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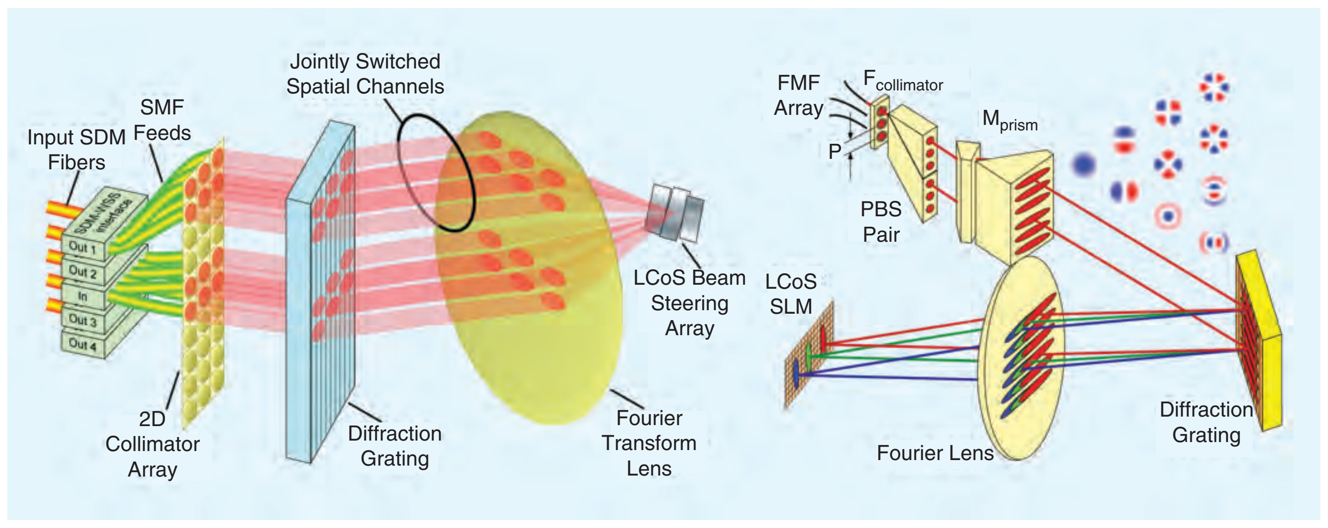
Realizing Spectrally-Spatially Flexible Optical Networks



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Research Highlights

Realizing Spectrally-Spatially Flexible Optical Networks

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The future scaling of optical networks will rely on higher capacity fiber links employing space-division multiplexing (SDM) in addition to established wavelength division multiplexing (WDM). Realizing such spatial-spectral optical networks in a cost-effective manner, balancing flexibility and complexity, was investigated in European Project INSPACE and its major findings are reported in this newsletter.

Introduction

Optical networks serve as the foundation of our information-based society, providing interconnectivity across the globe. As our human and machine data consumption continually grows, it is becoming more economically and technically challenging to scale the optical network, as the transmission capacity of the omnipresent single mode fiber (SMF) is being exhausted. The advent of SDM in recent years, whether in new fiber designs or in the form of SMF bundles, has demonstrated the pathway to higher capacity fiber-optic links. Yet concrete implementation of optical networks benefitting from the SDM paradigm are still lacking. For optical networks to successfully introduce the SDM capacity multiplier, new switching, routing, and multiplexing hardware has to be introduced, in addition to network provisioning and resource allocation algorithms, and means to mitigate new transmission impairments as linear and nonlinear crosstalk between spatial channels.

This article reviews the key innovations and outcomes of the three-year European research program, INSPACE, devoted to tackling the implementation issues of Spatially and Spectrally Flexible Optical Networks (SS-FON). We review proposed SDM solutions in Section 2, and then discuss the networking switching hardware required to route, add, and drop optical communication channels at network nodes in Section 3. Constraint-aware routing across space and spectrum allocations (RSSA) is covered in Section 4, followed by impairment mitigation in Section 5. We summarize our findings in Section 6, and provide a future perspective in the concluding remarks.

