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SPATIAL-SPECTRAL FLEXIBLE OPTICAL NETWORKING ENABLING SOLUTIONS FOR A SIMPLIFIED AND EFFICIENT SDM

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Lead Beneficiary : AIT

Contact Person : Dimitrios Klonidis
dikl@ait.gr

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Authors : I. Tomkos (AIT), D. Klonidis (AIT), P. Zakynthinos (AIT),
D.M. Marom (HUJI), D. Siracusa (CN)

This deliverable contains the INSPACE project concept paper that summarizes the main goals of the project and describes the adopted solutions for the project developments.

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Participants

The INSPACE Project Consortium groups the following Organizations:

No	Partner Name	Short Name	Country
1	Optronics Technologies S.A.	OPT	Greece
2	Telefonica Investigation y Desarrollo	TDI	Spain
3	The Hebrew University of Jerusalem	HUJI	Israel
4	Research and Education Laboratory in Information Technologies	AIT	Greece
5	Optoscribe Ltd.	OPTOSCRIBE	United Kingdom
6	Center for Research and Telecommunication Experimentation for Networked Communities	CN	Italy
7	Aston University	ASTON	United Kingdom
8	Finisar Israel Ltd.	FINISAR	Israel
10	W-Onesys, S.L.	WONE	Spain

Executive summary

This deliverable presents the INSPACE concept paper, in the form of a white paper, publicly available through the INSPACE web page.

The white paper addresses the scientific approaches that are proposed and followed by the EU funded project INSPACE, providing a novel networking approach that extends the established spectral flexibility concepts to the SDM domain. The networking approach in combination with the proposed technology developments in spatial signal manipulation and switching is expected to significantly simplify the super-channel allocation and control mechanisms, by removing current limitations related with the wavelength continuity and fragmentation issues. The new concept utilizes the benefits of the high capacity, next generation, few-mode/multi-core fibre infrastructures, providing also a practical short term solution, since it is directly applicable over the currently installed multi-fibre cable links. The realization of INSPACE approach is enabled by the development of novel multi-dimensional spatial-spectral switching nodes, which are fabricated by extending the designs of the existing flexible WSS nodes, incorporating advance mode/core adapting techniques. The concept is further supported by novel processing techniques that minimize the mode/core interference as well as new network planning algorithms and control plane extensions that are enhanced with the space dimension

The article introduces first the combined spatial and spectral optical networking concept and highlights the expected benefits of this approach as well as the key technology challenges. The new fibre types and the proposed node designs in support of SDM are presented next, concluding on the possible super-channel allocation schemes that could be introduced and implemented. Furthermore, the routing and resource allocation and optimization approaches are presented with emphasis on the new constrains that should be included in the routing algorithms in order to best exploit the spatial resources and transmission limitation. The final part of the paper focuses on the control plane approaches and the related challenges.

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The INSPACE concept paper

Title

Spatial-spectral flexible optical networking:
The scope and vision of EU project INSPACE

Authors

D. Klonidis, I. Tomkos, P. Zakynthinos, J.M. Rivas,	*Athens Information Technology*	*Greece*
D. M. Marom, M. Blau,	*The Hebrew University of Jerusalem*	*Israel*
D. Siracusa, F. Pederzolli, E. Salvadori,	*CREATE-NET,*	*Italy*
S. Sygletos, A. Ellis,	*Aston University*	*UK*
G. Papastergiou,	*Optronics S.A.,*	*Greece*
N. Psaila,	*Optoscribe Ltd.,*	*UK*
J. F. Ferran,	*W-onesys S.L.,*	*Spain*
S. Ben-Ezra,	*Finisar Israel Ltd.,*	*Israel*
F. Jimenez, J.P. Fernández-Palacios,	*Telefonica Investigacion y Desarrollo S.A.,*	*Spain*

Contact details:

Email: itom@ait.gr, dikl@ait.gr,

Abstract

The traffic carried by core optical networks grows at a steady but remarkable pace of 30-40% year-over-year. Advancements in optical transmission technologies and networking solutions continue to satisfy the traffic requirements by delivering the content over the network infrastructure in a cost and energy efficient manner. Such core optical networks serve the traffic demands in a dynamic way, in response to requirements for shifting of traffics demands, both temporally (day/night) and spatially (business district/residential). However, as the fundamental spectral efficiency limits of single-mode fibres are approached, the scientific community is pursuing recently the development of an innovative, all-optical network architecture introducing the spatial degree of freedom when designing/operating future transport networks. Space-division-multiplexing through the use of bundled single mode fibres, and/or multi-core fibres and/or few-mode fibres can offer up to 100-fold capacity increase in future optical networks. The EU INSPACE project is working on the development of a complete spatial-spectral flexible optical networking solution, offering the network ultra-high capacity, flexibility and energy efficiency required to meet the challenges of delivering exponentially growing traffic demands in the internet over the next twenty years. In this white paper we present the motivation, vision and main research activities of the INSPACE consortium towards the realization of the overall project solution.

Keywords: Space Division Multiplexing, Flexible Optical Networking

1. Introduction

The scale in network capacity – but also in energy consumption and in general economic viability – presses the industry to identify innovative technologies and network architectures, in order to overcome the expected fibre capacity limitations. This issue is exacerbated by the new traffic profile that is mainly dominated by rich content video and cloud services, imposing high traffic churn (i.e. high peak to average traffic ratio). In turn, this results in large bandwidth and capacity variations over time, increasing considerably the required capacity overprovisioning, far beyond the average network capacity. The concept of flexible (a.k.a. elastic) optical networking [1], [2] in combination with spectral efficient formats is widely explored in an effort to optimize the utilization of the network resources according to the varying traffic demands. However, due to the limited capacity growth potential of the single mode fibre, the nascent technology of space division multiplexing (SDM) in combination with legacy wavelength division multiplexing (WDM) is identified today as the only evident solution with the scaling potential to meet future traffic demands [3]-[5]. However, the current SDM solutions are targeting purely the capacity increase in point-to-point transmission systems. What still remains unexplored is the introduction of the space dimension in optical networking and the potential benefits offered by this additional degree of freedom, in terms of the overall resource optimization of the system. The realization though of this new networking approach requires additional technology developments in the field of spatial demultiplexing and most importantly in the switching of the optical contents over both the space and spectrum dimensions.

The introduction of the combined spectral and spatial optical networking and the study of the enabling spatial demultiplexing and switching technologies is the main focus of the EU project INSPACE. Moreover, the INSPACE project investigates the added value of the space dimension in the optimization of the network resources and explores new network planning and resource allocation approaches as well as the necessary control plane extensions.

This article highlights first, in section 2, the necessity to move towards the multi-dimensional flexible optical networking approach and introduces the combined spatial and spectral optical networking concept, its benefits and the key technology challenges. In section 3, the new fibre types and the proposed node designs in support of SDM are presented, concluding in section 4 on the possible super-channel allocation schemes that could be introduced and implemented based on the technology capabilities. The network planning, and resource allocation approaches for the optimization of the spatial and spectral resources are presented in section 5, with emphasis on the new constrains that should be included in the routing algorithms in order to best exploit the spatial resources and the transmission limitation. Section 6 presents the required control plane extension and the investigated approaches in order to fully exploit the space dimension capabilities at minimum added complexity. Finally, the conclusions and the key remarks are summarized in section 7.

2. Towards multi-dimensional flexible optical networking

Today, as data volumes grow and standard single-mode fibre (SMF) capacity is becoming a limiting factor, the spectral super-channel approach is introduced that utilizes spectrally flexible (a.k.a. elastic) formats for the dynamic and adaptive allocation of end-to-end demands with variable contents (i.e. requested data rates). Spectrally efficient formats [2] have evolved towards spectrally overlapped orthogonal frequency division multiplexing (OFDM) schemes and time overlapped Nyquist wavelength division multiplexing (NWDM) schemes, each one being implemented either in optical or electronic domain. The key characteristic of all these schemes is the bit rate and bandwidth adaptability of the transceivers [2], achieved by varying the number of subcarriers and the modulation levels (i.e. the format). Such bandwidth variable transceivers (BVTs) enable the definition of the "spectral super-channel" (S-SCh) as a networking entity with a variable spectral content able to transport a flexible capacity demand over an end-to-end path in the network. While the BVT defines the basic optical layer transport entity in spectrally flexible networks, the routing of the traffic in the network depends purely on the type of the bandwidth adaptive switches and their capabilities. Therefore in parallel with BVTs, flexible-grid WSSs are being introduced to handle such bandwidth variable super-channels. In a flexible-grid WSS, the spectral selection does not adhere to a fixed grid and can be provisioned according to required assignment; large contiguous spectral channel bandwidths can be defined. This capability is being utilized to create spectral super-channels, which consist of closely packed sub-channels that are routed through the network as one entity with no guard bands between the sub-channels. For example, a 200 GHz wide spectral super-channel can support 1 terabit/sec capacity using either OFDM or NWDM multiplexing. However, although the spectral super-channel approach can optimize the network resources by offering increased spectral utilization, it has a limited growth potential due to the "capacity crunch” [6], on account of the finite transport capacity of a given single mode fibre core and the limited gain bandwidth of optical amplifiers [7]. These issues will eventually lead to scalability issues and blocking situations for evolving spectral super-channels based optical networks [8].

