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 SECOND PROJECT PERIODIC REPORT

D1.6

Grant Agreement number:	619732
Project acronym:	INSPACE
Project title:	SPATIAL - SPECTRAL FLEXIBLE OPTICAL NETWORKING ENABLING SOLUTIONS FOR A SIMPLIFIED AND EFFICIENT SDM
Funding Scheme:	Collaborative project
Date of latest version of Annex I against which the assessment will be made:	April 2013
Periodic report:	1st □ 2nd √ 3rd □ 4th □
Period covered:	01 February 2015 – 31 January 2016
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2. 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

3. Publishable Summary

The publishable summary follows in the next pages and is presented as stand-alone document.

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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Duration: *February 2014 – January 2017*
Call Identifier: *FP7-ICT-2013-11*
Objective: *ICT-2013.1.1 Future Networks*
Funding Scheme: *STREP*
Total Cost: € 3.616 *m*
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

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 nascent technology of space-domain multiplexing (SDM) for high capacity transmission is the only solution with the scaling potential to meet future demands. 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. The current spatial integrating solutions are targeting purely the capacity increase in point-to-point transmission systems. What still remains unexplored is the extension of the EON concept in space domain, in which the 'spatial resources' (i.e. modes, cores or even single core fibres in fibre bundles) can be flexibly assigned to different traffic demands, increasing the degrees of flexibility, thus the network planning and optimization capabilities of the network. This leads to the spatially and spectrally elastic optical networking (SS-EON) concept, the promotion of which is the main goal of INSPACE project.

More specifically, 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 fibre infrastructures, providing also a practical short-term solution, since it is directly applicable over the currently installed multi-fibre cable links. For the realization of INSPACE approach, novel multi-dimensional spatial-spectral switching nodes are developed, 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 software defined networking (SDN) control plane approaches that efficiently handle the increased number of resources.

Technical Approach and Achievements

Research work within INSPACE has already resulted in significant conceptual and technology advancements in the area of SDM networking that are widely identified today by many researchers in a global scale. The key advancements are in the following areas:

- ✓ Introduction and definition of the joint switching and fractional joint switching concepts as simpler and potentially more cost-efficient versions of the fully flexible independent spectral-spatial switching concept. (Note: the new switching concepts are further supported by novel developments in switching hardware, SDN control and resource optimization algorithms).
- ✓ Design and development of SDM switches, including a) a multi-port WSS-based switching node for reconfigurable spectral-spatial switching arrangements extended to over 1×48 port count and b) a joint-switching FMF-WSS node for the common switching of all FMF modes as a single entity.
- ✓ Development of the fibre breakout modules for adapting the various fibre types to the input requirements of the node processing elements.
- ✓ Development of FMF and MCF transmission models for the proper evaluation of the proposed schemes and the performance limitations of the proposed switching elements.
- ✓ Development of routing and resource allocation algorithms for a) offline network planning and spatial-spectral resource optimization and b) in-operation mode. These algorithms pursued the maximization of the allocated demands, and exploited the spatial capabilities for the avoidance of fragmentation and blocking.
- ✓ Development of the control plane, including the interfaces with the nodes and network elements and incorporating the developed routing and optimization algorithms. The SDN controller for INSPACE is based on the OpenDayLight open-source framework.

The development work related with the aforementioned topics is presented in more detail in the following paragraphs.

