Deliverable 4.1

Report on implementation, integration and demonstration plans

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Author(s):	Name	Partner
	Achim Autenrieth	ADVA
	Arturo Mayoral	CTTC
	Ricard Vilalta	
	Raul Muñoz	
	Ramon Casellas	
	Ricardo Martínez	
	Michela Svaluto	
	Josep Maria Fabrega	
	Masato Nishihara	FUJITSU
	Tanaka, Toshiki	
	Tomoo Takahara	
	Jens, Rasmussen	
	Kai Habei	HHI
	Michael Schlosser	
	Xiaoyuan Cao	KDDI
	Noboru Yoshikane	
	Takehiro Tsuritani	
	Itsuro Morita	

	Yuki Yoshida	OSAKAU
	Akihiro Maruta	
	Ken-ichi Kitayama	
	Victor Lopez	TID
	Oscar Gonzalez de Dios	
	Juan Pedro Fernandez Palacios	
	Luis Miguel Contreras	
	Shuangyi Yan	UNIVBRIS
	Bijan R.Rofoee	
	Georgios Zervas	
	Reza Nejabati	
	Dimitra Simeonidou	
Checked by:	Victor Lopez	TID

Executive Summary

STRAUSS project is focus on having realistic results which are validated with prototypes not only for data plane, but also for and control plane solutions defined in the project. This deliverable presents the work that has been done in terms of implementation, integration and demonstration activities. This document provides a description of the plans and a preliminary description of the experimental activities done in the project. The experiments planed in this document provide a set of tests to tackle the problems that are faced in the project from a practical point of view. There are three main join activities:

- **OPS/OCS integrated network test-bed.** The OPS/OCS integrated network test-bed will be located in Japan and Europe and it will provide an integrated solution from an overall system perspective. The test-bed in Japan will focus on OPS, while the EU partners will focus on Elastic Optical Network (EON) to adopt the flexi-grid. With the advance of OPS and OCS technologies, an end-to-end Ethernet service provisioning and orchestration across multiple domains with heterogeneous transport and control plane technologies will be demonstrated for variable application scenarios.
- **SDN network architecture orchestration.** The SDN architecture will use a hierarchical approach based on the ABNO architecture, which has been proposed as a multi-technology and multi-domain network orchestration solution. The ABNO controller is the main component of the architecture and is responsible for controlling the workflows for both OF-controlled OPS and EON domains, which are run by KDDI and University of Bristol, respectively, an OF domain from ADVA in Telefonica premises and the GMPLS EON domain in CTTC.
- **Transport virtualization visor.** The proposed Virtualization Visor (VV) system architecture provides a mechanism for virtualizing transport nodes and links. The partitioning of the resources is performed by the VC, and to this end, the proposed system architecture incorporates a generic network abstraction mechanism for the different transport infrastructure resources (e.g., OPS, EON). Three virtualization domains are expected: (1) KDDI with an OF-controlled OPS domain, (2) CTTC with a GMPLS-controlled EON domain and (3) UNIVBRIS with an OF-controlled EON domain.

All previous experiments are defined based on the reported test-bed from each partner as well as a per-partner implementation, integration and demonstration plan for all partners involved in the project. Based on this plans and the facilities of each partner a summary of the participation of the partners in the activities is presented:

Joint activities	ADVA	CTTC	FUJITSU	KDDI	OSAKAU	TID	UNIVBRIS
OPS/OCS integrated network test-bed			X		X		X
SDN network architecture orchestration	X	X		X		X	X
Transport virtualization visor		X		X			X

Table of Contents

1 Introduction

The WP4 within STRAUSS project is focus on three activities: (1) implementation of virtualization layer, SDN orchestrator and network controllers based on WP3, (2) integration the work done in WP2 and WP3 and (3) experimental validation the targeted flexible optical infrastructure for Ethernet transport by means of demonstrations on test-beds in EU & Japan.

This document is the basis to do the activities in this work-package. This deliverable provides a description of the implementation, integration and demonstration plans to be done during the project. To do so, the document contains the test-bed of each partner as well as its plan to perform the implementation, integration and demonstration activities. The presentation of the test-beds is done first with the European partners and later with the Japanese partners. Finally, the document contains the implementation plans and a high level description of the demonstrators in the project (EU, Japan and intercontinental). The consortium has performed some proof of concept related with the data and control plane experiments on of them was accepted as a Post-Deadline paper in OFC 2014.

2 European test-bed implementation, integration and demonstration plans

2.1 Telefonica set-up

2.1.1 Overall set-up description

The test-bed in Telefonica I+D labs set-up is composed by three parts: the datacenter, the metro-core network and the control plane lab.

The data center set-up is composed by three servers (Intel(R) Xeon(R) CPU 5150@2.66GHz, 2 cores 4 GB RAM). Each server is formed by a set of host machines running OpenStack as the cloud computing software. The hosts run an instance of a virtual switch creating the internal network topology. The hosts are physically connected to HP 5406 OpenFlow controlled Switches via Gigabit Ethernet ports. Thus, the network topology in each datacenter contains a mix of physical and virtual switches. Each data center has its own independent OpenFlow controller and can be connected to the metro-core network via the HP switches.

The metro-core network set-up is composed by IP/MPLS and optical devices. The IP/MPLS devices are: 3 Juniper MX-240 routers, 2 CRS-3 and 3 Alcatel 7750. Moreover, Telefonica has two flexi-grid ROADMs from Cisco, four FSP3000 from ADVA and four optical nodes 6800 from Huawei.

The Telefonica I+D control plane test bed is composed by GMPLS nodes with software developed internally. The experimental setup is built with emulated nodes, which run in an Ubuntu server Linux distribution. Each emulated node implements a GMPLS stack (including RSVP, OSPFv2 and PCEP) and a Flexible Node emulator. There are two options to emulate the control plane: run each node in a PC or in a VM:

- For the first scenario, Telefonica has a set of 10 dedicated ASUS EEPC in the lab.
- For the virtualized environment, each GMPLS controller is a virtual machine and all are running is a server with two processor Intel Xeon E5-2630 2.30GHz, 6 cores each, and 192 GB RAM.

The GMPLS control plane stack and Flexible Node emulator are being developed in Java 1.6. Note that there is no hardware associated to this domain, only an emulation of the nodes. Currently, Telefonica GMPLS test-bed has the following functionalities:

- Signaling of Flexi-grid LSPs by means of GMPLS extensions for flexi-grid.
- Announcement of spectrum occupancy by means of OSPFv2 extensions for flexi-grid.
- Flexible node emulator.
- BGP-LS Speaker.
- Remote LSP instantiation from a PCE.

Finally, Telefonica has developed an ABNO controller, which supports inter-data-centre, multi-layer and multi-domain scenarios. This controller has interacted with the metro-core network set-up as well as with the control plane scenario.

2.1.2 Implementation, integration and demonstration plans

The ABNO architecture groups a number of standard components achieving different functionalities. For the set of use cases developed in this project, a set of extensions must be applied to the architecture in order to meet the requirements. The flexibility provided by the SDN framework can be exploited to pursuit several benefits, such as a better utilization of the network resources, in terms of capacity links, physical server consolidation, etc.

The modules of the ABNO architecture currently implemented are shown in Figure 1.

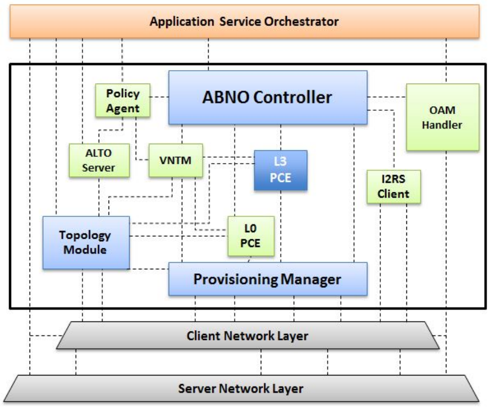


Figure 1: SDN controller

Following, a brief description of the relevant modules is presented:

- **ABNO Controller.** The ABNO Controller is the main component of the architecture and is responsible of orchestrating, and invokes the necessary components in the right order. It listens for request from the NMS/OSS and selects the appropriate workflow to follow in order to satisfy each request.
- **Path Computation Element.** The PCE is defined in RFC4655, and it is the unit that handles the path computation across the network graph. It can calculate traffic engineered end-to-end paths in order to optimize the optical spectrum consumption within the network.
  The PCE is capable of computing a TE LSP by operating on the TED regarding to the available bandwidth and network constraints. Coordination between multiple PCEs operating on different TEDs is also required for performing path computation in multi-domain (for example, inter-AS) or multi-layer networks.
- **Virtual Network Topology Manager (VTNM).** VNTM is defined in RFC5212 and it is in charge of maintaining the topology of the upper layer by connections in the lower layer. The LSPs established at the layer 0 network are advertised to the layer 3 resources as virtual links to provide connectivity.
  This entity simplifies the upper-layer routing and traffic engineering decisions as it hides the optical connections set up by the LSP. It can also respond to traffic demands, topology changes or network failures by releasing unused resources.
- **Topology Module.** The Topology Module is responsible for storing and providing network topology information, both per-layer topologies as well as inter-layer topology. One part of the module is devoted to getting and maintaining up to date the topology from the available sources (e.g. routing protocols, mainly for the more dynamic information). The other part of the module

is devoted to providing the information to the requesting parties such as the Provisioning Manager, PCE or VTNM.
The Topology Module has multiple databases: a view of each layer, the inter-layer information and an inventory DB with the configuration parameters of each of the resources (location, address, vendor…) and the details of the available interfaces of each the resources.

- **Provisioning Manager.** The Provisioning Manager is the unit in charge of configuring the network elements so the LSP can be established. It can do so both by configuring the resources through the data plane or by triggering a set of actions to the control plane.
There are several protocols that allow the configuration of specific network resources such as OpenFlow, Netconf, CLI and PCEP. The PCE protocol may be used for the establishment of LSPs as well, if extended following the crabbe-pce-pce-initiated-lsp-03 draft.

Below, a table showing the extensions needed for the different modules is shown including the due-date for the different tasks:

Table 1: Implementation, integration and demonstration plans for Telefonica

MODULE	FEATURE	DEADLINE
Topology Module	NOX support to interconnect with Bristol	M15
	TREMA support to interconnect with KDDI	M15
	ODL support	M20
	COP support	M30
Provisioning Manager	DataPathID provisioning	M19
	COP support	M30
	Multi-technology provisioning	M25
PCE L3	DataPathID support	M22
	Multi-layer algorithm implementation	M18
	Support for automatic OCS setup	M25
ABNO Controller	New workflows implementation to support DataPathIDs extensions	M19
PCE L0	DataPathID support	M21
VNTM	DataPathID support	M20
Preliminary TID integration and demo	Validation of the modules with dump interfaces to the controllers	M25

2.2 CTTC set-up

2.2.1 Overall set-up description

The CTTC contributes to the STRAUSS European Test-bed with a network scenario (Figure 2) for intra- and inter-datacenter connectivity controlled by a SDN IT and Network Orchestrator (SINO) architecture composed by two differentiated branches: IT resources orchestration and network resources orchestration.

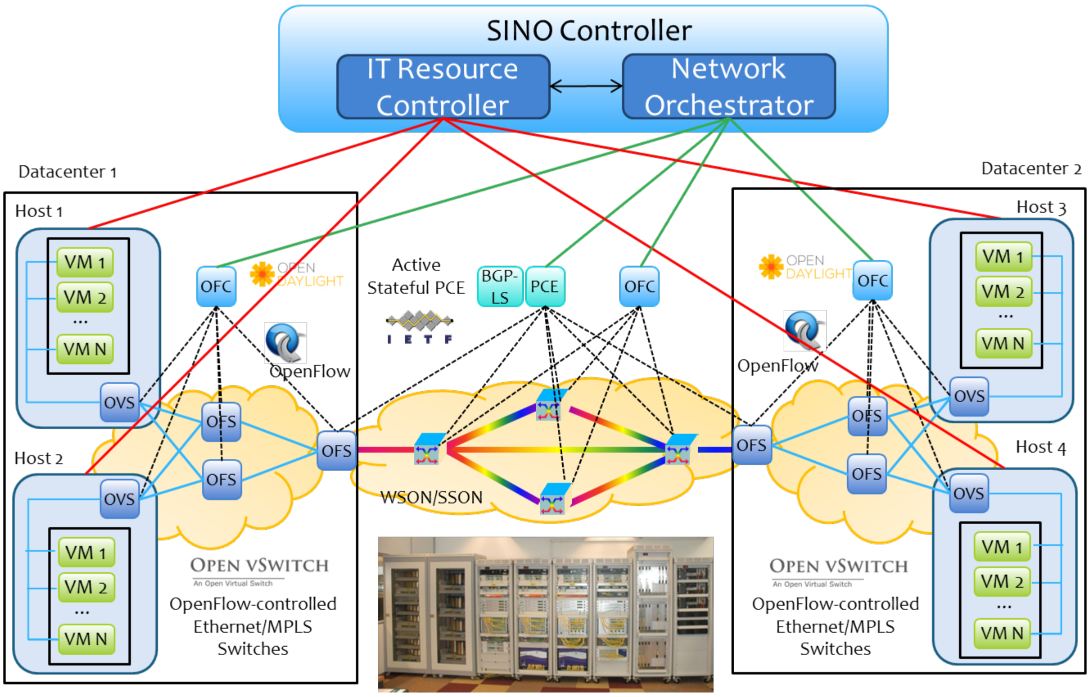


Figure 2: CTTC network scenario.

SDN IT and Network Orchestrator (SINO) Controller

The SINO controller is the responsible for the integrated management of IT and Network resources. It will require interaction with an IT Resource Controller and a Network Orchestrator. The SINO Controller will also expose a North-Bound Interface (NBI) programmed as a REST API offering integrated IT and networking services. Also a web GUI will be provided as a client of the REST API.

IT Resource Controller

The IT Resource Controller is the responsible for the Cloud Computing Platform of the ADRENALINE Test-bed. Thus, it is responsible of the management and deployment of virtual infrastructure resources (i.e., virtual compute and storage) in geographically distributed Datacenters (DCs).

The available hardware is composed by five physical servers with 2 x Intel Xeon E5-2420 and 32GB RAM each, one of them is a where the IT Resource Controller will be deployed, and the other four are compute (server pools) hosts for virtual machine (VM) instantiation.

Network Orchestrator

The Network Orchestrator main functionalities include the global network topology abstraction, technology-agnostic programmability of the network, inter-domain links management and optimal path computation. SDN orchestrator implements different interfaces to connect with the different network controllers, Representational State Transfer (REST) Application Programming Interfaces (APIs) for communication with OF controllers or PCEP in the case of an AS-PCE.

