D 2.1 DEFINITION OF USE CASES AND REQUIREMENTS FOR NETWORK, SYSTEMS AND SUBSYSTEMS

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The purpose of this deliverable is the definition of use cases selected according to the project vision and the extraction of the necessary network and systems/sub-systems requirements that will guide the development of the project. The deliverable examines in depth and completes the analysis started with the document PASSION_MS1_v2.0.pdf uploaded in the PASSION repository on March 29th, 2018 as a means of verification of the milestone MS1 achievement. Considered use cases will include metro interconnection, particularly focusing on end-to-end high-capacity metro transport for novel services and businesses. Based on the inputs related to the use cases, the specific requirements will be defined and further applied to design the programmable modular system and overall network architectures in the tasks T2.2 and T2.3. These will be also the inputs for the technical solutions developed within the work packages WP3 and WP4. Particularly, requirements are derived in terms of cost-efficiency, slice-ability, network resources and optical/network impairments tolerance in order to deal with Pb/s node capacities and increased transport distances.

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

PASSION will design metro area network (MAN) technology capable of addressing the challenges faced by network operators in the next decades. These challenges can be summarized as:

- the ability to allocate **ultra-high capacity** (over *n*xTb/s) in the MAN core over variable distances and arbitrary topologies
- the ability to **scale** up the network according to a pay-as-you-grow scheme. Especial focus set on the cost of such growth including aspects derived from the nature of spare components (fixed optics vs variable) and inventory requirements.
- the ability to **put that capacity wherever and whenever needed with a minimal blocking probability** i.e. maximum elasticity in the utilization of available bandwidth in order to **obtain multiplexing gains at the physical layer**. Provisioning times should be very short (in the order of seconds).
- the flexibility to **support any type of service** as derived from: 5G backhauling including all types of 5G traffic, 5G fronthaul transport, support of Mobile Edge Computing (MEC), new residential services demanding 1Gb/s, support of UHD TV, etc
- full dependability: implementation of **built-in protection schemes** both at layer 0 and above, that guarantee high degree of availability of connectivity.
- full support of interconnecting Content Delivery Network (CDN) nodes and high-performance computing locations for three cases: operator's computing nodes (including MEC and CORD), enterprise computational sites and Internet Application Service providers CDN nodes.
- **Co-existence** with currently deployed fixed WDM systems and frequency compatibility with flex-grid. **Fine granularity** needs to be provided in order to support a wide range of user rates.

1.2 METHODOLOGY

In order to address as many of the previously identified design challenges and validate their support by PASSION, we proceed with the following methodology to derive the concrete set of target characteristics that will guide the design cycle of PASSION:

1. **Reference topology**. Firstly, in section 2.1, we select the topology of a huge MAN network to be used in the analysis of the different use cases. Then we obtain and study the parameters that characterize such MAN, including the hierarchy of nodes, nodal degrees and distances.

2. **Use cases**. In sections 2.2 and 2.3 we define a number of Use Cases that will make full or partial use of the topology. This analysis will require the estimation of the offered traffic in each of the cases, and will determine the intended behavior of a network designed with PASSION technology. Each Use Case includes an initial description of how PASSION capabilities is expected to provide advantages to the network operator in terms of versatility and cost savings.

3. **Technical requirements**. Section 3 describes the specific functionalities and target performance parameters determined by the use cases together with the characteristics of the target topology that lead to a draft specification of technical features of the PASSION architecture and subsystems. An as-detailed-as-possible system description at the current stage of the project is made, with reference to the target bandwidths, granularities, control plane capabilities, etc to apply in the use cases. The initial methodology to perform a cost analysis for the planned use cases is drafted as well. The technical/cost constraints identified along the design cycle of the PASSION product will serve as input for the techno-economics tools released at the end of the project of application to optimal network planning.

2 PASSION REFERENCE TOPOLOGY AND USE CASES

In order to study the different use cases in an as-realistic-as-possible setting we shall use a real deployed topology from a real city of the world of 25 Million inhabitants, down to a certain hierarchical level (in particular, hierarchical level 3 as defined below). From that level on, the topology will be synthesized by replication of an existing sub-topology. Let us first review the hierarchy of nodes defined by the operator.

2.1 PASSION REFERENCE MAN TOPOLOGY

2.1.1 Hierarchy Levels

In a first approximation, the MAN network can be generically seen as a layered composition of ring-star topologies (*ring* within the same layer and *star* when aggregating) with *n* levels where a node at level *n* is connected to a pair of nodes in level *n* - 1. At the IP layer, the logical topology hides the optical rings and the aggregation/distribution hierarchy becomes more evident as shown in Figure 1.

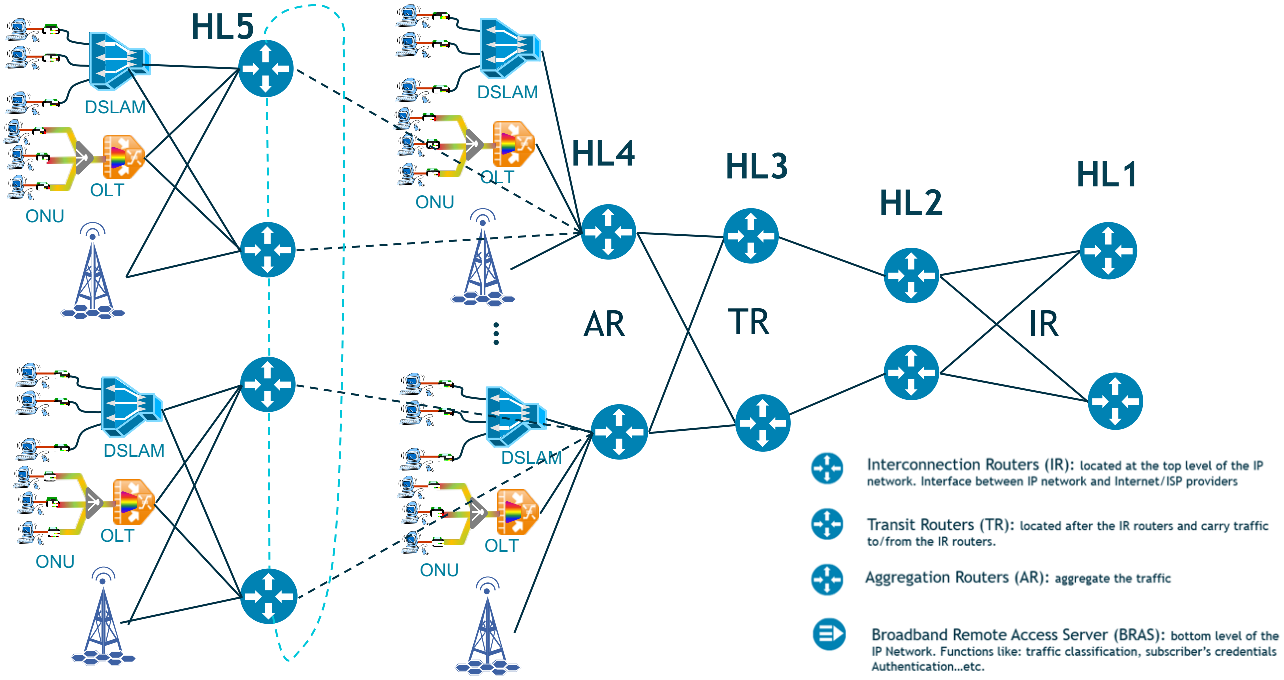


Figure 1. Schematic IP Layer hierarchy of routers

From left to right, the network includes the following component subnetworks:

- Access
- First Level of Aggregation
- Second Level of Aggregation
- Core

This creates a hierarchy of nodes whose terminology and purpose is also used at the optical layer. The hierarchy levels (HL) defined for a large MAN are five:

- **HL1:** the HL1 corresponds to nodes (routers) that make up the top level of the IP network on a national level, i.e. the backbone network. HL1 is also the interface between the IP network and Internet/ISP providers.
- **HL2:** This hierarchical layer does not aggregate any traffic. Traffic is only forwarded to the right HL2 or HL1 node. Important services like TV or CDN caching are hosted on these nodes.
- **HL3:** This layer carries out the traffic aggregation/distribution function. It collects the traffic from the different geographic areas of the MAN.
- **HL4**: The HL4 layer is composed by 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. Also, this layer aggregates traffic from different locations of the Metro network and from OLTs, DSLAMs and SWTs.
- **HL5**: The access layer comprises routers, ONTs, COs and BSs. Therefore, we shall assume that both HL5 and HL4 nodes can host, at the same time, routers, ONT, COs and BSs

2.1.2 A reference topology based on real sub-topologies

As stated above, we shall use a real topology from a real city of the world of 25 Million inhabitants, down to hierarchical level 3. From that level on, the topology will be synthesized by replication of an existing sub-topology. The market share of the sample operator is a base of 5 million subscribers of residential (FTTH) and mobile services (5G).

- **Metro-Core Network (HL1 / HL2).** The core network has the following HL1/2 sites (shown in Figure 2):

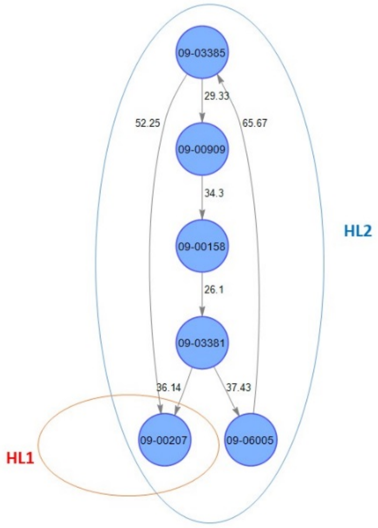


Figure 2 Physical Level Topology of HL1/HL2 Nodes

- **Second Level of Aggregation (HL3).** The second level of aggregation has the following topology (shown in Figure 3):

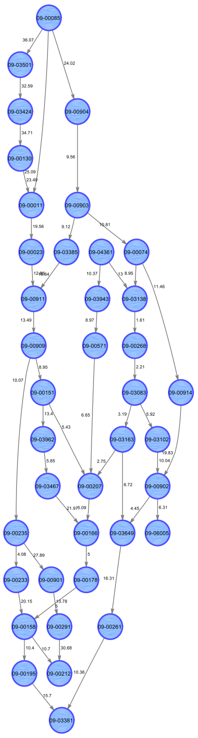


Figure 3. Physical Level Topology at HL3

The HL3 physical level view includes also the nodes in the ***Core Level*** since an HL1/HL2 node can be considered as yet another HL3 node to route a circuit.

Regarding the IP layer, as a general rule it can be assumed that each optical node represented in these topologies has at least a co-located router to aggregate/distribute IP traffic. However, most of the traffic traversing these sites is supposed to correspond to transit optical channels implementing the IP hierarchical topology. Hence, at the IP layer, all these nodes are connected with the previous (HL1/2) and the next hierarchical layer (HL4) with two logical links which are mapped to optical channels at the physical layer, which means that a logical link between HL3 and HL1 routers may imply the traversal of a number of HL3 and HL2 nodes at the optical layer.

- **First Level of Aggregation (HL4).** The first level of aggregation has the following topology (as shown in Figure 4).

Replicas of this subnetwork, that corresponds to a real HL4 topology, are directly attached to the second level of aggregation at the closest two HL3 sites. In other words, two of these nodes in Figure 4 are also HL3, and this first-level aggregation topology is replicated for each pair of nodes in the second level of aggregation in the synthesized reference topology.

- **Access Network (HL5)**. Finally, the access network has the following topology (as shown in Figure 5), which, again is replicated and attached to the next level as explained above.

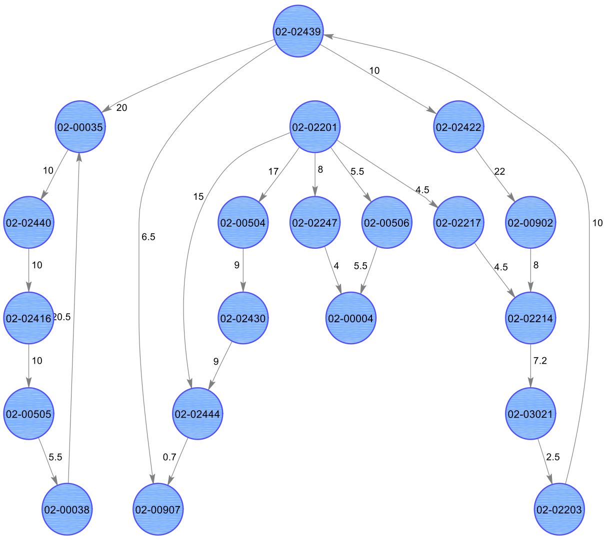


Figure 4. Physical Level Topology of an *HL4 Network*

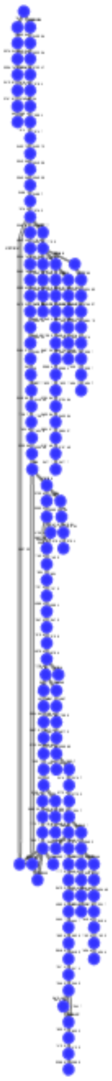


Figure 5. HL5 Nodes

A view of the whole network is shown in the Figure 6.

Figure 6. Whole Network

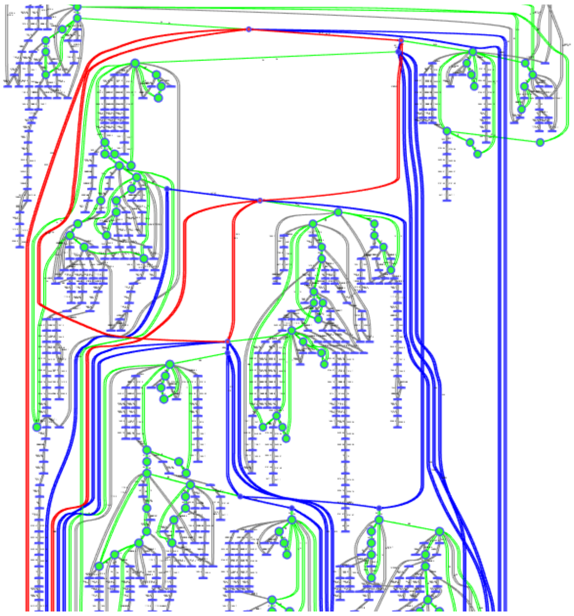
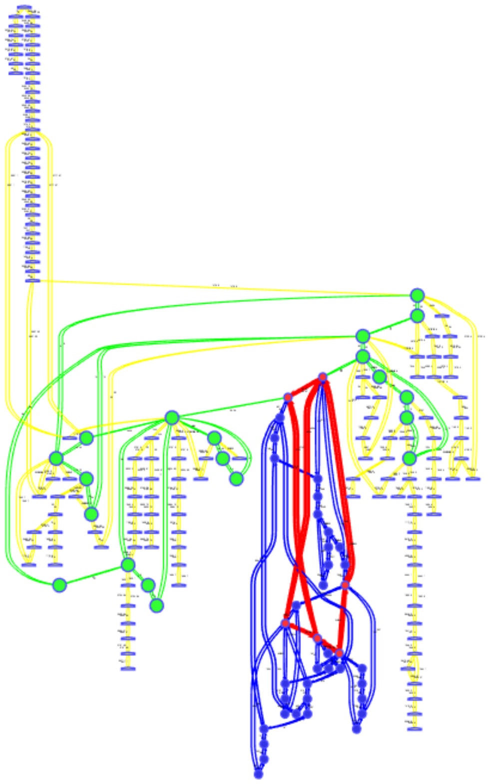


Figure 7. Zoom of part of Figure 6.

An example with only one subnetwork of aggregation/access level is shown in Figure 7.



Access / First Level of Aggregation / Second Level of Aggregation / Core

Figure 8. Metro-Core with the second level of aggregation and one aggregation-access subnetwork

2.1.3 Main characteristics of the target topology

A summary of the parameters of the target topology described in the previous section is given by:

- **Topology overview**
  - Core Network (HL1/2): 6 nodes ($N_{CoreNodes}$)
  - L2 Aggregation (HL3): 33 nodes ($N_{L2Nodes}$)
  - L1 Aggregation (HL4): 380 = 20 nodes/cluster x 19 clusters ($N_{L1Nodes}$, N_{L1Nets})
  - Access Network (HL5): 2432 nodes or base stations ($N_{AccessNodes}$)

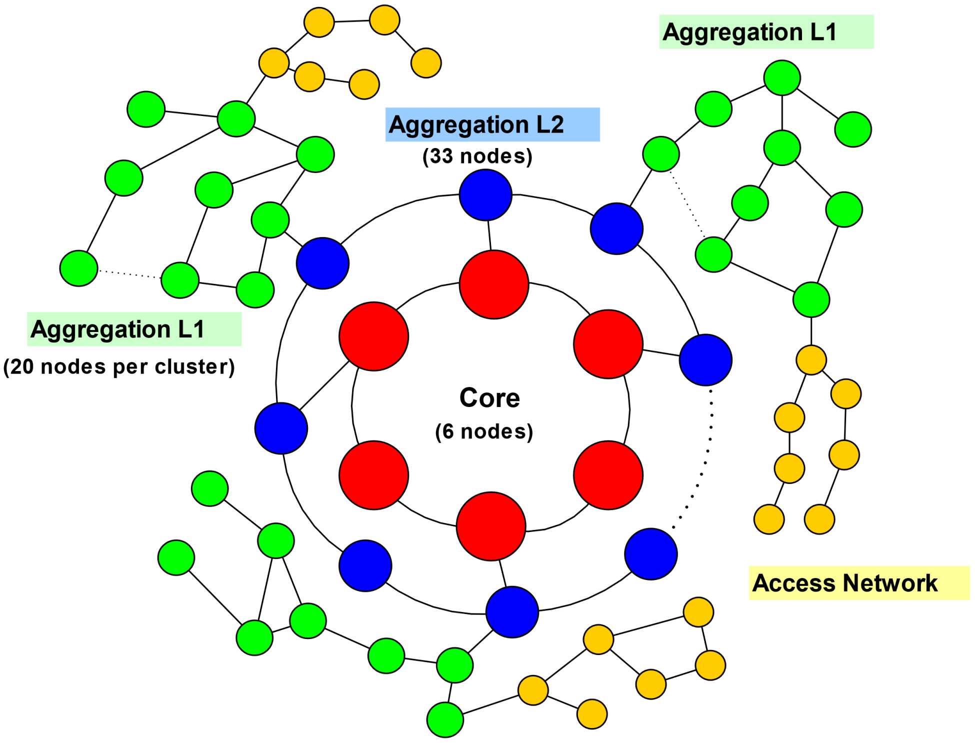


Figure 9. Structure Access-aggregation L1-aggregation L2-core of Telefónica reference metro network

Table 1 shows the distribution of link distances between the nodes of the same level of hierarchy.

Table 1 Link distances at the same level

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

Table 2 Nodal degrees at each level

Nodes degrees	Mean	Max	Min
Access Network	1.99	4	1
L1 Aggregation	2	2	2
L2 Aggregation	2.68	7	2
Core Network	5	6	4

Since optical circuits require the traversal of a number of physical links in order to interconnect the router of a given HL to a router of a different HL, it is relevant the characterization of path lengths in our reference network. Table 3 shows the statistics of path lengths between any two nodes of different HLs, assuming shortest path routing of circuits. The procedure to obtain these statistics is as follows: 1) Label all nodes according to the HL they belong to. 2) Obtain the shortest paths between all the nodes using the adjacency matrix. 3) Iterate over the shortest path matrix (symmetrical) and classify all the paths according to their source and destination's aggregation level. 4) Obtain the statistics from the classified paths.