The evident solution to extend the capacity of optical communication systems relies on the use of the space domain. The simplest way to achieve this is to deploy multiple systems in parallel. However, by simply increasing the number of systems, the cost and power consumption also increases linearly. In order to limit the increase in cost and power consumption, a degree of sharing has to be introduced, in terms of elements and resources among the spatially multiplexed systems that are deployed in parallel; in other words this denotes the need of a “spatial integration of system elements” [3]. To this extend significant research efforts have focused on the development and performance evaluation of few-mode fibres (FMF) and multi-core fibres (MCF) (e.g.[4],[5]), which can be seen as ‘integrated fibre’ media. This work is further supported by the development of integrated optical amplification systems as for example in [9], as well as the significant development efforts in the field of Tb/s integrated transponders (summarized in [10]).

In addition to the optical link capacity increase, an extension of the flexibility concept in space domain [11] can be envisioned, in which the ‘spatial resources’ can be flexibly assigned to different traffic demands, increasing the utilised degrees of flexibility and the network planning and optimization capabilities of the network. By expanding the concept of super-channels in the space dimension, one may consider multiplexing several S-SChs over a number of cores or modes in MCFs or MMFs respectively or even over SMF bundles in a multi-fibre cable. In turn this defines the “spatial-spectral super-channel” (S^2-SCh) networking entity, in which the channel allocation flexibility spans over both the spectrum and space dimensions.

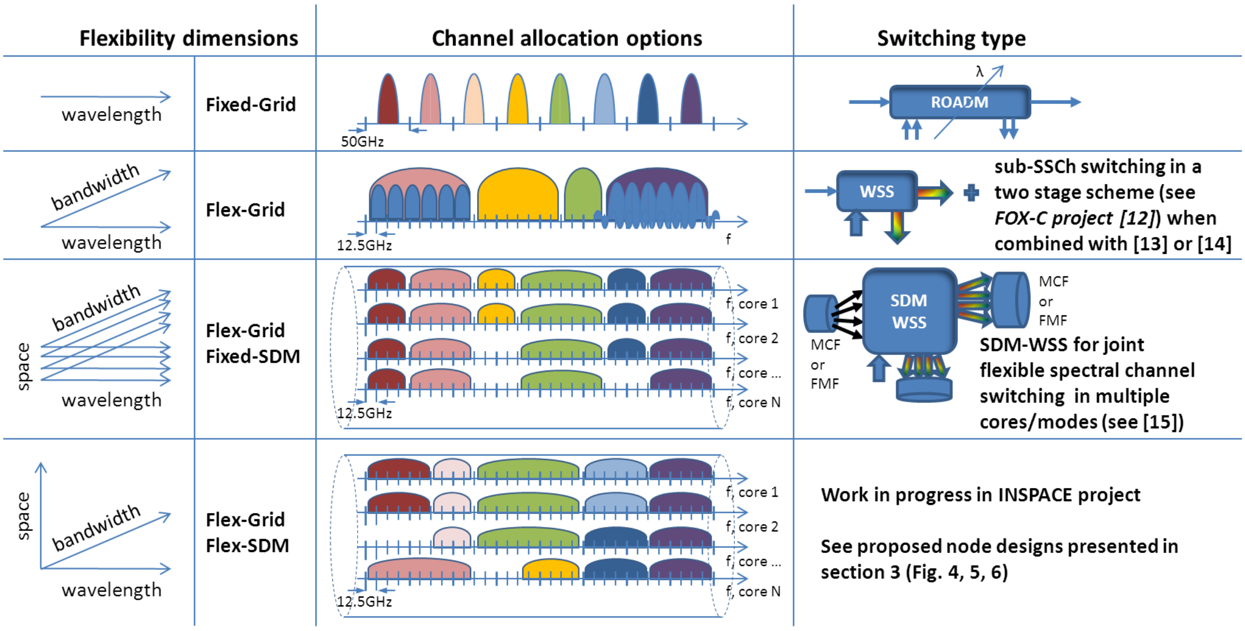


Figure 1 - Different channel allocation options according to their degrees of freedom and the related enabling switching solutions. (Note: in channel allocation options each colour indicate an allocated channel/SCh)

The technology advances both in terms of BVTs and switching elements enables the definition of different channel allocation options and in turn different networking approaches (see section 4). The channel allocation options are summarized in Figure 1, according to the relevant technology maturity. First the traditional fix-grid WDM approach is shown with tuneability in the wavelength dimension only. Next the flex-grid approach is presented, which spans over both the wavelength and bandwidth dimensions, allowing the allocation of spectrally elastic S-SChs with different data rates and formats. The latest research developments in EU project FOX-C [12] demonstrate the potential development of WSSs with sub-1GHz resolution [13], or even the processing (add/drop and erase) of spectrally overlapped contents in S-SChs [14], both resulting in a significant increase of the link spectral efficiency in flex-grid networks. The third case in Figure 1, considers the use of the space dimension only for multiplexing purposes increasing the overall capacity per fibre. In this case spectrally flexible S-SChs expand over all or some of the spatial fibre resources (i.e. modes or cores) and can be jointly switched in the nodes, utilizing the novel SDM-WSS design presented in [15]. The real use of all three dimensions: wavelength, bandwidth and space, is presented in the last allocation scheme in which the spectral and spatial fibre resources are used independently to allocate the traffic demands over S^2-SChs. For example, a S^2-SCh may be defined over a number of fibre cores, while in the remaining cores another S^2-SCh may be allocated, even with different spectral contents.

3. Technology advances that define the SDM flexible networking concept

The last allocation scheme presented above offers a multi-dimensional flexibility with respect to the allocation of the traffic demands. However, the exact definition of the allocated multi-dimensional channels depends on the switching technology capabilities (i.e. the demultiplexing and processing of SDM contents) and the type of SDM fibre (i.e. the effects that are imposed by the transmission medium on the multiplexed channels). Thus, before defining the spatial and spectral flexible optical networking options, the latest advances in optical fibres and the proposed multi-dimensional switching node designs are presented in the following subsections.

Optical fibres in support of SDM

Optical fibres in support of SDM transmission may come in many forms (see Figure 2). Single-mode fibre (SMF) is designed to allow light guiding of a single spatial mode in the core region by tailoring the refractive index profile and core dimensions. Multiple cores can be placed within a single fibre cladding, forming a multi-core fibre (MCF), with each core now supporting a single spatial mode. Hence MCF offers a capacity multiplier equal to the core count. Alternatively, the core dimensions or the refractive index contrast can be modified to support additional optically-guided spatial modes, which closely resemble Laguerre-Gaussian modes. These few-mode fibres (FMF) offer a capacity multiplier equal to the mode count. A somewhat more exotic fibre design is that of the annular core fibre (ACF), which supports multiple spatial modes confined to the annular core region. The annular structure is designed to support a single radial mode and multiple azimuthal modes.

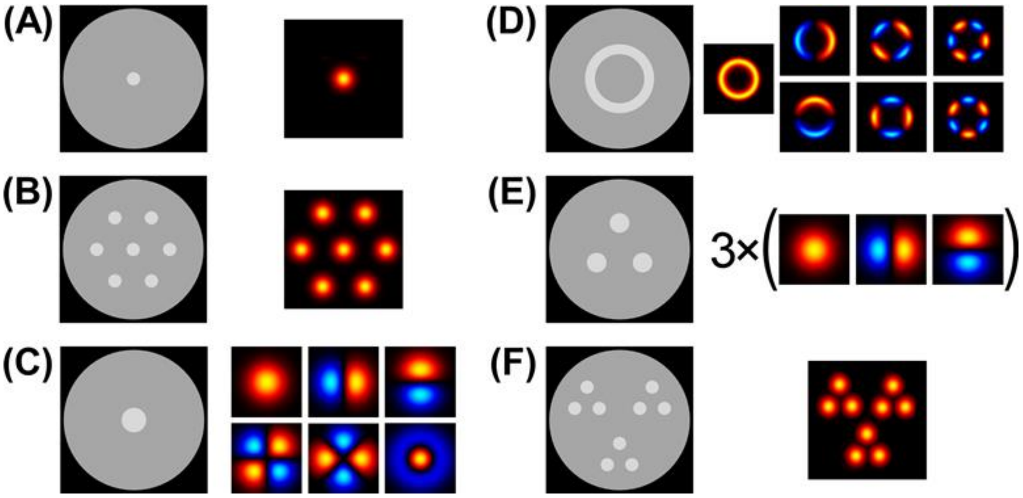


Figure 2 - Different types of fibres in support of SDM, showing their geometrical form and propagating spatial mode distributions. (A) Single-mode fibre, (B) Multi-core fibre, (C) Few-mode fibre, (D) Annular-core fibre, (E) Multi-core supporting few modes, and (F) Multi-core arranged in coupled subgroups.