Intra-DC network

The network scenario inside the data center includes an OpenFlow network domain based on Ethernet links and OpenFlow-Switches (OFS) (two for each datacenter location, one for working traffic, one for protection schemas) deployed in Custom Off The Shelf (COTS) hardware (Intel Core i7-3770 8GB RAM and Intel Server Board S1200BTSR motherboard) running OpenVSwitch (OVS) software.

Additionally, each compute node includes an internal Virtual Top of Rack (VTOR) switch to attach the VM instances inside the physical node, these switches are implemented in software using OVS technology.

Inter-DC network

The inter-DC network connects different DC locations and it comprises a GMPLS-controlled WSON domain. The inter-DC network Test-bed contains the following components:

- **All-optical Dense Wavelength Division Multiplexing (DWDM)** mesh network with two colour-less ROADMs and two OXC nodes providing reconfigurable (in space and frequency) end-to-end light-paths. The network includes 610 km of G.652 and G.655 optical fiber divided in 5 bidirectional links, in which optical amplifiers (Erbium-Doped Fiber Amplifiers or EDFAs) are allocated to compensate power losses in the C-band. Each optical node has two DWDM transceivers up to 2.5 Gbps and one at 12.5 Gbps with fully tunable laser sources.

- **Optical node architecture** is based on using Array Waveguide Grating (AWG) as DWDM (de-) multiplexers (8 and 16 wavelengths with 50 and 100GHz channel spacing, respectively), and Micro Electro Mechanical Systems (MEMS) as the switching technology.

- **The Packet Transport Platform** of the ADRENALINE test-bed is composed of packet switched nodes with integrated 10Gbps tunable DWDM transponders connected to the WSON. The implementation of the packet switched node is based on a multicore PC architecture (2 x Xeon Intel Processor E5520 2.26GHz and an ATX-compliant ASUS Z8NA-D6 motherboard) with Linux as operating system, provisioned with several Network Interface Cards (NICs).

Specifically, two of the three nodes are equipped with two quad port cooper Gigabit Ethernet (GE) PCI Express NIC (4x1GE) from Intel (Intel PRO/1000 GT Quad Port Server Adapter), and an optical 10 GE PCI Express NIC with a XFP transceiver port from Myricom. The third node is equipped with an additional 10GE PCI Express NIC with XFP.

- **Experimental Equipment**: 24 GSa/s Arbitrary Waveform Generator; 100 GSa/s (20 GHz) Real-Time Oscilloscope; up to 40GHz electrical/electronic components; up to 50 GHz optoelectronic components (including modulators, photo-detectors); programmable LCoS optical filter; S, C and L bands tunable laser sources; PMD emulation and CD & PMD analysis instrumentation; Optical Spectrum Analyzer.

- **Sliceable Bandwidth/Bitrate Variable Subsystems:** DSP-enabled software defined optical transmission systems based on multicarrier technologies supporting multiple formats (BPSK, M-QAM and M-PAM), using offline digital signal processing.

Specifically, related to the data plane level, the platform for optical OFDM systems is indicated in Figure 3.

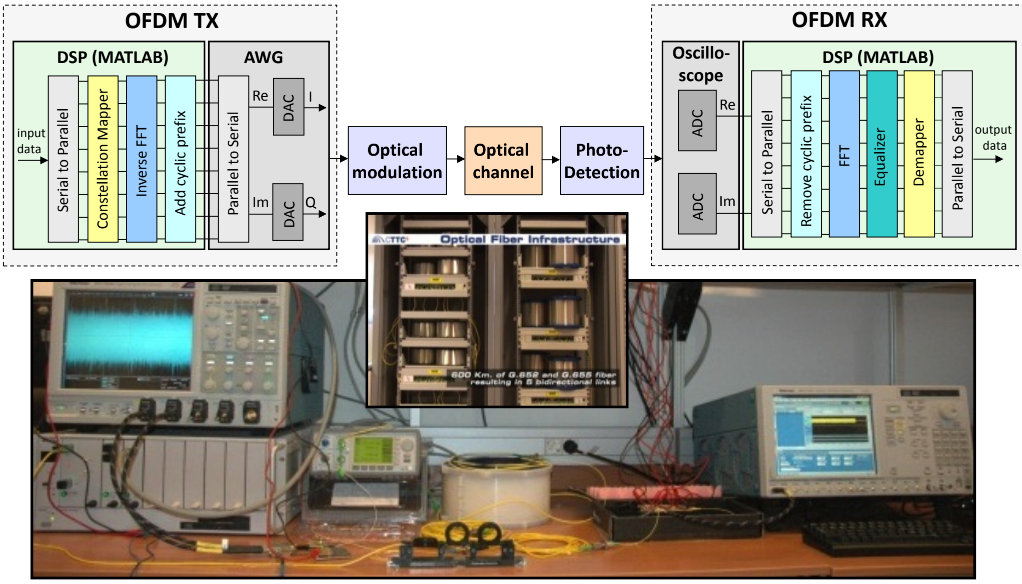


Figure 3: CTTC platform for optical OFDM systems.

SDN control plane

The CTTC Test-bed includes a control plane based in Software Defined Networking (SDN) architecture. The architecture includes centralized network controllers for each segment of the network and global orchestration between controllers. Following each control plane functional block is described:

- **Reconfigurable GMPLS Control Plane Network**: The reconfigurable network is used for deploying multi-domain and multi-layer GMPLS control plane networks for transport networks (e.g., MPLS-TP, WSON). Each GMPLS Controller implements the entire GMPLS protocol stack (RSVP-TE, OPSF-TE) and also the PCEP protocol. The control traffic is based on IP control channels (IPCC) carried at 1310 nm and C-band at the optical fiber with a line rate of 100 Mb/s using point-to-point links.

- **Active Stateful PCE:** The ADRENALINE network includes a Path Computation Element (PCE), which is a dedicated network entity responsible for doing advanced path computations. It discovers the network topology by sniffing the OSPF-TE traffic and it is store in a non-shared Traffic Engineering Database (TED).

Active and stateful capabilities grant the right to a PCE of establishing or tear down connections into the GMPLS control plane. The AS-PCE included in the ADRENALINE Test-bed implements these extensions an also allows external peer PCEP-Speakers to request Label Switched Paths (LSPs) establishment into the GMPLS control plane.

The system runs on top of a Debian GNU/Linux operating system and consists in a main multi-threaded asynchronous process, running as a PCEP/TCP server in order to accept and process path computation requests from the optical nodes controllers or from upper control entities into the SDN architecture.

- **OpenFlow controllers** for packet (OpenDaylight, NOX) and optical (CTTC proprietary) networks and OpenFlow agents for optical ROADMs in wavelength switched optical networks (WSON).

2.2.2 Implementation, integration and demonstration plans

The presented CTTC network scenario requires the following modules to be implemented:

Sliceable Bandwidth Variable Transceivers

CTTC implementation plans include the integration and experimentally evaluation of the OFDM-based transceiver designed and developed in T2.1.2. The software-defined sliceable bandwidth/bitrate variable transceivers will be tested onto the platform for optical OFDM systems using the ADRENALINE test-bed network controlled/managed by the GMPLS control plane. The transceivers programmability is enabled by off-line DSP. Specifically, several transceiver parameters can be adaptively selected, such as bandwidth, bit rate, modulation format, according to the requested demand and channel profile of the optical path to set-up. Thanks to the sub-wavelength granularity of OFDM, bandwidth manipulation is extended to the electrical sub-carrier level, including arbitrary sub-carrier suppression and adaptive bit and power loading, enabling fine bit-rate selection and an efficient use of spectral characteristics of transmission links. Different configurations will be tested for different optical paths of the ADRENALINE network in order to add flexibility to the system and enhance the overall sensitivity performance.

Furthermore, as OFDM-based transceivers intrinsically provide a self-performance monitoring technique, the system (monitoring) parameters, acquired in the electrical domain for channel estimation and equalization, will be used as valuable information for the adaptive transceiver re-configurability and the management of the rate/distance adaptive system.

SINO Controller

As explained, it is the responsible for the integrated management of IT and Network resources. It will require interaction with an IT resource manager and a network orchestrator.

- The SINO Controller will also expose a North-Bound Interface (NBI) programmed as a REST API offering integrated IT and networking services.

- A web GUI will be provided as a client of the REST API.

IT Resource Controller

This component will be implemented using OpenStack, although several modifications will be required like the OpenStack Neutron plugin. The OpenStack OVS Neutron plugin will be modified in order to fulfill the networking requirements by the Network Orchestrator, by allowing direct access to intra-DC SDN controller to each compute host OVS.

Network Orchestrator

The network orchestrator consists of four founding modules which will implement the designed Control Orchestration Protocol: (1) Network Orchestrator Controller, (2), Topology Manager Module, (3) Provisioning Manager Module and (4) Path computation module.

Table 2: Implementation, integration and demonstration plans for CTTC

MODULE	FEATURE	DEADLINE
SINO Controller	Preliminary SINO	M14
	SINO + REST API	M20
	Preliminary GUI	M24
	Final SINO	M30
IT Resource Controller	OpenStack DC	M12
	Preliminary Neutron Plugin	M12
	Final Neutron Plugin	M24
Network orchestrator	Preliminary Network orchestrator controller	M12
	Preliminary Topology Manager	M16
	Preliminary Provisioning Manager	M20
	Final Network orchestrator controller	M24
	Final Topology Manager	M26
	Final Provisioning Manager	M30
Preliminary integration and demo	Preliminary end-to-end virtual machine connectivity within CTTC	M24
Sliceable bandwidth variable transceiver	Integration and experimentally evaluation of the OFDM-based transceiver using offline processing onto the platform of the ADRENALINE test-bed	M30
Final integration and demo	End-to-end virtual machine connectivity using Control Orchestration Protocol	M30

The integration of the developed components will be executed prior to proposed demonstrations. According to the previous table, two CTTC network scenario demonstrations are expected: (1) preliminary end-to-end virtual machine connectivity, and (2) End-to-end virtual machine connectivity using Control Orchestration Protocol. The idea of the first experiment is to demonstrate the proposed architecture for network orchestration in WP3 will be presented by means of the deployment and interconnection of virtual machines using an interaction between OpenFlow and GMPLS protocols. Regarding the second experiment, it is focus the benefits of Control Orchestration Protocol for delivering end-to-end virtual machine connectivity.

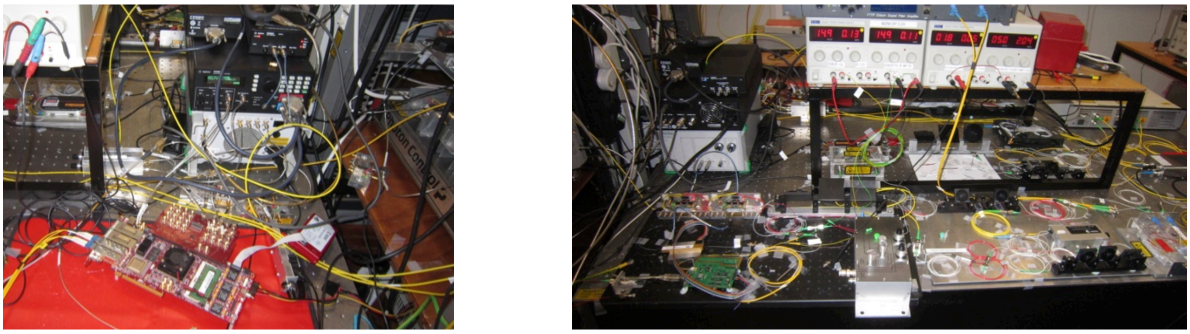
2.3 Bristol set-up

2.3.1 Overall set-up description

2.3.1.1 Data Plane

The test-bed in University of Bristol lab's set-up consists of OPS/OCS interface with sliceable, bandwidth variable transceiver, flexible/adaptable optical nodes based on Architecture on Demand (AoD) for elastic optical networks, and multi-format coherent detection system.

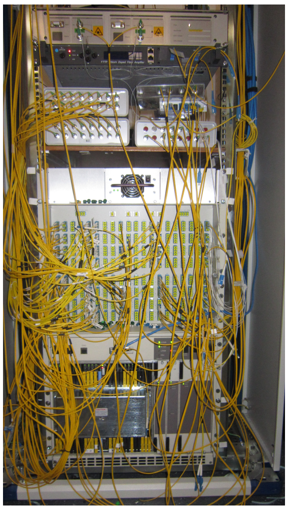
The OPS/OCS interface enables Ethernet connection between OPS-based metro networks to OCS-based core network. The interface includes three key subsystem: 1) optical comb generation, 2) OPS/OCS converter based high-performance FPGA, and 3) multi-format supported transmitter. The optical comb generator can generate a large number of optical carriers with variable channel spacing from 10G, 20G, and 40G. The total quantity of carriers can be controlled for generation of variable bandwidth super-channel signals. The generated optical carriers are launched into the multi-format transmitter for signal modulation. We can generate BPSK, QPSK, 16QAM and 64QAM signals up to 40Gbaud. The key component of OPS/OCS interface is the OPS/OCS converter based on high performance FPGA-based optoelectronics (HTG Xilinx V6 PCIE board). The OPS/OCS converter receives Ethernet packages using multiple SFP+ interfaces and then aggregated and groomed data streams based on its destination MAC address and the virtual network slices they belong to. The aggregated data are sent to different multiple format transmitters through SMA interface. The aforementioned multi-format transmitters with different modulation formats or symbol rate are attached to different egress ports of OPS/OCS converter, to generate signals with different modulation format according to the network capacity requirement. Current OPS/OCS interface can convert 1 channel Ethernet signal (10Gbit/s) to variable capacity OCS signals with QPSK or 16QAM modulation format up to 20Gbaud. Figure 4 shows the experimental setup.