Table 3 Path lengths between any pair of nodes of different Hierarchical Levels (HL)

Connected HLs	Mean (Km)	Mean (hops)	Max (Km)	Max (hops)	Min (Km)	Min (hops)	Std (σ) (Km)	Std (σ) (hops)
HL5 - HL4	30.33	13.38	78.48	35	2.33	2	15.30	6.95
HL5 - HL3	58.04	16.15	163.42	37	6.81	3	26.86	5.60
HL5 -HL2/1	42.44	15.70	104.63	41	0.50	2	18.86	6.56
HL4 - HL3	59.32	11.75	149.58	20	14.81	4	26.71	4.07
HL4 -HL2/1	43.02	11.11	90.28	22	8.50	3	17.52	4.86
HL3 -HL2/1	44.56	6.11	138.74	20	5.09	2	25.33	3.03

The previous distribution is a worst-case characterization of path distances among levels. In our target use cases we can quite realistically assume that the operator will set up circuits only between a given router at HL*n* and the physically closest two routers at HL*n+1*. In this case, the average and maximum distances are as shown in Table 4. The procedure to obtain these statistics is as follows: 1) Label all nodes according to the level of aggregation they belong to. 2) Obtain the shortest paths between all the nodes using the adjacency matrix. 3) Iterate over the shortest path matrix (symmetrical) and classify all the paths according to their source and destination's aggregation level. 4) For each node, keep the 2 shortest paths to each other level only. 5) Obtain the statistical information from the classified paths.

Table 4 Path lengths between a node and its closest two nodes of a higher Hierarchical Level (HL)

Connected HLs	**Mean (Km)**	**Mean (hops)**	**Max (Km)**	**Max (hops)**	**Min (Km)**	**Min (hops)**	**Std (σ) (Km)**	**Std (σ) (hops)**
HL5 - HL4	24.04	8.81	64.67	24	2.33	2	11.56	5.06
HL5 - HL3	23.20	11.07	51.19	25	3.25	3	8.62	4.61
HL5 -HL2/1	23.69	10.07	64.68	24	0.50	2	13.37	4.61
HL4 - HL3	24.73	7.17	36.84	12	11.25	4	7.10	3.92
HL4 -HL2/1	24.78	6.16	50.33	11	8.50	3	12.20	3.92
HL3 -HL2/1	33.77	3.42	138.74	7	5.09	2	24.29	1.42

This reference topology is used in the next section to estimate the traffic of the use cases where relevant. Particularly important are the statistics of HL4 to HL2/HL1 distance for Use Case #2.

2.2 PASSION USE CASES FOR THE METRO-REGIONAL NETWORK

2.2.1 Use Case #1: Cost-effective ultra-broadband transport and expansion in a large Metropolitan Area Network: 'pay as you grow' scheme

Use case #1 is the transport of data delivering Gb/s rates per user over one of the largest metropolitan areas of the world and the ability of the architecture to scale up following a 'pay as you grow' scheme.

Use case #1 is the most important one, as its purpose is assessing the benefits of the PASSION system to achieve the service level required by future MAN networks in terms of capacity and cost. Regarding cost, the ultimate target will be the estimation of the thresholds of profitability for the PASSION solution under different scenarios. For instance, determining what cost the PASSION transceiver or transponder can have over fixed optics so that there is effective gain from using advanced flexible dynamically configurable optics.

One important first step to determine the order of magnitude of the capacities to be supported at each hierarchical level. In particular, an estimation of peak capacities to be supported at HL1 can be performed by aggregating the expected peak rates of traffic as follows.

Let us assume that routers, ONT, COs and BSs, can be located at L1 and access network level. Therefore, the total number of potential nodes generating traffic is:

$N_{Nodes} = N_{HL5} + N_{HL4} = 2432 + 20\text{x}19 = 2812$

- **Cellular Traffic estimations**
  - $N_{Nodes} = 2812$
  - Cellular traffic
    - Peak rate per cell [ITU5/40-E] :
      - 20 Gb/s (DL)
      - 10 Gb/s (UL)

Consequently, the estimated aggregated downlink and uplink data rates are:

Total Cellular Traffic (Downlink) =

$\text{PeakAgg}DLRate_{Cell}$ x N_{Nodes}= 20 Gb/s x 2812 = 56.24 Tb/s

Total at Access Network (HL5): 48.64 Tb/s

Total at L1 Aggregation Network (HL4): 7.6 Tb/s

Total Cellular Traffic (Uplink)

$\text{PeakAgg}ULRate_{Cell}$ x N_{Nodes}= 10 Gb/s x 2812 = 28.12 Tb/s

Total at Access Network (HL5): 24.32 Tb/s

Total at L1 Aggregation Network (HL4): 3.8 Tb/s

- **Residential Traffic estimation**

Now, we compute the same uplink and downlink rate estimations regarding the residential traffic. We assume a target residential broadband of 1 Gb/s bidirectional service for the upcoming years, including IPTV. For the sake of the example, assume a 10 million population (Mexico DF + suburbs). Let 1/5 be the Operator's share of subscribers inside that population. Then, the potential number of users would be 2 million. Also, from previous subsections, we showed that the number of potential nodes serving these users is $N_{Nodes} = 2812$. Consequently, the number of users per (HL5/HL4) would be:

Users per node (N_{Users}): 2M users/N_{Nodes} = 711

Let O_{Subs} be the oversubscription factor ≈ 1:10. Then, it can be seen that the total aggregated traffic is:

Total Residential Traffic (Uplink / Downlink) =

$Rate_{ULDL} \text{ x } N_{Users} \text{ x } O_{Subs} \text{ x } N_{Nodes}$ = 1 Gb/s x 711 x 0.2 x 2812 = 200 Tb/s

Total at Access Network (HL5): 172.92 Tb/s

Total at L1 Aggregation Network (HL4): 27.08 Tb/s

- **Business Broadband and VPN**

Information related to enterprises has been gathered from official sources of the Mexican government [DENUE][INEGI]. Namely, small and medium sized enterprises in Ciudad de México state have been considered for the business broadband service estimations. Close inspection of the official data shows that there are 35094 enterprises with the above-mentioned characteristics. Assuming a share of 1/5 we have ~ 7000 enterprises, each demanding 10 Gb/s. Also, business VPN with symmetric 10 Gb/s. Therefore, the total data rate is:

Total traffic (Downlink / Uplink) = 7000 (10 Gb/s +10 Gb/s) = 140 Tb/s

Total traffic per HL5/HL4 = 140 Tb/s / N_{Nodes} = 50 Gb/s

- **Summary of estimations of total end-user peak traffic**
  - Cellular traffic
    - Downlink: ~56.24 Tb/s
    - Uplink: ~28.12 Tb/s
  - Residential broadband and IPTV
    - Downlink / uplink: ~200 Tb/s
  - Business broadband and VPN
    - Downlink / uplink: ~140 Tb/s

Considering all the above-mentioned numbers, we compute the mean traffic data rate from a given hierarchy level to the upper one. To that end, we take into account the aggregated data rates and the number of nodes at each level of aggregation. Table 5 shows the exchanged data rate between aggregation level per aggregation node.

Table 5 shows the exchanged data rate between aggregation level per aggregation node, it gives the order of magnitude of the capacities to be supported at each hierarchical level. In particular an estimation of peak capacities to be supported at HL1 has been performed by aggregating the expected peak rates of traffic. These figures assume a market share of the sample operator is 1/5 of the total business both residential and corporative. That means that a base of 5 million subscribers of residential (FTTH) and mobile services (5G) is served by the operator in a metropolitan area of 25 Million inhabitants. The volume of corporative traffic was estimated from the number of medium-sized enterprises in the country, demanding 10Gb/s connectivity (forecast for a 10 year horizon); again a market share of 1/5 is assumed. Finally, the estimation of 5G peak traffic can be derived from the 20Gb/s backhaul capacity per cell estimated by ITU [ITU5/40-E] and the number of cells in our topology (HL5).

Table 5 Total traffic matrix estimate in the medium term (10 years)

Exchanged **Peak Data Rate per node [Tb/s]** **Source\Destinat.**	Access Network (HL5)	L1 Aggregation (HL4)	L2 Aggregation (HL3)	Core Network (HL1/HL2)
Access Network (HL5)	-	0.1311 (UL)	-	-
L1 Aggregation (HL4)	0.1411 (DL)	-	0.9703 (UL)	-
L2 Aggregation (HL3)	-	1.044 (DL)	-	11.173 (UL)
Core Network (HL1/HL2)	-	-	12.025 (DL)	55.308 / 73.44 (UL) [1] 59.526 / 79.368 (DL)

Taking into account these numbers and the traffic forecast, a grow-as-needed approach, following a pay-as-you-grow model and based on a modular system architecture is crucial for suitably addressing this use case. Actually, modularity, programmability and flexibility are key to cope with the increasing requirements in terms of capacity and reach for the targeted networking segment. Furthermore, a modular design facilitates the scalability and a suitable sizing of the solution according to the network needs and/or specific node requirements. This also paves the way towards optical network disaggregation, while fostering interoperability. Recently, this concept has been gaining popularity, since this allows telecom operators and service providers to appropriately migrate and size their infrastructure, growing as needed. In view of an evolution towards this paradigm, different system aspects have to be properly designed to provide the scalability pursued by the service providers. Optimum technology solutions for increasing the capacity at extended optical reach, while maintaining low the cost, complexity and footprint are required. To this extent, PASSION modular system architecture should support and ease this migration, enhancing the scalability and allowing to appropriately size the infrastructure, following a pay/grow as-needed approach, at the different aggregation level and node type. This is facilitated by an architecture composed of multiple modules, which can be increased on-demand in order to improve the capacity and the potential of the system to adapt to the network requirements at each stage of its evolution and/or to properly size the nodes at each identified level of aggregation (HL1/2, HL3, HL4). Furthermore, software defined optical transmission and networking (SDOT and SDN) inherently provides flexibility, enabling optimal network configuration and management in support of the technological solutions.

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[1] 60 % Total traffic stays within core network, distributed between 4 core nodes; 40 % leaves the network and it is shared out equally between the 2 remaining nodes.

2.2.2 Use Case #2: Cost-effective ultra-broadband transport and expansion in a large Metropolitan Area Network: Dynamic capacity adaptation and HL3 IP off-loading

Another aspect of the metropolitan area studied in use case #1 is the possibility enabled by the PASSION architecture to perform IP offloading and dynamic capacity adaptation to traffic conditions. The capacity required at the core of the metro network suggests the introduction of the sliceable bandwidth/bitrate variable transceiver (S-BVT) at HL1-HL2. On the other hand, the expected variability of the traffic demand during the day in different metropolitan areas suggests that the capacity at layer HL3 can be shared by HL4s with complementary traffic patterns. In other words, HL4 could be equipped with S-BVTs with a higher channel spacing and HL1 and HL2 nodes can support S-BVTs to aggregate dynamic connections of variable capacity in time, following the demands of HL4s and offloading HL3s at IP layer, so that HL3 nodes can be mere optical wavelength switches. Therefore, the multiplexing can be performed at the optical layer and the total capacity required is similar to using IP.

2.2.2.1 Methodology for HL4 nodes classification: daily patterns per area

We use the same topology and peak rates as identified in case study #1 for each source of traffic. However, this time we consider the daily traffic variations according to the type of metropolitan area. The traffic patterns for areas are the ones identified in [Xu2017] for cellular traffic. The use of the cellular traffic patterns for the aggregate of all types of metro traffic is justified by the fact that the cellular traffic reveals when the users are or are not present at each time of the day in a given area. The peaks are:

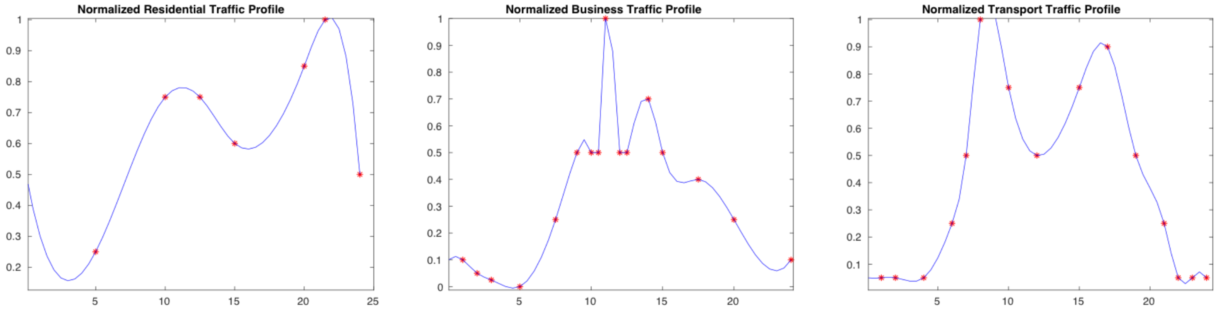
- ◦ Cellular traffic: peak rate per cell [ITU5/40-E] 20 Gb/s (DL), 10 Gb/s (UL).
- ◦ Residential broadband and IPTV with 1 Gb/s bidirectional service with 10:1 oversubscription
- ◦ Business VPN with symmetric 10 Gb/s.
- ◦ Transport traffic: our initial assumption is half of the cellular traffic specifications.

Once we have defined the types of traffic and their peak rates, we divide the suburbs in our topology into 5 different region types, according to the predominant type of nodes (i.e., predominant type of traffic) inside that suburb headed by an HL4 node. Namely, the authors of [Xu2017] identify 5 different kinds of regions, by means of a machine learning clustering algorithm:

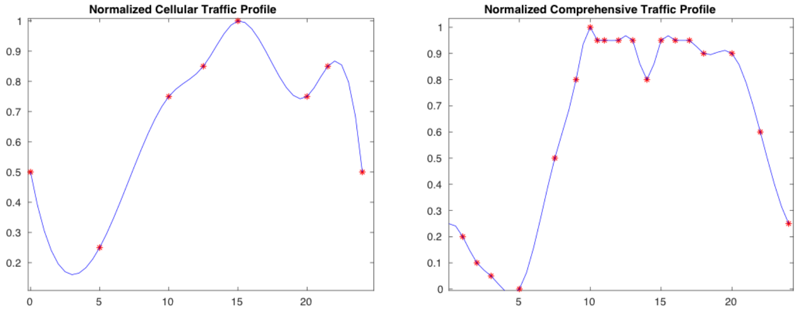
- #1) **Residential region**: 40% of the nodes handle residential traffic, 20% cellular, 22% transport traffic and 18% business traffic.
- #2) **Transport region**: 10% of the nodes handle residential traffic, 22% cellular, 44% transport traffic and 22% business traffic.
- #3) **Business region**: 15% of the nodes handle residential traffic, 18% cellular, 29% transport traffic and 37% business traffic.
- #4) **Cellular region**: 11% of the nodes handle residential traffic, 39% cellular, 28% transport traffic and 23% business traffic.
- #5) **Comprehensive region**: 29% of the nodes handle residential traffic, 23% cellular, 21% transport traffic and 26% business traffic. As it can be seen, it is a homogeneous kind of region in terms of traffic composition.

2.2.2.2 Daily traffic patterns

Once we modeled the potential distribution and composition of the traffic in each region of our topology, we combine this with temporal behaviour information [Xu2017]. We use this new dimension to weigh the peak values according to the temporal patterns that follow:



(a) Residential (b) Business (c) Transport



(d) Cellular (e) Comprehensive

Figure 10. Normalised daily activity pattern for various metropolitan area types

In order to produce these temporal patterns, we took the values of the daily peaks and valleys for each kind of traffic in a real topology, as studied in [Xu2015]. Then we performed an interpolation of these points over the time span of a day. In Table 6, we illustrate the values of these peaks and valleys for each type of region.

Table 6 Detail of the highest and lowest values of each day for each type of region.

Region	Residential	Transport	Business	Cellular	Comprehensive
Peak time	21:30	8:00 / 18:00	10:30	15:00	Not periodic (We choose one)
Valley time	3:00 – 5:00	3:00 - 5:00	5:00	3:00 – 5:00	5:00

2.2.2.3 Dynamic capacity reallocation opportunities

As a first approach to understand the shape of the aggregated traffic at higher aggregation levels of our topology and having in mind the complexity and the number of combinations in terms of the different kinds of suburbs, we study the aggregation of only 5 suburbs, one of each kind.

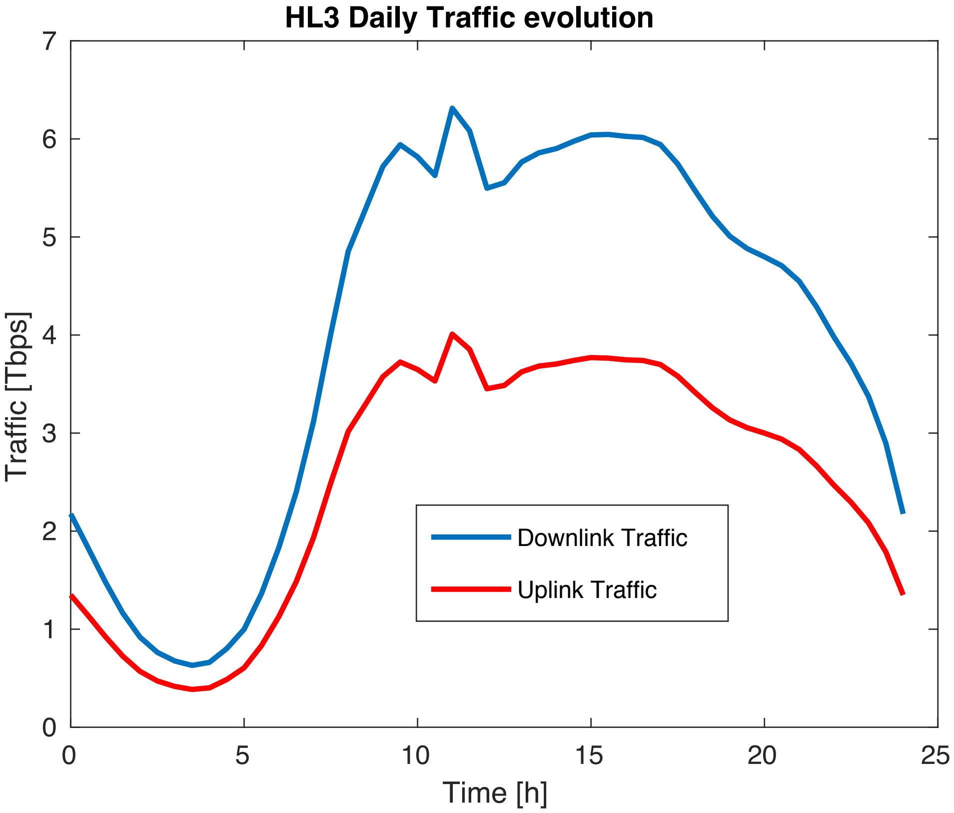


Figure 11 Temporal evolution of the aggregated traffic from 5 suburbs, one of each type.

Figure 11 shows the evolution of the traffic aggregation coming from all the 5 suburbs in a time span of a day. Note that new peaks and valleys arise after merging the traffic from all the regions. In order to obtain this evolution, we aggregate the peak values of all the nodes in each region according to their region type, i.e., according to the region’s distribution, and then we weigh them using the appropriate normalized temporal behavior presented in the previous section. In this example, the aggregation of all the traffic coming from the 5 suburbs is what the HL3 level of aggregation is going to see during the day. What is shown is the aggregation of the 5 basic components; in a concrete practical case, an HL3 node may aggregate a number of HL4 components of each type, e,g, 5 residential, 2 business, 1 cellular, 0 transport and 1 comprehensive.