From SDM fiber to network architecture

Optical fibers in support of SDM transmission may come in many forms (Fig 1), differing in refractive index profiles and design geometry. As the ground is still laden with many unused or 'dark' SMF, SDM links can be realized by bundling several SMF (Fig 1-a). The core dimensions and refractive index contrast can be modified to support additional optically-guided spatial modes (Fig 1-b). These few-mode fibers (FMF) offer a capacity multiplier equal to the mode count, yet are prone to mode mixing due to fabrication and installation perturbations. Mode mixing can be overcome by jointly processing the received signals on all the modes following coherent reception (as the optical phase information is required), and unraveling the mixed signals—a procedure called MIMO (multiple-input, multiple output) processing, which was originally conceived for wireless communications. The fiber cladding can host multiple cores, forming a multi-core fiber (MCF, Fig 1-c), with each core now supporting a single spatial mode. The core pitch dictates the amount of coupling between cores; large pitch designs can offer very low crosstalk levels, analogous in operation to an SMF bundle. Small pitch designs form 'supermodes' having distinct propagation modes analogous to a FMF.

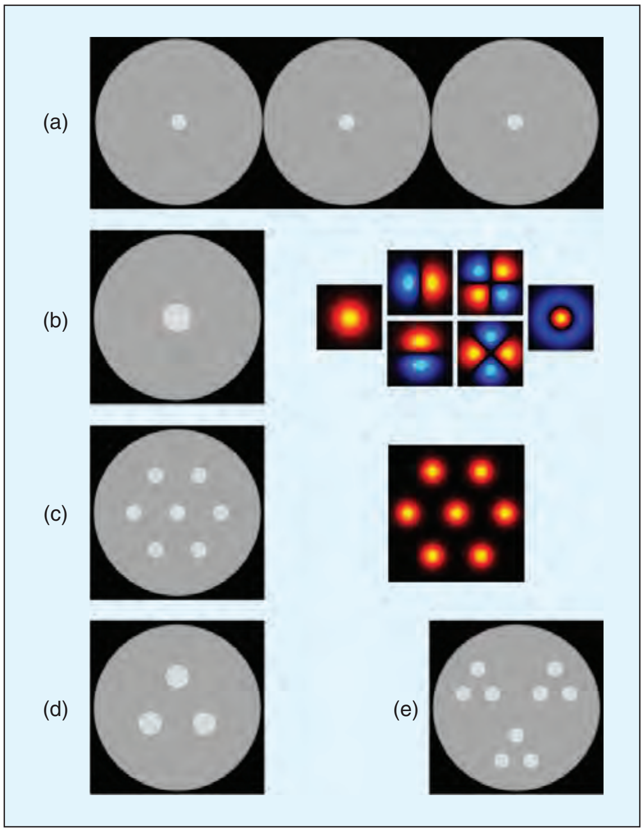

Fig 1. Fiber solutions for SDM deployment. (a) bundle of SMF, (b) FMF, (c) MCF, (d) FM-MCF, and (e) heterogeneous MCF.

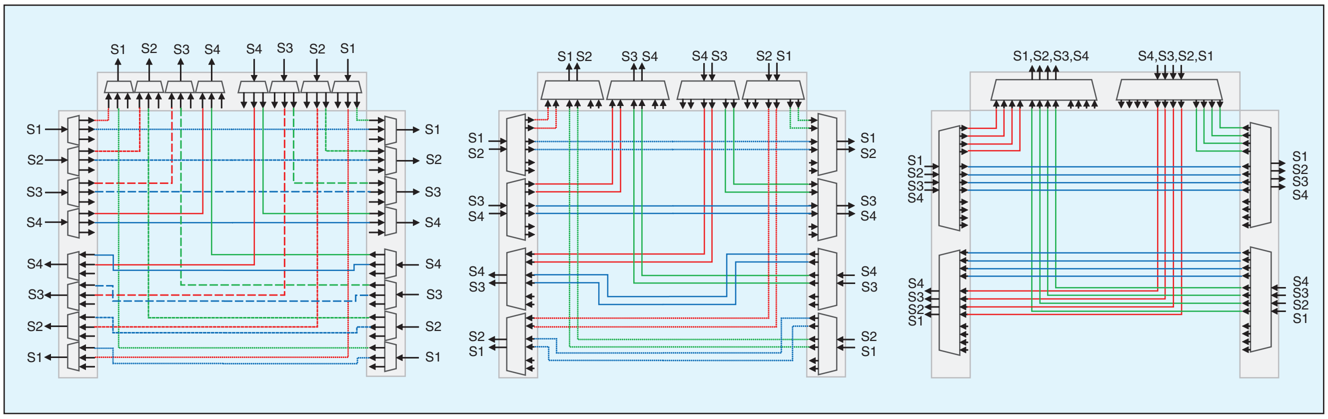

Fig 2. SDM node architecture under different granularity, for a four spatial dimension, degree three node. Left: Space-wavelength granularity, center: fraction space/full wavelength granularity, right: wavelength granularity.