INSPACE switching concept definition and support studies

The selection of a cost-effective technology for each element of an SDM network (e.g. transmission media, transceivers, amplifiers, or switches) may result in the introduction of additional physical-layer constraints as a consequence. While there are several studies investigating SDM transceiver technologies, limited research has been carried out regarding SDM switching technologies. Within the INPACE project, three switching technologies have been studied: (a) joint switching (J-Sw): all spatial modes/cores are treated as a single entity, while spectral slices can be freely switched by the WSS; (b) fractional joint switching (FrJ-Sw): a kind of hybrid approach in which a number of subgroups of G spatial modes/cores, as well as all spectral slices, can be independently switched to all output ports; and (c) independent switching (Ind-Sw): all spectral slices and spatial modes/cores can be independently directed to any output port. Ind-Sw brings a high level of flexibility for routing, space, modulation-level and spectrum assignment (RSMSA) since it allows the allocation of demands over different cores/modes and spectral slices with variable widths. In contrast, J-Sw constrains the RSMSA to one spatial super-channel (Sp-Ch) connection (spread over a number of modes/cores) per spectral slice, and therefore the unused modes/cores over a certain spectral width cannot be allocated to other demands. J-Sw is necessary for coupled multi-core fibres (MCF) or few-mode fibres (FMF) on account of inter-core crosstalk and mode coupling, but any switching option is suitable with uncoupled MCFs or bundles of single mode fibres (SMFs). While the choice of switching technology can restrict the flexibility of RSMSA algorithms (given that the coarse granularity of J- and FrJ-Sw penalizes the network spectral occupancy), it can also boost the economic feasibility of SDM solutions. For instance, J-Sw and FrJ-Sw allow the use of joint digital signal processing (DSP) at different degrees, which can lead to cost and power consumption savings of integrated receivers in SDM networks.

SDM switching nodes

Within the INSPACE project, a joint-switching WSS was first demonstrated with a seven-core MCF interfaced with mode demultiplexers to a commercial 21-port count WSS to realize a 7×(1×2) switching functionality. The disadvantage of this approach is the loss of routing flexibility. In the above example the WSS can only route to one of two output path options. During the second year of the project, the port count of the WSS was increased to better support SDM fibres with high number of modes/cores and provide more output switching paths. This has been achieved by arranging the fibre ports in a 2D array, so that the switching is performed in the vertical direction only and all the beams in one row are imaged onto another. Figure 1 describes the operation principle of a joint WSS for parallel spatial channels.

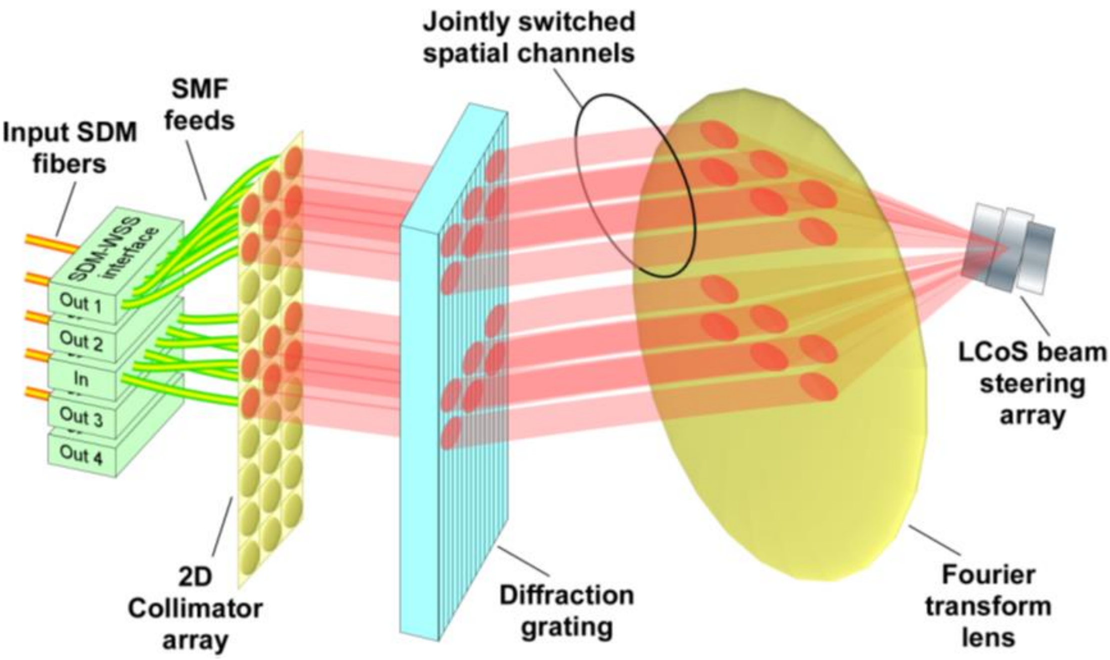

Figure 1: Joint WSS design using a 2D microlens array

In addition, within the INSPACE project, the implementation of a conversion process from standard WSS to joint-switch high-port WSS in support of the final demo implementation has been started. Figure 2 shows the fractional joint switching design with lane changes for the final demo, with four-count SDM routed as two groups of size two.