One of the key differentiating metrics between SDM supporting fibres is whether the modes remain uncoupled in transmission or potentially may be coupled due to manufacturing imperfections, as well as environmental effects such as bends, stress and temperature gradients. Coupled transmission implies that the modes intermix, yet the information is maintained within the set of modes. However, coupled transmission does require that these mixed modes must remain together in order to unravel the mixing at the receiver using digital signal processing. FMF and ACF are inherently prone to mixing as the modes spatially overlap and hence are categorized as a coupled SDM transmission medium. Even though in a simple MCF the cores are distinct, they may still couple if the cores are closely packed; conversely, the MCF can be specifically designed to remain uncoupled. One flavour of SDM purports to use an array of existing SMF; obviously this SDM solution can be categorized as uncoupled as the fibres are separated. The SDM fibre can also be designed to support multiple coupled spatial mode subgroups, yet have no coupling between the groups. Two such examples are a FMF-MCF hybrid, where there are uncoupled multiple higher index cores and each core supports several spatial modes, and a MCF design with an uneven spacing allowing only the closely packed cores to couple.

The adoption of new SDM-supporting fibres in the optical network potentially increases the capacity per fibre by factor M, the number of guided spatial modes. Considering each fibre mode still spectrally spans the optical communication band, then WDM can be applied, carrying N wavelength channels per spatial mode. Hence the WDM-SDM fibre capacity can be defined by a two-dimensional array, with wavelengths (λ_1, …, λ_N) and spatial modes (σ_1, …, σ_M) defining its columns and rows (see Figure 3).

While there are many SDM fibre alternatives that can be considered for implementing future WDM-SDM optical networks, for mesh node switching purposes, they can be categorized into three general archetypes:

1. Uncoupled spatial modes: Spatial channels remain distinct in fibre propagation and all ancillary network equipment, as would be experienced in uncoupled MCF or an SMF bundle. Therefore, individual spatial modes can be switched from one SDM fibre link onto another or add/drop operations applied for any spatial mode/wavelength channel combination.
2. Coupled spatial modes: Spatial channels mix throughout fibre transmission, as occurring in FMF and coupled MCF. As a result of the channel mixing, multiple-input, multiple-output (MIMO) processing is required in order to unravel the mixed information, which occurs after coherent detection of all the spatial modes at the SDM receiver. Since the information is mixed across all spatial modes, modes cannot be separated for switching to other destinations or information loss will be experienced. A complete MIMO receiver has to be employed in order to separate the SDM data, an operation performed at the channel destination, and not desirable at every mesh network node as network transparency will be lost.
3. Coupled spatial subgroups: Spatial modes may mix only within subgroups of the total spatial mode count. The subgroups are defined by the SDM fibre design, and the spatial modes belonging to a subgroup must not be separated in switching operation. Subdividing the spatial modes into subgroups of smaller size eases the switching limitations with respect to full mode coupling, while not reaching the full flexibility of uncoupled modes.

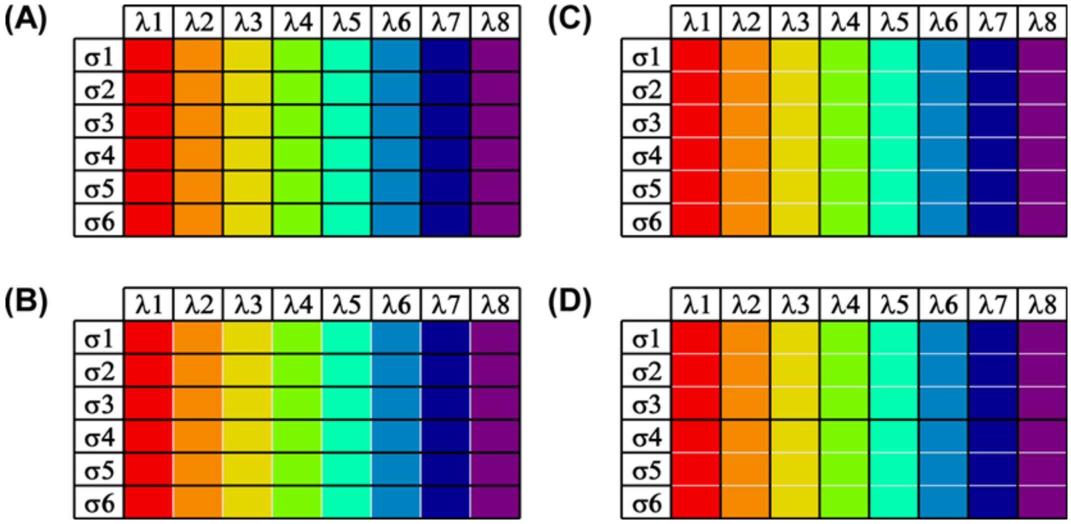


Figure 3 - Parsing the fibre's SDM and WDM channels for switching, where space modes (σ_1, …, σ_M) and wavelength channels (λ_1, …, λ_N) are fully utilized. (A) Each mode/wavelength channel can be independently switched, (B) Switching performed on mode basis across all wavelengths, (C) Switching performed on wavelength basis across all modes, and (D) Switching performed on wavelength basis and spatial mode sub-groups.

Multi-dimensional switching node designs

A multi-dimensional switching node may use all three granularity levels (space, wavelength, and time) or a subset of two of them depending on the technology capabilities. Utilizing the time domain requires active components and hence is reserved to IP routers that can utilize burst type communication or TDM leading to significant energy inefficiency. The EU project INSPACE will focus on the introduction of SDM at the optical level, where information can be routed transparently and most efficiently. However, transitioning to an optical network based on high capacity SDM fibre links is still far off and entails resolving many issues related to its physical-layer implementation, such as identifying the best SDM fibre option, the optical amplification means, the efficient space multiplexing and demultiplexing methods, and in particular the all-optical switching approaches that should occur at network nodes where information-bearing channels have to be routed towards their destinations within an optical mesh topology.

At the optical network nodes, the WDM-SDM traffic on each inbound fibre link has to be either redirected to outbound fibre links as part of the network information flow, or dropped to receivers for local consumption at the node's geographical location. Additional data is typically reintroduced, or added, in its place originating at clients associated with the node. The SDM fibre categories dictate the permissible switching operations that can transpire at the optical network nodes. We identify four alternative switching scenarios which strongly relate to the SDM fibre categories, forming multi-dimensional switching nodes of different granularities (i.e. as discussed before):

A. Independent spatial mode/wavelength channel switching (space-wavelength granularity): The WDM-SDM fibre capacity can be switched independently for every spatial mode and wavelength combination. This forms the finest switching capacity granularity, leading to the greatest flexibility at the cost of increased realization complexity. Employing independent mode/wavelength switching requires uncoupled SDM fibre.

B. Spatial mode switching across all wavelength channels (space granularity): The WDM-SDM fibre capacity is switched at the spatial mode level, independent of wavelengths. Hence the entire communication band per mode is jointly switched. At low spatial mode counts, space switching granularity is coarse (all WDM channels) but simple to realize. Employing independent mode switching also requires uncoupled SDM fibre.

C. Wavelength switching across all spatial modes (wavelength granularity): The WDM-SDM fibre capacity is switched at the wavelength level across all spatial modes, forming spatial superchannels that are routed through the network as one entity. Since the spatial modes are not separately routed, the network topology is similar to today's SMF networks, yet benefitting from the SDM capacity multiplier. Employing wavelength switching across all modes is obligatory for coupled SDM fibre, but can also be applied to uncoupled SDM fibres.

D. Wavelength switching across spatial mode subgroups (fractional space-full wavelength granularity): The WDM-SDM fibre capacity is switched at the wavelength level across smaller spatial mode subgroups. The switching operation is still in support of spatial superchannels within each subgroup, but applied independently to the subgroup elements. Employing the fractional space and full wavelength granularity capacity switching is in support of coupled subgroups SDM fibre, but can also be applied to uncoupled SDM fibres.

