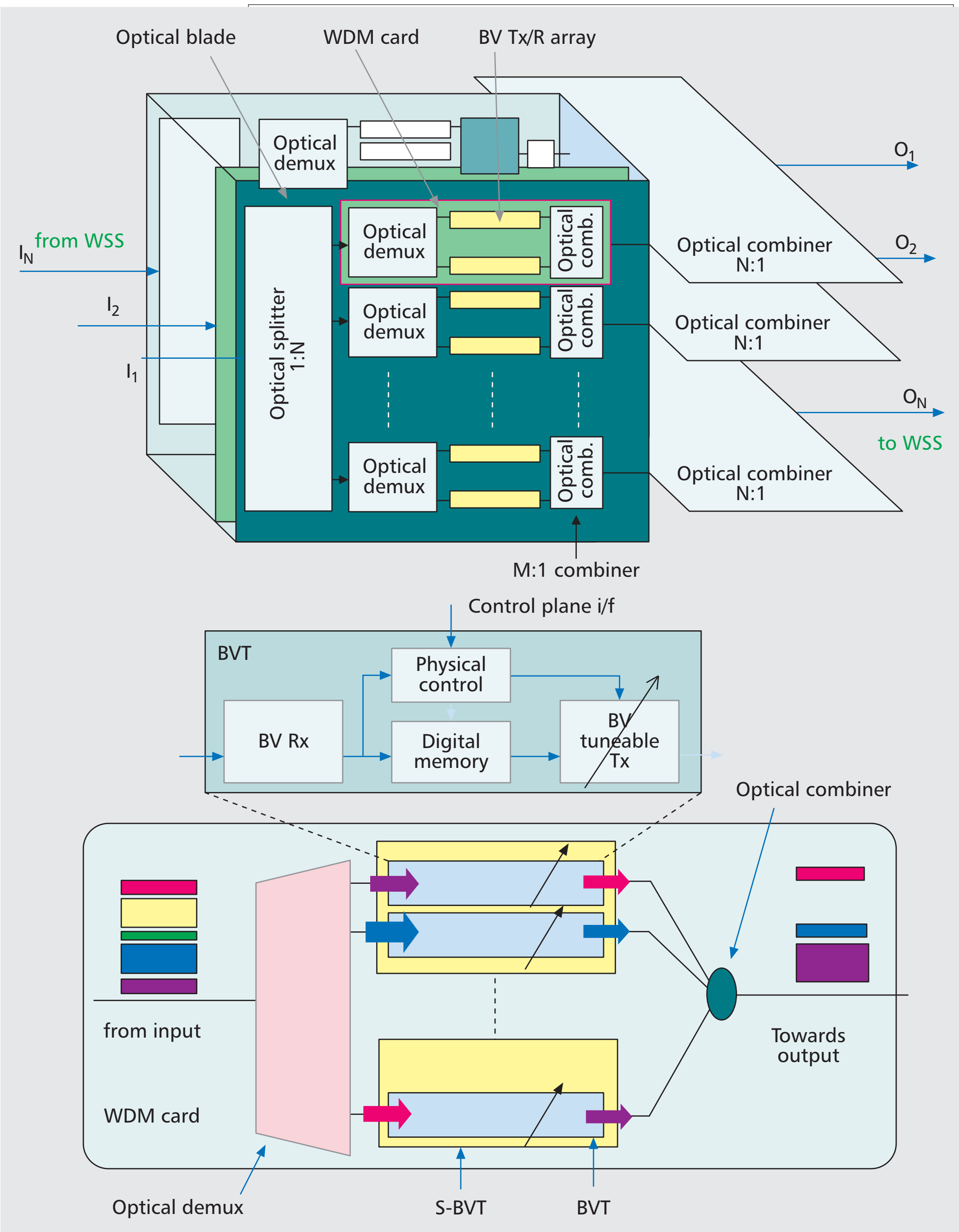

Figure 4. a) Overview of the SERANO architecture; b) details of the WDM card and the S-BVTs.

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formance is presented with a maximum power penalty of 1.9 dB.

With respect to node synthesis, to cope with the demanding traffic requirements of the optical network, NFP nodes have proven to be highly beneficial since an algorithm is used to calculate a synthetic node design providing the required functionality with available modules. Furthermore, if traffic requirements change, an alternative synthetic node design is calculated and implemented to fulfill the new requirements hitlessly (no traffic loss). Based on performance analysis, the NFP node has demonstrated hardware reductions (i.e., node cost) of up to 40 percent compared to static ROADMs through proper network design. This advantage also leads to 25 percent savings in the overall power consumption by diminishing the number of SSSs. Furthermore, NFP nodes also support node scalability. This scalability in the NFP node has also been studied, proving the possibility to reduce at least by half the number of hardware modules used, compared to other conventional architectures, by applying fiber switching, which involves simple cross-connections when several traffic demands require the same output port destination. This feature is only available in the AoD node, since the cross-connection can be configured depending on the traffic scenario.

