METRO-HAUL

METRO High bandwidth, 5G Application-aware optical network, with edge storage, compute and low latency

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Selection of metro node architectures and optical technology options

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Abstract

D3.1 reports details of the Metro Node and Optical Network Elements architectures together with the relevant design guidelines for the access-metro and metro-core edge nodes, as well as the WDM transport systems. The design guidelines and specifications for the technical implementations to be undertaken in WP4 and WP5 are reported, together with a complete outline of the activities undertaken in WP3 during the first year of the METRO-HAUL project.

[End of abstract]

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Executive Summary

The overall METRO-HAUL objective is to architect and design cost-effective, energy-efficient, agile and programmable metro networks that are scalable for 5G access and future requirements, encompassing the design of all-optical metro nodes (including full compute and storage capabilities), which interface effectively with both 5G access and multi-Tbit/s elastic core networks.

This deliverable D3.1 "Selection of metro node architectures and optical technology options" presents and discusses the most relevant options for WDM transport systems when considering METRO-HAUL requirements. The background context to much of the work being conducted within WP3 of the METRO-HAUL project is "disaggregation", which is a general approach to reduce CapEx and OpEx by exploiting the economies of scale occasioned by a number of longer- and shorter-term trends.

The disaggregation approach is that of sourcing HW directly and in sizeable volumes from original design manufacturers (ODMs), and selectively exploiting / adapting free and open source software. Network Operators are moving into the disaggregation direction, particularly by placing great emphasis on the virtualization of application layer network functions (core and edge). Operators are consolidating these into large central data centers and taking advantage of the well-established infrastructural technologies of data centers to house functions that were once assigned to HW dedicated devices and SWs.

Network operators are also now preparing to meet requests for computing, storage and networking capabilities from a diverse and heterogeneous set of new services by vertical actors interested in the introduction of automation, integrated control systems, distributed intelligence and new services to customers. Central Offices (COs) are therefore being transformed into data centers of a size and scalability appropriate to local needs, consolidating not only the computing resources but also those infrastructures dedicated to optical transport and access. In this respect, the CORD (CO Re-architected as a Data Center) initiative is of particular relevance.

The possibility of extending disaggregation to optical devices is also now emerging as a research topic, as a means to reduce initial and operational costs. However, the heterogeneous nature of optical metro networking, in particular regarding the metro-access segment, means that a single transmission technology is not expected to be adequate for all situations. Flexibility, transmission performance, scalability and low cost must therefore all be optimized in separate scenarios, therefore leading to potentially distinct technical solutions.

As such, descriptions of the large set of activities currently underway in WP3 are given in this document, dedicated to the development, design and investigation of the many possible technology solutions targeting low cost and / or high performance metro optical transmission. They cover the entire scope of the WDM metro network: from the flexible interfacing with the access segment, to the WDM metro transport infrastructure; from a general framework for monitoring and data analytics (MDA), to the design of an entire small miniaturized CO with all the needed functionalities.

The general METRO-HAUL metro network infrastructural framework is described in some detail, including a discussion on the next-generation of Central Office architectures. This is based on a modular approach, supporting: virtualization of almost all the functionalities traditionally implemented with several dedicated network appliances; the presence of computing and storage resources effectively integrated with packet and optical networking resources; and the support of disaggregation and vendor-neutral optical white boxes.

This document includes also the preliminary METRO-HAUL technologies and solutions for next generation optical metro nodes and interfaces. Nodes solutions include both WSS-based ROADMs and blockers enhanced with YANG modelling as well as innovative photonic integrated switch prototypes. Metro-haul interfaces, designed for high programmability and YANG modelling, include prototypes based on Multicarrier Modulation (MCM), dispersion-tolerant direct detection, low resolution DAC and ADCs for metro networks, and coherent solutions for filterless networks. These nodes and interface solutions under investigation have been proposed to properly address the multiple different requirements and scenarios of next generation metro networks, which vary according to the target size of the metro-regional network (e.g., small, medium and large), the topology (horseshoe, ring or mesh), the architecture (filtered or filterless), and the integration solutions with core/access segments (specifically discussed through programmable packet and control solutions).

A wide range of modulation formats are available and the selection of the best modulation format to deploy depending on the specific requirements of each network is also discussed in this report. For networks carrying relatively small amounts of data, modulation formats based on direct-detection should still lead to the most cost-efficient transmission solution. On the other hand, higher traffic requirements may lead to the adoption of modulation formats based on coherent-detection, which are also more cost-effective in meeting the expected traffic growth for an extended period of time. The node architecture will also impact considerably the cost and capacity of METRO-HAUL networks. While very simple filterless architectures based on splitters and combiners may be the most cost-efficient approach for small ring-based networks, their use in longer, more meshed networks may entail severe limitations. In this case, node structures with filtering capabilities (employing fixed-filters, band-filters or wavelength selective switches) may be a more efficient alternative as, besides potentially enabling a higher network capacity, they also grant higher levels of flexibility and re-configurability.

Within the project, a monitoring and data analytics (MDA) framework is also considered, to collect monitoring data from optical and packet devices. Specifically, MDA agents run close to the network nodes and collect monitoring data records from configured observation points in the nodes. Monitoring data can be locally analyzed in the MDA agent and can be used to tune parameters in the network devices and to notify the MDA controller about network anomalies and degradations. The MDA agent has been conceived to support multilayer disaggregated scenarios and can collect monitoring data from one or more nodes. The specific measurements that can be obtained from the different optical devices considered in the project, as well as from passive monitoring probes at the packet layer are detailed. In addition, applications of monitoring at the optical layer are presented.

Overall, this report describes a disaggregated but ordered approach to metro networking design, with functional and technological modules that can be integrated like a “Lego” kit, and that can be controlled and managed with SW unified modules.

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1 Introduction

This document D3.1 “Selection of metro node architectures and optical technology options” describes the results of the first year’s activity within Work Package 3, “Metro Node and Optical Transmission Solutions” in the METRO-HAUL project. It identifies and reports the context ("framework") for the design and planning of optical WDM metro networks suitable for supporting 5G access networking and its expected requirements. This framework takes the form of a metro-centric architectural vision focused on the so-called “disaggregation” approach that has been pushed down to the optical level. This deliverable reports on the infrastructural point of view with respect to metro node architectures, and is complemented by the companion document D4.1, “METRO-HAUL Control and Management Requirements and Framework” [1], which provides an in-depth overview of the associated control and management aspects.

The identification of a limited set of relevant interfaces to ensure optical and control / management compatibility within the disaggregated solution creates the framework for our optical WDM metro network design. For each interface and for the metro Central Offices (COs) as a whole, we also offer design guidelines and specifications, with the degree of associated detail depending on the maturity of each technology considered.

This D3.1 deliverable also provides necessarily short but complete descriptions of the large set of activities currently underway in METRO-HAUL dedicated to the development, design and investigation of the many possible technology solutions targeting low cost and / or high performance metro optical transmission. They cover the entire scope of the WDM metro network: from the flexible interfacing with the access segment, to the WDM metro transport infrastructure; from a general framework for monitoring and data analytics (MDA), to the design of an entire small miniaturized CO with all the needed functionalities.

As mentioned earlier, the common background context to much of the work described here is "disaggregation", which is a general approach to reduce CapEx and OpEx by exploiting the economies of scale occasioned by the confluence of several trends, some of which have only appeared relatively recently, while others are more long-term in nature. In particular, these trends include:

• The continued validity of Moore's Law, with a consequent increase in processing densities in the hardware elements of semiconductors (CPU, memory, ASIC switching, etc.) with considerable on-going decrease in size, cost, and energy consumption of HW chips dedicated to very complex functions;

• The presence in the market of general-purpose equipment at relatively low cost and with high performance ("i.e. Commercial Off the shelf" HW - COTS), that is flexible enough to cover many of the needs of computing, storage and L2 / 3 networking;

• The separation of the operating system software that controls and manages the storage, processing and networking elements from the HW (often COTS); i.e. the Software Defined Networking (SDN) approach;

• The emergence of Open Programming Interfaces (OpenAPI) that abstract the complexity of the underlying hardware;

• The ability to functionally abstract many network and application functions, identifying their essential characteristics and separating them from effective HW implementation; i.e. Network Functional Virtualization (NFV).

The trend toward “disaggregation” originally began in the world of “Hyperscale Operators” (Facebook, Amazon, Microsoft, Google and Apple) within their large data centers, concerning the associated networking aspects and efficient management of the offered services. The process continued by involving the infrastructural networks between data centers in terms of the level 2-3 functions, and then more recently has also started to involve optical transport for data center interconnection and more.

The disaggregation approach is that of sourcing HW directly and in sizeable volumes from the original design manufacturers (ODM), and then selectively exploiting and adapting free and open source software. The pure “bare metal” model (the ODMs physical HW being sourced separately from the SW operating system) is one of the approaches employed mainly for computing infrastructure and for packet switching fabrics. Whereas a “white box” approach, where the ODM pre-installs an operating system of choice and provides some level of support to the operator, is another common option (see, for example, reference [2] for details).

Network Operators are therefore also moving in the same direction; in particular by placing great emphasis on the virtualization of application layer network functions (core and edge). Operators are consolidating these into large central data centers (at least for all those functions that do not have latency problems), and taking advantage of the possibility of using well-established infrastructural technologies typical of data centers to house functions that were once assigned to HW dedicated devices and SWs.

In addition, network operators are also now preparing to meet requests for computing, storage and networking capabilities from a diverse and heterogeneous set of new services by vertical actors interested in the introduction of automation, integrated control systems, distributed intelligence and new services to customers, to be activated quickly and on-demand in industrial sectors different from that of telecommunications. Telecommunications Operators are looking with great interest at these new opportunities, and responding with an intense programme of work towards the standardization, research and deployment of new (5G) access technologies, and new efficient and flexible network infrastructures that are suitable to meet these new requirements.

In this heterogeneous context, the need to host distributed, maybe widespread and peripheral computing resources is also expected. This is leading to extending the concept of data centers to mini- and micro-infrastructures being placed within metro COs. Concurrently, there is also a need for metro optical transport infrastructure interconnection COs, that combine flexibility, efficiency, scalability and low cost requirements.

The extension of the concept of disaggregation is therefore emerging as one of the most interesting and promising approaches in metro networking. Local Exchanges (i.e. COs) can be transformed into data centers of a size and scalability appropriate to local needs, consolidating not only the computing resources but also those infrastructures dedicated to optical transport and access. In this respect, the CORD (CO Re-architected as a Data Center) initiative is also therefore very promising [3].

Moreover, the possibility of also extending the disaggregation to optical devices is now emerging as a solution to be explored in greater depth, so as to reduce initial and operational costs. However, given the heterogeneous nature of optical metro networking, in particular regarding the metro-access segment (which can involve extremely high-density urban areas and regional low-density population areas), a single transmission technology is not expected to be adequate for all situations. Flexibility, transmission performance, scalability and low cost must therefore all be optimized in separate scenarios, therefore leading to potentially distinct technical solutions.

However, everything must remain within a smoothly evolving framework so as to allow straightforward integration of the individual parts. The aim is therefore to lead to a disaggregated but ordered approach with potentially distinct functional and technological modules that can be integrated like a "Lego" kit, and that can be controlled and managed with SW unified modules.

METRO-HAUL is therefore an important contributor into the disaggregation context by trying, on the one hand, to explore the scope of optical disaggregation for enabling smoothly-evolved solutions independent of the transmission technologies used (for example, a few control models suitable for general use; a common unified framework for monitoring, etc.); whilst on the other hand, it is also proposing and exploring low-cost optical technologies optimized for the various network segments.

METRO-HAUL is an ambitious project conducting research into optical WDM metro networking technologies, and motivated to be synergistic and involved in the mutual exchange of results with other initiatives, including both standardization and open forum, where we aim to propose technology solutions and steer technical directions, as well as supporting and contributing to the evolution of existing solutions. The interest and leveraging of METRO-HAUL's implementations in CORD [3], ODTN [4], OpenCONFIG [5] and OpenROADM [6] is therefore also to be understood in this respect.

METRO-HAUL is focusing primarily on the optical transport infrastructure, as we believe we can give particularly important contributions into this area, since the disaggregation and availability of low-cost solutions is a field where the appropriate research and innovation are still very much needed.

This D3.1 document is structured as follows:

Section 2 reports on three reference metro-regional networks provided by TIM, BT and Telefónica. They are described from a topological and architectural point of view, considering the amount and type of traffic to be transported at the present and into the future, taking into account the evolution towards 5G scenarios and new services. They are included as reference scenarios to test the METRO-HAUL architecture and solutions.

Section 3 outlines the general METRO-HAUL metro network infrastructural framework. It includes a discussion on the architectures of COs, suggesting guidelines for a modular approach in their design and assembly. There follows an in-depth analysis of disaggregation as applied to metro WDM optical transport systems, including design guidelines and interfaces specifications, whilst the general characteristics of "transport optical services" are also outlined. Finally, a list of the guidelines and specifications is also given to support the associated development activities related to the control / management SW in WP4 and integration in the METRO-HAUL demos of WP5.

Section 4 outlines the most relevant options for WDM transport systems when considering the METRO-HAUL requirements. A wide range of modulation formats are considered and the selection of the best modulation format to deploy on a specific network topology is discussed. The node architecture is also expected to impact considerably on the cost and capacity of METRO-HAUL networks. While very simple filterless architectures based on splitters and combiners may be the most cost-efficient approach for small ring-based networks, their use in longer, more meshed networks may entail severe limitations. In this case, node structures with filtering capabilities (employing fixed-filters, band-filters, or wavelength selective switches) may be a more efficient alternative.

Section 5 investigates the preliminary METRO-HAUL technologies and solutions for next generation optical metro nodes and interfaces. Solutions for optical switching technologies include both WSS-based ROADMs and wavelength blockers enhanced with YANG modelling, as well as innovative photonic integrated switch prototypes. Interfaces and transceivers include prototypes based on Multicarrier Modulation (MCM), dispersion-tolerant direct detection, low resolution DAC and ADCs for metro networks, and coherent solutions for filterless networks. An innovative solution to enhance "legacy" PON devices to make them "SDN-compatible" is also included, together with the design and prototyping of a complete programmable micro data centre suitable for fitting into a small peripheral CO.

Section 6 describes the general METRO-HAUL framework, for monitoring and data analytics (MDA) concerning its impact on the data plane. Specifically, MDA agents run close to the network nodes and collect monitoring data records from configured observation points in the nodes. The MDA agent has been conceived to support multilayer disaggregated scenarios, and can collect monitoring data from one or more nodes.

Section 7 introduces the general methodology for evaluating METRO-HAUL solutions, which will be deepened and discussed in greater detail in WP2 (mainly T2.3). Here, only the initial evaluation approach that has been adopted is discussed, with its emphasis on the feedback and interactions with WP3.

Section 8 concludes the document.

2 Metro-Regional Reference Network Context

The following paragraphs analyse the Metro-Regional networks owned by the three Operators involved in the project: TIM, BT and Telefonica. These networks are described from a topological and architectural point of view, reporting on the number and size of the nodes, the average distances considered, and the amount and kinds of traffic being transported at the present and into the future, considering the evolution towards 5G scenarios and new services. The optical transport technologies used in different segments of the network are also highlighted. Together, this analysis acts as the starting point for the definition of the new METRO-HAUL network architecture, with its evaluation taking place according to the methodology reported in Section7.

2.1 TIM Metro-Regional Networks

The new Metro-regional WDM transport infrastructure of Telecom Italia (TIM) is in an advanced state of deployment. The network was planned to support the traffic from fixed residential, mobile (up to 4G and future 5G) and business customers, and is structured into 14 metro-regional areas covering the entire national territory of Italy. Each metro–regional area is covered by its own WDM network. On average, there are of the order of 100 nodes for each macro area, but variability is very high mainly due to the geographical conformation and distribution of populated areas in Italy. The range is from less than 30 nodes to more than 200 nodes, with network diameters ranging from 100 to 400 km; there is also a great variability in traffic distribution within each metro-regional area. A rough classification of network by size is given in the Table 1 below where three size classes are defined (Small, Medium and Large) to classify the networks, and the main parameters of each class are reported.

Table 1. Classification of TIM Metro-regional WDM networks by size with their main parameters

Metro- region class size	# of macro regions	Total Nodes	Metro Core BB nodes	Metro Core nodes	Metro Aggreg. nodes	Total links	Core Links	Extension Links
SMALL	5	≈ 50	1 to 2	≈ 8	≈ 42	≈60	≈10	≈50
MEDIUM	6	≈ 100	2 to 3	≈ 15	≈ 85	≈160	≈20	≈ 140
LARGE	3	≈ 200	2 to 5	≈ 40	≈ 160	≈260	≈ 40	≈ 220

A general scheme of the structure of TIM Metro-regional network is given in Figure 1. In the Metro-regional WDM infrastructure, depending on the amount of traffic gathered by each node and on its hierarchical role in relation to the connection with the core National backbone, there are three main kinds of central offices: Metro Aggregation (low traffic and a nodal degree less than three, in blue in Figure 1), Metro Core (collecting and grooming at level 2-3 traffic from metro access nodes, in orange in Figure 1); Metro Core Backbone (POPs for services and interconnection with the National backbone, in red in Figure 1; one to five for each metro-regional are, again with an high variability). The topology is meshed with a central core mesh between Metro Core and Metro Core Backbone nodes (red links in Figure 1), and an extension network connecting the Aggregation nodes with each other and with the Metro Core nodes (blue links in in Figure 1). Additional equipment is located in the customer premises (usually through spur connections, in green in Figure 1), but they are managed separately and are not a part of the Metro-regional topology.

Two types of optical transport equipment are actually deployed, namely multi-degree ROADMs (MD-ROADM) and full capacity up to degree-four Fixed OADMs (FOADM); MD-ROADM are mainly in metro aggregation and metro core nodes, while FOADM are in access nodes. Fiber is mainly standard G.652 with very few exceptions. Each macro-regional area is served by a single optical infrastructure network made up of a central mesh of interconnecting core nodes, and loose meshes, rings or possibly spurs connecting metro aggregation nodes to the central mesh. Network-wise the present choice is the adoption of fixed grid without colorless and directionless functionalities at the OADMs. Currently connections are mainly based on 10Gbit/s optical channels with a few 100Gbit/s coherent connections (normally used with 10x10G muxponder to increase spectral efficiency, and more rarely supporting native 100G circuits) in dense urban areas. Optical transparency within Metro-regional networks is assured for almost all required interconnections, while transparent interworking with the core and other metro areas is not allowed.

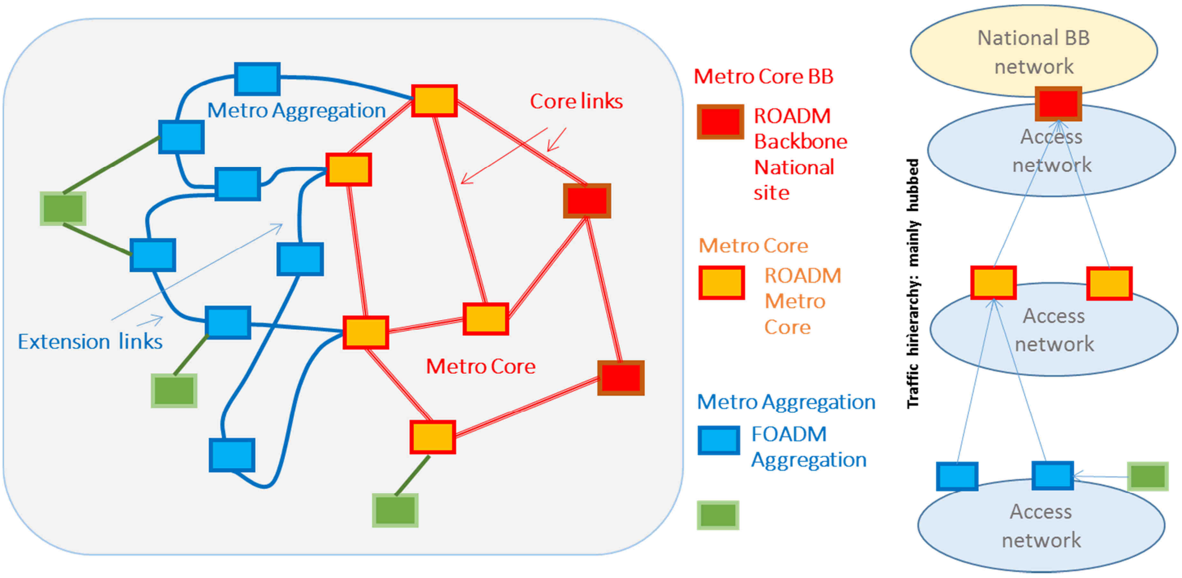

Figure 1. Structure of Metro-Regional TIM networks

The optical infrastructure supports a layer 2-3 network which is in charge of collecting and grooming traffic from all the access networks carrying it to the POPs of services and core network; current traffic from the periphery to the two metro core nodes is of a hubbed type. Dynamicity, resilience and traffic flexibility is managed by these L2-3 networks; the reason of this choice is that currently (and expected in the near future) the flows to be handled are rarely greater than a few Gbit/s. Flexibility at the optical layer is limited to the re-routing of optical channels and automatic channel equalization, and is mainly for maintenance and simplified provisioning purposes.

Figure 2 plots some of the key topological characteristics of the TIM Metro regional networks. On the left part of the figure the length distributions are plotted for both the Core (a) and the extension (Aggregation) (c) portions of eth network. Due to the large extension of Metro-regional areas covered by a single network, link distances in metro-core are quite high on average with a few links longer than 160 km. In the metro aggregation links are shorter and dominated by distances below 10 km, with a very low share of links longer than 40 km. Concerning the nodal degree, on the top right of Figure 2 (b) the nodal degree of Core nodes is plotted, evidencing a high level of degree connectivity for these nodes, with an average between 5 and 6, and reaching the maximum allowed value (for the ROADM technology selected for deployment) of 8 degrees in few cases. The dominant nodal degree in the Aggregation nodes (Figure 2, (d)) is 2, with a few cases of spur connections and also with only a few nodes used at their maximum capacity (that is 4 degree for the selected FOADM).

TIM can provide samples of network topologies of its Metro-regional networks for the network studies to be performed in the Metro-Haul project. These topologies can be taken as references to provide network solutions that can handle the new requirements emerging from Metro-Haul.

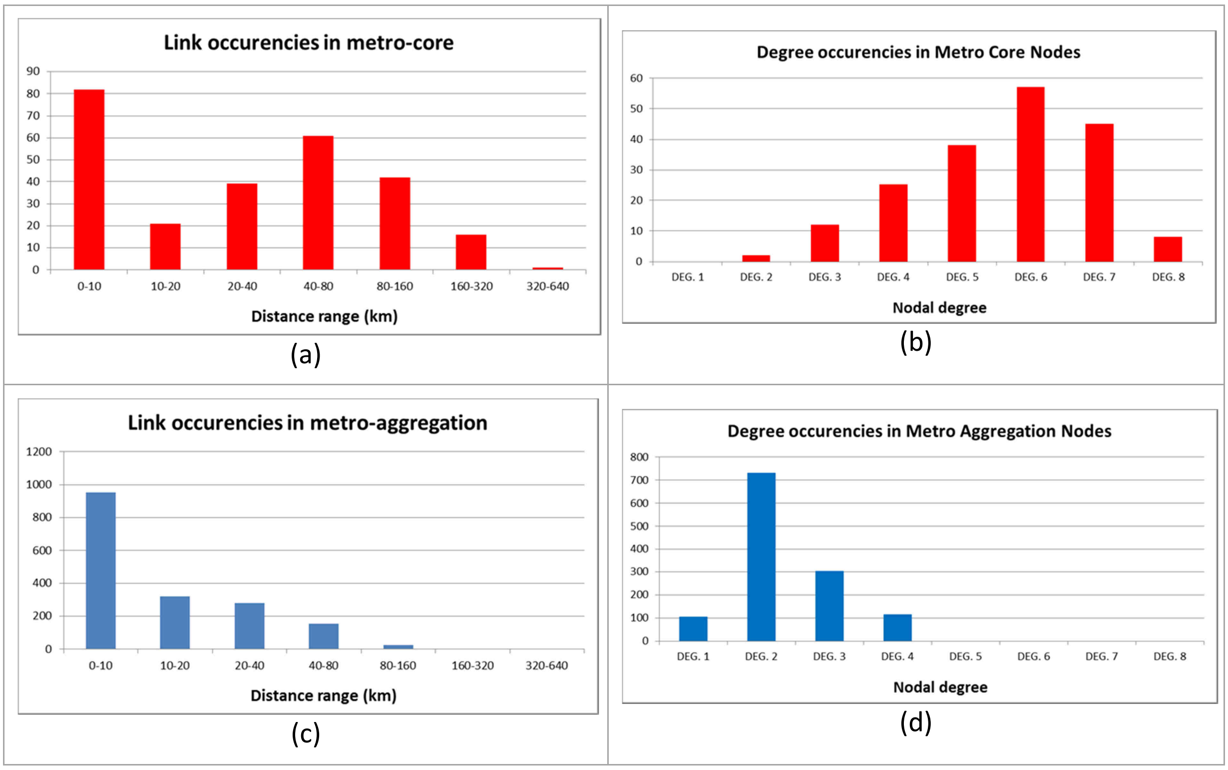

Figure 2. Statistics for link length (left) and nodal degree (right) for the Core part (top, in red) and the aggregation part (bottom, in blues) of the metro Regional networks. Data include all nodes and links of the WDM Metro-regional networks at the National level

2.2 BT Metro Networks

BT's network is divided between the access, metro and core. The core network consists of about 150 nodes, each of which has full any-any connectivity at the 100G optical layer. These nodes can be considered as MCEN nodes in the Metro-Haul architecture. The metro network connects these 'MCEN' nodes to around 1000 Local Exchange buildings (or Central Offices) and these can be interpreted as AMEN nodes in the Metro-Haul architecture.

Currently the metro network provides connectivity from all of the AMEN nodes into the core network, and this is typically achieved by a 10Gb/s DWDM network in a horse-shoe architecture where several AMEN nodes (typically between 8 and 12) are connected to two MCEN nodes which are at the ends of the chain, or horseshoe. This horseshoe allows two resilient routes into the core network for every AMEN node.

The following Table 2 provides the physical layer parameters that can be assumed for the BT metro network:

Table 2. Assumed optical fibre parameters for the BT metro network

Optical Fibre type	G652
Mean value of fibre attenuation dB/km at 1.55um	0.25
Range of values of fibre attenuation – e.g. min / max values to be	0.22 – 0.3

assumed dB/km	
PMD maximum value to be used (e.g. PMDQ) in ps/rt km	0.2
Chromatic Dispersion value ps/nm/km	20 ps/nm/km

A schematic horseshoe topology is shown below in Figure 3.

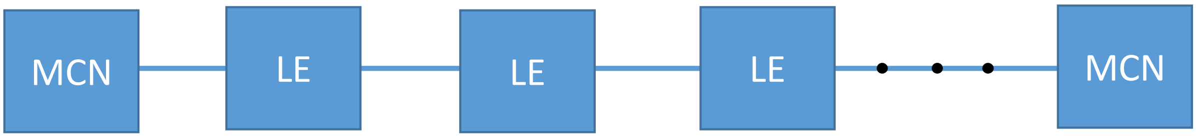

Figure 3. Horseshoe / chain architecture for current BT metro network

As is clear from this figure, the AMEN nodes (i.e. LEs) are essentially of degree 2. In practice there is currently no wavelength flexibility at these nodes; instead, DWDM multiplexing is achieved using fixed AWGs which are either set at 4 or 8 wavelengths (fixed wavelengths). If we stick with the existing horseshoe configurations, cost-effective flexible optical filters would be highly desirable to provide the dynamicity needed for 5G. Each LE can add/drop traffic, but this should be as flexible as possible (e.g. any node should be able to add/drop a wide range of wavelengths and there should be scope for dynamic add/drop).

Typical distances of these horseshoe optical circuits range up to 50km for the entire length. Some horseshoes will be longer than this of course – extending to over 100km for rural areas. BT has a deep interest in Single Fibre Working (SFW). This reduces the fibre utilisation to a single fibre between nodes, reducing cost.

Regarding traffic requirements, the key point here is that all traffic from the AMEN is expected to be hubbed up to the MCEN and fed through to DCs in the core network. There is no direct AMEN-AMEN traffic. BT's network growth continues at 40% year on year, so that BT is considering the migration from 10 Gb/s to 100 Gb/s coherent DWDM in order to accommodate 5G traffic growth demands, or alternatively the use of 25G formats, so avoiding the more expensive coherent technology.

There is a very interesting optimisation comparison between:

(i) Optically filtered networks with non-coherent modulation formats;
(ii) Filterless networks with coherent modulation.

BT has a full list of core and metro nodes that can be used for optimization studies. We are not restricted to using the existing horseshoes if better architectures emerge.

2.3 Telefónica Metro-Regional Networks

Telefónica is one of the largest network provider worldwide with operations in Europe (Spain, Germany, UK, France), Americas (Argentina, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Panama, Peru, Puerto Rico, Venezuela) and Asia (China). As such, it has many Metro network topologies deployed worldwide, involving many technologies and architectures. However, most MAN topologies have certain aspects and features in common which have been summarized in the following network topology of reference to be used within Metro-haul project for the purpose of research, testing of algorithms and technologies and validating Metro-haul experiments.

Figure 4 shows an example of a real topology from a real 25 Million population city in America, with 20% of users subscribed i.e. 5 Million residential subscribers (FTTH) and mobile users. Following Telefonica's internal naming and structure, a generic layered composition of ring-star topologies (ring within the same layer and star when aggregating) is shown, spanning typically four levels: access, first aggregation (L1) level, second (L2) aggregation level and core. At the IP layer, the logical topology hides the optical rings from revealing a clear hierarchy.

In a nutshell, we shall consider the following numbers regarding this large MAN topology:

- *6 Core Network nodes:*
    - These nodes (routers) make up the top level of the IP network on a national level, i.e. the backbone network. They are also the interface between the IP network and Internet/ISP providers, providing services like TV or CDN caching that are hosted at these nodes.
- *33 L2-aggregation nodes (19 with connectivity to L1 clusters, 14 transit nodes):*
    - This layer carries out the traffic aggregation/distribution function. It collects the traffic from the different geographic areas of the MAN.
- *380 L1-aggregation nodes (as 20 nodes/cluster x 19 clusters):*
    - The HL4 layer is composed of the routers located at the bottom layer of the IP network, and performs functions such as traffic classification, subscriber's credentials authentication, validation of users' access policies, routing data to the respective destination, etc. This layer also aggregates traffic from different locations of the Metro network and from OLTs, DSLAMs and SWTs.
- *2432 Access Network nodes:*
    - The access layer comprises routers, ONT, COs and BSs. Therefore, we shall assume that both HL5 and HL4 nodes can host, at the same time, routers, ONT, COs and BSs.

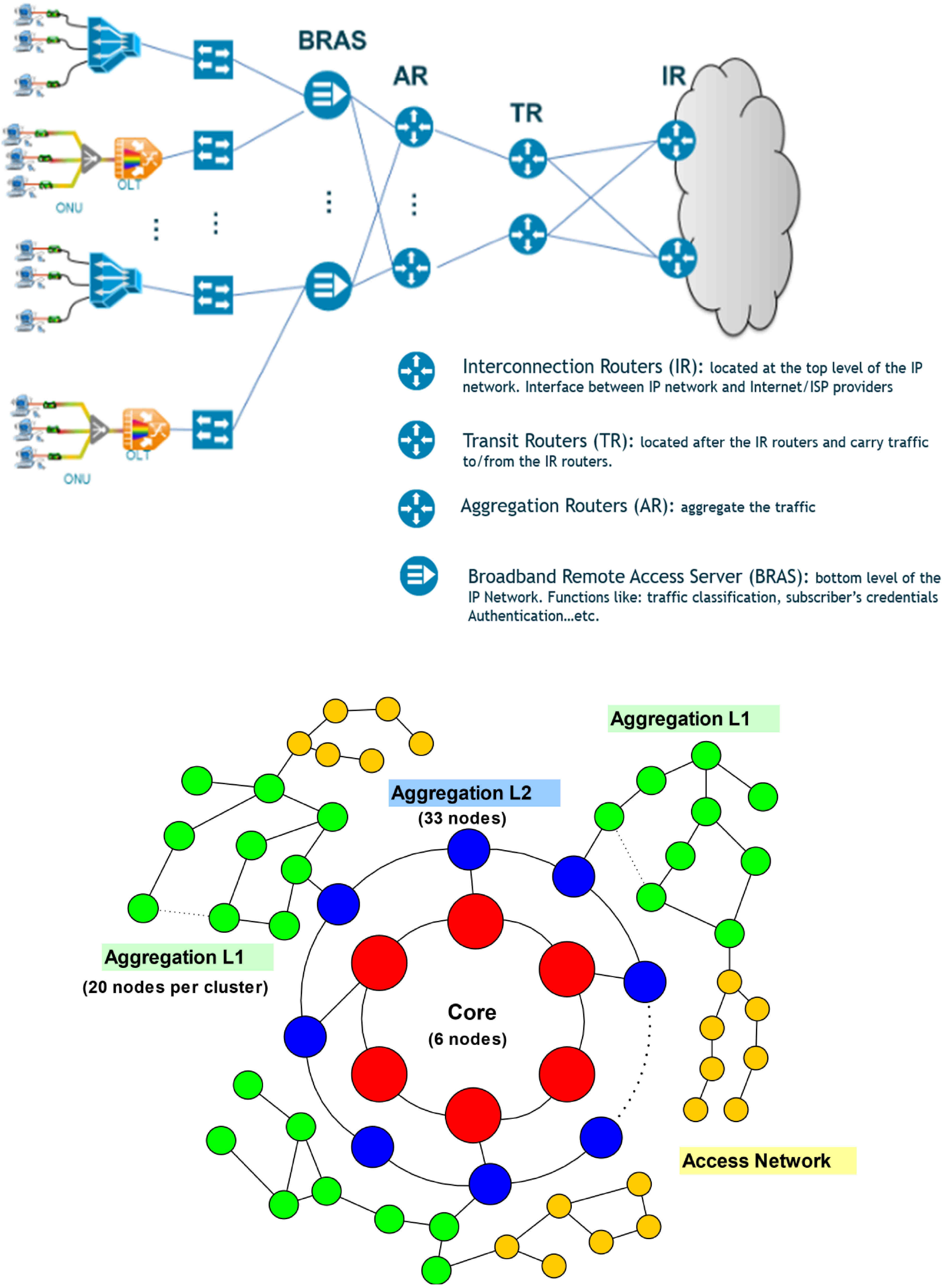

Figure 4. Telefonica's topology of reference for Metro-Haul

Regarding link distances between nodes of the same hierarchy level, Table Table 3 shows the average, min, max and standard deviation of fiber lengths.

Table 3. Link distances in the Telefonica Metro-Haul network.

Link distances [Km]	Mean	Max	Min	Std (σ)
Access Network	1.60	5.88	0	1.16
L1 Aggregation	8.69	22	0.50	5.98
L2 Aggregation	13.10	36.07	1.61	8.84
Core Network	40.17	65.67	26.10	13.96

3 METRO-HAUL Reference Infrastructure

The general METRO-HAUL reference architecture shown in Figure 5 schematically emphasizes the need for at least two hierarchical levels of "edge" nodes, facing respectively towards the core and towards the access network segment, to effectively allocate all the functionality needed for an agile and programmable metro network supporting 5G access and future requirements from vertical players. It is represented by two different types of functional nodes: MCEN (Metro Core Edge Node) and AMEN (Access Metro Edge Node) including full compute storage and networking capabilities interfacing respectively to the 5G access and to the multi-Tbit/s elastic core networks. A WDM metro optical transport infrastructure complements the picture.

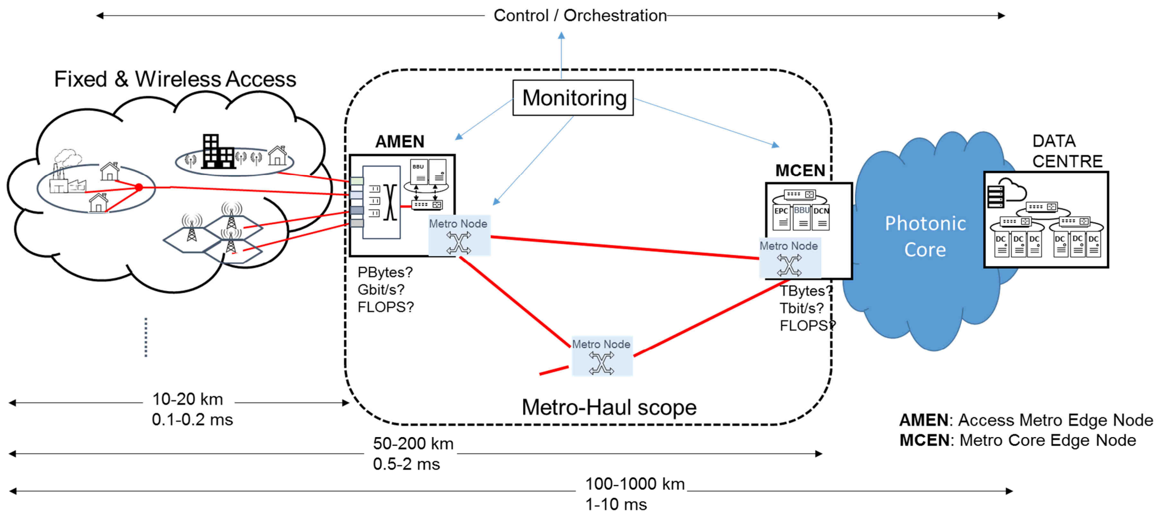

Figure 5. Reference Metro-Haul network architecture

Taking into account in particular the three operators' reference metro-regional networks described in chapter 2, and trying to identify a comprehensive architectural and topological picture where the functional elements identified by the reference nodes of Figure 5 could be mapped, we have obtained the network structure shown in Figure 6. It is actually based on three levels of nodes (or Central Offices)[1]: a Metro-Core, a Metro-Aggregation and a Metro-Access level. This network structure is primarily intended as a general metro scenario, mostly comprehensive of any metro network of interest within METRO-HAUL, and in particular of the operators' reference metro-regional networks described in chapter 2, where the different optical switching and transmission technologies are mapped.

In particular Figure 6 is a good representation of a typical metro-regional area of TIM's domestic network (Chapter 2.1) where the Metro-Aggregation segment is made up of medium / large size

[1] For the purpose of this document we often identify the term "node" with the term "Central Office" (CO). A CO is a physical place, being a building, part of a building (rooms), a container, a shelter, etc., including within it all the infrastructure necessary to implement a specific METRO-HAUL node architecture and all the support equipment needed (cooling, housing racks, redundant power supply, etc.). Often a CO node hosts several piece of equipment in several racks to fully implement a METRO-HAUL node. In some implementations a CO may be a single cabinet on the side of a road! The term "node" is mainly used to emphasize its "functional meaning".

nodes (COs), each subtending a relatively large sized access area with a meshed topology. Therefore the usage of (disaggregated) MD-ROADM Optical Network Elements (O-NEs) with nodal degree equal to three or higher is quite well justified. Conversely, the Metro-Access segment subtends somewhat smaller access areas, thus justifying the usage of low cost ROADMs, Fixed OADMs or Filter-less OADMs.

A typical BT metro area network could instead be well represented by the Metro-Access segment alone (green lines and boxes in Figure 6), directly connected to the POPs, without the mediation of a Metro-Aggregation segment (Chapter 2.2). Low cost ROADMs, Fixed OADMs or Filter-less OADMs are here the technologies of interest.

Finally, Telefónica has many different metro network topologies deployed worldwide and, in Chapter 2.3, the given example has a more articulated topology with respect to the one shown in Figure 6, being based on four levels: a core level, two levels of aggregation, and an access level. From the technological point of view of the WDM transport network, the two options for metro aggregation and metro access considered for the TIM network also apply here as well.

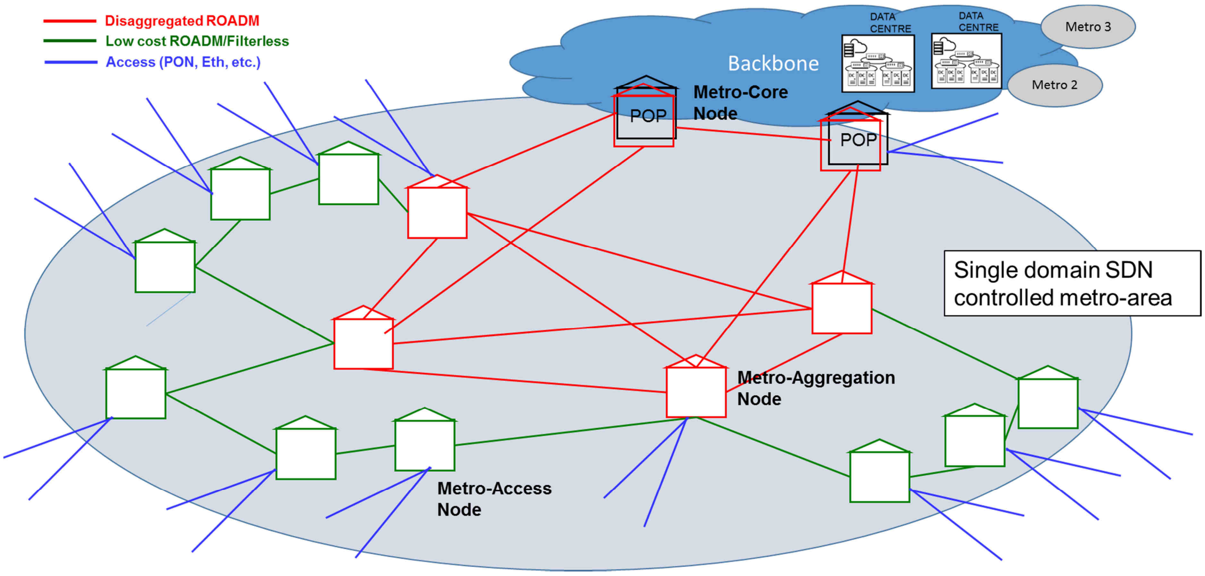

Figure 6. METRO-HAUL comprehensive reference network context

In Figure 6, big-data centers for cloud and core / edge (i.e. non latency-sensitive NFVs) could be located somewhere in the backbone. Different geographical metro-regional areas are separated from each other and interconnected only through the backbone by means of the nodes of the Metro-Core level (POPs).

In the peripheral part of the network, a few of the "green" COs could be housed in containers, shelters or even in cabinets (with cooling, power supply, servers, networking, access equipment, etc.). The MCEN functionalities are expected to be present mainly at the metro-core level, where the interconnection with the core network takes place, while the AMEN functionalities are expected to be present at all three levels, provided that an access network segment can be subtended by every CO (irrespectively of the hierarchical level).

Regarding the structure of the Central Offices itself, the CORD approach [3], where COs are architected as Data Centers, is considered as a good reference and starting point for the demonstration implementations within METRO-HAUL. This approach is also in line with the idea of virtualizing almost all the network core and edge functionalities traditionally implemented with several dedicated network appliances within a CO. As shown in Figure 7 (taken from [7]) network functionalities could be implemented using containers or virtual machines on a general purpose virtualization infrastructure mainly based on computing, storage and switching interconnection elements.