Routing in the WDM-SDM optical network is constrained by the employed switched capacity granularity, as the network provisioning algorithms must assign each information flow request onto a route that can be supported by the switching nodes and is contention-free. An additional degree of freedom implicit in the switching capacity granularity involving the wavelength space (options A, C, and D), is the ability to flexibly define the switched spectrum. The independent space-wavelength granularity (option A) is the smallest capacity block size and offers the greatest routing flexibility as even single wavelength and spatial mode requests can be accommodated. The alternative solutions (options B-D) utilize larger switching capacity granularities, by addressing all wavelengths (B), spatial modes (C), or spatial mode subgroups (D) as one entity. Such switching solutions may become inefficient when addressing small capacity requests, but the reduced hardware required to realize these degenerate switching solutions may be favourable implementation-wise. If using coupled SDM fibre, then jointly switching all spatial modes (option C) is mandatory. The capacity granularity can be reduced by provisioning narrower spectral bands by the switching hardware, which may require some customization. For example, if the switching hardware supports minimal bandwidth provisioning of 35GHz, then a six-wide SDM fibre can offer enough capacity to support one terabit per second as the minimal switched capacity, which is a reasonable starting point for future WDM-SDM optical networks.

After having defined the switched capacity granularity at the WDM-SDM optical network nodes, we turn our attention to their implementation details. The switching node must complete two functions: routing traffic from an input SDM fibre to an output SDM fibre and performing channel add/drop to be terminated at optical transceivers. Each solution entails its unique switching hardware, and various levels of complexity are associated with each granularity level. However, some elements are recurring and we briefly explain their operation. The WSS has been introduced earlier, and its flexible-grid implementation is assumed here. The WSS utilizes SMF at its input/output ports, and must be properly interfaced to the SDM fibre solutions. For MCF, a breakout device separates the M cores to M individual SMF. For FMF, a mode demultiplexer converts the M modes to M individual SMF. This operation does not necessarily require the modes to be mapped to individual output fibres; a unitary mode-mixing operation may be associated with the demultiplexer that can be subsequently undone in MIMO processing.

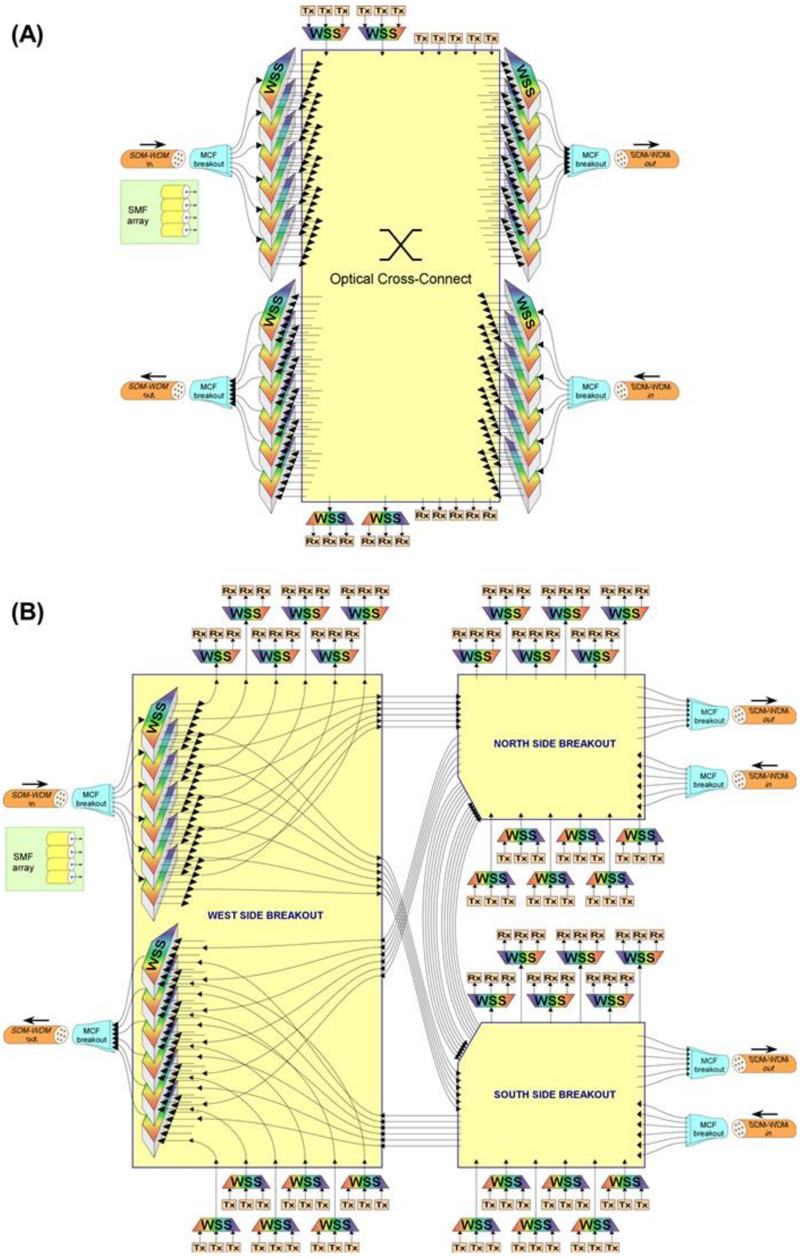


Figure 4 - Implementations for independent spatial mode/wavelength channel switching. (A) Optical cross-connect for full connectivity (only two fibre links shown), and (B) Route-and-select per each spatial mode.

Two possible implementations of independent spatial mode/wavelength channel switching (space-wavelength granularity) offering different levels of flexibility are shown in Figure 4. The first implementation makes use of a large optical cross-connect. To interface between the uncoupled SDM fibre solution and the OXC, each independent spatial mode is processed with a 1×K WSS. The WSS subdivides the WDM channels on each spatial mode according to destination, whether to an output SDM fibre (on a particular spatial mode) or to a drop port. On the output side a K×1 WSS multiplexes the channels onto a spatial mode of the SDM fibre. Single drop channels can be terminated directly at conventional receivers, and multiple drop channels can be separated further with another WSS. This architecture provides full routing flexibility thanks to the OXC, especially wavelength contention by enabling SDM 'lane changes', or routing of a wavelength channel from one spatial channel to another instead of the much harder wavelength conversion solutions proposed for SMF networks. Additionally, the transceiver elements are accessible to all fibre directions (and are further colourless and contentionless), resolving the directional limitation in route-and-select solutions. Having WSS pre- and post-process WDM channels enables flexible bandwidth allocation, as well as conserve OXC fibre ports as WDM channels destined to the same direction can be routed jointly.

The second independent spatial mode/wavelength switching solution eliminates the OXC, which is a costly element and single point of failure threat. Here, route-and-select is performed for each spatial mode independently. Each independent spatial mode is subdivided by a 1×K WSS and routed to output fibre destinations (mapped to the same mode on the output fibre, eliminating SDM lane change operation), or to a set of receivers associated with the spatial mode (i.e., directional in both fibre and mode sense). Hence, eliminating the OXC results in routing constraints.

The biggest disadvantage of the independent space-wavelength granular switching node designs is the amount of hardware required to implement them. Essentially, this entails scaling the WSS count M-fold, same as the capacity increase. Hence the mesh node cost scales linearly with the capacity gain, which is counter to the value proposition of SDM. We're seeking a sub-linear cost increase with capacity to maintain network economics, by way of better device and sub-system integration. With independent space-wavelength granular switching this requirement is not met.

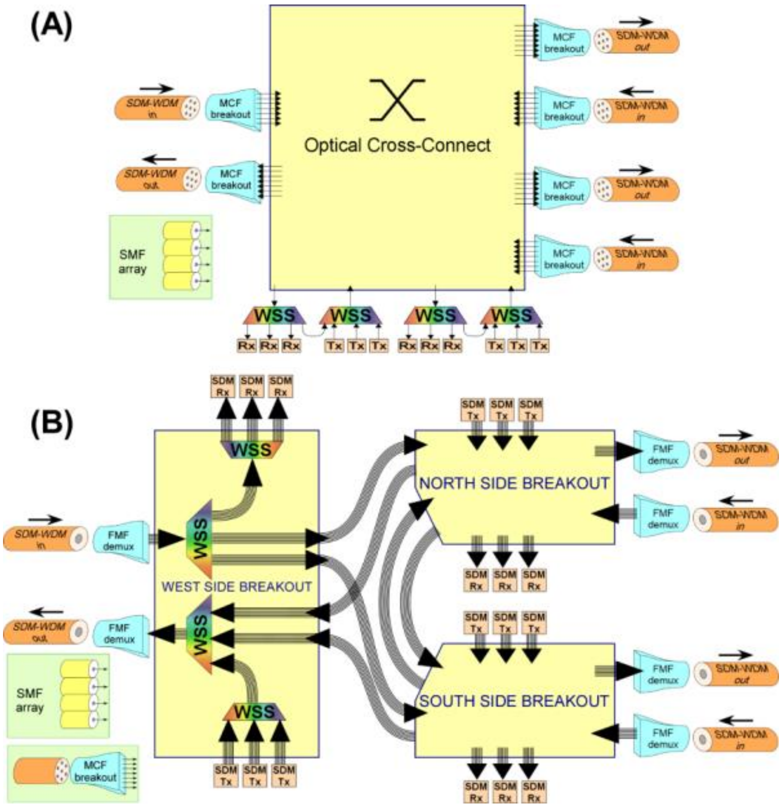


Figure 5 - Switching node designs for implementing: (A) space granularity, routing the entire communication band per spatial mode, and (B) wavelength granularity, routing all modes per wavelength.

