D2.4 - TECHNO-ECONOMIC ANALYSIS AND THE PASSION VISION ON FUTURE AGILE HIGH CAPACITY OPTICAL METRO NETWORKS

Project title	**Photonics technologies for ProgrAmmable transmission and switching modular systems based on Scalable Spectrum/space aggregation for future aglle high capacity metrO Networks**
Project acronym	**PASSION**
Grant number	**780326**
Funding scheme	**Research and Innovation Action - RIA**
Project call	**H2020-ICT-30-2017 Photonics KET 2017 Scope i. Application driven core photonic technology developments**
Work Package	**WP2**
Lead Partner	**TID**
Contributing Partner(s)	**VTT, OPSYS, EPIC, SMO**
Nature	**R (report)**
Dissemination level	**PU (Public)**
Contractual delivery date	**30/04/2021**
Actual delivery date	**30/04/2021**
Version	**1.0**

History of changes

Version	Date	Comments	Main Authors
0.0	17/11/2020	ToC agreed in plenary meeting	J.P. Fernandez-Palacios, D. Larrabeiti, G. Otero, P. Reviriego, J.A.Hernandez
0.1	13/04/2021	First draft distributed to contributing partners	J.P. Fernandez-Palacios, V.López D. Larrabeiti, G.

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0.2	27/04/2021	Second draft distributed	D. Larrabeiti, G. Otero, J.A. Hernández
0.3	28/4/2021	Contribution to chapter 2	G. Parladori, R. Morea, M. Zontini, R. Corsini, E. Beletkaia
0.4	29/04/2021	Final complete draft distributed for review	D. Larrabeiti
1.0	30/04/2021	Quality checked version	N. Tessema, N. Calabretta, P. Parolari, P. Boffi

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This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 780326.

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EXECUTIVE SUMMARY

D2.4 of PASSION project provides a techno-economic analysis of PASSION technology and draws conclusions about the specific use cases where PASSION can be a competitive solution for MAN networks. The methodology relies on the analysis of the so-called individual key building blocks (KBB) for the techno-economic analysis that were identified in MS11. Most of these KBBs are based on the Use Cases that have been identified during the project lifetime, which have been influenced by the development of the 5G standards and the latest market trends. The document proposes and develops methods to estimate the relative economic impact of each KBB of PASSION KBBs. Pay-as-you-grow and IP-offloading at intermediate hierarchical levels are identified as the most relevant features of PASSION toward a wide market adoption. Based on the analysis, a final section *PASSION vision on future agile high-capacity optical metro networks*, draws conclusions on the technoeconomic advantages of PASSION and its scope of application.

1 INTRODUCTION: METHODOLOGY FOR TECHNO-ECONOMIC ANALYSIS

The techno-economic analysis of an advanced high-capacity system such as the one envisioned in PASSION, oriented not for the current market and traffic needs, but for medium-term deployment, is complex. There are multiple factors not easy to forecast (market demand, traffic demand, novel competing technologies, new services enabled by the technology, impact of the 5G momentum, etc). The fabrication cost of the technology is a very relevant KBB, but from PASSION's perspective, there are many others more relevant than that one such as the size of the potential market niche. Moreover, the fabrication cost itself depends strongly on the amount of devices demanded by the market, namely transponders/transceivers and switches. Therefore, the use cases where PASSION technology provides an added value should be considered key building blocks at least as important as the cost of the hardware itself.

Use cases requiring mass fabrication, involving as many network nodes as possible, such as IP offloading, ultra-low latency 5G midhaul traffic transport, etc seem to be the real drivers for an eventual real deployment. However other use cases enabling new services such as the support of massive events with VR (Virtual Reality) or AR (Augmented Reality) have also an impact on revenue via new subscriptions or pay-per-view service. In this sense, a proper forecast of the traffic growth in the target exploitation timeframe is a fundamental parameter for the cost-effectiveness of the installation of variable bandwidth elements with more capacity than currently required. This indeterminism can be mitigated by a pay-as-you-grow business model, where the vendor takes part of the risk for the sake of fostering a technology shift toward variable-capacity photonics. Other key characteristics of PASSION such as programmability of the network can reduce OPEX, but competing Fixed Transceiver (FT) technology can also rely on SDN/NFV and hence, extra added-values need to be identified by means of use cases. What is clear is that multiple wavelength signaling and predictable (by simulation) QoT (Quality of Transmission) as enabled by PASSION modular approach can simplify control, planning and provisioning.