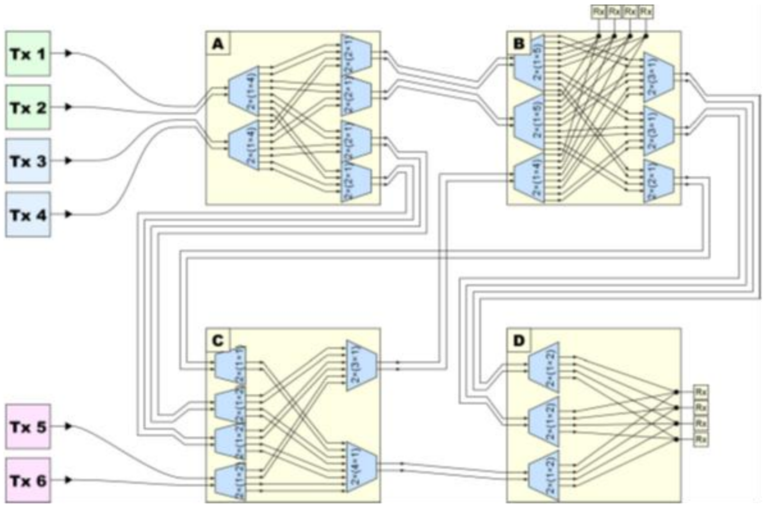

Figure 2: Fractional switching with sub-group lane changes

Adapters for SDM switches

The implementation of an MCF breakout device is aimed at providing low loss, low cross-talk remapping of the single-mode channels to individual cores of an MCF. Ultrafast laser inscription is a favourable manufacturing method for such devices as it offers integrated, compact and well controlled connections between MCF and SMF. 7-core fanout devices were initially developed and fabricated to match a short 5m length of MCF, which was supplied by Furukawa for the purposes of evaluation.

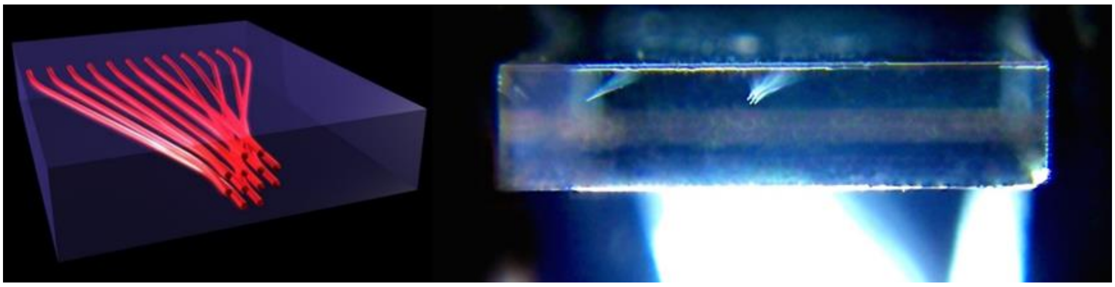

Figure 3: (left) Schematic diagram of 3D laser inscribed MCF breakout. (right) Close-up photograph of waveguide facet with 2D waveguide array at the centre of the glass die