Eliminating the WDM switching elements and realizing a space-granular capacity switching design significantly reduces the node hardware and cost (see Figure 5-A). An OXC receives all spatial modes along its input ports and switches each mode to an output SDM fibre, thereby completing the routing of the entire optical communication band (all WDM channels) to the output destinations. For the add/drop operation, the OXC can switch the dropped spatial mode to a port where a WSS separates the channels to be detected and the remaining channels are fed through to a second WSS which combines these channels with additional add channels back into the OXC for output fibre assignment. The WSS count in the node depends on the number of spatial modes allowed to be dropped, with a minimum of one spatial mode per fibre. But as this number increases, which is required to offer reasonable routing flexibility, the WSS count can again become prohibitively high.

Alternatively, the wavelength-granular capacity switching design (see Figure 5-B) utilizes a recently-introduced WSS modification, specifically designed for routing of spatial super-channels. The WSS is based on a conventional (SMF based), high-port-count WSS, and is made to operate with all the spatial modes of the input SDM fibre feeding a first subset of the WSS ports. The internal wavelength switching mechanism of the WSS (based on beam steering), steers the set of input ports onto a second subset of the WSS ports. When the ports are arranged in a linear, equi-spaced array, then the fibre ports are imaged from the first subset onto the second, switching in parallel all the fibres and hence the entire spatial mode set. This joint-switching WSS can be used to construct the conventional route-and-select architecture of the SMF networks, with the M-fold parallelism applied across all modes with a single switching module. The routed spatial super-channels traverse a first M×(1×K) for destination selection and a second M×(K×1) for combining the wavelength channels to the output SDM fibre. The dropped spatial super-channels are interfaced to SDM transceiver elements where MIMO processing is performed for information extraction in the case where the modes are mixed due to mode coupling from the SDM fibre. The scalability of this wavelength-granular solution to high mode counts (tens of modes) is presently undetermined, as joint switching WSS have limited fibre port counts. One of the main targets for the INSPACE project is to examine alternative designs and technologies for the development of joint switching WSS with support for high port counts.

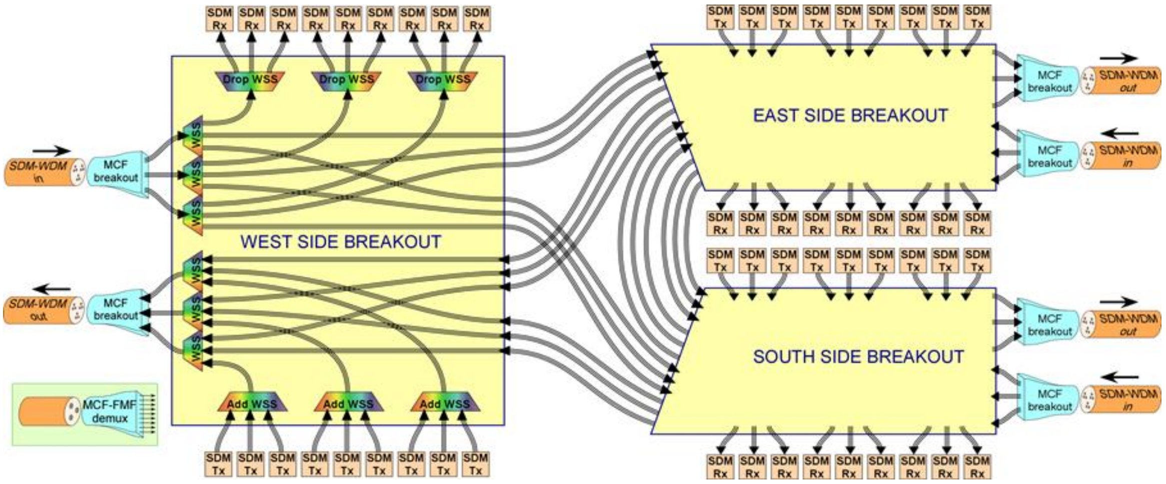


Figure 6 - Switching node design for implementing hybrid fractional space-full wavelength switching granularity, routing spatial super-channels spanning spatial sub groups.

The final variant is a space and wavelength hybrid design, which offers fractional space and full wavelength granular capacity switching (see Figure 6). This switching scenario is matched to an SDM fiber solution offering M spatial modes, where the modes can be divided to M/P independent subgroups, where modes are coupled within the individual subgroups having P modes. Each mode group must be switched jointly due to the inherent coupling, yet the groups can be switched independently of one another. The switching solution is the basic route-and-select topology applied to each subgroup using modified WSS that support the joint-switching concept. The solution is replicated M/P times, matching the subgroup count. This hybrid solution offers finer granularity than switching all modes (wavelength granularity), at a price of increased switching hardware, yet the price is a fraction (1/P) of the capacity gain. While the fractional space-full wavelength solution requires specific forms of SDM fibre, it can also be applied to uncoupled SDM fibre. This switching solution can more effectively address SDM fibres with very high spatial mode counts.

SDM transmission is a promising solution to the capacity limitation of SMF, but addressing the physical SDM elements of novel fibre types, supporting optical amplifiers, and mode multiplexers, without careful attention to optical networking implications misses an important element of the entire value proposition. In this paper we highlighted some of the implications of designing a WDM-SDM optical mesh network, concentrating on the switching node designs by which information flows need to be provisioned. We identified four categories of capacity granularities to be provisioned, applied across the space and wavelength domains. Each category can be realized with different optical switching gear at the network node, affecting the realization complexity and cost, flexibility, and scalability. These findings are summarized in Table 1.

Table 1 - Comparison of WDM-SDM switching alternatives

	Space-wavelength granularity	Space granularity	Wavelength granularity	Fractional space-full wavelength granularity
Realization	*With OXC:* High-port count OXC and at least 2*M* conventional WSS per I/O fibre link. *Without OXC:* 2*M* conventional WSS per I/O fibre link. 4*M* if WSS placed on add/drop.	Moderate port count OXC, and 2 WSS per mode selected for WDM channel add/drop.	4 joint switching WSS per I/O fibre link in route-and-select topology applied to all spatial modes in parallel.	4×*M*/*P* joint switching WSS modules per I/O fibre link.
Flexibility	*With OXC:* Each mode/WDM channel independent provisioned and routed. Supports SDM lane change. Single point of failure. *Without OXC:* Each mode/WDM channel independent provisioned and routed. Spatial mode maintained. Prone to wavelength contention.	The complete optical communication band is routed across network. Coarse granularity. If WDM channels need to be extracted from many modes then WSS count quickly escalates.	Each spatial super-channel provisioned across all modes. Susceptible to wavelength contention. Add/drop bound to direction.	Compromise solution using small SDM groups. More efficient when provisioning low capacity demands.
Scaling	With OXC: Can quickly escalate to very large port counts. Switching node cost linearly scales with capacity, no price benefit to SDM.	Conventional OXC can support foreseeable mode and fibre counts. OXC is single point of failure. Pricing favourable but with greater add/drop require more WSS modules.	Cost roughly independent of SDM count. Inefficient for low capacity connections due to minimum BW provisioned across SDM. Large SDM Rx/Tx are integration and DSP challenge.	Cost scales as group count. Groups can be turned on as capacity grows, offering pay-as-you-go alternative. Maintaining small group sizes facilitates MIMO processing at Rx.

It is premature at this early stage to deduce if there is an optimal solution to the WDM-SDM optical network. Different networking applications may likely have divergent conclusions. Assessment of the complete optical network must to take into account the physical layer attributes, the expected information flow scales and how efficiently they can be met given the minimum capacity granularity that is routed by the network, blocking probabilities due to contention for the provisioning of information flows, and cost of implementation, amongst other. As such, a complete analysis involves the contributions from different skillsets and it will likely require the concerted effort of many researchers in the field to analyze the performance level and benefits offered by WDM-SDM optical networks.

The first step for this analysis is to define the different flexible and multi-dimensional optical networking options that expand the allocation of traffic over both spectral and spatial dimensions. Such options are related with the different fibre types and switch designs. These options are presented in the following section.

4. Spatial, spectral or combined flexible optical networking?

The use of the space dimension in addition to the spectrum dimension could potentially lead to five different flexible optical networking options, which are summarized in Figure 7 and explained in the following paragraphs.