A reduction in terms of capital expenditure is achieved by equipment and device integration. As far as operational expenditures are concerned, the improved energy efficiency of EONs has an impact both from a network architecture perspective and at the individual component level.

THE SERANO ARCHITECTURE

A SERANO architecture is an integral building block of a Flex-OXC; it makes use of the unique features S-BVTs offer to reduce overall switching complexity and cost [5]. In particular, a fraction of the traffic through the Flex-OXC is added/dropped from/to the SERANO block by means of N I/O ports/fibers as illustrated in Fig. 4a. Each input fiber is terminated in an optical blade which consists of an 1:N optical splitter where each of the N outputs are sent to N WDM cards in parallel. As illustrated in Fig. 4b, a WDM card incorporates an optical demultiplexer followed by a multi-flow optical module consisting of fixed-receiver tunable-transmitter array pairs connected back to back with no client interfaces between them. Therefore, the functionality of this block is to terminate the signals of the entire comb of spectral slots but only full 3R regeneration to a selected number of flows (i.e., those directed to the selected output fiber at the desired spectral slot/modulation format).

The final stage of the WDM card consists of a combiner with M input ports, where M is the upper number of flows a particular input fiber may forward to a particular output fiber. In the final stage of SERANO, the outputs of each WDM card are passively recombined by means of an additional N:1 optical combiner. The SERANO block, apart from 3R and modulation format adaptation to tailor line rate to the subsequent transparent section length, provides for vendor interoperability, since the receiver-transmitter block arrays could potentially be purchased separately, and for spectrum fragmentation. The aforementioned SERANO architecture is flow and link modular since only the couplers need to be provisioned; the building blocks of optical blades and WDM cards can be added progressively following a pay-as-you-grow principle. It is also worth noting that no other switching technology, optical or electronic, is introduced since the main active building block is multi-flow optical module arrays. This integrates transmission and data forwarding, allowing the industry to concentrate on optimizing a single element for both functions. A preliminary physical layer performance/scalability of the proposed architecture, considering fixed-grid data center applications, is reported in [5].

ADVANTAGES OF FLEXIBLE OPTICAL COMMUNICATION SYSTEMS

Migration from fixed-grid networks to EONs provides several benefits. Hereafter, we summarize the most relevant.

Increased spectral efficiency: By enabling optimization of the spectral allocation on request, the flexible ITU channel grid increases SE and network capacity significantly. Deployed optical links can be used more efficiently, thus prolonging their lifespan.

Accommodation of 1 Tb/s and beyond client signals: Client signal bit rates of 1 Tb/s and beyond will inevitably exceed the limits set by the fixed 50 GHz channel grid. However, flex-grid architectures can accommodate such demands.

Dynamic reconfiguration: EONs enable dynamic reconfiguration of the network by using S-BVTs as basic building blocks. Such potential holds great promise for increased energy efficiency of the network and improved multi-layer protection applications.

Better economics: A reduction in terms of capital expenditure is achieved by equipment and device integration. As far as operational expenditures are concerned, the improved energy efficiency of EONs has an impact both from a network architecture perspective and at the individual component level. Another issue of fixed-grid networks is the number of transponders required, which may significantly increase when large bandwidth demands have to be accommodated by inverse multiplexing.

CONCLUSIONS

We have investigated the challenges deploying EONs for terrestrial European networks under the assumption that the currently estimated CAGR will be maintained until 2018. A comprehensive analysis of technical requirements and performance of novel key elements such as S-BVT and Flex-OXC has been performed according to the network capacity needs.

The novel concept of a multi-flow optical module, implementing a flexible subcarrier module, has been investigated and its performance using different transmission methods compared. Moreover, advanced DSP techniques and energy saving modulation formats have also been deeply studied.

Concerning the Flex-OXC architecture, two innovative and complementary solutions that can handle dynamic traffic and present a high level of scalability and flexibility, AoD and SERANO, have been investigated. These solutions enable a clear upgrade path towards EONs.

To conclude, we firmly believe that EONs will significantly postpone the imminent capacity crunch, and that an efficient bandwidth allocation will build the foundation of next generation optical networks.

ACKNOWLEDGMENT

This work was supported by FP-7 IDEALIST project, grant agreement number 317999.

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