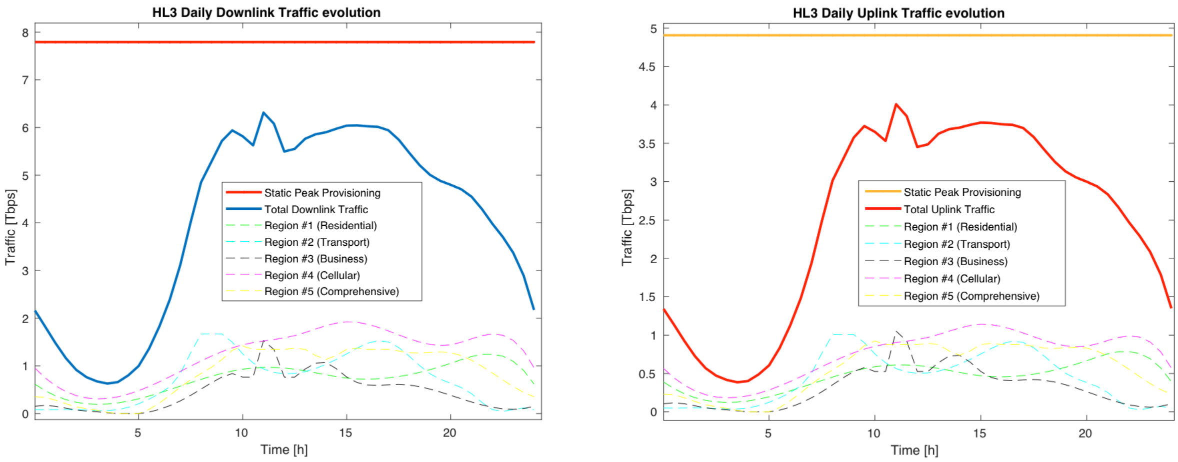


Figure 12 Downlink and Uplink aggregated traffic components

Figure 12 shows only the downlink and uplink components of the aggregated traffic, as well as the components that result in the blue aggregation, that is, the traffic that each one of the 5 suburbs are generating which correspond to every type of region. Additionally, we show in red color the capacity that would alternatively be reserved to provision the circuits using summation of the peak values of each region.

Closer inspection of Figure 12, reveals that the traffic produced by some of the different regions are not completely correlated. For instance, in the downlink components of the aggregated traffic, region #2 and region #3 (transport and business) experience an important drop in the capacity demand as we get close to noon. Conversely, region #1 (residential) and #4 (cellular) start to increase their bandwidth demands, probably because people is already at home after work. Another example, this time for the uplink, is the situation shown in Figure 8. At around 13:00h the business traffic drops as the cellular and comprehensive traffic (regions #4 and #5) keep increasing and start representing the main contributors to the total downlink capacity demand. In this situation, part of the capacity that was being provisioned for the business region can be reused in other regions as needed.

In summary, this means that we can find some complementarity of patterns of traffic demands from each region, which enables us to think about managing the total available capacity in more efficient ways or even in centralising this capacity in higher aggregation levels. The main idea that arises from this analysis is that S-BVTs can serve to dynamically change the provisioned capacity at the HL3 aggregation layer and make it available to each one of the regions/suburbs depending on the time of the day. In this way, we are able to adapt to the real-time traffic demands exploiting both spatial and time dimensions and achieving capacity multiplexing in the higher aggregation layers (HL2 and HL3), IP-off-loading the HL3 router bypassing the traffic at the optical layer toward HL2/HL1 nodes, where there is a huge centralised and dynamic capacity provided by S-BVTs. Taking this into account, removing (bypassing optically) HL4/HL3 nodes and delegating the provisioning to higher aggregation levels where we can concentrate dynamic capacity begins to appear as attractive solution.

2.2.3 Use Case #3: Interconnection for distributed Computation sites within the MAN: efficient protection schemes

The scenario for this use case is that of a computing service (e.g. CDN caching, augmented reality, etc) which is deployed in distributed virtualised way in a computer cluster distributed over various geographical locations. The idea is having at all time a secondary backup computing infrastructure to support failures of the closest primary cluster (located in the access) or overflows of computation resources from the primary cluster. Figure 13 depicts the idea. On the left, the current static configuration is shown. Each primary Computation / CDN location is backed by another remote CDN site on the same hierarchical level. This requires a permanent circuit to pair both IT resource pool sites and the provisioning of extra computing resources at both computational infrastructures to support failovers or traffic overflow from the other CDN. A centralized backup computational site in the MAN core segment would allow a higher utilization and multiplexing gain from CDN processors but the amount of permanent connections to deploy through the MAN from the access networks to the core would be too high to make it cost effective. Furthermore the utilization of these circuits would be too low, meaning a lot of unused transmission resources, including many fixed transceivers at the central computational site. Packet multiplexing techniques are not considered in this example as low latency is paramount in this scenario. Therefore, in PASSION we shall study multiplexing at the optical layer.

Figure 13 right shows the alternative setting using high-capacity S-BVT at the core and a simpler S-BVT (equipped with less elements) at the access CDNs. As it can be seen, local IT locations need not have spare resources to play the backup role anymore. All backup resources are located in the central CDN and shared by all computational sites in the MAN and only a few channels are reserved for traffic spilling over the access CDNs, which are dynamically taken on demand. Furthermore, the capacity of the channels can be adjusted to fit the needs of each primary CDN site.

This use case aims to demonstrate and assess the ability of the network to reconfigure itself in a flexible way to maximise the sharing degree of IT resources. The purpose of this use case is analysing how more expensive the Bandwidth-Variable transceivers can be w.r.t. fixed optics and still provide relevant savings in terms of transmission, computing and storage resources.

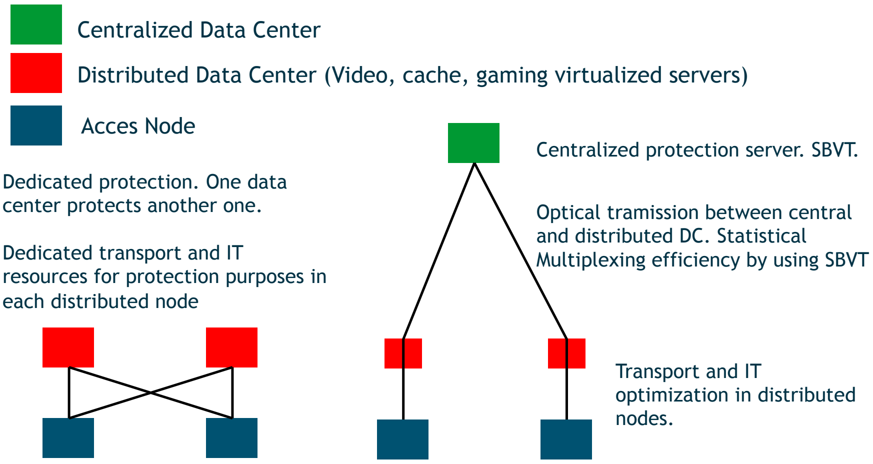


Figure 13. Pair-wise vs Centralized CDN service protection

No concrete rates are involved in this use case. However, it is clear that the higher the transceiver capacity at the S-BVT and the finer the supported granularity, the more efficient the system will be.

Reference numbers for CDN traffic will be studied in WP2. Preliminary estimations yield tens of Tb/s at the S-BVT and an allocation granularity starting at 10 Gb/s at the simpler S-BVTs for user traffic. If the CDN site act as a single virtual CDN, the rates are necessarily much higher 100-500Gb/s.

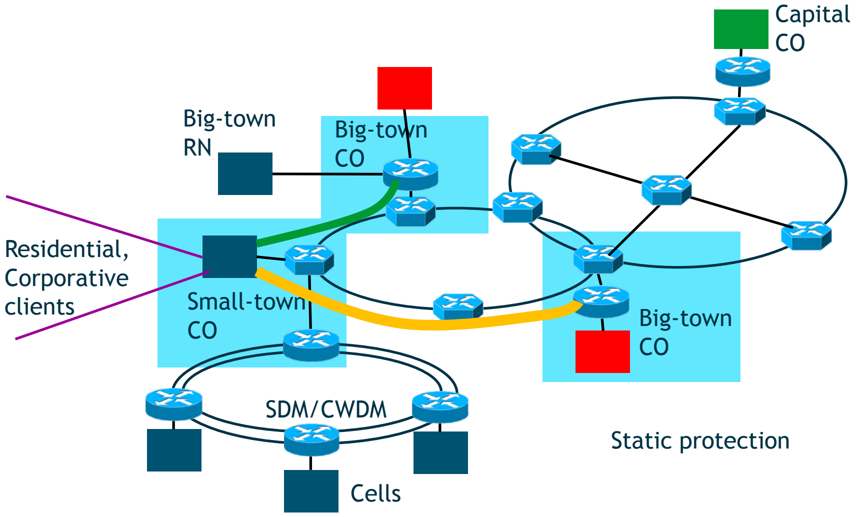


Figure 14. CDN Service protection: pairwise static setting

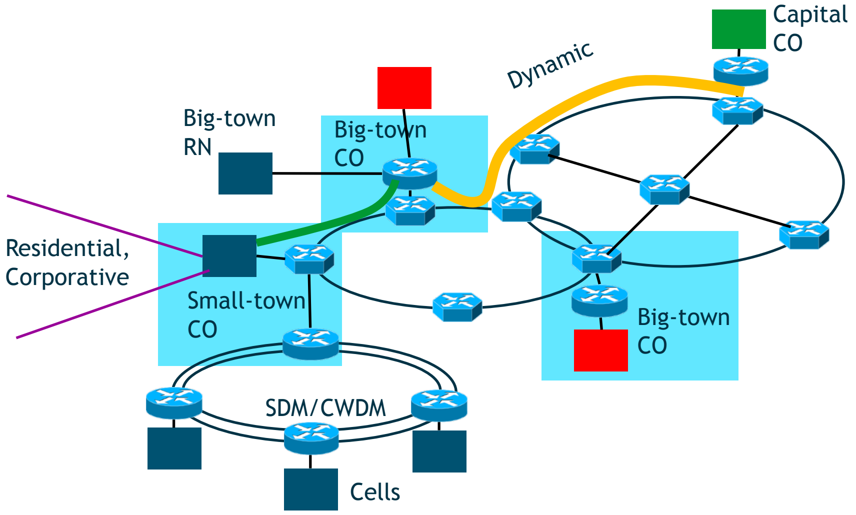


Figure 15. CDN Service protection: dynamic centralized SBVT-based setting

As mentioned, this scenario gives place to two applications: full CDN node failure protection or traffic overflow of one CDN node over another. An initial analysis of cost-effectiveness of the centralized approach, the case of overflowing traffic from the primary CDN node has been performed. Consider the two scenarios depicted in Figure 13. Scenario A (Figure 13 left) represents a group of *n* DCs located at *n* small cities. These DCs implement a pairwise protection system in which both can send overflow traffic to one another in case it is needed over fixed transceivers. On the other hand, Scenario B (Figure 13 right) shows a centralized backup system in which a S-BVT is used to cope with all the overflow traffic from all the local DCs. The circuits to the central system are setup only if the capacity of the local DC is overflown, thus saving circuits.

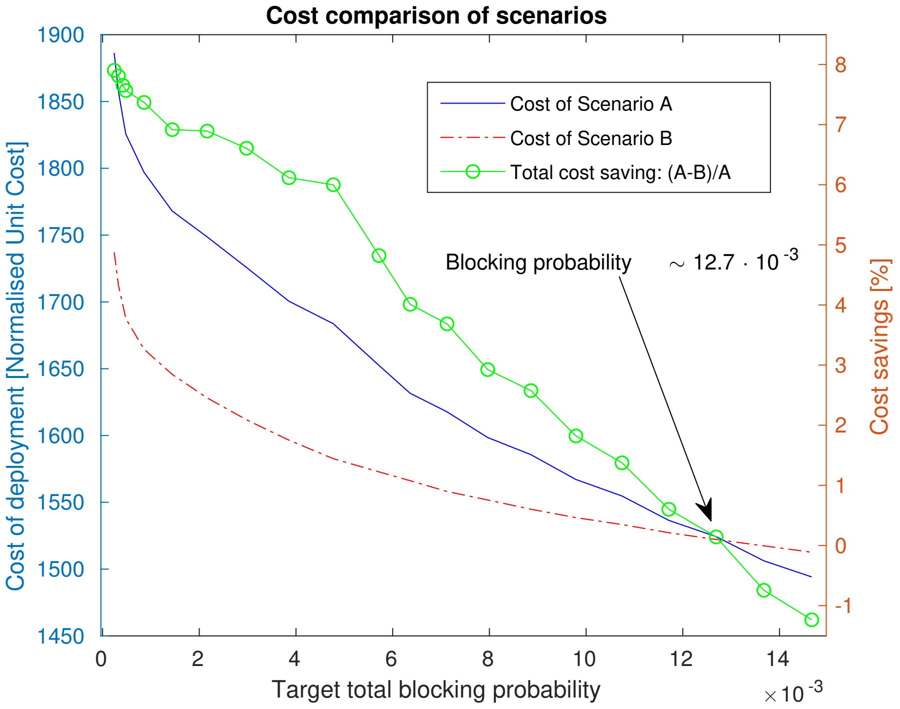


Figure 16. Cost in terms of number of total Virtual Machines required to guarantee a target blocking probability

Some preliminary tele-traffic analysis reveals that if we compare the amount of virtual machines required in each case to guarantee a target blocking probability, there is a wide range of blocking probabilities for which there is a relevant cost saving (see Figure 16) assuming Poisson arrivals for service requests to the local CDN nodes. More knowledge will be obtained from further simulations with the final constraints and features of PASSION technology.

2.3 USE CASE FOR THE METRO-AGGREGATION NETWORK

2.3.1 Use Case #4: Support of massive events: drastic dynamic re-allocation of capacity near the access

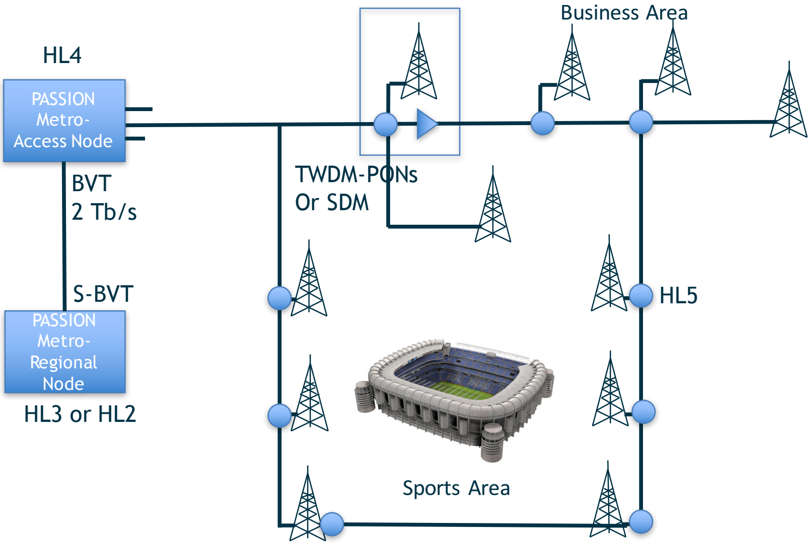


Figure 17 Supporting massive events: BVT at HL4

A particular case of the main Use Case #1 is the support of a cultural or sport events where a crowd of 5G or Wi-Fi users are actively using communication services. The interest of this use case comes from the fact that this is one of the most challenging situations for an access and metro network in terms of serviced traffic and hence it is a very proper scenario to assess the elasticity of the Metro network architecture produced by PASSION.

The question again is how much traffic this scenario generates. Several projects have estimated such figure, not always coincident:

This Use Case pertains to the Dense Urban use case family defined by the 5G-PPP and it was identified before by the METIS-II project [METIS-II]. This project named this use case as: *Test Case TC4: Stadium* under the “Great service in a crowd” scenario. An event such as a football match or a concert gathers a lot of people interested in watching and exchanging video, at the same time as they watch the event and is prone to the highest peaks of traffic (e.g. after a goal is scored) in both directions: people sharing videos taken in the stadium on social fora and people downloading re-plays. The METIS-II project estimates 0.1-10 Mb/s per m^2 (uplink+downlink) in a stadium area of 50,000 m^2 what involves **peaks of up to 500 Gb/s in a small geographical area**.

The User experience requirements defined by the Next Generation Mobile Networks (NGMN) Alliance in 2015 in their 5G White Paper [NGM15], provided consolidated 5G operator requirements intended to support the standardisation and subsequent availability of 5G for 2020 and beyond. NGMN identified 25 use cases. The use case category “broadband access in a crowd” estimates a demand of 3.75 Tb/s/Km2 (UL) and 7.5Tb/s Km2 (DL), meaning **1500/750 Gb/s (UL/DL)** per stadium.

On the other hand, the EU project 5G NORMA [NORMA] surveyed previous works and set as generic performance requirements for Enhanced Mobile Broadband (MBB) at least Tb/s/Km^2 what means 50Gb/s for a 50,000 m2 area.

Finally, the 3GPPP published in March 2015, a study on New Services and Markets Technology Enablers (SMARTER) TR22.891 [TR22.891] in order to identify high-level use cases and their related high-level requirements to enable 3GPP network operators to support the needs of new services and markets. The “market driver” for the stadium use case is *Broadband access in dense areas* and the HD video/photo sharing in stadium/open air gathering. This document collects use cases from white papers and projects.

Given the previous works a conservative figure of capacity is 1.5Tb/s for a big stadium. However, this estimation may fall short as there is a growing interest for new 3D and enhanced reality services in the stadium. We suggest the introduction of 2 Tb/s as a high capacity unit for the access in locations supporting a crowd of 5G users.

In this use case the elasticity of PASSION technology to allocate very large capacities near the access for a massive event and then re-use that capacity in another part of the MAN will be put to the test.

3 PASSION OPTICAL NODE ARCHITECTURE REQUIREMENTS. OVERVIEW OF THE PASSION ARCHITECTURE

From a telecom manufacturer perspective, in order to address the envisaged scenarios with the assumption done in the previous chapter, it is needed a careful study of the optical node architectures for each level of the network based on PASSION technology with the following characteristics:

- *Capacity*: At each network level, HL1-HL5 the size of the **switching capability and the granularity** should be addressed.
- *Interfaces*: At each network level, HL1-HL5 an increasing number of **physical interfaces** is required. Of course, a trade-off between the maximum number of interfaces supported by a node, the interface capacity, the mechanical dimension should be chosen according to the selected criteria (i.e. cost, performance, scalability and flexibility)
- *Network Layers*: considering that the identified use cases involve different network layer, from L0 (optical) to L3 (IP) and above, it is needed to identify where to allocate the proper **switching/routing capability**. This could be addressed using independent network elements for each location or integrating multiple technology within the same device.
- *Scalability*: the exponential growth of possible services with different requirements forces to pay a particular attention to scalability (i.e. the capacity to progressively increase the node performance from a minimum to a maximum setup).

Table 7 Capacities of PASSION optical nodes

# of nodes		2432	a/r	6.4	380	a/r	11.52	33	a/r	5.5	4	a/r	5.5	2		
	UNI	NHL5 nodes	NNI	UNI	NHL4 nodes	NNI	UNI	NHL3 nodes	NNI	UNI	NHL2 nodes	NNI	UNI	NHL1 nodes	NNI	
UPLINK		141			1,043			12,015			66,082			66,082		Bandwidth
DOWNLINK		131			969			11,163			61,395			61,395		Requirement
# of interfaces		# board			# board			# board			# board			# board		
target reach		tbd			tbd			tbd			tbd			tbd		
10	80	5		80	5											
100	4	1		4	1											
500		1	1	7	1											
2000					1	3	12	3								PASSION Module
8000								3	3	6	12		6	12		
16000																
112000											56	4		84	6	
Node capacity requirement		544			4,026			46,355			254,955			254,955		
Node capacity <- interfaces		3,400			21,400			96,000			992,000			1,440,000		
Matrix @L0 Optical		3,400			21,400			96,000			992,000			1,440,000		
Granularity		10			10			2,000			8,000			8,000		
Matrix @L1 OTN		tbd			tbd			tbd			tbd			tbd		
Granularity		tbd			tbd			tbd			tbd			tbd		
Matrix @L2 Ethernet		tbd			tbd			tbd			tbd			tbd		
Granularity		tbd			tbd			tbd			tbd			tbd		
Matrix @L3 IP		3,400			21,400											
Granularity		10G			10G											
assumptions:																
- **mechanics - ETSI chassis 300mm depth**																
- **A 16Tb/s interface in one board**																
- **Network "redundancy" to address protection capability is not addressed**																

Furthermore, the introduction of **network disaggregation paradigm** could be adopted in the definition of possible network “components” based on PASSION technology.

Taking into account the above consideration it is possible to make some hypothesis about the characteristics of PASSION based optical nodes, which can be summarised in Table 7.

The corresponding network architecture is summarised in Figure 18.