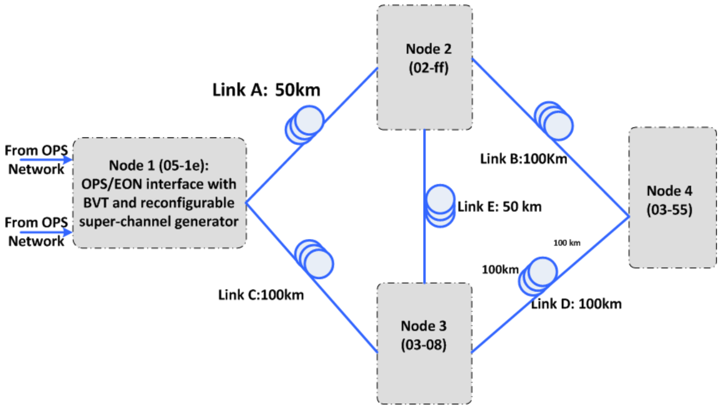
(a) (b)

Figure 4: Setup of OPS/OCS interface with Multi-format transmitter. (a) OPS/OCS converter; (b) Multi-format transmitter (QPSK, 16QAM)

The flexible/adaptable optical nodes for flexi-grid optical networks are achieved with several large port number fibre switches, based on either a beam-steering fibre switch or a 3-D MEMs switch. A variety of subsystems, such as CDC ROADM, fast time switching, and layer 2 interfaces, are connected and managed by the fibre switch, based on the architecture on demand concept. Several wave-shaper devices are deployed in the nodes to provide both fixed-grid and flexi-grid DWDM compatible optical node. The flexible/adaptable optical nodes can adapt its structure by reconfiguring the inter-connection of components and subsystems. Variable scale of add-drop bank can be synthesised according to the required capacity. The AoD concept can improve the use efficiency of available network resources. Figure 5(a) shows flexi-grid optical nodes based on a 3-D MEMS switch. Based on the flexi-grid optical nodes, we setup an elastic optical network with 4 nodes. The topology of the setup networks is shown in Figure 5(b).



(a)



(b)

Figure 5: (a) Flexi-grid optical node based on AoD; (b) Network topology with 4 AoD flexi-grid optical nodes

The multi-format coherent receiver in our lab can receive and analyse variable high-order modulation format signals up to 50Gbaud, with a 33GHz 80Gs/s real-time oscilloscope. The receiver can support BPSK, QPSK and 16QAM signals. Sets of Digital signal processing algorithms are developed for offline processing. Figure 6 show the control GUI for offline digital signal processing. The GUI captures raw data from real-time oscilloscope and then processes the signal to recover the constellations. The digital signal processing consists of CD compensation, time recovery, polarization de-multiplexing, frequency offset compensation, carrier phase estimation, BERT, etc.

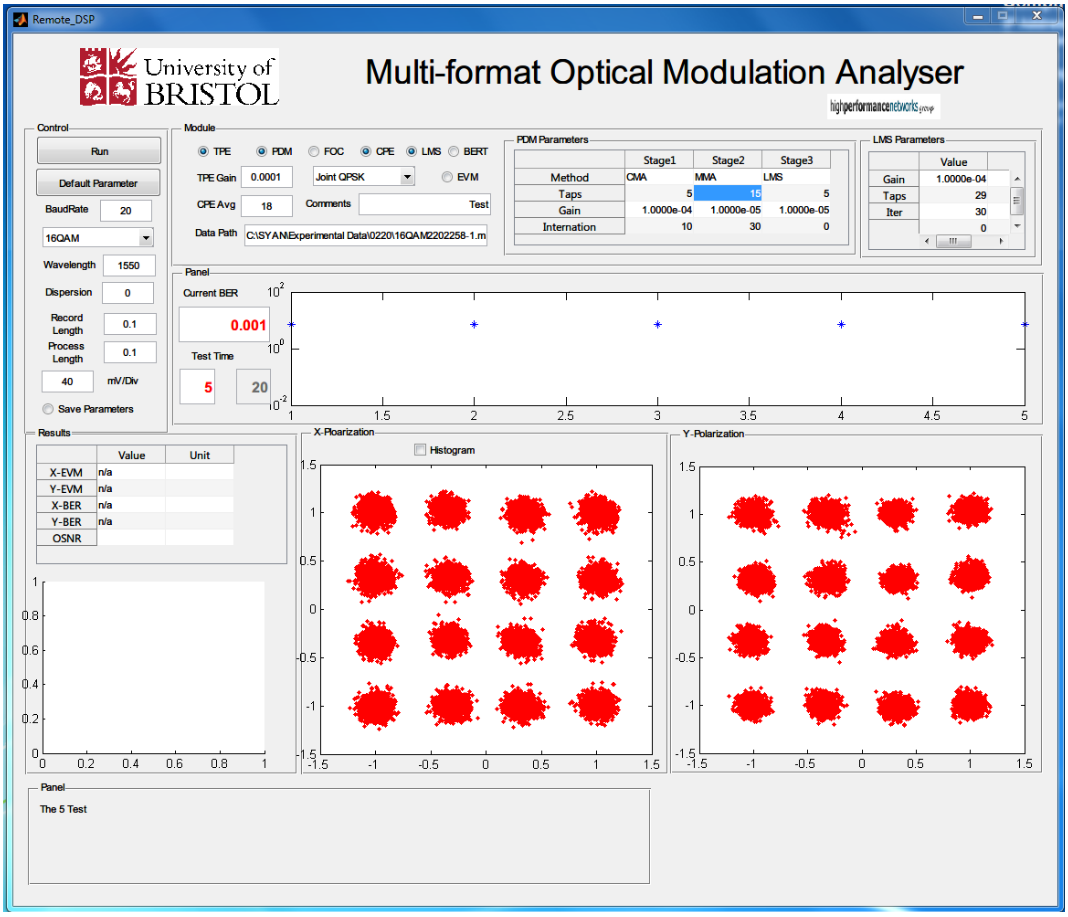


Figure 6: Control GUI for offline digital signal processing

2.3.1.2 Control Plane

For optimal super-channel routing over the flexible grid network an intelligent control plane is required. Univbris have opted to use SDN based control architecture for its domain to decouple the control and data plane which is in-line with the project view where the control plane and data plane are separated to enable flexibility and dynamicity.

The architecture consists of a logically centralized SDN controller, which uses OpenFlow protocol to discover the control features of individual devices. The OpenFlow supporting southbound interface of the controller discovers individual devices (in Bristol i.e. AoD, Fixed/Flexi grid and Ethernet nodes) capabilities and stores it in the topology DB that is exposed to applications via a northbound interface. The architecture building blocks are shown in Figure 7.

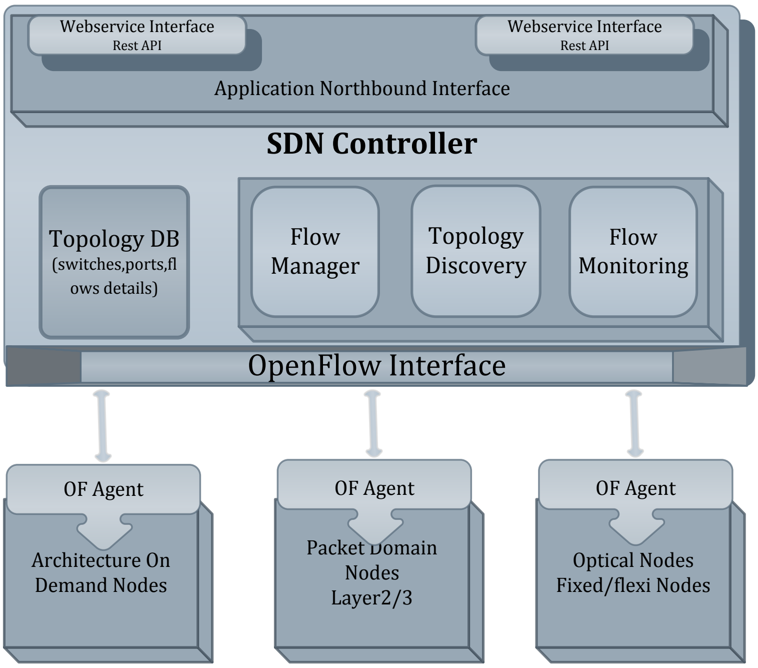


Figure 7: SDN Architecture

2.3.2 Implementation, integration and demonstration plans

Using the available test-beds, flexible elastic optical networks will be demonstrated. With the OPS/OCS interface, the OPS data will be converted to a super channel signals with several sub-carriers adopted different modulation formats signals. According to the total capacity requirements, we can configure the sub-carrier number, channel spacing, modulation formats to fine tune the aggregate capacity and achieve the maximum capacity. The implementation plan for OPS/OCS interface is illustrated in Figure 8. Several OPS/OCS converters will convert OPS data streams (in Ethernet packages) to OCS signals, which are used to drive several multi-format transmitters to obtain signals with different modulation formats. The generated signals are combined and grouped together to achieve super-channel signals with a reconfigurable super-channel signal assembler. An open flow based SDN controller will be developed to control the OPS/OCS interface.

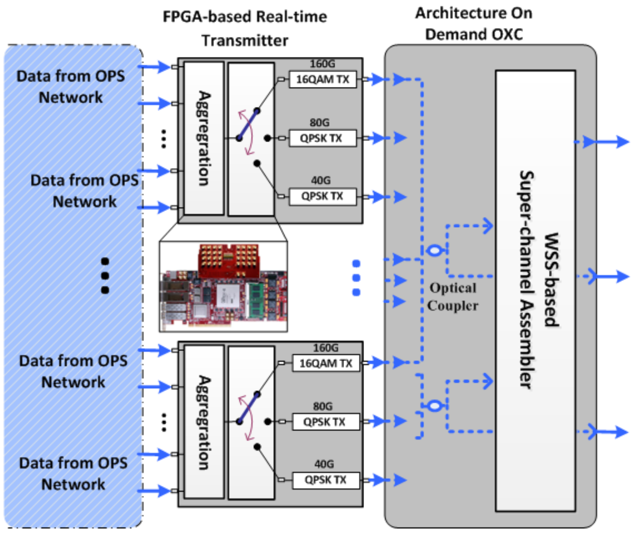


Figure 8: Implementation plan of OPS/OCS interface including OPS/OCS converter and super-channel generator

- OCS side BVT
    a. **Optical comb generation** with sub-carrier up to 20. The channel spacing can be configured 10 GHz, 20GHz, or 40GHz.
    b. **Multi-format transmitter** will increase the baudrate up to 40Gbaud, to provide several mixed rate lines with configurable modulation formats (QPSK, 16QAM).
    c. **Online reconfigurable multi-format transmitter** will developed to support adaptive modulation format configuration.
- **Control and management**
    a. **SND controller for the optical comb generation** will be developed to control the generated optical comb.
    b. Developments and extensiosn to the SDN agent for the interface
- OPS side aggregation
    a. Increased number of input 10GE ports
    b. Increase the capability of header matching of the Ethernet traffic based on VLANs as well as the MAC addresses (Destination and Source headers)
    c. Enhancing the capabilities of the FPGA interface in calssifying the traffic following different levels o QoS required.

Regards to the flexible/adaptable optical nodes for flexigrid optical networks, an online reconfigurable CDC ROADM will be implemented. The CDC ROADM will base on our proposed AoD ADB [GA14]. A demonstration experiment will be carried on to drop signals with variable baud rate and different modulation formats. The scales of the ROADM can be scaled up easily. Several features of flexible/adaptable optical nodes will be developed and demonstrated as bellows:

- Auto-configure the scale of **CDC ROADM**.
- **Gain equalization** for mixed line rate signals.

The whole demonstration plan is shown in Figure 9. With the OPS/OCS interface and the flexible/adaptable optical nodes, elastic optical networks will be demonstrated with mixed line rates, variable modulation formats. The demonstration experiments will explore the mixed line rate (10Gbaud, 40Gbaud), variable modulation formats (QPSK, 16QAM), and super-channel transmission to provide a flexible Ethernet inter-connection between OPS and OCS networks. As shown in Figure 9, the OPS/OCS interface converts several OPS data streams to a high capacity super-channel signals. The SC transmitter with 8 sub-carriers can support capacities from 160Gbit/s to 2.56Tbit/s, with either 40Gbaud PM-QPSK signals or 40Gbaud 16QAM signals for each sub-carrier. The flexible/adaptable optical nodes will drop the super-channel signals in different nodes for variable application scenarios.

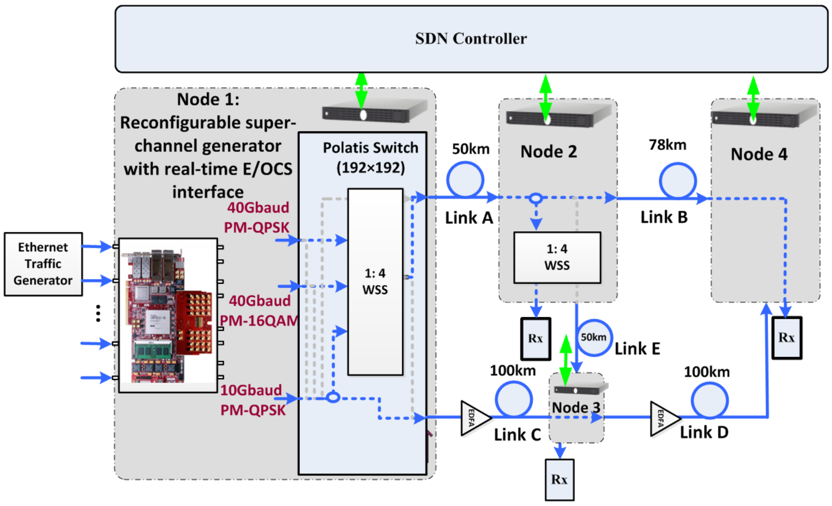


Figure 9: Demonstration plan of elastic optical networks

The SDN structure is shown in Figure 7. To support the demonstration plan in data plane, several key components will be developed and further improved.