The approach followed in this deliverable consists of describing the main KBB identified by PASSION as the most relevant in a MAN, analyzing them and quantifying their relative impact whenever feasible. The comparison with commercial conventional fixed-optic technology is a frequent way to assess the practical viability of PASSION elements, as operators are reluctant to change unless the economic advantages are clear. Both the operator's and vendor's perspective of the impact of each KBB is sketched in a table at the end of each KBB section. Based on the analysis carried out in the KBBs, the last section gives the ***PASSION vision on future agile high-capacity optical metro networks*** where several techno-economic conclusions are drawn.

2 KBB#0: HARDWARE COST AND ASSOCIATED OWNERSHIP COSTS

A very important KBB is the cost of PASSION hardware, as the additional cost of configurable optics based on tunable VCSELs, should be paid off by the advantages of PASSION implementing the use cases. Indeed, PASSION architecture has been carefully designed to meet the target use cases, including capacity, control plane and worst path requirements, while keeping low cost and low power consumption. Programmability and modularity are key features enabling the requested dynamicity and scalability to achieve this goal.

The following table outlines a comparative discussion of the arguments and trade-off points selected for PASSION toward achieving flexible high capacity at low cost and energy consumption.

Table 1 PASSION hardware design decisions toward cost and power saving

		PASSION solution	**Other available solutions**	**PASSION solution features**
TRANSCEIVER	**TX**	2-Tb/s SiPh module based on multiple long-wavelength VCSELs	400-Gb/s single coherent transceiver in Si	•dense PIC integration •energy-saving and compact design •modular approach •up to 16Tb/s exploiting PDM •direct modulation •VCSEL low cost and power consumption
	RX	coherent receiver with monolithically integrated tunable laser		•polarization handling on chip •no isolator •non-hermetic packaging •monolithic etalon-free widely local oscillator •chip and/or wafer level testing without package
NODE	**16x16 space switch**	polymer PLC	•MEMS-based 16x16 switch •3D MEMS-based switch	•high port count •low cost and power consumption •low coupling loss •reduced number of simultaneous switches •no moving parts
	WSS	SOA-based gate switches: •monolythic in InP platform; •hybrid (SOA array in InP and AWG demux/mux in SiP)	LCOS technology based WSS	•fast switching time •lossless •no EDFA booster •reduced form-factor •energy-saving
	1x8 MCS	SOA-based integrated switch	discrete wavelength blocker	•monolithic integration •no EDFA booster •reduced form-factor •energy-saving
NETWORK	**Control plane**	Smart SDN control plane	Proprietary control plane schemes	• smart all optical IP offloading interconnecting HL4 and HL1/2 levels wherever feasible • sophisticated protection mechanisms, level-to-level rather than constrained to horse-shoe or ring, SBVT based multipath
	Data plane	All optical HL4-HL2/1 support	IP/WDM IP level aggregation	• all optical IP offloading interconnecting HL4 and HL1/2 levels is feasible in large MANs • traffic grooming at the optical layer thanks to sliceability • saving of cost and power in HL3 routers and transceivers

We decided to base the assessment of the cost of PASSION solution on the comparison with the current state of the art technology available on the market. As preliminary consideration, we need to highlight some relevant points.

i. PASSION only addresses optical technology. In order to be able to perform a fair comparison with current products we need to estimate the cost of associated electronics to complete the solution
ii. Considering the PASSION hierarchy and modularity, during the project development, we made choices on components definition in terms of size, granularity, etc. These choices were based on criteria not necessarily addressing the product/application optimization, but instead addressing feasibility, demonstrability within the project timeframe.
iii. The maturity level reached by the different building blocks is not homogenous and for the techno-economic analysis we need to refer to further evolution steps to foresee a “final” solution.
iv. PASSION technology is suitable for a modular and flexible node architecture. This characteristic allows tailoring the node configuration according to its role in the network hierarchy (from HL5 to HL1), optimizing the transmission capacity and the switching granularity at each stage.

Evaluation of DSP Block

Referring to point i. the following scheme (Fig. X) describes the functional architecture of a standard transceiver device, as for example 400-Gb/s single coherent transceiver in Si, which we are using as reference.