There exists an intermediate pitch where coupling is random and strong, which has recently been shown to outperform SMF in nonlinear distortion buildup on account of the continuous mixing. SDM fiber can be designed to support limited mixing between sub-groups of spatial channels, yet have no coupling between the groups. Two such examples are few-mode MCF (FM-MCF, Fig 1d), where each core supports several spatial modes and no coupling between cores, and heterogeneous MCF (Fig 1-e) having uneven spacing which allows mixing among the closely packed cores.

The nature of the mixing between spatial channels in the SDM fiber impacts the networking functionality, as all channels that have experienced mixing must reach the receiver for joint MIMO processing to function. The ramification of this potential mixing is that for all service requests that are assigned on a spatial channel that may mix with others, then the service allocation must encompass all the possibly mixed spatial channels, even though it may be larger than requested. With this understanding, we can define the switching granularity, i.e. the minimum service allocation under different scenarios [1]:

Space-wavelength granularity: If spatial channels do not undergo any mixing, then services can be provisioned per spatial and wavelength channel. This forms the finest switching capacity granularity, leading to the greatest flexibility at the cost of increased realization complexity. Space-wavelength granularity is compatible with SDM links based on SMF bundles and MCF without mixing.

Wavelength granularity: When all spatial channels are possibly mixed, they must be routed together per WDM channel (linear crosstalk). This forms spatial superchannels that are allocated on a wavelength basis across the optical network for all service requests, no matter how small. Wavelength granularity applies to all mixing fiber media (FMF, some MCF), and can be implemented with reduced hardware count.

Fractional space-full wavelength granularity: For fiber designs that experience mixing constrained within sub-groups (i.e., FM-MCF, heterogeneous MCF), each sub-group must be jointly-routed. Fractional space/wavelength granularity is less restrictive than wavelength granularity, by service allocations to subgroups as opposed to the entire spatial mode/core count.

The switching granularity impacts the photonic switching hardware deployed within the optical network. At network nodes, which are interconnected via bidirectional fiber links to neighboring nodes and jointly creating a mesh network, ingress traffic needs to be routed to desired egress ports, or possibly dropped for local consumption. For a node connected to three neighbors, traffic should be routed to one of the two other links, as shown in the realizations of Fig. 2 for different switching granularities (note: add/drop not shown for brevity). For space-wavelength granularity, uncoupled spatial channels delivered via the ingress SDM fiber (or SMF bundle) are first spatially separated and then wavelength switched by wavelength-selective switches (WSS), one per spatial degree. Likewise on the egress side, a WSS gathers the traffic from other ingress ports and possible add channels, before all spatial channels are multiplexed to the SDM fiber solution. This solution encompasses as many WSS units as there are spatial channels, and hence does not provide significant cost savings unless multiple WSS units are co-packaged. However, this solution enables the greatest flexibility due to its finest granularity, under the constraint that no channel mixing occurs.

Wavelength granularity switching can be accomplished using the previous arrangement, by setting all the WSS units with identical commands for routing of spatial superchannels. This solution is not attractive due to the multiple WSS units; moreover, the intra-node connecting fibers must have similar lengths to contain differential group delays (DGD) between the spatial channels, further increasing costs. Alternatively, the WSS can be modified to support 'joint' (or 'ganged') switching. Under joint switching, each WSS is fed with multiple input fibers (the input set), which are jointly switched to one of several output fiber sets, which are then routed to the proper egress port. The hardware count per network node under joint switching is identical to today's optical networks, with a single WSS (albeit modified to support joint switching operation) performing the routing across the entire spatial superchannel. Modification of WSS for joint-switching action are discussed in the next subsection.

Implementing fractional space/wavelength granularity switching can be achieved with a joint-switching WSS, one per subgroup that experiences internal mixing. The desirable features of this solution are the reduced hardware count (number of WSS scale as the number of subgroups), and the smaller spatial superchannel size, as defined by the mixing channel count within a subgroup.

