FP7-ICT-GA 619732

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

SPECIFIC TARGETED RESEARCH PROJECT (STREP) INFORMATION & COMMUNICATION TECHNOLOGIES (ICT)

SEVENTH FRAMEWORK PROGRAMME

PUBLIC EXECUTIVE SUMMARY OF THE FIRST PROJECT PERIODIC REPORT

D1.4

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1. Participants

The INSPACE Project Consortium groups the following Organizations:

No	Partner Name	Short Name	Country
1	Optronics Technologies S.A.	OPT	Greece
2	Telefónica Investigación y Desarrollo	TID	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

2. Publishable Summary

Spatial-Spectral Flexible Optical Networking: Enabling Solutions for a Simplified and Efficient SDM

At A Glance

Project Website

www.ict-inspace.eu

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EC Contribution: *€ 2.577m*

Project Partners

- OPTRONICS TECHNOLOGIES SA (OPTRONICS), EL
- TELEFONICA INVESTIGACION Y DESARROLLO SA (TID), SP
- THE HEBREW UNIVERSITY OF JERUSALEM (HUJI), IL
- RESEARCH AND EDUCATION LABORATORY IN INFORMATION TECHNOLOGIES (AIT), EL
- OPTOSCRIBE Ltd. (OPT), UK
- CENTER FOR RESEARCH AND TELECOMMUNICATION EXPERIMENTATION FOR NETWORKED COMMUNITIES (CN), IT
- ASTON UNIVERSITY (ASTON), UK
- FINISAR ISRAEL LTD (FINISAR), IL
- W-ONE SYS S.L. (WONE), SP

Vision and Aim

Network traffic has consistently grown at an exponential rate, and there is no indication this relentless trend will cease. Industry is hard-pressed to identify how future networks will continue to scale in capacity, energy consumption, and economic viability as present day technologies are being stretched to their limits. The nascent technology of space-domain multiplexing (SDM) for high capacity transmission is the only solution with the scaling potential to meet future demands. However, there is still a large technological chasm between the transport solution and the SDM network implementation.

INSPACE proposes a novel networking approach by extending the established spectral flexibility concepts to the SDM domain and significantly simplifying the super-channel allocation and control mechanisms, by removing current limitations related with the wavelength continuity and fragmentation issues. This new concept utilises the benefits of the high capacity, next generation, few-mode/multi-core fiber 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. INSPACE 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 INSPACE consortium forms a strong industry driven research team targeting not only the demonstration of the new network concept and its ability to meet the challenges of delivering exponentially growing content over the next twenty years, but also the full exploitation of its potential towards commercialisation. In total, four EU countries (Greece, Italy, Spain, and United Kingdom) and one Associated Member State (Israel) are represented in the INSPACE consortium**.**

Main Objectives

INSPACE introduces a novel logical hierarchical structure for next generation multidimensional dynamic and elastic optical networks, based on enabling switching, transmission and processing technologies that allow the connection between spectral and spatial networking.

The two main themes are:

- ✓ To explore the additional degrees of freedom in signal multiplexing (offered by the latest advances in both multi-mode and multi-core fibre systems), with the purpose to exploit the emerging networking benefits arising from a combined Spatial/Spectral/Signal coding domain:
  - Design multi-dimensional resource allocation algorithms and study the required control plane extensions
  - Study the benefits of multi-dimensional signal allocation in terms of resource optimisation, energy consumption reductions and system cost savings

- ✓ To examine the capabilities of the enabling technologies in support of the multidimensional networking concept by focusing on:
  - Node switching hardware adapted to support SDM fiber links (SMF array/FMF/MCF) addressing the spatial and spectral domains
  - Interfacing technology to match the SDM transmission (Mode structure/core location) by demultiplexing to SMF edge arrangements.
  - Interplay between transmission format, electronic MIMO processing, switching solution effects, and information capacity.

Technical Approach and Achievements

Figure 1 shows a multidimensional structure for channel allocation where a number of degrees of freedom emerge and each of them can contribute to the total transmission capacity and network flows. The proposed logical hierarchal structure considers various fibre link types, with spectrally elastic contents, carrying multi-format signals. The considered SDM fibre link types are:

- ✓ An SMF bundle in a multi-fibre cable. Pros: well established components and infrastructure. Cons: Does not offer any fundamental decrease of cost with scale.
- ✓ A multi-core fibre (MCF) with isolated cores. Pros: information conduits remain pristine obviating need for MIMO processing. Shares advantages of SMF bundle but allows for shared amplification. Cons: Optical gain pumping efficiency is low due to low fill factor, and limited scalability as core pitch is large and fiber diameter is limited to 200 μm to remain flexible.
- ✓ A multi-core fibre (MCF) with closely spaced cores. Pros: Greater number of cores can be packed within the glass fiber, improved optical gain pumping

efficiency due to better overlap. Cons: Closely spaced cores exhibit weak coupling along propagation, requiring MIMO processing to unravel.

- ✓ A few-mode fibre (FMF). Pros: Greatest density of information channels and efficient gain mechanisms are being introduced. Cons: strong modal coupling in propagation, which can be unraveled with heavy MIMO processing and spatial multiplexing, is more difficult.