- **OF Agent**: The OpenFlow agent is a user-space process that runs on top of an optical node and connects to a configured OpenFlow controller. The agents are implemented following the OpenFlow protocol spec 1.0 and the addendum for circuit switched networks v0.3.The agent utilizes an internal API to communicate with the NEs, and the extended OF protocol to communicate with the controller. OF agent software provides a hybrid switch abstraction of the OF device.
- **Controller**: On the southbound, the controller uses an OpenFlow plugin to connect to individual OF agents. Once the capabilities are read the controller builds the topology, using the discovery module, of the whole network and stores in the Topology DB. The topology discovery module can present different abstraction views based on the application requirement. E.g for a PCE it presents the whole of the physical layer details and for a data centre function such as VM migration it hides low level details and just represents the nodes and link bandwidth as a graph. The northbound API uses this abstraction to expose the desired application topology. The flow manger module manages the flow modifications to individual devices. It receives the application path setup requests and breaks it down to individual cross connections based on the path details. E.g. say an application requests 200G connection on the data plane then the flow manager breaks down the request to flexible node terms i.e. the central frequency and slots required to satisfy 200G. The flow monitor module keeps track of the existing network flow states and for Ethernet devices it also maintains the flow density which can be used for traffic characterization.
- **Northbound API**: A Restful API is exposed to the applications to make use of the controller functionalities. The calls are as follows

urls	Description
GET_TOPOLOGY	Circuit & Packet OpenFlow switches connected to controller. Provides full details i.e. switch & port descriptions
GET_GRAPH	Connected nodes with QoT details
GET_DPIDS	Provides all ckt & packet DPIDs
GET_PORTS/<DPID>	Returns ports for a particular switch
CFLOW_MOD/<dpids,ports,wavelengths>	Push circuit flows

Figure 10: SDN calls of Northbound API

MODULE	FEATURE	DEADLINE
Super-channel transmitter	Mixed modulation formats, up to 40Gbaud	M14
	Real-time modulation adaptable based on high-bandwidth DAC	M20
SDN controller for Super-channel transmitter	Support modulation adaptable feature	M16
	Optical Comb controller	M18
	Channel Spacing Selection	M16
	Initial implementation of OPS/OCS interface controller	M18
	Final implementation of OPS/OCS interface controller	M24
Integrated OPS/OCS interface demo	Number of input ports up to 2	M20
Reconfigurable CDC ROADM demo	Online reconfigurable ROADM	M16
Final integration and demo	Flexible optical networks with mixed line rate and variable modulation format signals	M30

Table 3: Implementation, integration and demonstration plans for Bristol

2.4 ADVA set-up

2.4.1 Overall set-up description

In addition to the ADVA test-bed located at the premises of Telefonica in Madrid, Spain, ADVA hosts an in-house SDN / Control Plane test lab with an SDN/OpenFlow enabled colorless directionless ROADM network. The lab contains three ADVA FSP-3000 ROADMs equipped with the latest offerings from the ADVA product family (GMPLS controlled, SDN/OpenFlow enabled, and Flex-Grid ready). The test-bed can also be extended to evaluate scenarios with additional network elements using a GMPLS simulator. Some of the notable features available on the test-bed include:

- **GMPLS control plane** protocol software with distributed or centralized Path Computation Element (PCE).
- **Optical Network Hypervisor** for ADVA FSP-3000 ROADMs with OpenFlow 1.0 and 1.3 north-bound interface (NBI) and proprietary RESTful southbound API.
- **FSP Network Manager** / Service Manager.
- **SDN/OpenFlow Controller OpenDaylight** and **Floodlight**
- Cloud-Control Software **OpenStack** and **OpenNaaS**
- Optical Transport Network Applications: **ADVAlanche** and **Avior**

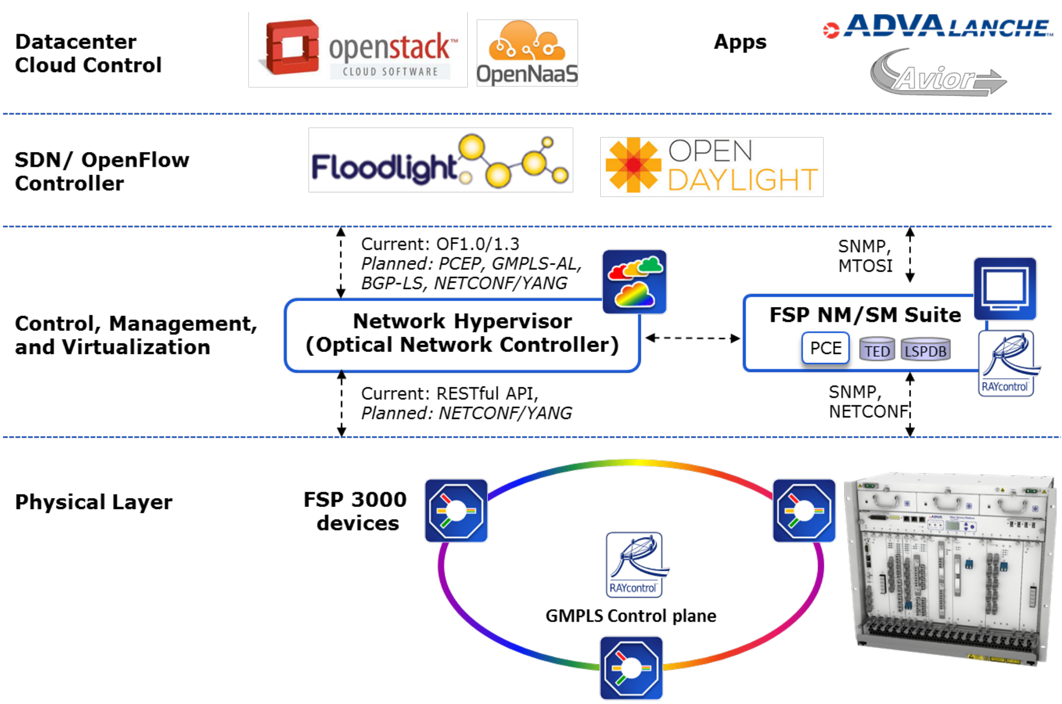


Figure 11: ADVA network infrastructure

The Optical Network Hypervisor currently supports an abstraction of the optical network as a **Single Virtual Switch**. In this mode the complete optical network is encapsulated and abstracted as a single virtual (Ethernet) switch. This allows e.g. a straight-forward interconnected of SDN islands (e.g. Data centers) over an optical long haul networks.

2.4.2 Implementation, integration and demonstration plans

Within STRAUSS, the Optical Network Hypervisor is extended to additionally support an **Abstract Link Model**. In this mode the client OpenFlow controller has a reduced visibility of individual network elements and limited control over the optical network. This mode provides a balance between Single Virtual Node and Direct Model and allows a configuration on the level of abstraction and control provided to client SDN controllers.

Below, a table showing the extensions needed for the different modules is shown including the due-date for the different tasks:

Table 4: Implementation, integration and demonstration plans for ADVA

MODULE	FEATURE	DEADLINE
NBI: OpenFlow Protocol	OpenFlow Protocol version 1.3	M12
	OpenFlow Protocol version 1.4	M15
Abstraction Models	Virtual switch model	M12
	Virtual link model	M18
	GUI-aided virtual topology establishment	
		M18
Planned Features	Direct Model Support (CDPI)	M24
	Carrier Ethernet devices integration –	M24
	Additional NBIs (BGP-LS, PCEP, …)	M27

2.5 HHI set-up

2.5.1 Overall set-up description

HHI develops a real-time OFDM-Transmitter capable of data rates (gross) up to 64Gbit/s. A real-time OFDM-MAC processor with four 10G Ethernet inputs (SFP+) is also included. The optical transmission is based on application of a MZM using a real-valued OFDM signal, which has been generated by means of an electrical IQ-Modulator and two DACs. A block diagram of the OFDM transmission system is shown in Figure 12.

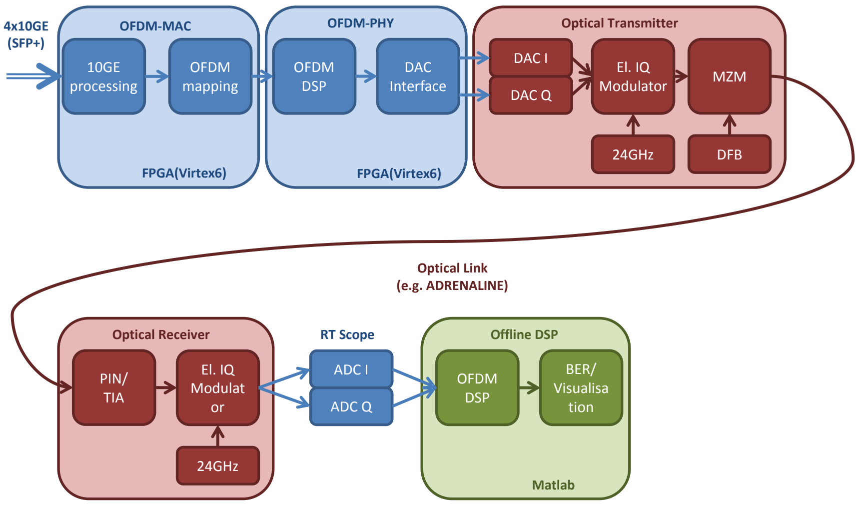


Figure 12: OFDM transmission system including the real-time transmitter

OFDM-MAC

The real-time OFDM-MAC processor is implemented on a Virtex6-based FPGA platform. It schedules incoming Ethernet frames from one of the four 10G inputs to the respective sub-carriers of the OFDM system. The sub-carrier mapping for the ONU is flexible, i.e. one ONU can be assigned 1 or 256 sub-carriers, allowing data rates of up to 10Gbit/s per ONU.

OFDM-PHY

The real-time OFDM-PHY is being realized with up to 1024 sub-carriers with three different modulation formats, namely BPSK, QPSK, and 16-QAM. Alternatively sub-carriers can be turned off. The two DACs for the in-phase (I) and quadrature (Q) signals operate at sampling frequencies of up to 16 GS/s. Therefore a total bitrate (gross) of 64 Gbit/s can be achieved, when all sub-carriers carry a 16-QAM signal.

Optical transmitter and receiver

The optical transmitter uses intensity modulation by means of an electrical IQ-modulator and an optical MZ-modulator. The LO frequency is located at 24 GHz in order to avoid interference at the receiving side. The receiver uses a PIN receiver (32GHz bandwidth) with an integrated TIA. The down-conversion is also realized using an IQ-modulator. Both baseband signals are then forwarded to the ADCs of a RT oscilloscope. A more detailed description of the OFDM system can be found in in deliverable D4.1.

2.5.2 Implementation, integration and demonstration plans

First tests of the real-time OFDM transmitter (PHY module) have shown severe distortions mainly caused by the IQ imbalance of the electrical modulator at the transmitter. Therefore a more sophisticated correction algorithm is currently investigated for the off-line receiver. After completion of this task, the transmitter will be carefully tested in a lab environment before it can be demonstrated in the ADRENALINE test-bed.

The implementation of the MAC processor will be continued. All block concerning the Ethernet frame handling and the OFDM sub-carrier mapping are currently implemented. Simulations have shown timing errors in the design, which have to be fixed first. After completion of these tasks, MAC and PHY modules have to be tested together to find any remaining errors and to confirm an error-free operation of the entire OFDM transmitter.

The implementation of the OFDM transmitter (MAC and PHY) allows for a flexible bit- and power-loading. There are three (four including the off state) different modulation formats and 32 different power levels for each sub-carrier possible. In order to give the user access to bit- and power loading an interface (e.g. USB) for controlling from a computer/micro-controller has to be implemented.

Table 5: Implementation, integration and demonstration plans for HHI

MODULE	FEATURE	DEADLINE
OFDM-Transmitter-PHY	PHY-Module ready	M18
MAC-Processor	MAC-Processor ready	M24
OFDM-Transmitter	Completion of integrated OFDM-Transmitter (PHY, MAC, CONTROL)	M30

3 Japanese test-bed implementation, integration and demonstration plans

3.1 Overall prototype description

Figure 13 is an overview of the OpenFlow-controlled variable-capacity OPS network test-bed in Japan. Key components are a) OpenFlow-compatible Optical Packet Switching (OPS) router, b) 100Gbps-class Discrete Multi-Tone (DMT) transponder, and c) Extended OpenFlow controller with OpenFlow agents. Each network element is individually developed by OsakaU, Fujitsu, and KDDI, respectively, and will be connected to the JGN-X test-bed in NICT, which is consist of d) 2 huge-capacity Optical Packet and Circuit Integrated (OPCI) routers, to demonstrate an OpenFlow-based OPS network. (For the specification of the OPCI routers, see [Fu12]).

Furthermore, the OPS test-bed will be remotely controlled through the Japanese nation-wide network test-bed, JGN-X, to demonstrate large-scale and multi-domain OpenFlow-based network control. (See https://www.jgn.nict.go.jp/english/index.html for the detail of JGN-X).

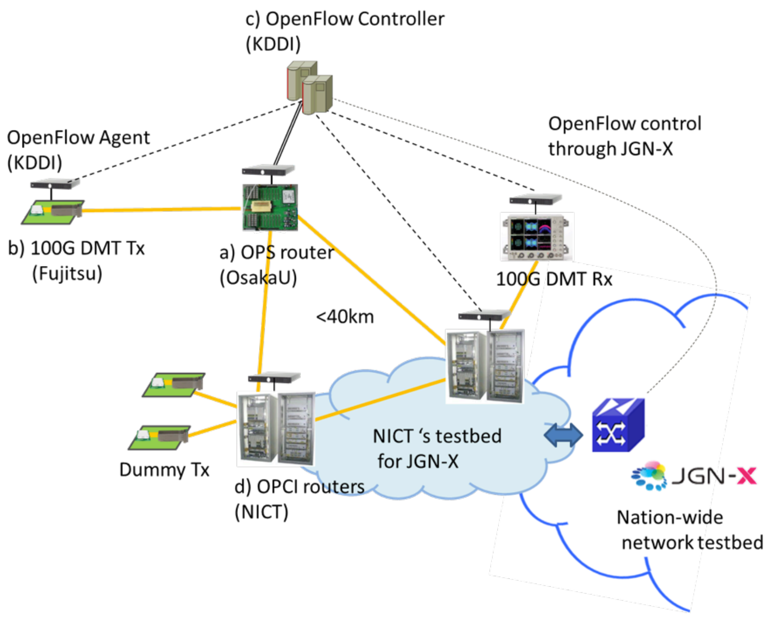


Figure 13: Overview of Japanese test-bed

3.1.1 OPS/OCS test-bed

Though OpenFlow is developed for a network with a centralized control plane, OPS network is basically a self-routing network. Therefore the distributed implementation of OpenFlow is a notable challenge for future software-defined elastic OPS networks as discussed in D3.1 Section 3.2.2. To investigate the feasibility of the hop-by-hop optical packet switching under the OpenFlow control, a novel 100Gbps-class OPS router will be developed at OsakaU. Figure 14 shows the configuration of the OPS router. The router consists of the following components;

- **4×4 nano-second speed optical switch** implemented by EpiPhotonics PLZT Optical Switch EPS0404, which enable transparent and high-speed optical packet switching within 10 ns.

- **Fiber delay line (FDL) buffer and buffer manager:** Owing to the fixed-length variable-length (FL-VC) optical payload concept (D2.1 Sec. 3.2.2), a simple recirculation buffering, e.g., STARLITE switching, can be adapted. 2 FDL with 1 time slot delay (100-200 ns) will be implemented.
- **Label detector** which based on a 12.5GHz photo receiver and a FPGA board for label processing. The receiver can detect up-to 10 Gbaud OOK-formatted optical label. The label processor is connected to the OpenFlow agent developed by KDDI and communicates with the OpenFlow controller through the agent when a new flow comes.
- **High-speed memory bank and optical switch driver:** the switching tables are loaded onto the memory bank. The table can be updated by the agent and the bank switching enables high-speed optical switch reconfiguration within 100 ns.
- Label detector, switch driver, buffer manager and memory bank will be integrated onto a high-speed FPGA board.