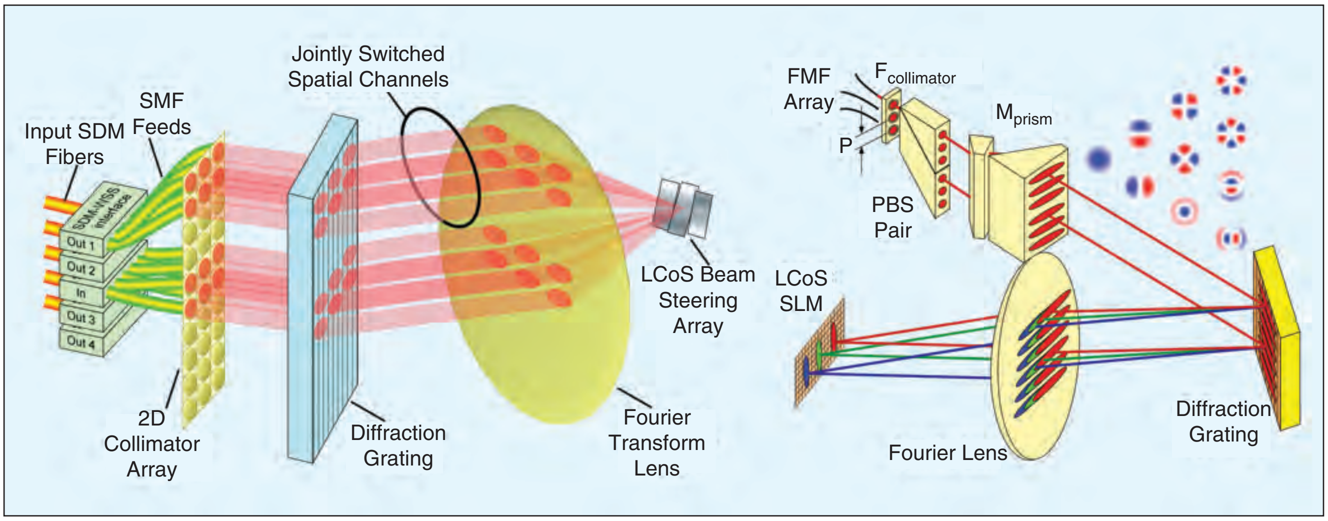

Fig 3. Left: SDM WSS with spatial diversity spanning two dimensions. Spatial channels are remapped to rows of the array, and switching is performed in the vertical direction. Input row(s) steered to desired output row(s). Right: FMF-WSS with multi-mode beams propagated and steered within the WSS.

As an example, consider an SDM solution having 12 spatial channels operated on a 50 GHz grid. Under space/wavelength granularity, the minimum allocation bandwidth is 50 GHz, with a four-degree node requiring 96 WSS units. For wavelength granularity, the minimum allocation bandwidth is 12 × 50GHz, but only 8 WSS are required for traffic handling. The intermediate solution of fractional space granularity, with four subgroups of size three, would provision the minimum allocation bandwidth of 3 × 50 GHz, and require 32 WSS units. Note that the hardware advantages of wavelength granularity and fractional space/wavelength granularity can be extended to SDM fibers which do not introduce mixing, to benefit from network cost-reductions. When no mixing occurs, the subgroups can also be defined with different grouping sizes, to better accommodate demands of disparate sizes.

Joint-switching WSS

With the networking tradeoffs of joint-switching WSS established, we next explore how to implement such modified switches. The variants of joint-switching WSS we investigated can be categorized to two main types: WSS employing spatial diversity and WSS switching multimode beams [2].