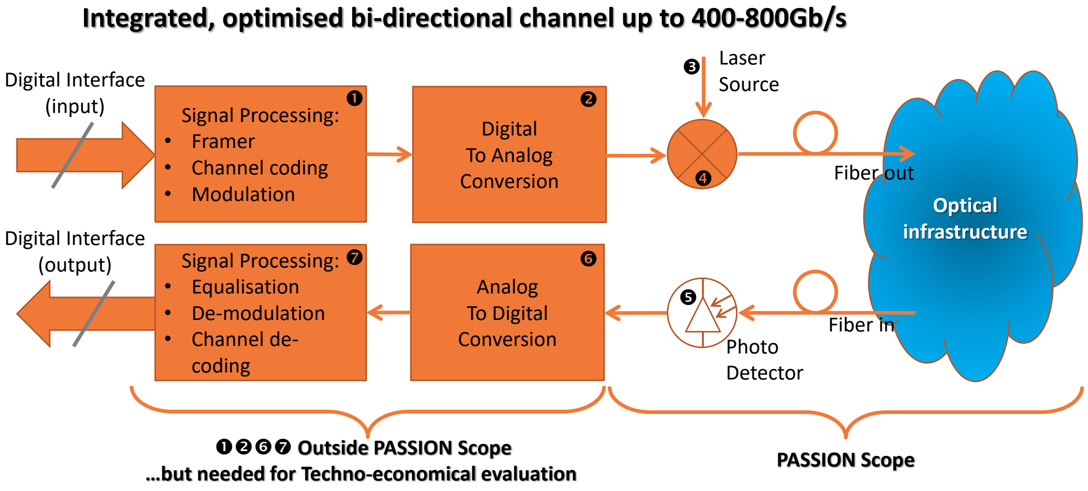


Figure 1 Standard Transceiver Structure

According to the proposed scheme ❶❷❻❼ are not developed within PASSION project but should be evaluated for a complete techno-economic analysis. Leveraging on the knowledge of the current DSP implementation for coherent transceivers we may estimate cost, complexity and power as follows:

Cost

Looking at the current 100G coherent transceiver, we estimate that the electronics account for 30% of the cost. Of course, this evaluation is not considering the huge NRE cost for coherent DSP development (estimated in 25-30ML€). As it can be observed in the figure, the DSP cost on the total transceiver cost decreases with Data Rate increase, representing about 22% of the cost for a 400G coherent transceiver.

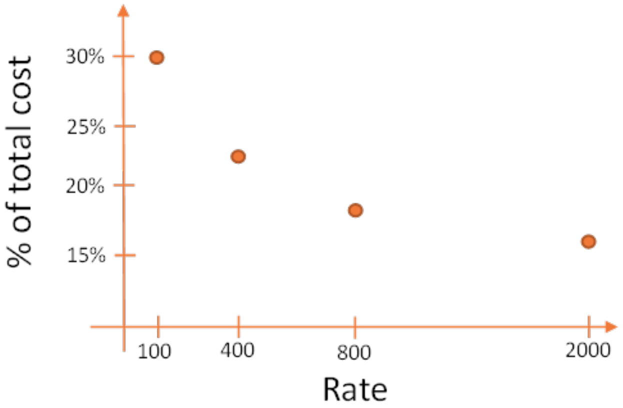


Figure 2 Percentage of DSP cost with respect to total cost of different rate [Gbps] transceivers.

Complexity

If we consider as a measure for DSP complexity the product of number of gates for the frequency, we estimate that it is more than double for the 400G coherent transceiver DSP with respect to the 100G one, while should be about a factor five for a foreseen 2T coherent transceiver (at the moment not commercially available).

Power

Looking at the current coherent transceiver power consumption figure, PASSION may scale accordingly.

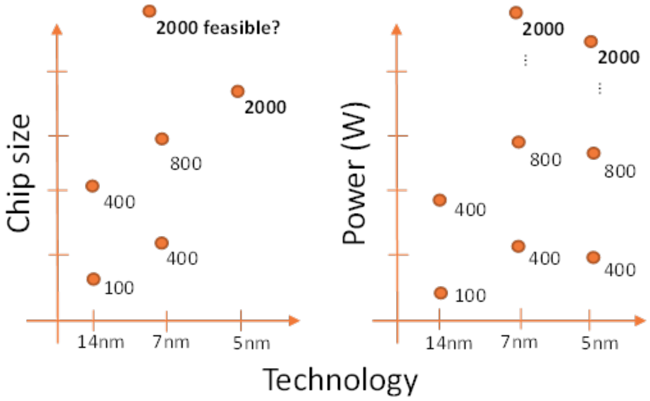


Figure 3 Chip size and power dissipation

Node issues

One of the most important characteristics of MAN traffic that is exploited in the design of PASSION's solution is the fact that most of the carried traffic is hierarchical. All the traffic is aggregated towards the core (HL1 or HL2) and distributed to the edges. The remainder intra-level traffic is estimated to be 10% in the traffic model based on data from operators. This fact makes it possible to introduce a number of architectural simplifications that have a relevant impact on the cost of the equipment and transmission resources required to deliver the services.