Transmission models and MIMO approaches

A nonlinear fibre model for FMF was developed, considering a discretization of core-cladding imperfections of real fibres. We also derived an analytical formula which can be used to estimate the inter-modal nonlinear power spectral density, and carried out a statistical study of the impact of some of the main impairments in FMF transmission: group delay and linear mode coupling. The fibre model was used to estimate the nonlinear noise power for a range of different linear coupling strengths, see results in Figure 4. For the crosstalk values shown by the majority of FMFs (from -50 to -20 dB/100m), the nonlinear noise is not accurately estimated by either the weak linear coupling regime or the strong coupling regime. However, the overall conclusion that the stronger coupling reduces nonlinear noise power remains valid. We have assessed for the first time the level of intermediate coupling required to minimize nonlinear noise in coupled few-mode propagation below that of uncoupled single-mode propagation. We observe a reduction of nonlinear noise below that of uncoupled single-mode propagation for linear coupling values above -20dB/100m.

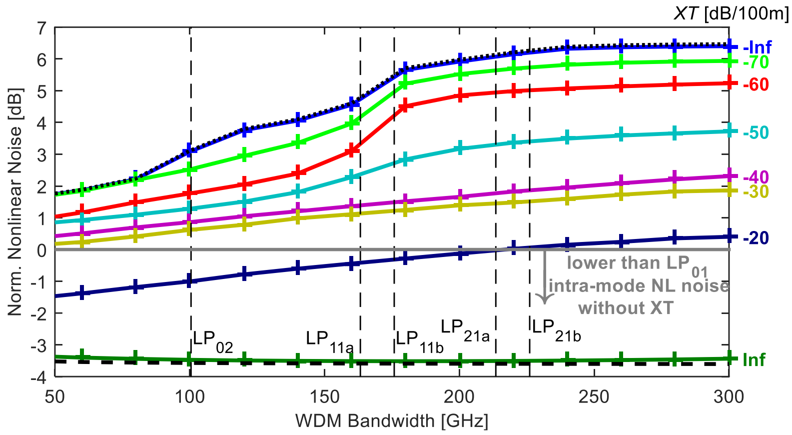

Figure 4: Total nonlinear noise power in the LP01 mode as a function of WDM bandwidth showing analytical predictions from strong (dashed) and weak (dotted) regimes along with numerical simulations (solid) for different mode coupling strengths (colours)

MCFs with negligible crosstalk between cores have been investigated by extending the *enhanced* Gaussian noise model to include a term to account for the inter-core crosstalk. The analytical expressions of the statistical characteristics of the crosstalk in a homogeneous MCF are provided and used to estimate the SNR penalty due to the power coupling between cores.

For transmission performance estimation over a lightpath composed of several links and nodes, including spectrally uniform devices (like splices, amplifiers, demultiplexers, etc.) and spectrally non-uniform devices (like WSSs), each device is defined by its transfer tensor (frequency dependent or degenerate), and the response of the whole system is obtained by tensor multiplication of all system components and fibre.

The influence of uniform devices is limited to mode mixing and mode dependent loss or gain (MDL or MDG). While MDL (or MDG) are performance-degrading, mode mixing is not necessarily a problem. Splices and amplifiers may introduce mode mixing due to mismatch of fibres (due to alignment errors or different fibre profile). Modal gain and noise figures of SDM amplifiers from experiments were adopted for the component models. Experimental measurements verified that amplification introduces negligible crosstalk between the modes/cores. Hence the modelling of SDM amplifiers is one of gain and additive noise alone. On the other hand, simple SDM demultiplexing (direct contact/spot based multiplexer/photonic lantern) induces strong mode mixing unless designed specially otherwise (e.g. mode-selective photonic lantern).

Spectrally non-uniform devices introduce spectral trimming of the signal, thus requiring the considerations of bandpass width and flatness, which will also impact the efficiency of the network. SDM-WSSs can be roughly divided into two categories: (1) high-port-count SMF WSS adapted for SDM (SDM-WSS) and (2) FMF-WSS. In FMF-WSS, the passband of the switch is reduced due to crosstalk between the guided modes. In separately-switched SDM-WSS, the passband is limited due to possible errors of alignment between the different spatial channels, resulting in spectral shifts of the frequency response.