A spatial diversity WSS is based on a conventional WSS design, which has all the input/output fiber ports dispersed and imaged to the same positions at the switching plane, where in operation the single input beam is directed toward a desired output fiber on a wavelength basis. Since all the fibers are imaged to the same position, the beam steering can simultaneously redirect multiple beams incident on it, with all beams experiencing the same beam steering shift. If the WSS input/output fibers are arranged in a regularly spaced array, then the steering of a set of inputs is reimaged onto different sets of outputs. Associating the groups of fibers with SDM fiber interfaces allows switching all the spatial channels to their destinations, gaining the SDM capacity multiplier without increasing the WSS count (same WSS count as SMF implementations). This spatial diversity technique reformats the channels of the SDM fiber to spatially separated and parallel beams enabling their joint switching with the same hardware complexity as the SMF based WSS. Joint switching WSS solutions based on spatial diversity reduce the number of supported output SDM destinations by the spatial channel count due to the fiber port grouping. Thus, the ROADM node and the underlying WSS has less switching destinations and reduced support for add/drop ports. Fractional joint switching alleviates this issue by subdividing the spatial degree to several groups, with each WSS handling smaller SDM groups thereby providing enough output switching paths remaining for enabling full ROADM functionality. Another development to circumvent the port limitation we developed based on the spatial diversity concept, arranges a high port count WSS where the fiber array is configured in a two-dimensional configuration (Fig 3-left), with SDM groups remapped to rows and different rows belonging to output switching alternatives [3]. To complement the spatial diversity solution, SDM fibers are interfaced to the WSS with spatial demultiplexers. In our work, these demultiplexers were based on three dimensional waveguides optical inscribed within glass, and capable of interfacing to FMF and MCF.

Spatial diversity solutions require the WSS optics to handle many more free-space beams than switching ports, due to the spatial multiplier. This strains the optical design of the WSS (performance and size). For FMF based systems, the fibers can be directly interfaced to the WSS foregoing demultiplexing and spatial diversity. The beams within the WSS become multi-mode, but otherwise traverse the same optical elements as a conventional WSS. The number of free-space beams within the WSS equals the number of switching ports (Fig 3-right). However, the spatial mode structure of the beams impacts the spectral channel characteristics. At the beam-steering plane, where the beams are spatially dispersed, flexible channel extent is defined by a phase spatial light modulator used for writing linear phase ramps. Beam modes of optical frequencies that strike the channel edges experience clipping, which impacts each mode differently and disrupts mode orthogonality (resulting

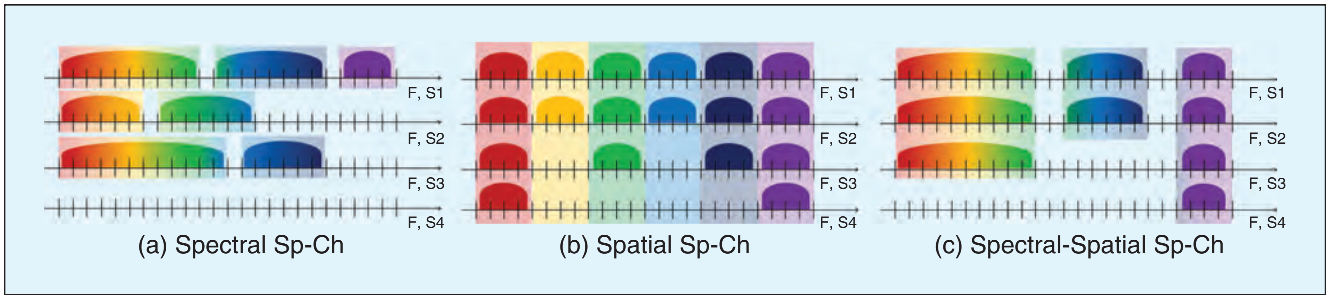

Fig 4. Three resource allocation policies identified for SDM networks based on different transceiver technologies.

in mode dependent passbands and spectrally dependent mode mixing at channel edges). This leads to larger spectral transition bandwidth between the pass-band and the block-band. Hence, larger guard bands are required between adjacent wavelength channels, impacting the spectral utilization of the communication band. Conversely, higher spectral resolution optics can be employed to achieve conforming transition bands.

Routing space/spectrum allocations

While the extra dimension introduced by SDM provides more capacity in response to a large traffic increase, dynamic allocation policies need to address the disparate behavior of traffic and its fluctuations. The two main technology areas limiting channel allocation and routing options in an SDM/WDM based optical network are *fiber types* and employed *switching paradigms* [4].