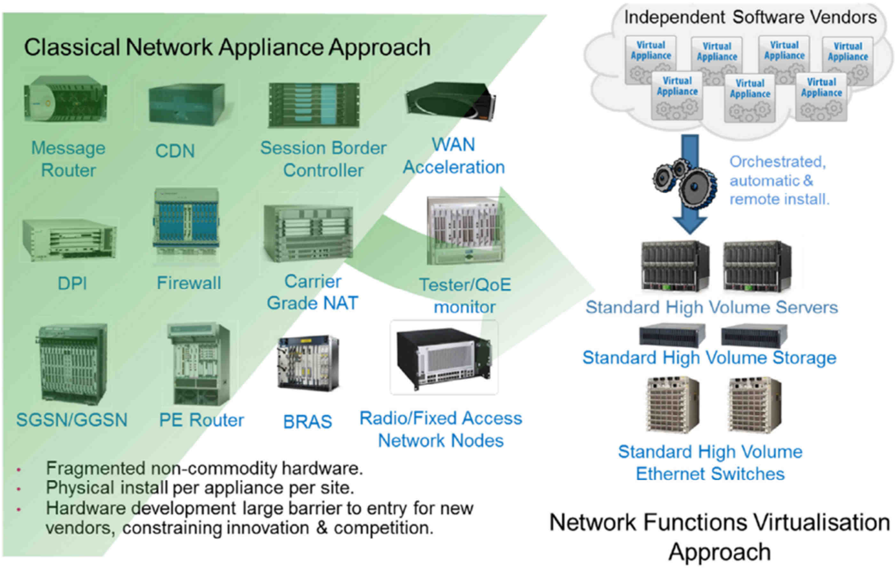

Figure 7. Vision for Network Functions Virtualization [7]

In principle, the same infrastructure architecture can be considered for all the COs: they should substantially differ only in size, depending on their geographical position and on the amount of traffic and the functionalities they must handle.

Generally speaking, network functions and client-specific applications can be located in different network nodes according to their different requirements, such as latency constraints, traffic distribution efficiency, ease of management of homologous functions in a single site, and so on. As explained in more detail in chapter 3.2, a modular approach should be followed in designing COs, where basic hardware and software components can be chosen, composed and assembled akin to a Lego kit, to simplify installation and management.

Within METRO-HAUL, the earlier deliverable D2.1 “Definition of Use Cases, Service Requirements and KPIs” [8] investigated the actual requirements that new 5G services are expected to demand from network nodes, analyzing a variety of service use cases. This analysis allows us to make hypotheses reagarding the average requirements in terms of “throughput”, “storage” and “computing capacity” of the AMEN and MCEN node types. These requirements are reported in the Table 4 below taken from D2.1.

Table 4. AMEN and MCEN average capacity requirements derived by use cases studied in D2.1

	AMEN	MCEN
Throughput	1.1/1.4 Tb/s	1.2 Tb/s
Storage capacity	4.2 TB	100TB
Computing capacity	1700vCPU	250vCPU

It is important to note that the requirements reported in Table 4 are only to be considered as an example because they are obtained with specific assumptions relating to: 1) the set of services that brings traffic to the metro network; 2) the number of residential customers or business facilities (e.g., automated factory's plants) served by each MCEN; 3) the placement of specific service dependent functionalities (e.g., cache memory) at the AMEN, MCEN or the Backbone; and 4) the number of AMENs associated to a MCEN. One achieves quite different figures for the requirements listed in Table 4if these assumptions are different.

3.1 METRO-HAUL Central Office Architecture

The METRO-HAUL project aims at providing a new definition of the Central Office architecture, targeting the support of the new generation metro network while providing effective functional capabilities to the expected new and virtualized 5G services. Currently deployed COs were mainly designed for legacy telecommunication equipment, with limited remote control capabilities and, most important, not designed to provide computational and storage capabilities effectively integrated with packet and optical networking resources. In the following, the proposed METRO-HAUL solution for the 5G CO is highlighted.

The METRO-HAUL infrastructure interconnects many locations within an area of metropolitan or regional size (Figure 6). Each location has its own Central Office where pieces of equipment combining networking, processing and storage resources are installed. Locations are connected by a fiber cable network, which, in a field network, are normally subject to topological (if the fiber is owned) or market (if the fiber is rented) constraints. Devices inside Central Offices are modular and are composed of different components made with a variety of technologies and operating at different layers. An important assumption is that items of equipment and SW inside a node are provided by different vendors according to the model of hardware and software disaggregation.

Metro Haul nodes instantiated in Central Offices implement layer 0-1 (optical domain), layer 2 transmission and switching (frame domain) for Add&Drop purposes, and moreover Edge Computing capabilities, provided by a local pool of servers to instantiate virtual network functions (VNFs) with configurable amounts of processing, memory and storage. All the devices are assumed to be controlled by a SDN / NFV Node Controller, which is in charge of assuring the integration and coordinated functioning of such disaggregated components.

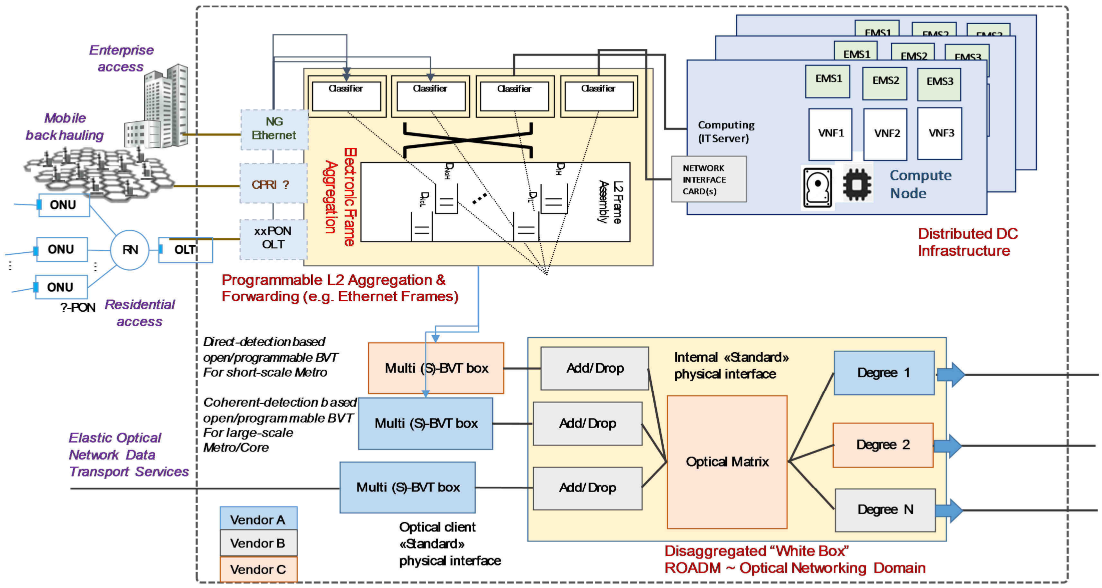

Figure 8. Disaggregated METRO-HAUL Central Office

Figure 8 shows schematically the functional architecture of the METRO-HAUL CO. The general node architecture includes VNFI capabilities with a local Compute Node, realizing caching and virtualized services running close to the access in order to serve users with reduced latency. The electronic frame aggregation implements classifiers and switching, directing the traffic from / to access and metro-core sections. In particular, in the AMEN version, 5G access (e.g., CPRI) and optical access (e.g. xPON) are directly attached to the aggregation stage. Traffic to the metro network is directed to the optical white boxes. As far as optical transmission devices, multi-vendor (sliceable) bandwidth variable transponders - (S)BVTs - with different capabilities depending on the role of the node inside the network, distances to be covered, and so on, could be employed. Other low cost solutions are considered as well for covering the peripheral part of the network (Figure 6). The disaggregated white box MD-ROADM is the reference option for switching in the optical domain, but other type of switching / filtering technology, like filterless solutions, are also considered where possible, for obtaining cost savings. As said before, each device, equipped with a dedicated SDN agent, may be from a different vendor and connected by means of standard data plane interfaces.

Specific specializations of the generic architecture are as shown in Figure 8, and involve the AMEN nodes to interface with heterogeneous access technologies and the MCEN nodes, which are gateways towards the core transport network and comprise core-oriented capabilities.

The infrastructure made of interconnected locations (COs) hosting AMENs and MCENs is composed of the set of heterogeneous resources listed below:

- *An optical network:* the Disaggregated Optical Layer that provides high bandwidth, low latency connections between nodes and constitutes the core part.
- *Packet switched networks*: providing connectivity to customers, NVFI servers and related endpoints.
- *Passive Optical Networks* (PON) that provide connectivity to users.
- *ETSI NFVI Points of Presence* (NFVI PoP) encompassing multiple compute nodes in which virtualized network functions can be executed.

Of all these infrastructural networks we believe that the parts where enhancements and substantial effort in innovation and research are most needed are the purely optical ones, namely the disaggregated optical network and the passive optical network; especially if an extensive integrated automation approach is envisioned. Therefore this document mainly addresses the optical nodes and networks, although general guidelines for the assembly of a complete CO are given in next section.

3.2 Guidelines for METRO-HAUL Central Office Design and Assembly

The METRO-HAUL architecture shown in Figure 8, once developed and defined in its details by the project, will be adapted to the context in which it will be deployed. In particular, METRO-HAUL applicability will have to take into account the specific needs of the operators and their legacy constraints, such as, to mention the most important, the candidate locations for the CO hosting and the supporting fiber network.

Recent proposals made by open source foundations [9] and forums [10] to which operators look with great interest, define a simplification of COs in terms of both HW and SW, thanks to the application of virtualization and disaggregation concepts. Such simplification can be obtained by defining a restricted set of “standard” blocks that can be flexibly used to build Central Offices (i.e., instantiating SW implementing network functions on generic HW). This is in contrast to the legacy approach, which is characterized of a large variety of specialized equipment. CO configurations obtainable from these blocks will be easily and quickly adapted to all the locations where a CO has to be installed. This avoids an extremely tailored project of each CO site, because possible configurations in combining few blocks (or even modules made of some blocks) would be limited, so that both capital expenditures and operational costs can be reduced.

Capital expenditure could be reduced because a restricted set of configurations of HW equipment (packet and optical), servers and part of the SW, can be identically pre-assembled ready for installation. Additional specialized SW can be installed at each site on the basis of the specific needs of that site, but would only represent a part of the entire SW required. Taking into account that numbers can be quite significant (hundreds or even thousands of Metro CO sites in a country), considerable benefit from the economies of scale associated with such homogeneity in CO HW and SW configurations is expected.

Operational cost reductions can also be achieved when a CO is installed for the first time, as all the equipment is already assembled and cabled in a rack and possibly included in an appropriate container (e.g. for COs that are not hosted in a building but are required to be situated in an open location). Other operational costs, such as periodic maintenance, faults detection and repair etc., are also expected to be reduced due to the restricted standard configurations of equipment and the consequent possible standardization of procedures.

The concept of making and deploying COs described above is in principle applicable also with traditional equipment solutions (i.e. non-disaggregated and mono-vendor), but the flexibility allowed with disaggregation, especially in SW components, should increase the achievable benefit of such an approach.

To give an example of the above-mentioned approach, Figure 9 shows how types of basic building blocks can be defined to build a CO to cover the needs for all the COs of the metro segment of the network. Concerning the front end with the access, a limited set of cards exploiting OLT function (or similar, depending on the option choice on the access technology) can be assumed to be available. A restricted set of equipment options are assumed in the optical layer, for instance, adopting three classes of equipment with graduated levels of complexity and cost.

The bottom right box of Figure 9 shows three classes of optical equipment:

- a first class of equipment implements a simple very low cost Add&Drop system with limited functionalities and low flexibility (e.g. a filterless solution) suitable for peripheral nodes which have to handle few optical connections with no or a limited requirement on reconfigurations;
- a second class of partially flexible equipment (e.g., F-OADM) conceived for nodes playing an intermediate role in metro network hierarchy, which have to handle a number of connections but with limited requirements on flexibility;
- a third class of full flexible switches (e.g. MD-ROADM) suitable for nodes with the highest role in the network hierarchy that have to handle many connection flexibly.

Ideally, in this model each type of optical node should have only one standard configuration that would be suitable for matching all the situations: this helps in reducing the spread of configurations. For the switching, storage and computing equipment the model is exactly the same as the described above for optical equipment. The top right box of Figure 9 shows three sizes of HW sets for the L2/3 switching fabric (made with one or more switches) plus storage and computing capabilities on servers (i.e., small, medium and big size configurations).

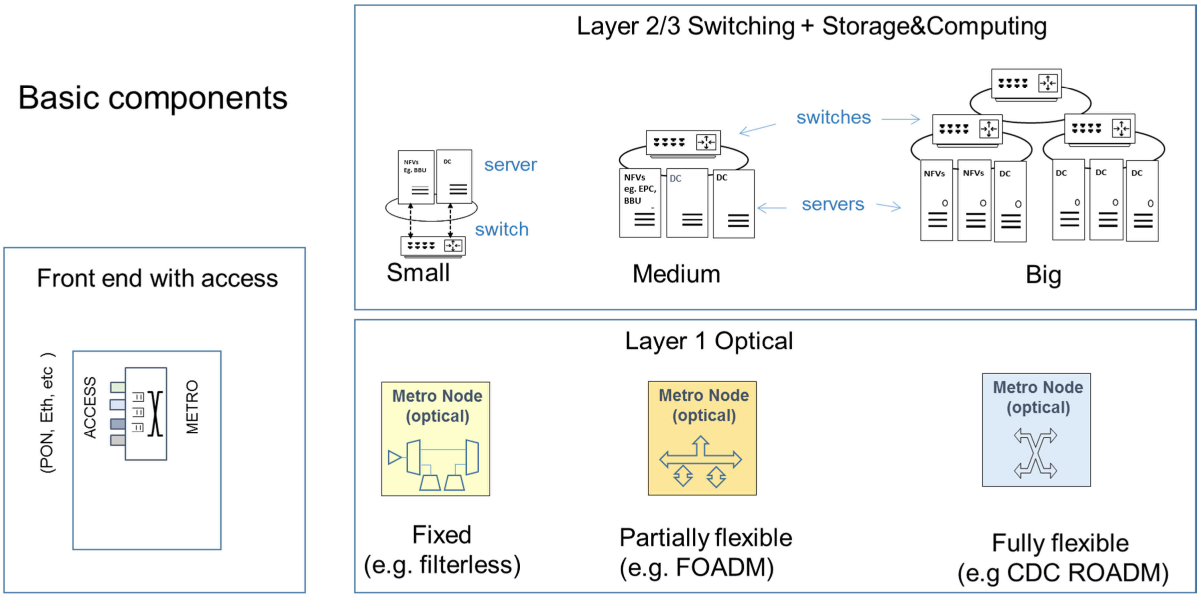

Figure 9. Building blocks required to assemble a METRO-HAUL CO

Using the basic building blocks above presented, two options have been identified as possible strategies in METRO-HAUL CO building and deployment.

A first option, hereafter called the "module based" approach, assumes that a set of predefined modules, suitable for use within a similar context, are built with a defined set of available blocks. Once the modules are defined and are made available, a CO can be built up using one or more modules interconnected together.

A second option, called "block based", results in a more flexible approach (but more articulated) than the previous one, and assumes that a CO can be freely made from a set of the defined basic blocks.

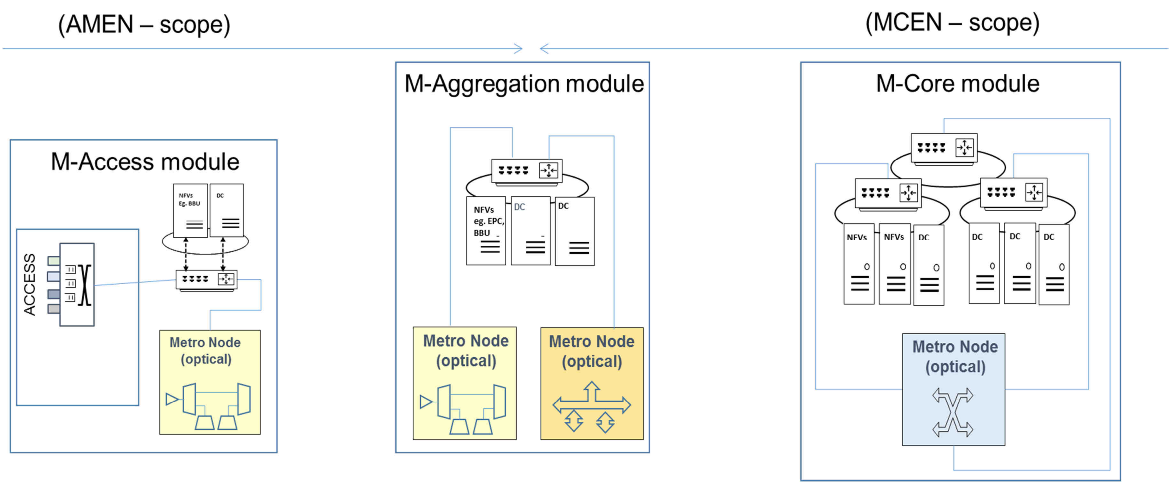

Figure 10. Modules obtained from basic building blocks and their role in metro network hierarchy

In Figure 10 an example of a module-based approach for a metro CO is given. Each module can be preassembled and used, alone or in combination with more than one of the some or of a different kind, to build a CO playing a specific role in the hierarchy and with specific needs. The access module (M-Access) includes an access block (with the possibility of including more than one block, according to need), a small L2/L3 switching and Storage&Computing block, and a small size low cost optical Add&Drop block. It could be suitable for Metro-Access, and within the METRO-HAUL framework it is a candidate to cover the AMEN functionalities when the requirements are not very high (limitations are due to very basic optical Add&Drop functionalities). The aggregation module (M-Aggregation) includes blocks of intermediate capacity, complexity and flexibility, and at the optical layer it is suitable to interwork both with the access part and the core part of the network, thanks to equipment of two types (e.g, filterless and F-OADM). Access blocks are not included in the aggregation module, and so a CO should include one or more access modules in addition to an aggregation module for gathering traffic from the fixed access. The core module (M-Core) is of high capacity, performance and flexibility equipment at the optical, packet and computing levels. Also for this module the access capability is not included, and so an access module should also be added alongside the core module in the CO, so as to gather traffic from the fixed access. In the METRO-HAUL framework this module is the candidate to cover those functionalities required by the MCEN.

Figure 11 below gives an example on how the basic modules shown in Figure 10 can be used to obtain an Aggregation Central Office and a Core Central Office. In the first case, shown on the left part of the figure, an M-aggregation module is integrated with one or more access modules to ensure the access traffic collection. This example could cover a high specification AMEN node, while for an AMEN with lower required capabilities one or a few M-Access modules could be sufficient. In the right part of Figure 11 a modular solution for the CO playing the role of Metro Core node (i.e. an MCEN in METRO-HAUL) is depicted. Also in this case, alongside the specific M-Core module performing high specification networking, computing and storage tasks, there are one or more M-Access modules for access traffic gathering.

Figure 12 gives the alternative model for CO implementation starting from building blocks, i.e. the “block based” approach. In this case the basic blocks are combined without the constraint of having to be a part of a module, so that and some resource optimization can be achieved but at the cost of a larger spread of CO configurations across the whole set of the operator's exchanges. This therefore loses the potential CapEx and OpEx advantages associated with the homogeneity achievable with the module based approach. Figure 12 shows implementations with blocks of two flavours of AMEN nodes, Metro Access (AMEN “basic”) and Metro Aggregation (AMEN “plus”), and a MCEN node with access capabilities.

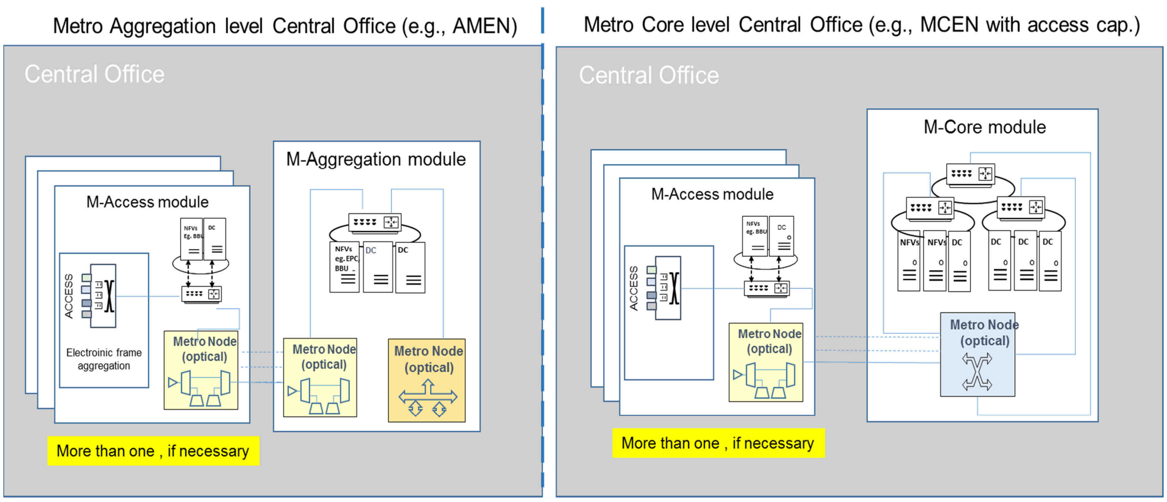

Figure 11. Aggregation and Core Metro Central Offices obtained from the module based approach (“module based” approach for CO making)

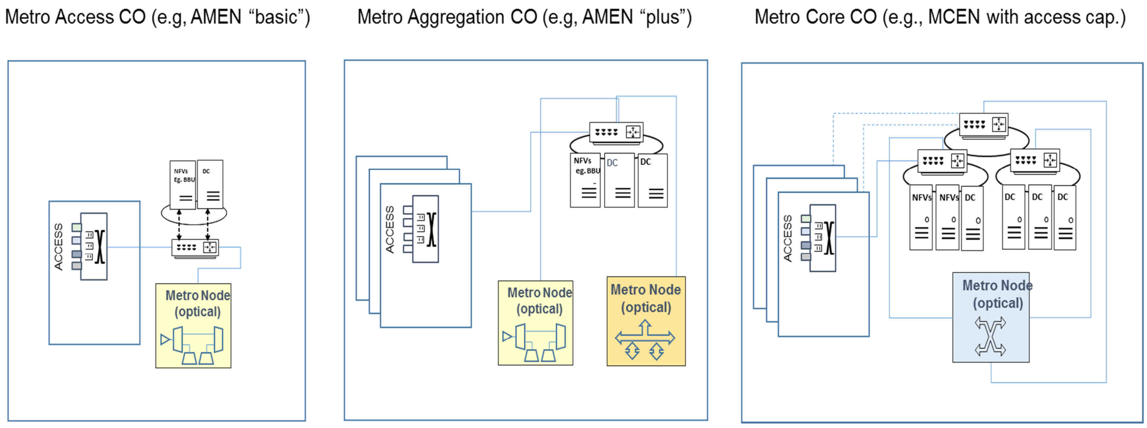

Figure 12. Access, Aggregation and Core Metro Central Offices obtained from the block based approach ("block based" approach for CO making)

3.3 METRO-HAUL Optical WDM Transport Network

The term "transport" has a certain degree of ambiguity associated with it, and can be either understood in a narrow sense, to exclusively include the technological areas most appropriate to the physical layer (WDM, digital OTN, SDH), or in an extended sense to include any network with Traffic Engineering capabilities.

In the context of this document, we interpret the term in a restricted sense, binding it further to the technological domain of the OTN (Optical Transport Network) in both its digital and optical analogue declinations, with particular reference to the latter one. Furthermore, OTN is considered here only in respect to its capability of adapting, multiplexing, adding line code, protection and OA&M functionalities to a digital client and not for its routing capabilities. The digital client mainly considered here is Ethernet, although many of the considerations apply to a more general class of signals as well.

Generically, we call systems complying with these restrictions: "**Optical WDM Transport Systems (WDM-Systems)**"; and the relative transport network: **Optical WDM Transport Network (WDM-Network)**. In METRO-HAUL only the WDM-Systems and Network are considered.

As a further remark, in METRO-HAUL all the relevant optical paths within a metro WDM-Network are considered transparent; this however does not means that all the possible optical paths must be transparent. For this reason, optical regeneration functionalities are not the primary focus of the activities. At the other end, 3R digital interconnections among different metro-segments (e.g. between metro-aggregation and metro-core; and metro-core towards a backbone network) are well within the scope of the METRO-HAUL project.

Having these restrictions in mind we can therefore contextualize the overall METRO-HAUL objectives of architecting and designing cost-effective, energy-efficient, agile and programmable metro networks that are scalable for 5G access and future requirements, encompassing the design of all-optical metro nodes.

With specific reference to the metro Optical WDM transport network and optical node infrastructure, innovative solutions therefore need to mainly target two aspects: flexibility and low-cost.

The technological aspects and the relative WDM-System approaches proposed within METRO-HAUL will be discussed in depth in section 4. Here the general architectural aspects, which are essentially technology independent, are discussed in some detail.

A very promising approach is so-called “disaggregation”. In the context of WDM transport network this term refers to the possibility of breaking a “monolithic” (and mono-vendor) optical network into “disaggregated” blocks, enabling “multi-vendor” scenarios where innovations can be independently brought at their own individually required pace into the different parts of the network.

The essential modularity of this approach potentially enables the breaking of the “vendor lock-in” and opens it out to a fast and continuous introduction of innovative and open solutions. This in turn should support a broad range of tailored trade-offs among low cost solutions, so as to drive flexibility and a fast response to new service requirement from vertical applications, as well as accommodating most network scenarios potentially faced by a telecom operator. A suitable selection of devices and the buy-(install-) as-you-grow approach (expected as a common practice in a modular open disaggregated ecosystem), should also contribute to enhance energy-efficiency in the network; although this goal can only be fully reached by approaching the problem from a more global perspective including the whole network layers and pool of services offered by a telecom operator.

Optical disaggregation is, however, mostly associated with metro regional networks (due to heavy physical impairments in long haul transmission which often require ad-hoc solutions), and is possible only in the presence of a standard (or at least multi-sourced agreed) mature ecosystem of optical network elements, control, management, design and planning software [2].

METRO-HAUL is deeply involved in the process of creating this optical disaggregated ecosystem, both exploring and demonstrating it [11], collaborating with conventional and open standards fora [12], [6], [13] and software development initiatives [3], [4] and also proposing consistent and integrated visions [2],[14].

Analyzing the approach in greater depth, essentially, a disaggregated optical transport system can be considered to be made of different pieces of optical equipment housing similar network functions, possibly consisting of several shelves or blades, but seen by management and control systems as a single management entity through a suitable Open API, often termed South Bound Interface (SBI). These optical network equipments (O-NEs) can be classified into the following categories, extracted from reference [2] to which the reader is referred for additional in depth discussion of “disaggregation”:

- **Client to WDM adapter (TP)**, such as transponders (1-1 mapping of clients to line side interfaces), muxponders (N-1 mapping and multiplexing) and switchponders (N-M mapping, switching and multiplexing);
- **MD-ROADM (Multi-Degree Reconfigurable Optical Multiplexer),** including wavelength or spectrum Add&Drop, switching, amplification and equalization optical functions. In some implementations the node is assembled from several separate modular subsystem blades, one for each line degree or Add&Drop chain. Integrated Optical Wavelength Cross Connects O-NEs are included in this category as well;
- **Line Terminal (LT)**: a single line side optical multiplexer often providing colourless functionalities. Often several LT blades may be interconnected to form a MD-ROADM;

- **Fixed Filtered OADM (F-OADM) and Fixed Filterless OADM (Fls-OADM)**, including Add&Drop, amplification and equalization optical functions;
- **In Line Amplifiers (ILA)**: inserted in a long transmission line between LTs or MD-ROADMs to recover optical attenuation.

A suitable interconnection of these O-NEs with the addition of a WDM transport controller / management SW makes a complete system:

- **TPs constitute the "Digital to WDM adaption layer" (DtoWDM)**, being in charge of the adaption of digital client signals to analogue "media channels";
- **MD-ROADMs, F-OADM, Fls-OADM, ILAs and LTs constitutes the actual "WDM Analogue transport layer" (A-WDM).**

A disaggregated system can be, therefore, designed, assembled, integrated and tested starting from a Control SW together with different levels of O-NEs disaggregation: some already-assembled DtoWDM and A-WDM layers, or all or some O-NE category as elemental bricks, or even from subsystem blades on bare metal HW.

Depending on the disaggregation level, several scenarios can be envisaged as follows.

3.3.1 Fully Aggregated Optical Domains

When O-NEs, A-WDM and the controller are provided by the same vendor (as is currently the most deployed scenario), this can be considered a fully aggregated optical domain (Figure 13). The vendor controller manages equipment via an SBI, which can be proprietary, implementing tailored equalization algorithms. This controller can implement an open NBI used to send information of the underlying optical network (in a simplified abstract model) to be used by higher order controllers or orchestrators. This NBI should be standard to enable flexible management and end-to-end service provisioning also through multiple domains.

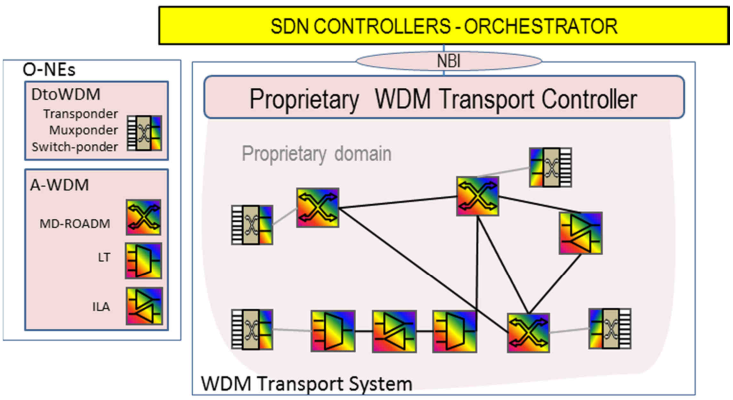

Figure 13. A fully aggregated optical domain: modified from [2]

This scenario is the current evolution of mono-vendor WDM transport systems, with the introduction of an open NBI for controlling and managing the whole network island in a more flexible way. In the METRO-HAUL context this scenario is considered mainly for compatibility reasons, as it is expected that in most networks a mix of "legacy" and disaggregated solutions could coexist.

3.3.2 Partial Disaggregation: Open Line System and Multi-Vendor Transponders

In this approach (Figure 14a and Figure 14b), the DtoWDM layer (i.e. TPs) are decoupled from the mono-vendor and proprietary A-WDM layer, also called Open Line System (OLS). This OLS, a proprietary "black box" analogue transport system, is open to support Optical Channels from external TPs as client signals, whose characteristics are specified by the Single Wavelength Interfaces (SWI). An OLS-NBI API is needed to configure and report events from the OLS. This OLS-NBI should be standard to help in the process of vertical integration with the Open WDM Transport Controller of the whole WDM system.

The partial disaggregation approach can be attractive for many reasons: first of all, the analogue domain and the related tricky development, testing, and management of complex control equalization loops to mitigate transmission impairment are demanded of vendors which usually own such expertise: moreover, the most recent and performing technologies (and possibly cheaper) can also be selected as needed on the TPs side, which is where innovations are provided frequently, independent of one specific vendor roadmap solution.

It is not strictly required that transponders are integrated and controlled by a WDM transport controller with a standard SBI, as dedicated drivers/adapters for specific SDN controllers may be developed by the transponder vendor itself. However with a standard one it would be possible for the OLS controller itself to take charge of TPs, saving the OLS-NBI and simplifying the integration process and network operations (Figure 14b).

In addition, a standard for full interoperability among TPs provided by different vendors is not mandatory (TPs can be matched pairs from the same vendor) even if, in such a case, constraints in the purchasing process and in horizontal integration would be relaxed. Moreover, TP interoperability may limit the transmission performance. On the contrary, the SWI must be standard and it must be possible to properly monitor and equalize signals at the SWI to clearly separate the DtoWDM and A-WDM domains, ensuring stable operation and easy troubleshooting.

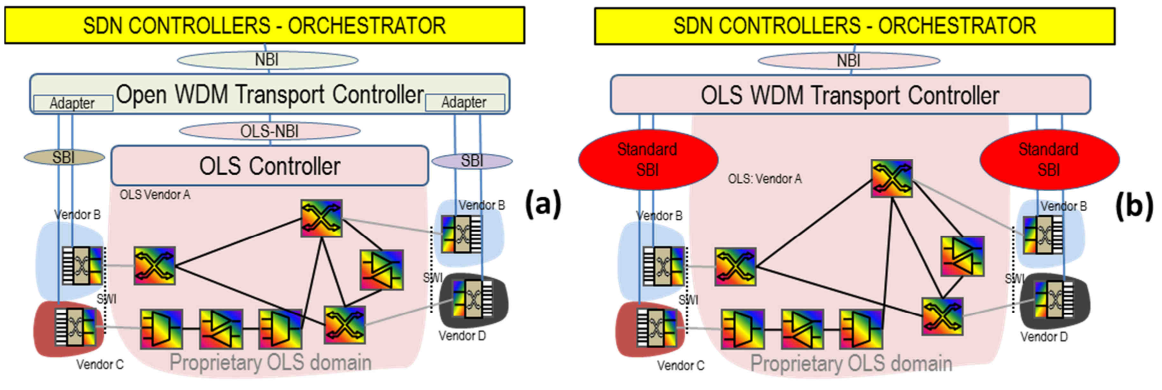

Figure 14. A partially aggregated optical domain with (a) proprietary SBI, or (b) standard SBI; modified from [2]

3.3.3 Full Disaggregation: Multi-Vendor Optical Network Elements/Subsystems

A fully disaggregated approach (Figure 15) implies that not only a vertical integration of control and management SW is foreseen, but also horizontal compatibility is required to allow network elements (or, in extreme disaggregation, even optical subsystems on a blade stacked to build a network node as shown in Figure 15) from different vendors in the same optical domain. In this inherently multi-vendor scenario, to support compatibility at the data plane, both the SWI and Multi Wavelength Interface (MWI) must be standard and well detailed. Also, a standard SBI is

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mandatory, because in this scenario the WDM controller is necessarily vendor agnostic: moreover, it also has to face all the analogue transmission issues (equalization, transients suppression, etc.). For this latter reason, the WDM controller is the most critical element of the whole chain and is likely to be provided by a system integrator which owns the optical systems planning and design expertise: however, open planning and design tools with simplified features (an initiative in TIP is ongoing [15]) would also allow skilled users (not necessarily a design expert) to perform some tasks, such as, for example, getting bills of material, equipment configuration and interconnection schemes for a multi-vendor disaggregated environment.

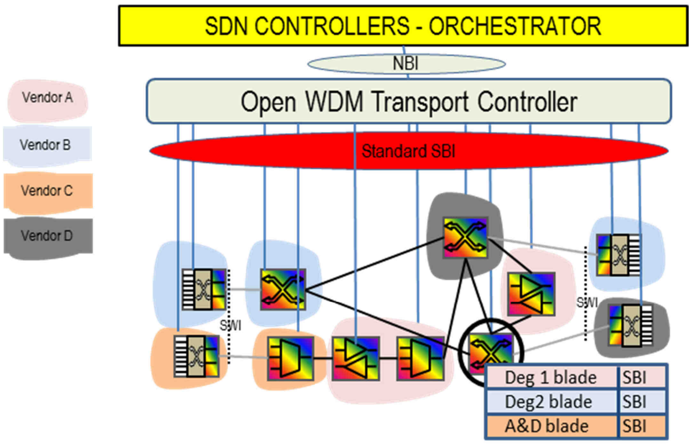

Figure 15. A fully disaggregated optical domain; modified from [2]

3.3.4 Guidelines and Initial Requirements for Horizontal and Vertical Interoperability

The disaggregation alternatives outlined in the previous sections imply some level of involvement of a telecom operator in the processes of designing, developing and testing of a WDM-system. This involvement could be direct or through a trusted System Integrator (SI).

Disaggregation also enables several degrees of multi-vendor environments: the vendors' role becomes that of a supplier of certified software and hardware "blades" or subsystems, including the specification rules for configuration, interconnection and operation. The system assembly involves mainly the SI in all the phases of design and integration, while the telecom operator can be directly responsible for validation and testing.

Table 5 is a schematic summary of the different roles of the involved actors for the three disaggregation alternatives being discussed in METRO-HAUL.

Table 5. Schematic map of actors involved in WDM-System assembly

	Fully Aggregated Domain	**Partial Disaggregation**	**Full Disaggregation**
WDM-System	From a Vertical integrated Mono-Vendor	Assembled by a System Integrator	Assembled by a System Integrator
WDM Transport Controller		From a Transport Controller Vendor (could be integrated with the A-WDM Controller)	From a Transport Controller Vendor

DtoWDM layer (TPs)		Multi-vendor: from TPs vendors	Multi-vendor: from TPs vendors
A-WDM layer		From the OLS Mono-Vendor	Multi-vendor: from equipment or subsystem blade vendors
A-WDM (OLS) Controller			

To simplify system integration and to allow an effective operation of a disaggregated WDM-System, the identification and specification of some relevant interconnection interfaces is paramount. In fact, in a disaggregated WDM-System HW and SW functional modules (O-NEs, Control and Management SW, subsystems blades, etc.) are ideally vendor agnostic, interchangeable and modular.

We can classify the interconnection interfaces into two broad categories:

- **Horizontal interfaces** assures physical and optical compatibility (horizontal interoperability) among: (a) DtoWDM and A-WDM; or (b) O-NEs of the same kind (e.g. TP versus TP); or (c) O-NEs belonging to the same network layer (e.g. O-NEs of the A-WDM layer); or (d) optical subsystem blades. Specifications include the ranges for relevant physical and optical parameters.
- **Vertical interfaces** assure compatibility between O-NEs and control, management and monitoring SW subsystems (vertical interoperability). SBIs and NBIs are within this category. Specifications include communication protocols, information models, and lists of relevant configuration and status entities.

Table 6 lists the relevant horizontal interfaces for the considered degrees of optical disaggregation, whilst Table 7 gives a list of the relevant vertical interfaces.

Table 6. Interfaces to be specified for horizontal optical interoperability

	Fully Aggregated Domain	**Partial Disaggregation**	**Full Disaggregation**
SWI specification		Mandatory	Mandatory
MWI specification			Mandatory
TP to TP interoperability specification		Not strictly mandatory (TPs in matched pairs from the same vendor)	Not strictly Mandatory (TPs in matched pairs from the same vendor)
A-WDM Layer Optical subsystems (EDFA, attenuator, etc.) interoperability specification			Mandatory only in disaggregation up to the subsystem blades

Table 7. Interfaces to be specified for integrated Management and Control

	Fully Aggregated Domain	**Partial Disaggregation**	**Full Disaggregation**
WDM-System NBI specification	Mandatory (a standard is not strictly needed)	Mandatory (a standard is not strictly needed)	Mandatory (a standard is not strictly needed)
A-WDM Controller NBI specification (OLS-NBI)		Mandatory (not applicable if OLS Controller is able to manage third party TPs and a TP SBI standard exists)	
TP SBI specification		Mandatory (a standard is not strictly needed)	Mandatory
A-WDM layer O-NEs **(MD-ROADM, LT, ILA, etc.)** **SBI specification**			Mandatory
A-WDM Layer Optical subsystem blades (EDFA, attenuator, etc.) **SBI specification**			Mandatory only in disaggregation up to the subsystem blades

Within METRO-HAUL all these aspects of horizontal and vertical interoperability are being addressed, although not all to the same degree of depth.

More specifically, attention is mainly dedicated to specifying interfaces supporting METRO-HAUL prototypes in WP3, implementations in WP4, and integration in the "vertical demos" in WP5.

Furthermore, it should be stressed that all the requirements given here are being subjected to a process of continuous refinement during the project lifecycle, so that they should be considered more correctly as "design guidelines", as they certainly do not pretend to be prescriptions to be observed as if they were true standards within the project.

3.3.4.1 Single Wavelength Interface (SWI)

This is the optical interface between the Digital-to-WDM adaption layer (DtoWDM) and the analogue WDM optical domain (A-WDM layer) of a WDM-System. In the specific case of partial optical disaggregation, it specifies the analogue optical interoperability between transponders, muxponders or switchpondes on the one side, and an Optical Line System (OLS) on the other. Common analogue parameters and their ranges are specified.

This interface covers also the case of transceivers (pluggable or not) integrated in a L2/3 switching fabric or other NE, directly interfacing with the analogue WDM optical domain.

Conversely this interface is not dedicated to an analogue transparent and flexible interconnection among two A-WDM domains (or two OLSs); optical interconnection between different metro segments deploying different optical transmission technologies but within a single optical managed domain are part of the MWI specification.

Similar specifications are already given by the OpenROADM MSA 2.2 [17], and it was agreed that they are already sufficiently completed to be adopted as a reference within METRO-HAUL. Accordingly, Table 8 is in line with them.

Specifications are given for single channel client signals; an extension to include super-channel clients (OTSiG, see section 3.3.5.1) is a topic for further study. The list of parameters included in Table 8 and their ranges are not intended to be exhaustive of all METRO-HAUL scenarios, but instead serve as a useful guideline for developments in WP4 and WP5. In particular, only the common analogue values needed for compatibility at the A-WDM client side are given: other transmission parameters connected to links length and amplifier performance, and all the parameters affecting system linear and non-linear performance (e.g. modulation format, acceptable minimum OSNR, etc.) are not included in this specification as they are given in chapter 4.

In the table “input” means from the DtoWDM to the A-WDM (e.g. from a transponder output line port to an OLS input client port). “Output” means the opposite.

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Table 8. SWI initial specification

Single Wavelength Interface (SWI)				
	Min	**Max**	**Unit**	**Note**
Input – Output power ranges				
Per channel input power range	-6	+3	dBm	Technology independent.
Per channel input OSNR (0.1 nm)	30(?)		dB	
Per channel output power range	-22	+1	dBm	Reference range selected for compatibility with 100G DP-QPSK and Cortina Staircase FEC @17 dB OSNR (0.1 nm). Extended ranges could be considered for specific applications. Reduced ranges should be accommodated by the A-WDM system.
Total output power		+13	dBm	Assuming multiple unfiltered channels and coherent filtering at receiver: up to 20 channel at max per channel output power. A different value could be considered for specific applications. Does not apply for DD solutions.
Fixed spectral grid				
DWDM frequency grid (fixed grid)		50-100	GHz	All A-WDM should support at least one of these two values.
Central frequency Range	C-band	C+L-band		Typically 96 channels at 50GHz (191.35-196.1GHz). Actual range depends on the specific A-WDM System implementation. Ranges could be on a port basis. Fixed filtered ports could accept a single frequency value. Colourless ports could have a maximum acceptable range up to the maximum specified for the whole A-WDM System.
Center frequency accuracy		1.8	GHz	
3 dB clear channel half bandwidth	-19	+19	GHz	
Flexible spectral grid				
Central frequency granularity		6.25	GHz	
Frequency slot width granularity		12.5	GHz	
Frequency slot width range (MC)	37.5 (25)	C-band	GHz	Actual range for Media Channel frequency slots depends on the specific A-WDM System implementation.
Frequency Range	C-band	C+L-band		Typically (191.325-196.125 GHz). Actual range depends on the specific A-WDM System implementation. Ranges could be on a port basis. Fixed filtered ports could accept a single frequency value. Colourless ports could have a maximum acceptable range up to the maximum specified for the whole A-WDM System.
Center frequency accuracy		1.8	GHz	
Channel dead-bands	6 (Typical)		GHz	The actual 3-dB clear effective channel bandwidth is the MC nominal slot width minus two times the channel dead-band.

3.3.4.2 Multi Wavelength Interface (MWI)

This interface is intended for horizontal compatibility among O-NEs within an A-WDM layer.

In METRO-HAUL several technological options are simultaneously considered for WDM-Systems in order to cover all the facets of METRO-HAUL comprehensive reference network context (Figure 6). All the options so far considered are discussed in some detail in chapter 4. Dedicated MWIs are under study for each option separately, as they are designed to address different targets.

3.3.4.3 Transponder to Transponder Interoperability

METRO-HAUL does not address a specification for a multi-vendor interoperability between the line sides of generic coherent or Direct Detection transponders. METRO-HAUL is following the evolution of official standards and MSAs in this respect starting from the ongoing work in ITU-T SG15 Q11 and OIF [16] and the evolution of OpenROADM MSA [17].