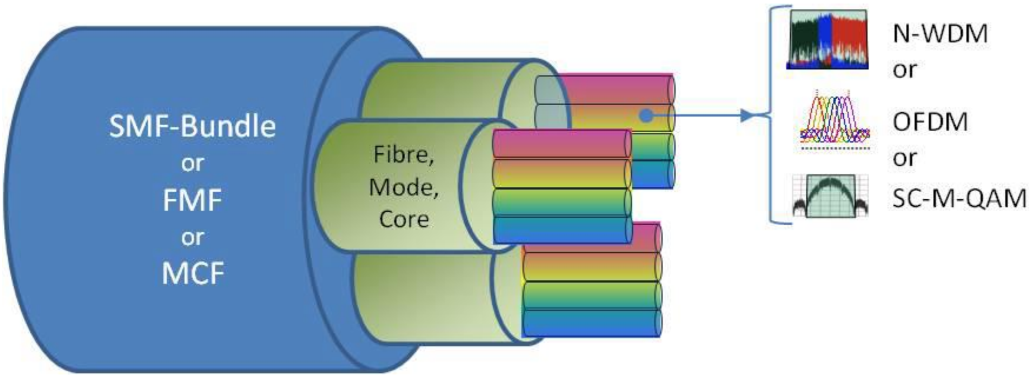

Figure 1: Multi-dimensional structure for channel allocation, spanning space, wavelength, and Time

The aforementioned SDM structures give rise to the following hierarchical levels for networking:

- ✓ The spatially multiplexed fibre, core or mode level (at the highest layer).
- ✓ The spectrally multiplexed level (at the middle layer) considering either:
  - Fixed grid spectral containers: single slot channels or super-channels based on spectral concatenation of multiple signals each on a dedicated frequency slot.
  - Flex grid spectral containers: where single optical signals or super channel structures are allocated.
- ✓ The signal format level (at the lowest layer) considering M-QAM signals of various formats.

Figure 2 represents the flexible channel allocation concept where channels can be accommodated over one or multiple modes/cores occupying a single or multiple spectral slots and transmitted using different modulation levels.

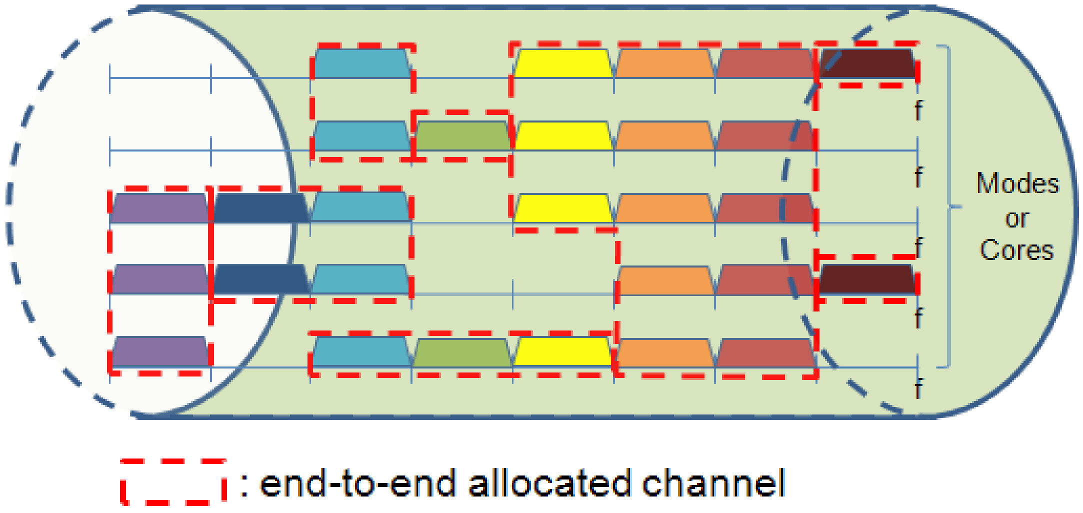

Figure 2: Multi-dimensional channel allocation concept: Spatial expansion of the spectrum over multiple modes/cores and therefore definition of a super-channel over two dimensions (instead of the spectrum only dimension) denoted by red dashed lines

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. INSPACE will focus on the optical level, where information can be routed transparently and most efficiently. Aiming for ultra-low energy consumption figures, the frequency and space dimensions will be explored. We present five possible switch design solutions for a spatial-spectral node design that will serve to demonstrate the concepts behind INSPACE:

1. Bundle of SMF and independent fibre switching with designated WSS/OXC (spacespectrum granularity).
2. MCF decoupling and independent core switching with designated WSS/OXC (spacespectrum granularity).
3. MCF decoupling and WSS joint spectral switching across all cores in space (spectral granularity spanning space).
4. FMF decoupling and WSS joint spectral switching across all modes in space (spectral granularity spanning space).
5. FMF spectral switching of all fibre contents at once (w/o decoupling) with custom WSS (spectral granularity spanning space)

These five scenarios are seen to reduce to two prototype node solutions. The first offers switching granularity down to the spectral and spatial domains. The second node switching solutions offers granularity at the spectral domain (as is performed today using wavelength selective switches, WSS), yet performed across all spatial channels simultaneously. In other words, the space domain becomes degenerate. There is a third alternative, not outlined above, where switching may be performed at the spatial domain for the entire spectral signal. However, since the spatial range (1-10 spatial channels) is much smaller than the spectral range (5 THz bandwidth accommodating ~100+ spectral channels), this solution does not support add-drop effectively.