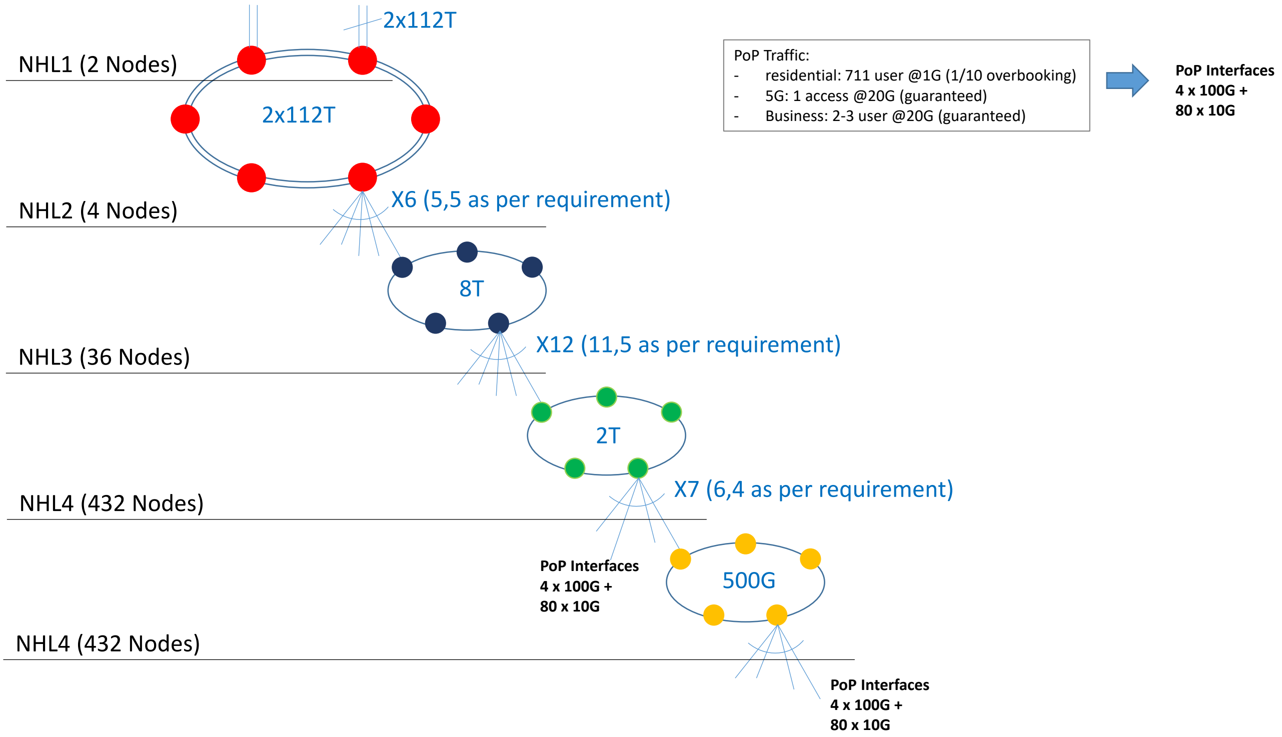


Figure 18 Network structure and PoP Interfaces

This preliminary analysis will be further developed taking into account the technological progresses in WP3 and WP4 progress and the economic figures that will be collected and consolidated during the development process. In particular, the analysis will address mechanical and power figures to identify realistic applications of PASSION technology.

3.1 CAPACITY AND GRANULARITY

The previous section has described the use cases addressed by PASSION. Use case #1 estimates the expected traffic within 5 years, once 5G gets deployed and the residential service has been set to 1Gb/s symmetric as the standard FTTH service rate to be commercialized. The target context is a 10-million-inhabitant city where the operator has 2 million subscribers of FTTH including the multiservice bundle telephony, internet, 100-channel 4K TV and business VPN services. From the analysis, it is evident that the dominant component of traffic comes from the residential service. For the estimation, we assumed an oversubscription rate of 10:1 in FTTH access and that all the traffic goes up to the core (6 nodes). From the total traffic - approximately 400 Tb/s plus 370 Tb/s going up and down respectively through the core- it is assumed that 60% remains within the MAN (crossing

NHL2 nodes or accessing service provisioning nodes attached to NHL2 nodes), and 40% is Internet traffic leaving the MAN (over NHL1 nodes), roughly 80 Tb/s.

Table 8 Outline of peak traffic requirements

Topology			
NHL1	2		
NHL2	4		
NHL3	33		
NHL4	380		
NHL5	2432		
NPoPs (NHL4+NHL5)	2812		
5G			
5G-DL (Gb/s/cell)	20	5G-UL (Gb/s/cell)	10
RDL (Gb/s)	56240	R(UL Gb/s)	28120
RHL4DL (Gb/s)	7600	RHL4UL (Gb/s)	3800
RHL5DL (Gb/s)	48640	RHL5UL (Gb/s)	24320
Residential			
subscribers	2000000		
subscribers/node	711		
oversubscription	10		
RDL per user (Gb/s)	1	RUL per user (Gb/s)	1
RDL (Gb/s)	200000	RUL (Gb/s)	200000
RHL4DL (Gb/s)	27027	RHL4UL (Gb/s)	27027
RHL5DL (Gb/s)	172973	RHL5UL (Gb/s)	172973
Business			
enterprises	7000		
RDL per client (Gb/s)	20	RUL per client (Gb/s)	20
RDL (Gb/s)	140000	RUL (Gb/s)	140000
RHL4DL (Gb/s)	18919	RHL4UL (Gb/s)	18919
RHL5DL (Gb/s)	121081	RHL5UL (Gb/s)	121081
MAN Core traffic			
Total rate DL (Gb/s)	396240	Total rate UL	368120
60% remains in core	237744		220872
40% leaves MAN	158496		147248
Rate per NHL2 (Gb/s)	59436	Rate per NHL2 (Gb/s)	55218
Rate per NHL1 (Gb/s)	79248	Rate per NHL1 (Gb/s)	73624
Access traffic			
Rate per PoP (Gb/s)	141		131

However, this estimation can fall short if the oversubscription rate needs to be reduced as new services appear, become popular and the average user consumption grows. As Table 9 reveals, the need for Pb/s switching capacity per node as pursued by PASSION is only reached for oversubscription rates close to 2:1 in FTTH for symmetric 1 Gb/s in our target city network.

Table 9 Traffic per core node as a function of oversubscription ratio in a 1Gb/s FTTH service in the PASSION reference network

Oversubscription ratio N:1	Rate per NHL1 core node (Tb/s)
10	79.248
9	101.470
8	129.248
7	164.962
6	212.581
5	279.248
4	379.248
3	545.915
2	879.248
1.78	1002.844
1	1879.248

Given these results, and the fact that these peak traffic estimations are conservative as the oversubscription ratios reveal, it can be claimed that the target capacity of PASSION is future-proof.

Granularity

Regarding the transceiver and switching granularity:

- the average peak traffic per node (HL4, HL5) expected in the access is 141 Gb/s (for 10:1 oversubscription), which suggests the use of 100-200Gb/s as the practical starting point as switching unit in the access-metro segment. Obviously finer switching units is desirable as long as the switching technology employed does not put a penalty when aggregating.
- At the core (HL1, HL2), the target is tens of Tb/s (for 10:1) according to the estimations for HL1 and HL2 nodes, so that rates for transceivers starting at 10 Tb/s are desirable. Regarding S-BVT, the most flexible capability would be to support dynamic optical channels starting at 100Gb/s as per the rate selected for the access, so that it is possible to establish all-optical circuits from access to core. The support of lower rate channels is obviously an interesting feature.
- At intermediate levels (HL3) the rates should facilitate the transition from 100G to 10T, so units of Tb/s for transceivers appears to be the right choice. 500G, 1T, 2T are rates that allow to adapt to the actual size of the subnetwork below the node. The support of S-BVT functionality at a lower rate than at the core is also a flexible implementation option.

According to previous requirements, the PASSION architecture guarantees the necessary granularity through the development of a photonic S-BVT able to support target capacities higher than Tb/s per spatial channel, higher than 100 Tb/s per link and Pb/s per node by means of spectral and spatial aggregation. PASSION S-BVT exploits Vertical-Cavity Surface-Emitting Laser (VCSEL) sources, each one operating at a different 25-GHz spaced WDM wavelength in the C-band (covering 4 THz), directly modulated to obtain up to 50 Gb/s rate, to target up to 8-Tb/s WDM aggregated capacity at a single polarization. 16 Tb/s per spatial channel are achieved exploiting polarization-division multiplexing, while the spatial dimension of 7 cores multi-core fibers (MCFs) or 7 fibers in a bundle allows enabling up to 112 Tb/s aggregated capacity per link. This target is pursued with a modular approach, as shown in the Figure 19.

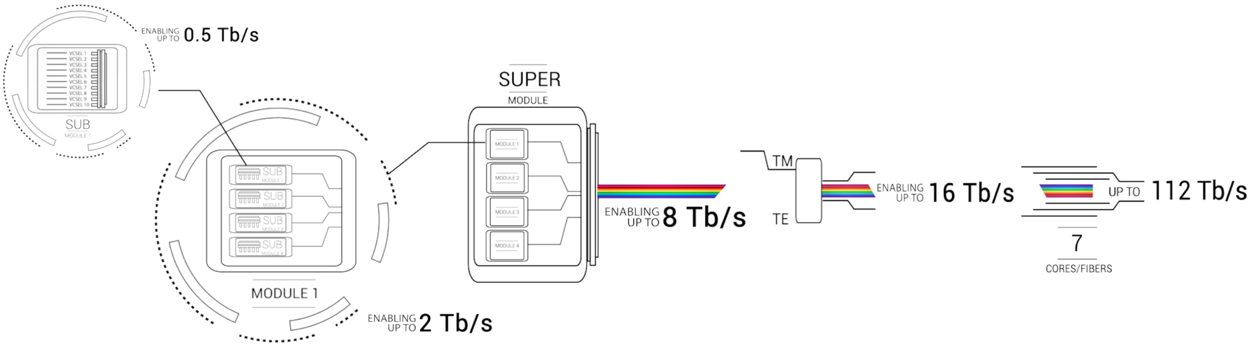


Figure 19 Example of Tx module granularity exploiting the spectral and space dimensions

A 40-VCSEL based module is built by integrating 4 sub-modules, each one containing 10 VCSELs. The 40 operating wavelengths cover the entire C-band with 100 GHz granularity. This module constitutes the PASSION S-BVT fundamental module (building block of the modular S-BVT architecture), exploited for example at the HL4 in the metro-access network as described in the PASSION network use case 1. By directly modulating each VCSEL at 50 Gb/s, an aggregated capacity of up to 2 Tb/s per fundamental S-BVT is obtained, as shown in Figure 19.

By combining four of these fundamental modules a fully equipped transmitter (Tx) supporting 160 channels (covering the entire C-band with 25 GHz channel spacing) constitutes the S-BVT super-module (characterized by 8 Tb/s capacity). Accordingly, a 25 GHz (super)-wavelength granularity is achieved. Thanks to polarization-division multiplexing (PDM), two super-modules can be combined to get up 16 Tb/s capacity. The single 8-Tb/s super-module or the 16-Tb/s pair of PDM super-modules constitute the PASSION S-BVT employed at the HL1/2 in the metro-core network described in the PASSION network use case 1. The granularity assured by the development of the VCSEL-based modules and super-modules offers the ability to match the request of a “pay as you grow” scheme in future metro networks. Space-division multiplexing (SDM) can be exploited to further increase the S-BVT capacity, as shown in Table 10. Particularly, to target the maximum capacity of 112 Tb/s, exploiting a 7-core fiber of a bundle of 7 fibers, 7 pair of PDM super-modules (composed of 4 fundamental modules each) are required at the S-BVTx.

Table 10 S-BVT sub-, fundamental and super- modules: wavelength allocation, capacity and granularity

PASSION Tx	**Number of sources**	**λ spacing**	**Capacity per polarization**	**PDM capacity**	**SDM capacity**
Sub-module	10	400 GHz	0 – 0.5 Tb/s	-	-
S-BVT fundamental module	40	100 GHz	0 – 2 Tb/s	0 – 4 Tb/s	0 – 28 Tb/s
S-BVT super-module	160	25 GHz	0 – 8 Tb/s	0 – 16 Tb/s	0 – 112 Tb/s

Regarding the sub-wavelength granularity, each module is equipped with an array of adaptive DSP. By adopting multicarrier modulation, either discrete multi-tone (DMT) or orthogonal frequency division multiplexing (OFDM), it is possible to obtain a subwavelength granularity of the order of tens of MHz at the digital/electrical level. For example, considering an OFDM signal with 512 (digital/electrical) subcarriers and 20 GHz of bandwidth a subcarrier granularity of less than 40 MHz is obtained. This parameter is flexible and can be adapted at the DSP according to the target requirement or module design/type. In addition, the adaptability of the DSP is further enhanced by the bit and power loading (BL/PL) algorithm, such as the Levin-Campello or Chow's algorithms. This enables optimal assignment per each subcarrier, according to the channel state information (CSI) that is retrieved at the S-BVRx by transmitting a probing (uniform loaded) signal. Thanks to this approach, the transmission is suitably adapted to the network traffic demand or specific use case needs over the targeted network path. Specifically, the rate can be maximized at a fixed performance activating the rate adaptive (RA) BL/PL assignment and the performance can be maximized at a fixed rate with margin adaptive (MA) BL/PL algorithm. Further details on S-BVT will be given in Sec. 3.2.3.

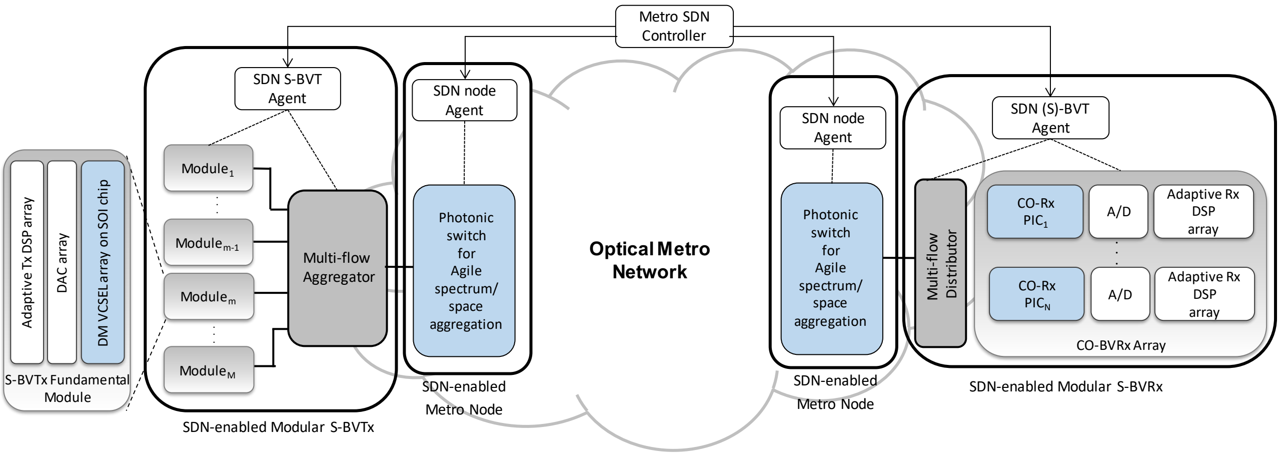


Figure 20 Schematic of the programmable (SDN-enabled) modular S-BVT equipped with multiple modules at the transmitter (S-BVTx) and at the receiver (S-BVRx) for agile spectrum/space aggregation.

3.2 OPTICAL NODE SYSTEM AND SUBSYSTEM REQUIREMENTS

The use cases discussed above serve to estimate the traffic demands and functionalities of optical switching nodes, which themselves determine the capacity requirements of systems and subsystems. In this section, the switching node functionalities in a flexible reconfigurable add and drop multiplexer (ROADM) are explained. Next, the parameters of the switching node components are derived from the capacity requirement of the presented use cases.

3.2.1 Switching node architecture and component functionality

Current state-of-the-art metro networks are quite static and present limited flexibility and scalability. The optical node architecture in the PASSION project will be a key enabler of network flexibility and agility required to address cost and efficiency requirements. Spectral/space dynamic switching and aggregation enables to fulfill the agile and high capacity requirements within the metro-core nodes. This metro network concept will leverage modularity and exploits the SDN paradigm in order to efficiently allocate/use the overall network resources transforming the operation of todays network infrastructure and reducing overprovisioning and margins.

Figure 21 shows a generic architecture of an optical switching node envisioned in the PASSION project. At the heart of the PASSION node is the photonic switch providing connectivity between the express and add/drop traffic. It shows the ability to generate traffic with varying bandwidth and data rates, optical switching components for handling the *express traffic*, *added traffic* and *dropped traffic and coherent receiver modules (CRMs)*. The locally generated traffic and aggregated traffic are merged as *added traffic*.

Hence, the switching functionality is implemented via *photonic switches*, *add switches*, *aggregate/disaggregate switches*, and *multicast switches* (MCS). The system capacity is enhanced by using the space and spectrum. The spectral diversity is enabled via WDM inputs and outputs, while the space diversity is enabled with multi-core fiber inputs and outputs as explained in Section 3.1. Implementing polarization independence of TE and TM modes (dual polarization) leads to doubling of the available capacity.

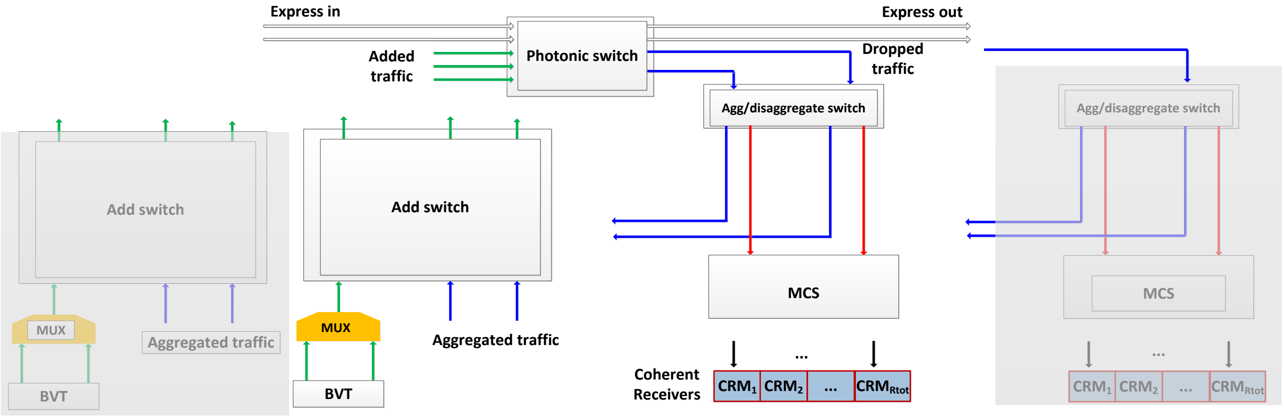


Figure 21 Optical node architecture, with sub-component functionality (S-BVT, MCS, CRM)

The *photonic switch* provides space based switching of the traffic at any input port to any output port which are either assigned to *express out* path or *dropped traffic* path. A high level of flexibility is needed to be able to fully reconfigure the data traffic, while being able to add/drop on the fly and to guarantee full link usage at the same time. This is done by including spectral slicing, space switching, and aggregation functionalities. The Aggregate/Disaggregate switches do the routing of the dropped traffic either to the MCS switch or Add switch on the level of wavelength granularity. The Add switch provides aggregating tasks for the WDM inputs originating from S-BVTs or from the Aggregate/disaggregate switch to the add ports of the photonic switch. In this way, the available transmission resources are efficiently used. The capability of the S-BVT to generate traffic with variable bandwidth based on the granularity principle given in Section 3.1 meets the agile capacity requirement of the nodes. Add ports of the photonic switch allow to flexibly add each of the requested channels.

The drop part diverts some of the link traffic to drop it at the receiver side. For this purpose, the MCSs enable colorless and contention-less switching to efficiently use the CRMs. Each CRM contains M coherent receivers each of which is equipped with its own local oscillator, and the total number of receivers is $M \times R_{tot}$.