More relevance is given to the interoperability from DtoWDM and A-WDM (section 3.3.4.1) while interoperability between TPs is considered not strictly mandatory, as TPs in matched pairs from the same vendor are often a simple and valuable solution (e.g. they fit in perfectly with the partial disaggregation approach described in section 3.3.2, and could be acceptable in some fully disaggregated implementations as shown in Table 6).

Moreover, the expected near term introduction of pluggable Digital Coherent Optical sub-assembly (DCO) from some vendors like Acacia [18], with performance not far from to actual state-of-the-art digital transmitter/receiver couples, but with the promise of lower costs, are likely to push system vendors to widely adopt them. Matched pluggable DCO couples should interoperate smoothly, and hopefully should be compatible with several pieces of equipment from different vendors.

3.3.4.4 A-WDM layer Optical Subsystem Interoperability

In this document a generic specification for interoperability among subsystems from different vendors is not given, as all the actual implementations in METRO-HAUL are still in a development phase targeting specific use cases. For more details the reader is referred to section 5.

Furthermore, full disaggregation up to the subsystem level is not expected in the short-medium term time frame, with the only exception being of a sort of hybrid approach, with multi-vendor optical subsystem disaggregation limited to MD-ROADMs. Other O-NEs are still multi-vendor, but not disaggregated at the subsystem level. This is motivated by the presence on the market of the so-called ROADM blades (line degrees and Add&Drop complete subsystems on separate blades) (e.g. [19][20][21]) that can be assembled to form a complete MD-ROADM (see inset in Figure 15). Specifications for this particular case of hybrid fully-optical disaggregated approach are partially covered by OpenROADM [22].

For the sake of laboratory experimental evaluation of WDM-systems within METRO-HAUL, interoperability specifications for most subsystems, like EDFA and WSS modules, could be simply extracted from the optical specifications included in the commercial data-sheets of the components.

3.3.4.5 WDM-System NBI and Optical Line System NBI (OLS-NBI)

Here only a brief summary is reported for the sake of completeness, as a more detailed discussion of NBIs is included in D4.1 "METRO-HAUL Control and Management Requirements and Framework" [1].

Transport API [23] is a standard API defined by the Open Networking Foundation (ONF) that allows a TAPI client, such as a carrier's orchestration platform or a customer's application, to retrieve information from and control a domain of transport network equipment, such as a Transport SDN Controller. In other words, TAPI is a standard NorthBound Interface for a Transport SDN Controller. It supports both high-level technology-independent services (i.e., intent-like) and detailed technology-specific services, depending on policy.

In METRO-HAUL, the TAPI framework has been selected as a NBI interface (towards Orchestrators or towards parent controllers, as in the OLS-NBI case).

3.3.4.6 South Bound Interfaces (SBIs)

Only a brief summary is reported here for the sake of completeness, as a more detailed discussion of SBIs is included in the parallel D4.1 "METRO-HAUL Control and Management Requirements and Framework" [1] deliverable.

The METRO-HAUL consortium is adopting the OpenConfig YANG model for TP O-NEs of any kind belonging to the DtoWDM layer. An agent for O-NE controllers is being developed within the project. However, the developed agents could not include all the optional modules described within the OpenConfig models.

The OpenROADM models will be specifically used within project to model MD-ROADM O-NEs, with possible extensions to include F-OADM and FIs-OADM also being analysed. However, the developed agents can not include all the optional modules described within the OpenROADM models.

To enable the support of all experimental optical devices that will be developed within the METRO-HAUL project, the aforementioned OpenConfig and OpenROADM models could be extended within the project (e.g., some fields can be added / modified).

Many commercial devices currently available amongst the project's partners are based on YANG models not consistent with OpenConfig or OpenROADM devices. Such kinds of device will be supported at the controller by developing a device-specific NETCONF driver.

3.3.5 Services of Optical Transport Connectivity

Generally speaking, a network connectivity service is offered by a network to support the transparent interconnection among client devices (hosts) via the considered network domain. These devices do not explicitly form part of the network domain itself (i.e. they are not managed and modelled in detail within it), but they are attached to the physical network infrastructure at its access points (POPs). It is the task of the managed server network to take charge of the correct adaptation (mapping, multiplexing, etc.) of these client signals into suitable "server transport container", and of their routing through the network to guarantee transparent end-to-end connectivity.

What is discussed in this section is generally at a high level and is independent of the actual choices made in terms of the YANG model architecture and field specifications at both NBIs and SBIs.

For a more detailed discussion on how these requirements impact specific implementations within METRO-HAUL, the reader is referred to the parallel deliverable D4.1 "METRO-HAUL Control and Management Requirements and Framework"[1].

More explicitly, concerning the transport of client signals over an optical WDM transport Network infrastructure in the METRO-HAUL context, the list of high-level guidelines given in Table 9 should be applicable.

Table 9. High-level requirements and specifications for METRO-HAUL optical transport connectivity services

1	Basic connectivity services are: the reservation / creation / modification / deactivation of end-to-end transparent transport "Optical Tunnels" in the network between two access points, for a well-specified digital client or an analogue CBR signal (broadcasting / multicasting is not considered here as an elemental service, although it is technically feasible in filterless optical networks).
2	Requests for complex and/or higher layer network services (e.g. multi point L2/3 VPNs) are to be explicitly translated into requests for basic connectivity services. The subset of service requests involving pure optical connectivity (digital and / or analogue) are passed to the transport network controller and are split, if needed, by appropriate control/management entities (e.g. transport service orchestrator), into a finite set of separated basic connectivity service requests.
3	Client signals are uniquely identifiable in all their details, including the information content and the characteristics of the physical interfaces. Furthermore, there is a well-defined procedure of mapping them (adaptation) into the optical network.
4	Each optical transport network domain is abstracted toward higher hierarchy entities (“Clients”, which are actually requiring the services to the optical network) at NBI as a single managed topological entity with a defined number of access points (POP). The network operator must be able to add additional topological and status information and make it visible to the Client. Furthermore, the operator is always entitled to allow the automatic management of the Optical Tunnels by the Client.
5	It must be possible to dedicate topological subsets of the network to distinct customers (slicing).
6	Controllers dedicated to physical network domains must be able to export sufficient topological and status information and control methods through open or standardized NBI interfaces to perform all activities related to the execution of the required services.

These requirement apply to:

- A WDM-System as a whole, independently of the disaggregation degree considered, providing design guidelines for the NBI API of a Proprietary WDM Transport Controller (Figure 13) or of an OLS WDM Transport Controller (Figure 14b) or an Open WDM Transport Controller, (Figure 15).
- An analogue Open Line Systems, providing design guidelines for the OLS-NBI API (Figure 14a).

3.3.5.1 Digital Signals and Optical Channels

As briefly described in the introduction of section 3.3 a WDM-System includes a Digital-to-WDM adaption layer (DtoWDM) and a WDM Analogue transport layer (A-WDM), making the network intrinsically a two-layer one. Therefore two classes of services can be offered to customers:

- **digital optical transport services** involving the transport of digital information through the WDM-System;
- **analogue optical transport services** involving the transport of analogue “optical channels” directly by the A-WDM layer of the WDM-network. A network supporting this class of serviced is often said to “support alien lambdas”.

In order to transport digital client information through a WDM-Network it must be adapted and digitally "wrapped" (for example to enhance performance through coding and to add OA&M overhead) at the DtoWDM edge.

Often this mapping involves the ODU (Optical Data Unit) and OTU (Optical Transport Unit) transport units, which provide the adaptation and multiplexing functionalities of digital client signals and the functions of control, performance management, continuity and alarming and protection of the digital information transported between 3R regeneration points in the WDM optical network.

More precisely, two classes of OTU modules (and corresponding ODU containers) should be distinguished: OTUk (for transported signals with a capacity of up to 100 Gbit/s) and OTUCn for multiple transport units of 100 Gbit/s [24][2]. Furthermore, at the ODU level, one should speak of "rigid" ODUs in terms of capacities and adaptation modalities, and "flexible" ODUflex in the capacity and modality of adaptation of digital clients. Obviously, all these options are not mutually exclusive and can coexist in the same network.

The reference unit to be transported in the A-WDM layer is the "Optical Tributary Signal Assembly" (OTSiA), which is in a one-to-one relationship with the OTU transport module mapped on it. The OTSiA is an abstract management / control entity that represents and groups the set of modulated and coded optical carriers onto which the digital information to be transported is transcribed, the OTSiG (Optical Tributary Signal Group), and the corresponding overhead management / control unit not associated and transported on the network through a dedicated management channel (OSC), OTSiG-O.

Each OTSi part of the OTSiG group represents a single modulated optical carrier on which a part of the digital information to be transported is transcribed; obviously there are several possible variants of the OTSi, characterized by the central frequency and by an explicit list of all its characteristics (modulation format, signal optical bandwidth, etc.) or possibly implicitly by a suitable application identifier[3].

Each OTSi is carried individually by a Network Media Channel (NMC), logical topological entity representing the end-to-end "optical tunnel" through the serial concatenation of all supporting media channels between an OTSi modulator and an OTSi demodulator. All the OTSi's that are members of the same OTSiG are carried over the same fibre.

Finally, network media channels are mapped onto a concatenation of media channels for routing through the A-WDM layer.

Media Channel (MC) is the most important topological construct in the A-WDM layer, and represents both the path through the optical network and the resources it uses (central frequency

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[2] Annex H of G.709 includes also digital signals with capacity non-multiple of 100 Gbit/s (e.g. 150 Gbit/s) providing a OTUCn-M frame, consisting of *n* instances of OTUC, ODUC and OPUC overhead and *M* 5 Gbit/s OPUCn tributary slots. For example, OTUC2-30 corresponds to an OTU signal at 150 Gbit/s with 30 (5 Gbit/s) tributary slots and 2 instances of overhead. Note that these containers are suitable for transporting ODUCn of reduced capacity (20n-M).

[3] An application identifier includes the application codes defined in the appropriate optical system Recommendations or MSAs, as well as the possibility of proprietary identifiers. The identifier covers all aspects of the signal, including forward error correction, baud rate and modulation type.

and frequency slots). A media channel is delimited by two media ports at its ends and can be composed of a concatenation of other media channels (formally a NMC is a MC, but within the METRO-HAUL context we consider it as a separate entity representing the end-to-end “optical tunnel”). Within the network, a media channel can pass through many filters whose width can be variable: the frequency slot of a (concatenated) media channel is that part of the frequency common to all the slots allocated for the filters. A media channel can be configured to carry one or more OTSi’s, and must necessarily be instantiated prior to activation of the client optical signal.

Note that, in general, to transport an OTSiG, more than one concatenation of media channels could be activated at the server level at the same time (a sort of limited form of “optical inverse multiplexing”). In fact an OTSiG could be split into several disjoint groups of OTSi’s (for example groups could be created collecting together OTSi’s using adjacent spectral slots to be transported by a single concatenation of MCs, and assign a different MC concatenation for each group; an OTSIG composed by *N* OTSi’s all lying on non-adjacent 50 GHZ frequency slots are intrinsically generating *N* disjoint groups); the constraint that all the OTSi’s that are members of the same OTSiG are carried over the same fibre must anyway be kept. In the following we will identify each group with the term **OTSi-subG**.

We can now identify the generic requirements applicable to the two service categories being considered here.

3.3.5.2 Generic Requirements for Digital Optical Transport Services

The service consists in the activation / deactivation of a transparent point-to-point digital transport channel in response to a request between two POPs of the WDM-System for a specific client technology (ETH, OTN, SDH, etc.). The server network is a whole WDM-System.

Upon activation, the entity requiring the service is explicitly or implicitly specifying the details of the characteristic information to be transported (client type, bit-rate, hierarchical level in the client architecture, parameters to be negotiated, etc.); the requests and the constraints to be respected for the selection of the routing (disjoint flows, latency, etc.); the level of desired resilience (protection, restoration, pre-planned mixed forms, etc.); the QoS level to be respected (priority levels, etc.); and other possible accessory services to be activated (such as flow monitoring, explicit visibility of the routing, etc.).

The activation of the service involves the configuration by the WDM-System of the digital client-side interfaces of a suitable DtoWDM device according to the characteristics of the specific type of client; the management of the client adaption and mapping, its routing and the activation of a trail (or tunnel) ODUk / flex (if applicable) between the two POPs with the required characteristics; the creation, configuration and activation of any protection groups or other resilience features (restoration, etc.); and the activation and provision of ancillary services.

If a suitable supporting optical channel (OCh) or OTSiG (and the supporting concatenation of already activated network media channels) already exists between the two DtoWDM devices attesting the digital client signal (see section 3.3.5.3 for details), the activation process is completed. Otherwise, the activation of the service also requires the preliminary verification of the availability of appropriate one or more concatenations of media channels between the two DtoWDM devices at the access points. If successful, the media channels between the two POPs are activated with the required characteristics, and with the creation, configuration and activation of any protection groups or other resilience features (restoration, etc.), and the activation and provision of ancillary services (e.g. performance monitoring).

Actually, the request of the digital transport service internally (within the WDM-System) triggers a request for a supporting analogue transport service (see section 3.3.5.3). All of this process is hidden to the entity requiring the service, and is completely under the responsibility of the Controller of the WDM-System, irrespective of the optical disaggregation considered. From the perspective of the entity requiring the service, the WDM-System is indistinguishable from a fully aggregated WDM transmission system with a suitable NBI API.

3.3.5.3 Generic Requirement for Analogue Optical Transport Services on the A-WDM Layer

This transport service is of an analogue nature and requires the presence of optical continuity with acceptable degradation of the client optical signal between the two POPs of the analogue optical layer of the server network domain (A-WDM or OLS). As such, the customer flow does not undergo any 3R regeneration along the route (optical transparency).

In addition, the service is aimed at optical channel clients in the form of OTSiG (or Och) that carry OTU digital information modulated onto one or more carriers.

In general, the OTSi's of the client OTSiG could be presented not all together to the A-WDM network at the same access port of the analogue network (remembering that an OTSiG could be split into sub-groups of OTSi's); so more properly the client is, in general, asking for a transport service from a group of *P* related optical ports in POP A to a group of *P* related ports in POP Z, where the *N* optical carriers of the OTSiG (organized in *M* of OTSi-subG's) are attested. In the following we will call this group of ports the "Access Port Group"(APG).

The service consists of: (a) providing a logical NMC for each OTSi (*N* in total) with trail termination points (TTPs) at the client equipment line interfaces, and connection termination points (CTP) at the two supporting access ports of the A-WDM network; (b) a set of *M* supporting concatenations of media channels from POP A to POP Z, one concatenation for each "Access Port-sub-group" of the "Access Port Group" supporting all the carriers part of a specific OTSi-subG, of the *M* OTSi-subG's into which the OTSiG is split, globally configured to carry the whole OTSiG optical signal (Och); that is the whole set of modulated optical carriers onto which the digital information is distributed.

A concatenation of media channels is created having a common clear effective channel bandwidth sufficiently "big" to contain all the client OTSi's included in a specific OTSi-subG of the client OTSiG (which is then routed as a single entity with the constraint that all the OTSi-subG's of the same client must physically use the same fibres in the links along the network).

It is evident that there are considerable degrees of freedom in the coding and modulation of the OTU customer signal forming the OTSiG optical signal that more properly represents the information to be transported.

It should also be noted that the optical network server (A-WDM or OLS) must know enough details about the structure of the optical signal to be transported (both of the OTSiG as a whole and of each OTSi), in order to be able to:

- evaluate the impact on the other channels caused by both linear and nonlinear cross-talk, and by the induced variation, static and dynamic, on the saturation and equalization levels of the optical amplifiers;
- identify the minimum frequency slots of the media channels to be used to carry each OTSi-subG of the OTSiG;

- assign to the individual carriers of the OTSiG a related network media channel to be used for power and frequency monitoring services of the carriers and for intra-media channel equalization services;
- identify the accessory information to be transported on the overhead not associated with the optical signal (formation of the OTSiA);
- quantify for each potential route, the level of performance degradation on the digital signal carried in the optical signal, induced by the worsening of the signal-to-noise ratio, the returned signal power to the receivers, the presence of nonlinear crosstalk and linear distortions from the filtering effects, and from the fluctuation ranges and dynamics thereof;
- quantify the performance margin at the time of activation and for all potential future states of the network.

With particular reference to OTU4 and OTUCn (-M) transport units, which correspond to a whole class of coherent single and multi-carrier optical demodulated flows, the service request must therefore report explicitly (or allow implicit deduction through a suitable list of application identifiers) the information reported in the category list given below.

1. General characteristics of the required service. The following information should be provided by the entity requiring the service to the A-WDM (OLS) controller:

   - The digital client OTU module (OTUx, OTUC-n, OTUCn-M) to be transported;
   - A set of unique port IDs (identifiers) in POP site A (respectively Z) identifying ports in the "Access Port Group";
   - The list of constraints to be respected for the selection of the routing (diversity compared to other flows, latency, etc.);
   - The characteristics of desired resilience (protection, restoration, pre-planned mixed forms, etc.);
   - the QoS level to be respected (priority levels, etc.);
   - other possible accessory services to be activated (such as monitoring of single OTSi carriers, intra-media channel equalization, explicit visibility of routing, etc.).

2. Encoding and modulation information of the mapping of the client OTU signal onto the OTSiG optical signal. The following parameters should be provided by the entity requiring the service to the A-WDM (OLS) controller:

   - An OTSi-ID (identifier) for each OTSi in the OTSiG;
   - A Set-ID (subgroup identifier) for each OTSi-subG and the mapping of OTSi-IDs in each subgroup;
   - The mapping between OTSi-ID and port ID (and the induced the mapping of OTSi-subG into port-ID identifying the "Access Port-sub-group") ;
   - The signal bandwidth of each OTSi-subG as a whole, including the needed guard bands and the central frequency (not needed to comply with flexgrid central frequency and slot width granularities);
   - For each OTSi:
     - The modulated signal bandwidth (e.g. at -20dB) including guard bands to account for laser central frequency tolerance and to ensure negligible crosstalk amongst adjacent carriers (not needed to comply with flexgrid slot width granularity);
     - The central frequency (not needed to comply with flexgrid central frequency granularity);

  - Optionally: the spectral optical profile of the carrier (could be given by a trapezoidal shaped mask having a larger base as compared to the carrier modulated signal bandwidth; or by a profile identifier and a roll-off factor);
  - Symbol rate, modulation format, FEC / coding type of the single carrier;
  - Any other parameters to be identified.

3. Tolerance and performance acceptable ranges. The following parameters should be provided by the entity requiring the service to the A-WDM (OLS) controller:

   - For each OTSi-subG the maximum acceptable relative power unbalance between carriers during propagation;
   - The acceptable signal power range at receiver for each the individual OTSi carriers;
   - The acceptable total power range at the OTSi receiver input;
   - Minimum level of tolerated OSNR; maximum level of degradation due to non-linearity for each OTSi;
   - Maximum tolerated level of distortion due to filtering for each OTSi;
   - Maximum tolerated PMD chromatic dispersion for each OTSi;
   - Any other parameters to be identified.

4. Information on the state of propagation degradation already suffered by the input signal. The following parameters should be provided by the entity requiring the service to the A-WDM (OLS) controller:

   - Current OSNR level at the input port for each OTSi;
   - Optionally: relative unbalance between carriers within each OTSi-subG already undergone during propagation in previous network domains;
   - Optionally: PMD and chromatic dispersion already accumulated in other domains;
   - Optionally: degradation due to accumulated non-linearity;
   - Optionally: distortion level due to filtering;
   - Any other parameters to be identified;

This last information regarding the transmitter OSNR level could be useful for the management of multi-domain scenarios in which intermediate domains receive service requests from a multi-domain controller, and in which the input signal has already undergone partial degradation.

In many situations of practical interest, the information of group 3 could be summarized, together with others from group 2, in application identifiers specific to the type of client signal: the domain controller should be able to implicitly derive the necessary information from the application identifier.

Returning to the specificity of an analogue optical transport service, we can distinguish two cases according to the set of negotiable parameters:

- **Analogue optical service without negotiation:** the information of group 1 together with application identifier (or explicit lists of encoding and modulation parameters and tolerance and performance ranges) are explicitly stated in the request and are not negotiable;
- **Analogue optical service with negotiation:** all or some of the coding and modulation parameters are negotiable.

Case without negotiation

When requesting activation of the service, the digital OTU module (OTUx, OTUC-n, OTUCn-M), the application identifier (or the parameters of encoding and modulation and tolerance and performance ranges in explicit form) and the requests and the constraints in group 1 are uniquely specified.

The activation of the service requires the verification of the availability of an appropriate set of concatenated media channels between the access points to serve all the OTSi-subGs, satisfying the required constraints, the end-to-end performances and without impacting on the existing flows in the network. If successful, the set of concatenated media channels between the two POPs is activated with the required characteristics, and with the creation, configuration and activation of any protection groups or other resilience features (restoration, etc.), and the activation and provision of ancillary services (e.g. performance monitoring).

Case with negotiation

When requested to activate the service, the digital OTU module (OUTx, OTUC-n, OTUCn-M) is given together with the list of requirements of group 1.

A list of available application codes (or a set of coding and modulation parameter groups and a tolerance and performance range in explicit form) are specified by the client, and sorted according to the client priority level. The mapping options are negotiated with the supporting network controller to find the best mapping of the OTU client information in a OTSiG compatible with the optical transport network.

The activation of the service requires the checking each option, presented by the client in priority order, against the availability of an appropriate set of concatenated media channels between the access points to serve all the OTSi-subGs satisfying the required constraints, the end-to-end performances, and without impacting on the existing flows in the network. If successful, a set of concatenated media channels between the two POPs is activated with the required characteristics and compatible with the highest possible priority level specified by the client.

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4 METRO-HAUL Options for WDM Transport Systems

Depending on the characteristics of the METRO-HAUL network and target applications/capacity, different WDM transport systems may be recommended. In shorter and low capacity links, simple filterless topologies employing only simple modulation formats may be sufficient, while ROADM-based architectures and more advanced modulation formats may be required for the longer, more meshed networks. The different network topologies with relevance for the METRO-HAUL scenarios are presented in this chapter, as well as an overview of the most promising modulation formats for each case.

4.1 Modulation Formats Suitable for METRO-HAUL Scenarios

While transporting the maximum capacity per transmission fiber is one of the main requirements when choosing modulation formats for optical core networks, this is not necessarily the case for metropolitan networks. In this case, achieving the lowest cost per transmitted bit is just as important a decision factor, if not the most relevant one. Indeed, very simple, low capacity interfaces have historically provided the best solution for metropolitan scenarios. This approach is, however, being challenged by the ever-increasing demand for capacity.

Table 10 Modulation formats with high potential for METRO-HAUL networks.

Modulation format	Tx DSP	Tx Front-end	Rx Front-end	Rx DSP	Bitrate per channel	Dispersion Compensation
QPSK/ M-QAM	yes (optional)	DAC (optional) + IQ-MZM	CO	yes	Up to 600 Gbps	DSP
NRZ	no	MZM	DD	no	Up to 50 Gbps	Si-integrated ODC or legacy DCF
4-PAM	no	MZM	DD	no	Up to 50 Gbps	Si-integrated ODC or legacy DCF
DMT/OFDM (Adaptive BPSK/M-QAM per subcarrier)	yes	DAC + MZM	DD	yes	Up to 50 Gbps	DSP or Si-integrated ODC or legacy DCF (Not required up to 35km at 50Gbps)
IQ-Duobinary	yes (analogue)	IQ-MZM	DD	no	Up to 50 Gbps	Si-integrated ODC or legacy DCF (Not required up to 15km at 50Gbps)

Table 10 provides an overview of modulation formats with high potential for METRO-HAUL networks. These modulation formats comprise quite a broad range of alternatives, from the very cheap but with reduced spectral efficiency NRZ employing direct-detection (DD), up to 64-QAM modulation employing coherent-detection (CO), which has the capacity to transmit as much as 600

Gbit/s in a bandwidth of just 75 GHz, but requires the use of a much more complex, and therefore more costly, RX structure.

Table 11 Detailed description of modulation formats considered for METRO-HAUL scenarios.

Modulation format	RX	DSP at RX	Symbol rate [GBd]	Data rate [Gbit/s]	Grid [GHz]	Required OSNR [dB]	SE [bit/s/Hz]	RX Input power range [dBm]
NRZ	DD	no	10	10	50	14.8 (BER 10^{-9})	0.2	[-18 0]
IQ-Duobinary	DD	FEC	53.5	50	75	18	0.66	[-10 +5]
DMT/OFDM (adaptive BPSK/M-QAM)	DD	yes (advanced)	20	50	25/37.5/50	34.2	2/1.66/1 (adaptive)	[-25 -5]
QPSK	CO	yes (light)	25	100	37.5	15.6 (BER 10^{-9})	2.7	[-20 0]
QPSK	CO	yes (advanced)	32	100	37.5/50	14.5/14	2.7/2	[-20 0]
8-QAM	CO	yes (advanced)	32	150	37.5/50	18.5/18	4/3	[-20 0]
16-QAM	CO	yes (light)	12.5	100	25/37.5	22.5 (BER 10^{-9})	4/2.7	[-20 0]
16-QAM	CO	yes (advanced)	32	200	37.5/50	20.5/20	5.3/4	[-20 0]
32-QAM	CO	yes (advanced)	32	250	37.5/50	23.5/23	6.7/5	[-20 0]
64-QAM	CO	yes (advanced)	32	300	37.5/50	26.5/26	8/6	[-20 0]
QPSK	CO	yes (advanced)	64	200	75/87.5/100	18.3/18/18	2.7/2.3/2	[-20 0]
8-QAM	CO	yes (advanced)	64	300	75/87.5/100	22.3/22/22	4/3.4/3	[-20 0]
16-QAM	CO	yes (advanced)	64	400	75/87.5/100	24.3/24/24	5.3/4.6/4	[-20 0]
32-QAM	CO	yes (advanced)	64	500	75/87.5/100	27.3/27/27	6.7/5.7/5	[-20 0]
64-QAM	CO	yes (advanced)	64	600	75/87.5/100	30.3/30/30	8/6.9/6	[-20 0]

Table 11 provides additional information for a wide range of signal formats that will be considered for the METRO-HAUL transmission scenarios. While NRZ and coherent modulation formats with baud rates equal or smaller than 32 Gbaud are already quite mature and commercially available, coherent modulation formats with a baud-rate of 64 Gbaud are still state-of-the art. These modulation formats are, however, quite promising as their very high capacity provides the potential to achieve a reduction of the cost per transmitted bit. Furthermore, METRO-HAUL is also dedicating efforts to investigate alternative modulation formats for direct detection that can better tolerate undercompensated chromatic dispersion with low transponder complexity, such as the IQ-Duobinary as well as DMT.

4.2 Filterless Network Architecture

The correct selection of the modulation formats to use is one the most critical parts when designing a WDM transport system. Another just as important step is the selection of the network node architecture to deploy, as it will impact considerably the total network cost as well as the maximum capacity and reconfiguration capability of a network. The filterless approach is presented and discussed in this section.

4.2.1 DuFiNet Architecture

A filterless metro network architecture identified as Dual Fibre Network (DuFiNet), as depicted in Figure 16, is investigated in METRO-HAUL. It employs two separate fibres in a bus topology where one fibre is used for adding traffic/channels (upstream fibre) and a second for dropping traffic/channels (downstream fibre). The two fibres together with the Access Metro Edge Nodes (AMENs) and Metro-Core Edge Node (MCEN) comprise the Metro network. In DuFiNet, there is no direct connectivity between AMENs; instead, the channels transporting the "add" traffic are inserted onto the upstream fibre by means of a 3 dB coupler in the ADD section of an AMEN. They are passively combined with the wavelength channels in transit, so the traffic from all AMENs is transported to the MCEN where the wavelengths are either transparently steered (via a suitable WSS) to the downstream fibre, or are terminated, regenerated and groomed before being forwarded to the Core or back downstream.

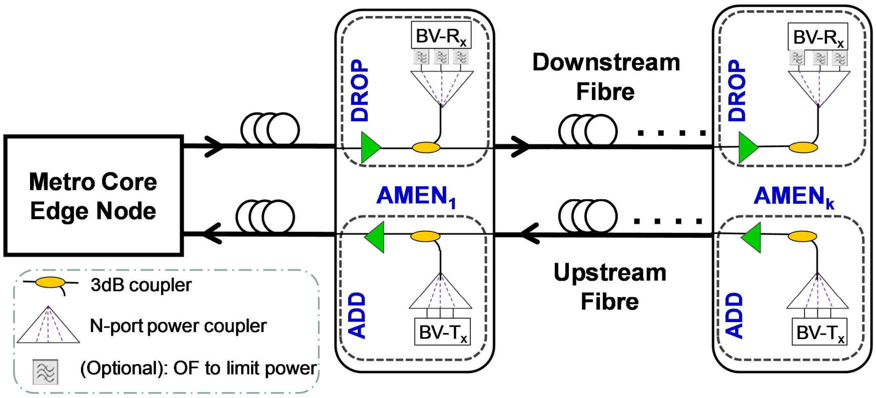


Figure 16. Schematic illustration of the DuFiNet architecture

The channels in the downstream direction are broadcast to all AMENs and a copy of the entire wide-band signal is tapped-off by a 3-dB coupler in the DROP part of every AMEN. As such, the proposed architecture allows for a complete decoupling between the ADD and DROP transportation paths. As is shown in Figure 16, the transmitter/receiver blocks are attached to the 3dB coupler in the Add&Drop sections, respectively, by means of N-port power couplers. Here, the term "filterless" refers to the absence of any optical filter in the transit path of AMEN, as such filtering is responsible for limitations like filter narrowing [25] and extra cost. The use of demultiplexers or optical filters is not precluded at the Add&Drop segments as their use does not induce performance degradations. A (tunable) filter is optionally attached to each output port of the N-port power coupler in the DROP section, to limit the total power entering the receiver as in [26].

An advantage of the DuFiNet is that, by separating upstream and downstream traffic, only one 3dB coupler is required per fiber per AMEN, instead of two as in other filterless architectures [27][28], improving the OSNR performance of the link while still overcoming restrictions in the utilisation of the available spectrum as well as limitations in the attainable capacity. Moreover, thanks to the filterless transit ("through") path, the architecture is transparent to modulation format and channel bandwidth requirements offering considerable control and management simplifications. Finally, it is also the lowest cost solution possible.

Based on the arguments of [29], high and small capacity channels employing mixed modulation formats will coexist in metro networks. To address the former, we consider systems that employ coherent channels at 100 Gbit/s and NRZ channels at 10 Gbit/s simultaneously. The presence of NRZ channels forces the use optical dispersion compensation modules (DCMs). Since DCMs are deployed, we also consider the potential of "lite" Bandwidth Variable Transceivers (BVTs) for coherent 100 Gbit/s transmission. Lite BVTs are medium-haul transceivers that trade DSP functions for lower cost/power consumption. However, they might be employed only under high performance physical layer conditions. In this context, we therefore study two different configurations for the AMEN's Add&Drop sections, as illustrated in Figure 17.

In the first alternative (C-I), a dispersion compensating fiber (DCF) is placed periodically in the transit part of all AMENs providing a compensation ratio (CR) of CR=95% for the dispersion due to the previous single mode fiber (SMF) section. In the second alternative (C-II), the DCF is placed only at the ADD and the DROP parts of an AMEN before the 3dB coupler. In C-II, the DCF at the ADD compensates for the dispersion from the particular AMEN until the MCEN whilst the DCF in the DROP compensates for the accumulated dispersion from the MCEN until that particular node. We assume there are up to 16 channels per AMEN. When coherent and NRZ channels coexist, these are packed in separate sub-bands; the filters at the output ports of the power couplers, besides limiting the optical power, are also used to select the NRZ channels. The two configurations, C-I and C-II, differ in cost, as two-stage EDFAs are used in C-II. The corresponding EDFA gains are shown in red in Figure 17 for C-I and C-II. The EDFAs employed in the transit path of an AMEN exactly compensate for the SMF losses, which also includes the losses due to the DCF for C-I. No in-line EDFAs are employed.

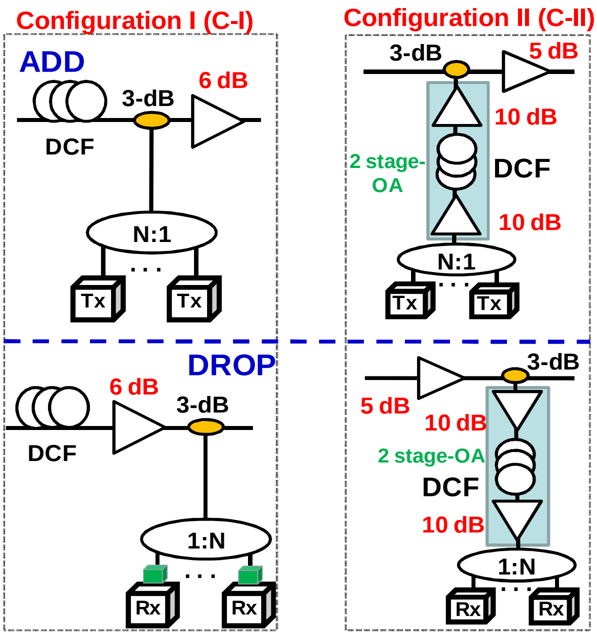


Figure 17. The Add&Drop sections of AMEN in detail

The impact on the system performance due to: i) modulation formats, by considering transmission with QPSK, 16-QAM and NRZ; ii) optical bandwidth; iii) baud-rate; iv) guard-band; and v) channel spacing, have been studied. In particular, for coherent channels we benchmark a "dense" (S-I) and a "coarse" (S-II) 16-QAM with a PM-QPSK (S-III) system as in Table 12. Finally, S-IV consists of two sub-bands with an equal number of NRZ and QPSK channels per sub-band.

The distance between AMENs is set to 10 km, and there are 6 dB losses at the MCEN due to the WSS that is compensated for by an EDFA. The SMF and DCF parameters are: α= 0.2dB/km, D=17ps/nm/km, γ=1.317, $W^{-1}km^{-1}$; and α =0.5dB/km, D=-85ps/nm/km, γ=0, respectively. The EDFAs are characterized by a constant noise figure of 6 dB.

Table 12. Signal formats for DuFiNet

	System I (PM-16QAM, Dense)	System II (PM-16QAM, Coarse)	System III (PM-QPSK)	System IV (NRZ and PM-QPSK)
Baud rate	12.5 Gbaud	12.5 Gbaud	25 Gbaud	10 Gbaud
Optical Bandwidth	12.5 GHz	12.5 GHz	25 GHz	10 GHz
Guard Band	12.5 GHz	25 GHz	12.5 GHz	40 GHz
Channel Spacing	25 GHz	37.5 GHz	37.5 GHz	50 GHz

The physical layer degradation was assessed by means of the optical signal-to-noise plus interference ratio (OSNIR).

$$OSNIR = \frac{P}{P_{ASE} + P_{FWM}} \quad (1)$$

where *P* is the power per channel. The GN model is valid only under considerable dispersion [30][31], which *is not* our case due to: i) the relatively short transparent length, and ii) the employment of a dispersion managed system. Therefore, the power of four-wave mixing (FWM) is given by [31]:

$$P_{FWM} = \frac{6/5 \cdot \gamma^2 L_{eff}^{\ 2} P^3 N_s^{\ 2} c}{\lambda^2 B^2 D \sqrt{\left(\frac{2}{a}\right)^2 + z / \left(\sum_{k=x_1}^{x_2} \frac{1}{1 + \left(2k\pi / aL(1-CR)\right)^2} \right)^2}} \cdot Log \left[\frac{N_{ch}^{\ 2} \pi \lambda^2 B^3 D / (B + 2GB)}{4c\left((N_{ch}-1)/2\right)^{\frac{2GB}{B+GB}}} \sqrt{\left(\frac{2}{a}\right)^2 + z} \right] \quad (2)$$

where $x_1 = -\frac{\lambda^2 B^2 DL(1-CR) N_{ch}^{\ 2}}{16c}$, $x_2 = \frac{\lambda^2 B^2 DL(1-CR) N_{ch}^{\ 2}}{2c}$, $z = 2L^2(1-CR)^2(N_s^{\ 2}-1)$, N_{ch} *is* the number of channels, *L* the distance between AMEN.

To assess the capacity limit over transparent lengths appropriate for Metro links, the remotest upstream k^{th} AMEN in Figure 16 adds its full capacity while the other AMENs progressively add their full capacity in the upstream path. At the MCEN, the wavelength group is transparently forwarded to the downstream fibre and it is finally dropped at the $(k-1)^{th}$ AMEN. This is the worst possible scenario for the central channel in the spectrum added at the k^{th} AMEN. For low P values, Eq. (1) is OSNR-limited, while for high P values it is FWM-limited. The value of P_{opt} balancing the two effects is the one that maximises OSNIR. The OSNIR values of the k^{th} node vs. the cascaded AMENs for P_{opt} are illustrated in Figure 18.

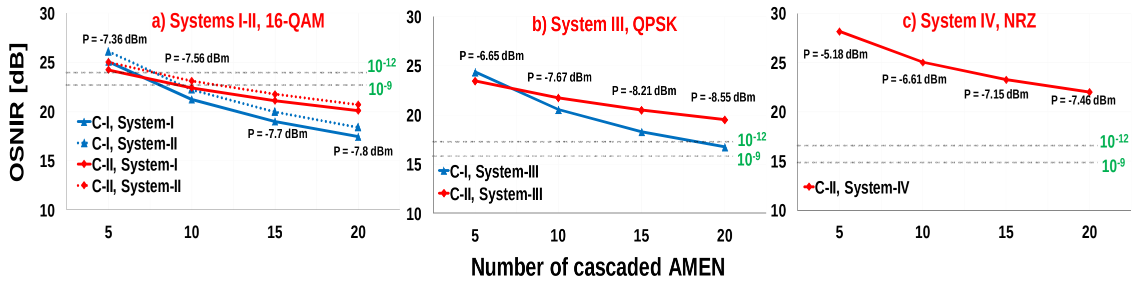


Figure 18. OSNIR values for different systems and configurations

Evidently from Figure 18 (a) and (b), C-II surpasses C-I in performance. This is because the in-line dispersion compensation in C-I allows the FWM products to add-up in phase, strengthening the impact of FWM at longer transparent lengths. To deploy "lite" BVTs, a high performance optical layer is mandatory, with indicative performance thresholds as listed in Table 13, which is obtained from $BER_{QPSK} = 1/2 \cdot Erfc\left(\sqrt{OSNIR/2}\right)$ and $BER_{16QAM} = 3/8 \cdot Erfc\left(\sqrt{OSNIR/10}\right)$.

Table 13. Representative OSNIR values

BER	OSNIR for PM-16QAM	OSNIR for PM-QPSK	OSNIR for NRZ
10^{-12}	23.9 dB	17.0 dB	16.1 dB
10^{-9}	22.5 dB	15.6 dB	14.8 dB

Table 14. OSNIR [dB] and total system capacity (in a bandwidth of 5 THz), assuming BER<10^{-9}

Path Characteristics	DuFiNet Configuration I/ Configuration II (QPSK)	DuFiNet Configuration I/ Configuration II (16QAM-Dense)	DuFiNet Configuration I/ Configuration II (16QAM-Coarse)	DuFiNet Configuration II (Mixed NRZ-QPSK)
2 spans of 10 km	29.30 / 24.92	29.99 / 25.83	31.01 / 26.66	27.62
4 spans of 10 km	25.6 / 23.9	26.29 / 24.73	27.31 / 25.52	27.37
6 spans of 10 km	23.38 / 23.06	24.06 / 23.83	25.08 / 24.58	27.30
8 spans of 10 km	21.79 / 22.35	- / 23.07	23.48 / 23.79	26.01
10 spans of 10 km	20.55 / 21.74	- / -	- / 23.11	25.03
12 spans of 10 km	19.54 / 21.2	- / -	- / 22.52	24.24
14 spans of 10 km	18.7 / 20.72	- / -	- / -	23.57
16 spans of 10 km	17.97 / 20.28	- / -	- / -	22.99
18 spans of 10 km	17.33 / 19.88	- / -	- / -	22.48
20 spans of 10 km	16.76 / 19.52	- / -	- / -	22.02
Capacity [Tb/s]	**13.33**	**20**	**13.33**	**6.27**
Number of channels	**133**	**200**	**133**	**114 (57 QPSK; 57 NRZ)**

From the results shown in Figure 18 and also in Table 14, it is deduced that the most robust modulation format is coherent QPSK, as it provides a BER of at least 10^{-12} without FEC even after a cascade of 20 AMENs, with a total length of 200 km. The same conclusion is drawn for a system with mixed coherent QPSK and NRZ channels. On the other hand, only 12 AMENs with a total length of 120 km are feasible without employing FEC when a coarse 16-QAM system is employed and a BER < 10^{-9} is required. If system-II is used, which has twice the guard-band of System-I but at the expense of a lower number of channels, the OSNIR is improved by a moderate ~1dB.

The impact of these findings in DuFiNet's operation are considerable: under small/moderate connectivity requirements, the QPSK modulation may be employed. When the required connectivity increases (e.g., a new AMEN is added), the modulation format may switch to 16-QAM so that some spectral slots/channels are released and made available to connect the new AMEN. For an even higher number of nodes and/or longer lengths, the remotest nodes may still use QPSK modulation while the inner AMENs, that span shorter lengths, can use 16-QAM.

4.2.2 Maximum Capacity of Drop&Waste Architecture

While the previous section presents the cheapest possible solution for a METRO-HAUL network, this section analyses the most typical filterless approach, which consists in the Drop&Waste (D&W) topology. The fundamental blocks for this topology are splitters and combiners, used to drop and add new channels to the network, respectively.

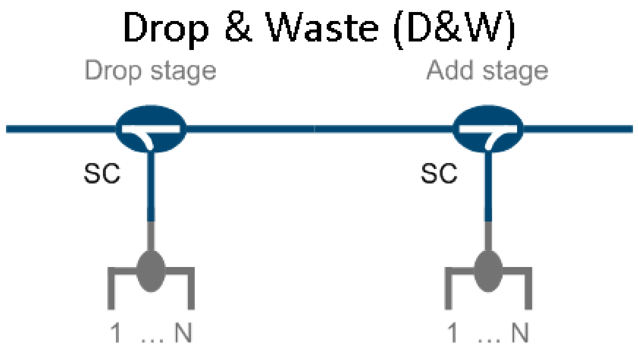


Figure 19. Typical structure of a D&W node

The D&W topology is particularly interesting in ring and horseshoe networks, where the wavelength blocking characteristic of this topology is not very critical. In this case, the add/drop nodes have only a nodal degree of 2, and are implemented as shown in Figure 19.

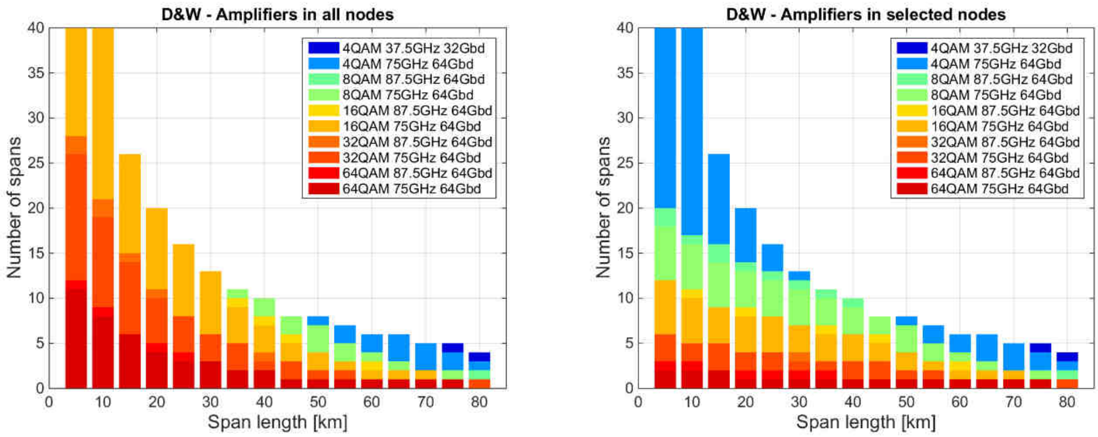


Figure 20. Best modulation formats considering D&W architecture and different link characteristics with optical amplification in all nodes (left) or in only selected ones (right)

Figure 20 shows the best channel format that can be used in a horseshoe/ring D&W network considering different span lengths and number of spans. The considered channel formats are the ones shown in Table 11 (based on advanced DSP), which are sorted by capacity with the spectral efficiency used to solve ties. Figure 20 is obtained by numerical simulation assuming a loss of 8 dB at each node (express layer), connector losses of 0.5 dB, an EDFA noise figure of 6 dB and linear fiber transmission along SSMF characterized by an attenuation coefficient of 0.25 dB/km. An average power level of 0 and 3 dBm are set for the 32 and 64 Gbaud signals, respectively. The signals are launched into the optical fiber with an OSNR of 35 dB and a minimum system margin of 3 dB is imposed to guarantee the correct system operation during an extended period of time. The maximum span count and path length are set to 40 and 400 km, respectively. Two different approaches are considered for the amplifiers placement: 1) they are placed at the output of each node and set to compensate the accumulated loss; or 2) they are only placed in nodes where the preceeding total accumulated loss exceeds 20 dB and are set to compensate a fixed loss of 20 dB. This approach enables a more cost efficient deployment of amplifiers, but at the trade-off of a worse optical performance.