The pure SDM approach (as defined in the physical layer) denotes that at the end of each transmission link a spatial-demultiplexer is placed prior to a spectral-demultiplexer to process and extract the spatially multiplexed data. The spectrally flexible networking concept that is studied for common SMF-based systems can be equally applied to SDM systems, assuming that a spatial-demultiplexing process applies at the end of the links (Figure 7 – case A). In this case, the space dimension relates with the multiplexing stage of the physical layer and has no role in networking layers. Therefore, in principle there is no difference with the spectrally flexible networking concept that spans over multiple parallel links. Evidently, this scheme represents the natural evolution of today's transmission systems towards higher capacity systems, considering the use of links with bundles of SMF. However, it is also applicable to MCF systems with uncoupled cores in order to avoid cross-talk between cores carrying independently assigned end-to-end S-SChs.

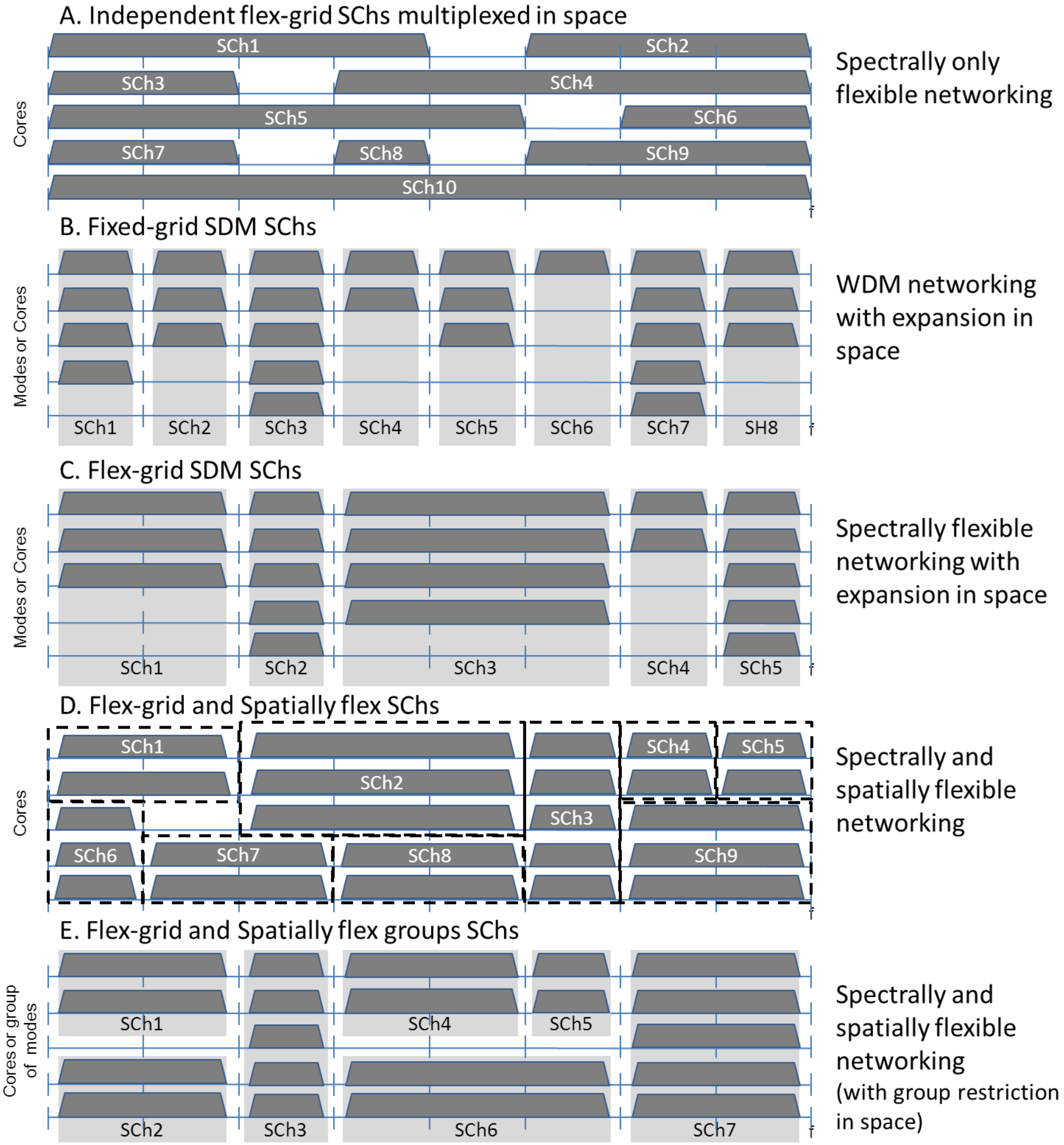


Figure 7 - The different flexible optical networking options offered with the use of the space dimension in addition to the spectrum dimension

An alternative could be to use elasticity in space dimension instead of the spectrum dimension (Figure 7 – case B). Channels can be allocated over a fixed spectral grid (as in the case of WDM systems) and may have the ability to flexibly expand over some or all of the modes/cores in the fibre. For example a 100Gb/s DP-QPSK demand can be allocated inside a 50GHz grid and occupy one core in a MCF, while a 400Gb/s demand is allocated over 4 cores inside the same grid. Networking can then rely on common WDM allocation and routing schemes. Also the transmitter and receiver designs are simplified due the use of a common transmission and local oscillator laser. In this case, the spatial elasticity makes the spectral elasticity requirements obsolete. Moreover, a pure spatially flexible optical network maintains the network planning and operation simplicity of fixed grid WDM networks, avoiding issues like spectral fragmentation and complex resource optimization and control, as in the case of spectrally flexible networks. However, this networking solution is not capable to make real use of the capacity increase benefits of SDM. Limited resource utilization is expected due to the required spectral gaps between adjacent fixed-grid channel and mainly due to the unutilized spatial resources from low capacity demand. The scheme is applicable to any type of MMF or MCF with coupled or uncoupled cores.

A more efficient scheme compared to the pure spatially flexible networking concept can be proposed by allowing spectrally flexible contents to be allocated over the space dimension (Figure 7 – case C). This approach leads to the flex-grid SDM scheme and is primarily enabled by the novel joint spatial switching elements proposed in [15]. From the networking point of view the network planning and operation complexity follows that of spectrally flexible networks with the main difference being in the allocation options for the SChs. Similar to a spectrally flexible approach, the scheme also allows the adaptation of the signal format (i.e. bandwidth) to the transmission reach target, which can be an important issue for SDM transmission due to cross-channel interference in MMFs and MCF with coupled cores. The flex-grid SDM solution is expected to have better resource utilization than the pure spatially flexible (i.e. fixed-grid SDM) solution for large capacity demands due to the efficient use of the spectral resources, however the optimum use of the spatial resources still remains an issue.

Evidently, the most flexible networking approach is to combine elasticity in both spectrum and space dimensions (Figure 7 – case D). In this case, the available end-to-end resources could be identified over a pool of spatial and spectral slots in the links that form the end-to-end path, assuming that innovative multi-dimensional nodes are in place able to perform switching in both dimensions independently. The additional use of the space dimension is expected to increase significantly the complexity of the network planning and resource optimization algorithms compared to the spectrally flexible networking approach, but can potentially lead to significant benefits. Spectral fragmentation issues (see next section) can be resolved via switching of the fragmented spectral slots in the space dimension, while also new approaches for network resource virtualization and content aware IP mapping over the optical layer can be adopted with the spatial allocation of virtualized network segments. The scheme requires the use of MCFs with uncoupled cores to achieve independent switching of cores in the space dimension.