OsakaU also implemented three optical packet generators. The packet generator consists of a 10GHz optical gate switch driven by 10Gsps arbitrary waveform generators (Tektronix AWG7122C). The generator is used to *packetize* the optical signal stream generated via Fujitsu's DMT transmitter and appends up-to 10GHz OOK-formatted optical label on top of the DMT packet. The label format will be compatible to that in the NiCT's OPCI routers. These packet generators are also employed for the dummy packet generation in the test-bed.

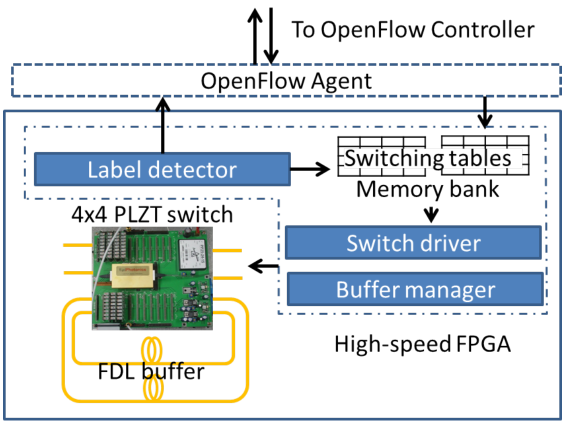


Figure 14: Configuration of the OPS router

3.1.2 Discrete Multi-Tone (DMT)-based sliceable variable-bandwidth transceivers

Software-defined sliceable variable-bandwidth transceiver is one of key technology to maximize the flexibility and scalability of the network. DMT is the OFDM-based multi-carrier modulation format and it is suitable for sliceable variable-bandwidth transceiver from its high efficiency and unique flexibility of bandwidth based on the adaptive bit loading of sub-carriers. The DMT transceiver is consisted by DMT modulator/demodulator, optical transmitter, and optical receiver.

- **DMT modulator / demodulator** is a digital signal processor that generates and demodulates a DMT signal. It consisted by a FPGA for signal processing and a PC for control and monitor. It is connected with the OpenFlow agent developed by KDDI and some parameters are controlled and monitored by the OpenFlow Controller.

- **Optical transmitter** is consisted by a high speed DAC, a linear driver amplifier and an optical modulator. The digital DMT signal generated by the DMT modulator is converted to the analog signal. After amplified by the driver amplifier, the electrical DMT signal is converted to an optical DMT signal.
- **Optical receiver** is consisted by a photo-detector with linear trans-impedance amplifier and a high speed ADC. The optical DMT signal is received by photo-detector and converted to the electrical signal. The analog electrical signal is converted to a digital signal by the high speed ADC and injected to the DMT demodulator.

Following table shows the typical specification of DMT-based sliceable variable-bandwidth transceiver.

Table 6: Specification of DMT-based sliceable variable-bandwidth transceivers

Items	Parameters	Values
Transmission characteristics	Maximum data rate	100 Gbps
	Maximum transmission distance	40 km
	Maximum BER	1×10^{-3}
Interface	Optical transmitter output	DMT optical signal
	Optical receiver input	DMT optical signal
	Network Controller IF	Ethernet
Controllable parameters from Network Controller	Sub-carrier number	128, 256, 512, 1024, 2048
	Transmission policy	Predetermined policies with different data rate
Monitor parameters to Network Controller	SNR	Average of sub-carriers
	BER	Total of sub-carriers
	Data rate	Total of sub-carriers

3.1.3 OpenFlow controller

We use Trema controller on a server (Quad-Core AMD Opteron Processor 2382@800.000MHz, 4 cores 16 GB RAM) in order to control the OPS network. Trema is an open source development platform for Ruby and C-based software-defined networking (SDN) control applications, such as OpenFlow controllers. Since the OPS is not supported by Trema controller, we extended label flow control of Trema controller (i.e. extended Packet_In and Flow_Mod messages) to simplify forwarding optical packets in a flow. The extended Packet In and Flow Mod messages include optical label information and an action message for controlling the OPS, respectively. Thanks to the extension, the controller can control the OPS network.

3.1.4 Connection with JGN-X Test-bed

An OpenFlow-controlled OPS network mainly comprises of an SDN Controller, OPS nodes and OpenFlow-based OPS agent (OFA) as shown in Figure 15. The OFA is an extended OpenFlow switch that acts as a proxy for the southbound OPS node. The OPS node we used in our demonstration is the optical packet and circuit integrated (OPCI) node provided by NICT. Its structure is shown in Figure 16. The OPCI node we used attaches a unique label called OP-ID to packets according to its label-mapping table and forwards packets according to its own forwarding table. In order to configure its label-mapping table and forwarding table via OpenFlow, the OFA virtualizes the resources of the OPS node (ports and links, etc.), and translates the OpenFlow protocol messages into commands that can be understood by the OPS node, thus enabling the communication between the Controller and the OPS node through message exchange and protocol translation in the OFA.

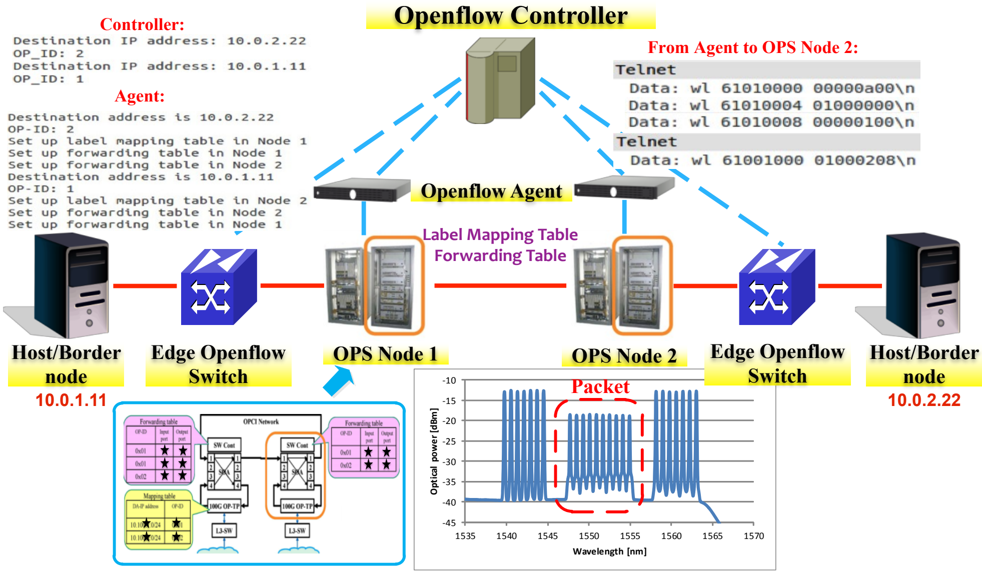


Figure 15: OpenFlow-controlled OPS network

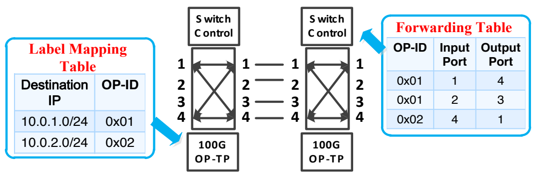


Figure 16: OPS node structure

Due to the flow-based OpenFlow control, incoming packets are classified and aggregated into flows at the host/border node. When Edge OpenFlow switch finds a packet with no match against the Flow-table (typically the case for the first packet in a new flow), it forwards the packet-in message to the OpenFlow controller. The OpenFlow controller would then process the packet-in message, calculate the route and assign the incoming packet with an OP-ID according to its destination IP address. Afterwards, the Controller sends out Flowtable modification messages to the OFAs and Edge OpenFlow switches in order to set up Flow-tables. OpenFlow protocol is extended to include OP-ID information in the Flowtable modification messages. Whenever OFA receives a request from the Controller for Flow-table modification, it abstracts the corresponding information (OP-ID, ports, etc.) and translates it into standard CLI commands, which are later sent to the OPS node for table configurations (label-mapping table and forwarding table).

The experimental results of the demonstration are shown in Figure 15 as well. The demonstrated OpenFlow-controlled OPS network comprised of an OpenFlow controller, two OPCI nodes with corresponding OFAs, the attached host nodes and edge OpenFlow switches. Traffic were generated between two host nodes (IP address were 10.0.1.11 and 10.0.2.22 respectively). The OP-ID assignment process and table set up information were shown in the figure, as well as the commands sent from OFA to OPCI nodes. The optical spectrum of the transmitted packets (the middle waveband) was also shown in the figure (the side bands were OCS signals transmitted through the OCS module of the OPCI nodes).

3.2 Implementation, integration and demonstration

The integration and demonstration plan of the Japanese test-bed is listed in the following table including the due-date for the different tasks:

Table 7: Implementation, integration and demonstration plans for Japanese test-bed

MODULE	FEATURE	DEADLINE
OPS router	label detector designing	M15
	buffer manager designing	M17
	FDL buffer implementation	M19
	SW driver implementation	M19
	first stage OPS router prototype	M22
	OpenFlow support	M25
	second stage OPS router prototype	M30
DMT transceiver	Basic configuration	M15
	Distance enhancement up to 40 km	M22
	OpenFlow support	M25
OpenFlow Controller	OPCI router support	M15(TBD)
	OPS router support	M25
	DMT transponder support	M25
Large-scale demonstration	connectivity of OPS router with OPCI router	M25
	OpenFlow-based OPS network demo. in JGN-X test-bed in NICT	M27 (TBD)
	JGN-X connection	M30

4 Intercontinental EU-Japan test-bed

4.1 OPS/OCS integrated network test-bed

4.1.1 Overall prototype description

The OPS/OCS integrated network test-bed located in Japan and Europe, to provide an integrated solution from an overall system perspective. The Japan partners will provide a strong expertise and experience in OPS technology. The test-bed in Japan will focus on optical packet switching technology to provide a solution to ultrafast, energy- and resource-efficient data transport. OPS can provide times-sliced sub-wavelength logical path preferably in metro area network (MAN) and intra data center network. While the EU partners will focus on Elastic Optical Network (EON) to adopt the flexi-grid, which uses 12.5GHz spectrum slices for adaptively allocating bandwidth variable connections and, thus, improves the spectrum usage. With the advance of OPS and OCS technologies, an end-to-end Ethernet service provisioning and orchestration across multiple domains with heterogeneous transport and control plane technologies will be demonstrated for variable application scenarios.

Several key technologies will be involved in the overall prototype.

- Sliceable, variable-bandwidth transceiver technologies
- DMT based single wavelength 100G transceiver technologies including distortion compensation and optical performance monitoring techniques using DSP
- Sliceable, bandwidth and bitrate variable Optical OFDM transceiver
- Flexible/adaptable optical nodes for flexi-grid DWDM networks
- Based on the AoD concept, flexible/adaptable optical nodes are achieved with an optical back plane based on large-port-number fiber switch. All the available hardware resources are connected to and managed by the back plane. According to the network requests, the optical node can synthesis its architecture to provide requested functions and interconnections. When a dramatic change of network request occurs, the optical nodes can adopt new structure to fulfill new requests. The online reconfiguration of the flexible/adaptable node enables network resource rebalance and network optimization.
- Optical packet switching technology and integrated interface
- The integrated interface converts the OPS data streams to OCS domain and loads the data to a software defined bandwidth variable transceiver (BVT), to forma a super-channel signal. The integrated OPS/OCS interface is critical components which bridge multiple domains to enable an end-to-end Ethernet transparency.

4.1.2 Integration and demonstration Plans

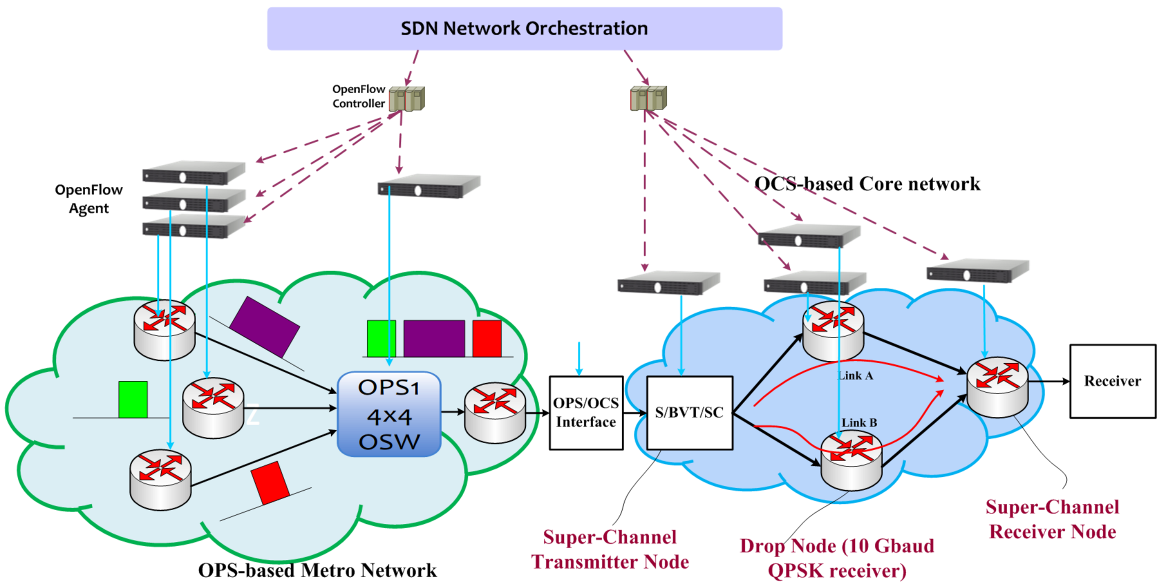


Figure 17 Integration and demonstration plan of OPS/OCS integrated test-bed

The integration plan of OPS/OCS integrated test-bed is shown in Figure 17. In the OPS side, 100Gb/s-class DMT packet transmitter (DMT-TX) is developed which exploits its flexibility to generate fixed-length distance-adaptive optical packet. The packet length is fixed to ease the buffer scheduling algorithm while 1024 sub-carriers in each payload are adaptively modulated to maximize the payload capacity according to the transmission distance. The flow control technique in OF naturally fits to such variable-capacity OPS. The OF controller informs DMT-Tx of the possible routes to the destination, and DMT-Tx determines the bit rate for a given distance. The intermediate OPS node switches the packets according to the OF-enabled switching (SW) table.

The integrated OPS/OCS interface will act as a bridge to connect the OPS domain and OCS domain. The OPS data streams are converted to OCS domain. After grooming and aggregating in the OPS/OCS converter, the OCS data will be modulated to several sub-carriers by bandwidth variable transmitters (BVT) to achieve a capacity tunable super-channel signals. The super-channel signal can be reconfigurable in total bandwidth, modulation formats, thus to change the total capacity.