Table 15. Maximum carried capacity [Tb/s] with D&W architecture (number of channels between parentheses)

Path Characteristics	Capacity [Tb/s] D&W (filterless)
5 spans of 20km	36.0 (60)
10 spans of 5km	36.0 (60)
10 spans of 10km	36.0 (62)
10 spans of 15km	35.0 (64)
15 spans of 10km	30.0 (60)

In order to translate the use of the best channel formats shown in Figure 20 into an actual network capacity, Table 15 shows the maximum carried capacity in a network with different characteristics, assuming a hub-and-spoke model and the deployment of amplifiers in all nodes. The transmission over the entire C-band (4.8 THz) is assumed. The analysis of Table 15 shows that the combined use of advanced modulation formats with a D&W topology potentially enables achieving a very high capacity in typical METRO-HAUL transmission scenarios.

4.3 Open Experimental Filterless Testbed

In order to experimentally validate various filterless concepts, an open filterless testbed infrastructure has been assembled at HHI, providing various options for modulation formats and channel spacings in the C+L-band.

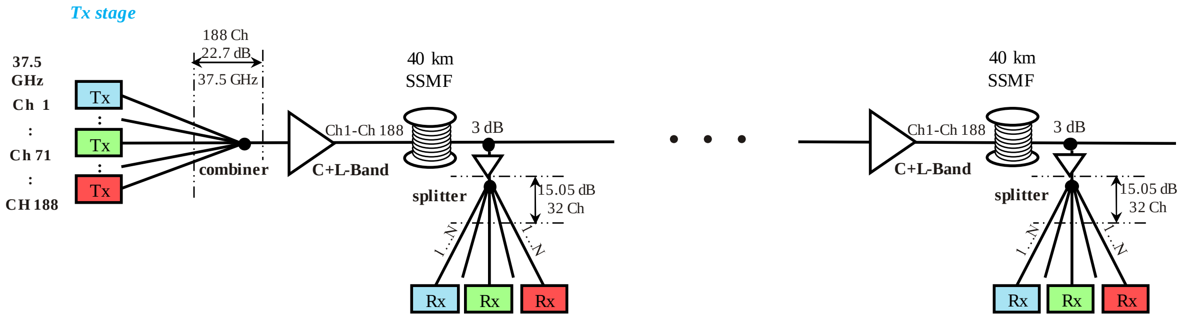


Figure 21. Concept for a testbed of DuFinet downstream and drop path of a D&W network

Figure 21 shows the concept for the drop path of the Drop & Waste network topology which is equivalent to the DuFinet downstream. Here 188 channels are generated at the Tx stage in the C- and L-bands. Each span consist of an C+L-band EDFA, 40 km of SSMF (variable length options) and a 3 dB coupler for the drop stage. Each drop stage can receive 32 channels in the C- and L-bands and consists of an EDFA followed by a passive splitter with a loss at the drop stage of 15 dB (i.e. 32 channels). At the Rx, a coherent receiver with TIA is employed in order to combine optical and electrical amplification. This concept is realized in a filterless testbed as shown in Figure 22.

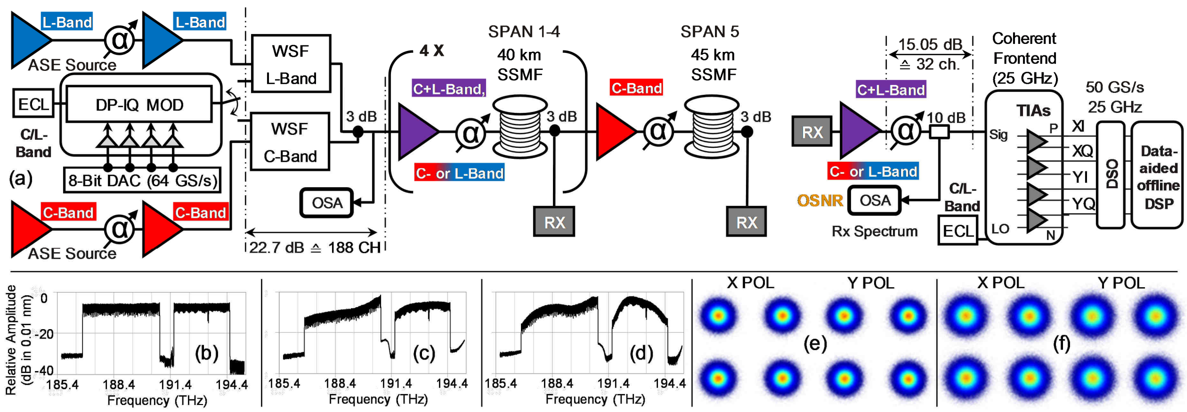


Figure 22. (a) Filterless C+L lab testbed at Fraunhofer HHI, (b) Tx spectrum, (c)BtB Rx spectrum (d) span 4 Rx spectrum, (e) BtB received constellation and (f) span 4 received constellation

Figure 22 provides an overview of an emulated 188 channel system with a division of the C-band into 79 channels and L-band into 109 channels at 37.5-GHz spacing (from 194.45 to 191.6 and from 190.8125 to 186.7625 THz). The 32-GBd QPSK channel-under-test (CUT) is generated from a tunable external cavity laser (ECL, 16 dBm) using a LiNbO3 dual-polarization IQ modulator. The IQ modulator is driven by four outputs of an 8-bit, 4-channel, 64-GS/s digital-to-analogue-converter (DAC) followed by 4 linear driver amplifiers. This allows to consider the QPSK and M-QAM configurations discussed in section 4.1. Up to 187 interferer channels can be shaped from two amplified spontaneous emission (ASE) sources including two programmable wavelength selective filters (WSFs). The attenuation of both WSFs is set such that the CUT experiences an additional loss of 22.74 dB in order to emulate filterless combining of 188 channels. The resulting flat spectrum after the WSF is shown in Figure 22 (b). The back-to-back (BtB) spectrum after the Rx-EDFA is shown in Figure 22 (c), where the spectral gain tilt is visible. The spectrum at the end of span 4 (after 160 km) is shown in Figure 22(d). For reference, recovered constellations for BtB and after span 4 at 194.45 THz are reported in Figure 22 (e) and (f).

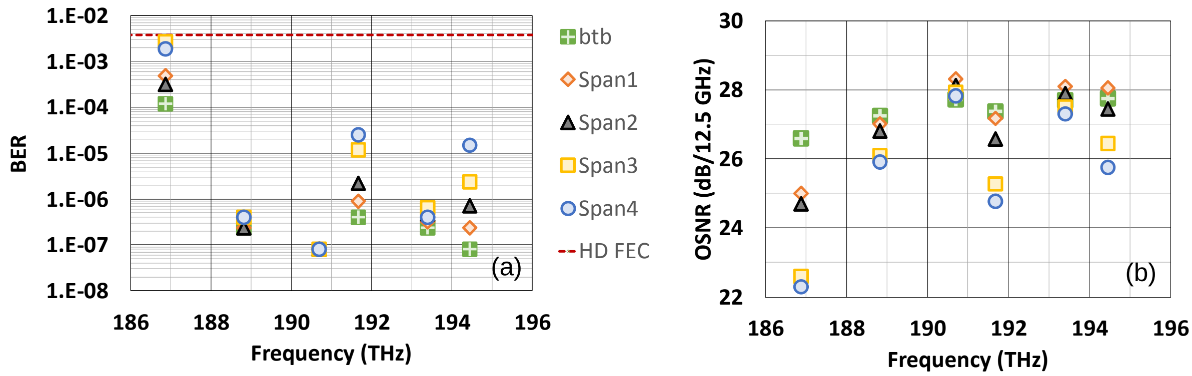


Figure 23. C+L-Band transmission results for (a) BER vs. frequency and (b) OSNR vs. frequency

Figure 23 shows the results for BER versus frequency and OSNR versus frequency for transmission in the filterless testbed from Figure 22. The degradation in OSNR over the link (up to 3.3 dB over 160km) is visible in Figure 23 (b). Since the EDFAs do not include gain-flattening filters, the impact of the gain tilt (cf. Figure 22(c) and (d)) is visible in Figure 23 (b), where the OSNR of all outer channels in the C-band and the lower channels in the L-band is decreased considerably. This degradation is also reflected in the BER at Figure 23 (a). All six measured channels could be transmitted within the HD-FEC limit of $3.8*10^{-3}$. In the considered configuration, distances of more than 160 km in the L-band are not possible for all channels since lower frequencies suffer from additional OSNR degradation. For increased transmission distance (i.e. more than 160 km) transmission must be performed in the C-Band. One option for the DuFiNet architecture could be a mixed network (as in Figure 22 (a)) with C+L-band in the first spans and C-band only in the last spans.

The filterless testbed will remain operational until the end of the METRO-HAUL project and is designed as an open platform to test also the Drop&Waste architecture as well as filtered approach with wavelength blockers in the add/drop node.

4.4 Filtered Network – Broadcast&Select

This section presents the Broadcast&Select (B&S) architecture. This node architecture is more complex, and therefore costlier, than the filterless one, but provides the flexibility that may be mandatory in many cases. The fundamental blocks for this node architecture are optical splitters (for the channel drop) and optical filters/WSSs/wavelength blockers (for the add/multiplexing of channels).

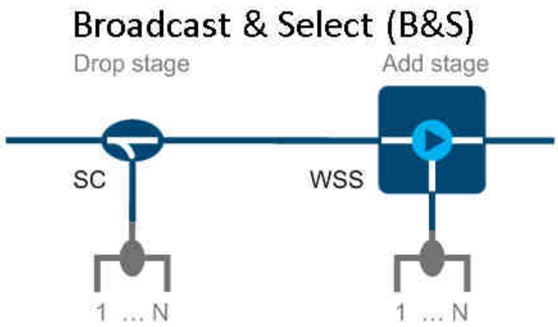


Figure 24. Typical structure of a Broadcast&Select node

The wavelength selection capability of the B&S architecture makes this architecture a very efficient topology for meshed networks and also a relevant alternative for the ring and even horseshoe topologies where the hub-and-spoke model is not realistic. In this case, the add/drop nodes are implemented as shown in Figure 24.

In order to reduce the cost of the B&S architecture, the WSS may be exchanged with wavelength blockers. This approach corresponds to a “slightly” filtered solution. Such a configuration enables wavelength re-use after dropping, while keeping the filterless network’s advantages of multicast capability, flexible channel allocation and (semi-)grid-less operation. The capability of grid-less operation is mainly determined by the blocking options (granularity) offered by the wavelength-blocker device. The configuration of the node, in this case, is as shown in Figure 25. It is mainly intended to be used with coherent modulations formats since, in that case, no additional filters are required at the splitter ports for dropping wavelengths. However, in an upgrade scenario where direct detection formats, like NRZ, are still employed, filters like AWGs can be included at the drop ports. Moreover, the amplifier stages at the edges of the node could be equipped with dispersion compensation modules to enable sufficient transmission reach for IM-DD formats. However, the targeted application should be a network with coherent transponders. Since the transmission distance in a metro network is limited to, at most, a few hundreds of kilometers, the focus can be laid on low-cost and low power consumption coherent transponders with potentially reduced DSP functionalities. Indeed, the capability to compensate high amounts of chromatic dispersion or PMD is not required. Additionally, stringent power/OSNR requirements are also not to be met.

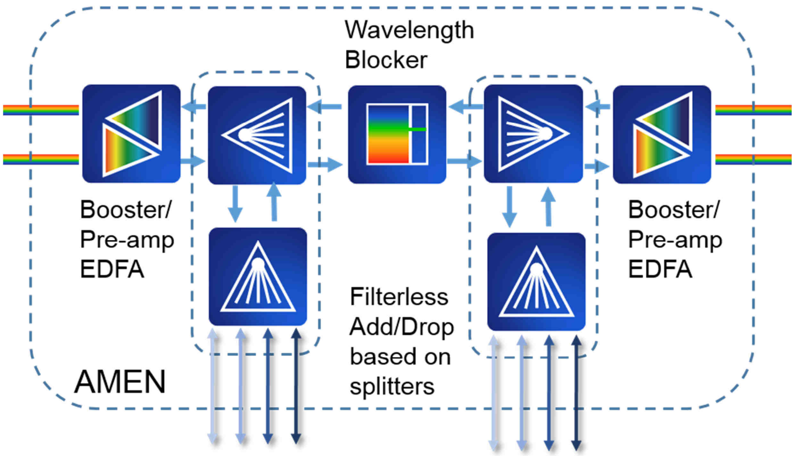


Figure 25. B&S node architecture employing only a wavelength blocker as filtering device

To optimize the throughput of such a node, splitting ratios of the couplers have to be determined carefully. Dependent on the link lengths, the splitting ratios could be chosen differently for each AMEN. For longer links, it could be beneficial to transmit a higher amount of power through the node and drop a lesser fraction, resulting in a nearly constant OSNR in all nodes and enabling the use of the same modulation format in the whole ring/horseshoe and on each wavelength. Moreover, in the case of very short links or ring scenarios, it might be possible to omit the booster EDFA and thus simplify the whole architecture.

Instead of optimizing the splitting ratio, the nodes can be equipped with flexible transponders with the ability to switch between different modulation formats according to the targeted reach and available OSNR. Presuming coherent transmission, due to the flexible choice of channel allocation, an arbitrary combination of transponders with different bandwidth requirements and from various vendors can be combined in the metro ring.

There are some aspects which need to be elaborated more in detail:

- Since for metro scenarios low-cost devices will be used at the transponder side, laser side modes are an issue to consider when adding channels without any filtering. Limitations for side mode suppression ratios according to the envisioned total number of channels have to be determined.
- The blocking ratio in the wavelength blocker, e.g. the attenuation of the blocked wavelengths, has to be set carefully to allow wavelength re-use without significant penalty. The influence of residual cross-talk dependent on the modulation formats in use should be investigated.
- Modern low-cost transponders, e.g. based on Silicon Photonics modules might include an amplifier (EDFA or SOA) already in the transmitter module and, thus, already broadcast broadband optical noise in addition to the signal. By coupling together many of those channels without using multiplexer filters, the noise adds up and reduces the available OSNR. This effect has to be taken into account when choosing or designing the transponders which should be used in such a scenario.

4.4.1 Maximum Capacity of Broadcast&Select Architecture

A similar analysis as the one done in 4.2.2 for the D&W architecture is done in this section to assess the potential of B&S architecture.

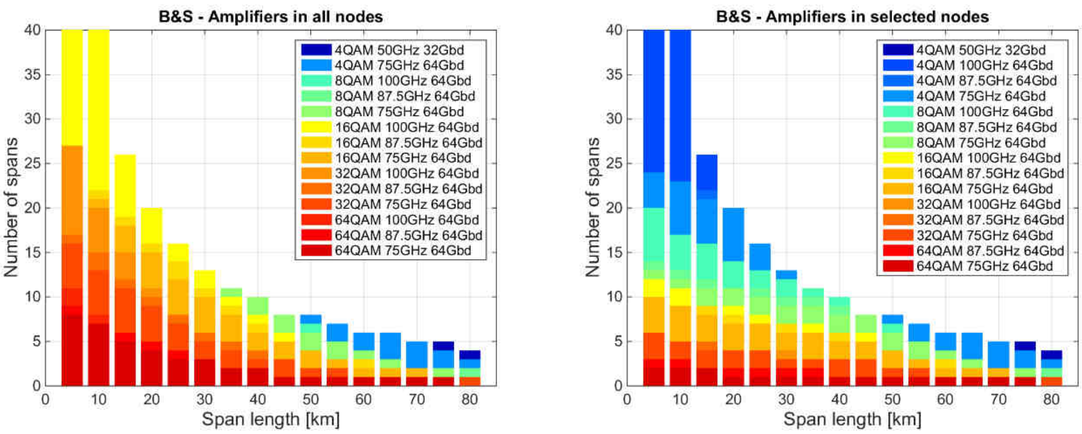


Figure 26. Best modulation formats considering B&S architecture and different link characteristics with optical amplification in all nodes(left) or in only ones(right)

Figure 26 shows the best channel format that can be used in a B&S network considering different span lengths and number of spans. The considered channel formats are the ones shown in Table 11 (based on advanced DSP), which are sorted by capacity with the spectral efficiency used to solve ties. The same system parameters as the ones considered for Figure 20 are also considered in this case. The only difference is in the use of a WSS instead of a combiner to multiplex channels. In this case, the express layer is still modelled by the same total loss, but additional filtering penalties are also taken into account. These filtering penalties are evaluated considering the transfer functions of commercially available WSSs. As expected, the main difference between using a D&W and a B&S architecture is the impossibility of using the tighter channels spacing when traversing a high number of nodes in the case of the B&S architecture. If the network was mainly composed of nodes with higher nodal degree (highly meshed), the use of a WSS (B&S) could become more advantageous with respect to using simple combiners (D&W) as its insertion loss would be smaller. However, that is not a typical case in metro scenarios.

Table 16. Maximum carried capacity [Tb/s] with B&S architecture (number of channels between parentheses)

Path Characteristics	B&S (100GHz grid)	B&S (50GHz grid)	B&S (flexi-grid)
5 spans of 20km	27.0 (45)	28.5 (95)	36.0 (60)
10 spans of 5km	24.0 (40)	27.0 (90)	36.0 (60)
10 spans of 10km	24.0 (40)	27.0 (90)	35.0 (62)
10 spans of 15km	24.0 (44)	27.0 (94)	30.0 (64)
15 spans of 10km	22.5 (45)	26.3 (94)	30.0 (60)

Table 16 shows the maximum carried capacity in a B&S network with different characteristics, assuming a hub-and-spoke model and the deployment of amplifiers in all nodes. The transmission over the entire C-band (4.8 THz) is assumed. The analysis of Table 16 shows that the combined use of advanced modulation formats with a B&S topology in a flexi-grid scenario enables one to achieve a capacity similar to the one attained by a D&W topology for typical METRO-HAUL scenarios (when considering a hub-and-spoke model). However, the B&S topology enables the reuse of the frequencies in the intermediate nodes, thus potentially enabling a much higher total network capacity. Moreover, the B&S topology is also much more efficient if any of the nodes of the network has a higher than 2 nodal degree. Some capacity penalty is observed in the case of using a fixed-grid of 100 GHz instead of flexi-grid, which results from the impossibility of using the most spectrally-efficient channel formats. This limitation is slightly obviated in the case of using a fixed 50 GHz grid. However, this grid precludes the use of 64 Gbaud signals and, therefore, a much higher number of interfaces is required in this case.

4.5 Experimental High-Capacity Waveband Add&Drop Ring Testbed

The capability of switching high-capacity signals with high-order modulation formats is assessed experimentally in this section for the add-drop node with B&S architecture and wavelength blockers. A ring topology interconnecting 3 node prototypes is employed, as shown in Figure 27 (a). It includes the experimental set-up with detailed structure of Node 1. Twelve 50-GHz spaced DWDM channels (1555.34 nm-1561.01 nm) are modulated using a 28 GBaud QPSK transmitter followed by the polarization and odd/even channel decorrelation stages, as shown in Figure 27 (b). The generated signal is distributed to the 3 nodes as add traffic (Add 1, Add 2 and Add 3), where it is separated into two waveband signals each containing 6λ×112 Gb/s dual-polarization (DP) QPSK data. 6λ×112 Gb/s DP QPSK data is gated by the FPGA-based node controller to emulate the tunable adding operations as shown in Figure 27 (a).

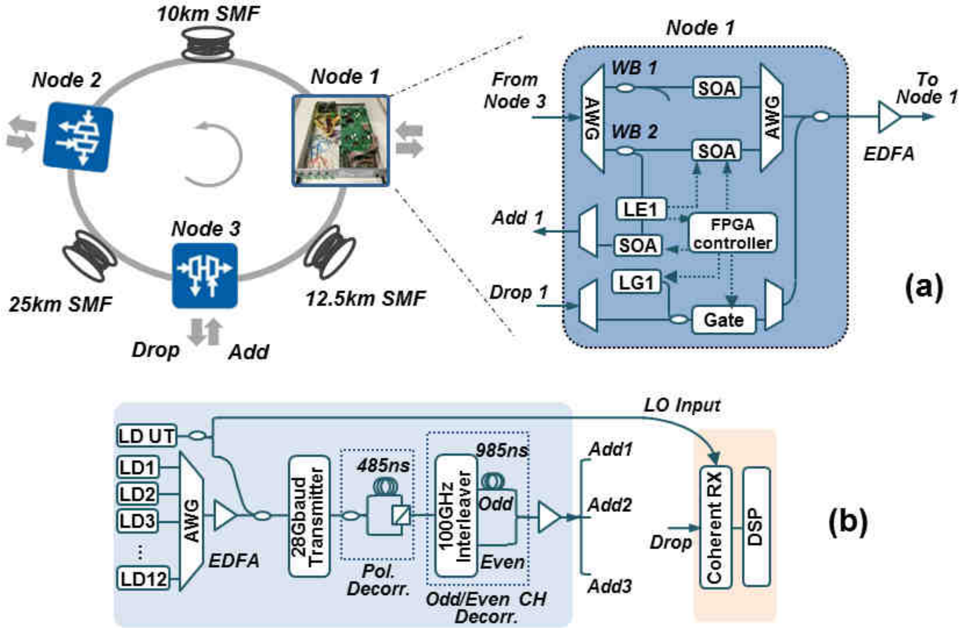


Figure 27. (a) 3 nodes ring network and schematic of Node 1 in the experiment set-up. (b) 112 Gb/s QPSK traffic generation and detection

The optical spectra of the input, drop ports for each waveband, and the output of Node1 is illustrated in Figure 28.

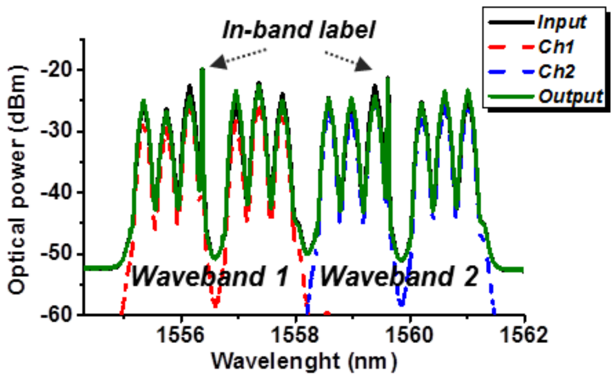


Figure 28. Spectra of input, drop ports and output for Node 1

The controller sets the SOA gates to drop/continue or drop-and-continue the wavebands. The dropped channel is detected by the coherent receiver and captured by a real-time 40 GSa/s oscilloscope for demodulation by offline DSP. From a practical point of view, the local oscillator (LO) should be implemented by a tunable laser controlled by the node controller. The total input optical power to each node is 1 dBm and the SOA gates are biased at 80 mA. The BER curves for the dropped channel at λ of 1557.36 nm at the three different nodes are illustrated in Figure 29 (a). The measured OSNR penalty was less than 0.8 dB at BER of 1×10^{-3}. Figure 29 (b) reports the BER for all channels at the drop port of Node 1 with a received OSNR of 16 dB. Similar performance has been observed over 12 wavelengths. The small difference that can be perceived is mainly due to the residual unbalanced input power. It can be seen that the dispersion is well compensated for by the DSP, and wavelength independent operation with limited OSNR penalty caused by the ASE from the SOA noise has been achieved.

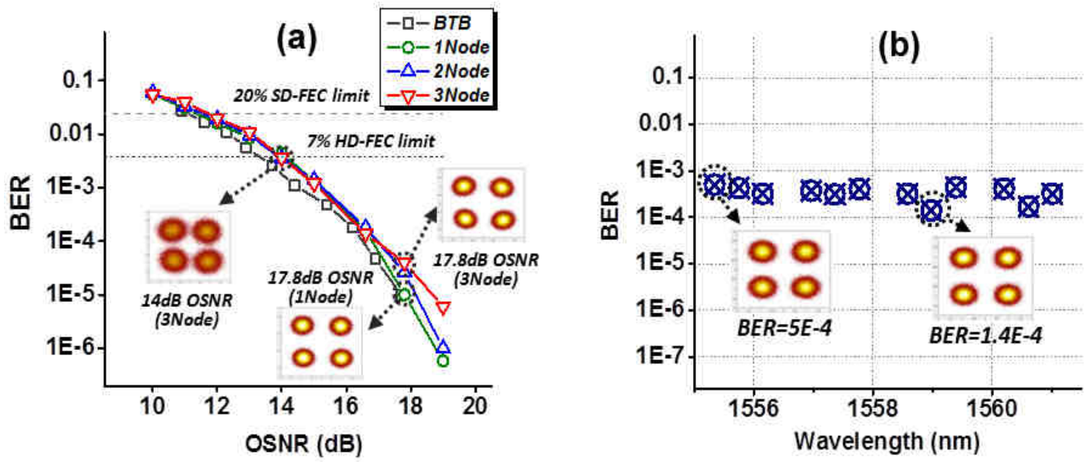


Figure 29. (a) BER curves for dropped traffic at 3 nodes. (b) Wavelength dependency

Scalability investigation

The capability of switching more wavebands is also investigated for the add-drop node. More wavebands are inserted into the WDM traffic and the BER curves of the switched traffic after one node when three (18λ) and four wavebands (24λ) are processed is illustrated in Figure 30. Compared with the back-to-back BER curve, negligible penalty is found when scaling the number of waveband channels. This indicates that the OADM is capable of processing multiple wavebands with very limited performance degradation.

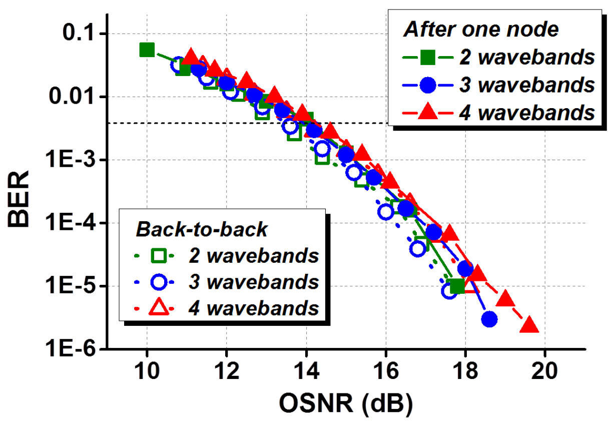


Figure 30. BER curves for 2, 3, and 4 wavebands after single node

The capability of supporting multiple waveband channels crossing a large number of add-drop nodes is experimentally assessed by employing the 25-km length recirculating loop set-up shown in Figure 31.

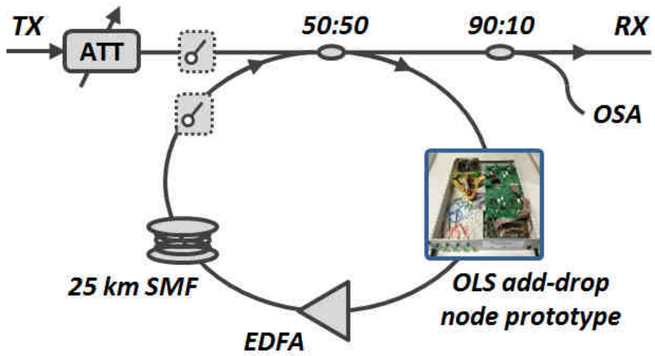


Figure 31. 25 km looping setup with OLS add-drop node prototype

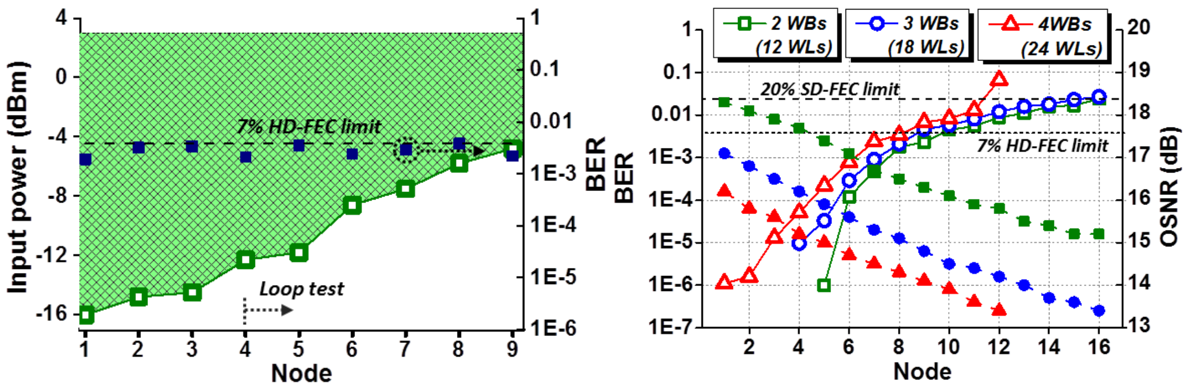


Figure 32. (a) Input power dynamic range for 2 wavebands. (b) BER and OSNR for 2, 3, and 4 wavebands in looping test

First, two wavebands are sent into the loop with input power controlled by an attenuator. To guarantee a BER below 7% hard-decision (HD) FEC limit, the minimum input optical power for different numbers of loops is analyzed (see Figure 32 (a)). A large dynamic range (covered by the green area) of more than 7 dB is achieved for 9 loops (225 km), showing the tolerance to the power fluctuation experienced by the traffic. Figure 32 (b) shows the BER and OSNR for 2, 3 and 4 wavebands. The degradation caused by the amplifier results in a linear (0.25 dB/node) OSNR decrease of the received (drop) signal. For 2 wavebands (12λ), operation below HD-FEC and soft-decision (SD) FEC limit is obtained when considering 9-node (225 km) and 15-node (375 km), respectively. Scaling the number of wavebands leads to a small OSNR degradation. For 4 wavebands (24λ) traffic, 8-loop and 11-loop operation is obtained below HD-FEC and SD-FEC limit, which accounts for 2.688 Terabit/s total capacity over 200 km and 275 km, respectively.

The results presented in this section show that transmitting wavebands in metro networks can be an interesting solution for metro networks. In this case, high-capacity signals with high-order modulation formats can be cost-effectively switched into metro-networks, which enables the simultaneous high capacity and flexibility desired for optical networks, but at a fraction of the cost that would be required by state-of-the-art ROADMs.

5 METRO-HAUL Devices and Subsystems Prototypes

This Chapter details the preliminary METRO-HAUL technologies and solutions for next-generation metro optical nodes and interfaces.

All relevant technological options have been considered, aiming at identifying the most suitable solutions according to the target size of the metro-regional network (e.g., small, medium and large, see Ch. 2), the topology (horseshoe, ring or mesh) the architecture (filtered or filterless), and the integration solutions with core/access segments. Furthermore, this chapter aims at providing key specifications on nodes and interfaces to support WP2 studies (e.g., techno-economic analysis, architectures for disaggregation, etc.) as well as WP4/WP5 demonstrations. To this extent, the considered solutions include all levels of deployment maturity, ranging from commercial products, to prototypes obtained as the integration of commercially available subsystems, and up to extremely innovative prototypes exploiting photonic integration. This way, the research focus can cover both available and innovative data plane architectures, providing a common modelling and control framework suitable for the integration and demonstrations of the whole METRO-HAUL solution.

More specifically, the METRO-HAUL optical node prototypes include:

1) multi-degree ROADM targeting the OpenROADM MSA YANG Device model validation and enhancement;
2) a two-degree ROADM prototype for design and investigation of fully disaggregated solutions;
3) a ROADM solution based on splitter and wavelength blocker architecture for semi-filterless solutions;
4) innovative photonic integrated optical switching solution for add/drop module of (disaggregated) ROADM;
5) Multi-purpose modular and loss-less photonic integrated wavelength selective switches for WDM cross-connect switch (N degree) and add/drop node (2 degree).

At the interface/transmission levels, the following METRO-HAUL prototypes are under development:

1) Programmable sliceable transceiver based on multicarrier modulation (MCM);
2) Transceiver solutions for dispersion-tolerant direct detection;
3) Spectral-efficiency tunable transmitter with probabilistic-shaping;
4) Elastic transponders with low resolution DAC and ADCs for metro networks;
5) Commercial transponder enhanced with specifically designed NETCONF/YANG modules;
6) Digital sliceable bandwidth variable transponder for filterless networks ;
7) Coherent transponders to be used in the filterless architectures.

Finally, the integration to core and access is specifically addressed by focusing on:

1) Programmable packet switching solution for interconnection of access and core segments;
2) PON termination to metro node and its abstraction.

5.1 METRO-HAUL Optical Network Elements

5.1.1 MD-ROADM Prototype

This subsection reports on the ROADM prototype available in the TIM Laboratories. It is based on a single component, namely the Lumentum TrueFlex® Twin High Port Count WSS (Figure 33).

Figure 33. Lumentum TrueFlex® Twin High Port Count WSS

This component has been provided by the supplier on an evaluation board, and is configurable through an RS-232 interface. Its functional scheme is reported in Figure 34. It contains two identical independent WSS modules, both with 21 mono-directional optical ports. Each of the two modules can be programmed to create one or more media channels within the C-band, each characterized by a central frequency, a spectral width and an attenuation (in the range from 0 to 25 dB), between the so-called *common* port (*c*) and each of the other 20 (*p1-p20*) ports.

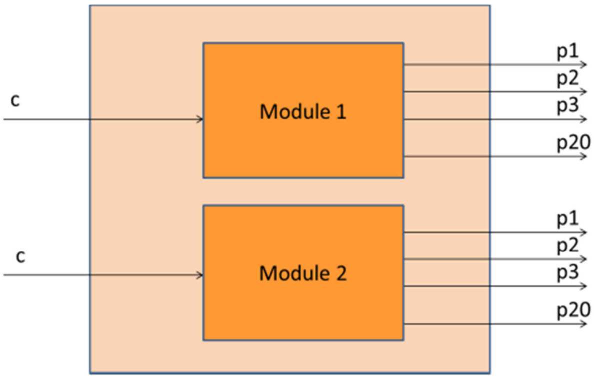


Figure 34. Twin 1 x20 WSS functional scheme

Several media channels, not necessarily contiguous, can be configured at the same time providing that, for each module, spectral windows don't overlap, i.e. the common port cannot be connected with more than one port using the same spectrum portion. The component supports both fixed and flexible grid modes of operation.

Moreover, due to a peculiar behaviour reported as "directivity" in the device documentation and experimentally verified, when a media channel is configured between the common port and an add-drop port, the same spectral window is also created between several other pairs of ports. In particular (referring to the ports numbering shown in Figure 34), when a media channel is configured between port ***c*** and a given port ***px***, an identical media channel is automatically arranged between the pairs of ports ***py*** and ***pz***, where *x*, *y* and *z* follow this basic rule:

$$y+z=x \quad (3)$$

We realized that the “directivity” behaviour could be leveraged by suitably wiring and configuring the component in order to use it as a complete bidirectional non-blocking ROADM, with native colourless and directionless capabilities. In particular connecting the device ports as shown in Figure 35, we achieved a complete ROADM with 2-3 degrees and 1-2 Add-Drop modules and an internal switch-and-select architecture; the figure in particular shows the case with 3 degrees, named EAST, NORTH and WEST, and a single Add-Drop module.

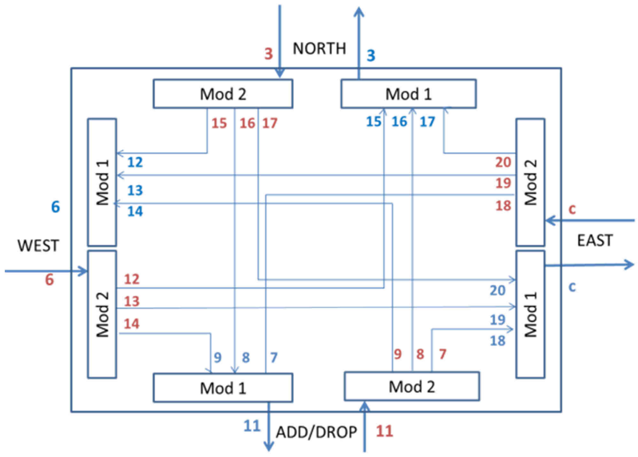


Figure 35. ROADM with switch-and-select architecture

This solution allows the use of disjoint spectrum portions in the transit directions between different line interfaces. Moreover the same portion of the spectrum in transit between two line interfaces can be used to carry traffic from the third line interface to the local ADD-DROP port, thus obtaining a non-blocking architecture. For example, referring to Figure 35, if a media channel is configured between port c and port 18 of both WSS modules (x=18), the same media channel is created between ports 11 and 7 (y=11, z=7) of both modules, thus the media channel can transit between the EAST degree and the ADD-DROP port in both directions. At the same time the media channel is created between ports 3 and 15 (y=3, z=15) and between ports 6 and 12 (y=6, z=12) of both modules, thus it can also transit between NORTH and WEST degrees.

This behavior, coded in Eq. (3), must be carefully addressed at the network control level in a meshed topology in order to avoid unwanted detrimental optical loops.

The TIM ROADM device also includes a controller prototype, able to create and delete optical cross-connections inside the nodes. The controller is based on the NETCONF protocol and on an accurate modelling of the device, following the “OpenROADM MSA YANG Device model” (v. 2.2, [6]).

Two prototypes were successfully used in many experiments, also including a geographical link in between. Notably, in the PANTHER EU project [32], 25 Gbaud signals have been transmitted and properly received over two metro links of the TIM network (a two-span link of 156 km and a three-span link of 232 km), attached to the line sides of the two ROADMs, see Figure 36. This experiment confirmed that the ROADM prototype characteristics (Table 17) are suitable for transmission applications in metro networks.

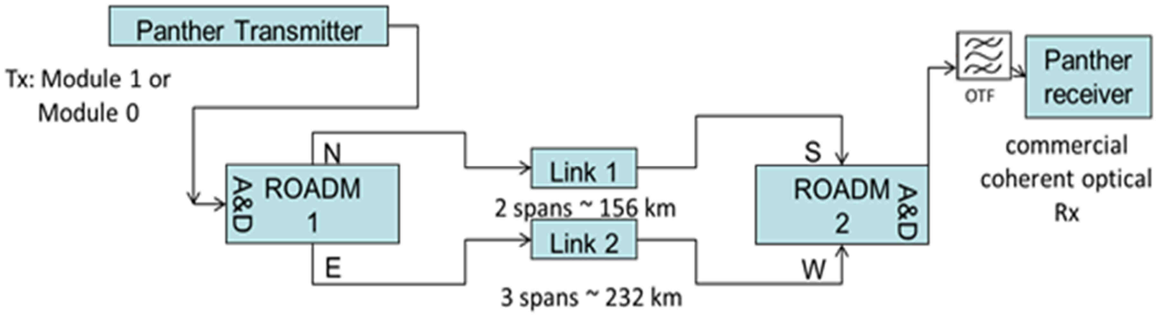


Figure 36. End-to-end Panther transceiver flow through TIM ROADMs and TIM metro network (taken from Deliverable "PANTHER D6.5: Development of edge SDN switch and evaluation in real network settings", PANTHER EU project)

Table 17. TIM ROADM main characteristics

ROADM					
	Value	Min	Max	Unit	Note
GENERAL PARAMETERS					
Degrees		2	3	Number	
Channel Spacing	Flex			GHz	
Coloured local add/drop	YES				
Colourless and fixed grid local add/drop	YES				
Colourless and flexible grid local add/drop	YES				
Directional local add/drop	NO				
Directionless local add/drop	YES				
Contention-less local add/drop	YES 2 degrees, NO 3 degree				
OPTICAL PARAMETERS					
-1 dB bandwidth line input to line output (passthrough)	34 at 50 GHz slot width			GHz	Average value
-3 dB bandwidth line input to line output (passthrough)	40 at 50 GHz slot width			GHz	Average value
-1 dB bandwidth line input to drop	34 at 50 GHz slot width			GHz	Average value
-3 dB bandwidth line input to drop	40 at 50 GHz slot width			GHz	Average value
-1 dB bandwidth add to line output	34 at 50 GHz slot width			GHz	Average value

-3 dB bandwidth add to line output	40 at 50 GHz slot width			GHz	Average value
ROADM WITH NO AMPLIFIERS					
Insertion Loss - line input to line output (passthrough)	11±1			dB	Average value
Insertion Loss - line input to drop	11±1			dB	Average value
Insertion Loss - Add to line output	11±1			dB	Average value
ROADM WITH AMPLIFIERS					
Channel gain - line input to line output (passthrough)	N.A.	N.A.	N.A.	dB	
Channel gain - line input to drop	N.A.	N.A.	N.A.	dB	
Channel gain - Add to line output	N.A.	N.A.	N.A.	dB	
FLEXIBLE GRID					
Operating frequency range	N.A.	191.15	196.25	THz	
Flexible grid central frequency granularity	3.125	N.A.	N.A.	GHz	
Flexible grid slot width granularity	0.5	N.A.	N.A.	GHz	
MEDIA CHANNEL					
Media Channel width	N.A.	12.5	500	GHz	
Guard-band inside Media Channel	5	N.A.	N.A.	GHz	Two spectrum slices placed at the left and the right border of Media Channel, where it is not possible allocate a Network Media Channel

Also, in the ORCHESTRA EU project [33], a similar configuration was realized to demonstrate the ORCHESTRA's dynamic network operation capability in a real network. The two ROADMs prototypes were able to create and modify a media channel (re-routing it from the three-span link to the two-span link) as requested via a SDN controller by the ORCHESTRA control and management plane solution (Figure 37), reacting to a degradation of the Quality of Transmission. Besides the optical transmission aspects, this experiment[4] confirmed that the TIM ROADM can be used in an SDN environment.

[4] At the time of that experiment, the controller prototype was based on OPENFLOW protocol: afterwards, a new version supporting NETCONF was developed.