Starting from basic building blocks it is possible to figure out a suitable node architecture, or better a set of modular nodes, to build the network infrastructure for the identified use cases. Architecture, interface type, node capacity choices will determine the effectiveness of the overall solution. In a generic node, we can identify the following main subsystems:

1. I/O cards – it is possible to select different architectural choices:
    a. Transceiver based – transmitter and receiver are on the same submodule and supply symmetric bandwidth. It requires further integration steps with respect to the project target.
    b. Parallel Transmitter independent from Parallel Receiver. We push for parallelism and we can better address asymmetric bandwidth.
2. Central “matrix” in charge to add/drop and switch traffic – the project develops all these blocks, and according to the specific need of the node it is needed to choose the capacity and the granularity of:
    a. Aggregate/Disaggregate Switches
    b. Add/Drop
    c. Multicast switches
3. Mechanical Chassis – it is possible to identify different the size of the physical equipment depending on the characteristics of the node selected on the previous points.

In order to “navigate” different choices/alternatives SMO developed this table for the HL3 node architecture.

Table 2 Design alternatives for HL3 ROADM architecture

Granularity (Gb/s)	50	# of I/O Card (ref. ETSI 300mm)			HL3 Requirements		ROADM		
Rate (Gb/s)	Parallelism (λ)	Transceiver Option	Independent TX	Independent RX			Add/drop	λ-switch	Spatial Switch
500	10	1	1	1					
2000	40	currently not feasible	1	1					
8000	160	currently not feasible	2	2					
16000	320	currently not feasible	4	4	(x12)	→	(x1) about 10% local traffic	320x320	not required
112000	2240	currently not feasible	30	30					

Transceiver issues

One of the key questions to have a positive business case for PASSION is: how much should S-BVT super-modules and S-BVT basic modules cost to achieve a percentage cost reduction? Although this question will be dealt with in detail in another deliverable, in order to answer it 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 S-BVT transponder reuses the optical spectrum to transmit to multiple destinations. On the other hand, a pool of N small fixed transceivers (FT) or tunable transceivers (TT) may actually provide a similar service to an S-BVT. FTs are cheaper but have an implicit lack of flexibility allocating wavelengths through the network, and hence the blocking probability is expected to be very high. A pool of independent TTs does not have such limitation but it has a high cost and introduces a complex problem in terms of QoT estimation for the newly tuned wavelengths and for the existing circuits. Therefore, an arrayed system like PASSION, with predictable QoT can bring saving in terms of OPEX and enhanced reliability of circuits. This property of PASSION S-BVT adds on the advantage of having an integrated device, the S-BVT, with a density N times higher than with individual FTs or TTs.

In summary, the operator and vendor perspectives of the impact of this KBB are outlined in the next table. The combined impact is also outlined in the right-most column.

Table 3 KBB#0 impact

KBB	**Operator perspective**	**Vendor perspective**	**Overall impact**
Hardware cost: Hardware cost and associated ownership costs: design decisions	High impact PASSION makes available a huge flexible capacity at low cost, featuring sliceability, SDN, high capacity Compatibility with existing systems and disaggregation needs to be studied.	High impact. Massive demand can lower fabrication cost Need to review the current node architecture, optimizing the node composition according to the network hierarchy Big investments for further integration steps are needed	High impact Potential massive deployment of PASSION if the fabrication cost per Gb/s attained is lower than with FTs. A practical target is set as 2x the cost of a 400G fixed transponder for the 2T S-BVT.

3 KBB#1: ECONOMIC IMPACT OF USE CASE #1: COST-EFFECTIVE ULTRA-BROADBAND TRANSPORT AND EXPANSION IN A LARGE MAN: PAY AS YOU GROW

D2.1 described the target use cases of PASSION. Use case #1 is the main one as its aim is the transport of future traffic in a very large MAN. To this end, PASSION defined a reference topology, based on real sub-topologies, and estimated the traffic to be transported in the period 2025-2035 in this network. This way it is possible to estimate the amount of units necessary to transport all this traffic and compare its cost with FT-based DWDM schemes in the target time frame. This is the basic methodology designed for this use case.