Resource optimization and allocation algorithms

The development of several dynamic and static resource allocation algorithms for SDM networks is crucial for the INSPACE project. It needs to take into account the presence and characteristics of SDM media (coupled vs. uncoupled) and optical switches (independent, joint or fractional joint switching). Two simulations tools were developed, along with several static and dynamic resource allocation policies, for the RSMSA problem. Regarding static planning, a tool based on simulated annealing was developed and tested using a realistic traffic matrix and topology provided by partner Telefónica. We showed that the performance of J-Sw and FrJ-Sw converges to that of Ind-Sw as the traffic increases (see Figure 5). In fact, when the total offered load to the network justifies the introduction of SDM, the performance of J-Sw and FrJ-Sw becomes similar to that of Ind-Sw. While a complete techno-economic analysis of the INSPACE solution is under study, we anticipate that the cost reduction due to the switching infrastructure as well as the possibility of using integrated spatial Sp-Ch transceivers will prove FrJ-Sw and J-Sw as potential candidates for SDM networks. Regarding the dynamic online resource allocation, several heuristics were developed, showing that spectral super-channels can be more efficient yet costlier that their spatial counterparts, and that, among the many possible alternatives, DP-8QAM is the best single modulation format for a typical European national SDM transport network.

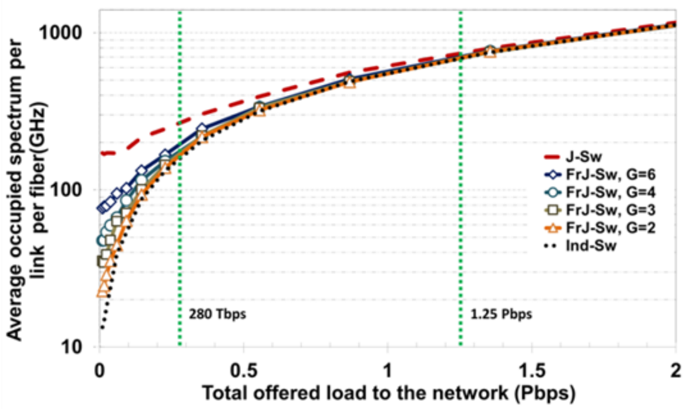

Figure 5: Average occupied spectrum per link per fibre for Ind-Sw, J-Sw and FrJ-Sw (with number of fibres per group (G) varying from 2 to 6) in an SDM network based on bundles of 12 SMFs

SDN-based controller for INSPACE

The INSPACE SDN controller is based on a layered architecture, somewhat reminding that of an Operating System (OS), as shown in Figure 6: at the highest level stands the System application programming interface (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 Applications 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, behaving in a manner akin to OS Device Drivers.