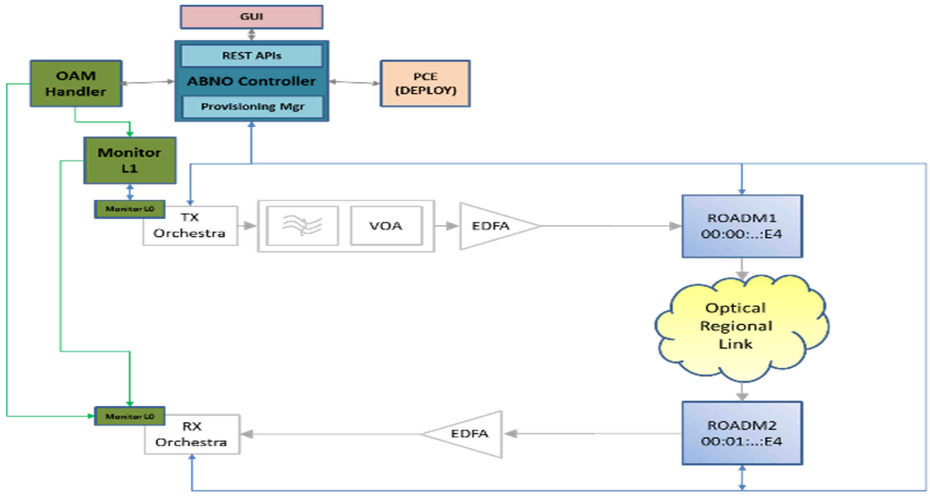


Figure 37. ORCHESTRA Control and Management planes deployed for the Field Trial, including TIM ROADM prototypes and TIM metro network (taken from Deliverable "ORCHESTRA D6.3: Field validation of ORCHESTRA solution", ORCHESTRA UE project)

Considering the small number of line degrees provided by this solution, this prototype is meant to be used in low-dense areas, such as metro-access networks, where a high nodal degree is not needed. In these areas, the flexibility provided by ROADMs, with respect to FOADMs, would be very useful in terms of OpEx reduction; yet commercial ROADM deployment is highly limited due to the high cost of purchasing and installation (CapEx). The prototype presented above could allow one to overcome this issue, as it drastically reduces the required number of WSS modules (by a factor of four with respect to the traditional layout of 3-degrees directionless ROADM node built with interconnected discrete WSS modules, typically in the number of eight), allowing significant savings in term of CapEx.

As usual in ROADMs, in addition to the WSS components, optical amplifiers (booster and/or preamplifiers) could be needed, to recover both the attenuation of fiber links in the network and the insertion loss of WSS modules. However, it should be noted that for our prototype, the measured insertion loss between ROADM lines is around 10 dB, which is mostly in-line with the figures of a traditional switch-and-select ROADM built with interconnected discrete WSS modules, so the required number of optical amplifiers should be the same in the two cases, not affecting the cost difference.

The prototype configuration could be slightly modified to cover several different applications suitable in a metro-access network. In particular, to complete the Add&-Drop side, we have added one mux/demux module (a commercial 40 channels 100 GHz fixed grid), thus achieving a directionless and colored ROADM (Figure 38a), but replacing the mux/demux with a simple coupler/splitter (for instance 1:8), and using coherent interfaces at the transponder side, would preserve the colorless feature of the prototype (Figure 38b).

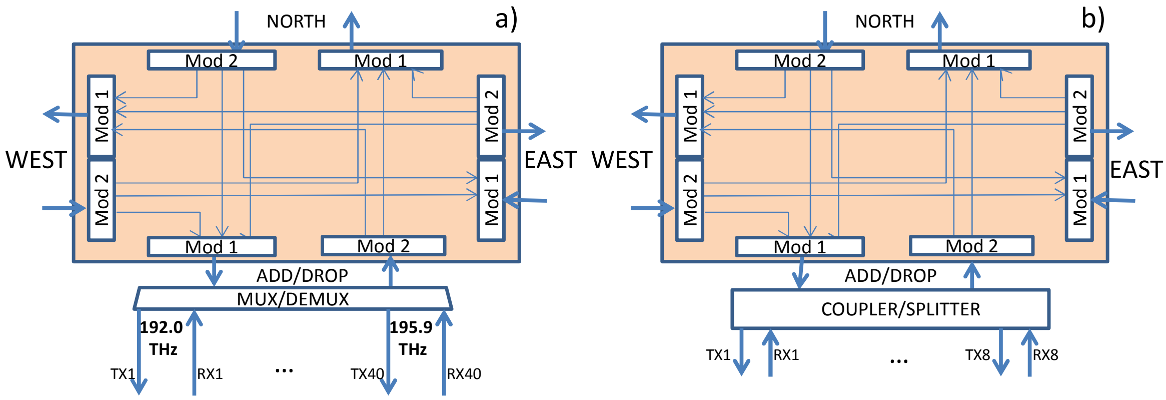


Figure 38. a) colored-directionless solution; b) colorless-directionless solution

Another interesting application for the metro area is the 2-degrees ROADM installed in ring topologies, to collect traffic from several sites to a hub node (e.g. in backhauling applications). Converting one of the three line side (e.g. the NORTH one) to a second add/drop connected to another mux/demux, the "directivity" behavior would allow the creation of the same media channel simultaneously between, for example, one mux/demux and the WEST line and between the other mux/demux and the EAST line, to support dual-homing optical protection scheme, as shown in Figure 39.

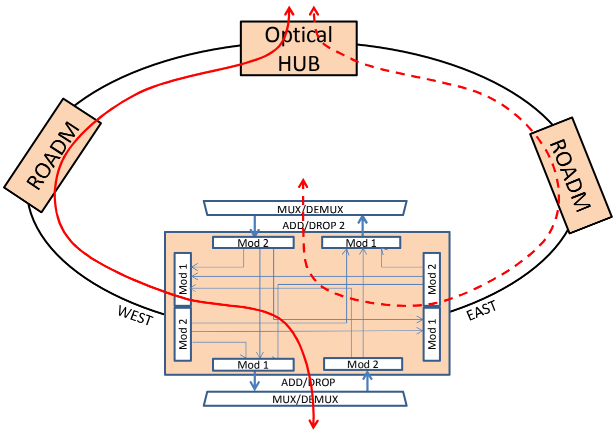


Figure 39. 2-degrees ROADM in ring topology with dual-homing protection

5.1.2 Fully Disaggregated 2-Degree ROADM Prototype

This subsection presents the ROADM prototype implemented at the CNIT Lab. It is a two-degree switch-and-select ROADM (ROADM-2 in Figure 40). Each degree includes input and output directions. Each direction is equipped with a 1xN bandwidth variable wavelength selective switch (BV-WSS) and an optical amplifier. In addition, a Variable Optical Attenuator (VOA) is present at the output side to regulate the transmitted optical power. The ROADM also includes two types of monitoring elements: photodiodes detecting the pass-through optical power and a low-resolution optical spectrum analyzer (OSA) for advanced monitoring functionalities. The ROADM is implemented in a disaggregated way, relying on hardware components provided by different vendors. The east degree is provided as a single Lumentum white box employing a BV-WSS with N=20 ports. The west degree is fully disaggregated with two Finisar BV-WSS (N=4), two Ericsson optical amplifiers, and one ANDO OSA (optionally introduced for advanced monitoring functionalities). All aforementioned ROADM components are controlled as optical white box elements through custom-built software agents based on NETCONF/YANG.

In terms of detailed specifications, the table introduced in the previous subsection is substantially valid also for this fully disaggregated 2-Degree ROADM prototype, given the use of same/similar building components.

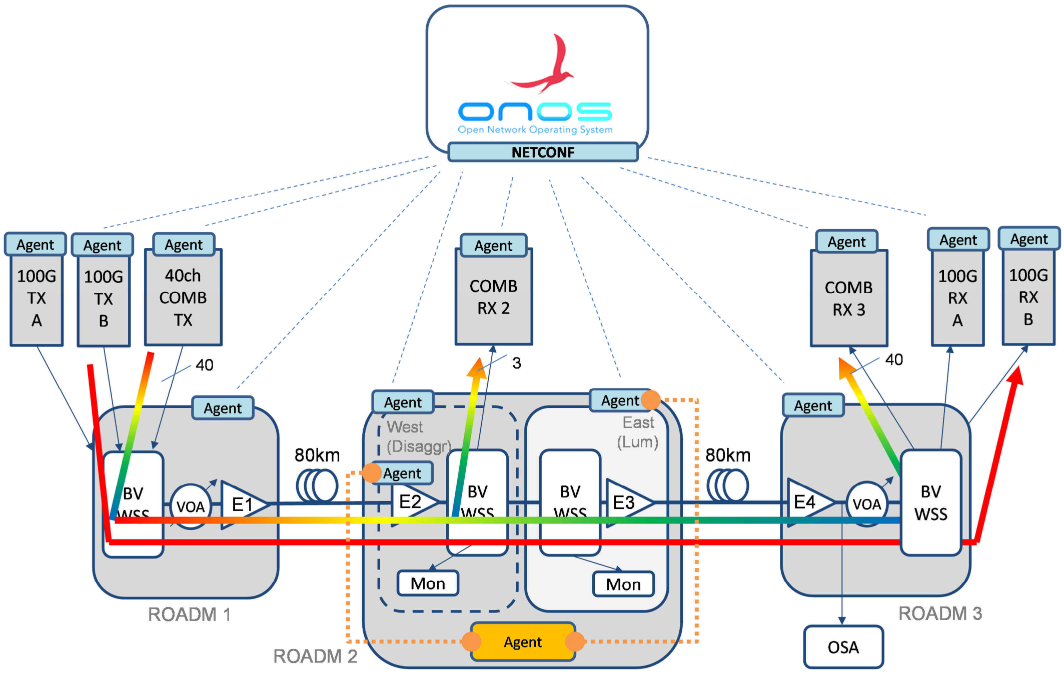


Figure 40. Fully disaggregated ROADM (ROADM 2) and its experimental validation within an SDN-controlled network testbed

An experimental demonstration of the implemented disaggregated ROADM was carried out at the OFC 2018 Demo Session, as a joint METRO-HAUL work among CNIT, UPC, TIM and Ericsson [34]. The optical testbed shown in Figure 40 was set up in the Pisa Lab. The testbed included three ROADMs, interconnected through fiber links of around 80 km, two 100 Gb/s transponders (type A), two custom built off-line 100 Gb/s transponders supporting LDPC code adaptation (type B), and a comb source injecting 40 channels in the whole C band, modelled as a chassis of 40 independent transponders.

First, the provisioning of the 100 Gb/s channel was performed on the 100 Gb/s transponder, driven by the centralized SDN controller through NETCONF (e.g., add/drop at specific wavelength and direction). Specifically, the ONOS Optical Intent module was utilized at the controller to enforce the request of the optical connection. Then, the controller performed the path computations and decomposed the computed path in the set of configuration rules to be installed in each optical device. For instance, the transponder configuration included the frequency slot, the port, and the additional parameters such as the FEC type to be used. Similarly, the ROADM was configured considering input port, frequency slot and output port. After this phase, the controller effectively sent, in parallel, the NETCONF based configuration messages to each devices. After confirmation, the Optical Intent was considered to be active in the network.

After establishing the new Optical Intent, a procedure for the alignment to the target-power identified by the controller was locally performed at the ROADM. This step was applied by the agent of the ROADM (ROADM2 in figure) by specifically accounting for all available configuration options for amplifiers and WSS. For example, the local algorithm operated on the WSS per-channel attenuation, successfully obtaining the expected target optical per-channel launch power. Such elaborations were typically completed in a sub-second scale.

5.1.3 ROADM Based on Splitter and Wavelength Blocker Architecture

Within the project ADVA investigates optical nodes with simplified ROADM architectures based on wavelength blockers and optical splitters. The structure of the node is shown in Figure 25. The basic technology of the wavelength blocker resembles that one of the WSS. It is based on LCoS (Liquid Crystal on Silicon) technology similar to a WSS, but offers blocking, power-levelling and monitoring within a single LCoS chip. The channel spacing and channel center frequencies can be varied to enable a flexible spectrum allocation. Common scenarios might include 100 GHz, 75 GHz or 50 GHz channel spacing with a center frequency granularity of 12.5 GHz.

Table 18. ADVA ROADM main characteristics

ROADM					
	Value	Min	Max	Unit	Note
GENERAL					
Degrees	2			Number	
Channel Spacing	Flexible			GHz	
Coloured local add/drop	Yes				YES/NO
Colourless and fixed grid local add/drop	Yes				YES/NO
Colourless and flexible grid local add/drop	Yes				YES/NO
Directional local add/drop	No				YES/NO
Directionless local add/drop	Yes				YES/NO
Contention-less local add/drop	Yes				YES/NO
OPTICAL PARAMETERS					
-1 dB bandwidth line input to line output (passthrough)	Full C-band			GHz	If no channels are dropped
-3 dB bandwidth line input to line output (passthrough)	Full C-band			GHz	If no channels are dropped
-1 dB bandwidth line input to drop	Full C-band			GHz	
-3 dB bandwidth line input to drop	Full C-band			GHz	
-1 dB bandwidth add to line output	Full C-band			GHz	If no filters for TX ASE suppression included

-3 dB bandwidth add to line output	Full C-band			GHz	If no filters for TX ASE suppression included
ROADM WITH NO AMPLIFIERS					
Insertion Loss - line input to line output (passthrough)	TBD			GHz	Depends on splitting ratios
Insertion Loss - line input to drop	TBD			dB	Depends on splitting ratios
Insertion Loss - Add to line output	TBD			dB	Depends on splitting ratios
ROADM WITH AMPLIFIERS					
Channel gain - line input to line output (passthrough)	TBD			dB	Maybe no amplifier needed here, to be evaluated
Channel gain - line input to drop	TBD			dB	
Channel gain - Add to line output	TBD			dB	Depends on actual transponder and splitting ratio
FLEXIBLE GRID					
Operating frequency range		191.25	196	THz	
Flexible grid central frequency granularity	TBD, e.g. 12.5			GHz	
Flexible grid slot width granularity	TBD, e.g. 25 GHz			GHz	
MEDIA CHANNEL					
Media Channel width		TBD	TBD	GHz	
Guard-band inside Media Channel	TBD			GHz	Two spectrum slices placed at the left and the right border of Media Channel, where it is not possible allocate a Network Media Channel

5.1.4 Photonic Integrated Optical Switch to Perform Add&Drop in an Open ROADM Node Architecture

This subsection presents the photonic integrated switching element available at the Ericsson Lab and implemented as joint work between Ericsson and CNIT. In particular, this collaboration started within the IRIS EU project (Contract Number: 619194). IRIS has provided the photonic integrated optical switch technology which is going to be utilized as a multiple transponder aggregator for add and drop operation in flexible optical node architectures. In METRO-HAUL, Ericsson and CNIT, besides improving current deployment status, enhance the IRIS device by providing YANG-based modelling and control to actively integrate the switch within disaggregated metro network nodes. The architecture of the photonic integrated switch can be used to aggregate transponders in an open ROADM node (as the one described in the previous subsection) and perform Add&Drop operation in a WDM system, as shown in Figure 41.

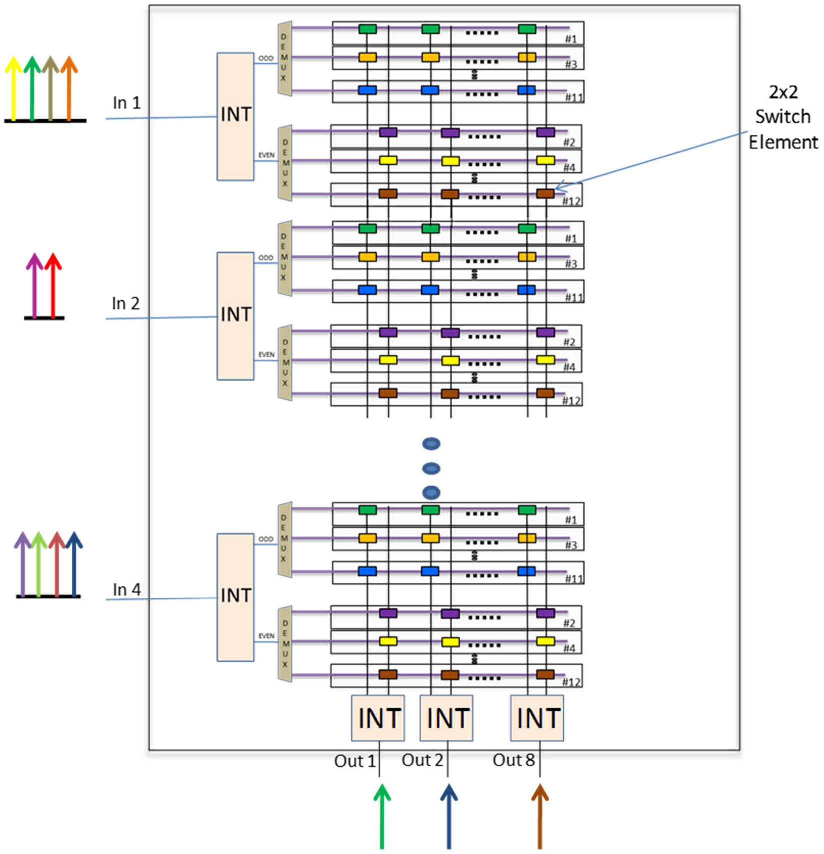


Figure 41. IRIS architecture for transponder aggregation function to perform Add&Drop operation in a WDM system

The same device can be used for both dropping WDM channels from the line input ports (In *n*, *n* from 1 to 4) to local drop ports (Out *n*, *n* from 1 to 8) and adding local channels to the line output ports: this can be achieved by simply inverting the direction of the optical flows thanks to the definition of a common architecture. In the Drop switch, four sets of up to 12 WDM channels, 200 GHz spacing, arrive at each of the four-line input ports and are coupled to the chip by single polarization grating couplers (SPGC). Due to the single polarization of the SPGC to perform polarization independent switching operation, the photonic switch is doubled, and the two add/drop modules are combined in a polarization diversity scheme as reported in Figure 42. The optical path is split into two, so that the energy coupled with each principal state of polarization of the switched wavelength can be always selected and routed with no penalty. The two designed optical paths have the same optical length.

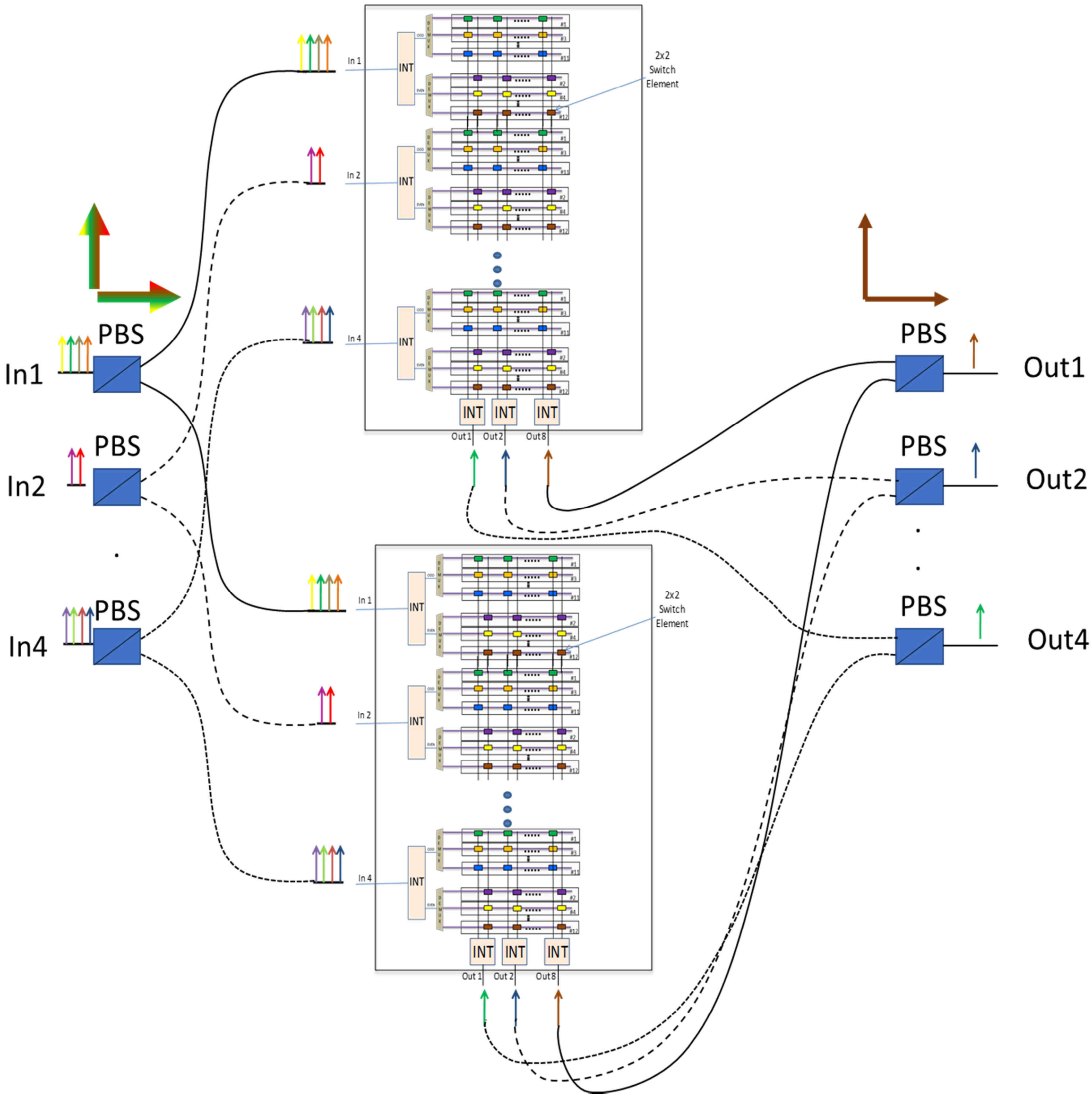


Figure 42. Add&Drop architecture for transponder aggregation function in polarization diversity mode for infield applications

Interleaver blocks separate the input channels into odd and even channels, in order to increase the wavelength spacing in the switching matrix and to relax the channel isolation requirements. Then, two types of demux blocks, one working with odd wavelengths and one with even wavelengths, demultiplex the odd/even separated channels. At the demux output, the signals are sent to the switching matrix constituted by an optical crossbar of micro-ring resonators (MRR) wavelength selective switch elements. The matrix has 4 × 12 rows connected to 4-line inputs and 8 × 2 columns connected to 8 optical receivers (in the transponders). In the switching matrix, the single wavelengths travel on the row until they get to the column connected to the drop output. At this crossing point, there is a MRR switch element, which is thermally tuned (activated) in resonance with the signal wavelength. Therefore, the signal couples to the resonators and is transferred to the corresponding drop column. Two waveguides are connected to each drop port: one handling the odd wavelengths, and the other handling the even wavelengths. An interleaver couples the odd or even wavelengths to the drop port where a SPGC performs coupling to an optical fiber. In the Add switch, worked by inverting the signals' direction, up to 8 wavelengths coming from eight tunable transmitters enter the switch from the local ports (add ports). Interleavers at each add input direct the signal to the odd or even column of the matrix switch. The ring resonator resonances in the matrix are off with respect to the signal wavelength except for those ring resonators placed at the crossing between the proper direction to which the signal has to be added. In correspondence to those crossing the signals are deviated horizontally toward the output multiplexer. After the multiplexer the signals reach an interleaver, which combines odd and even wavelengths onto the same output fiber. Monitor photodetectors are placed at strategic input and output locations to allow monitoring of the different blocks.

A NxM optical switch mainly for data center application could use the same physical architecture of the Add&Drop module in Figure 41, but a different mode of operation is as depicted in Figure 43 since in this application, differently from Figure 41, multiple channels can be wavelength multiplexed by the switch at the output ports. The output wavelength combs are formed by adding at the matrix cross-points the proper channels along the path through the switch matrix columns and the various channels are switched and multiplexed simultaneously in each vertical column of the fabric by fully exploiting the wavelength selectivity of the MRRs.

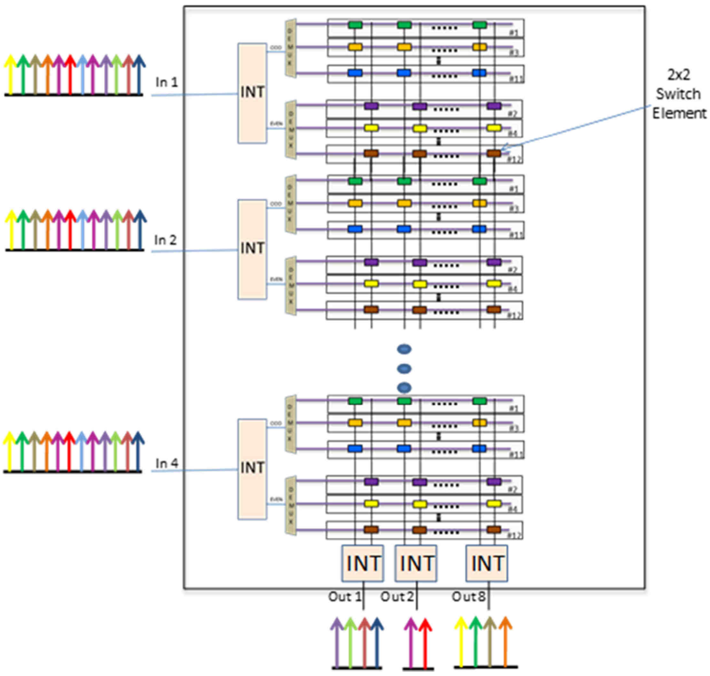


Figure 43. IRIS used as NxM switch for data centers

Hitless operation of the switch in the case of Add&Drop operation

An essential general requirement for a switch matrix is the hitless behavior consisting of not disturbing the already-established input-to-output connections when a new connection is configured by setting the proper switch elements. This condition never occurs in the IRIS switch used as add/drop module, since in each row only one fixed wavelength is propagating after demultiplexed by the AWG, and in each column only one variable wavelength can propagate at a time when the column is connected to a transponder.

When a free input wants to be connected to a free output, this operation must necessarily involve tuning the micro-ring at the crossing point between a free row and a free column so that the already-established connections are not disturbed, because the receiver in the transponder can only be disturbed by the tuning of microrings in its column. In the case that one transponder must change wavelength, a micro-ring in the same column but in a different row must be tuned on-resonance and the previous micro-ring must be tuned out of resonance: there may be a short transient in which both wavelengths are received, but this can be easily handled by tuning out the previous wavelength before tuning in the new wavelength with a delay of few microseconds.

A NxM optical switch for data center multiple channels are switched and wavelength multiplexed by the switch at the output ports, and if we want to totally re-use the IRIS fabric architecture, then the tuning strategy should be changed. In fact to add, for example, λ3 (see Figure 44) to a drop multiplex traveling on a certain column of the switch matrix, we have to tune on-resonance the MRR relative to λ3 and doing that we may disturb for a short while λ1 and λ11 if they are already part of that multiplex. To avoid that, the tuning algorithm could be based on asynchronous resonance tuning of individually controllable multiple coupled micro-rings (at least two rings). If the multiple resonances are not matched during tuning, all wavelengths pass, and the rings are adjusted to resonance at the new wavelength only avoiding any disturbances to the already established wavelengths. Hitless operation in coupled ring switch elements has been reported in [35][36].

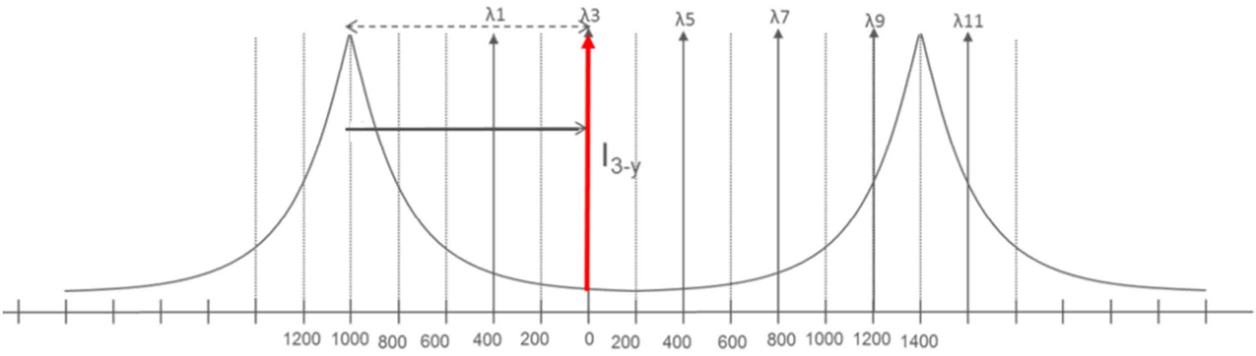


Figure 44. Hitless operation in NxM switch for data center

Device specifications

The requirements of the different integrated optical circuit blocks have been defined for the switch by fixing the maximum crosstalk level acceptable by the system and by fixing the maximum allowed insertion loss. The maximum accepted crosstalk level has been specified by the maximum acceptable power penalty of 1 dB for both add and drop switching subsystems. For this calculation we have taken as reference the equation and graphs reported in [37].

The worst-case crosstalk analysis has been presented in [38] with the result that the dominant crosstalk is the interferometric crosstalk to which a 1-dB penalty has been assigned. Among the various crosstalk sources, the non-ideal isolation of the MRRs is the dominant one since, together with the wanted channels at a certain wavelength, the other three disturbing signals (to be added in the worst case on other fiber lines) at the same wavelength can be present. To keep this type of crosstalk contribution as low as possible, the resonances of the MRRs in each row are kept reasonably far from the channel wavelengths when the micro-ring is in OFF. They are kept 1000 GHz distance from the wavelength channel, so as to benefit from the high isolation achieved in this condition. Additional interferometric crosstalk contributions are given by the non-ideal isolation of the waveguide crossing and interleaver, but they are specified to be sufficiently low (>45 dB for waveguide crossing and >20 dB for interleavers).

The maximum accepted on-chip loss has been set to <13 dB.

Concerning the signal pass-band, the requirement was based on the support of both intensity modulation-direct detection transmission at 10 and 25 Gb/s and coherent QPSK transmission at 100 Gb/s. In Table 19 the main design specifications are summarized, and have been taken as input parameters by the optical circuit designers.

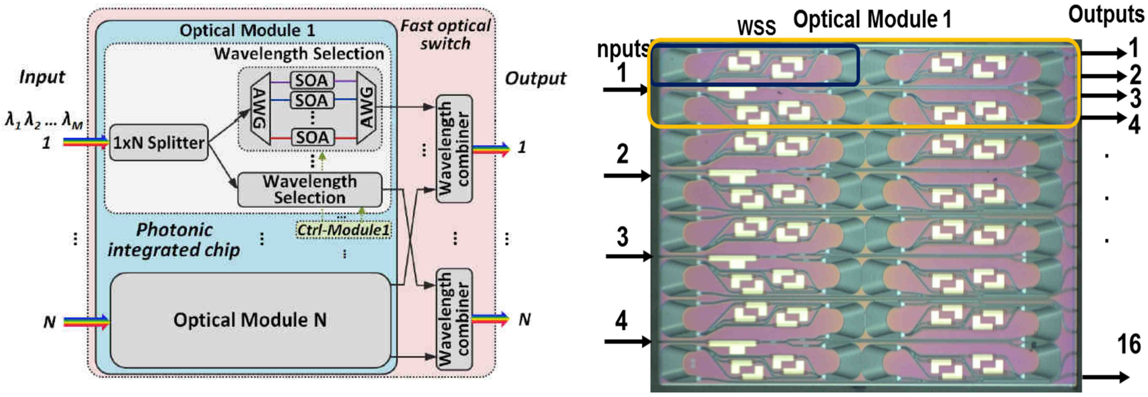
Table 19. List of some applicable circuit requirement specifications with maximum accepted on-chip loss <13 dB (i.e. measured for the longest optical path traversing the greater number of crossing points in the matrix); total number of wavelengths 12; total number of input ports 4; total number of output ports 8

Add/Drop Module in an Open ROADM Node					
	Value	Min	Max	Unit	Note
GENERAL					
Operative open-ROADM Degrees			4	Number	
System Wavelength Range		1542	1562	nm	
Channel Spacing			200	GHz	
Total number of line ports	Line		8	Number	
Total number of add/drop ports			8	Number	
Colourless and fixed grid	Yes				YES/NO
Directionless	Yes				YES/NO
Contention-less	Yes				YES/NO
OPTICAL PARAMETERS					
-1 dB bandwidth line input to drop		50		GHz	
-1 dB bandwidth add to line output		50		GHz	
Channel isolation at 200 GHz offset		20		dB	
Channel isolation at 400 GHz offset		25		dB	
Channel isolation at 600 GHz offset		30		dB	
Channel isolation at 1000 GHz offset		35		dB	

5.1.5 Multi-Purpose Modular and Loss-less Photonic Integrated Wavelength Selective Switches for WDM Cross-connect Switch (N degree) and Add&Drop Node (2 degree)

TUE is designing and fabricating a novel multi-purpose modular and loss-less photonic integrated wavelength selective switch (WSS) for metro-access nodes, which could also be extended to realize a metro-core node. Photonic integration enables low power and low cost solutions, while on-chip gain is exploited to compensate the losses as well as equalizing the optical power channel acting as multiple discrete VOAs integrated in a single device. Moreover, per channel optical power monitoring functionalities is naturally supported in the photonic integrated WSS. The modularity of the proposed WSS enables one to increase the input/output port count as well as the interconnection in order to realize a switch and select ROADM with variable degree according to the required functionalities in the network.

The architecture of the photonic integrated WSS is reported in Figure 45(a). The modular photonic integrated WSS consists of N WDM inputs, and each WDM input is fed into one module that processes in parallel the M wavelength channels. Each 1xN WDM PIC switch module includes an SOA booster amplifier followed by a 1:N splitter to broadcast the WDM channels to the N wavelength selective switches (WSS). Each WSS can select one or more wavelength channels and forward the channels to the output ports according to the switching control signals. The WSS consists of two AWGs (1xM AWG and Mx1 AWG) and M SOA-based optical gates. The first 1×M AWG operates as a wavelength de-multiplexer. Turning the M SOAs ON/OFF determines which wavelength channel is forwarded to the output or is blocked. The second M×1 AWG operates as a wavelength multiplexer. Hitless operation and multicast operation is naturally supported by this architecture. The broadband operation of the SOAs enables operation with any wavelength and bandwidth. Moreover, the amplification provided by the booster amplifier and SOA optical gates compensate the losses introduced by the broadcast splitter and the two AWGs. Each module can be fully controlled by a dedicated agent which is interfaced via the SBI to the control plane. This controller is in charge to reconfigure the switch. Moreover, the photonic integrated switch can also expose specific parameters such as optical power per channel. This also allows the control plane to properly vary the power per channel for full equalization of the WDM channels. Therefore, a YANG-based control will be developed to actively integrate the switch in the considered disaggregated metro and access network node. Figure 45(b) show a fabricated photonic integrated WSS with 4 modules (4 WDM channels per module) exploiting InP technologies. More than 68 SOA amplifiers have been integrated into a single chip. In METRO-HAUL, TUE will design and fabricate chips with modules with at least 8 WDM channels.



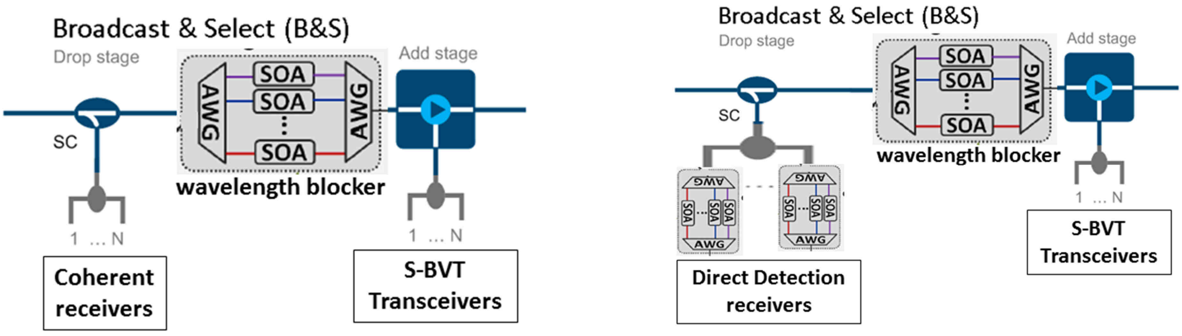
(a) (b)

Figure 45. (a) Modular architecture of the photonic integrated wavelength selective switch. b) Fabricated 4 modules InP photonic integrated wavelength selective switches

The versatile operation offered by the modular architecture can be exploited to build a directionless and colourless ROADM with variable nodal degrees for implementing metro access and metro core nodes as well as an aggregator for the S-BVT transponders and multicast-and-select switches for contention-less ROADMs.

5.1.6 A Degree 2 Low-Cost ROADMs Based on Wavelength Blockers

The photonic integrated WDM switches based on the modular WSS can be configured to achieve a degree-2 low-cost colourless ROADM as described in section 5.3. In this configuration a minimum of two wavelength selectors (wavelength blockers) are needed to implement this function. The schematic is reported in Figure 46 in the case of using coherent receivers (Figure 46(a)) or direct detection receivers (Figure 46(b)). Note that in the direct detection operation, extra wavelength blockers at the receivers have been employed as tunable filters with integrated SOAs that also act as power equalizers.



(a) (b)

Figure 46. Degree-2 low cost ROADM with (a) coherent receivers, and (b) direct detection receivers

5.1.7 A Degree N ROADMs Based on Wavelength Selective Switches

Multiple photonic integrated WDM switches based on a modular WSS can be employed to achieve a degree-N directionless and colourless ROADM. As shown in Figure 47, multiple wavelength selective switches are interconnected in order to achieve the required configuration in a similar fashion as reported in section 6.1. The figure reports, as an example, a degree-4 ROADM. Only the connections coming from interface 1 (red connections) has been drawn for sake of clarity of the picture given the large amount of interconnections. The N-arm power splitter (in this case N=4) broadcasts the WDM channels at the network interface 1 to the other 3 network interfaces and to the local drop interface. Each output network interface includes 4 wavelength blockers. 3 wavelength blockers are connected to each input interface (coming from the respective splitters), whilst the 4th wavelength blocker is connected to the local add interface. This schematic allows for directionless operation. The schematic can be scaled to N degrees (N network interfaces) by updating the 1:4 power splitter with a 1:N power splitter, and by increasing to N the number of wavelength blockers per network interface. Providing colourless operation to the ROADM requires that the drop interface employs wavelength selective switches (not reported in the figure). Moreover, where contention-less operation is required, multicast and select switches should be employed at the drop interface. Photonic integration of the N wavelength blocker and optical splitter (with embedded SOA amplifiers) is an effective solution for scaling the modular ROADM architecture.

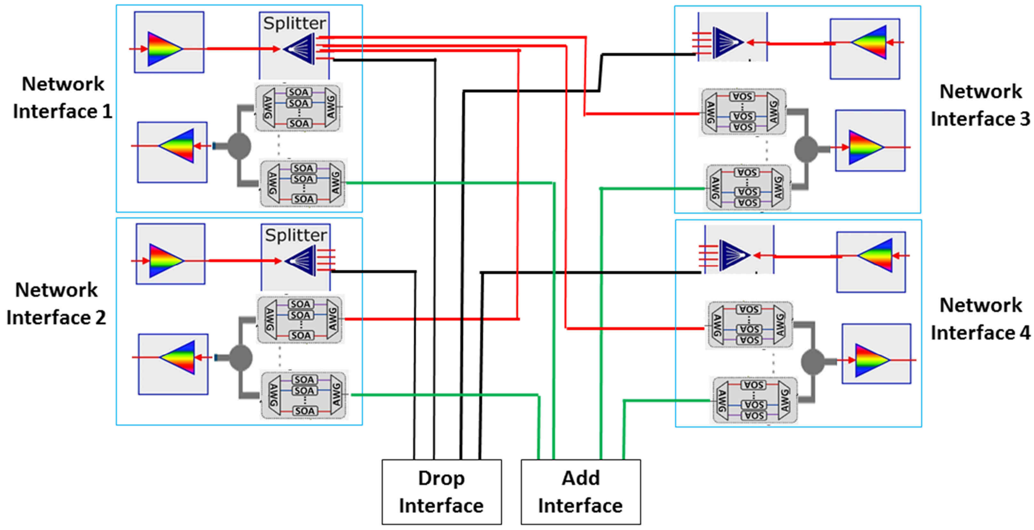


Figure 47. Degree-N ROADM schematic

Table 20. Device specifications

ROADM					
	Value	Min	Max	Unit	Note
GENERAL					
Degrees	N	2	8	Number	
Channel Spacing	Fixed	50	400	GHz	
Coloured local add/drop	Yes				YES/NO
Colourless and fixed grid local add/drop	Yes				YES/NO
Colourless and flexible grid local add/drop	Yes				YES/NO
Directional local add/drop	Yes				YES/NO
Directionless local add/drop	Yes				YES/NO
Contention-less local add/drop	Yes				YES/NO
OPTICAL PARAMETERS					
-1 dB bandwidth line input to line output (passthrough)	Full C-band			GHz	If no channels are dropped
-3 dB bandwidth line input to line output (passthrough)	Full C-band			GHz	If no channels are dropped
-1 dB bandwidth line input to drop	Full C-band			GHz	
-3 dB bandwidth line input to drop	Full C-band			GHz	
-1 dB bandwidth add to line output	Full C-band			GHz	If no filters for TX ASE suppression included
-3 dB bandwidth add	Full C-band			GHz	If no filters for TX

to line output					ASE suppression included
Photonic WDM wavelength selective switch					
Insertion Loss - line input to line output (passthrough)	TBD			dB	Depends on splitting ratios
Insertion Loss - line input to drop	TBD			dB	Depends on splitting ratios
Insertion Loss - Add to line output	TBD			dB	Depends on splitting ratios
ROADM WITH AMPLIFIERS					
Channel gain - line input to line output (passthrough)	TBD			dB	Maybe no amplifier needed here, to be evaluated
Channel gain - line input to drop	TBD			dB	
Channel gain - Add to line output	TBD			dB	Depends on actual transponder and splitting ratio

5.2 METRO-HAUL Transceivers: Multi-Rate, Multi-Format, Elastic, Transceivers

5.2.1 Programmable Sliceable Transceiver Based on Multicarrier Modulation (MCM)

Figure 48 shows the architecture of an innovative programmable sliceable bandwidth variable transceiver (S-BVT) under development at CTTC Lab. It is composed of two modules. Additional modules can be ideally included in order to improve the capacity and the potential of the S-BVT to adapt to the network requirements in a grow-as-needed approach. Each module can be enabled or disabled according to the network need, and is based on multicarrier modulation (MCM) with receiver configuration adopting direct detection (DD).

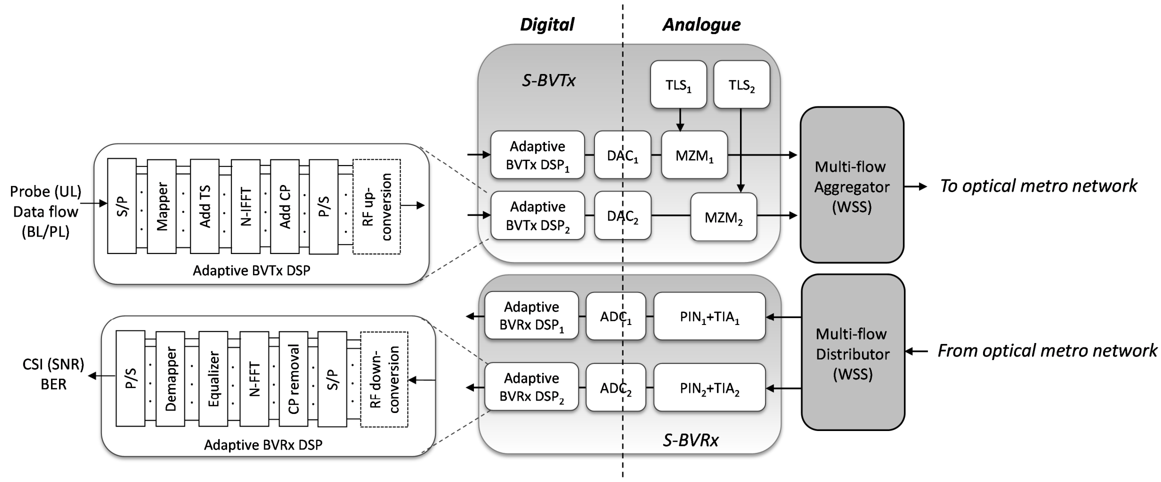


Figure 48. Programmable S-BVT composed of two BVT modules based on MCM (DMT/OFDM) and DD. In the insets the adaptive DSP at the BVTx and BVRx are detailed

This is a flexible and programmable multi-rate, multi-format, multi-reach modular transceiver generating/supporting up to two flows/slices and adopting cost-effective optoelectronic subsystems. Particularly, the bandwidth variable receiver (BVTx) optoelectronic frontend consists of a simple Mach-Zehnder modulator (MZM), driven by a tunable laser source (TLS) for arbitrary wavelength selection, and the bandwidth variable receiver (BVRx) adopting DD requires a simple photo-detector (PIN) with transimpedance amplifier (TIA).