In the OCS networks, elastic optical networks will be setup with flexible/adaptable optical nodes. The super-channel signals will transfer through elastic optical networks and dropped at destination node.

Due to the physical limits, we don't have direct connections between EU test-beds and Japan test-beds. An Ethernet traffic generator will be used to simulate the link between OPS and OCS domains by regenerating the offline data to Ethernet traffic.

Several key functions will be implemented and demonstrated in joint experiments in EU and Japan as bellows:

OPS side:

- Packet forwarding algorithm for the OpenFlow-based OPS network domain.
- Joint experiment by using the variable bandwidth transponders in EU and JP.

OCS side:

- Demonstration 1: ROADM structure reconfigurable: broadcast-select to select-route
- Demonstration 2: Arbitrary wavelength slot (super-channel signals) drop and add operation.

OPS/OCS interface:

- Demonstration 1: Real-time OPS packet to OCS converter based on High-performance FPGA with aggregating function. 10Gbit's OPS packet (Ethernet signals) will be converted to 20Gbuad 16QAM or QPSK signal in OCS side.
- Demonstration 2: Supper channel signal assembling. Several channels will be assembled to super-channel signals for future large bandwidth Ethernet, for example 1Tbit/s Ethernet. Flexile signal assembling will be demonstrated.

MODULE	FEATURE	DEADLINE
ROADM structure reconfigurable demo	Online reconfigure structure of ROADM: Broad-select to select-route	M24
Arbitrary wavelength slot dropping and adding	Arbitrary wavelength band operation tested with super-channel signals	M24
Real-time OPS/OCS converter	10Gbit/s input to 20Gbaud QPSK/16QAM signals	M24
Super-channel signals assembling	Total capacity from 300Gbit/s to 1Tbit/s	M24
Packet forwarding algorithm	the OpenFlow-based OPS network domain	M25
Joint experiment in EU and JP	by using the variable bandwidth transponders	M22

4.1.3 Preliminary tests

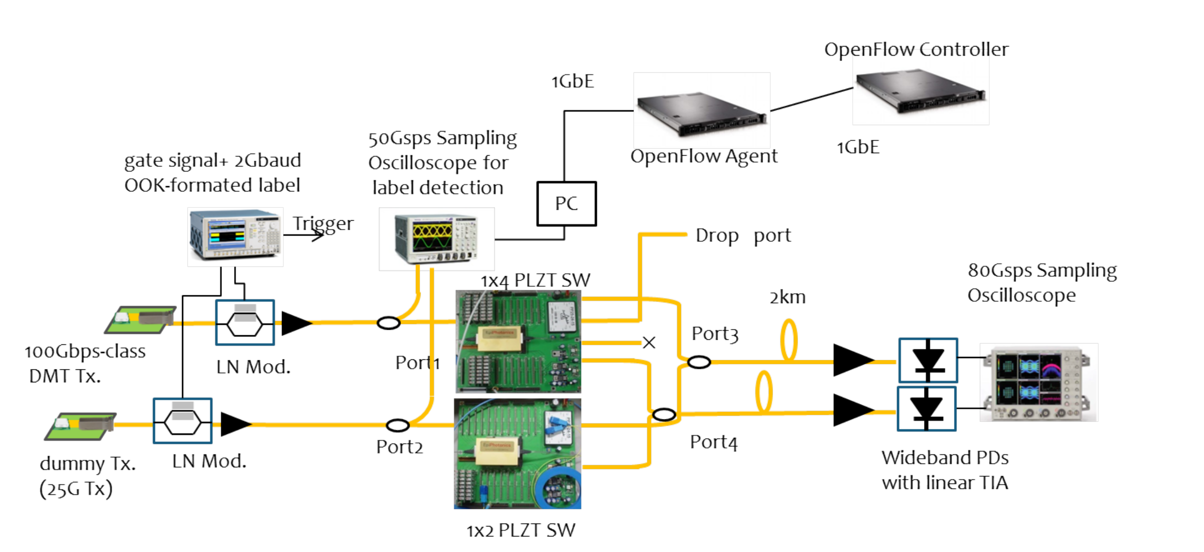


Figure 18 100Gbps-class DMT-based OPS test-bed prototype with OpenFlow controll

The DMT-based OPS test-bed prototype is shown in Figure 20 Elastic optical network based on flexible/adaptable optical nodes. Some preliminary results are shown in Figure 19.

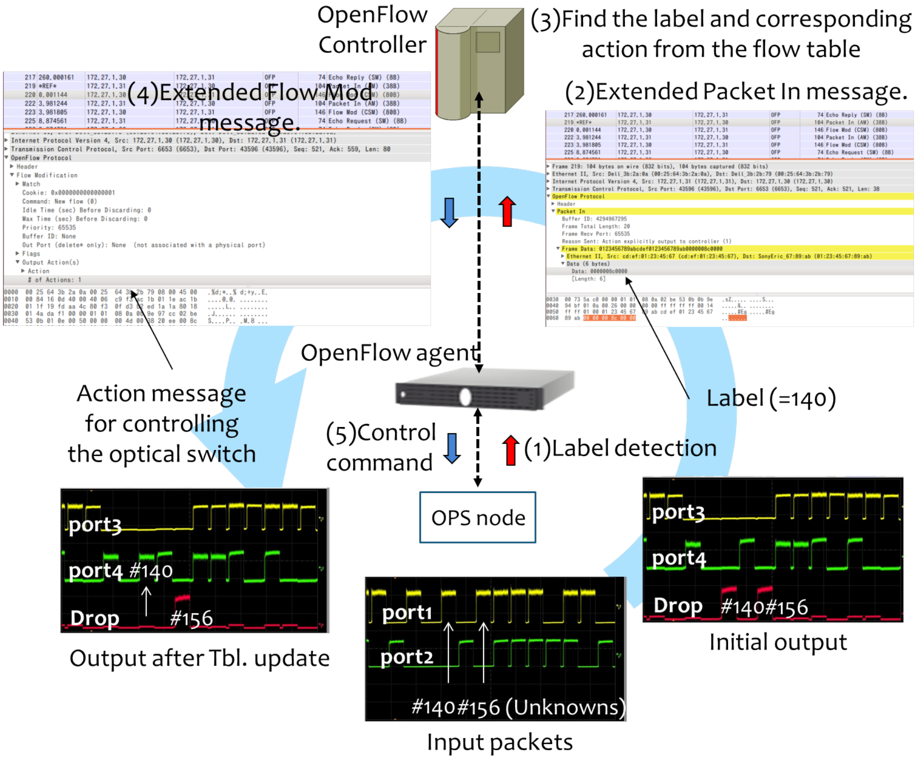


Figure 19 Demonstration of the flow assignment in OpenFlow-based OPS

In OCS side, we setup elastic optical networks with four AoD-based optical nodes, which are based on several polatis beam steering fiber switches. The network topology is shown in Figure 20. The Node 1, based on architecture-on-demand (AoD) concept, reconfigure the capacity of BVT for different application scenarios.

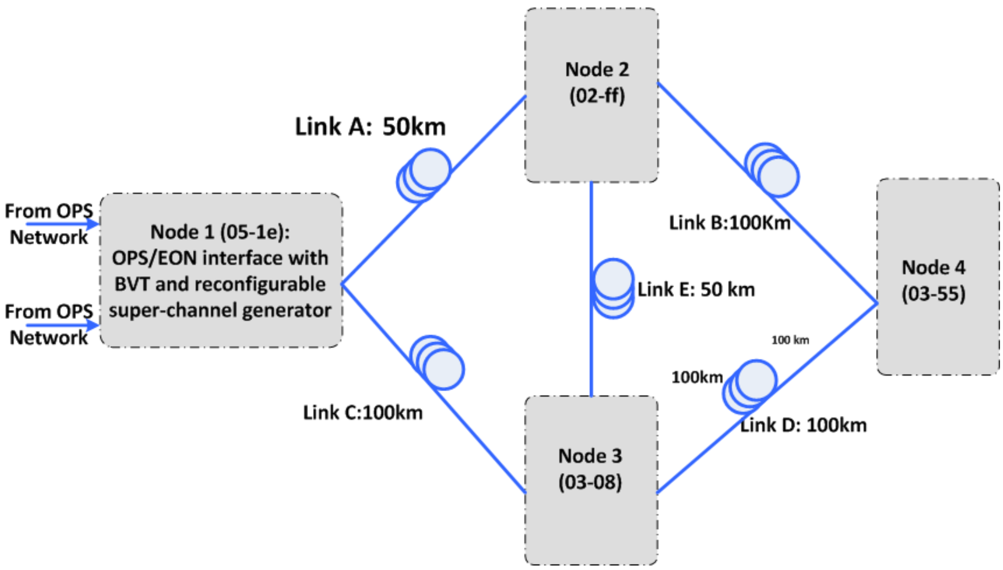


Figure 20 Elastic optical network based on flexible/adaptable optical nodes

The integrated OPS/OCS interface is implemented using high performance FPGA (HTG Xilinx V6 PCIE board), receive Ethernet traffic using multiple 10GE SPF+ modules, and then process and groom the traffic to drive a sliceable, programming BVT. The BVT can adopt 10Gbaud PM-QPSK, 20Gbaud QPSK or 20Gbaud 16QAM signal formats for variable scenarios. In one application scenario, we generate an 8-sub-carrier super-channel signal with modulation format programmability for each sub-carrier in a 50GHz grid, to provide bandwidth from 80Gbit/s to 1.28 Tbit/s and more flexibility.

4.2 SDN network architecture orchestration

In this section we propose an SDN Network Orchestration International Test-bed. The Network Orchestration will be performed by means of the Application Based Network Operations (ABNO) architecture, which has been previously described.

4.2.1 Overall prototype description

The ABNO Controller will be used to provide end-to-end network connectivity through several heterogeneous control domains. In Figure 21 an overall description of the EU/JP international test-bed is provided including each partner expected contributions. The test-bed consists of the integration of four heterogeneous control domains with an ABNO-based network orchestrator. Following it is described each partner contributed domain:

- Telefonica offers the ABNO controller to work as SDN orchestrator.
- KDDI provides an OpenFlow-enables OPS control domain.
- UNIVBRIS provides an OpenFlow-enabled Elastic Optical Network control domain, with a hybrid OPS/EON node.
- CTTC provides a GMPLS-enabled EON control domain.
- ADVA provides an OpenFlow-enabled EON control domain.

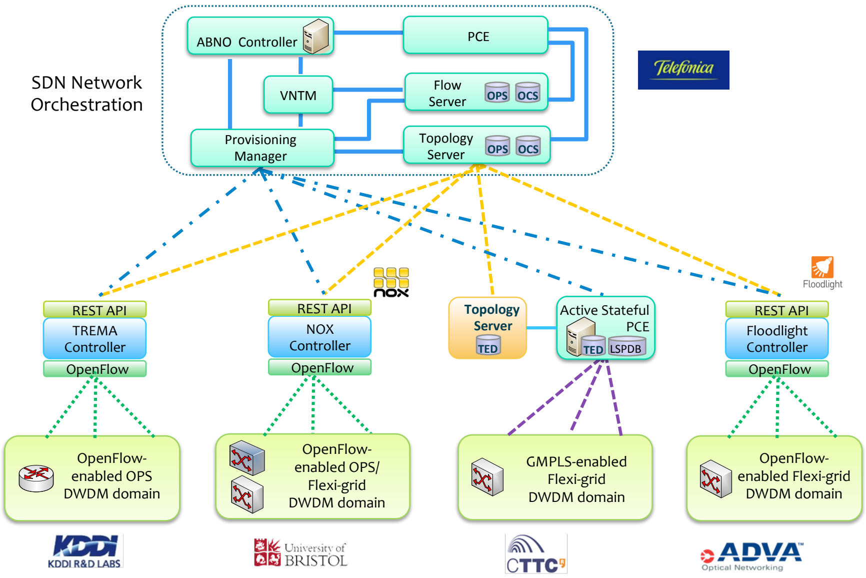


Figure 21: SDN network architecture orchestration through multi-layer/multi-technology domains

4.2.2 Implementation, integration and demonstration plans

The implementation plan for this activity is the following:

Table 8: SDN network architecture orchestrations implementation, integration and demonstration plans

MODULE	FEATURE	DEADLINE
Individual test-beds	KDDI, UNIVBRIS, CTTC, ADVA control domains	M24
Preliminary orchestrator implementation	TID ABNO components with the interfaces of each partner.	M25
Test-bed interconnection	OpenVPN for control message exchange	M26
Preliminary integration of WP3 control plane paradigms and orchestrator	Control Orchestration protocol validation	M28
Experimental validation of STRAUSS concepts in Europe	Control Orchestration protocol tests for EON domains.	M33
Final validation	Final validation including OPS/EON domains	M36

4.2.3 Preliminary tests

Preliminary tests on ABNO architecture have been presented as a post-deadline paper at Optical Fiber Communication Conference and Exposition (OFC) [Yoshida14].

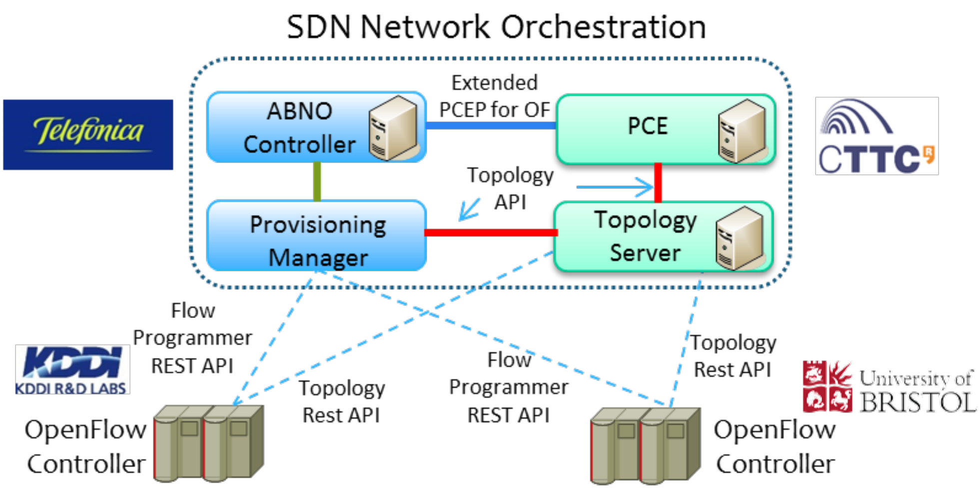


Figure 22: Orchestration in OF-based OPS-EON network demonstrator

The ABNO architecture has been proposed as a multi-technology and multi-domain network orchestration solution. The ABNO controller is the main component of the architecture and is responsible for controlling the workflows for both OF-controlled OPS and EON domains, which are run by KDDI and University of Bristol, respectively (Figure 22).