Three channel allocation options are explored and presented in Fig. 4, which in turn lead to different transmitter/receiver design considerations [5]. Fig. 4(a) shows the case in which demands are transported in form of spectral super-channels, i.e. demands spread over a contiguous portion of spectrum, enough to accommodate them, in a single spatial dimension. Spectral super-channels can improve the spectral efficiency by decreasing the guard bands between sub-channels. Nonetheless, SDM networks based on spectral super-channels require independent-switching based nodes which are the most costly switching elements. Practically speaking, a spectral super-channel allocation policy can be used only for SDM networks based on uncoupled transmission media. On the other hand, Fig. 4(b) illustrates the case in which demands are transported in the form of spatial super-channels, i.e. demands spread across the spatial dimensions over a given spectral slice (e.g. one optical carrier under wavelength granularity). Spatial super-channel allocation policy can be considered for any type of transmission medium, but is necessary for SDM networks based on coupled transmission media. A spatial super-channel allocation policy allows: i) decreasing the optical switching complexity, since spatial channels are switched in groups rather than independently at the price of a potential reduction in routing flexibility; and (ii) additional cost reduction due the possibility of sharing network elements among different spatial dimensions (e.g., a number of super-channel constituents can share lasers and DSP modules, which can lead to cost and power consumption savings of integrated transceivers in SDM networks) [6], [7]. A third possible policy is spectral-spatial super-channel, shown in Fig. 4(c), would emerge from the combination of the aforementioned spectral and spatial super-channel allocation policies, i.e. demands spread across a number or all of the spatial dimensions over a contiguous portion of spectrum. One can say that spatial super-channel is a particular case of spectral-spatial super-channel when the spectral width of spectral-spatial super-channel is as narrow as a single optical carrier [6].

Commercially speaking, the design and operation of optical networks is based on the assignment of the appropriate network resources in order to establish the end to end service, or lightpath. Established lightpaths must have guaranteed quality of transmission (QoT), ensuring adequate transmission performance for the provisioned service. We have developed simple scaling rules for predicting signal degradation for SS-FONs in order to provide an accurate QoT estimation. The QoT estimator calculates the performance of coherent multi-level phase modulated signals when propagated over an optical uncompensated SDM link (i.e. FMFs, MCFs, bundles of SMFs) that is composed of several amplified spans. The tool supports SDM networks based on both fixed-grid WDM and grid-less multi-carrier multiplexing schemes exploiting Nyquist-WDM and orthogonal frequency division multiplexing. The estimator is capable of predicting the QoT of new lightpaths to be established in a network, as well as their impact on the existing lightpaths. The QoT estimation mechanism requires information about the network topology, link characteristics, signal types (baud rate and modulation format), and lightpaths currently established in the network (i.e. occupied spectral slots on each spatial mode).

Transmission impairments

Parallelism is a key target to be achieved in SDM networks, in fiber and components, to reduce costs. However, the denser the integration of the spatial channels is, the higher is the potential crosstalk (XT) among them. Such spatial XT is expected to be mitigated by MIMO processing at the receiver side, with a complexity scaling determined by the number of spatial channels squared and their corresponding temporal differential group delay (DGD) spread which is to be retimed. MIMO processing can compensate all the linear impairments in SDM transmission systems as long as mode dependent losses are low and the additive optical noise from amplifiers not excessive.

Several strategies may be employed to minimize the MIMO processing complexity. Under transmission media that exhibits overall mixing between all modes/cores, it is desirable to reduce the DGD spread. Combining fibers with opposite DGD characteristics is one possibility (as was done for chromatic dispersion compensation before the adoption of coherent reception). However, there is no standard FMF

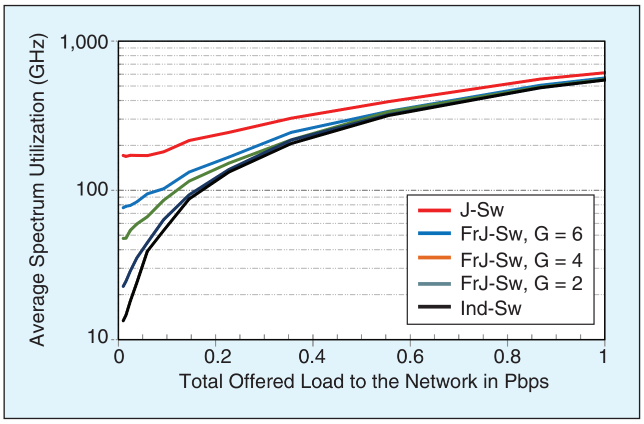

Fig 5. Future scaling study of the Telefónica Spanish national network, showing average spectrum utilization per link per fiber for different switching paradigms considered, using 12 spatial channels [4].