The main motivation behind this presented architecture is the bundling of traffic in space and wavelength dimension to efficiently utilize resources. When the node needs capacity upgrade, the same blocks are repeated (as shown in the shaded blocks in Figure. 21) as a result of the flexible and modular design of the node architecture. On the same line of thinking, when the node pipes (multi-core fiber input/outputs of the node) are not fully exploited, the traffic is locally dropped to maximize aggregation and is re-sent for full capacity node utilization.

3.2.1.1 Photonic space switching functionality

The use of high port count inter-connectivity functionality generated by the photonic space switching is important to provide non-blocking switching between the express traffic and the add/drop traffic. It sends the express traffic through the node towards the next destination nodes. In the presence of high capacity at the node (i.e. several wavelengths per port and large port count) switching of wavelength bundles from input to the output ports reduces granularity routing complexity. This reduces the system cost as less switching components are required as wavelength granularity is avoided at this core switching stage. The wavelength selective features are implemented through the Add/drop and Aggregate/disaggregate functionalities. In PASSION project, control information from an SDN agent provides switching information between the express line traffic and the add/drop traffic.

Since the photonic space performs central switching functionality, it presents a single point-of-failure in the metro-core scenario. The solution to this is the use of an identical core photonic space switch for protection purposes. To support scalablity, the design of the photonic space switch targets a low-cost and large port count implementation.

3.2.1.2 Adding and dropping switch functionality

The add/drop functionalities provide connectivity by adding to or dropping from the express traffic at the local optical node. In support of greater operational flexibility, and with the advent of wavelength-tunable transceivers, the wavelength selective switch (WSS) is a popular choice for “colorless” add/drop ports. In a 1×N WSS configuration, wavelengths can be routed from an input of the network node to any output fiber, or channels can be locally added/dropped.

In order to enable direction-less, and contention-less performance, reachability of a wavelength from any input to any output port is fulfilled via an M×N WSS so that dropping/adding to any desired direction is possible. The CDC attribute is also enabled via the use of multi-cast switches (MCS) in the drop direction in which the signals at the input ports are broadcast to all output ports (all directions: direction-less) irrespective of the wavelength (color-less). Contention avoidance in the WSS units is enabled by switching multiple inputs of the same wavelengths to different output ports. This applies for the Add switch WSS and the Aggregate/disaggregate switch WSS units. Within the MCS, the use of space switch selects a single input to a given output regardless of wavelength thereby avoiding contention.

In PASSION, scalability to high capacity in the add and drop functionality supports the use of modular approach where new add/drop modules are used to support new subscribers as shown in Figure. 21.

3.2.1.3 Aggregation/Disaggregation switch

The benefits of spectral superchannels for high-throughput transmission, system component integration, and reduction in the number of switching components have been widely studied and demonstrated. MCFs have been of interest recently, and their benefits for increasing per-fiber throughput and enabling system component integration has been demonstrated.

As the bit rates of routed data streams exceed the throughput of a single WDM channel, spectral and spatial traffic aggregation becomes essential for optical network scaling. These aggregation techniques reduce network routing complexity by increasing spectral efficiency to decrease the number of fibers, and by increasing switching granularity to decrease the number of components in a photonic switch matrix. Spectral aggregation yields a modest decrease in the number of fibers but a substantial decrease in the number of switching components.

3.2.1.4 Multicast switch

To achieve a CDC performance the aggregate/disaggregate switch functionality is supported by a MCS solution for the drop wavelength channels. A MCS splits the drop signals and delivers a copy of all the drop channels to each attached receiver. The embedded function of a tunable wavelength filter after the MCS isolates a single drop channel from the selected direction and thus implement contentionless operation of the node. In principle the coherent detectors with tunable local oscillator can also be used for this purpose. However, pre-coherent detector, results in higher sensitivity.

3.2.1.5 Parameters of the switching node

Table 11 shows the parameters and their respective symbols of the switching nodes involving the number of input/output ports, percentage of input/output ports dedicated for input/output traffic.

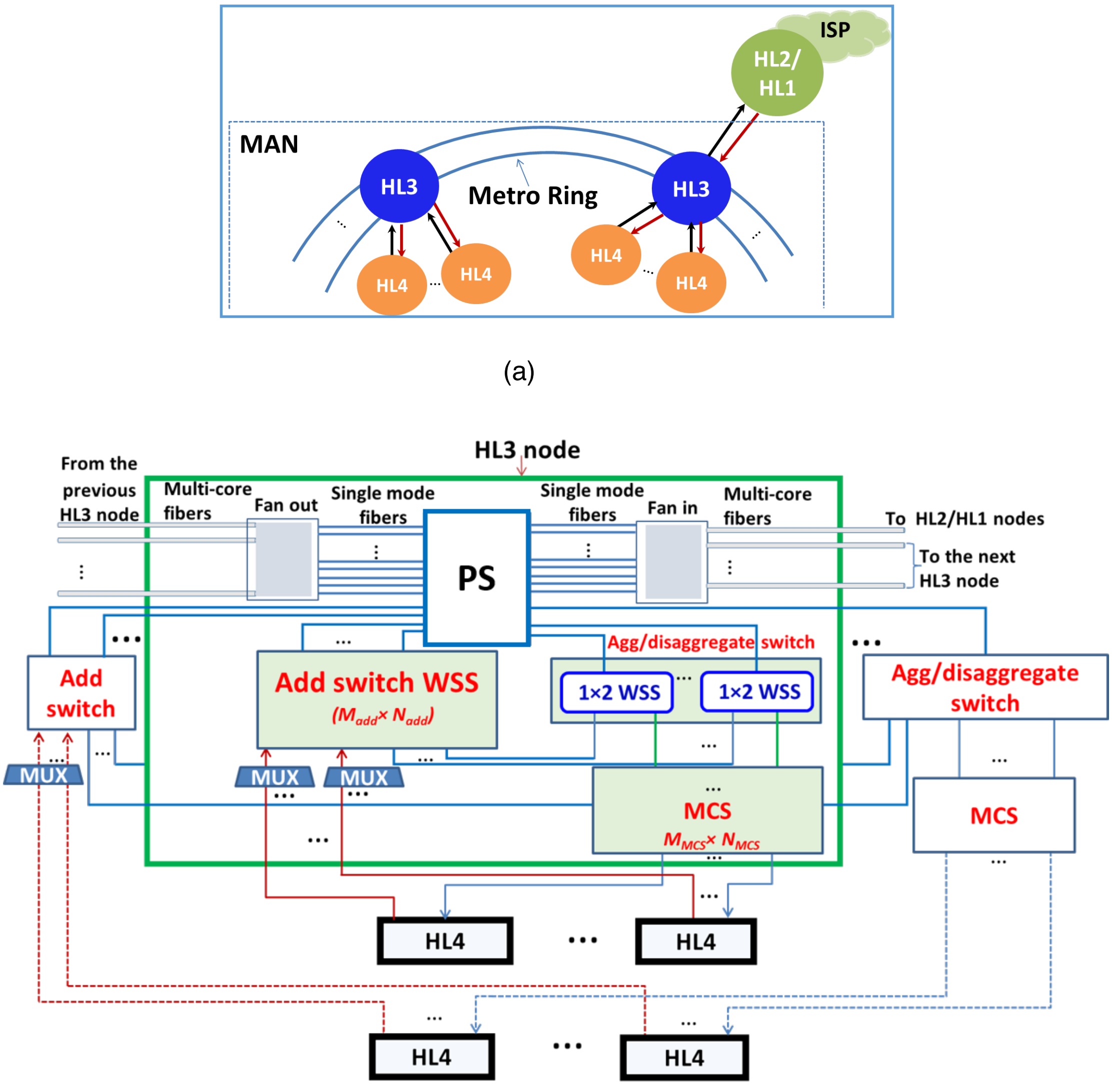
As described in the previous section, HL3 combines aggregation and distribution of traffic into different areas of MAN via its optical switching capability. Furthermore, it facilitates connectivity of users to the outside world (internet) via connectivity to HL2/HL1. Basically, the functionality in the HL3 nodes can be listed as follows:

- Connectivity with the adjacent HL3 nodes for both DL and UL: used for distributing traffic to the right HL3 nodes;
- Connectivity with HL4 nodes: connectivity between enterprise internet traffic, example VPN;
- Connectivity with HL2/HL1 nodes: used for internet access, etc.

Table 11 Parameters of PASSION optical switching node

	Parameters	Symbol
Photonic switch	Total number of wavelengths	λ_{tot}
	Total number of input ports	M_{ph}
	Total number of output ports	N_{ph}
	Total number of ports for dropped traffic	D
	Total number of ports for outgoing traffic	P_{thr}
	Total number of ports for incoming traffic	P_{inc}
	Total number of ports for added traffic	A_d
	Percentage of input ports for added traffic	a (%)
	Percentage of input ports for dropped traffic	d (%)
Add Switch	Total number of input ports	M_{Add}
	Total number of output ports	N_{Add}
	Number of modules of the add switch	Mod_{Add}
Aggregate/disaggregate Switch	Total number of input ports	M_{Agg}
	Total number of output ports	N_{Agg}
	Percentage of ports connected with MCS	mcs (%)
	Number of modules of the add switch	Mod_{Agg}
Multi-cast switch	Total number of input ports	M_{MCS}
	Total number of output ports	N_{MCS}
	Number of modules of the MCS	Mod_{MCS}

Figure 22(a) shows a portion of the ring metro network; HL3 nodes are connected to each other, to the HL4, and HL2/HL1 nodes. Figure 22(b) shows the switching functionalities carried out by the switching components. The high capacity inter-connection between the HL3 nodes and the connection to the HL3 and HL2/HL1 nodes is carried out via multi-core fibers. The fan-out and fan-in structures facilitate the connection of the multi-core fiber with a single mode fiber. The PS handles the switching of the input traffic toward the respective destination either to the adjacent HL3 nodes or HL2/HL1 nodes. The DL traffic is handled via an Aggregate/disaggregate switch which contains a 1X2 WSS per port for discriminating the traffic destination either to adjacent HL3, HL2/HL1 nodes or to the HL4 nodes. For the UL traffic from HL4 nodes, a WSS based Add Switch is used to enable a CDC addition of the traffic to the HL3 nodes. A wavelength multiplexer might optionally used before the Add switch for aggregation purposes. The PS ultimately then switches the added traffic to the desired HL4 or HL3 nodes or forwards it to HL2/HL1 node.



(a)

(b)

Figure 22 (a) Scenario network connection at HL3 node in MAN (b) Switching node architecture to support the network (this illustrates the connection of a single HL3 nodes to adjacent HL3 nodes, HL2/HL1 nodes and HL4 nodes)

The modularity of the switching components is used to handle the traffic increase in the MAN core network. As such, new modules of Aggregate/disaggregate switch, Add-switch, and Multi-cast switch are added as shown in Figure 22(b). The modular design consists of increasing the number of ports of PS and adding new modules of Add switch, Aggregate/disaggregate switch and MCS. Use of dual polarization helps relax the required increase in the number of ports of the PS.

3.2.2 Applying the use case scenarios

The traffic requirements of the use case scenario #1 is summarized in Table 12, as it is relevant in the discussion of the requirement of the switching nodes. It is evident that HL3 is an all photonic switching node since it is responsible for traffic aggregation and classification. That means HL3 nodes are connected with each other for the sake of traffic classification and they do link traffic from

HL4 nodes to HL2/HL1 nodes for the purpose of traffic aggregation. In the use-case #1, there are 33 HL3 nodes (optical switching nodes) which are connected with each other in a ring network. The total traffic at the HL3 nodes (198.2 Tb/s for UL and 226.24 Tb/s for DL) is the sum of the traffic generated by the HL4 nodes and HL5 nodes. For HL3, assuming uniform traffic distribution, the capacity per node is 198.2 Tb/s/33=6.006 Tb/s in the UL and 226.24 Tb/s/33=6.8557 Tb/s in the DL.

Table 12 Summary of the capacity (Tb/s) at HL1, HL2,..., HL5

Level	Total Capacity for Use-case #1: Cost-effective ultra broadband transport and expansion in a large MAN in a pay-as-you-grow approach		
	Cellular (Mobile) Peak capacity per cell	Residential Subscriber rate : 1 Gbps uplink, 1 Gbps downlink	Business VPN Subscriber rate : 10 Gbps uplink, 10 Gbps downlink
HL1/ HL2	Capacity per HL2/HL1 is 11.73 Tb/s per node for UL and 12.025 Tb/s per node for DL		
HL3	Number of nodes: 33 Uplink: 3.8+27.08/2+35 +24.32+172.92/2+35Tb/s=198.2 Tb/s, capacity/node=6.006 Tb/s Downlink:7.6+27.08/2+35+48.64+172.92/2+35=226.24 Tb/s, capacity/node=6.8557 Tb/s		
HL4	Number of nodes 380, Uplink:3.8 Tb/s, 10Gb/s per node downlink:7.6 Tb/s, 20 Gb/s per node	Number of nodes: 380 Uplink:27.08/2 Tb/s,35.6 Gb/s per node Downlink:27.08/2 Tb/s,35.6 Gb/s per node	Number of nodes: 1400 Uplink: 35 Tb/s, 25 Gb/s per node Downlink:35 Tb/s, 25 Gb/s per node
HL5	Number of nodes 2432 Uplink: 24.32 Tb/s, 10Gb/s per node Downlink:48.64 Tb/s, 20Gb/s per node	Number of nodes: 2432 Uplink:172.92/2 Tb/s,35.6 Gb/s per node Downlink: 35.6 Tb/s, 35.6 Gb/s per node	Number of nodes: 1400 Uplink: 35 Tb/s, 25 Gb/s per node Downlink:35 Tb/s, 25 Gb/s per node

Four of the HL3s are connected directly with HL2/HL1. These nodes do the job of traffic classification via their link to the neighboring HL3 (both for the DL and UL) and traffic distribution in their connection to HL4 nodes (in the DL), as well as HL2/HL1 nodes.

Parameterization of the HL3 nodes

Referring to the traffic situation in Table 12, the total number of HL4 nodes for all the three applications (Mobile, Residential and Business VPN) is 380+380+1400=2160 while the total number of HL3 nodes is 33. Considering an even distribution of traffic in the HL3 nodes, the number of HL4 nodes connected with a single HL3 node is 66. The total traffic of the HL3 (198.2 Tb/s for UL and 226.4 Tb/s for DL) is the sum of the traffic from the HL4 and HL5 nodes.

Table 13 Switching node parameters of an HL3 node

Total traffic per HL3 node	Value
Total required capacity	6.006 Tb/s for UL, 6.88557 Tb/s for DL
Total available capacity	8 Tb/s for UL, 8 Tb/s for DL
Wavelength parameter	Value
λ_{tot}	140
Required capacity per single wavelength	42.9 Gb/s UL, 48.9 Gb/s DL
Available capacity per single wavelength	57.1 Gb/s UL,57.1 Gb/s DL
Add switch parameter	Value
$[M_{add},N_{add}]$	[4,2]
Maximum available input port capacity	2 Tb/s
Maximum available output port capacity	8 Tb/s
No of modules (Mod_{Agg})	14
Required total capacity	6.006 Tb/s
Maximum available capacity	8 Tb/s
Additional units	1 multiplexer, 1 interleaver
Aggr/disaggregate Switch parameters	Value
$[M_{agg},N_{agg}]$	[2,4]
mcs(%)	50
Required total capacity	6.88557 Tb/s
Maximum available capacity	8 Tb/s
No of modules (Mod_{Agg})	14
Additional units	1 multiplexer, 1 interleaver
MCS parameters	Value
$[M_{MCS},N_{MCS}]$	[2,22]
Maximum available input port capacity	8 Tb/s
Maximum required output port capacity	20-35 Gb/s
Maximum available output port capacity	20-57.1 Gb/s
No of modules (Mod_{mcs})	3
Additional units	2: 1X3 splitter, 1: shuffle network, 140 tunable filters
PS parameters	
$[M_{PS},N_{PS}]$	[14+2,14+2], 14 ports belong to HL3 ring
Percentage of ports connected to Add switch: a (%)	12.5
Percentage of ports connected to Agg/disaggregte switch: d (%)	12.5
Maximum input and output port capacity	16 Tb/s
Number of multi-core fibers	2 7-core fiber (input) and 2 7-core fiber (output)

The traffic going to a single HL3 is :

- UL: 6.006 Tb/s. This amount of traffic goes as an input to the Add switch in the HL3 node from the 66 HL4 nodes.
- DL: 6.8557 Tb/s. This amount of traffic goes as an output of the MCS in the HL3 node towards the 66 HL4 nodes.

Thus, based on this, we can define the required physical parameters of the Add switch, Aggregate/disaggregate switch and the MCS. The total number of wavelengths λ_{tot} is chosen to be 140 allowing for an available capacity of 8 Tb/s both for the UL and DL. By doing so there is extra room for additional (oversubscription) capacity requirement of more than 1 Tb/s.

Add switch: the Add switch is 4X2 WSS with a maximum capacity of 2 Tb/s per port. Since the number of wavelength is 140 which is too many to be incorporated for PIC WSS realization and an interleaving unit and multiplexing units are used together. The interleaver has 14 outputs, therefore 14 modules of the Add switch are incorporated. That means a single WSS handles a total of 10 wavelengths. The separate outputs of the interleavers are thus spectral slices handled by different switching modules. The input ports have a maximum capacity of 2 Tb/s and the output ports have a capacity of 8 Tb/s (corresponds to a case where all added ports of the traffic are diverted to the same output port of the Add switch).

Aggregate/disaggregate switch: the Aggregate/disaggregate switch also accommodates 140 wavelengths in total. Since it is WSS based, an inter-leaver is used to spectrally slice the wavelengths into 14 slices via a 1X14 inter-leaver.

Multi-cast switch: the MCS is a 2X22 broadcast and select switch, consisting of 1X22 splitter and 22 X1 space switches. Three modules are used to connect to 66 HL4 nodes. At the input of the HL4 nodes, a tunable filter is used to select the right wavelength sets.

PS: Looking into the PS, we find that the total capacity passing through can be taken to be equivalent to the total capacity of the 33 HL3 nodes i.e. 198.2 Tb/s for the UL and 226.24 for the DL. That is because in the ring network of the HL3 nodes, single HL3 nodes switch the traffic originating from all of the HL3 nodes. Since the core network is connected with multi-core fibers, the number of multi-core fibers connected at the input and output of the PS can be calculated as follows:

- UL (the input ports are considered uplink)= total UL capacity of HL3 nodes – UL capacity of all HL4 nodes connected with a single HL3 node=198.2-6.006 Tb/s=192.194 Tb/s, considering a total capacity of 16 Tb/s with dual polarization per single core, the total number of cores=12.01 by rounding up to 14, 2 7-core fibers can be used
- DL (the output ports are considered downlink) = total DL capacity of HL3 nodes – DL capacity of all HL4 nodes connected with a single HL3 node=226.24-6.885 Tb/s=224.467 Tb/s, the total number of cores=13.71 Tb/s by rounding up to 14 Tb/s, 2 7-core fibers can be used.
- Two fan-out and fan-in are used to adapt the multi-core fibers to single mode fibers to be connected as input and output.
- The number of input ports connected with the multi-core fibers both at the input and output is 14 each having a capacity of 16 Tb/s.

Parametrization of the HL4 nodes

Even though, no optical switching is put on the HL4 nodes, the routing and aggregation functionality can be employed with low cost switches based on wavelength blockers for a simple add/drop functionality. The schematic representation of the envisioned HL4 nodes is shown in Figure 23. It typically consists of a de-multiplexing Arrayed waveguide grating (AWG) at the input. The HL4 nodes are connected via a WDM link. At each HL4 node a 1:2

splitter is used to tap the drop signal which is broadcasted to a number of splitters to HL5 nodes. A tunable filter at the input of the HL5 nodes enables a colorless and directionless drop of signals. The wavelengths destined to the local HL5 nodes will be blocked by the gate switches based on a semiconductor optical amplifier (SOA). On the other hand, wavelengths destined for the next HL4 node are passed by the turning on the SOA gate switches. On the add/drop side, an *access interface* is used to handle traffic from /to all HL5 nodes.