The multiple (two) flows are optically aggregated/distributed by using a bandwidth variable (BV) wavelength selective switch (WSS), or spectral selective switch (SSS), that can be implemented in liquid crystal on silicon (LCoS) technology. This element can also be suitably programmed/configured to serve as: i) a filter bank to enable single sideband (SSB) modulation of each generated flow/slice; or/and ii) an optical orthogonal transform processor for superchannel generation. SSB-OFDM allows the achievable reach to be extended thanks to its higher robustness against chromatic dispersion with respect to DMT, which in turn is more cost-effective and does not require any additional filtering stage.

In addition to the spectral manipulation with super-wavelength granularity (in the optical/analogue domain), sub-wavelength granularity (in the electrical/digital domain) is also supported by the S-BVT, thus characterized by a high degree of reconfigurability/flexibility. Specifically, at each BVT module, the (offline) adaptive digital signal processing (DSP) supports MCM, either DMT or OFDM, and a multiple format mapper. The mapper enables uniform loading (UL) of the digital/electrical DMT/OFDM subcarriers or a bit and power loading (BL/PL) algorithm, adopting adaptive modulation formats including BPSK and M-QAM (with $M=2^n$ and $2 \le n \le 8$), for achieving multiple rate/reach. Thus the sub-wavelength granularity is defined as the ratio between the slice/flow bandwidth (BW) and the number of electrical/digital DMT/OFDM subcarriers.

The S-BVT allows one to select/adapt/configure variable parameters, such as the number of enabled slices, the occupied frequency slots (i.e. the bandwidth occupancy), the aggregator transfer function per port, etc. Table 21 summarizes some relevant parameters of the considered prototype. With respect to the digital part, by suitably selecting the DSP mode, it is possible to activate the transmission of uniformly loaded probing signals. This allows one to retrieve the channel state information (CSI), by means of calculating the SNR per each subcarrier. Accordingly, the subcarrier loading is adapted to achieve the successful data flow transmission at a target bitrate (in margin adaptive, MA, mode) or at a target performance (in rate adaptive, RA, mode), which requires to select the suitable gap. The BER over the established path (target reach) is calculated at the BVRx DSP. Different FEC options, either hard-decision (HD) or soft-decision (SD), and the related overhead (e.g. 7% or 20%) - varying the total overhead and thus the achievable net bit rate - are taken into account to target a certain BER (e.g. 10^{-3}, $4.62 \cdot 10^{-3}$, or $2 \cdot 10^{-2}$).

For the digital-to-analogue conversion (DAC), different sample rates are available (up to 24 GSa/s and 64 GSa/s); while the analogue-to-digital conversion (ADC) is performed using a digital oscilloscope with maximum sample rate of 100 GSa/s. Depending on the adopted element the signal bandwidth could be affected/limited.

The programmable elements at the optoelectronic front-end of the BVT module include the TLS for enabling/disabling the transmission of each flow and the corresponding wavelength and power setting. The photo-detectors at the receiver can also be enabled/disabled, accordingly. The external modulator (MZM) bias can also be suitably selected for working at the quadrature or close by the null point.

Table 21. S-BVT parameters per flow/slice detailed for the transmitter (BVTx) and the receiver (BVRx)

TRANSMITTER per flow/slice					
	Value	Min	Max	Unit	Note
Tunability range		196.071 1529	191.929 1562	THz nm	
DWDM frequency grid (fixed grid)		50	100	GHz	ADRENALINE testbed
DWDM grid central frequency granularity (flexible grid)	6.25			GHz	ADRENALINE testbed
Center frequency accuracy	1			GHz	
Transmitter Bandwidth (-3 dB)	25			GHz	
Transmitter Bandwidth (-20 dB)	40			GHz	
Line Rate		10	50	Gb/s	Back-to-back
Net Line Rate		8.8	44	Gb/s	Overhead: HD-FEC, CP, TS
Line Coding	OFDM				
FEC type	N.A.				Standard HD-FEC (alternatively SD-FEC) considered, not implemented.).
Baud rate	20			Gbaud	
Output power range	0			dBm	Typical output power
Minimum OSNR	35			dB	In 0.1 nm. At the output of the transmitter
RECEIVER per flow/slice					
Input power range		-25	-5	dBm	Input of the preamp
OSNR BtB tolerance	34.2			dB	In 0.1 nm. For 50 Gb/s, HD-FEC

Electrical/optical performance monitoring is achieved by means of a synergistic interworking among the data plane elements and control plane. The digital parameters of the S-BVT that can be particularly monitored per each flow/slice are: i) the SNR of each digital/electrical DMT/OFDM subcarrier, providing the CSI; and ii) the BER.

Monitoring parameters of the analogue optical system can be the TLS output power, the BVTx output power and the BVRx input power. It is worth mentioning that these parameters can be monitored with the aid of a data plane element external to the S-BVT (e.g. OSA).

The proposed S-BVT has been experimentally assessed in a back-to-back (B2B) set-up. Particularly, a single slice can support a maximum capacity of 50 Gb/s adopting a BVT configuration with SSB-OFDM and DD. The adaptive loading is implemented in DSP, with the SSB performed at the BV-WSS so that a DAC at 64 GSa/s is required. An example of BL assignment is shown in Figure 49, considering the CSI retrieved at the BVRx after transmission of an OFDM signal with UL (4-QAM) over a targeted path of the 4-node ADRENALINE network.

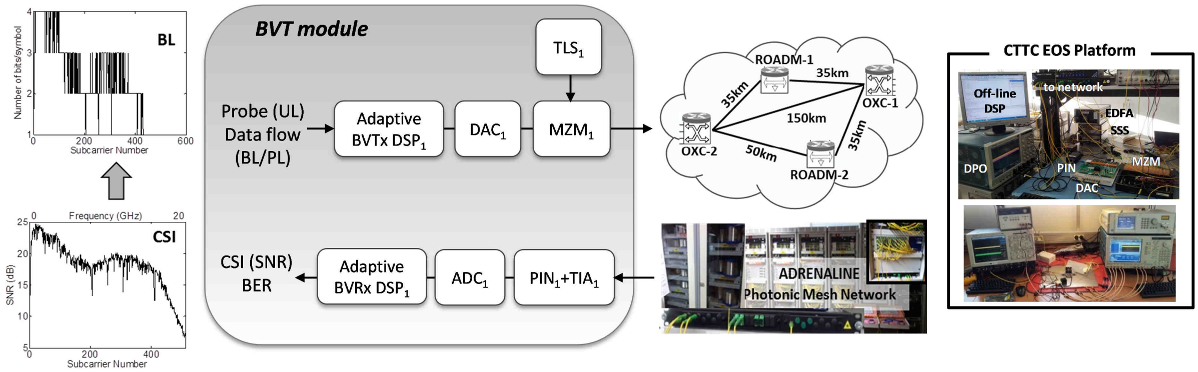


Figure 49. BVT module (slice 1 of the two-flow S-BVT of Figure 44) and example of BL assignment for transmission over the ADRENALINE network. In the insets: details of the network and pictures of CTTC experimental platform for optical OFDM systems (EOS)

A more cost-effective BVT configuration adopting DMT with lower speed DAC (28 GSa/s) and DD has been assessed for transmission in an optical system adopting lossless SOA-based switching nodes. In particular, up to four SOA-based nodes with fiber links of 25 km and up to two optical add/drop nodes adopting WDM filtering and SOA-based wavelength selectors with fiber links of 25 km has been considered. The BVT performance has been assessed for the BL algorithm with MA at a fixed gross bit rate of 28 Gb/s and for RA over different transmission distances at a target BER of $3.8{\cdot}10^{-3}$ [39].

In **Errore. L'origine riferimento non è stata trovata.**, we have proposed and experimentally assessed a hybrid and electro-optical MCM scheme exploiting super/sub-wavelength granularity for flexible/efficient multiple-flow transmission within elastic optical metro networks. Specifically, multiple OFDM electrical signals/flows are multiplexed into superchannels by optically implementing the discrete wavelet packet transform (DWPT) and its inverse. This approach is proposed to increase the spectral efficiency. In fact, the multiple flows can be packed with no guard-band, and unlike the fast Fourier transform (FFT), the wavelet finite bases functions present both time and frequency localization, enabling simpler implementation.

In **Errore. L'origine riferimento non è stata trovata.**, it has been proven that this S-BVT scheme enables one to pack multiple flows at 25 Gb/s each (in B2B), adopting a transceiver configuration based on DMT (10 GHz bandwidth and sample rate of 20 GSa/s) and DD, adopting external MZM (biased at the quadrature point) and TLS. Also a configuration based on amplitude modulation (MZM biased close by the null point) and coherent BVRx has been envisioned to improve the capacity/reach performance of the transceiver. The BV-WSS can be suitably programmed by selecting the appropriate attenuation/phase of each port to set the transfer function corresponding to the resulting concatenated wavelet filtering stage. For the proof-of-concept the Haar wavelet has been considered, to be compared with the adoption of a simple coupler for two flows (matching of performance has been observed). Actually, the aggregator can also be implemented using Mach-Zehnder interferometers integrated by employing silicon-on-insulator (SOI) technology, to further enhance the solution power efficiency at the expense of the system programmability/flexibility.

Furthermore, the assessment has been also performed in the ADRENALINE testbed, showing that up to 120 km and 3-hop paths can be successfully covered. Control aspects have also been analyzed, including the YANG model and the configuration of the S-BVT and its slices, as shown in Figure 50.

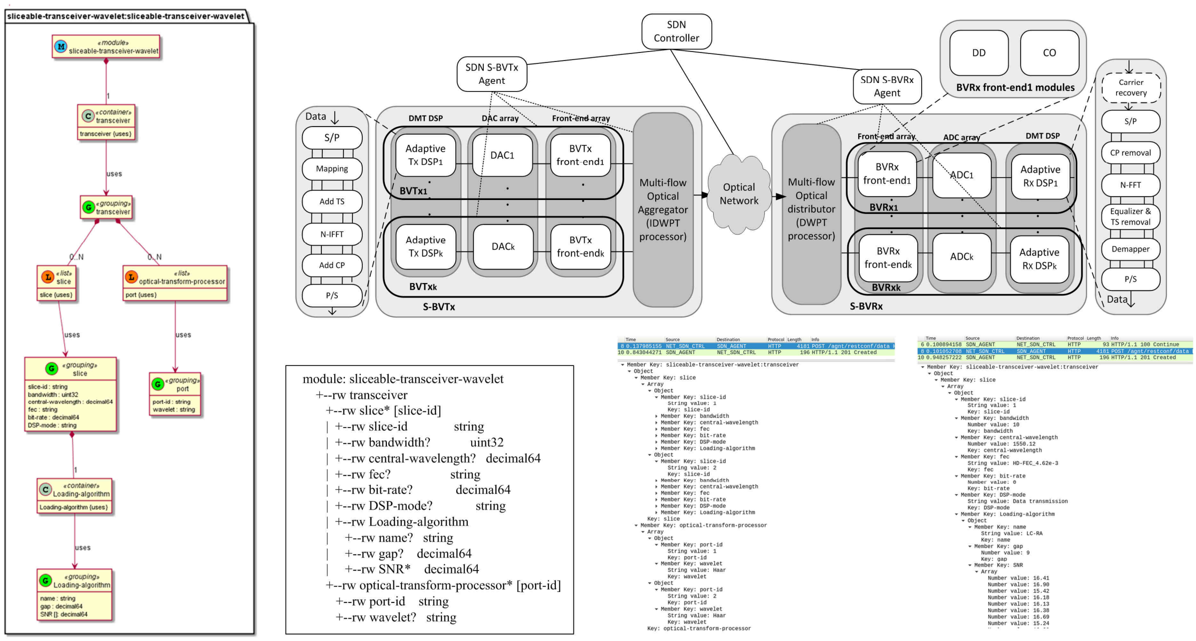


Figure 50. S-BVT adopting the BV-WSS as optical processor for packed superchannel generation, YANG model and configuration of the S-BVT and one of its slice

5.2.2 Transceiver Solutions for Dispersion-Tolerant Direct Detection

This subsection reports on the on-going joint work by CNIT and Ericsson on innovative transceiver solutions for dispersion-tolerant direct detection. High speed optical direct detection (DD) interfaces based on DWDM technology could meet the needs for capacity growth in the Metro segment to support the new 5G infrastructure. To increase the bit-rate without requiring the installation (or the upgrade) of bulk dispersion compensating modules, enhanced chromatic dispersion tolerant transmission solutions can be beneficial, exploiting alternative modulation formats and/or smart photonic-integrated modules.

Tolerance to chromatic dispersion can be enhanced through a proper combination of coding and pulse shaping, as demonstrated by the combined amplitude and phase shift (CAPS) codes [41]. CAPS codes of any order can be detected with the same DD receiver used for OOK; however their generation is not as simple, as an order-n coder has 2^n states and signals and the use of a 2-channels DAC (for the in-phase and quadrature components) is required. CNIT-Ericsson transceiver for Metro networks is based on a simplified implementation scheme that approximates the CAPS-3 code without the need of a DAC. The schematic of the transmitter is depicted in Figure 51. Such an architecture, named IQ-duobinary (IQduo) can reach a similar performance as CAPS-3, so allowing for significant savings in the required hardware at the transmitter [42]. This simplified approximation of a CAPS-3 signal is obtained by associating a quadrature component to a duobinary coded signal, by means of an IQ-MZM. Such a component is simply given by two attenuated replicas of the duobinary signal itself, respectively anticipated and delayed by a symbol time T. IQduo extends the tolerance to chromatic dispersion with respect to simple OOK, while maintaining the same hard threshold symbol-by-symbol receiver used for OOK, at the expense of a marginally higher cost transmitter. The gains g1 and g2 need to be chosen by design, and can be tailored to optimize performance according to the desired reach.

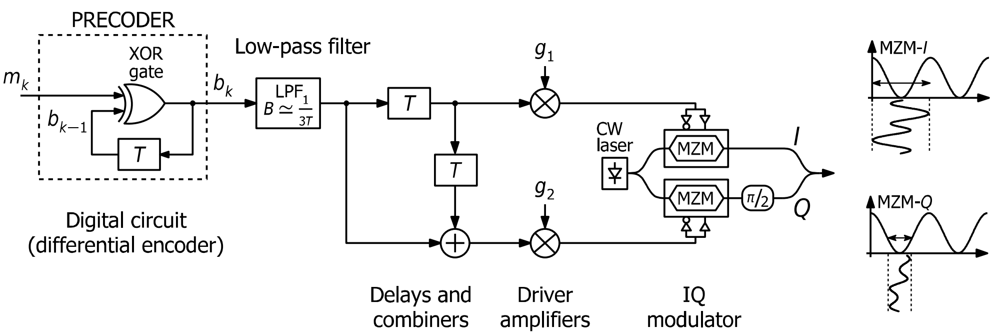


Figure 51. Schematic of the IQ-duobinary transmitter

An extensive experimental comparison between various modulation schemes all delivering a fixed bit rate of 50 Gb/s [43] confirms that the CAPS-3 format outperforms the OOK and PAM4 signalling schemes in terms of the maximum reach and required optical power at the receiver. In addition, the 50 Gb/s CAPS-3 signal is found to achieve an excellent dispersion tolerance over a broad range of transmission distances (0 to 20 km). IQduo is found to achieve a reach of 17 km, that is slightly lower than CAPS-3, as expected.

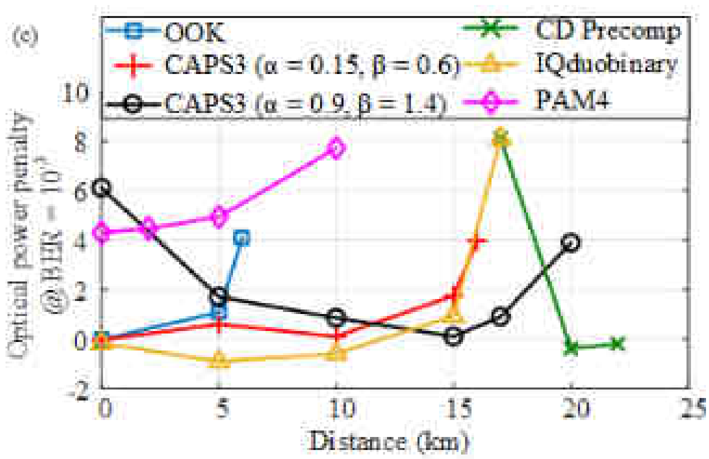


Figure 52. Optical power penalty at BER = 10^{-3} for various modulation schemes all delivering a bit rate of 50 Gb/s. The optical power penalty is calculated relative to a reference required received optical power of OOK in back-to-back to achieve BER of 10^{-3}

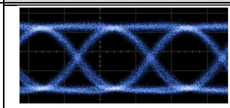
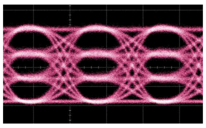
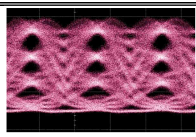
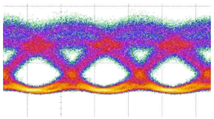
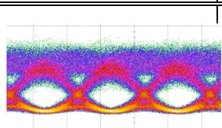
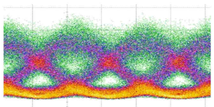
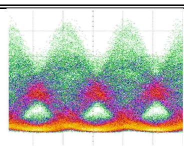
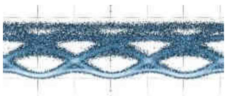
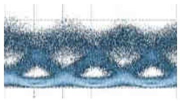
As depicted in Figure 52, the maximum achievable distance for OOK is 6 km, obtained while having to increase the received optical power by 4 dB relative to the back-to-back case. On the other hand, PAM-4 is capable of reaching at most 10 km with a severe optical penalty of nearly 8 dB with respect to OOK B2B. The performance of 50 Gb/s CAPS3 has been evaluated considering two different configurations (corresponding to different settings): in a first configuration (red crosses), CAPS3 shows only 2 dB penalty up to 15 km and can reach up to 16 km at the expense of a higher penalty of 4 dB. Even longer distances can be reached by reconfiguring the modulation parameters (black circles), enabling transmission of up to 20 km with 4 dB of penalty, at the expense of an increased penalty at very short distances 0-5 km due to the introduced pre-distortion. IQduo (triangles) shows a very low (or even negative) penalty up to 15 km. The penalty increases for longer distances, reaching 8 dB at a maximum reach of 17 km. Table 23 shows the received eye diagrams for the different modulation schemes all delivering 50 Gb/s at different reaches. These considerations also apply to different bit-rates, keeping in mind that the effects of chromatic dispersion scale quadratically with the symbol rate. Therefore, at 25 Gb/s CAPS-3 and IQduo allows an optical reach of up to about 80 km and 70 km, respectively, while OOK is limited to 20 km and PAM-4 to about 45 km [44].

Table 22. Device specifications

TRANSMITTER					
	Value	Min	Max	Unit	Note
Tunability range		196.300 1528	191.300 1568	THz nm	
DWDM frequency grid (fixed grid)		25 50	50 100	GHz	25Gb/s 50Gb/s
DWDM grid central frequency granularity (flexible grid)	6.25			GHz	
Center frequency accuracy		-1	+1	GHz	
Transmitter Bandwidth (-3 dB)		9	18	GHz	
Transmitter Bandwidth (-20 dB)		17.5	35	GHz	
Line Rate		26.75	53.5	Gb/s	
Net Line Rate		25	50	Gb/s	Considered Overhead 7% HD-FEC
Line Coding					
FEC type	N.A.				Standard HD-FEC considered, not implemented.
Baud rate		26.75	53.5	Gbaud	
Output power range		0	+10	dBm	Typical output power
Minimum OSNR	40			dB	In 0.1 nm. At the output of the transmitter
RECEIVER					
Input power range		-10	+5	dBm	
Minimum required OSNR in BtB	19			dB	at 0.1 nm, for 50 Gb/s, 7% HD-FEC (BER=$3.8x10^{-3}$)

In the Metro scenario it should be considered that there are also several sources of attenuation (link losses, wavelength multiplexing and demultiplexing at the hub node and to the OADMs, splitters and couplers) that may require the use of optical amplification to boost the signal beyond receiver sensitivity. In this context, the system performance can be limited by the OSNR induced by the ASE noise rather than the inherent receiver sensitivity. Table 23 also reports reference OSNR values at pre-FEC BER = 3.8x10^{-3} for the different modulation schemes all delivering 50 Gb/s.

Table 23. Received eye diagrams of different modulation schemes all delivering 50 Gb/s at different reaches. Required OSNR for BER = 10^{-3} is reported as well

50Gb/s	B2B	10 km	15 km	20 km	Req. OSNR BER = 3.8x10^{-3}
OOK		---	---	---	17 dB
PAM4			---	---	29 dB
CAPS3					18 dB
IQduo				---	19 dB

5.2.3 Reach Extension by Photonic Integrated Optical Dispersion Compensator (ODC)

To enable further reach extension for C-band high bit-rate transmission without requiring complex DSP, dispersion compensating devices based on integrated photonics are gaining momentum because they can be embedded in plug-and-play optical transceivers similar to the current Small Form Factor (SFP) modules. All-pass microring resonators have been demonstrated to be suitable as a suitable solution for the design of compact optical dispersion compensator (ODC) devices [45]. An ODC able to compensate the chromatic dispersion of a 10 km G.625 SMF, at a wavelength of 1550 nm, can be implemented as a cascade of three all-pass microring resonators opportunely designed. The insertion loss of the ODC is in the order of 1dB due to the propagation losses within the ring resonators, and the ODC is transparent to the modulation format and can be applied, e.g., to OOK, PAM-M, CAPS, IQduo, etc. Furthermore, as shown in Figure 53, more ODC blocks can be cascaded to compensate for longer distances. By combining ODC and optical switches, reconfigurable transponders operating on a wide range of fiber lengths can be designed [46]. Table 24 summarizes some examples of the optical reach expected for different modulation formats at 25 Gb/s and 50 Gb/s with and without ODCs. Longer reaches can be enabled by adopting different ODC configurations.

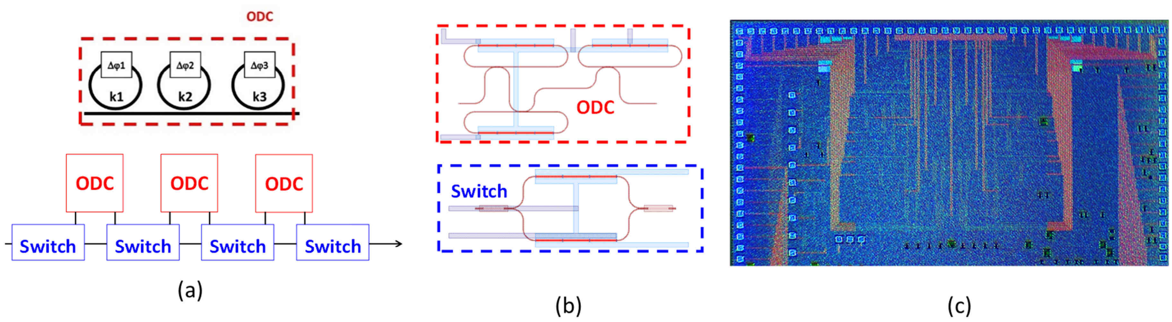


Figure 53. Schematic of the three microrings ODC and of the reconfigurable ODC module (a); mask layout of the ODC and the optical switch (b); Optical microscope picture of the fabricated device (c)

Table 24. Optical reach for different modulation formats at 25 Gb/s and 50 Gb/s with and without ODCs. Longer reaches can be enabled by different ODC configurations.

Speed	Modulation Format	w/o ODC	1 ODC	2 ODC	3 ODC
25 Gb/s	OOK	20km	30km	40 km	50 km
	PAM4	45 km	55 km	65 km	75 km
	CAPS3	80 km	90 km	100 km	110 km
	IQduo	70 km	80 km	90 km	100 km
50 Gb/s	OOK	6 km	16 km	26 km	36 km
	PAM4	10 km	20 km	30 km	40 km
	CAPS3	20 km	30 km	40 km	50 km
	IQduo	17 km	27 km	37 km	47 km

Optical reach extension of up to 30km for a 50 Gb/s OOK transmission was demonstrated in [46], exploiting a 3-stage Silicon-Photonics integrated ODC. Doubling of the bit rate up to 100 Gb/s was also enabled thanks to the support of polarization multiplexing on the fabricated device. A limited penalty of 2.5 dB at BER=10^{-3} was measured, due to the 50 GHz optical bandwidth limitation of the fabricated sample, that can be improved by modifying design parameters. Figure 54 reports the eye diagram for 50 Gb/s OOK after propagation over 30 km of SMF and chromatic dispersion compensation in the ODC (left), as well as the optical power required at the direct detection OOK receiver as a function of the transmission length, for achieving a BER = 10^{-3} (right).

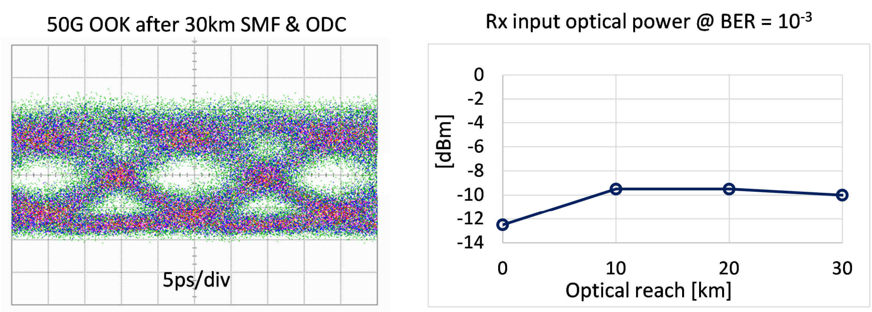


Figure 54. Eye diagram for 50-Gb/s OOK after propagation over 30 km of SMF and chromatic dispersion compensation in the ODC (left). Optical power required at the direct detection OOK receiver as a function of the transmission length, for achieving a BER = 10^{-3} (right)

5.2.4 Spectral-Efficiency Tunable Transmitter with Probabilistic-Shaping (PS)

This subsection presents the on-going work at UNIBRIS on a spectrally-efficient tunable transmitter adopting probabilistic-shaping (PS). A modulation-adaptable transmitter could offer different spectral efficiencies with variable signal formats. However, modulation-adaptable transmitters could only offer several discrete spectral efficiencies over large intervals. For dynamic network planning and optimization, the extra link margins are relatively small. Thus, a spectrally-efficient tunable transmitter with a fine granularity is becoming a critical technology to take full advantage of the gained extra margins.

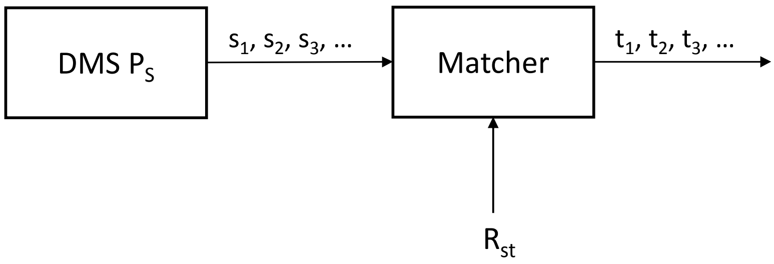


Figure 55. The source symbols are transformed by the distribution matcher

A probabilistic-shaping (PS) spectral-efficiency tunable transmitter is developed to provide a fine SE adaptability. To shape the input distribution, we start with the family of Maxwell Boltzmann (MB) curves, which is introduced in[47] to optimize the achievable information rate (AIR) for this bit-metric decoding in an AWGN channel. On the other hand, nonlinear shaping loss is found to have a relatively minor impact on MB-based PS around the optimal launch power in a multi-span system. To numerically transform a discrete memoryless source (DMS) into a DMS with a target distribution, we use constant composition distribution matching (CCDM), which perfectly emulates the target DMS with respect to the normalized informational divergence and the entropy rate if the size of the matched symbol blocks is large [48]. A conceptual diagram of PS matcher is given in Figure 55, where s_i are the source symbols with distribution P_s. In our case, the source symbols are just raw bit streams with a uniform distribution. t_i are the shaped output symbols with distribution P_t , which indicates the MB distribution in our case. R_{st} is the ratio of the input length to the output length, which is the only parameter we use to tune the shape of the MB distribution, i.e., the larger R_{st} will flatter the distribution. When R_{st} reaches $log_2(M)$, where M denotes the QAM size, the output symbols will diverge to a uniform distribution. As each matcher generates one-dimension shaped symbols, for QAM shaping, we need 2 PS matchers which operate in parallel.

The method to find an optimized input for a particular signal-to-noise ratio (SNR) is discussed in [49]. In practice, it is not necessary to adaptively optimize the distribution along the whole SNR range. Reference [47] reports that just a few input probability mass functions (PMFs) from the family of MB distributions are sufficient per QAM format to realize large shaping gains over a wide range of SNRs, shown in Figure 56, which simplifies the implementation and design of the PS.

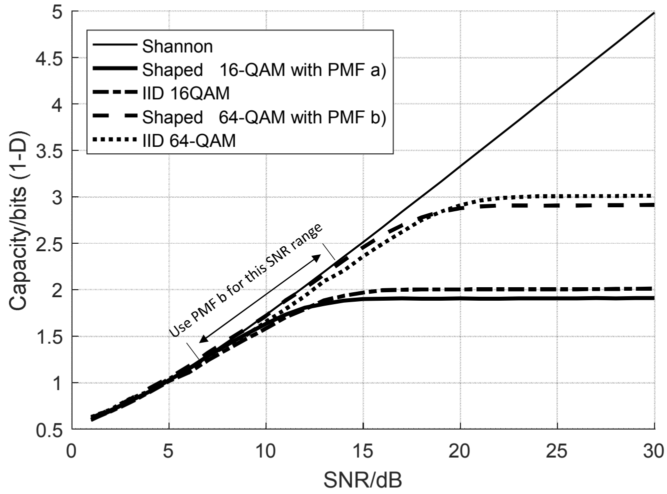


Figure 56. Use fixed PMF for a wide range of SNR in PS

The experimental setup for the probabilistic-shaping (PS) spectral-efficiency tunable transmitter is shown in Figure 57. A dual-channel 50 Gs/s arbitrary waveform generator (AWG) is used to drive an IQ-modulator to achieve the designed PS-BVT.

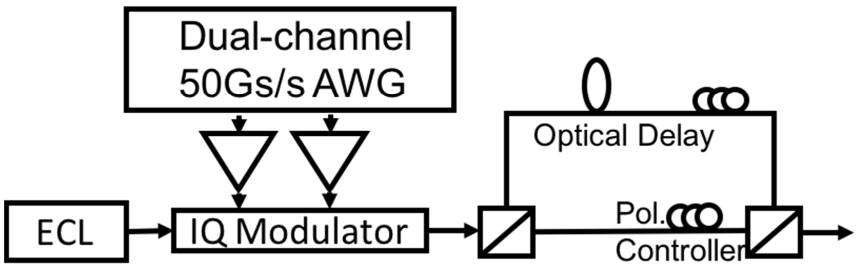


Figure 57. Experimental setup of a probabilistic-shaping (PS) spectral-efficiency tunable transmitter

5.2.5 Elastic Transponders with Low Resolution DAC and ADCs for Metro Networks

Within this decade, the number of coherent transponders dedicated to metro networks is expected to grow from 28 % to 58 % of the overall deployed coherent solutions [50], raising the need for specific developments and optimizations. Metro networks are often heterogeneous, i.e. they consist of legacy 10 Gb/s channels with dispersion managed optical links, mixed with higher capacity coherent channels (e.g. 100 Gb/s). They are also more cost-sensitive than long-haul networks and at the same time less constrained by reach and hence propagation impairments, thus promoting innovations in DSP [51].

Coherent transponders are flexible and can operate at various symbol rates, modulation formats (e.g. QPSK, 16QAM, 64-QAM) and employ Nyquist pulse-shaping to be highly spectrally efficient. For such functionalities, DACs are mandatory and represent the major part (40 %) of the overall DSP power consumption [50]. Customarily, coherent transponders employ 6- or 8-bit DACs that were originally developed for long-haul applications. These high-resolution DACs are mainly limited by their electronic bandwidth, which can be mitigated by means of pre-emphasis algorithms [52] whose implementation increases the overall DSP power consumption. A solution to reduce the DSP power consumption is to lower the DAC resolution down to 4 bits and below [50], [49], but with the disadvantage of increasing quantization noise. Recent efforts focus on assessing the quantization noise penalty due to a limited ADC resolution [53].

We experimentally investigate the quantization penalty in presence of a reduced DAC resolution for square modulation formats. We run a set of experimental back-to-back measurements with an 8-bit DAC at 88 S/s from which we select the active quantization levels to reduce the physical number of bits. An optical attenuator associated with an amplifier ensures a constant optical power into the coherent mixer and we vary the OSNR value by ASE loading. We generate 44 Gbaud signals with 16QAM and 64QAM using Nyquist RRC 0.02. We optimize the clipping value for each resolution of the DAC and compensate the DAC limited bandwidth. At the receiver side, we use an 8-bit ADC and classical coherent DSP with channel equalization and resampling at 1 SPS with a constant modulus algorithm, carrier phase estimation and constellation analysis to extract the SNR and BER. In Figure 58, we show the impact of the limited DAC resolution on the performance. For 16QAM at 44 Gbaud, the reduction from 8-bit to 4-bit DAC induces a penalty of ~1dB at a BER of 10^{-3}.

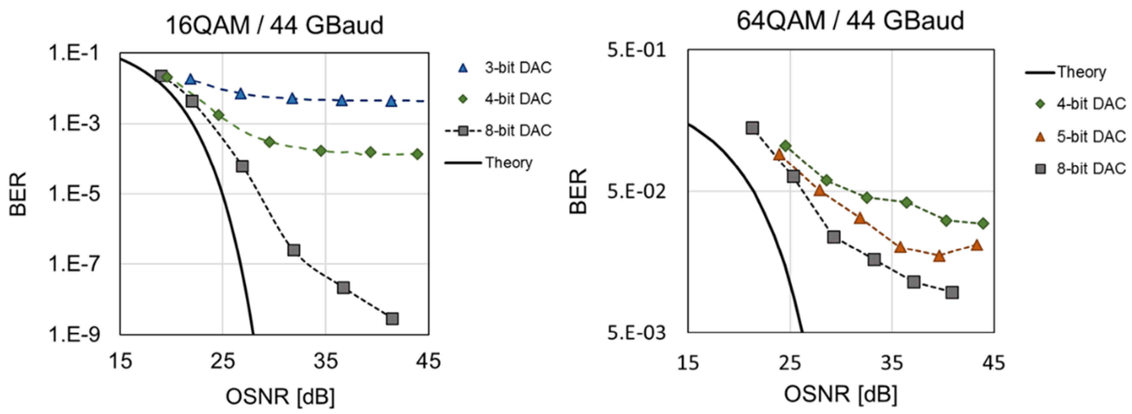


Figure 58. Experimental results with various DAC resolutions

We now model the coherent transmitter as shown in Figure 58(a). Without loss of generality and for simplicity, we only depict a single polarization transmission. For each polarization, two independent DACs convert the real and imaginary component of the electrical field. The DAC outputs are amplified before I/Q modulators and the transmitter optical output power is denoted P. The channel is modeled by a AWGN source of variance σ^2 and the coherent receiver block is assumed distortion free. The DAC quantization penalty is measured by the signal-to-quantization-noise ratio (SQNR) at the symbol decision stage (after propagation and receiver digital signal processing). We considered an additive quantization noise model, thus:

$$SQNR = \frac{P}{\sigma_q^2 \cdot C} = \frac{P}{E\left[\left(x_q - x\right)^2\right] \cdot C} \quad \mathrm{PAPR} = \frac{\max\{|s(n)|^2\}}{E[s(n)^2]} = \frac{X_{max}{}^2}{\sigma^2} = \frac{\left(2^{PNOB-1}\right)^2}{P}$$

where $\sigma_q^2 = E\left[\left(x_q - x\right)^2\right]$ is the mean square error between the quantizer output x_q and its input x. The constant C represents all the filtering processes that contributes to increase the SQNR. The mean square error depends on: the resolution of the quantizer, the amplitude distribution of the quantization levels and the probability density function of the input signal.

Probabilistic shaping was recently introduced and is now widely used in long-haul networks where the high resolution of the DAC makes the quantization penalty negligible. To maximize the benefits of shaping in metro networks, there is a need to study transmitter impairments such as low-resolution DAC quantization noise. We study the case of a combined geometrically- and probabilistically-shaped constellation that requires a minimal implementation penalty to reach the

Shannon limit [54]. To maximize the mutual information with respect to the same modulation where all points are equally likely, the transmitter modifies the probability distribution of constellation points of amplitude |a| to match with the Maxwell-Boltzmann distribution $Prob(a) = e^{-\nu|a|^2}$where ν is the shaping parameter as illustrated in Figure 59(b). In the context of shaping, several methods exist, such as geometrically circular [55]and geometrically circular and probabilistically shaped (CPS) QAM [56].

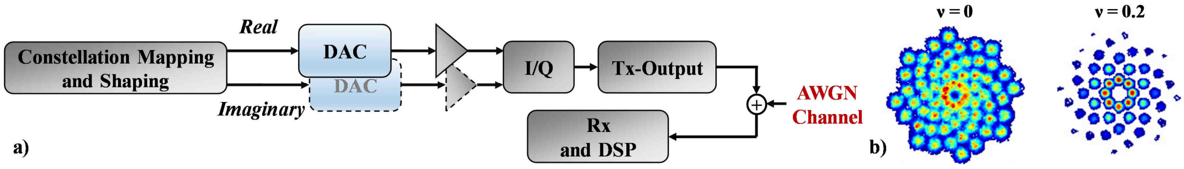


Figure 59. (a) Simulation setup for one polarization; (b) CPS-64QAM with a uniform 4-bit DAC

In [57], we propose to design a nonuniform low resolution DAC to enhance the signal-to-quantization-noise ratio (SQNR) as shaping emphasizes nonuniform distribution of the signals at the DAC input for which the uniform quantizer may not be optimal. One solution to increase the SQNR is to clip the input signal [58], which increases the output power P while maintaining an acceptable amount of distortion. Another solution is to modify the distribution of the quantization levels according to the statistics of the input signals, resulting in a nonuniform quantizer [58]. We compare a nonuniform quantizer minimizing the DAC output distortion with the uniform quantizer at optimal clipping ratio in the specific case of CPS-64QAM with 4-bit resolution DAC. The input data are 2^{16}-long random symbol sequences mapped on CPS 64-QAM at 2 samples per symbol. The waveforms are filtered by a root-raised-cosine filter of roll-off factor β = 0.1. The SQNR gain is defined as the difference between the SQNR with the nonuniform quantizer and the SQNR with the uniform quantizer at optimized clipping ratio. For the uniform quantizer we first determine the optimal clipping ratio by measuring the SQNR for various clipping ratios, as shown in Figure 60(a). We define the clipping ratio as the ratio between the input signal standard deviation and the maximum DAC output amplitude. In Figure 60(b) we show the SQNR gain when employing the nonuniform quantizer for various levels of shaping. In the absence of probabilistic shaping (ν = 0), we have a SQNR gain of +0.5 dB. When ν increases the SQNR gain increases until it reaches +1 dB with ν = 0.2. We observe that the SQNR gain is more important for ν = 0.2, because the probability density function of the signal being quantized is narrower and hence benefits more from nonuniform quantization. In Figure 60(c), the system ΔSNR gain (using 1/SNR = 1/SQNR + σ²/P) is plotted for various SNRs associated to its optimized ν parameter. From ΔSNR = +0.4 dB at SNR = 30 dB (system limited by transceiver impairments), ΔSNR decreases down to +0.1 dB when the transmission is limited by the AWGN.

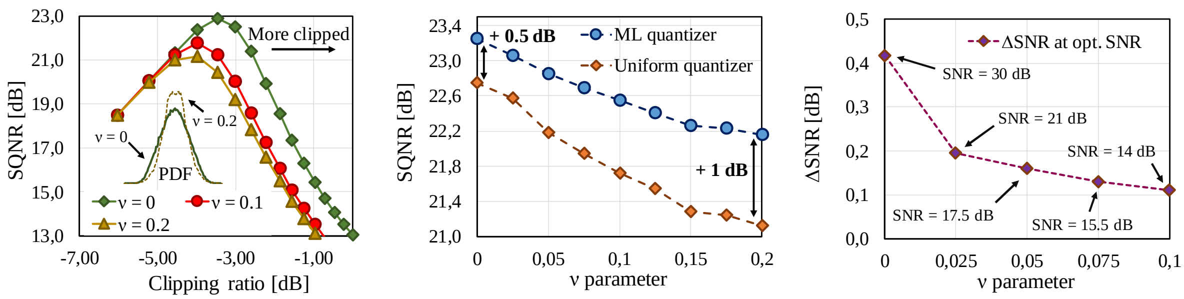


Figure 60. (a) SQNR for CPS 64-QAM for various ν parameters and clipping ratio with a uniform quantizer (b) SQNR for CPS 64-QAM with nonuniform and uniform quantizer (c) Corresponding ΔSNR with optimized ν parameter for each SNR

5.2.6 Commercial Transponders Enhanced with NETCONF/YANG Modules

Two off-the-shelf PM-QPSK 100G Ericsson muxponders are available at the CNIT Lab. The muxponders, fully tunable in the whole C band (central frequencies in the 50 GHz spacing) support two FEC types (standard and proprietary). Differently from the off-line transponder prototypes described in the previous section, these 100G muxponders enable real-time transmission and monitoring experiments.

Table 25. Transponder specifications

TRANSMITTER					
	Value	Min	Max	Unit	Note
Tunability range		191.35	196.1	THz	
DWDM frequency grid (fixed grid)	50			GHz	
DWDM grid central frequency granularity (flexible grid)				GHz	no
Center frequency accuracy		-2	+2	GHz	
Transmitter Bandwidth (-3 dB)				GHz	
Transmitter Bandwidth (-20 dB)				GHz	
Line Rate	120.5793882			Gb/s	
Net Line Rate	100			Gb/s	ODU-4
Line Coding					
FEC type	1) SD-FEC; 2) SD-FEC-Low-latency				proprietary
Baud rate	30.14484581				
Output power range	0			dBm	fixed
Minimum OSNR	14			dB	From measurements
RECEIVER					
Input power range		-15	0	dBm	
OSNR BtB tolerance				dB	

Management and configuration can be performed either through the graphical user interface (GUI) of the proprietary element manager or through proprietary APIs. These APIs have been exploited in the implementation of an agent module, whose architecture is shown in Figure 61.

The agent has been implemented in Python. A NETCONF server is the northbound interface of the Agent, for communication with the SDN controller and/or an OAM (Operation, Administration and Maintenance) handler. A local database is maintained at the agent to store configuration and state parameters, in agreement with the YANG models of the related device. Monitoring information towards SDN controller and/or OAM handler is supported through synchronous and asynchronous notifications, allowing bottom-up communication of device specific parameters such as link quality degradation and physical failure detection. To avoid scalability issues at the SDN controller and/or OAM handler, notifications are typically forwarded every 15 minutes. In the case of specific warning (e.g., when a critical threshold is exceeded, when a parameter deviates from typical operational values), telemetry streaming can be activated, enabling the device to continuously send accurate monitoring information (e.g., every few seconds, according to device capabilities). In particular, upon NETCONF degradation notification, the upper layer OAM may decide to trigger a set of telemetry subscription instances for fine-grained live monitoring. The subscription specifies the target device, the physical parameter to monitor and the requested sampling interval. To this purpose, the agent exploits the gRPC protocol for the telemetry service. gRPC servers at the agent receive the telemetry subscription and start pushing real time streaming of the monitored data directly received by the hardware drivers. The architecture allows each subscription, also referred to as bundle subscription, to configure a number of monitoring parameters.