and mode count established yet, which deters development of FMF compensating fibers. An alternative approach is to introduce strong mixing characteristics, which reduces the DGD accumulation by constant energy transfer between fast and slow modes. However, the mixing characteristics in FMF are in the weak regime, causing the DGD to increase linearly with transmission distance. To induce strong mixing in FMF, we have devised a discrete spatial phase element that cross-couples modes. The phase element is printed directly on the fiber facet, and can be placed periodically along the transmission fiber to operate in the strong mixing regime. Further advantages of strong mode mixing include the averaging of mode dependent losses, and the reduction of the nonlinear impairment accumulation.

A second alternative to reduce impairments is to adopt SDM fiber coupling that is restricted to modes/cores belonging to a subgroup. With this approach the number of modes handled by the MIMO processor is reduced, which is highly favorable due to the square law dependence.

The power consumption of the MIMO processing can be a limited factor in the maximum capacity and achievable reach of SDM networks [8]. Our analysis shows that by shifting from parallel SMFs implementations to FMFs, the power-limited reaches reduce significantly as the number of modes increases. Network-wide speaking, MIMO processing for a 4-mode FMF network requires more than twice the power required for SMF and 2-mode FMF based networks to achieve similar performance[8].

Key networking findings

The joint switching approach advocated by the INSPACE project offers a compact spatially integrated solution that eliminates the need of multiple-WSS elements and complex control plane processing. This is done at the expense of reduced resource utilization, when the overall traffic load is relatively small. On the other hand, the more complex (in terms of required number of WSS elements) independent switching and fractional joint switching paradigms perform well for networks with high level of traffic diversity. Studies have shown that in addition to its cost benefits joint switching can perform significantly better in high diverse traffic scenarios, if spatial super-channels occupy smaller spectral width which can be switched by WSSs with finer granularity and higher resolution [4]. It has been demonstrated that spectral switching granularity must be adaptable to the traffic size in order to achieve globally optimum spectrum utilization in an SDM network, for which spectrally flex-grid ROADMs and bandwidth-variable transceivers are a requirement [4]. Additionally, our studies have shown that as the rate of service integration increases the network performance of the joint switching (i.e. fixed SDM) converges to that of independent switching (i.e. flex-SDM), Fig. 5.

Furthermore, our studies related to the cost benefits of INSPACE proposed solutions showed that, after the transceivers, the second most costly element is the A/D nodes (consisting of WSS and multicast switch modules) [7]. Our analysis showed that the most cost-effect SDM ROADM architecture is the one which i) maximizes the number of available A/D ports, and ii) does not heavily increase the port count of pass-through WSSs. It has also shown that joint-switching based ROADMs are more cost effective than those implementing independent and fractional joint switching [9]. We anticipate that the cost reduction due to the switching infrastructure as well as the possibility of using integrated spatial super-channels transceivers will prove joint switching as potential candidates for SDM networks.

Conclusion

INSPACE introduced a novel networking approach that extends the common spectral flexibility concept to the SDM domain and simplifies the super-channel allocation and control mechanisms. This new concept utilizes the benefits of the high capacity few-mode and multi-core fiber infrastructures, while it is also directly applicable over the currently installed multi-fiber cable links. The main novelty and the key enabler for this approach is in the development of multi-dimensional spatial-spectral switching nodes, which are fabricated by extending the existing flexible WSS nodes, incorporating advance mode/core adapting techniques. Further major development in support of the SS-FON concept include novel network planning algorithms and software defined networking (SDN) control plane approaches, able to efficiently handle the increased number of resources.

Commercially speaking, the current growth in the photonics industry is driven by the sales in the field of high data rate transceivers. This is expected to last at least for another 5 years as technology will move towards 400 Gb/s data rates. In the same time, it is expected that providers will start investigating the spatial expansion of their systems in order to meet the future capacity demands. However, the increased capacity would also require increased flexibility in switching nodes. The INSPACE node technologies and control solutions are well aligned with this time frame and could potentially play an important role, in the upcoming years, in the way that integrated high capacity data channels are handled in the space dimension. One should also consider the SDM potentials and in particular the SDM switching requirements for the handling of the capacity expansion in datacenters, which is another fast-growing market due to the numerous cloud based services.

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