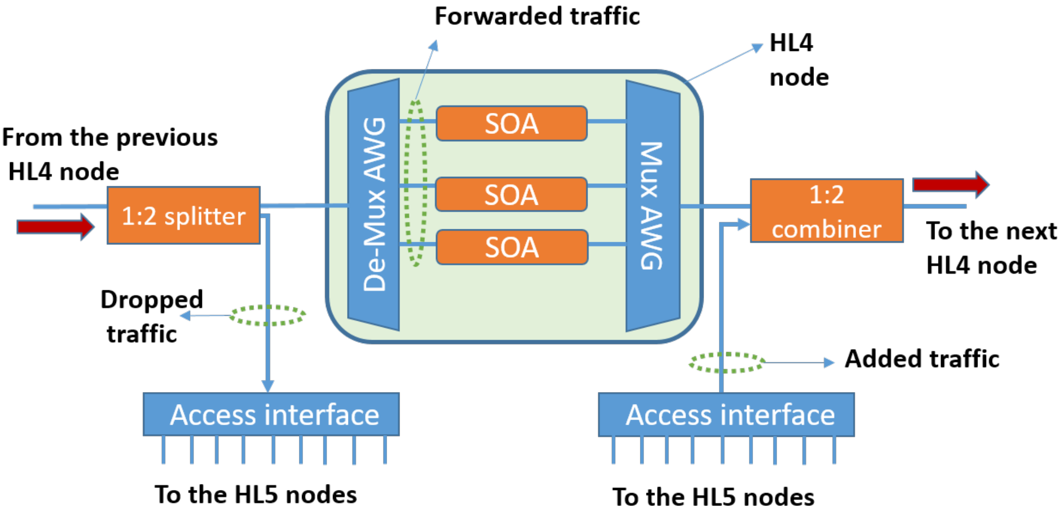


Figure 23. Schematic representation of an HL4 node with add/drop functionality

Considering the traffic distribution given in use-case #1, the number of HL5 node connected to a single HL4 node is calculated as follows:

- Cellular 2432/380 = 6.4 (approximated to 7)
- Residential 2432/380 = 6.4 (approximated to 7)

Therefore the splitter and combiner losses in the HL4 node will be acceptable to mobilize a low-cost add/drop functionality. Based on the number of HL4 nodes, the add and drop capacity requirement in the HL4 nodes is calculated as follows:

Uplink (UL): Residential = 7 x 10 GB/s (UL capacity @ HL5 node) =70 Gb/s
: Cellular = 7x35.6 Gb/s (UL capacity @ HL5 node)=249.2 Gb/s

Downlink (UL): Residential = 7 x 20 GB/s (UL capacity @ HL5 node) =140 Gb/s
: Cellular = 7x35.6 Gb/s (UL capacity @ HL5 node) =249.2 Gb/s

Based on this traffic requirement, the number of wavelengths allocated for residential network is 2 for UL and 4 for DL as indicated in Table 14. Therefore, the capacity requirement per wavelength is 35 Gb/s (both for UL and DL) in a residential network. The available capacity is 57.1 Gb/s per wavelength there by allowing a total available capacity of 114.2 Gb/s for UL and 230 Gb/s for DL, enabling capacity over subscription of more than 40 Gb/s.

The number of wavelengths allocated for Cellular networks is 6 both for UL and DL paths. The required capacity per wavelength is 41.6 Gb/s while the available capacity per wavelength is 57.1

Gb/s. The total available capacity in an HL4 node for cellular network is 342.6 Gb/s (both UL and DL) which gives room for over subscription of capacity by more than 90 Gb/s.

Table 14 Capacity requirement of an HL4 node for Add and drop traffic

Network	Residential	Cellular
Number of wavelengths	2 for UL, 4 for DL	6 for UL, 6 for DL
Required capacity per wavelength (Gb/s)	35 for UL, 35 for DL	41.6 (both for UL and DL)
Available capacity per wavelength (Gb/s)	57.1 (both for UL and DL)	57.1 (both for UL and DL)
Required Uplink (add/DL) capacity (Gb/s)	70	249.2
Available (add/UL) capacity (Gb/s)	114.2	342.6
Downlink (drop/DL) capacity (Gb/s)	140	249.2
Available (drop/DL) capacity (Gb/s)	230	342.6

3.2.3 Slice-ability: Sliceable Bandwidth-Variable transceiver (S-BVT)

The S-BVT supports the on-demand configuration of programmable network functions, such as rate, bandwidth, path adaptation and slice-ability. Particularly, the slice-ability is the ability of the transceiver to allocate its capacity into one or several independent optical flows that can be transmitted towards one or multiple destinations [Sam15]. Thus, its bandwidth can be sliced to serve several independent traffic demands simultaneously, by flexibly partitioning the available resources. Therefore, the S-BVT can be seen as a transceiver of great capacity composed by a set of virtual lower-capacity BVTs. According to this definition, each module composing the transceiver, either fundamental or super-module, can be considered an S-BVT, if the high-capacity flow generated at the transmitter side can be sliced into multiple flows of lower capacity direct towards different nodes of the network or towards the same destination over multiple independent paths (inverse multiplexing) [Sva16].

As mentioned in Sec. 3.1, the S-BVT is modular (for the sake of convenience, we report the schematic also here in Figure 20) and offers a wide range of (sub- and super-wavelength) granularities, supporting different capacities according to the traffic demand, network evolution and specific node type and aggregation level. The S-BVTx is composed of M fundamental modules. In order to cover the entire C-band with densely (25-GHz spaced) allocated channels, 4 of them equipped with VCSELs operating at different center-wavelengths should be integrated in a super-module, as defined in Sec. 3.1. This architecture scales with the network requirements, traffic demand growth, and/or node type/aggregation level, by adding multiple modules as needed, up to a total maximum capacity of 112 Tb/s by integrating 7 pairs of PDM super-modules, considering a fully-equipped S-BVT for a spatial dimension of 7 cores/fibers. Thus, spectral and spatial slice-ability is enabled, fully exploiting all the available resources/dimensions (including the polarization).

It is worth noting that each fundamental module can be seen as an S-BVT, since it integrates an array of 40 VCSELs that can be suitably enabled/disabled for generating an aggregated flow, which can be opportunely sliced at the network node(s). Each VCSEL is working at an operating wavelength, which can be selected on-demand by means of the S-BVT agent, following the corresponding SDN-controller command. According to Table 10 in Sec. 3.1, the VCSEL center-wavelength spacing at the sub-module is 400 GHz, at the fundamental module is 100 GHz and at the super-module is 25 GHz. The dense spectral channels allocation is obtained by enabling all the VCSELs of the S-BVT super-module, since each fundamental module is equipped with VCSELs operating at center wavelengths spaced apart 25 GHz among each other. The wavelength plan of a fully-equipped super-module is illustrated in Figure 24 in relation to the corresponding sub-/fundamental-module of the S-BVT. In addition, each wavelength can be fine-tuned within a range of ±75GHz with respect to the center-wavelength. This feature eases the generation of super-channels and mitigates the spectrum fragmentation even for not fully-equipped S-BVT.

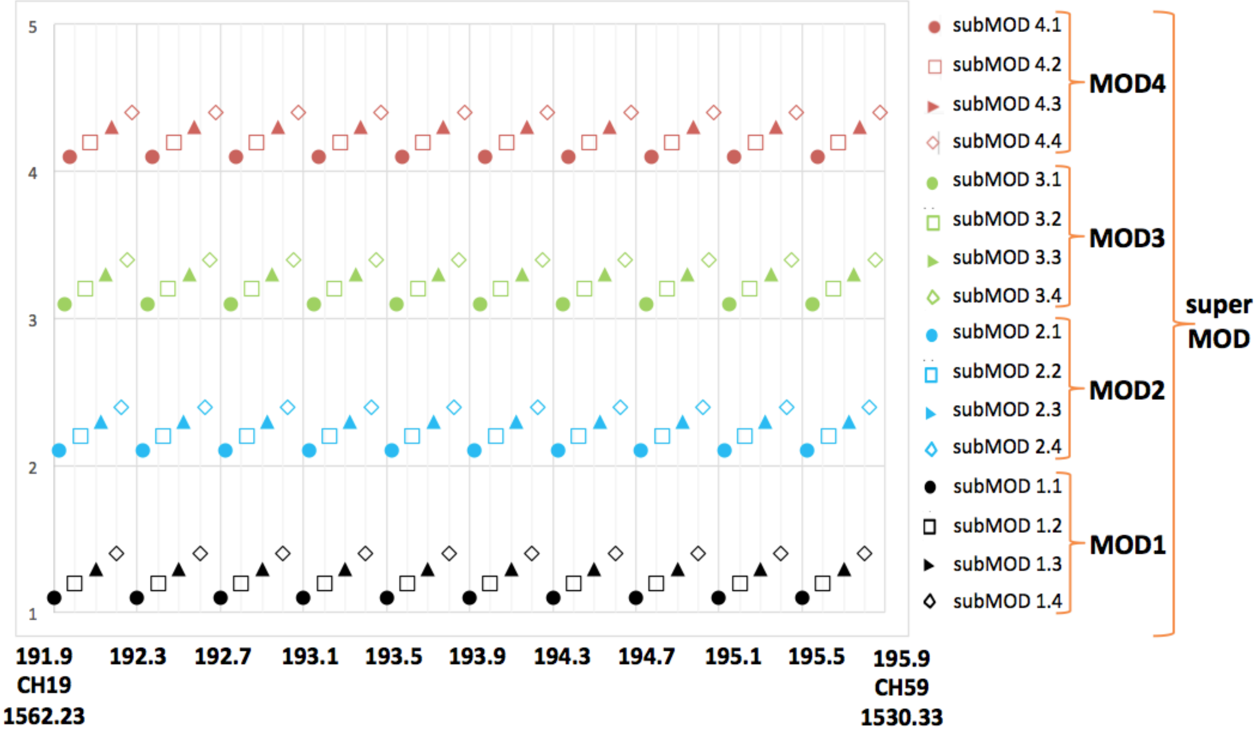


Figure 24 Wavelength plan covering the entire C-band, corresponding to the VCSEL center wavelengths (indicated with circle, square, triangle and diamond, respectively) of the different sub-modules composing the fundamental modules (indicated with colors).

As evidenced in Figure 20, an S-BVT composed by M fundamental modules at the transmitter side can be arbitrarily configured by the SDN-controller enabling/disabling each sub-module VCSEL, according to the traffic demand and the target reach of the connection to be established, taken into account the wavelength plan of Figure 24 and the available spectral/spatial resources. At the receiver side, the number of required coherent receiver (CO-Rx) of the S-BVRx array is N, where N can be different from M. In fact, depending on the aggregation level and node type, the S-BVRx can be equipped with an arbitrary set of CO-Rx that can grow as needed. Considering the use case #1, the network topology and the different aggregation level, a high capacity multi-flow, generated at a fully-equipped S-BVT (composed by one or multiple super-modules), can be sliced and the lower capacity flows directed towards different nodes equipped with a reduced number of modules, concurrently serving multiple destination nodes at variable rates. Similarly, the flows from different nodes (for example at HL4) equipped with S-BVT adopting simple fundamental modules, can be aggregated to be received by a high-capacity fully-equipped super-module S-BVT with the required CO-Rx array (for example located at HL1/HL2). Additionally, the traffic demand can be split/sliced into multiple flows routed via multiple independent paths to the same end-node, enabling inverse multiplexing. A multi-flow superchannels is appropriately distributed to the CO-Rx array by an optical filtering element either at the S-BVT or the network node. A requirement, to allow that any wavelength is received at any CO-Rx module, is that it is equipped with a tunable local oscillator.

These S-BVT advanced functionalities with the flexible VCSEL wavelength selection, the local oscillator tunability and the adaptive (digital/electrical) subcarrier loading (enabled by the multicarrier modulation, as detailed in Sec. 3.1) allow a very agile networking and provide the PASSION system architecture with enhanced flexibility and adaptability to the network requirements, mitigating the spectrum fragmentation and enabling a (soft) migration towards more flexible, dynamic and disaggregated paradigms.

3.2.4 Optical impairments tolerance

Recently, VCSELs potential has been shown at 1550 nm with advanced modulation formats for 100G applications ranging from short reach to metro networks [Xie14, Xie15], as well as for passive optical networks (PONs) and metro/access elastic optical networks (EONs) [Wag17, Nad17]. In [Nad17], a transparent service delivery at variable data rates has been demonstrated in a SDN converged elastic metro/access optical network with cost-effective programmable transceiver based on VCSEL technology. In that experiment, a directly modulated VCSEL of 4.5 GHz bandwidth working at 1539.61 nm was used for implementing the transmitter module. Up to 16 Gb/s with 9 GHz maximum spectral occupation was achieved, adopting DMT with BL/PL and direct detection (DD), considering a minimum power budget of 20 dB in the access segment. A maximum transmission distance of 200 km has been successfully covered, considering 50 km PON tree and a 150 km single hop path of a metro network. The achieved rate was about 8 Gb/s (half of the maximum rate) at the target BER.

Widely tunable micro-electro-mechanical system (MEMS) VCSELs, that allow adapting the operating wavelength over a spectrum range of more than 60 nm [Pau15], have been considered for converged WDM-PON applications. This type of VCSELs, with 3-dB bandwidth of 7 GHz, was successfully demonstrated for DMT transmission at 26 Gb/s over 40 km of SSMF [Wag17]. This VCSEL technology has been also explored for implementing the building block, or specific modules, of an S-BVT able to cover extended reach, targeting the metro segment [Sva18a, Sva 18b]. To this extent, single sideband (SSB) OFDM modulation has been considered to make the direct modulated signal more robust against chromatic dispersion. In this case, a SSB optical filter is required. This operation can be performed at the S-BVT aggregator stage or at the network nodes if suitably equipped with bandwidth variable wavelength selective switches, so that the optical filtering could be performed at any node, not only at the sliceable transceiver.

The performance, in terms of impairments tolerance and capacity, of a BVT module, adopting a widely tunable MEMS VCSEL, has been assessed in [Sva18a]. SSB-OFDM is compared to pure

DMT transmission over different paths of the CTTC testbed network ADRENALINE, shown in Figure 25, which consists of four nodes and five amplified links ranging from 35 km to 150 km [Mun17]. Two nodes are optical cross-connects (OXCs) and two are reconfigurable optical add-drop multiplexers (ROADMs). The 35 km link between OXC-2 and ROADM-1 is flexgrid, as the nodes are equipped with programmable spectrum selective switches modules.

For the system assessment, a BVT based on a widely tunable VCSEL module at the BVTx and a pre-amplified DD receiver (PIN with TIA) at the BVRx front-end has been set-up. The BVT is equipped with adaptive DSP enabling rate/distance and bandwidth variable transmission. The independent digital signals are converted to analog with a 64GSa/s DAC; at the BVRx, the photodetected signal is captured by an oscilloscope at 100GSa/s for demodulation and further error counting, considering a target BER of 4.62·10-3 (HD-FEC with 7% overhead over a total of 13.4%). The VCSEL wavelength is widely tunable within a range of up to 60nm. With a fine adjustment of MEMS, bias and temperature control, the VCSEL can be tuned to operate within the C-band with flexgrid granularity (6.25 GHz and 12.5 GHz frequency slots). The VCSEL is directly-modulated with DMT with 512 subcarriers over 16 GHz (corresponding to about 30 MHz of electrical/digital subcarrier granularity) and BL/PL algorithm is adopted at the DSP. The channel state information (CSI) is retrieved at the adaptive BVRx DSP with a uniform loaded (4QAM) probing signal. According to the corresponding signal-to-noise ratio (SNR) profile, the maximum bitrate, below the target BER threshold, in back-to-back (B2B) is 33.2 Gb/s at 1550.12 nm, and slightly lower (29.8Gb/s and 31.3Gb/s, respectively) at the edge channels of the ITU grid, which have been considered (1530.33 nm and 1561.42 nm). The maximum bandwidth with assigned bits is 10.5GHz, corresponding to a spectral occupation of two flexgrid slots of 12.5GHz. In the case of SSB transmission, the spectral occupation is halved and the B2B bitrate below the target BER is 31.7Gb/s at 1550.12nm. This value is slightly lower than DMT, due to the narrow SSB filtering and the VCSEL wavelength fluctuations. Therefore, the BVT capacity in B2B with optimized BL/PL assignment and 10.5 GHz bandwidth occupancy is above 30 Gb/s as shown in Figure 26 (a).

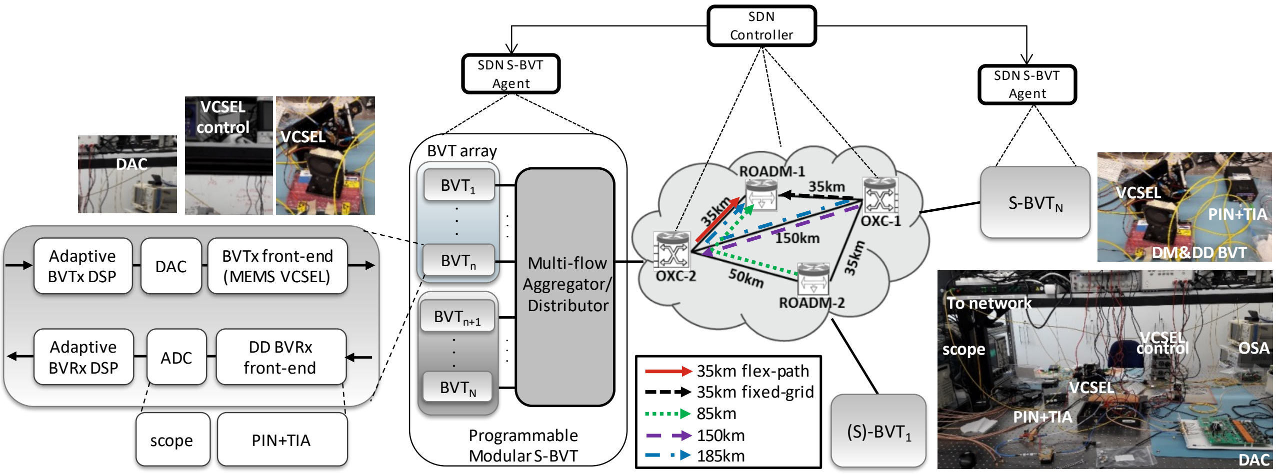


Figure 25 Schematic, set-up and pictures of the programmable SDN-enabled S-BVT adopting MEMS VCSEL at the BVTx front-end. The ADRENALINE network paths which has been used for the performance assessment are illustrated.

After the B2B case, we assessed the case of transmission over the ADRENALINE flexgrid path (flex-path) of 35km. Considering DMT, the bitrate at the target BER (RA algorithm) decreases to 21.1Gb/s with the tunable VCSEL set to operate at 1550.12nm. Similar performance was achieved at 1530.33nm (19.8Gb/s) and 1561.42nm (20.5Gb/s). By configuring the multi-flow aggregator, consisting of a bandwidth variable WSS, as SSB filter, 28.5Gb/s can be achieved at 1550.12nm. Next, we evaluated the capacity performance of the BVT at 1550.12nm below the BER threshold for DMT and SSB transmission over different ADRENALINE paths of 85km, 150km and 185km. SSB modulation supports bitrates greater to 20Gb/s up to a 2-hop path of 185km, as shown in Figure 26 (a), due to its higher robustness against chromatic dispersion. This is also evidenced in Figure 26 (b) and (c), showing the SNR performance for the SSB-OFDM and DMT, respectively. In addition, in this case the spectral efficiency is doubled, since only half of the optical bandwidth occupancy is required with respect to the DMT signal. Particularly, the spectral occupancy in terms of assigned flexgrid frequency slots of 12.5 GHz for the case of DMT is two (25 GHz), while for the SSB-OFDM slice/flow is only one (12.5 GHz). Finally, Figure 26 (d) shows the OSNR analysis in B2B.