Although PASSION has a modular approach, “pay as you grow” is not supported in PASSION by purchasing and plugging in new modules. The reason is that the basic module (2Tb/s) has too much capacity for the medium-term needs in a MAN. On the other hand, the granularity of 50Gb/s is adequate given the current rates of FTs and the cost of the hardware is expected to remain mostly flat with the number of wavelengths given the arrayed fabrication process. Therefore, the way PASSION will achieve the “pay as you grow” target demanded by operators is via a software license scheme: the progressive activation of transmitters and receivers by software, either remotely or locally. This approach has a number of advantages: there is no need to upgrade the hardware -just the software-, the possibility to move the purchased licenses to activate wavelengths from one transceiver to another (if the traffic distribution changes), no additional slots need to be occupied in the routers, enhanced reliability without physical replacement (damaged VCSELs may be backuped by others available in other wavelengths), etc.

The impact of this KBB is very high, given the number of cities and nodes in large cities. As depicted in Figure 4, in a mid-size country like Spain, a telecom operator may need tens of HL1/HL2 nodes, hundreds of HL3 and thousands of HL4. The amount of 2Tb/s SBVT and HL4 switches to be fabricated for each use case is a decisive factor driving the impact of the KBB.

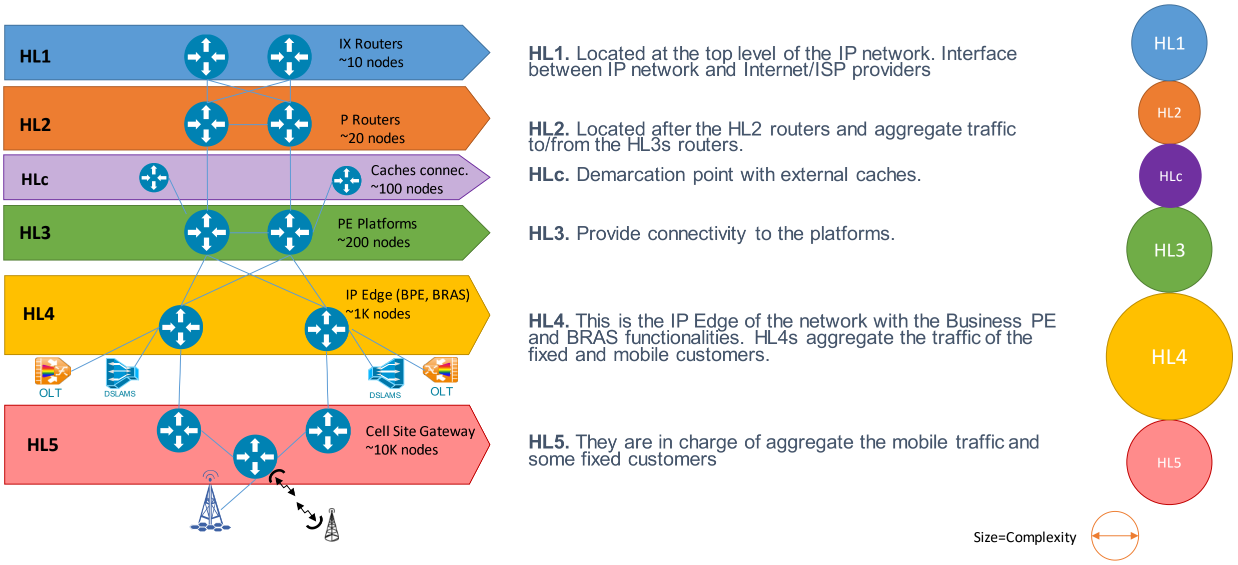


Figure 4 Amount of HLs nodes in Spain

The operator's and vendor's perspective of the impact of this KBB are summarized in the next table. The combined impact is also outlined in the right-most column.

Table 4 KBB#1 impact

KBB	Operator perspective	Vendor perspective	Overall impact
UseCase#1: Cost-effective ultra-broadband transport and expansion in a large MAN: Pay as you grow	High impact PASSION makes available a huge capacity that needs no hardware upgrade for a long time. High OPEX savings. Pay as you grow is a requirement.	High impact. All HL4s may require 2Tb/s transceivers. License cost for per-VCSEL activation may adapt to competitor's costs to induce a technology shift by operators. 380 2T SBVTs per large city.	High impact Potential massive deployment. CAPEX/OPEX savings for operators and high number of units can be sold. Fabrication and maintenance costs needs to be low enough for vendors to afford the pay-as-you-grow scheme.