The Topology Server recovers the topology exposed by each OF controller North-Bound Interface (NBI), and it is fed both to the PCE and the Provisioning Manager. The PCE is the network element which handles the path computation across the network graph provided by the Topology Server (Figure 23) and it has been extended for OF [Vilalta13] (Figure 24).

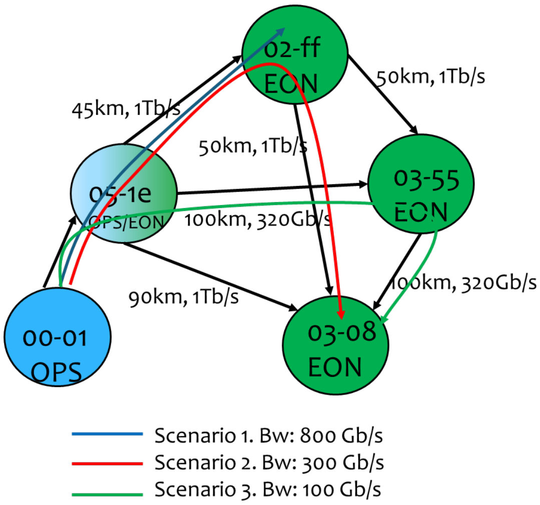


Figure 23: PCE network graph including OPS and EON domains

```
▷ PATH COMPUTATION REQUEST MESSAGE Header
▷ RP object
▽ END-POINT object
    Object Class: END-POINT OBJECT (4)
    1110 .... = Object Type: 14
  ▷ Flags
    Object Length: 20
    Source OF Address: 0x0000000000000001
    Destination OF Address: 0x0000000000000308
▷ BANDWIDTH object
▷ METRIC object
```

```
▷ PATH COMPUTATION REPLY MESSAGE Header
▷ RP object
▽ EXPLICIT ROUTE object (ERO)
    Object Class: EXPLICIT ROUTE OBJECT (ERO) (7)
    0001 .... = Object Type: 1
  ▷ Flags
    Object Length: 48
  ▽ SUBOBJECT: OpenFlow Unnumbered Interface ID: 0x1:3
      0... .... = L: Strict Hop (0)
      Length: 16
      Reserved: 0x0000
      SUBOBJECT: OPENFLOW Prefix
      Interface ID: 3 (0x00000003)
  ▽ SUBOBJECT: OpenFlow Unnumbered Interface ID: 0x51e:194
      0... .... = L: Strict Hop (0)
      Length: 16
      Reserved: 0x0000
      SUBOBJECT: OPENFLOW Prefix
      Interface ID: 194 (0x000000c2)
  ▽ SUBOBJECT: OPENFLOW Prefix: 0x308
      0... .... = L: Strict Hop (0)
      Length: 12
      SUBOBJECT: OPENFLOW Prefix
▷ OBJECTIVE FUNCTION object (OF)
▷ METRIC object
▷ METRIC object
▷ METRIC object
▷ LABELSET object
```

Figure 24: Wireshark capture of PCEP messages with OF end-point objects

The Provisioning Manager is responsible for the actual flow establishment request to the OF controllers through each specific controller's NBI. In Figure 25, the different messages exchanged are detailed.

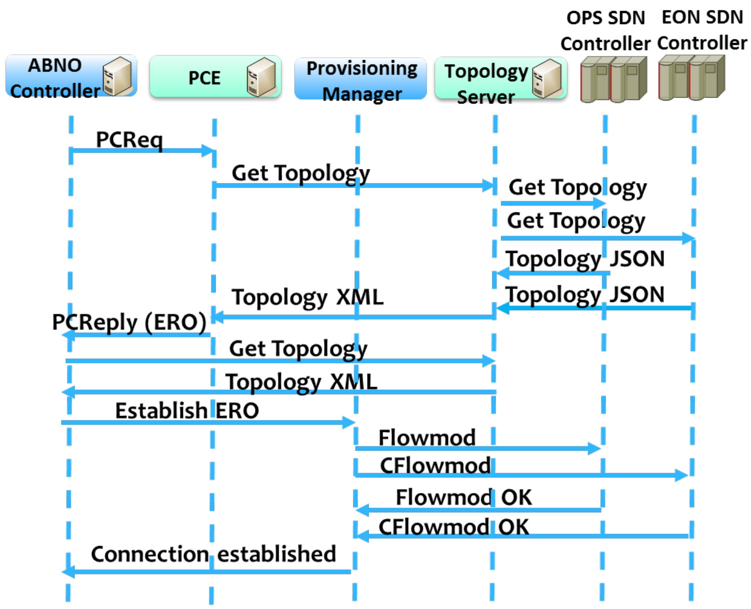


Figure 25: ABNO controller message exchange

We propose three different scenarios where an OPS node (00-01) is connected to EON through an OPS/EON edge node (05-1e), where OPS-EON interface card is placed.

In the first scenario, a bit rate of 800Gb/s for transporting aggregated OPS frames (each of them up to 108.2 Gb/s with a distance of 2km) is requested end-to-end. The PCE computes a path from node 00-01 to receiver at 02-ff. Then, the Provisioning Manager requests the required flow establishment towards each domain. At the reception of the flow request, the OPS OF controller assigns OPS label 140 to the output port connected to edge OPS/EON node. The EON OF controller calculates that 800Gb/s require 2 QPSK 4QAM sub-carriers, which are setup at the S-BVT by choosing the spectrum range and slots (i.e., 193.627-194.027 THz with 50GHz). The setup delay for this first scenario is around 26s (Figure 26). The setup delay has been decoupled in path computation time (including topology request, Tpce), OPS flow (Tops) and EON flow (Teon) setup delays.

The second scenario consists of an aggregated request of 300Gb/s from 00-01 to receiver at 03-08. The behavior of OPS OF controller is similar to the three scenarios, while the EON OF controller assigns 2QAM sub-carriers, which are setup at S-BVT, with a global setup delay of 34s.

Finally, the third scenario requests 100Gb/s, which on the EON requires 2QPSK sub-carriers. The setup delay is around 36s.

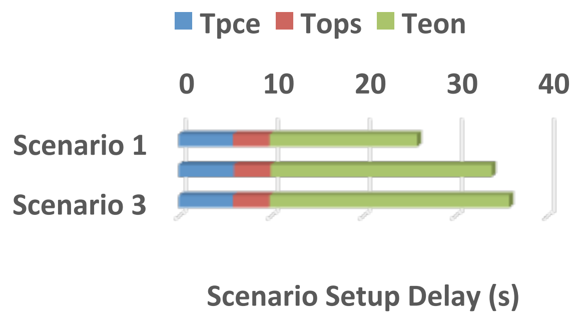


Figure 26: Scenarios Setup Delay (s)

4.3 Transport virtualization visor

4.3.1 Overall prototype description

The overall proposed virtualization architecture has been described in D3.1. The proposed Virtualization Visor (VV) system architecture (see Figure 27) provides a mechanism for virtualizing transport nodes and links. The partitioning of the resources is performed by the Network Virtualization Controller, and to this end, the proposed system architecture incorporates a generic network abstraction mechanism for the different transport infrastructure resources (e.g., OPS, EON).

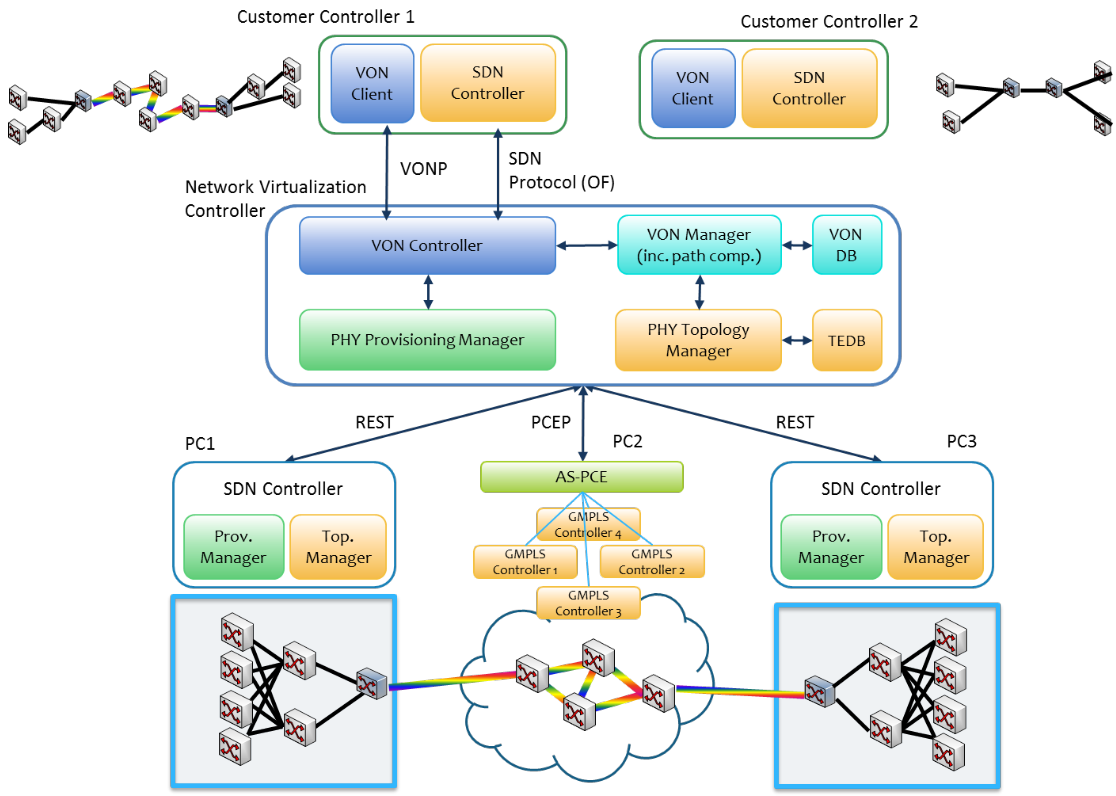


Figure 27: Virtualization Visor Architecture

A Customer Controller (CC) is an SDN Controller run by a VON customer upon a detailed VON request. The CC is responsible for controlling the requested VON. A CC shall issue a VON request during its initialization by means of VON Protocol to the Virtualization Composer.

A Network Virtualization Controller (NVC) is the central component of the VV architecture. The NVC is responsible for receiving VON request, processing them and allocate them. Moreover, the NVC is responsible for the resource abstraction, acting as a proxy of an SDN protocol (e.g., OpenFlow) between a CC and the required Physical Controllers (PC).

A Physical Controller (PC) is the centralized instance of control in charge of the physical infrastructure (i.e., SDN controller or AS-PCE). A PC is typically technology and vendor dependent, so the NVC shall implement different PC plugins. It is assumed that a PC is able at minimum to provide network topology and flow programming functionalities.

In Figure 28, the proposed international test-bed is shown. A NVC will be the responsible for providing the requested Virtual Optical Networks and offer them to the Customer Controller.

Three virtualization domains are expected:

- KDDI provides an OF-controlled OPS domain.
- CTTC provides a GMPLS-controlled EON domain.
- UNIVBRIS provides an OF-controlled EON domain.

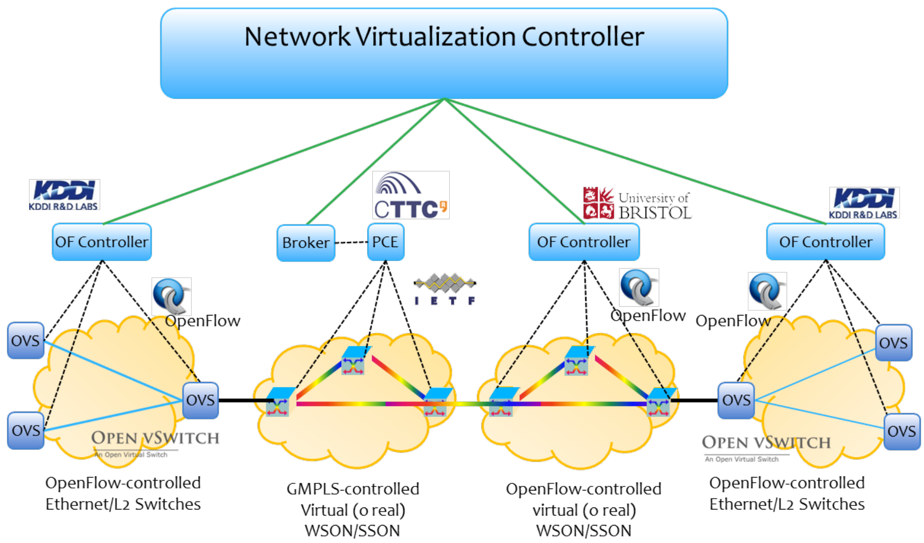


Figure 28: Intercontinental EU/JP Test-bed for Transport Virtualization

4.3.2 Implementation, integration and demonstration plans

The implementation plan for this activity is the following:

Table 9: Transport Virtualization implementation, integration and demonstration plans

MODULE	FEATURE	DEADLINE
Individual test-beds	KDDI, UNIVBRIS, CTTC, control domains	M24
Preliminary Virtualization	CTTC NVC	M25

Composer		
Test-bed interconnection	OpenVPN for control message exchange	M26
Preliminary integration of WP3 virtualization architecture	VON protocol validation	M28
Final validation	Final validation including OPS/EON domains	M36

4.3.3 Preliminary tests

Preliminary results the first version of the virtualization architecture has been presented as a regular paper at Optical Fiber Communication Conference and Exposition (OFC) [Vilalta14].