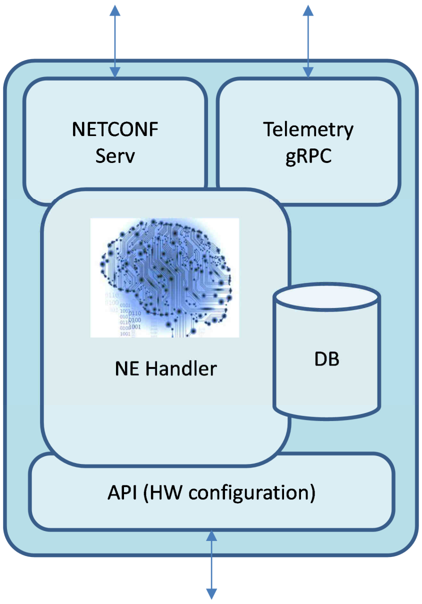


Figure 61. Architecture of the software module controlling the network element (i.e., proprietary hardware), enabling NETCONF/YANG SDN control

Additional off-the-shelf muxponder solutions provided by Coriant are available at the TIM lab, in the framework of a joint METRO-HAUL collaboration targeting the deployment of innovative disaggregated metro-solutions combining both recently released devices and innovative research solutions. Specifically, two Coriant Groove platforms are available, supporting rates at up to 200 Gb/s and NETCONF/YANG control [59].

5.2.7 Digital Sliceable BVT for Filterless Networks

Multi-flow digital sliceable bandwidth-variable transponders (DS-BVT) are proposed by HHI as efficient and flexible transponder architecture for filterless optical networks. A DS-BVT digitally modulates a certain spectral range (e.g. several ITU-T flexgrid slices) which is limited by the analogue bandwidth of its components such as the DAC, ADC, optical modulator, driver amplifiers and TIAs. By digitally generating and receiving several subcarriers in the frequency domain, a DS-BVT can set up several optical flows to different destinations. In a filterless D&W scenario, a single DS-BVT could serve several AMENs, whereas for traditional BVTs, the whole spectral range of the BVT is wasted at a single AMEN destination.

A block diagram of the DS-BVT is shown in Figure 62(a). The DSP part at the transmitter consists of a FEC encoder, subcarrier modulation and pulse shaping, as well as a nonlinear pre-distortion stage to compensate for transmitter component impairments. At the receiver DSP, the received subcarriers are demultiplexed after the optical frontend has been compensated. The target subcarriers are further processed by standard single-carrier DSP before FEC decoding. The prototype (cf. Figure 63) currently supports a DAC sample rate of 64 GS/s but can be upgraded to 92 GS/s. Flexible subcarrier generation is supported on the 6.25-GHz center frequency grid with subcarrier spacings of 6.25 GHz, 12.5 GHz and 25 GHz. Mixed spacings are possible. Single-carrier operation is also supported. Each subcarrier is modulated with M-QAM. This allows one to achieve a fine granularity in net data rate per subcarrier. Figure 62(b) shows the simulated optical output spectrum of a DS-BVT operating with six subcarriers on a 6.25-GHz grid. Each subcarrier is modulated with 60-Gb/s DP-32QAM (net rate of 50 Gb/s). In this configuration, the DS-BVT can serve up to 6 target destinations.

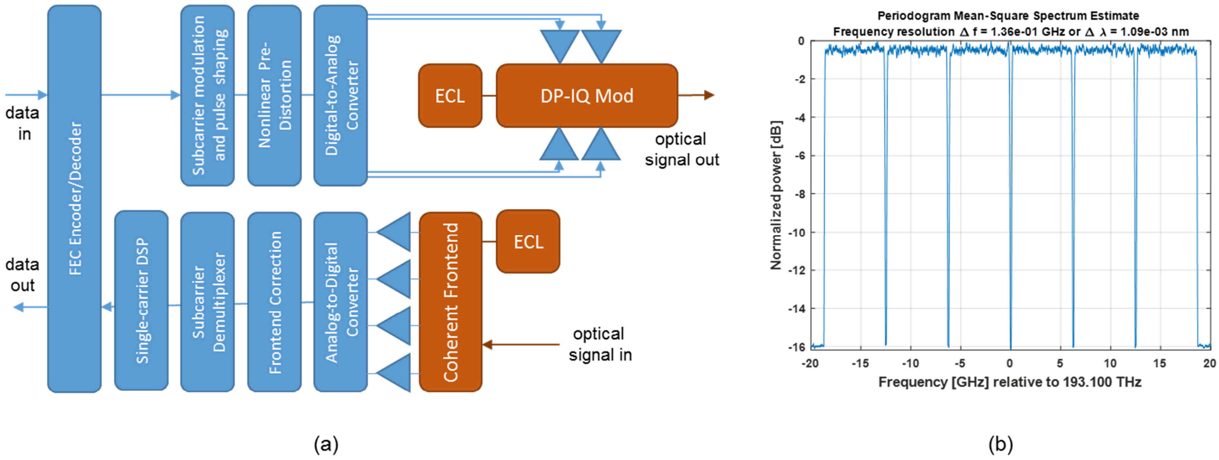


Figure 62. (a) Block diagram of a DS-BVT including flexible digital subcarrier generation and reception. (b) Optical spectrum of 6×60 Gb/s DP-32QAM subcarriers (50 Gb/s net rate per subcarrier) on 6.25-GHz channel spacing

Figure 63. Optical waveform generator prototype in filterless testbed

Table 26. DS-BVT specifications

TRANSMITTER per flow/slice					
	Value	Min	Max	Unit	Note
Tunability range C-band		196.25 1527.6	191.5 1565.5	THz nm	
Tunability range L-band		191.1 1568.77	186.35 1608.76	THz nm	
DWDM frequency grid (fixed grid)		50	100	GHz	
DWDM grid central frequency granularity (flexible grid)	6.25			GHz	
Center frequency accuracy	1			GHz	
Transmitter Bandwidth (-3 dB)	20 (typ.)			GHz	
Line Rate		12	448	Gb/s	Per subcarrier
Net Line Rate		10	400	Gb/s	Per subcarrier
Line Coding	M-QAM				
FEC type	TPC, LDPC, HD				TPC/LDPC with different rates
Baud rate		6	32	Gbaud	Per subcarrier
Output power range	C-band: -2.4 L-band: -3.4			dBm	Typical output power
Minimum OSNR	31			dB	In 0.1 nm. At the output of the transmitter
RECEIVER per flow/slice					
Input power range				dBm	Depending on subcarrier configuration
OSNR BtB tolerance				dB	

5.2.8 Coherent Transponders for Filterless Nodes

ADVA is considering filterless (or semi-filterless) nodes based on wavelength blockers. If no filters are present in the drop path of the node, coherent detection is necessary. The main reason for coherent transmission, however, is to enable highest capacities. Commercially available coherent transmitters will be used in the system, as well as pre-prototypical lab setups. One commercial transponder considered here is part of ADVA's CloudConnect solution [61] and is able to generate DP-QPSK, 8-QAM and 16-QAM at 32 GBaud. Therefore a comparison of the different modulation formats in terms of reach and system requirements is possible.

For the lab setups, higher symbol rates and modulations up to 64 GBaud/64QAM are considered and new technologies are explored. In [62] a silicon photonics Mach-Zehnder modulator monolithically integrated with a segmented BiCMOS driver is evaluated. Figure 64 shows the model of such an IQ modulator device for one polarization. One system parameter to be designed carefully is the length of the RF phase sifters. A shorter phase shifter is desirable since this reduces the number of RF amplifier segments and thus the power consumption of the device. Simulations with measured device data explore the effect of different phase shifter lengths inside the modulator design on the system performance for DP-4 to 16QAM. The results are shown in Figure 65. For comparison theoretical curves and simulation results for conventional Lithium-Niobate ($LiNbO_3$) modulators are included as well. To achieve a sufficient performance of 64 GBd DP-4QAM and DP-16QAM transmission for typical metro-node distance links modulator RF phase shifters with 4 mm length are sufficient. In that case the penalty compared to $LiNbO_3$ modulators reach is up to 1 dB for DP-16QAM at the FEC limit of 2.2e-2. DP-64QAM operation was achieved with 6 mm devices, however, with very low system margin.

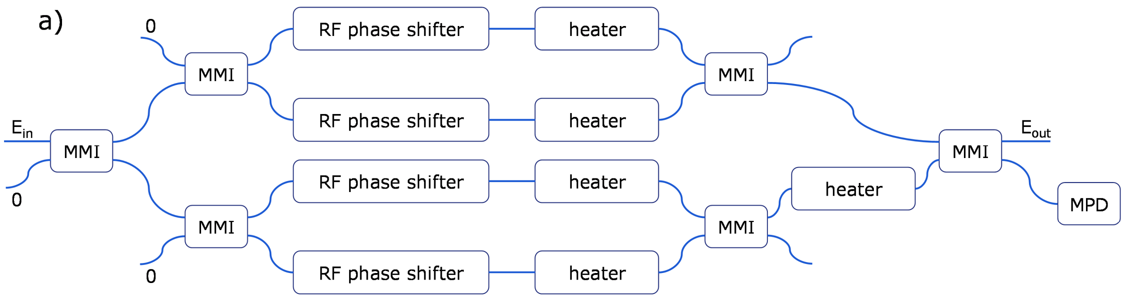


Figure 64 Structure of single polarization SiPh IQ modulator. MMI: multimode interference coupler, MPD: monitor photodiode

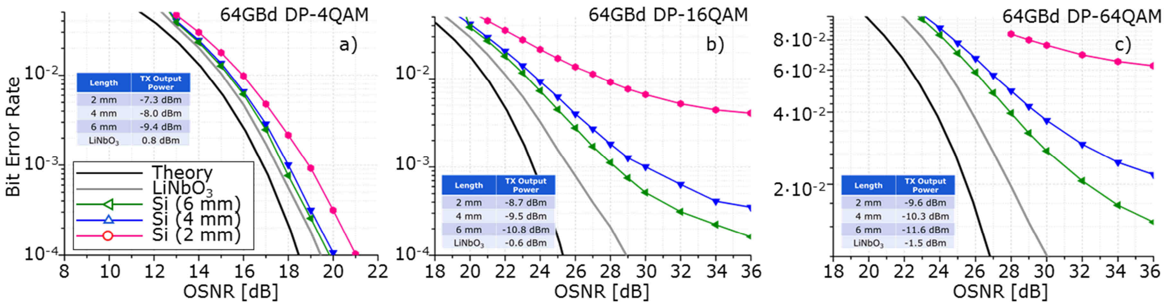


Figure 65. OSNR performance comparison for different phase shifter length in a silicon photonics IQ modulator with segmented driver

5.3 Programmable AMEN/MCEN for Interconnection of Access and Core Network

This section reports on the programmable edge-node (AMEN/MCEN) solution under development at UNIBRIS.

5.3.1 Generic Edge-Node Interface

The Metro-Haul project is developing a generic programmable edge-node (AMEN/MCEN) interface that aggregates multiple heterogeneous services from the access network and sends the traffic to either the core network or to the metro network. Hence the edge node is a point of aggregation of heterogeneous services from the access network. As shown in Figure 66, the designed edge-node interface needs to handle network traffic from either data centers, metro networks, or 5G back-haul applications. The heterogeneous network traffic requires an easily-updatable traffic processing capability, such as the support for new protocols. On the other hand, varying traffic capacity needs across applications requires programmable transmitters to be able to provide just-enough-bandwidth optical signals for further transmission in core/metro networks. Thus, the generic edge-node interface needs to offer a network function programmable capability to handle different network protocols and programmable bandwidth variable transmitters (BVTs). The generic edge-node interface is intended to support both AMEN and MCEN nodes. In some cases, the AMEN and MCEN can coexist as a single node. Therefore, the generic edge-node interface connects to multiple BVTs to connect to both the core and metro networks.

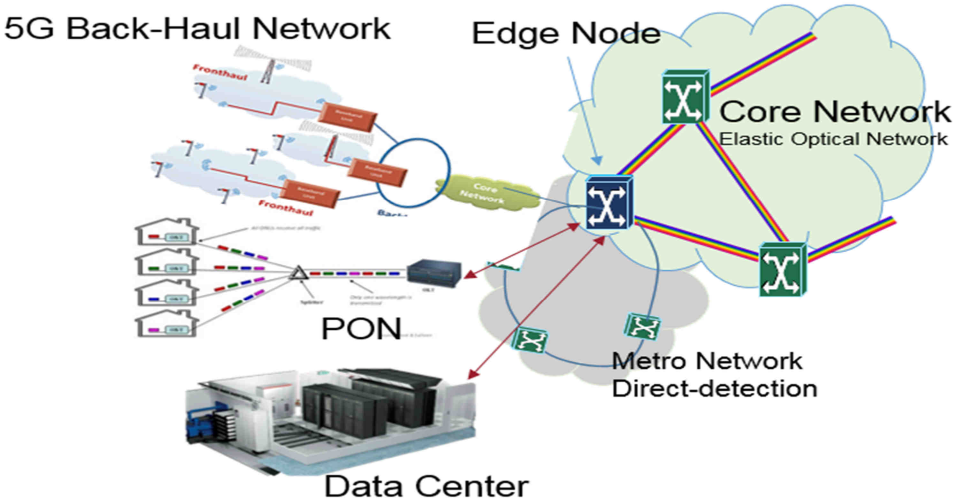


Figure 66. Generic architecture of Metro-Haul network from the Edge Node perspective

The design of the AMEN/MCEN node includes FPGA-based traffic processing and the FPGA-driven BVTs. The following section provides details about the functionalities, design, validation, prototype, and current plans for the edge node (AMEN/MCEN) devices

5.3.2 FPGA-Based Traffic Convergence and traffic Processing Platform

In this section we provide an overview of the features and capabilities of the FPGA prototype that will be demonstrated for Metro-Haul.

Traffic aggregation and convergence: The edge node (AMEN/MCEN) is capable of aggregating traffic from different access networks (CPRI, PON, residential Ethernet etc). Our group has demonstrated CPRI integration into the FPGA data plane (under submission) and our existing prototype can aggregate Ethernet traffic. Hence our solution can map 5G access traffic (Ethernet, wireless or cellular) to metro/core networks.

Traffic processing and shaping based on QoS requirement: The edge node has traffic shaping and packet processing capabilities, with traffic aggregation from heterogeneous networks (based on Ethernet headers, source ports), traffic scheduling, traffic prioritisation based on packet headers, HW-based monitoring, and statistics framework etc. All the above features are run-time programmable through register control interface.

Network function programmable node: The edge-node interface solution is connected to servers (discussed below in prototype section) to enable the addition of compute and storage capabilities to the edge node. Such an architecture enables network function programmability in the node and demonstrate the features of edge computing node for 5G networks. [63] shows that implementing multiple network functions on programmable hardware to provide function-based virtualization can improve the performance of the metro node.

5.3.3 AMEN/MCEN Node Design

Figure 67 shows the architecture of the FPGA design for the AMEN/MCEN node based on the P4 [64] approach. Our current approach is based on P4, but we are also exploring other architectures that can meet the requirements of Metro-Haul and seamlessly integrate with existing access solutions. The current testbed provides two input ports that can connect to heterogeneous access networks (WiFi, PON etc). The arbiter is used for aggregating the input traffic sources so that traffic scheduling mechanisms (or user-logic ideas) can then be implemented. The user-logic implementation can be use-case specific and can provide various abilities like VLAN tagging, ACL, firewall, latency aware scheduling etc. For this case, we explain application-aware offloading using DSCP headers. The match-action table in the traffic scheduling part can be configured on a run-time basis to provide the aggregation or segregation features. We are also exploring different architectures and adding multiple features that can improve the flexibility and performance of the edge node. The design is currently integrated into a simple control plane that can modify the properties of the edge node on the fly. The design also includes registers to monitor the packet and byte count.

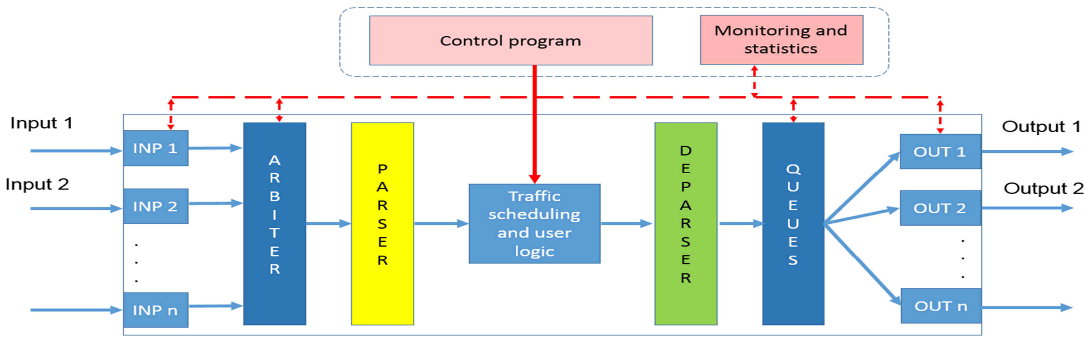


Figure 67. Generic architecture of the Metro-Haul network from an Edge Node perspective

Figure 68(a) shows the evaluation of the performance of a P4 node against existing software solutions for simple packet forward functionality. Each packet coming into one port is forwarded to another port without any additional processing. The average latency of the hardware forwarding (P4-HW) is around 2.33 µs, the average latency of the SW forwarding is around 19.30 µs, and that of the VM is about 240 µs. Thus, based on performance and application properties, certain functions (mostly packet processing) can be implemented in hardware for better performance. Figure 68(b) shows a histogram diagram of the distributions of the latency with 1000 packets under different offload scenarios. It is observed that the average latency of the electrical offload is the highest, corresponding to 31.99 µs, and optical offload of Class B is the least at 2.03 µs. This implies that latency-critical applications offloaded to an optical network by our programmable edge node will have a better quality of service than when running on an electrical network.

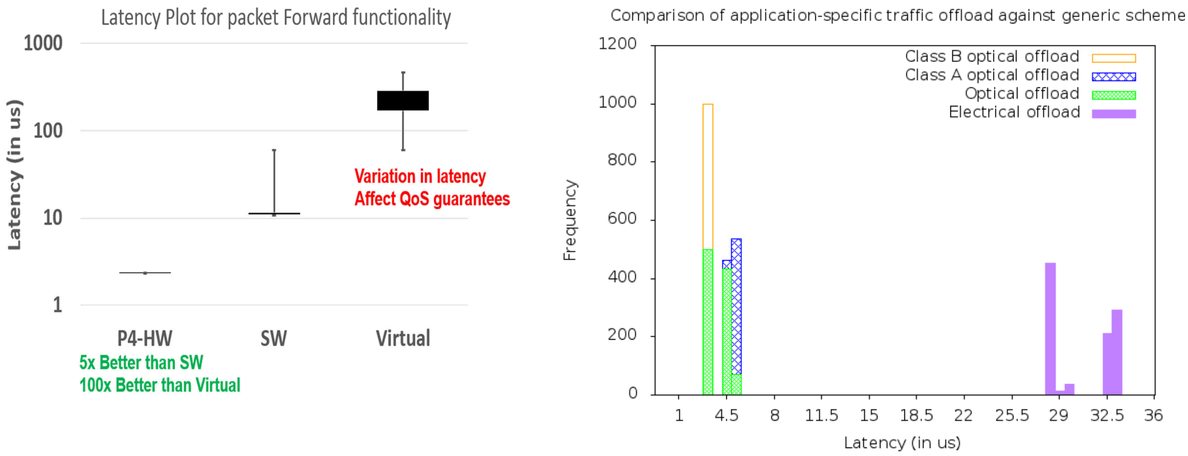


Figure 68. (a) Latency benchmark of hardware Vs Software approach (b) Application Aware traffic offload vs generic approaches

5.3.4 Implementation and Prototype Details

Figure 69 shows the prototype of the edge node in a modular fashion termed “5G in a Box”. The solution has high density storage and compute resources that is capable of supporting emerging 5G applications within the edge node. Table 27 shows the resources available in our prototype and their specification.

Table 27. Specification of the AMEN/MCEN Prototype (FPGA section only)

Component	Specification
Compute	Intel Core i7-7700K Processor, 64G RAM
Storage	256 GB – 1 TB
Network (FPGA)	Xilinx FPGA (Virtex 7), 4 ports (10G capable)
Network (NIC)	Solarflare NIC , 2 ports (10G capable)

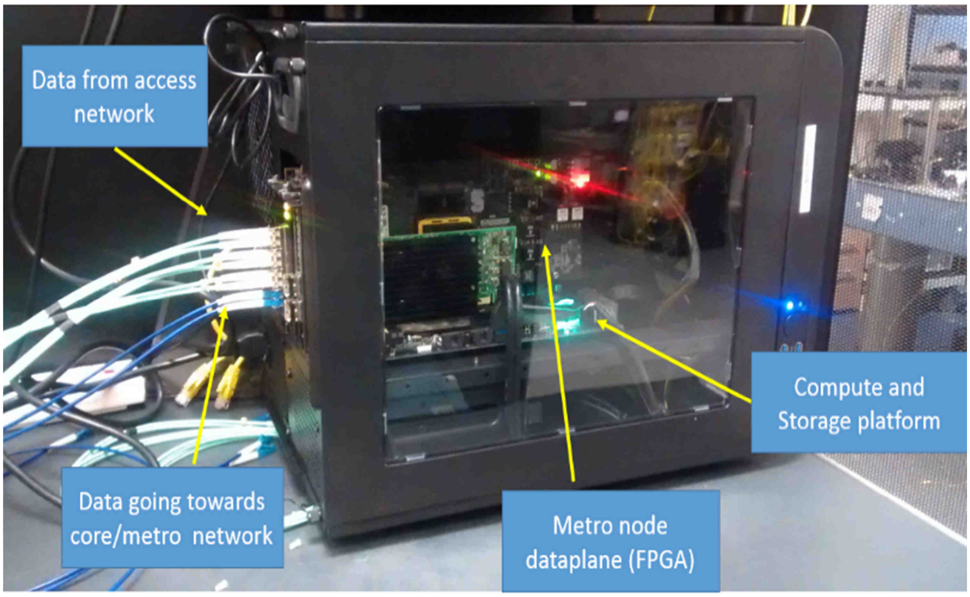


Figure 69. Prototype of the Metro Haul Edge Node

5.3.5 FPGA Control of Bandwidth Variable Transmitter

The FPGA-enabled BVTs uses FPGAs to process the incoming traffic from OTN, Ethernet and other networks. The FPGA parses the incoming traffic and drives the modulation-adaptable transmitter with the capability to switch modulation in less than a second. The bandwidth variable transmitter can adopt different modulation formats to adjust the offered optical bandwidth. The variable modulation formats with different spectral efficiencies can be adopted for different transmission coverages. A fast-tunable modulation-adaptable transmitter is implemented as shown in Figure 70(a). Both the FPGA and the transmitter are controlled by a local agent (RMAT agent) to adapt the optical signal modulation format. The modulation-adaptable transmitter can be potentially integrated with an SDN controller.

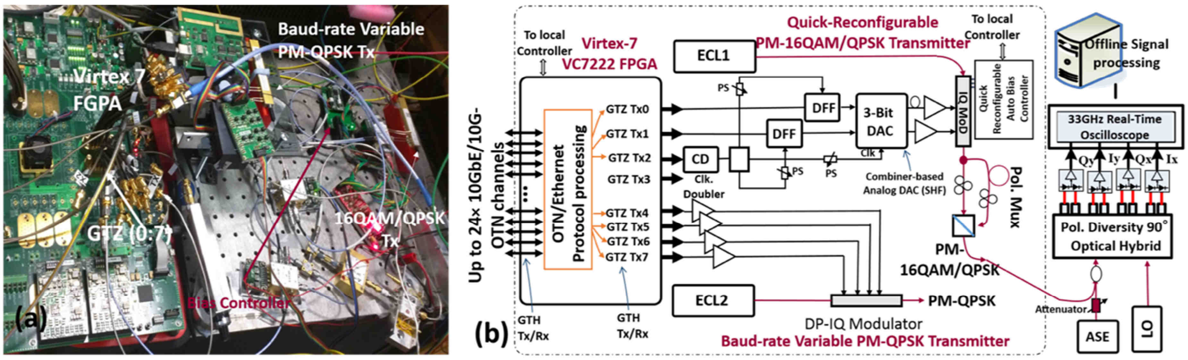


Figure 70. (a) Lab setup and (b) Experimental setup of real-time modulation-adaptable transmitter

As shown in Figure 70(b), three serial GTZ transmitters drive the modulation-adaptable transmitter. Among these, two GTZ transceivers handle the data, while another GTZ provides a half clock, which is doubled by a clock doubler (CD) to synchronize two digital flip-flops (DFF) and a 3-bit DAC. The DFFs are used to improve the signal quality. After regeneration, two data streams are sent to a 3-bit DAC (from SHF) to obtain multiple level signals. The 3-bit DAC is an analogue device based on power combiners, which can provide a wide bandwidth and high signal quality with precise phase matching.

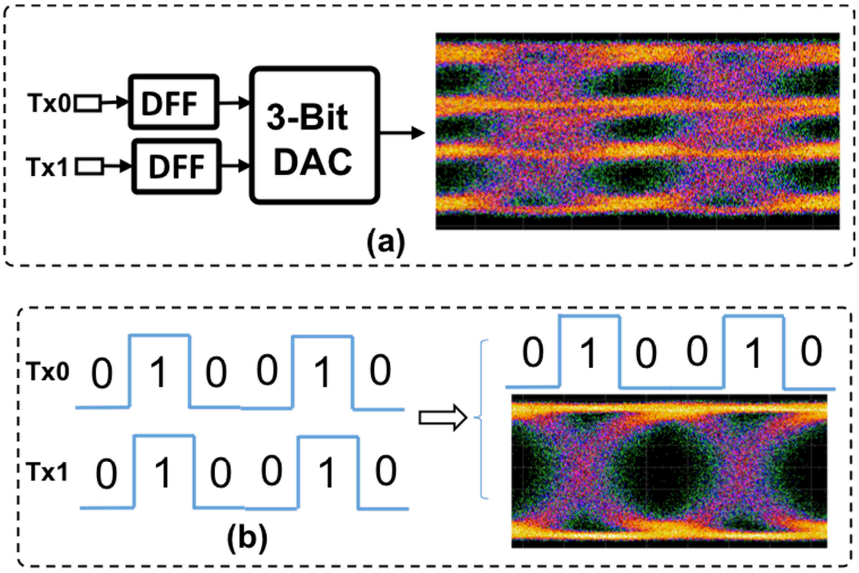


Figure 71. Principle of modulation adaptability: (a) 4-level drive signal generation with two independent data; (b) 2-level drive signal generation with two identical data

Figure 71 shows the operation principle for the modulation adaptability. The modulation adaptability is achieved by reconfiguring the driving signals. As shown in Figure 61(a), two independent data streams after the 3-bit will generate 4-level signals. The electrical eye diagram of the 4-level signal is measured with a 50 GHz oscilloscope and shown in the insets of Figure 61(a). The 4-level signal then drives an IQ modulator and 16QAM signals can be generated. For the QPSK signal generation, two identity signals are sent out from two GTZ transceivers. After the combination in the 3-bit DAC, only two level signals can be generated with a maximum amplitude. Thus the generated 2-level signals drive the IQ modulator to generate QPSK signals. Based on this principle, the optical modulation can be programmable by manipulating the data of the two GTZ transmitters on the FGPA. The modulation-adaptable transmitter generates 26 Gbaud PM-QPSK/16QAM signals. In our demonstration, a reconfigurable bias controller stored two sets of parameters for two different bias states and provided a quick switch between the two states. With the developed RMAT controller, both the FPGA and the bias controller could reconfigure the modulation format quickly. The transmitter can be potentially integrated with the SDN controller.

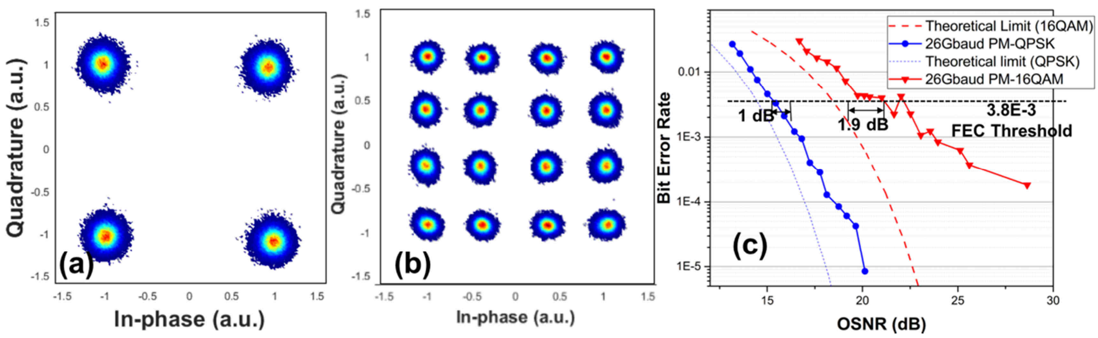


Figure 72. Recovered constellation distributions for (a) QPSK and (b) 16QAM ; (c) BER vs. OSNR performance test

The received signal distributions are shown in Figure 72(a) and (b) for PM-QPSK and PM-16QAM signals. Assisted by two DFFs, the output signals of the FPGA serial transmitters are improved considerably, and lead to high-quality signals. By adding extra ASE noise to the signal, we tested the OSNR vs. BER curve and show the results in Figure 72(c). The required OSNR to achieve BER = 3.8E-3

(7% FEC threshold) is about 20.3 dB and 15.36 dB for PM-16QAM and PM-QPSK signals. Regarding quick reconfiguration of the modulation format, we use the optical spectra as an indicator for stable bias controlling. The auto-bias controller recorded two sets of the bias parameters for both QPSK and 16QAM, thus the corresponding parameters can be retrieved in advance. Without the locking time, the bias controller can switch its operation status quickly. The auto-bias controller is also controlled by the developed RMAT agent. Including the switching time of the bias controller, the preliminary test shows the modulation adaptability can be performed in less than one second.

5.4 The PON Termination to an AMEN and its Abstraction

This section reports on the programmable edge-node (AMEN/MCEN) solution under development at OLC for integration between metro and access (PON) networks. In the context of dynamic clouds, the AMEN may include networking, processing and storage resources. The architecture for such a cloud node OLC is considering consists of a number of access network termination points, a (mini)-datacentre (mDC) and a L2 switch (OTN/Carrier-Ethernet/Ethernet). In particular, in the framework of METRO-HAUL, the building blocks of an AMEN are depicted in Figure 73.

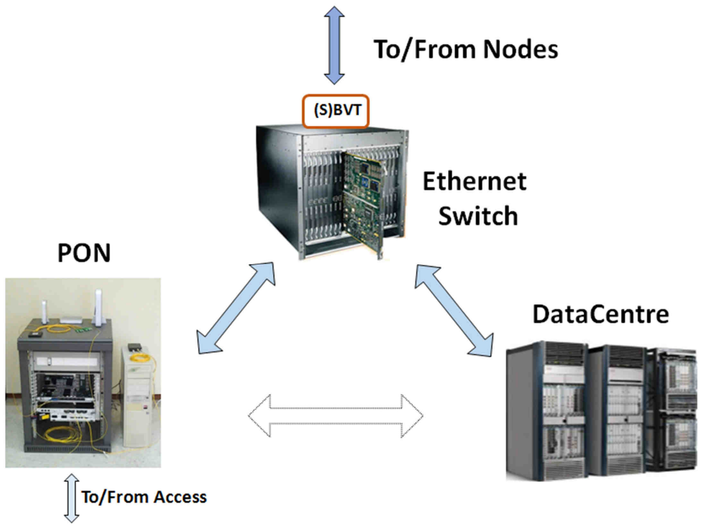


Figure 73. A schematic illustration of the main building blocks of an AMEN

As the L2 switch we have selected an Ethernet switch, while we are considering a Passive Optical Network (PON) as the Access technology terminated to the Metro network. Although we have selected an Ethernet switch, other L2 technologies (Carrier-Ethernet, OTN) might also be employed in the presence of additional Access technologies; notably, mobile traffic. Nevertheless, in the context of PON and ptp Ethernet connection a legacy Ethernet switch suffices. OLC's objective in METRO-HAUL is to develop a unified control and management scheme for the building blocks of an AMEN depicted in Figure 73, constructed by means of deployed systems adopting a *partially disaggregated* platform. In particular, although the benefits of full disaggregation are clear, operators across the globe have a huge investment in systems purchased from different vendors. This investment has to be protected for a period of > 10 years so our efforts are concentrated in developing the necessary SDN-enabled control plane to render these systems interoperable.

Having this as our goal, Figure 74 presents a high-level view of the traffic flow within an AMEN and the architecture of the control-plane that is under development by OLC. The traffic from the Access is terminated at the OLT and is forwarded to the L2 switch where the flows from (heterogeneous) access technologies are aggregated and they are forwarded either to the DC for processing associated to cloud services, and/or towards the Metro network [65]. This is the upstream flow direction, while in the downstream flow direction the processes are reversed. This traffic is designated as ‘user-to-content’ or “South-North”. It should be pointed out that to support cloud applications there could also be ‘content-to-content’ or “East-West” traffic flows, where again the L2 switch is forwarding that traffic to the DC to support this interconnection requirement. The coexistence of N-S and E-W flows means that Metro should accommodate traffic with two dissimilar profiles.

As a first step to the deployment in the construction of an AMEN, OLC presents the methodology adopted for PON abstraction that allows one to virtualize a PON infrastructure down to the ONU level. This gives the opportunity to METRO-HAUL to directly interface the PON to a number of verticals, as elaborated below.

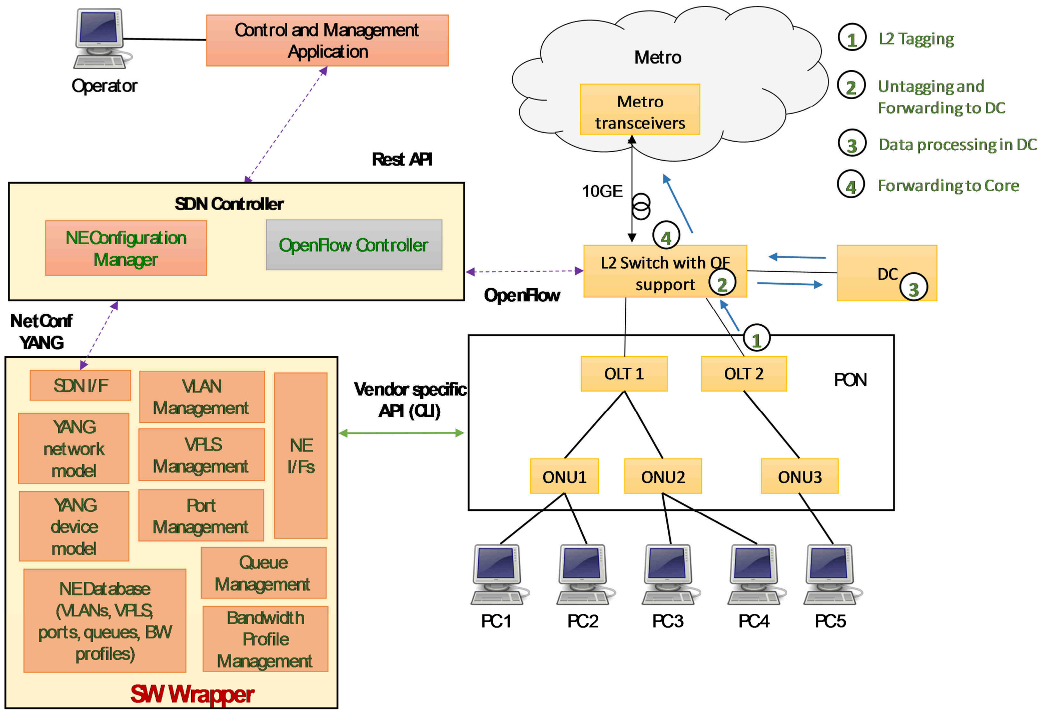


Figure 74. Traffic flow directions and a schematic layout of the SDN-enabled control plane

The cornerstone of the architecture is the adoption of an abstraction scheme, which represents the PON as a legacy OF/Netconf-enabled switch [65], as depicted in Figure 75(a). Under this abstraction, the network-facing physical ports of a PON i.e. the upstream port of OLT (p1) and the downstream ports of ONUs (p2-p5), are portrayed as the logical ports of a switch. The proposed abstraction scheme offers two advantages: a) it hides the PON specific details of forwarding and control/management operations; b) vendor-specific configuration commands are automatically translated and executed by the PON components. Therefore, the forwarding command messages are exchanged by means of the standard OF protocol, while (re)configuration is realized by means of the Netconf protocol.

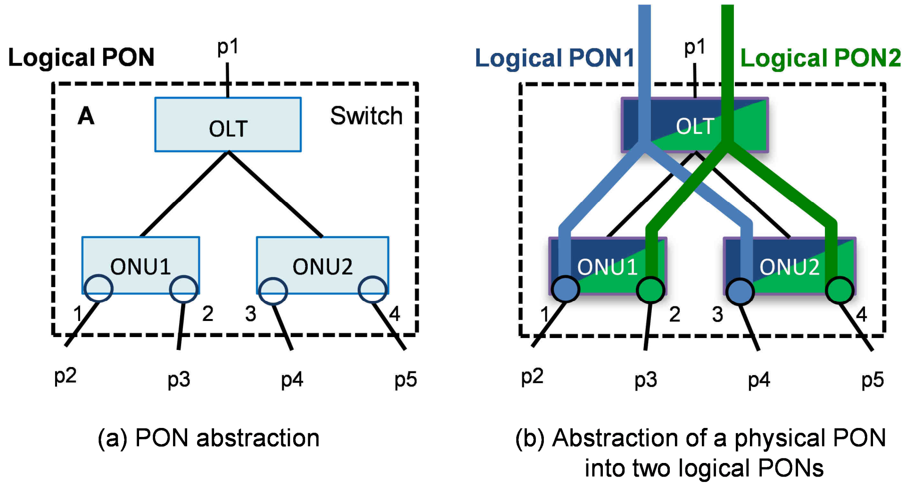


Figure 75. A schematic representation of PON abstraction

Under this scheme, the PON is operated as an OF-controlled L2 switch. The novelty of this approach is that it is a truly plug-and-play solution, in the sense that standard protocols are used; there is no need for OF protocol extensions or upgrades to the already deployed SDN control/management tools. Operators may simply connect the OF-enabled PON infrastructure into their network and integrate the provided YANG model into the NETCONF infrastructure. Moreover, this approach allows one to capitalize on the increased penetration of OF/NETCONF in other network segments (WAN/Metro).

Furthermore, this scheme is extended to support PON slicing, since several OF-controlled switches can be abstracted over the same physical GPON. Under this mode, each of these switches can dynamically control a subset of the GPON resources. Thus, a PON is partitioned into several logical PONs where each one of them consists of a logical-OLT (having a slice of the physical OLT) and from several logical-ONUs that may include any combination of ONUs, ONU ports or even ONU port slices. The objective of this slicing approach is to come up with an infrastructure ready to support multi-tenancy in the context of Infrastructure-as-a-Service. This is shown in Figure 75(b), where the logical PON of Figure 75(a) is partitioned into two logical PONs/SDN-controlled switches, assigned to different operators. As an example, the logical PON 1 assigned to operator A, includes a slice of the upstream OLT port (p1), and the ports p2 and p4 of two ONUs, while the logical PON of operator B consists of a slice of the upstream OLT port (p1) and the ports p3 and p5 of two ONUs.

6 METRO-HAUL Monitoring System

Within the project, a monitoring and data analytics (MDA) framework has been defined that is able to collect monitoring data from a number of monitoring systems being developed, ranging from the optical layer to the MPLS layer. The MDA framework includes MDA agents running close to the network nodes, and a big data centralized MDA controller running in the control and management plane.

MDA agents are multi-node agents that collect monitoring data records from configured observation points (OP) in the nodes, which can be used to discover knowledge from data (KDD) and to proactively implement local control loops to tune parameters in the network devices and to notify the MDA controller about network anomalies and degradations. The MDA agent has been conceived to support multilayer disaggregated scenarios.

In the following subsections, we first define the different interfaces where monitoring should be available, considering a multilayer partially disaggregated data plane architecture. Next the architecture of the MDA agents is presented. Two subsections follow that offer an insight into the monitoring at the optical layer, with two applications and the monitoring at the MPLS layer.

6.1 Interfaces and Monitoring

We consider a MPLS-TP-over-optical multilayer network, where the partially disaggregated data plane consists of three elements nodes: the MPLS-TP (L2) switch, the Transponder (TP) node, and the optical (L0) switch [66]. For the sake of simplicity, we denote as *L2* (electronic) both, the Ethernet and the MPLS-TP network sub-layers, whereas we denote as *L0* the whole optical layer, which includes the channel sub-layer (TPs) as well as multiplex/transmission sub-layers (L0 switches) [67].

Let us now define the interfaces within the multilayer network architecture. Three types of interfaces are generically considered in every network (sub-) layer (Figure 76a): *i) server interfaces* (SIs), providing access to a given network layer; *ii*) *network interfaces* (NIs), connecting nodes in the same network layer. NIs can be physical or logical interfaces, as will be described below; and *iii*) *client interfaces* (CIs), that access the server network layer. Interface pairs CI-SI between network (sub-) layers, as well as NI-NI in the same network (sub-) layer are connected through an inter-layer or network layer link, which creates the multilayer network topology.

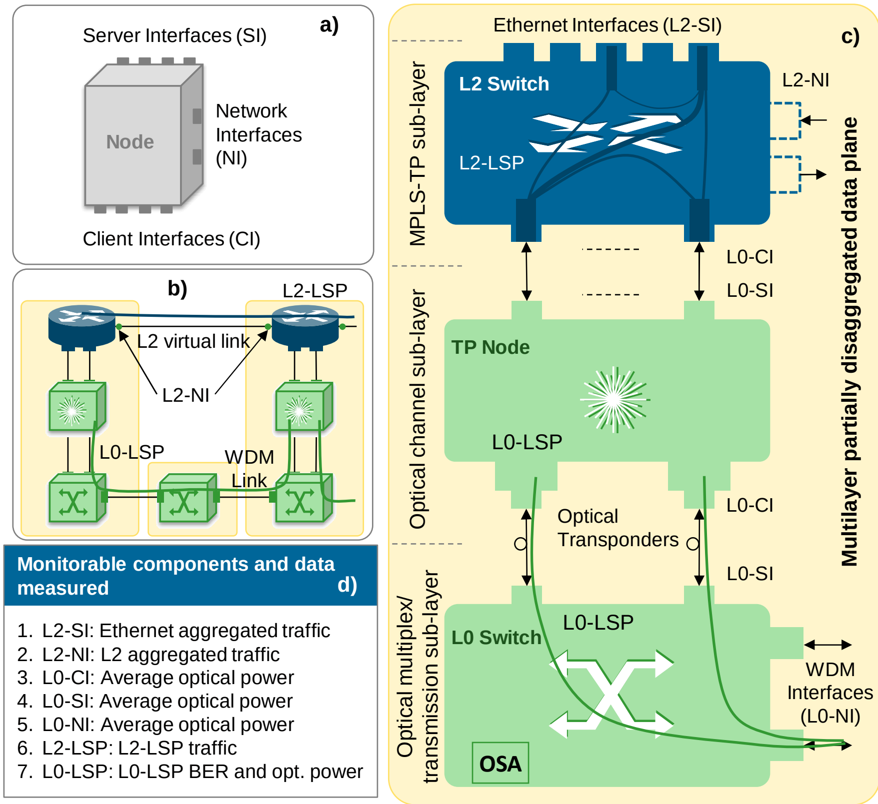


Figure 76. Multilayer partially disaggregated data plane architecture, interfaces, and monitorable data

Regarding inter-layer adaptation, we assume that it is performed inside the network nodes; specifically, Ethernet to MPLS-TP and MPLS-TP to the optical layer adaptation are performed inside the MPLS-TP switches, whereas optical (gray) to WDM (colored) adaptation is performed in the optical transponders inside TP nodes. Finally, network connections (LSPs) are created between two nodes in the same network (sub-)layer (Figure 76b).