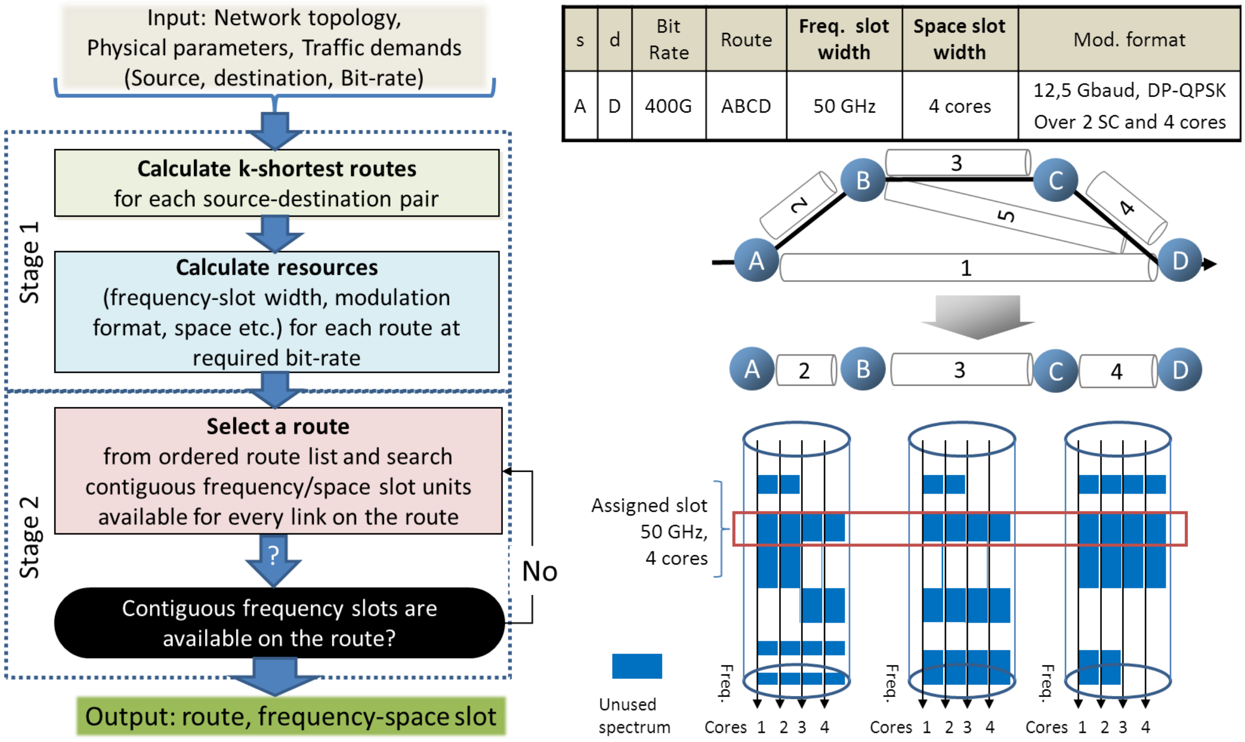
Finally, an alternative scheme for combined spectral and spatial networking could consider the allocation of SChs on independent groups of cores or modes rather than individual ones (Figure 7 – case E). This case can be seen as a combination of cases C and D presented above. The spatial groups can be treated as a single switching entity either if they are fully utilized or not (as in case D), while spectral elasticity is maintained within them (as in case C). This approach could potentially relax the technology related design complexity of the node (i.e. by reducing the number of required spatial ports), in the expense though of some resource underutilization compared to the previous case. The scheme is applicable to MCF with uncoupled cores and possibly to MCF with coupled cores assuming that the spatial groups are properly allocated over distant cores with minimum interference between them. Moreover, this scheme could be attractive in particular for the case of the newly developed MCF with few-mode cores (FM-MCF) [16], where each one of the few mode cores is a spatial group that can be handled independently to the rest of the fibre cores.

It is noted that the combined spectral and spatial flexible networking is a new research topic and significant research effort is required in order to identify and quantify its full potentials and complexity limitations. Moreover, a detailed evaluation of the different flexibility schemes presented above is currently missing from literature and is one of the key goals of INSPACE project. The following section presents the required approaches in terms of network planning and resource optimization algorithms, which are essential for the evaluation of the different flexibility schemes.

5. Network planning and resource optimization approaches for SDM networks

Network planning enables the assignment of network resources (e.g. transponders, switching elements, spectrum, fibre cores/modes etc.) to connections, in order to satisfy a defined optimisation objective, while adhering to a given set of constraints. The optimization objective can be tuned to meet different criteria – including the minimization of the required spectral resources, the minimization of the capital expenditures for network equipment, and the maximization of the energy efficiency. The set of traffic demands that have to be accommodated, and the capabilities that are offered by the considered network equipment are generally considered as input. The network topology can be either given as input or provided as a result from the optimization process. The capabilities that are offered by the network equipment impose a set of constraints on the feasible assignments. For example, the granularity with which the spectrum of an optical channel can be increased is restricted by the capabilities of the optical switches deployed along its path.

All the network planning and resource optimization algorithmic approaches follow in general two stages, as it is shown in the example of Figure 8. In the first stage, a route list with necessary resources (frequency slot width, modulation format, number of cores etc.) is created. Given the network topology and physical parameters, an ordered list of k-shortest routes for each source-destination pair is first created. Then the required resources (spectral and/or spatial) are calculated for each route at the required bit-rate, taking into account linear and nonlinear impairment factors or simpler being based on expected and pre-calculated transmission reach values. The second stage allocates contiguous resources to the route. When a connection request arrives, a route is selected from the ordered route list created in the previous stage in sequence. The necessary resources are found from the list. Then a search is performed for the available contiguous resources in every link on the route and the lowest available contiguous resources are selected. If no available contiguous resources are found on the route, an alternate route is selected from the route list.



s	d	Bit Rate	Route	**Freq. slot width**	**Space slot width**	Mod. format
A	D	400G	ABCD	50 GHz	4 cores	12,5 Gbaud, DP-QPSK Over 2 SC and 4 cores

Figure 8 - An example of the process and the main calculation steps for identifying and assigning a capacity demand in a flexible network.

Conventional fixed-grid networking solutions, as shown in the first row of Figure 1, require the application of Routing and Wavelength Assignment (RWA) algorithms. These algorithms guarantee that the traffic demand is appropriately routed between all source-destination node-pairs. RWA algorithms also impose constraints that are required in the network planning process, such as wavelength continuity (i.e., imposing that the same wavelength is used in all of the links traversed by the connection) and single wavelength assignment (i.e. imposing that on each link each wavelength can be used by only one connection).

The emergence of flexible optical networking (second row in Figure 1) poses significant challenges on the networking level, requiring a number of contiguous spectrum slots to be assigned to each connection, instead of a certain wavelength, as in the fix-grid case. Additionally, the continuity of these spectrum slots should be guaranteed in a similar manner as wavelength continuity constraints are imposed. This leads to the development of routing and spectrum allocation algorithms (RSA) [17]. Moreover, as additional degrees of freedom are allowed by flexible optical networks – new relevant constraints are required to be considered. For example, the ability to select the modulation level on a connection basis introduces the constraint of achieved transmission reach for a required bit-rate that serves a traffic demand. To this end routing modulation level and spectrum allocation algorithms (RMLSA) have been proposed and summarized in [18]. These algorithms can address the offline network planning phase, or they can be applied to dynamically provision connection requests [19], [20]. As connections are dynamically established and released, the issue of bandwidth fragmentation arises – leading to increased blocking probabilities. Thus, the development of spectrum defragmentation algorithms is required [21], [22].

With the advent SDM technologies, the additional dimension of space can be added to the networking "toolbox". In [11] and [23] the use of spatial super-channels is proposed, and defined as groups of same-wavelength sub-channels, transmitted on separate spatial modes but routed together. This case is shown in the third row of Figure 1 and corresponds to options B and C presented in Figure 7. Moreover, new constraints that relate with the types of fibres and the spatial interference among co-propagating signals must be included in this case. By exploiting the full potentials of the space dimension, as an additional degree of freedom to spectrum and bandwidth allocation options, (as shown in the bottom row of Figure 1 and referring to options D and E in Figure 7), the definition of routing, space, modulation level and spectrum allocation algorithms (R-S-ML-SA) emerges. However, only a very limited amount of works have addressed this issue. In [24] the first hierarchy for dynamic multidimensional spatial and spectral optical networking is proposed and complemented with adaptive coded-modulation to form the basis of a novel elastic networking concept. The resource allocation for flex-grid SDM networks with MCF has been addressed for a dynamic scenario in [25]. Also recently a joint spectral and spatial network planning strategy for networks employing MCFs was presented in [26] taking into account the inter-core crosstalk impairments.

Within INSPACE novel network planning techniques are developed, focusing both on the use of spatial super-channels and hybrid spatial-spectral super-channels, according to the different options described in section 4. As conventional RWA and RMLSA algorithms cannot be applied in spatial-spectral flexible networks, enhanced routing and resource allocation algorithms are required to be developed, considering also the spatial cross-talk and switching impairment constraints in addition to the transmission related constraints. The optimization objective of the developed planning algorithms requires to be tuned to meet the minimization of capital expenditures for network equipment, as well as the maximization of energy efficiency. Such studies are essential in order also to identify the optimum switch design (or equally the allocation option) in terms of added complexity. Furthermore, the computation time of the developed routing and resource (re)allocation algorithms is becoming an important issue due to the multiple degrees of freedom, especially when such algorithms are considered during the network operation phase.

6. Control plane extensions required for SDM networks

Control plane solutions for optical transport networks have been steadily evolving in the last decade in order to adapt to technological breakthroughs and to offer a wider set of network functionalities, while guaranteeing an effective management of network resources. In fact, besides basic functionalities including: interaction with the clients, admission control, routing algorithms, lightpath provisioning and survivability, future network controllers/orchestrators are expected to provide advanced functionalities such as real-time service modification, in-operation planning and optimization, programmability, virtualization, and refined monitoring procedures.

The possibility to exploit the space dimension as a further degree of freedom poses new challenges on the optical control plane side. Alongside with the offered capacity increase and the additional networking features mentioned in the previous sections, the use of the space dimension in flexible networks mainly implies a significant change in the network model (related to the representation and configuration of nodes, switches, fibres, amplifiers, etc.), plus additional switching constraints to be carefully taken into account. Moreover, one of the functionalities that could benefit from the introduction of the spatial flexibility in network is virtualization. In fact, it would be possible to instantiate virtual slices embedded on top of different space dimensions of the same physical substrate. From the isolation perspective, with some flavours of SDM (e.g. bundle of single-mode fibres or multi-core fibres) it would also be possible to provide physical isolation by matching logical partitions to spatial dimensions.