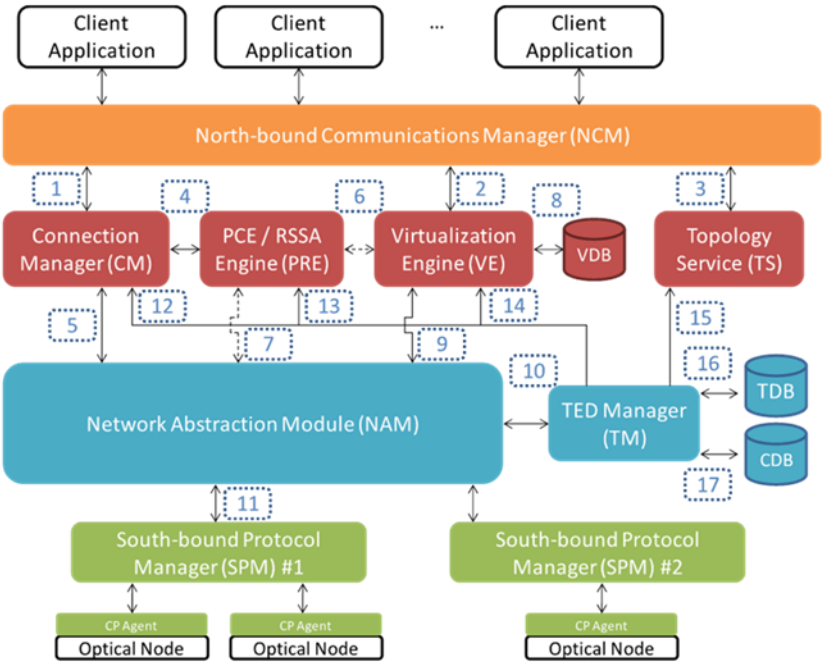

Figure 6: Internal controller architecture and OS analogy

Summary of achievements

According to the work presented above the main achievements so far with the INSPACE project are summarized in the following table:

Achievements and Progress Beyond the State of the Art
– Development of the SDM node and SDM amplification models for the evaluation of node switching impairments – Investigation of the impact of inter-core crosstalk and filtering effects through a 7-core MCF in combination with node cascading using a VPI/Matlab simulation – Development of a FMF model including linear mode coupling and inter-modal nonlinear coupling by considering a discretization of core-cladding imperfections of real fibres – One single expression linking the group delay spread to the fibre correlation length was validated considering FMFs guiding 3 and 6 modes, for the first time – Investigation of the impact of resource provisioning, channel routing and network blocking on an SDM-based backbone network constructed from the current SMF-based national network deployed in Spain by Telefónica by adding new fibres to all links – Investigation of resource provisioning approaches (in the form of spectral or spatial super-channels), and evaluation of their performance for several spatial switching strategies. – Completion of designs of the transceivers and ROADMs – Preliminary study on migration from today’s SMF networks to multi-fibre and multi-band networks comparing the two approaches

- Initial evaluation of the Telefónica national network cost for different switching strategies only taking into account the cost of WSSs
- Completion of the design and realization of spatial-spectral WSS-based switching node for the 1×48 high-port-count WSS. A larger device was built in practice, with 57 fibre ports
- Completion of the full design of the FMF-WSS including design improvements
- Development of routing and resource allocation algorithms for network planning
    - For the offline planning:
        - Development of a simulation tool that incorporates
            - a load-balancing engine (based on diverse-routing) element and a connection breakdown module
            - a simulated annealing meta-heuristic optimization tool for best path and spatial/spectral resource selection equipped a multi-starting-point generator to avoid local minima, thus yielding a nearly optimal global solution
    - For the online (in-operation) scenario.
        - Development of two online tools implementing different heuristics to evaluate the advantages of dynamic bandwidth-allocation in an SDM optical network
        - Definition of heuristics for advanced switching strategies to optimize the allocation of a large number of small demands for the joint switching case (worst-case scenario)
- Detailed definition of the control plane interfaces and the interactions between the modules
- Development of the control plane for INSPACE. The solution is based on the OpenDayLight open-source framework
- The final test-bed design has been concluded
- The INSPACE control framework and the interfaces with the WSS-based nodes have been fully defined and implemented
- In regard to the standardization activities during the second year of the project, a refined and complete version of a proposal to ITU with feedback from NTT was finished and submitted to SG-15 of ITU-T in February 2016

Expected Impact and actions

The existing network infrastructure and installed technologies are not able to keep pace with the enormous growth of traffic demands and quality of service metrics such as latency and packet loss rate. At this point, rather than making evolutionary upgrades to the underlying network infrastructure, and in an attempt to maintain a basic operation of the Internet, INSPACE follows a revolutionary path which will offer a future-proof solution. INSPACE is today among the few pioneers on a global scale that propose a novel SDM networking approach while successfully developing the required switching and control solutions for the proposed concept. In addition, preliminary work related to techno-economic and migration studies has already been performed showing the potential benefits of joint and fractional joint switching in terms of the expected traffic loads in the next five years and beyond and in comparison with alternative solutions proposed today.

Additionally, the INSPACE partners have initiated a very active role in the related ITU standardization committees presenting a draft of the switching concepts and the supported capabilities. Significant allies in this effort are NTT and NOKIA. This also proves the potential of the INSPACE research.