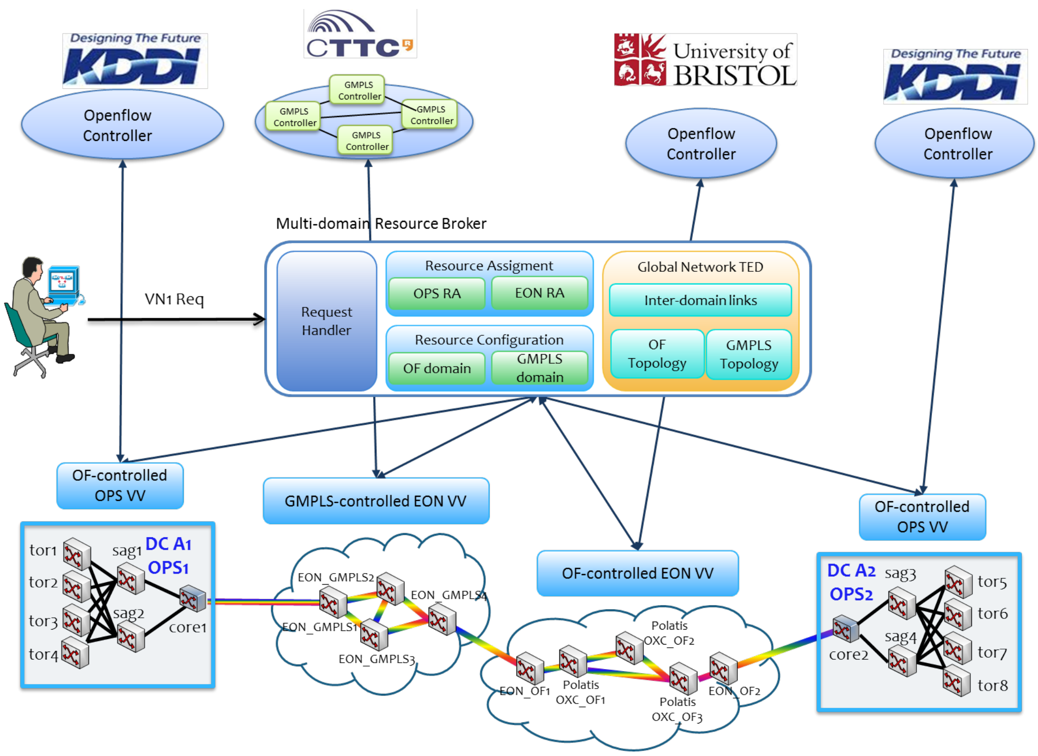


Figure 29: Virtualization Test-bed Architecture

In this paper, the authors have proposed a virtualization mechanism which allows the composition of Virtual Optical Networks (VON) across different transport technologies (i.e., OPS, EON) and control plane technologies (e.g., OpenFlow or GMPLS). The obtained VON domains can be controlled by GMPLS or OpenFlow (depending on the virtualization technology) and a service orchestration mechanism could be used to provide end-to-end connectivity.

The proposed Multi-domain Resource Broker (MRB) system architecture provides a mechanism for virtualizing transport nodes and links. The partitioning of the resources is technology dependent, and to this end, the proposed system architecture incorporates a generic network slicing abstraction mechanism for the different transport infrastructure resources (e.g., OPS, EON).

Three different implementations of the network slicing abstraction mechanism have been proposed, with the purpose to provide a virtualization mechanism in GMPLS-controlled EON, OF-controlled EON and OF-controlled OPS.

The MRB controls the VON deployment by means of the different Virtualization Visors (VV) (Figure 29). These VV are responsible for the virtualization of optical infrastructure domains. Each proposed VV partitions each domain resources (i.e. links and nodes) into virtual optical resources. Later, the obtained virtual optical resources are composed into actual VONs, controlled by either a GMPLS or an OpenFlow control plane, assigned by each VV.

The MRB consists of four main components:

- Request handler
- Resource assignment
- Resource configurator
- Global network TED

The request handler accepts VON requests from a client, using incoming TCP sessions for the reliable delivery, and handles these requests asynchronously and dynamically. A VON Request consists of a XML file, describing the requested virtual nodes, the requested virtual links between these nodes and the required minimum guaranteed bandwidth. For each VON setup request a VON identifier (VON-ID) is assigned. The VON-ID will be used by the MRB to map the assigned resources in each domain to the VON request.

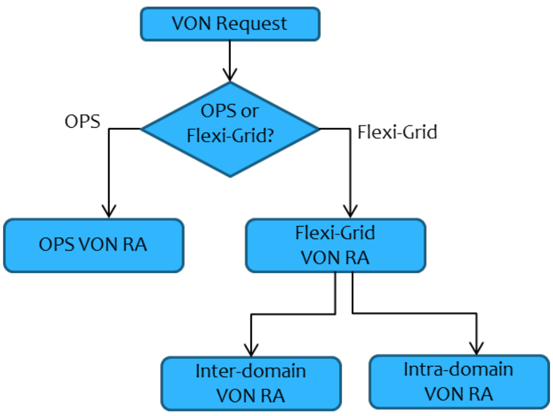


Figure 30: Virtual network allocation algorithm

Resource assignment algorithms need to be introduced, focusing on the optimal planning (i.e., off-line) or the dynamic request allocation (i.e., on-line) of VON requests. We have developed an algorithm bundle (Figure 30), including several algorithms designed for different scenarios (i.e., single/multi-domain flexi-grid, OPS). The algorithm bundle reads the information of physical networks (e.g., the network topology and the availability of physical resources of each domain, such as ports or spectrum slots, and the inter-domain connectivity) from the global network TED, which is the infrastructure resource database and contains all the necessary information on the virtualized resources, such as spectrum availability or virtual control resources, as well as the status of the inter-domain links, and is obtained from a local XML file, although a topology discovery mechanism for VV is expected (e.g., topology server, BGP-LS [Cuaresma13]). Taking into account the above inputs and optical constraints (i.e., spectrum continuity), the algorithm bundle will compose a VON that can satisfy the user's request and optimize the physical resource utilization.

A Multi-Domain Shortest Path First-Fit Spectrum Allocation algorithm is used to find a physical path for each virtual link (Figure 30). To satisfy the Spectrum Continuity Constraint (SCC), an available first-fit Frequency Slot (FS) with the requested bandwidth is located among all the available spectrum slots for the whole multi-domain EON topology. After running the algorithm bundle, all the involved network resources for configuring the flexi-grid equipment are generated as outputs and sent to the corresponding VVs. The OF VV consists on an OpenFlow FlowVisor, while the GMPLS VV consists on a previously proposed Resource Broker for deploying virtual GMPLS-controlled elastic optical networks.

To experimentally evaluate the proposed virtualization architecture, we built a heterogeneous multi-domain international test-bed comprising an EON domain in the High Performance Networks group at University of Bristol (UK), a layer 2 optical packet switched domain in KDDI R&D Labs (Japan) and an EON domain in CTTC (Spain) as shown in Figure 29.

The University of Bristol test-bed is comprised of an in-house built 8x8 (4x4 bidirectional) BV-OXC utilizing two BV-WSS switches with internal recirculation fiber loops to emulate multiple nodes; a BV transponder (BV-TX & BV-RX) supporting C-band and 3 OpenFlow-enabled Polatis fiber switches. The CTTC GMPLS control plane platform of the ADRENALINE Test-bed includes 14 nodes that run GMPLS Controllers with emulated EON hardware. A packet-based emulated network with a DC network topology (including ToR, aggregation and distribution layers) has been deployed in KDDI. The international connectivity between the MBR and the different VV running on each test-bed is provisioned over VPN Tunnels over Internet.

Figure 31 shows the message exchanges between the MRB and the different network elements responsible to setup a virtual network. A user creates a virtual network request (VN1) which might imply several domains, and sends it to the MRB via XML interface. The MRB runs the proposed algorithm and for each required domain contacts the required VV. In the example shown, an OF-controlled EON VV and a GMPLS-controlled EON VV are contacted.

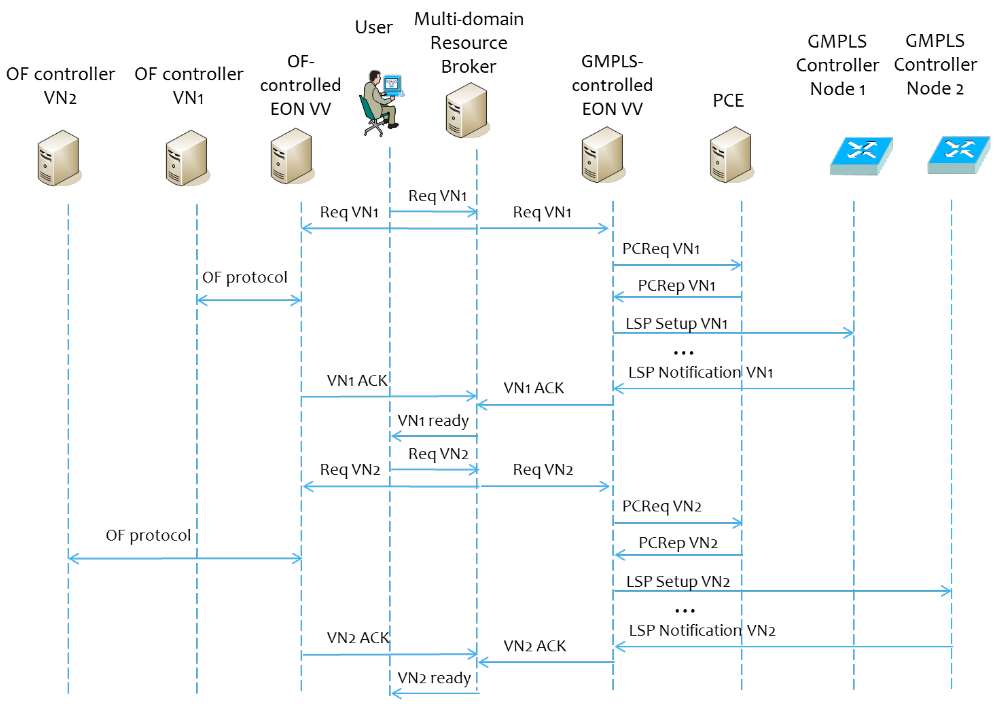


Figure 31: Multi-domain resource broker message exchange

The OF-controlled EON VV corresponds to an optical Flowvisor, so the VV uses the XML-RPC API to create the required slices through the definition of the required flow-spaces for each slice.

The GMPLS-controlled EON VV is requested via a proprietary interface which has been previously described. Once the different VVs notify that the virtual resources for VN1 have been allocated (VN1 ACK), the user is notified with the assigned resources (VN1 ready).

Table 10: Example of VN1assigned slices

VN1	Assigned slice
tor1 – tor5	tor1-sag1-core1-eon_gmpls1-eon_gmpls2-eon_gmpls4-eon_of1-Polatis_OXC_OF1-Polatis_OXC_OF3-eon_of2-core2-sag3-tor5
tor5- tor4	tor5-sag3-core2-eon_of2-eon_of2-Polatis_OXC_OF3-Polatis_OXC_OF1-eon_of1-eon_gmpls4-eon_gmpls2-eon_gmpls1-core1-sag2-tor4

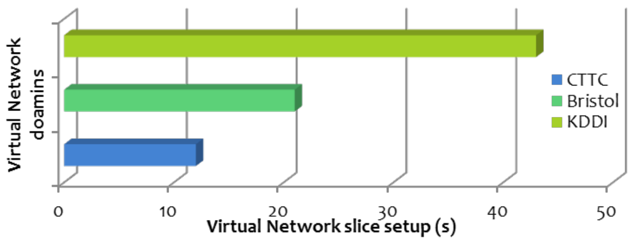


Figure 32: Virtual Network Domains slice setup time (s)

Table 10 shows an example of assigned slices to a Virtual Optical Network. Figure 32 shows the results that were obtained to verify the functionalities of the proposed MRB architecture for different network domains (alternating CTTC, University of Bristol and KDDI domains). The VON Domain slice setup time is affected significantly by control plane VPN delay as well as the communication method between each OF agent or GMPLS controller and its corresponding NE. The different VON domain slice setup times can be easily explained by the fact that different VV using different technologies where used in each domain. Also the different intra-domain network topologies explain the obtained results, which are tightly coupled with each intra-domain topology. It is also remarkable the need for a faster interface towards FlowVisor, where several requests for different flow-spaces could be grouped allowing faster VON domains slice setup times.

5 Conclusions

This document contains a description of the plans and a preliminary description of the experimental activities done in the project. Moreover, it reports the work that has been done in terms of implementation, integration and demonstration activities that has lead to high impact publications in the first year of the project.

There are three main join activities planned for the project: (1) OPS/OCS integrated network test-bed, (2) SDN network architecture orchestration and (3) Transport virtualization visor. Based on the test-bed from each partner and the plans, a summary of the participation of the partners in the activities is presented in Table 11:

Table 11: Per-partner activity summary table

Joint activities	ADVA	CTTC	FUJITSU	KDDI	OSAKAU	TID	UNIVBRIS
OPS/OCS integrated network test-bed			X		X		X
SDN network architecture orchestration	X	X		X		X	X
Transport virtualization visor		X		X			X

The objectives defined for this year in WP4 were the following:

1. Japan Test-bed: Discrete Multi-Tone Transceiver Demonstrator.
   - O4.1: First trial of the FPGA implementation for DMT transceiver demonstrator.
   - O4.2: Preliminary implementation, integration and demonstration plan for preparing DMT transceiver demonstrator.
2. EU Test-bed: Flexi-grid demonstrator
   - O4.3: Preliminary implementation, integration and demonstration plans for Flexi-grid data plane technologies.
   - O4.4: Preliminary implementation, integration and demonstration plans covering the SDN orchestrator, the OpenFlow controllers and the COP agents connecting to the orchestrator.
   - O4.5: Preliminary implementation, integration and demonstration plans for virtualization Composer and Partitioner for Single domain virtual resource allocation.
3. EU-Japan Test-bed:
   - O4.6: Preliminary implementation, integration and demonstration plan for the control plane interconnection of the test-beds.

Based on the information presented on this document, the STRAUSS project can claim that the objectives for this work-package have been fulfill in the first year.

6 List of acronyms

BGP-LS	Border Gateway Protocol- Link State
BV-OXC	Bandwidth Variable – Optical Cross-Connect
COP	Control Orchestration Protocol
GMPLS	Generalized Multiprotocol Label Switching
NE	Network Element
OCS	Optical Circuit Switching
OCS	Optical Circuit Switching
OF	OpenFlow
OFS	OpenFlow switch
ONF	Open Networking Foundation
OPEX	Operational Expenditures
OPS	Optical Packet Switching
OPS	Optical Packet Switching
OFDM	Orthogonal Frequency Division Multiplexing
PCE	Path Computation Element
QoS	Quality of Service
SDN	Software Defined Networks
TED	Traffic Engineering Database
VC	Virtualization Composer
VON	Virtual Overlay Network
VP	Virtualization Partitioner
WDM	Wavelength Division Multiplexing
XML	Extensible Markup Language

7 References

All the reference material and the list of acronyms have to be listed in alphabetic order.

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8 Document History

Version	Date	Authors	Comment
0.01	15/04/2013	TID	Proposed ToC of the document
0.5	30/04/2013	WP4 members	Modification in the ToC after calls and discussion
0.8	9/05/2014	WP4 members	Contributions to the individual test-bed section
1.0	14/05/2014	TID	Editorial work and integration of the contributions
1.5	16/05/2014	WP4 members	Contributions to the intercontinental test-bed sections
2.0	20/05/2014	TID	Editorial work, abstract and conclusions description version
2.5	23/05/2014	WP4 members	Section Review and modifications in the preliminary version
3.0	25/5/2014	TID	Final version