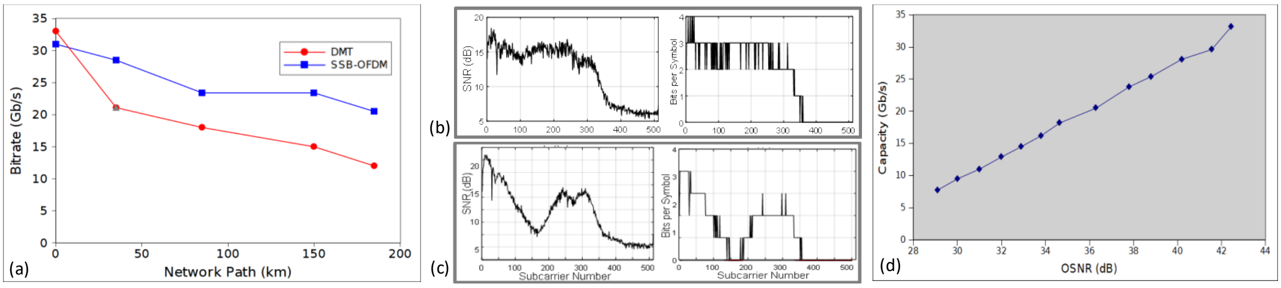


Figure 26 Performance of BVT based on MEMS VCSEL and DD; maximum bit rate versus ADRENALINE paths (a), example of CSI over 35km path and optimal bit loading assignment per subcarrier for SSB-OFDM (b) and DMT (c); capacity vs OSNR in B2B (d).

Adopting larger bandwidth VCSELs, like the ones implemented within PASSION, and using high-performance DAC/ADC, higher capacities can be achieved. A single VCSEL with 3-dB bandwidth of 15 GHz, directly modulated with DMT and using DD, has been demonstrated for short-reach applications at 100Gb/s [Xie15]. Up to 95 Gb/s (net data rate of 79.2 Gb/s) has been achieved over 4 km of standard single mode fiber (SSMF). If coherent detection is considered, the achievable reach can be further extended to target the metro/regional segment, as shown in [Xie14] by adopting 4-PAM modulation format and PDM. It should be also pointed out that DMT can be also conveniently combined with coherent detection to improve the optical impairments tolerance and extend the achievable reach as demonstrated in [Fab15].

Table 15 summarizes the results reported in this section for the different types of VCSEL-based transmitter, modulation and detection.

To determine PASSION S-BVT transmission capabilities, we performed preliminary simulations featuring the parameters of the PASSION architecture. In particular, in the simulations, the VCSEL model resembles PASSION devices (5 MHz linewidth, 18-GHz E/O bandwidth, chirp factor α=3). The adopted DMT signal is obtained with expected bias current and modulation depth, and displays 256 subcarriers with a 2%-cyclic prefix (CP). VCSELs emissions are aggregated in the PASSION module through the 100-GHz wavelength multiplexer described in the deliverable D3.1, whose ideal transfer function is used to filter the VCSEL output. The impact of further filtering is taken into account with 25-GHz channel spacing WSS [Pul11] to be compliant with the PASSION network infrastructure. Coherent detection is performed at the receiver side, employing 25-GHz PDs and a local oscillator (100-kHz linewidth and 13-dBm optical power).

Table 15 Reported capacities for different VCSEL-based transmitters, modulations and detection.

Modulation format & detection type	**VCSEL-based Tx**	**Operating λ**	**3-dB BW**	**Performance**			**Target Application**	**Ref.**
				Capacity	***Link***	***FEC limit***		
DMT & DD	Large-BW VCSEL Tx	1550nm	15GHz	95Gb/s	4km	$1.5\cdot10^{-2}$	Short-reach	[Xie15]
DMT & DD	MEMS-VCSEL Tx	Tunable	7GHz	26Gb/s	40km	$2.26\cdot10^{-3}$	Converged WDM-PONs	[Wag16]
DMT & DD	VCSEL-based BVT	1539.61nm	4.5GHz	8Gb/s	200km	$4.62\cdot10^{-3}$	Metro/Access	[Nad17]
DMT& DD	MEMS-VCSEL (S)-BVT	Tunable	7GHz	12Gb/s	185km	$4.62\cdot10^{-3}$	Metro Networks	[Sva18a]
SSB-OFDM & DD	MEMS-VCSEL (S)-BVT	Tunable	7GHz	20Gb/s	185km	$4.62\cdot10^{-3}$	Metro Networks	[Sva18a]
PDM 4-PAM & CO-detection	Large-BW VCSEL Tx	1550nm	15GHz	100Gb/s	400km	$1.5\cdot10^{-2}$	100G Metro Networks	[Xie14]

Digital signal processing (DSP) provides chromatic dispersion compensation, digital symbol synchronization, CP removal, sub-carriers phase recovery, demodulation and error count. The capacity is evaluated performing bit loading with a target BER of 3.8 10^{-3} corresponding to 7% overhead hard decision FEC limit. Single-channel single-polarization results are displayed in Table 16 and 17, where the performance in terms of transmitted capacity and maximum achievable reach in case of either 35-km or 65-km SSMF span length is shown. Table 16 presents DMT with dual sideband (DSB) modulation performance as a reference, and SSB- DMT modulation after crossing up to 5 filters (WSS) and considering different OSNR values. In both cases the signal bandwidth occupancy is 20-GHz. SSB is obtained by exploiting a WSS detuning of 9.5 GHz with respect to the VCSEL carrier. The considered transmitted power is 0 dBm and the amplifier noise figure is 6 dB.

Table 16. Capacities for single-channel, single-polarization transmission for DSB and SSB DMT modulation with signal occupancy of 20 GHz

	OSNR = **40 dB** Reach$_{35km}$ = **70 km** Reach$_{65km}$ = **n.a.**	OSNR = **35 dB** Reach$_{35km}$ = **210 km** Reach$_{65km}$ = **65 km**	OSNR = **30 dB** Reach$_{35km}$ = **735 km** Reach$_{65km}$ = **260 km**	OSNR = **29 dB** Reach$_{35km}$ = **945 km** Reach$_{65km}$ = **325 km**	OSNR = **25 dB** Reach$_{35km}$ = **2310 km** Reach$_{65km}$ = **780 km**
DSB (MUX module) B_{signal} = 20 GHz	96 Gb/s	68 Gb/s	44 Gb/s	41 Gb/s	18 Gb/s
SSB w 1 WSS	76 Gb/s	71Gb/s	57 Gb/s	54 Gb/s	42 Gb/s
SSB w 2 WSS	74 Gb/s	68 Gb/s	56 Gb/s	53 Gb/s	42 Gb/s
SSB w 5 WSS	64 Gb/s	60 Gb/s	54 Gb/s	51 Gb/s	40 Gb/s

Table 17 shows the performance in terms of transmitted capacity and maximum reach for different OSNR values and after crossing up to 5 filters (WSS). A DSB DMT signal with 10 GHz bandwidth occupancy (optical spectrum width around 20 GHz) and either 35-km or 65-km SSMF spans are considered. Again, the transmitted power is 0 dBm and the amplifier noise figure is 6 dB.

Table 17 Capacities for single-channel, single-polarization transmission for DSB DMT modulation with signal occupancy of 10 GHz

	OSNR = 40 dB Reach$_{35km}$ = **70 km** Reach$_{65km}$ = n.a.	OSNR = 35 dB Reach$_{35km}$ = **210 km** Reach$_{65km}$ = **65 km**	OSNR = 30 dB Reach$_{35km}$ = **735 km** Reach$_{65km}$ = **260 km**	OSNR = 25 dB Reach$_{35km}$ = **2310 km** Reach$_{65km}$ = **780 km**
DSB (MUX module) B_{signal} = 10 GHz	64 Gb/s	50 Gb/s	31 Gb/s	20 Gb/s
DSB + 1 WSS	59 Gb/s	48 Gb/s	30Gb/s	20 Gb/s
DSB + 2 WSS	55 Gb/s	46 Gb/s	30 Gb/s	20 Gb/s
DSB + 5 WSS	47 Gb/s	41 Gb/s	28 Gb/s	20 Gb/s

These preliminary results provide a first indication on PASSION S-BVT optical impairments tolerance, although they don't take into account non-linear propagation, cross-talk effects and non-ideal behavior of the DAC/ADC, which will be included in next assessments according to the actual metro network topology.

According to these results, PASSION S-BVT architecture adopting large bandwidth VCSELs operating at different wavelengths can provide high capacity (up to 50Gb/s and beyond) per BVT flow. The multiple modules can be suitably enabled/disabled for wavelength selection and bandwidth-variable adaptation. The finer granularity and adaptability is also achieved thanks to the multicarrier modulation, DMT or OFDM, and the adaptive loading algorithms. Coherent reception allows to enhance the optical impairments tolerance and thus extend the achievable reach.

3.3 CONTROL PLANE REQUIREMENTS

The macroscopic purposes and basic functions to be supported by a control plane are: i) the processing of incoming connectivity requests, ii) the automatic computation a feasible route and selection of optical resources satisfying the received connection demands, and iii) the automatic configuration of the underlying transport network according to the selected path and resources fulfilling the targeted request.

In PASSION project, the control plane deployment will be based on the basis and principles of a Transport Software Defined Networking (T-SDN) controller [Jan16]. In short, a T-SDN controller is a logical centralized control entity providing a set of control functions such as the path and resource computation, the topology management and the consequent connection provisioning via the network programmability and configuration. To this end, the T-SDN controller uses to provide two main open application protocol interfaces (APIs): the Northbound Interface (NBI) and the Southbound Interface (SBI). Figure 27 depicts the targeted architecture to be deployed in the PASSION project showing the aforementioned control functions, the required APIs (NBI and SBI) and the necessary databases to provide support for the whole control operations. For the sake of completeness, such required repositories are: the traffic engineering database (TED) and the Connection database (DB). The former allows maintaining an updated view of the network topology and resources (e.g., S-BVT and link spectrum availability) to be used as input for dynamically computing the received connections. The latter is used to keep track of the connections being active within the transport optical network infrastructure. In the following, we will concentrate on detailing the requirements of both NBI and SBI interfaces supporting the features and characteristics of both the PASSION targeted devices and use cases as well as outlining the required operations and functions to be done in the T-SDN controller.

3.3.1 NBI Requirements

The NBI allows external applications (e.g., third-party clients attached to a network service provider) commanding and requesting dynamic bandwidth allocation for specific connectivity services. Such requests should specify the set of remote sites (e.g., different remote CDN locations as described in the targeted use cases in section 2.2.3) to be interconnected through the optical infrastructure along with the demanded set of QoS requirements: bandwidth (bits/s), maximum tolerated latency (in ms), availability level, etc. The definition and specific details in terms of the selected protocol, data model and encoding to be eventually deployed for the PASSION NBI will be addressed in the forthcoming deliverable D2.2. Herein, we will focus on detailing the NBI requirements from a high perspective.

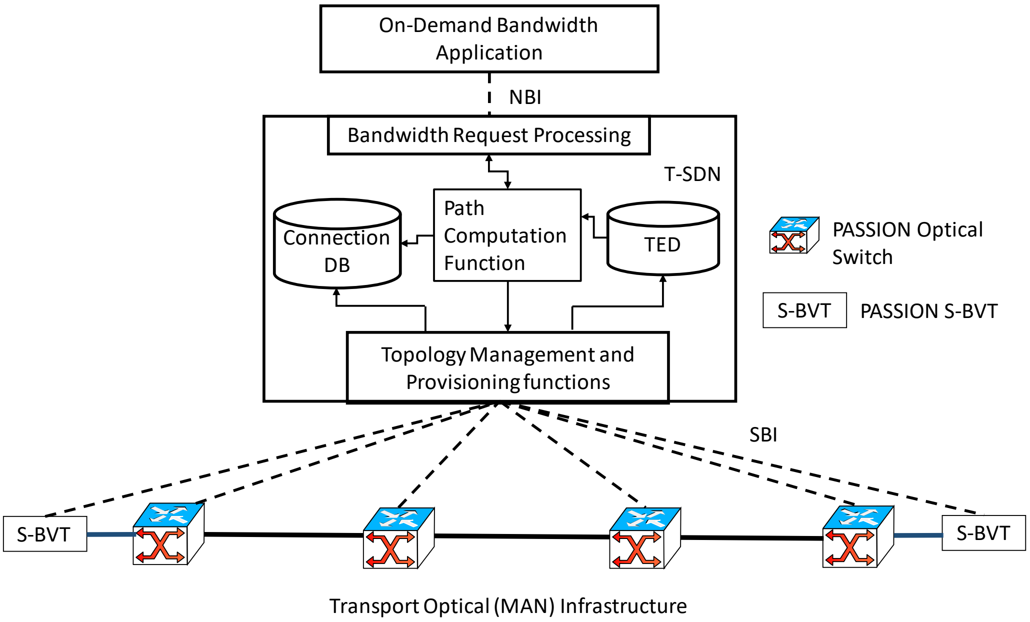


Figure 27 Targeted PASSION Control Plane Architecture

Upon receiving a connectivity service request via the NBI, T-SDN controller processes the received request and proceeds on triggering the computation and selection of the optical resources that will eventually accommodate the connection demand. To do this, the path computation function uses as input the updated information of the network connectivity and resource status. This information as mentioned above is stored in the TED repository which is updated via the T-SDN controller topology management function. Different options for TED updating are available (e.g., either asynchronously via a well-defined link state protocol such as Border Gateway Protocol Link State - BGP-LS or synchronously / on-demand via a proprietary protocol implementation, e.g. REST API). The selection of the updating mechanism and protocol for the PASSION T-SDN controller is under-decision and will be detailed in the upcoming D2.2. That said, and for the sake of completeness, the TED information should store related attributes and characteristics of the underling optical transport infrastructure. Without loss of generality, this information includes: the availability of the S-BVT devices and their capabilities (e.g., supported modulation formats and FEC), the optical link spectrum occupancy, the status of the optical switch ports, link distances, etc. One may observe that TED information can be sorted as static and dynamic oriented. The static information regards attributes and capabilities of the transport network infrastructure which do not change as connections are allocated and released (e.g. the S-BVT supported features such as modulation format, FEC, central frequencies of the VCSEL devices constituting the S-BVT, link distances, etc.) On the other hand, dynamic TED information is related to those attributes that are modified as connections are served and removed. Dynamic information encompasses the link spectrum availability, the number of available VCSEL devices within the S-BVTs, etc.

The devised path computation algorithm has to consider not only the service requirements and the TED information to output a feasible connection, but also needs to take into account the set of constraints derived from the underlying transport network infrastructure. These set of constraints include: the optical spectrum continuity and contiguity (i.e., allocating the same optical spectrum in all the links along the computed path), limitations of the considered VCSEL transmitters and coherent receivers (i.e., tunability of the nominal central frequency, supported symbol rates, modulation formats, FEC, …), the maximum reachable distance, potential signal degradations caused by accumulated physical impairments, etc. If the path computation succeeds, the output will be composed of: i) the set of nodes and links to be traversed, ii) the selected optical spectrum (i.e., either the central frequency and slot width for optical flexi-grid technology or WDM channels), iii) the pool of VCSELs in each module and sub-module in the PASSION transmitter device solution and their configuration (e.g., modulation format, FEC, etc.), iv) the receiver configuration. All the above configuration characteristics constituting the computed path are then passed to the T-SDN controller provisioning function. This is the responsible for the actual programmability to the underlying transport network infrastructure (i.e., optical switches and transmitter and receiver devices). To do that, the T-SDN controller relies on the SBI to enable the communication with such network elements which is described in the following sub-section.

3.3.2 SBI Requirements

Likewise, in the NBI, here it is described the requirements to be covered by the SBI leaving the specifics of final decided implementation with respect to the protocol and encoding in the next deliverables to be produced (e.g., D2.2). As discussed above, the SBI is the mean that enables the T-SDN controller communicating with the agents governing each network element and device within the PASSION transport network infrastructure. Currently, a myriad of protocol implementations and solutions are available such as REST API, NETCONF, Path Computation Element Protocol (PCEP) with Central Controller capabilities, etc. [Jan16][RMAR17]. Regardless of the selected protocol, the aim of the SBI is twofold: i) providing the network element programmability using an open API; ii) retrieve information of the status of the network elements and devices for computing paths relying in a well-defined and open API. It is worth mentioning the necessity of using open APIs which is seen as essential to instruct the configuration of the underlying infrastructure avoiding the cumbersome vendor lock-in. That is, regardless of the vendor device or equipment, the same SBI can be used to provide the configuration.

Focusing on the specific PASSION solution, the following parameters should be programmed via the SBI for the network elements and devices:

- PASSION Optical Switches: the SBI specifies unambiguously the inputs and outputs switch ports along with the optical spectrum features (e.g., nominal central frequency and slot width) of the optical connection being set up. This allows communicating the switch agent how configuring the internal components forming the optical switch architecture (e.g., WSSs) [D4.1].
- PASSION VCSEL Transmitter: the SBI indicates the module Id., sub-module Id. and number and identifiers of the VCSELs to be activated at the ingress endpoint for accommodating the targeted connection service. For each VCSEL element it is needed also to determine configuration parameters such as the modulation format, the optical power, the FEC, etc.
- PASSION Receiver: the SBI allows configuring the coherent receiver/s to be activated at the egress endpoint. This entails carrying the receiver identifiers along with the configuration parameters such as the central frequency, the modulation format, the optical power, etc.

The establishment of an optical connection is assumed successfully set up when all the involved network elements and devices respond via SBI that the configuration commands were properly attained. Once the T-SDN controller receives those response messages, the optical connection is stored in the Connection DB. This information is relevant to not only keep track of the existing connections along with their allocated resources at the T-SDN controller, but also may result very useful for providing advanced network functions targeting connection re-configuration / restoration and/or Operation, Administration and Management (OAM) functionalities.

3.3.3 Possible mapping in the emerging Standards

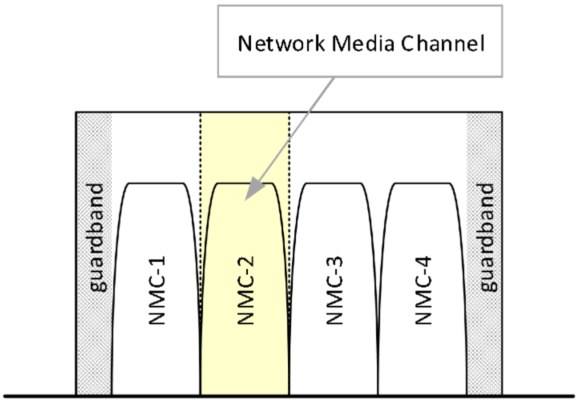
The possibility to map PASSION technology and related network architecture in the current standardization activity is analyzed in this paragraph. In particular, the reference SDN model considered here is the Transport API T-API model driven by ONF [GitHub].

This is a very important point, which may greatly enhance the PASSION impact from industrial point of view.

The network model proposed here addresses the provisioning of the network connectivity (end-to-end view). The proposed model abstracts the basic principles of the PASSION modular approach, so to be scalable with respect to the number of elementary clients that can be used as inputs for a sub-module, the multiplexing capability of a module, the number of polarizations and the number of fiber cores used. It is future proof for the possible evolution of the technology. Furthermore, the proposed model allows to represent the network connectivity according to a disaggregated Network Element (NE) view.

The multiplexing of the optical signals up to the transmission over the fiber belongs to the PHYSICAL MEDIA LAYER, i.e. optical signals are associated to a Media Channel layer as specified by ITU-T G.872. According to this view, each individual optical client (input to the S-BVT fundamental module) maps into an Optical Tributary Signal (OTSi, formerly named in ITU-T as «OCH», Optical Channel). As the OTSi is already covered in the T-API model for SBI purposes, it may require some extensions to include the provisioning of the PASSION-specific parameters. According to ITU-T G.872, each OTSi is guided to its destination by an independent Network Media Channel (NMC). The NMC may exist without an active OTSi (it's a potential allocation of the spectrum).