Control plane architectures able to realise the aforementioned functionalities, as well as the envisioned extensions needed to introduce space dimension multiplexing in optical networking, range from "legacy" solutions based on the GMPLS protocol suite (to be adequately extended) to more modern Software Define networking (SDN) based approaches.

GMPLS-based architectures investigated so far can be mainly differentiated on the basis of their computation and control capabilities. They range from fully distributed solutions relying on source routing to centralized ones based on the Path Computation Element (PCE). Centralized architectures are able to exploit dedicated computational resources to compute paths, store information about network status, and, in the most recent flavours, modify already active connections (i.e., active stateful PCE) or even autonomously setup or release connections independently from clients, thus behaving as a full network controller (i.e., PCE with instantiation capabilities). Despite all the different PCE/GMPLS flavours, functionalities such as programmability and network virtualization are difficult to implement in practice using such architectures. The IETF PCE-based "Architecture for Application-based Network Operations" (ABNO) [27] tries to fill this gap by proposing a modular framework composed of multiple existing building blocks (e.g., PCE). ABNO aims at providing advanced functionalities able to optimize traffic flows between applications, coordinate programming and provisioning of network resources, facilitate grooming, scheduling and optimization, and provide Virtual Private Network planning.

In parallel with the aforementioned PCE/GMPLS evolution, the SDN technology has been introduced, initially in the context of packet switching (e.g., within data centers). In SDN a centralized controller is in charge of the orchestration and effective abstraction of the underlying infrastructure. The interface between the application and control layer goes under the name of northbound interface and is specified by application programming interfaces (APIs). Furthermore, SDN is designed to provide direct programmability of forwarding functions through the southbound interface, most often through the OpenFlow protocol (especially in packet-switched networks). This way, no distributed protocols are adopted and vendor interoperability can be better guaranteed by simply mandating a standard southbound interface. Moreover, a large community is nowadays actively contributing to SDN development through open source implementations (e.g., OpenDaylight [28], ONOS [29]).

From the performance perspective, the use of GMPLS in optical networks has demonstrated its capability to guarantee adequate recovery time in case of optical network failures, while some concern is still present when SDN is considered. On the other hand, centralized SDN enables more accurate device configurations and facilitates advanced data plane solutions for network defragmentation and dynamic adaptation [30].

In a medium/long term perspective, the introduction of SDM will require further adaptations, as preliminary proposed in [31]. The node models will need to take into account new designs and switching capabilities (and restrictions) of SDM WSSs and ROADMs. Also the link models will need to include fibre types and physical characteristics, while dynamic algorithms for routing and spectrum allocation will have to consider the new switching features and constraints introduced by SDM. With respect to the southbound protocols, neither

GMPLS nor OpenFlow support handling transmission impairments and optical filter configurations in a standardized fashion, nor do they support SDM fibers and switches. To address these issues, the additional efforts that are in place to define the formal model of optical devices could foster the adoption of additional protocol solutions (e.g. XML-based protocols like NETCONF) to directly program optical devices.

Such innovations will impact virtually all the elements of an optical control plane.

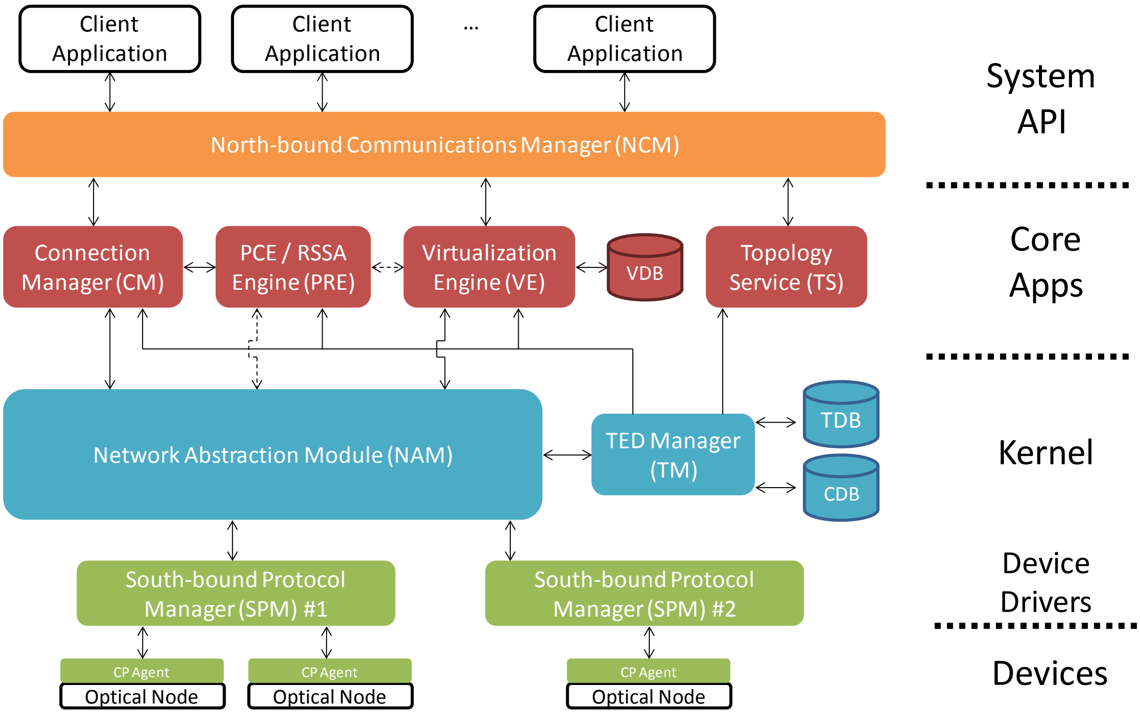


Figure 9 - INSPACE control architecture (including the most relevant modules and interfaces).

The INSPACE control plane (shown in Figure 9) will adopt a centralized SDN approach, realized through a layered architecture, somewhat reminding that of an Operating System (OS): at the highest level stands the System API layer, which implements a number of functions and services made available to clients (i.e., third-party applications). Below that is the Core Applications layer, which includes a number of first-party applications that implement the functionalities offered to third parties. Below the Core Apps is the Network Abstraction Module, which, like an OS Kernel, is responsible for managing devices (including memory, here represented via the Traffic Engineering Database (TED) manager module) and offers a unified interface irrespective of the peculiarities of the underlying hardware. Finally, at the lowest layer sit one or more modules that implement the translation between the internal representation and the format expected by devices, in addition to managing device configurations sessions, thus behaving in a manner akin to OS Device Drivers. Please note that, regardless of which southbound protocols will be developed within INSPACE, the architecture can be extended to support further protocols by implementing additional Southbound Protocol Managers to handle the translation from/to that protocol's specific information model, however it is encoded.

7. Conclusions and remarks

This white paper summarized the vision and activities of EU project INSPACE which tries to use of the space dimension (SDM) in addition to WDM for improving the capabilities of future optical networks. SDM has been primarily introduced in an effort to increase the overall capacity of optical transmission systems. However, by extending also the well-studied spectral flexibility concept in the space dimension, the spectrally and spatially flexible networking concept is introduced, in which the spatial resources (fibres, cores or modes) are considered in addition to spectral resources (wavelength, bandwidth and modulation format) for the overall network planning and resource optimization. This new concept generates several potentials (compared to traditional reconfigurable WDM and GMPLS-based approaches) primarily with respect to channel allocation, resource optimization, defragmentation, joint IP/Optical layer optimization and virtualization, but also significant challenges in terms of complexity and network control issues that require to be explored, in order to fully exploit the potential benefits of a spatially-spectrally flexible network solution. The different allocation options, as well as the potential benefits and challenges were identified in this article.

Finally, it is worth noticing that the realization of the spectrally and spatially flexible networking concept requires to be supported by key technology innovations in data transmission, switching and network elements, in order to provide the ability to route traffic demands that are adaptively allocated over multiple data dimensions. Currently, significant research efforts have shown impressive results in new MCF, MMF and FM-MCF types for SDM, ultra-high capacity data transmission over MCF/MMF systems and novel designs of SDM-WSS switches. Despite these efforts, a major practical limitation is still evident and relates with the enormous cost for replacing the existing fibre infrastructure with the new SDM fibre types. A more short term approach considers the use of fibre bundles for the increase of the link capacity in networks. However, even in this case the spectrally-spatially flexible networking concept could be applicable, since it can expand the spectral flexibility in the space dimension, providing a powerful solution for the overall resource optimization and the introduction of advanced network operating functions such as defragmentation, IP/Optical layer integration and spatial virtualization.

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