Figure 76c shows an example of a multilayer partially disaggregated data plane. The L2 switch includes Ethernet interfaces (L2-SI), being the access of client traffic to the network. Ethernet frames are tagged, creating L2-LSPs that are switched and leave the switch through outgoing L2 virtual links (*vlink*); note that in such case end NIs are logical interfaces. To access the network, other Ethernet switches or even IP routers might exist being connected to the MPLS-TP switch through Ethernet client interfaces (L2-CI). The TP node integrates optical transponders, so vlinks are supported by optical connections, i.e., L0-LSPs, in the optical layer.

In the presented model, outgoing L2 traffic leaving the L2 node through a given vlink is first aggregated and then adapted to the optical layer and sent through a L0-CI toward the TP node. The optical signal is converted back to a flow in the electrical domain and injected into an optical transponder that converts the flow to a WDM signal using a pre-determined modulation format. The WDM signal is sent to the collocated L0 switch, which includes Wavelength Selective Switches (WSSs) and forwards the optical signal through the corresponding WDM interface toward a neighbouring L0 switch. When the WDM signal arrives to the remote location, the inverse procedure is performed to bring the electronic flow to the egress L2 switch. From the perspective of the L2 layer, the two end L2 switches appear connected through a L2 link (the vlink).

Each of these interfaces and network layer connections are denoted *monitorable components* as they can provide monitoring data regarding their performance, when Ops are activated on them. The table in Figure 76(d) details the data that can be retrieved from any of the monitorable components. Specifically: *i*) incoming/outgoing Ethernet traffic can be monitored in L2-SIs; *ii*) L2 traffic for the corresponding LSP can be monitored in L2-LSPs; *iii*) aggregated L2 traffic can be monitored in L2 vlink endpoints (L2-NIs); *iv*) average optical power can be monitored in L0 interfaces; and *v*) bit error rate (BER), power, and other parameters of the corresponding L0-LSP can be monitored at the subcarrier module of the transponders.

Regarding monitoring, passive techniques are the most-common choice in optical networks, since they entail using non-invasive methods to obtain measurements; examples include measuring the Bit Error Rate (BER) in optical transponders, optical power in fiber links, as well as acquiring the optical spectrum across the whole C-band in links using optical spectrum analyzers (OSAs).

In contrast, active monitoring is becoming very common at the packet layer. The difference between passive and active monitoring lies in the way resources are used for the measurements; passive monitoring devices are dedicated resources that perform measurements periodically, whereas active monitoring devices need to be allocated to perform measurements.

6.2 MDA Agent Architecture

The MDA architecture is distributed, such that a number of MDA agents are managed by the centralized MDA controller in the control and management plane [68]. The number of MDA agents may vary depending on the size of the network, geographical extension, and/or any other criteria.

MDA agents are designed to configure monitoring and telemetry, as well as to collect measurements from one or more nodes in the disaggregated data plane (Figure 77). While each node controller usually controls one single node and exposes one single interface toward the SDN controller, MDA agents are designed to be in charge of monitoring and telemetry of a set of nodes. MDA agents consist of two building blocks, the *local configuration* module and the *local KDD* module. The local configuration module is in charge of receiving configurations and exposes a RESTCONF-based NBI to the MDA controller. Finally, a number of node adapters (one per node) are used to implement the specific protocols exposed by every node controller for node configuration and for monitoring data collection.

Although we assume that node controllers' NBIs are based on a common YANG data model, different protocols for configuration, monitoring, and telemetry might be considered (e.g., NETCONF, IPFIX, and gRPC-based protocols for configuration, monitoring and telemetry, respectively, NETCONF for everything, or any other combination). For this very reason, node agents include bespoke node adapters implementing specific protocols and function mapping for the underlying node controller.

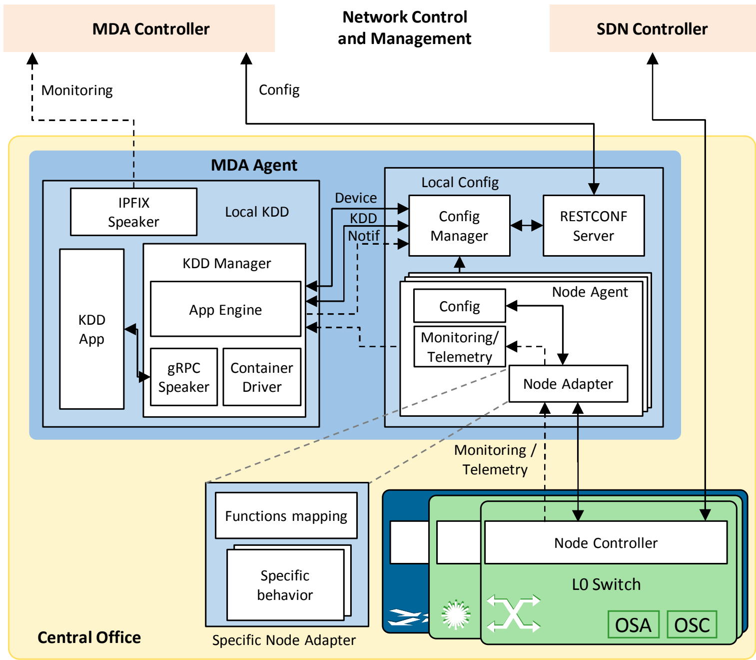


Figure 77. MDA agent architecture and interfaces

An autodiscovery function allows the retrieval of the available monitoring capabilities for each node, as well as already configured Ops. This functionality is of paramount importance in brown-field scenarios, where the network is already in operation.

Regarding the local KDD module, its original scope in the *MDA agents* was to apply data analytics to the measurements received from the nodes focused on the KDD process. Because the granularity of data records received from physical devices is generally finer than that used to export data toward the MDA controller, data records are temporally stored and aggregated; this opens the opportunity to apply data analytics techniques directly in the network nodes. Hence, upon reception of monitoring data records from an OP, the KDD application manager looks at the message mapping database to find the sample handler in charge of aggregating data records of the given type, stores them in the observation point's temporal repository, and calls the KDD process in charge of processing those data records. In the case where the KDD process discovers a pattern in the data, a notification to the controller can be sent.

The output of the data analytics procedure is forwarded to the MDA controller to implement network-wide control loops; two types of messages are supported: *i*) IPFIX-based monitoring messages including processed monitoring samples (i.e., values are averaged over the selected monitoring period, e.g., 15 minutes); and *ii*) through asynchronous notifications using the RESTCONF NBI. Regarding telemetry, measurements are locally processed by specific KDD processes in the MDA agent to reduce data exchange with the MDA controller. Note that telemetry measurements might be taken on a sub-second basis, so the analysis is performed locally in the MDA agent and results can be conveyed to the MDA controller for decision making.

6.3 Monitoring at the Optical layer

As anticipated in Section 6.1, the optical layer can be monitored by performing measurements of the transmitted and received optical power of the signal (this can be done per-channel or aggregated) at different intermediate points, acquiring the optical spectrum also at intermediate points, and measuring pre-FEC BER and (O)SNR at the receiver. In Metro-Haul, there is a large diversity of devices, each of them performing measurements. Aiming at clarifying the set of measurements that every single optical device is able to perform, Table 28 collects them together with some useful information including periodicity and granularity.

Table 28. Measurements provided by optical devices

Device (Partner)	Measurement	Units (periodicity and others)	Meaning
OSA	Optical Spectrum	<frequency (GHz), power(dBm)> Resolution: 625MHz Periodicity: 1 sec.	Ordered list of frequency-power pairs for the whole C-band
CNIT Disaggregated ROADM	optical power	Periodicity: 1 second	per-port optical power and per-(configured) channel optical power
Ericsson Photonic integrated optical switch	optical power	Periodicity: 1 seconds	Per-port optical power
CNIT transponder prototype	Pre-FEC, RX power		Off-line transmission system (all parameters available after data acquisition)
100G off-the-shelf muxponder (CNIT Lab)	Pre-FEC BER, OSNR, RX optical Power	Periodicity: 3-10 seconds (according to the number of queried parameters)	Pre-FEC BER, OSNR, RX optical Power
CTTC transceiver prototype	Pre-FEC BER, electrical SNR, Rx optical power		Off-line transmission system (all parameters available after data acquisition)
ADVA ROADM based on wavelength blocker	Optical Power	dBm periodicy 1s	Power of individual channels before and after equalization, received and transmitted power of EDFAs
ADVA transceivers, commercial	Pre-FEC and post-FEC BER, SNR, Rx power	adjustable	
ADVA transceivers, lab	Pre-FEC BER, Rx power		Off-line transmission system
UNIBRIS transceiver prototype	Pre-FEC BER, Rx power, OSNR		Off-line transmission system
UNIBRIS transceivers (commercial)	Pre-FEC and post-FEC BER, SNR, Rx power	adjustable	Pre-FEC and post-FEC BER, SNR, Rx power
Nokia Bell Labs Prototypes	Pre-FEC and SOP in real-time	programmable	
Nokia Bell Labs Prototypes	Other parameters such as power	~1s	

Examples of the use of the above measurements are detailed in the following subsections.

6.3.1 BER Anomaly Detection

In this section, we focus on pre-FEC BER degradation detection and propose the BER Anomaly Detection (BANDO) algorithm [69] that can be placed inside the MDA agents, close to the monitoring points, to reduce the amount of monitoring data to be conveyed to the control/management.

We assume that metered pre-FEC BER data for every connection is collected at a given rate and stored in a vector *M* of fixed capacity *n*. The BANDO algorithm analyses pre-FEC BER data to detect gradual changes with time that might derive into BER degradation and intolerable BER values, as well as sudden anomalous BER values.

Figure 78 illustrates three cases of BER evolution with time, where the dark continuous line represents the monitored BER. In addition, two different limits are presented: *i*) *BER max* is the maximum pre-FEC BER that the equipment can correct; and *ii*) a BER threshold for the current connection computed as a function of the estimated BER (e.g., 5*estimated BER) and represents the maximum tolerable BER for such a connection.

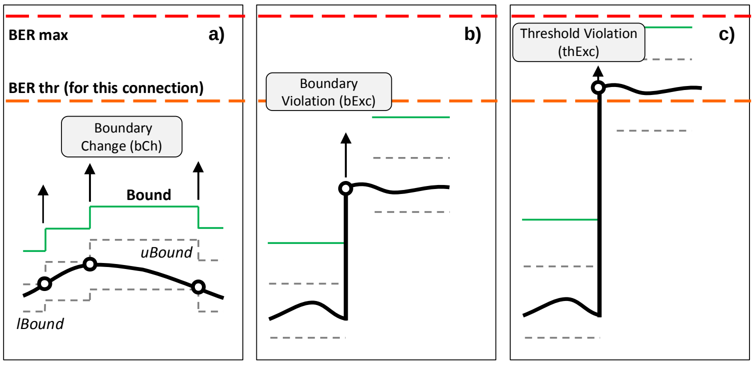


Figure 78. BER and boundaries evolution with time

To follow BER evolution with time, an *outer boundary* is used to anticipate any BER threshold violation and to detect sudden BER variations. In addition, two *inner boundaries*, named as a lower boundary (*lBound*) and upper boundary (*uBound*), are used to trigger boundary re-estimation when the measured BER reaches, exceeds or falls below one of them. Inner and outer boundaries are estimated as $bound = \mu(M.ber) +/- k \cdot \sigma(M.ber)$, where $\mu(M.ber)$ and $\sigma(M.ber)$ are the mean and the standard deviation computed on the last *n* BER measures and *k* is a multiplicative factor different per each boundary. Every time an event occurs, a notification is sent to the MDA controller to be further analysed; defined events include: *i*) the *boundary* is re-estimated (*bCh*), *ii*) the boundary is exceeded (*bExc*), *iii*) BER exceeds the threshold (*thExc*), and *iv*) the BER falls below the threshold (*thDec*).

Figure 78a presents an example of monitored BER evolution over time causing boundary changes. As soon as the monitored BER crosses one of the inner bounds, a boundary re-estimation is triggered, and a notification is sent toward the controller. Note that such boundary changes do not necessarily entail excessive BER, so the notification has an INFO severity level. Figure 78b) and Figure 78c) present two examples of sudden BER variation where the bound and the BER threshold is exceeded, respectively. In such cases, boundaries are reset, and notifications are sent to the controller with WARNING and MAJOR severity levels, respectively. Note that, in the case where pre-FEC BER exceeds the maximum BER, a notification will be sent with a CRITICAL severity level.

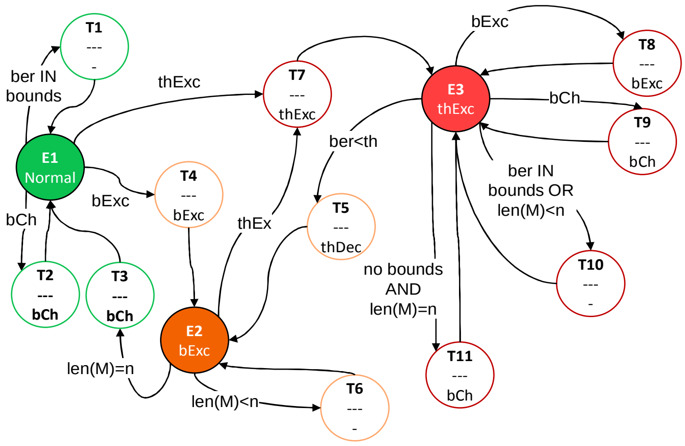


Figure 79. BANDO finite state machine

The BANDO algorithm has been designed as an finite state machine (*fsm*) with three main states and 11 transient states (Figure 79); main states are used to store whether BER status is normal or has exceeded either the boundary or the threshold, whereas transient states are used to produce notifications and actions (i.e., boundaries re-estimation or reset). Every time a sample arrives, two fsm transitions are performed, one to obtain the output and action, and another to move to the new main state.

State E1 (*normal BER*) is reached when the last BER value falls below the boundary and the threshold. Transitions to transient state T1 follow BER within boundaries, while transitions from transient states T2 and T3 re-estimate the boundaries (as in Figure 78a). State E2 (*boundary exceeded*) is reached when the last BER value has exceeded the boundary, but it is still below the threshold (as in Figure 78b). Transitions from transient states T4 and T5 reset boundaries, so *n*-1 new samples are needed to arrive to re-compute new boundaries. Finally, state E3 (*threshold exceeded*) is reached when the last monitored BER is above the threshold (as in Figure 78c). Transitions from transient states T7 and T8 reset boundaries, whereas from transient states T9 and T11 re-estimate them.

6.3.2 Optical Spectrum Analysis

In this section, let us consider the characterization of an optical spectrum by extracting its main features. In particular, we examine the optical spectrum of a 100 Gb/s DP-QPSK modulated signal acquired by an OSA with 625 MHz granularity presented in Figure 80(a).

In general, QPSK optical signals present a flat spectral region around the central frequency, sharp edges, and a round region between the edges and the central frequency. When the signal is properly configured, its central frequency should be around the center of the assigned spectrum slot to avoid filtering effects, and it should be symmetrical with respect to its central frequency. On the contrary, when a misconfiguration occurs, the optical spectrum is affected as shown in Figure 81. In the case of filter shift (Figure 81a), the optical spectrum would be asymmetrical, in the case of filter tightening, (Figure 81b) the edges of the optical spectrum would get noticeably rounded due to the degradation in both sides of the slot, and in the case of laser drift, the central frequency of the signal would be shifted with respect to the assigned slot; (Figure 81c).

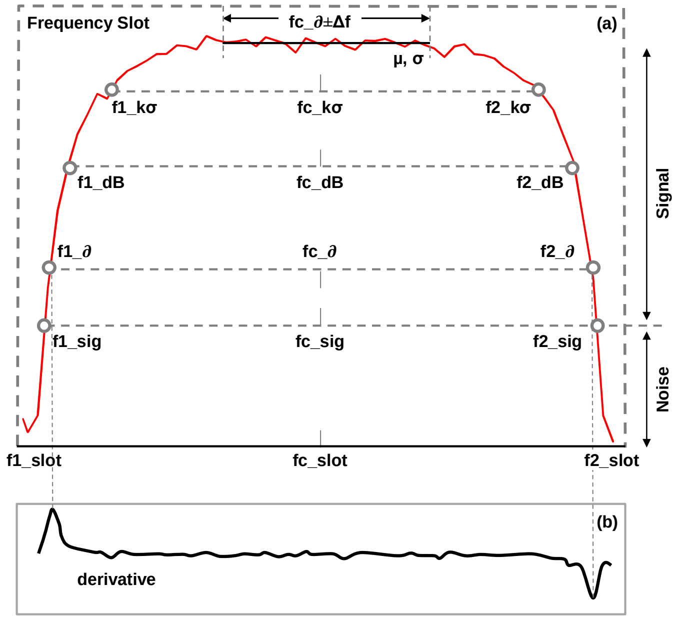


Figure 80. Relevant signal points (primary features)

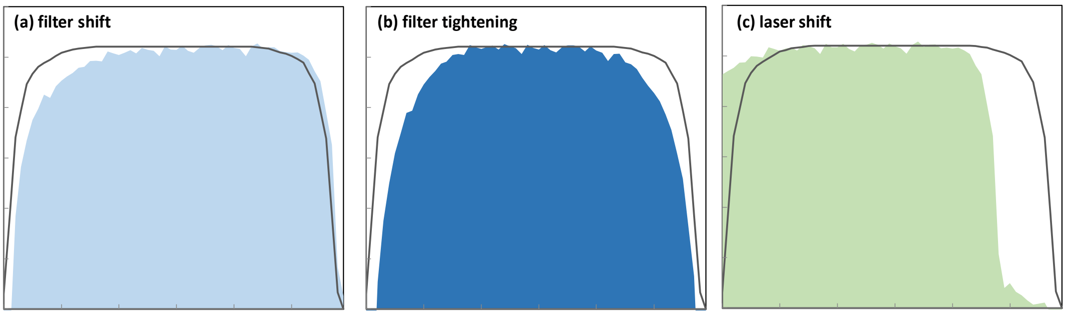


Figure 81. Solid black line represents the spectrum of a non-degraded signal. Solid areas represent the spectrum of signals affected by different soft failures: (a) filter shift, (b) filter tightening, and (c) laser shift

In order to detect the above distortions, a module, named FeX in [70], primarily pre-processes the optical spectrum of the signal. The first pre-processing step consists in equalizing power, so the maximum power is set to be 0 dBm. Then, the derivative of the power with respect to the frequency is computed. Figure 80(b) illustrates the derivative of the example optical signal; note that sharp convexity is observed close to the edges.

After pre-processing, the FeX module characterizes the mean (μ) and the standard deviation (σ) of the power around the central frequency ($fc\pm\Delta f$), as well as a set of primary features computed as cut-off points of the signal with the following power levels: *i*) equalized noise level, denoted as *sig* (e.g., -60dB + equalization level); *ii*) edges of the signal computed using the derivative, denoted as ∂; *iii*) a family of power levels computed with respect to μ minus $k\sigma$, denoted as $k\sigma$; and *iv*) a family of power levels computed with respect to μ minus a number of dB's, denoted as *dB*. Each of these power levels generates a couple of cut-off points denoted as $f1_{(\cdot)}$ and $f2_{(\cdot)}$. In addition, the assigned frequency slot is denoted as $f1_{slot}$, $f2_{slot}$.

Although features are computed from an equalized signal, note that signal distortion due to filter cascading effect has not been corrected as yet. This effect might induce the wrong diagnosis of a filter problem for a normal signal. To overcome this drawback, a *filter mask* can be used to compensate for the effect that a normal signal would suffer after passing a defined number of filters_before computing its features. Filter masks can be easily obtained by means of the theoretical signal filtering effects or experimental measurements taken for a distinct number of cascaded filters.

Other features are computed as linear combinations of the primary features, and focus on characterizing a given optical signal; they include: *i*) bandwidth, computed as $bw_{(\cdot)}=f2_{(\cdot)}-f1_{(\cdot)}$; *ii*) central frequency, computed as $fc_{(\cdot)}=f1_{(\cdot)}+0.5*bw_{(\cdot)}$, as well as the shifting of the central frequency $\Delta fc_{(\cdot)}=fc_{(\cdot)}-fc_{(slot)}$; and *iii*) symmetry with respect to a reference (frequency slot or derivatives), computed as $sym_{(\cdot)\text{-ref}}=(f1_{(\cdot)}-f1_{ref})-(f2_{ref}-f2_{(\cdot)})$.

These features can be used as input for algorithms that can identify soft-failures and their magnitude.

6.4 Monitoring at the Packet Layer

To monitor the network at the MPLS layer, two different types of probes are being developed: active and passive network probes. Active network probes are covered in WP4, whereas passive network probes are covered in this work package.

Passive probes capture and measure existing network traffic at packet level. In the Metro-Haul project, these measurements will be developed for 100-Gbps Ethernet links. Passive probes will be able to provide the following measurements:

Table 29. Measurement provided by the passive network probe

Measurement	Units	Meaning
Bytes time series	Bytes per second (second granularity)	Time series of the number of bytes seen per second at a capture vantage point. Such time series could be generated for several VLAN tags, MPLS labels, or pairs of MAC addresses. In the latter case, both directions of the communication could be measured separately.
Packets time series	Packets per second (second granularity)	Time series of the number of packets seen per second at a capture vantage point. Such time series could be generated for several VLAN tags, MPLS labels, or pairs of MAC addresses. In the latter case, both directions of the communication could be measured separately.
Flows time series	Active network flows per second (second granularity)	Time series of the number of active network flows per second at a capture vantage point. Each flow is identified by its 5-tuple (source and destination addresses and ports and transport protocol). Such time series could be generated for several VLAN tags, MPLS labels, or pairs of MAC addresses. In the latter case, both directions of the communication could be measured separately.

Passive probes are continuously capturing the network traffic, so it is not necessary to set up the monitoring process.

Measurements from the network (flows, bytes and packets per second) are stored on the probe for later use/analysis. In order to export these measurements to a collector, we use IPFIX records [71]. Passive probes provide an IPFIX exporter, which allows the integration of the probe with other monitoring systems that use this standard for data transmission. An example is the CASTOR architecture, which can take in IPFIX records from our probe for their use in a real autonomic orchestration platform for transport networks [72].

These IPFIX messages are sent in a binary format that contains the measurements of interest and the timestamp at which the measurements were taken. For instance, the demo shown at OFC'18 [72] sent packets and bytes per second, although both the format and our system can be expanded to include more measurements, such as the network flows seen in the probe, or any other measurement that can be of interest to network operators.

Right now, the most challenging network measurement is the number of active flows in a 100-Gbps link per unit of time (we consider an active flow any one that has transmitted at least one packet in such period). Given the data link rate, to obtain such a measurement we plan to design a custom circuit for this, implemented in a reconfigurable device (FPGA) for prototyping purposes. Additionally, we are targeting Xilinx's VCU118 development board to accelerate the development cycle, and uncouple the implementation of the printed circuit board of the hardware system that processes the traffic.

The major drawback of a FPGA-based solution for measuring the number of active flows is that the number of concurrent flows that can be monitored is limited by the size of the high-speed, low-latency memories embedded in the FPGA device. A-priori, we think it is feasible to keep the state of millions of concurrent flows. If more concurrent flows need to be monitored, alternative solutions will need to be explored, such as using external memory banks or a hybrid solution such as the one presented in the IDEALIST project [73]. In the latter, the FPGA was connected to an off-the-shelf server via a PCIe connection. The FPGA received 10-Gb/s Ethernet traffic and preprocessed it, offloading the most computationally heavy operations. Preprocessed traffic was sent to the host server, which was in charge of maintaining the flow table. While this solution proved to be helpful at 10 Gb/s, it is necessary to study if it can be scaled to 100 Gb/s.

Sometimes, passive probes also need to store the captured traffic. Given the data rate of the links we are monitoring, our approach for traffic retention is based on the use of NVMe drives, directly attached to PCIe bus using four lanes per drive, which can save data faster than current SATA/SAS hard-disks. Moreover, in order to keep data rate constraints, it is also necessary to write to several NVMe drives in parallel, bypassing the kernel using an SPDK approach [74].

Another approach to monitor these 100 Gbps links passively is to reduce the amount of traffic that is processed in the network probe. For this traffic thinning, several strategies can be taken into account, processing the packets in an FPGA and sending a lower amount of information to a cheaper network probe:

- Filtering just that traffic that is important to monitor, based on protocol filter rules, ranging from MAC addresses, VLAN or MPLS tags, and up to TCP or UDP ports [75].
- Forward to the probe just packet headers of those packets with encrypted or binary payload [76].
- Forward to the probe just the packet headers of those packets coming from "heavy-hitter" connections [77].
- De-duplicate packets that have been duplicated in the capture process [78].

Based on these thinning ideas, PSAMP [79] provides a standardized method to support passive monitoring applications. Generally speaking, PSAMP can be conceived as a smart extension to IPFIX, adding complex models, providing the capability of reporting the full data frame header/payload. Monitoring applications like anomaly traffic detection can enormously benefit of such capabilities, provisioning the system of enriched metrics.

It is foreseeable that the FPGA can integrate a PSAMP-like process to send IPFIX records with configurable fields from the packet headers to a probe, reducing even more the number of packets that the probe has to process.

The existence of summarized data, and its correlation, empowers the estimations that a passive probe is able to extract from the network: statistics, delay estimations or post-incident forensic inspections extend the traditional volumetric analysis.

7 Metro Network Evaluation Methodology

Evaluation of the different Metro-Haul networking solutions requires a variety of technical approaches, in order to appropriately assess the networking designs and dimensioning parameters emerging from the project. To that end, within WP3 we are considering an evaluation strategy encompassing a variety of approaches, so as to achieve a comprehensive understanding of the proposed Metro-Haul solutions. The proposed evaluation approach comprises a number of tools and methodologies being employed by the project partners, including commercial, open source and in-house developed software planning tools. In addition, experimental evaluation of subsystems or complete WDM transport solutions, demonstrators (including vertical demos) as are described in the WP5, and techno-economic studies are additionally important aspects of the overall evaluation methodology. As such, the overall evaluation is of necessity transversal to the Metro-Haul project, although it is also clearly an important feature of the task T2.3 of WP2 “Network Architecture Design and Evaluation”.

This section therefore describes the initial approach we are adopting for our metro network evaluation methodology, as a systematic effort (emanating in task T2.3), with an emphasis in this D3.1 deliverable on the feedback and interactions with the WP3. In particular, we describe the initial techno-economic (T-E) analysis that is being undertaken within WP3, to understand the various technological alternatives for metro networking in realistic scenarios, with the pros and cons of the alternatives highlighted.

With respect to the techno-economic analysis, we have chosen to adopt the Net2Plan open-source planning tool [80] as a common framework for collaboration among partners in the techno-economic analysis, exploiting its various functionalities for T-E purposes, and the available open interfaces. Net2Plan also helps in the dissemination of results in public repositories, for public validation and inspection.

The techno-economic approach and analysis is focused on four sequential stages, as described below.

Stage 1: Definition of reference architectures. The first stage leverages the Net2Plan-GIS extension recently presented for the Net2Plan tool [80], for importing Geographical Information System (GIS) data from public repositories. A number of maps can be imported that permit the estimation of city population densities, as well as city layouts, as indicated in the Figure 53, below.

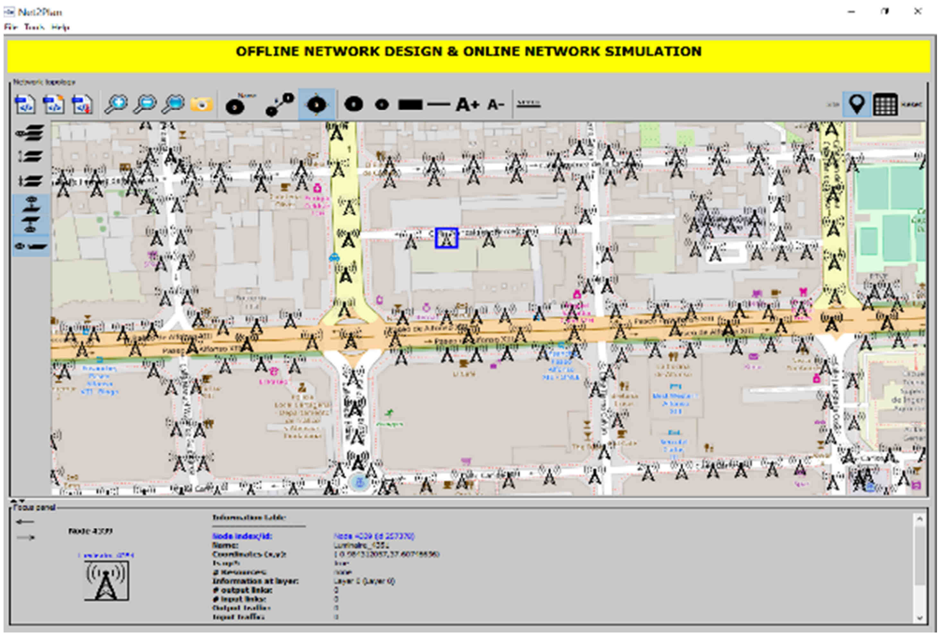


Figure 53. Net2Plan data imported through Net2Plan-GIS

Benefiting from this, the first stage of the T-E analysis consists of creating a Net2Plan (.n2p) file, using a number of reference metro network topologies (nodes and links). However, due to issues of confidentiality, these topologies are not real (since the true data are not available), but they are realistic. In this context, 'realistic' means that their main parameters such as node degree histograms or link length histograms match existing topologies for which only anonymized data are available. Two reference topologies have thus far been proposed: one for the region of Murcia (Spain), and one in the vicinity of Milano (Italy).

Stage 2: Definition of reference user demands for identified 5G services. The outcome of the previous Stage 1 is subsequently used to couple node positions with population densities, so as to help in creating more realistic traffic maps for the services described in deliverable D2.1; i.e. the traffic generated by the users using 5G advanced services, that are expected to impact on the metro network. In this case, the outcome of Stage 2 is the generation of the following two outputs: (1) Net2Plan traffic generation algorithms (.java); (2) traffic traces in readable formats (e.g. CSV files). Two aspects are important to note here:

- The traffic is time dependent; that is, the traces are not static, but reflect the temporal variations of the traffic, e.g. over one day on a diurnal basis. The important point here is the ability to model the 'tidal' movement of people when going to work in the morning and returning home in the evening, which act together to stress the network.
- The demands are multi-dimensional. In this context, a demand consists of moving a quantity of data between nodes (over a particular bandwidth), but also accessing network intelligence services that consume IT resources (CPU, RAM, HD) in the AMEN and MCEN nodes.

The outputs from this Stage 2 are accessible in the Metro-Haul public repositories, so that the 5G reference topologies and provided traffic traces can be exploited as a public benchmark for Metro-Haul and other projects.

Stage 3: Joint IT and transport resource allocation algorithms. The Net2Plan tool permits multiple partners to implement their optimization algorithms, and easily integrate them into the tool. The algorithms of interest in Metro-Haul are those that receive the input data coming from the reference topologies and traffic demands, and decide at each moment of time, how demands are to be served, and how the IT and transport network resources are to be allocated. Metro-Haul partners collaborate in this third stage of the T-E analysis to produce novel algorithms tuned to the different technological alternatives (i.e. filterless and non-filterless architectures), hardware limitations, and tunability ranges etc. Use of a common framework such as Net2Plan allows a quicker and automated process for the comparison of results. Partners also have the option of disseminating their algorithm codes to the Metro-Haul repository, for public inspection and dissemination purposes.

Stage 4: Network dimensioning and techno-economic analysis. One of the important objectives of the Metro-Haul project is to produce a cost model that permits the translation of network dimensionings into an overall cost of ownership. This feeds into the techno-economic analysis, as part of the metro network evaluation, and additionally covers aspects such as energy consumption, so as to provide an overall insight into the total cost and scalability of the metro network design solutions emerging from the project.

An important aspect of the evaluation process is therefore a set of techno-economic analyses and recommendations underpinned by appropriately detailed metro network databases and repeatable tests. These have also been designed to be available for public inspection in the Metro-Haul repositories. Net2Plan therefore contributes an important T-E role to the overall evaluation methodology, since it provides a common framework for the reference scenarios representation, development of algorithms by project partners, and a speeding-up of the analysis phase thanks to the tool's automatic performance calculations.

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8 Conclusions

In this D3.1 document, we have reported on a selection of relevant metro node architectures and optical technology options for future metro networks, which will be able to support 5G and the new heterogeneous services from emerging new “vertical actors”. This deliverable has also included the relevant design guidelines for metro-access and metro-core edge nodes, as well as the design guidelines and specifications for the technical implementation of the proposed optical infrastructural elements. The document is the result of the first year of activities in WP3 of the METRO-HAUL project.

The analysis started from the discussion of three reference metro-regional networks provided by the METRO-HAUL operators (i.e., TIM, BT and Telefónica), from which it emerged that the most commonly deployed technology is based on F-OADM and 10 Gb/s WDM interfaces. However, several different scenarios were identified in terms of: (1) number of nodes, from small networks including 10/20 nodes up to large networks with even 200 nodes; (2) topologies, from horseshoe to ring and mesh; and (3) distances between nodes, from 50 km up to 100 or even 200 km or more. Such heterogeneous reference scenarios, together with the need to support the metro evolution towards 5G, has driven the investigation of multiple different architectural choices and technological solutions at the level of the Central Office, transmission and network solutions, and node and interface technologies.

The general METRO-HAUL metro network infrastructural framework has also been described in some detail, including a discussion on the next-generation of Central Office architectures. This is based on a modular approach, supporting: (1) virtualization of almost all the functionalities traditionally implemented with several dedicated network appliances; (2) the presence of computing and storage resources effectively integrated with packet and optical networking resources; and (3) the support of disaggregation and vendor-neutral modelling of white boxes. An in-depth analysis of disaggregation as applied to metro WDM optical transport systems including design guidelines and interfaces specifications has been given, with the general characteristics of “transport optical services” also outlined.

The most relevant innovative transmission and network solutions for WDM metro have been considered and discussed, with several modulation formats analysed in terms of target bit rate and complexity (e.g., the presence of DSP), and included QPSK/M-QAM, 4-PAM, DMT/OFDM and IQ-Duobinary. Both filterless and filtered (i.e., ROADM-based) solutions have been discussed and compared in terms of their capacity and complexity, showing that both technical solutions represent a suitable metro technology, according to the chosen reference network scenario (e.g., size, and expected capacity, etc).

Advanced solutions for next-generation optical metro nodes and interfaces have also been presented, detailing METRO-HAUL prototypes of WSS-based ROADMs and wavelength blockers enhanced with YANG modelling, as well as innovative photonic integrated switch prototypes. Prototypes of interfaces and transceivers were also discussed, as well as an innovative solution to enhance “legacy” PON devices to make them “SDN-compatible”, together with the design and prototyping of a complete programmable micro data centre suitable for fitting into a small peripheral CO.

Finally, the general framework for monitoring and data analytics (MDA) of data plane resources has also been presented, together with a general methodology for evaluating the METRO-HAUL solutions in line with the WP2 approaches.

This D3.1 document feeds into WP2 for the design of next-generation cost-effective metro architectures, into WP4 for the definition of the network elements and solutions to control, and also into WP5 for the definition of the experimental demonstrations including verticals.

9 List of Acronyms

Acronym	Description
ABNO	Application Based Network Operations
ACL	Access Control List
ACTN	Abstraction and Control of Traffic-Engineered Networks
ADC	Anaolog to Digital Converter
AIR	Achievable Information Rate
AMEN	Access Metro Edge Node
API	Application Programming Interface
ASE	Amplified Spontaneous Emission
A-WDM	WDM Analog transport layer
AWG	Arrayed Waveguide Grating
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BiCMOS	Bipolar Complementary Metal Oxide Semiconductor
BL	Binary Loading
B&S	Broadcast&Select
BPSK	Binary Phase Shift Keying
BS	Base Station
btb	back to back
BVRx	Bandwidth Variable Receiver
BVT	Bandwidth Variable Transponder
BV-WSS	Bandwidth Variable WSS
BW	BandWidth
CAPEX	CAPital EXpenditure
CAPS	Combined amplitude and phase shift
CCDM	Constant Composition Distribution Matching
CDN	Content Delivery Network
CI	Client Interface
CNC	Customer Network Controller
CO	Central Office
COM	Control, Orchestration and Management
CORD	Central Office Re-architected as a Data-center
CP	Control Plane
CPE	Customer Premises Equipment
CPRI	Common Public Radio Interface
CPU	Central Processing Unit
CSI	Channel State Information
CTP	Connection Termination Point
CUT	Channel Under Test
DAC	Dgital to Analog Converter
DCF	Dispersion Compensation fiber
DCM	Dispersion Compensation Module

DCO	Digital Coherent Optical sub-assembly
D&W	Drop & Waste
DD	Direct Detection
DFF	Digital Flip Flop
DMS	Discrete Menoryless Source
DMT	Discrete MultiTone
DP	Data Plane
DP-	Dual Polarization
DS-BVT	Digital S-BVT
DSCP	Differentiated Services Code Point
DSLAM	Digital Subscriber Line Access Multiplexer
DSP	Digital Signal Processing
DtoWDM	Digital to WDM adaption layer
DWDM	Dense WDM
DWPT	Discrete Wavelet Packet Transform
EC	European Commission
ECA	External Cavity Laser
EDFA	Erbium Doped Fiber Amplifier
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
Fls-OADM	Filterless OADM
FOADM F-OADM	Fixed OADM
FTTH	Fiber To The Home
FWM	Four Wave Mixing
GMPLS	Generalized Multi-Protocol Label Switching
GN	Gaussian Noise
gNMI	gRPC Network Management Interface
GPON	Gigabit PON
gRPC	Google's Remote Procedure Call
HD	Hard Disk
HD-FEC	Hard Decision FEC
IHSDN	Interface between the parent controller (Orchestrator) and the packet / optical controllers
ILA	In Line Amplifier
IM-DD	Intensity Modulation - Direct Detection
IO2	Operator – VIM for Authentication (Keystone), Instantiation of VMs (Nova), Basic Intra-node connectivity (Neutron)
IO3	Operator – NFVO (OSM). Based on OSM interfaces and APIs.
IO4	Operator – Monitoring
IOS	Interface between Orchestrator – WIM [NFVO-TSDN, follow OSM]

IPFIX	Internet Protocol Flow Information Export
IPNFVO	NFVO – Planning Tool – Interface for planning and placement
IPON	Interface to the SDN PON controller – Controller Specific
IPSDN	SDN – Planning Tool – Interface for planning (SDN) [Complements IPNFVO]
IPVIM	VIM – Planning Tool – Interface for planning and placement (VIM) [Complements IPNFVO]
IQ	In-phase Quadrature
JSON	JavaScript Object Notation
KDD	Knowledge Discovery from Data
KPI	Key Performance Indicator
LCoS	Liquid Crystal on Silicon
LDPC	Low Density Parity Code
LO	Local Oscillator
LSP	Label Switching Path
LT	Line Terminal
MA	Margin Adaptive
MAN	Metro Area Network
MANO	Management and Orchestration
MB	Maxwell-Boltzmann
MAC	Media Access Control
MC	Media Channel
MCEN	Metro Core Edge Node
MCM	MultiCarrier Modulation
MCOM	Interface between the monitoring system and the SDN controller (parent) or the NFVO
MDA	Monitoring and Data Analytics
mDC	Mini Data Center
MDSC	Multi-Domain Service Coordinator
MD-ROADM	Multi Degree ROADM
M-QAM	M-order QAM
MPLS	Multi Protocol Label Switching
MPLS-TP	MPLS Transport Profile
MSA	Multi-Source Agreement
MRR	Micro Ring Resonator
MWI	Multi Wavelength Interface
MZM	Mach-Zehnder Modulator

NBI	North Bound Interface
NE	Network Element
NETCONF	NETwork CONFiguration protocol
NEW	New Acronym
NFVO	Network Function Virtualization Orchestration
NI	Network Interface
NIC	Network Interface Card
NFV	Network Function Virtualization
NFVI	NFV Infrastructure
NMC	Network Media Channel
NRZ	Non-Return-to-Zero
NVMe	Non-Volatile Memory Express
OADM	Optical Add Drop Multiplexer
OA&M	Operation Administration and Maintenance
OCh	Optical Channel
ODC	Optical dispersion compensator
ODU	Optical Data Unit
ODUk/Cn	Optical Data Unit-k/Cn
ODUflex	Flexible ODU
OF	OpenFlow
OFDM	Orthogonal Frequency Division Multiplexing
OIE	Optical Infrastructure Element
OIF	Optical Internetworking Forum
OLS	Open Line System
OLT	Optical Line Terminator
O-NE	Optical NE
ONOS	Open Network Operating System
ONT	Optical Network Terminator
ONU	Optical Network Unit
OOK	On Off Keying
OP	Observation Point
OPEX	OPerating EXpenditure
OPU	Opical Payload Unit
OPUk/Cn	Optical Payload Unit-k/Cn
OSA	Optical Spectrum Analyser

OSC	Optical Supervisory Channel
OSNIR	Optical Signal-to-Noise plus Interference Ratio
OSNR	Optical Signal-to-Noise Ratio
OST	Optical Sub-System
OTN	Optical Transport Network
OTSi	Optical Tributary Signal
OTSiA	OTSi Assembly
OTSiG	OTSi Group
OTSiG-O	OTSiG Overhead
OTU	Optical Transport Unit
OTUk/Cn	Optical Transport Unit-k/Cn
OTUCn-M	Optical Transport Unit-Cn with n OxUC overhead instances and M 5G tributary slots
P4	Programming Protocol-Independent Packet Processors
PAM	Pulse-amplitude modulation
PCIe	Peripheral Component Interconnect Express
PL	Power Loading
PMD	Polarization Mode Dispersion
PMF	Probability Mass Function
PM-QPSK	Polarization Multiplexing QPSK
PNC	Provisioning Network Controller
PON	Passive Optical Network
POP	Point Of Presence
PS	Probabilistic Shaping
PSAMP	Packet Sampling
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
RA	Rate Adaptive
RAM	Random Access Memory
ROADM	Reconfigurable OADM
RPC	Remote Procedure Call
SAS	Serial Attached SCSI
SATA	Serial Advanced Technology Attachment
SBI	South Bound Interface
SBVT, S-BVT	Sliceable BVT

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SD-FEC	Soft Decision FEC
SDH	Synchronous Digital Hierarcy
SDN	Software Defined Network
SFP	Small Form Factor
SI	Server Interface
SI	System Integrator
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SOI	Silicon On Insulator
SPGC	Single Polarization Grating Couplers
SSMF	Standard Single Mode Fiber
SSB	Single SideBand
SSS	Spectral Selective Switch
SPDK	Storage Performance Development Kit
SQNR	Signal to Quantization Noise Ratio
SWI	Single Wavelength Interface
TCP	Transmission Control Protocol
T-E	Techno-Economic
TIA	TransImpedence Amplifier
TLS	Tunable Laser Source
TP	TransPonder
TTP	Trail Termination Point
UDP	User Datagram Protocol
UL	Uniform Loading
VIM	Virtual Infrastructure Manager
VLAN	Virtual Local Area Network
VNF	Virtual Network Function
VOA	Variable Optical Attenuator
VPN	Virtual Private Network
VTEP	Virtual Tunnel End Point
VXLAN	Virtual Extensible LAN
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WIM	WAN Infrastructure Manager

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WP	Work Package
WSF	Wave Selective Filter
WSS	Wavelength Selective Switch
xPON	X version of Passive Optical Network

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