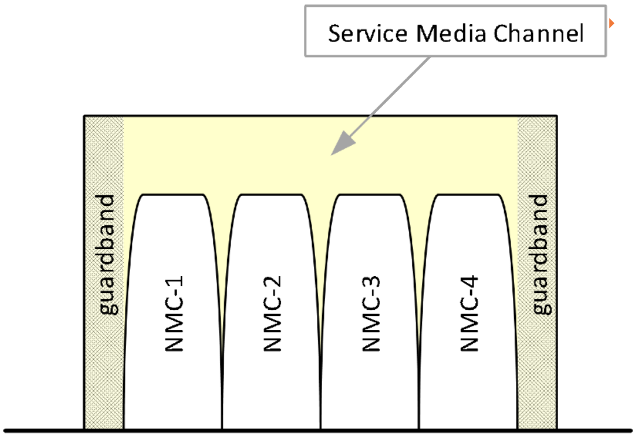
In this modeling, the Network Media Channel is defined as the fraction of spectrum associated to an OTSi without the guard band.



- Network Media Channel (NMC)
  - Continuous spectrum bandwidth used to represent the signal component generated by an optical transmitter
  - Define by center frequency and width
  - Do no require to be aligned to ITU grid but are technology dependent (channel power monitor and transmitter)
  - NMC have to be routed together (have to go to the same port when using WSS technology)
  - Could not overlap guard band

Figure 28 – Definition of Network Media Channel (NMC)

For the network connectivity, the T-API model is defining the concept of «Service Media Channel» (SMC), used also in parallel similar SDN project as for instance Facebook TIP. The SMC is essentially a logical container representing a part of spectrum encompassing one or more NMCs including a guard band at its boundaries.



Service Media Channel (SMC)

- Continuous spectrum bandwidth define by lower and upper frequency
- Could be aligned on ITU grid (could be 6.25 GHz)
- Include guard band (could be 6.25 GHz and it is technology dependent)
- SMC are indivisible when using WSS technology (port to port where the NMC have to be routed together)
- SMC could contain 0 to n NMC, not necessarily contiguous
- SMC could be requested at a domain level to represent the contiguous spectrum offered by an optical domain

Figure 29 – Definition of Service Media Channel (SMC)

An extension of TAPI Model should be introduced: For routing purposes, SMCs sharing the same routing over the same physical media (fiber) may be grouped together in a logical association named «Service Media Channel Assembly» - SMCA (Facebook TIP uses the term "SMC Group", SMCG, to express the same concept)

There are some constraints:

- On a transponder, an OTSi can be associated with one and only one NMC
- On a transponder, multiplexer or WSS, a NMC may belong to one and only one SMC
- On a transponder, multiplexer or WSS, a SMC may belong to one and only one SMCG

The overall network model is intended to represent a connection-oriented infrastructure:

- NMCs are defined regardless of the actual presence/activation of the associated OTSi, OTSi can be dynamically turned on or off
- SMC routing is defined regardless the actual association with the contained NMCs, i.e. it is possible to define the SMC routing also on an empty SMC. In the specific case of the PASSION project, the guardband used for the SMCs is the guardband defined for the overall C-Band spectrum
- SMCA routing is defined regardless the actual association with the grouped SMCs, i.e. it is possible to define the SMCA routing also on an empty SMCA
- The connectivity can be in principle setup via SDN Controller or Control Plane (GMPLS with appropriate extensions)

The overall model is intended to support dynamic bandwidth allocation:

- OTSi associated to a NMC can be dynamically activated/deactivated
- NMCs inside a SMC can be added/removed or enabled/disabled dynamically (same resulting effect as 1.)
- SMCs can be added/removed to/from a SMCA dynamically

Once the SDN Controller has setup the routing e.g. from A to Z, it will be possible to dynamically extend or reduce the allocated bandwidth operating only on 1./2. or 3. (or a combination of), without redefining the connectivity and the circuits obtaining a simpler and faster provisioning, expecting faster reactivity as per use cases requirements.

According to PASSION multiplexing structure, it is possible to define the corresponding Muxponder Model:

- Each individual port of the S-BVT fundamental module (VCSEL) maps into an OTSi+NMC at 50 Gb/s
- Each S-BVT fundamental module maps into an SMC encompassing the relevant 40 NMCs, with SMC maximum capacity of 2Tb/s
- Each S-BVT super-module maps into an SMCA encompassing the relevant 4 SMC from each fundamental model SMCA, with SMC maximum capacity of 8Tb/s
- The second polarization adds a second SMCA structured as described above. Each individual core of the multi-core fiber will then carry up to 2 SMCA, with OMS/OTS maximum capacity of 16 Tb/s
- The overall 7-core fiber will then carry up to 14 SMCA, with overall transport of 112 Tb/s

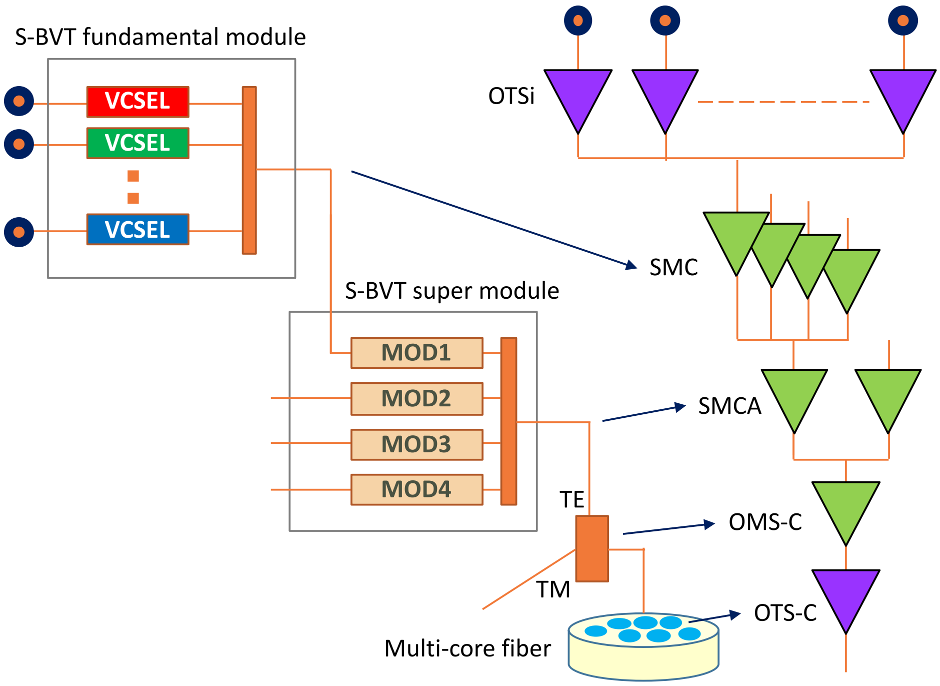


Figure 30 – Muxponder Model

To be noted: this schema applies to any implementation based on the same PASSION scheme. Different figures in term of individual ports/port rate, fundamental modules per chip, number of polarizations, number of cores per fiber will result in a different cardinality but the network model will remain the same providing a scalable, disaggregated architecture.

More in detail the proposed SMC Structure:

- Each SMC allocates 40 NMCs equally spaced
- The first NMC of each SMC is properly shifted in the spectrum so that the overlap of the 4 SMCs of the SMCA covers the full C-Band with 160 non-overlapping NMCs

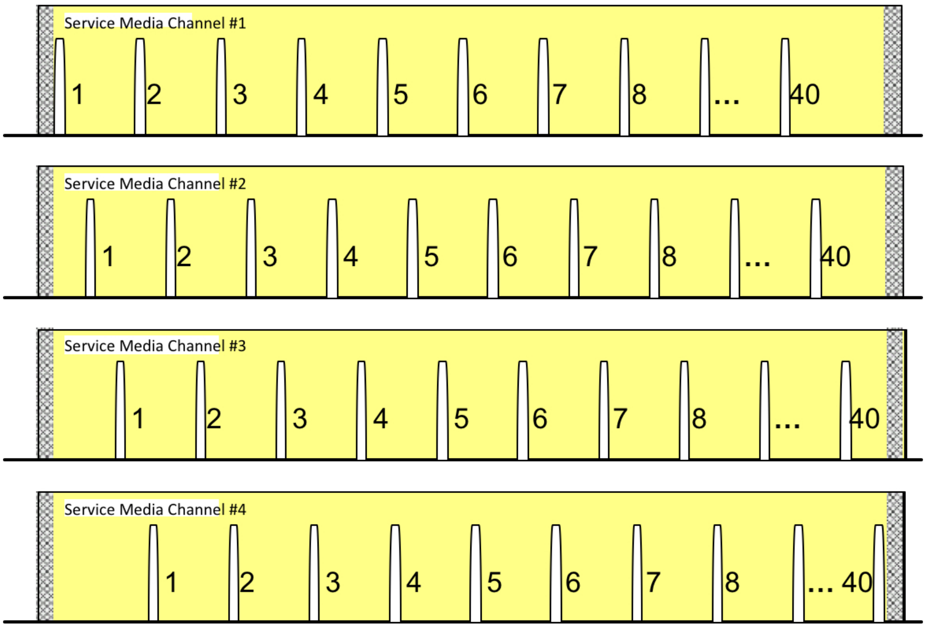


Figure 31– SMCA Structure

This approach is highly scalable, e.g.:

- The bandwidth of each NMC may be narrower
- The spacing between NMCs inside an SMC may be narrower
- The number of NMCs in a SMCA may be higher
- The number of SMCs in a SMCA may be higher
- The NMC width/spacing may be flexible (provided there's no NMC overlap in the resulting SCMA)

The resulting network architecture can be depicted as follow:

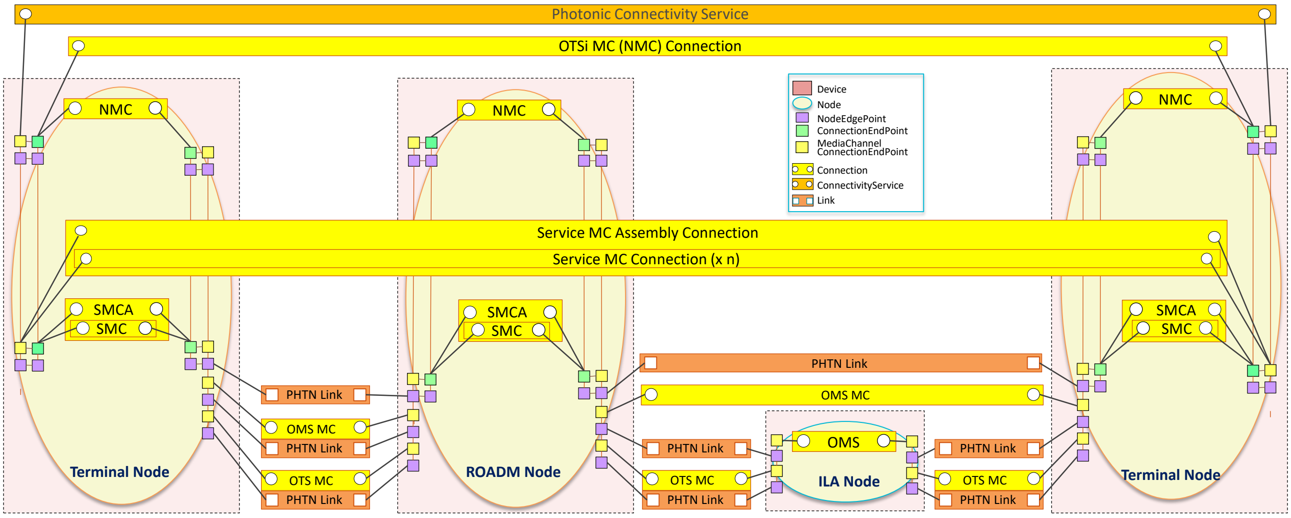


Figure 32 – Overall Network Architecture

Finally, some preliminary consideration on OAM issue is given: associating the SMC to the fundamental module enforces a more realistic network representation of hardware failures with a finer granularity. The failure of an individual fundamental module will affect only the relevant SMC and not the SMCs of the remaining modules

OSC can be exploited at several layers to carry the associated OH information:

- OH of the individual OTSi (OTSiA according to ITU-T definition): standard monitoring of the individual OTSi
- OH of an aggregation of NMC (NMCA): monitoring of individual/bundle of NMCs
- OH of an aggregation of SMC (SMCA): monitoring of the individual/bundle of SMCs
- OH of the OMS-C (Optical Multiplex Section in C-Band) carrying the SMCAs: standard OMS monitoring of the aggregated multiplex
- OH of the the OTS-C (Optical Transmission Section in C-Band) carrying the OMS-C: standard OTS monitoring

3.4 COST-EFFICIENCY REQUIREMENTS

PASSION solutions can be industrialized if they present a positive business case for network operators, so that total costs of ownership for transport metro network deployments are reduced by introducing PASSION concepts.

PASSION economic drivers will mainly come from IP transport network simplification by keeping IP routers just at the edge of the network (e.g HL1, HL2 and HL4) and using pure optical transport in between.

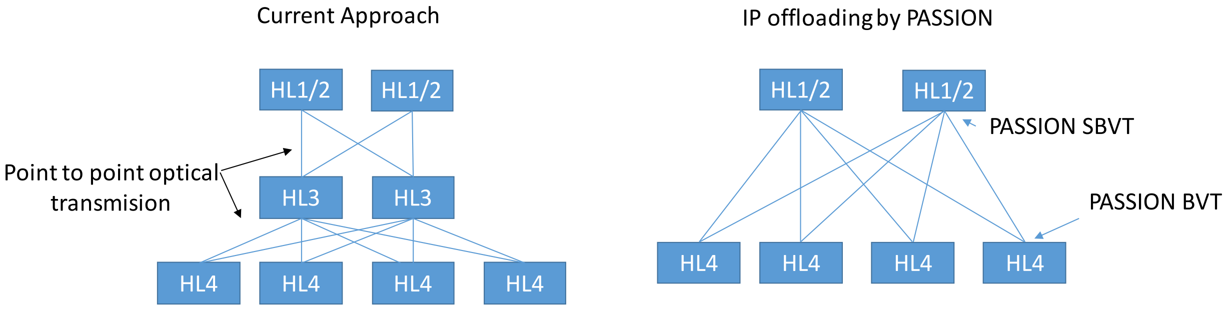
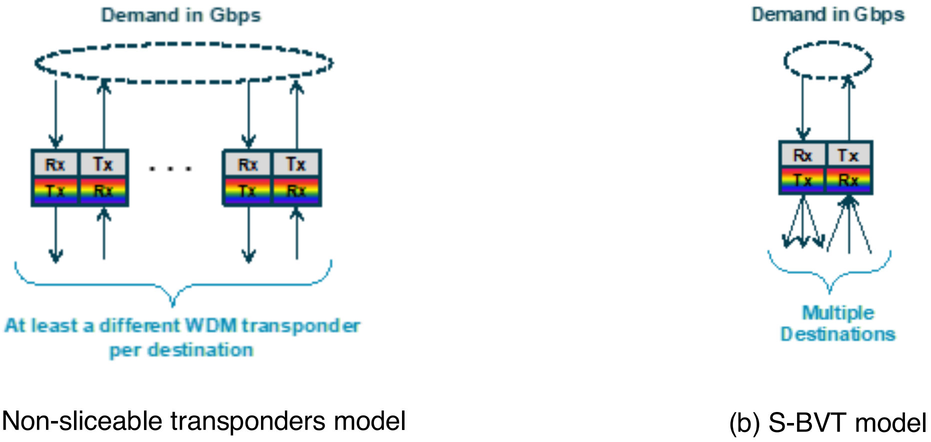


Figure 33 IP offloading by PASSION

The introduction of flexible and high capacity S-BVT supermodules at 8-16 Tb/s in metro core nodes (HL1 and HL2 of PASSION reference network) and S-BVT basic modules at 1-2 Tb/s at IP edge nodes (HL4) would support a flexible connectivity enabling elastic bandwidth on demand without intermediate optoelectronic conversions at HL3 level.

The key question to have a positive business case for PASSION is: how much should S-BVT supermodules and S-BVT basic modules cost to achieve a percentage cost reduction? To answer this question, two node models should be compared: (a) current model without sliceable transponders and (b) node with S-BVT. The main difference between both models is that the non-sliceable transponder model requires at least one interface for each destination, while SBVT transponder reuses the optical spectrum to transmit to multiple destinations.



(a) Non-sliceable transponders model

(b) S-BVT model

Figure 34 Models for the study with and without S-BVT

The aim of this work is to identify the target cost and energy consumption of 16-8 Tb/s S-BVT supermodules and 1-2 Tb/s S-BVT basic modules to reduce of a 30% transponder costs and energy consumption in the PASSION reference network scenario. This target cost and consumption should be calculated in relation with estimations for non-sliceable transponders. As already described in section 2.2, in PASSION a modular approach will be exploited: just a single 40-VCSELs module is designed and developed, so 4 identical modules are used to realize the 160-ch super-module achieving 8 Tb/s capacity. This modularity offers the ability to fabricate and stock only one module type, with a significant impact on the expected S-BVT final cost.

4 CONCLUSIONS

This report has described three use cases identified by the PASSION consortium as the right target scenarios to study the performance and techno-economic viability of PASSION technology developments. Once the use cases have been defined, a preliminary analysis of the traffic requirements of the three use cases was performed. The most demanding use case, use case #1, aims to deliver multi-service connectivity to one of the largest cities in the world. The analysis, based on a MAN topology supporting cellular networks, corporative and residential services, shows that the traffic to be carried by a core metro node in a large metropolitan area may get over 1 Pb/s if the oversubscription ratios in the residential access keep going down as it is the normal trend in the next years. The analysis also reveals the switching requirements at each aggregation level of a MAN in Tb/s (Table 7), the target supported lengths and hops for the optical channels required by the use cases (Table 4).

From these initial set of requirements for the target use cases and topology, expressed in terms of bandwidth, switching granularity, supported path distance and hops, control plane and cost-efficiency goals, this report has drafted a preliminary configuration for systems and subsystems in Section 3 which define a starting set of design targets for PASSION developments. A key element of the PASSION system is the S-BVT, as it will allow to obtain multiplex gains at the optical layer, off-loading the IP layer at HL3 as addressed in use case #2.

The S-BVT subsystem is based on PASSION technology exploiting VCSEL sources, each one operating at a different 25-GHz spaced WDM wavelength in the C-band (4 THz), directly modulated to obtain up to 50 Gb/s rate at a single polarization. This objective is pursued with a modular approach, as shown in Table 10 where the different capacities achieved at the level of sub-module, module and super-module are shown. Polarization-division multiplexing (PDM) and space-division multiplexing (SDM) are exploited to further increase the S-BVT subsystem capacity.

An SDN-based agile smart control plane is expected to enable the dynamic bandwidth allocation capability required to implement all the use cases and to take into account specific physical constraints imposed by the designed system and the network itself.

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6 ACRONYMS

AWG	Arrayed Waveguide Grating
BS	Base Station
BVT	Bandwidth-Variable Transceiver
CDN	Content Delivery Network
CO	Central Office
CORD	Central Office Re-architected as a Data Center
CWDM	Coarse Wavelength Division Multiplexing
DC	Data Center
DCI	Data Center Interconnection
DMT	Discrete Multi-Tone
DSLAM	Digital Subscriber Line Access Multiplexer
EON	Elastic Optical Networks
FTTH	Fiber to the Home
IT	Information Technologies
HLn	Hierarchy Level n
IP	Internet Protocol
IPTV	IP Television
MAN	Metropolitan Area Network
MCF	Multi-Core Fiber
MEC	Mobile Edge Computing
MEMS	Micro-Electro-Mechanical System
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONT	Optical Network Terminal
PDM	Polarization-Division Multiplexing
RN	Remote Node

SOA	Semiconductor Optical Amplifier
SBVT	Sliceable Bandwidth-Variable Transceiver
SDM	Space-Division Multiplexing
SDN	Software-Defined Networking
SDOT	Software-Defined Optical Transmission
SOI	Silicon On Insulator
SSMF	Standard Single-Mode FIber
SWT	Switch
UHD	Ultra-High Definition
VCSEL	Vertical-Cavity Surface-Emitting Laser
VPN	Virtual Private Network
WDM	Wavelength-Division Multiplexing