Achievements and Progress Beyond the State of the Art

✓ Network and system definitions and specifications have been identified in the project.
✓ Channel allocation possibilities, fiber characteristics in support of SDM, switching designs and control plane architecture requirements have been also included.
✓ The definition of practical node implementation requirements and reference networks for system analysis have been achieved.
✓ Regarding the performance characterization, a fibre model has been developed during the first year of the project that matches the theoretical statistics of the group delays and will become a very useful tool for the dimensioning of FMF systems.
✓ The design of spatial-spectral WSS-based switching node is completed for the high port count WSS, with the solution based on a 2D fiber array.
✓ The first prototype of 2×4×16 WSS was built and is now under testing.
✓ A FMF transmission model including the linear mode coupling and inter-modal nonlinear coupling has been developed.
✓ For the first time, one single expression linking the group delay spread to the fibre correlation length was validated considering FMFs guiding 3 and 6 modes.
✓ The development of state-of-art DSP for MIMO processing is progressing. Results have shown a correct working of the frequency domain equalization (FDE) for a 3-modes fibre. FDE is the preferred choice in view of the results obtained on the complexity equalization of time-domain equalization (TDE) and FDE (FDE shows a relatively insensitivity to channel memory length).
✓ The network model and the target resource allocation scenarios were defined.
✓ A trade-off between spectral efficiency and number of transmission devices was identified, and some initial investigations were carried out, including the development and testing, via simulations, of some heuristic assignment policies for SDM networks.
✓ An investigation of possible protocols to interact with and configure physical devices was performed.
✓ Different architectures for the INSPACE Control Plane were investigated, ranging from fully distributed GMPLS to partially centralized solutions based on a PCE to a fully centralized SDN-based controller, which was selected as the most promising and objective-abiding solution.
✓ Significant effort has been made to define the modules and interfaces of such an architecture, including examples of how they work together to implement the most relevant requirements.
✓ Regarding the implementation of the selected solution, an initial draft of the YANG model to be used by the southbound communication protocol was developed.
✓ The commands to control both standard and SDM WSS were defined.
✓ Some preliminary work related to the test-bed requirements have been made. Two test-beds, one to demonstrate the networking functionality and another one for long-haul transmission have been proposed.
✓ The exploitation activities during this period have focused on providing the basis for a business plan for the INSPACE project.
✓ The standardization activities during the first year of the project have focused on identifying the different areas of SDM optical networks were standardization

actions have to be taken and identifying different organizations involved. Three main standardization areas, namely SDM fiber manufacturing, SDM control plane and joint switching ROADM are being studied and monitored by INSPACE partners.

Expected Impact

There is an imperative need to develop the future ultra-high-capacity, ultra-low-latency, ultra-energy-efficient network infrastructure that would serve as the "arteries", "veins" and "heart" of the future internet for many decades to come. At some point in time, the existing network infrastructure and technologies will not keep pace with the enormous growth of traffic demands and quality of service metrics as latency and packet loss rate. At this point, and rather than making evolutionary upgrades to the underlying network infrastructure in an attempt to maintain a basic operation of the Internet, we will need to follow a revolutionary path which will offer a future proof solution. This is exactly the promise of INSPACE and the SDM technology solutions that the project introduces into the network. INSPACE focuses on the development of novel/innovative all-optical network solutions and the associated switching systems, not currently available in the market, which will be able to realize a paradigm shift in the way all-optical networks are designed and operated. According to the INSPACE concepts, the future all-optical networks would be based on spatial multiplexing, enabled by multi-core and few-mode optical fibres and supported by a variety of new components/subsystems and associated technologies that promise to push the achievable capacity and energy efficiency of current optical communications systems by at least one order of magnitude. There is simply no other solution in the horizon (as far as the core optical networks are concerned) that not only can meet the requirements for a) an expected capacity increase by a factor of 10, and b) an improvement in the energy efficiency by a factor of 4, but it can actually push these improvements to even higher numbers! The INSPACE project brings together partners who will design an innovative technological solution keeping also one eye on its socio-economic impact. INSPACE indirectly provides societal impact with regard to the accessibility of EU citizens to broadband networks, and the reduction of the carbon footprint of ICT equipment. Providing superior flexible bandwidth and ubiquitous access to the network by using low-cost network solutions allows the price of bandwidth to be dropped dramatically, enabling those who cannot afford expensive broadband connections to participate in the information society. Besides, the project's node architecture is an eminent example of how INSPACE technologies can serve the important societal goal of greening ICT, while at the same time improving its performance.