The cost analysis in the next KBB applies the license-based pay-as-you-grow scheme hereby proposed. Operators pay per licensed lambda.

4 KBB#2: ECONOMIC IMPACT OF USE CASE #2: COST-EFFECTIVE ULTRA-BROADBAND TRANSPORT AND EXPANSION IN A LARGE METROPOLITAN AREA NETWORK: DYNAMIC CAPACITY ADAPTATION AND HL3 IP OFF-LOADING

As described in D2.1, the purpose of this use case is taking advantage of the fact that most traffic (90%) is hierarchical traffic (uplink aggregation and downlink distribution) to optimize its transport through the MAN. The idea is aggregating at the electronic layer of HL4s the traffic from their HL5s and perform an all-optical transport lightpath from each HL4 nodes to the closest HL1/2 by-passing HL3s at the optical layer. HL4s are equipped with 2T S-BVTs and HL1/2 are equipped with either 8 or 16T S-BVTs (the latter considers exploiting dual-polarization multiplexing). HL3 IP layer is only used for non-hierarchical traffic and to add/drop its local traffic.

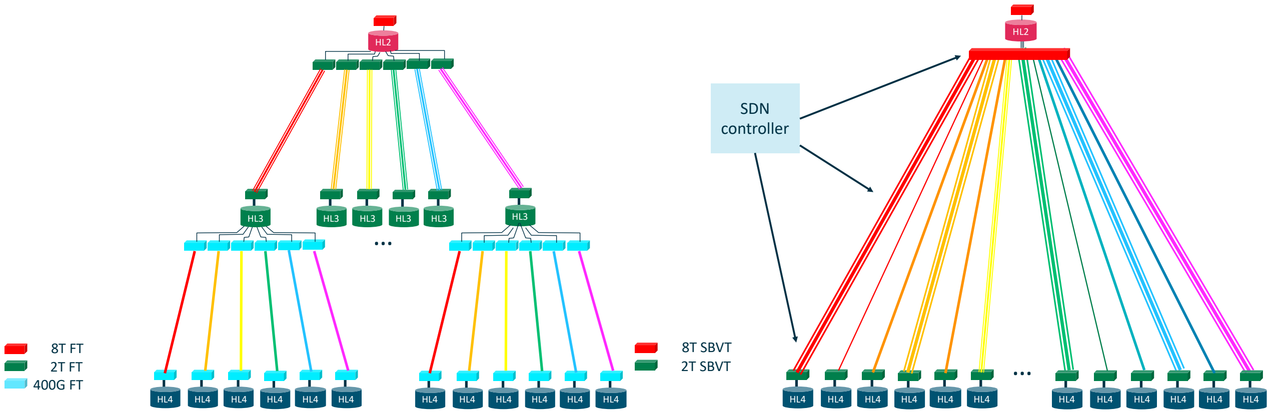


Figure 5 IPoverWDM vs HL3 IP-Offloading

Is should be noted that this does not mean that HL4-HL4 or HL4-HL3 is not supported. As a matter of fact, this non-hierarchical traffic can be carried without the need for additional transceivers. That is, in this use case we shall not make use of the sliceability property of S-BVTs that may be used for connecting neighboring-HL4s or for HL4-HL3 links to carry non-hierarchical as illustrated in Figure 6, because according to Telefonica's estimation the fraction of this traffic is under 10% and could be left out of the calculus to provide a gross estimate of infrastructure cost [D2.1].

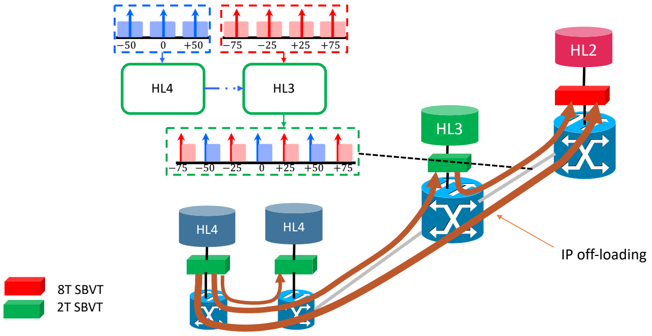


Figure 6 Connectivity options provided by sliceability in the MAN stemming from an HL4 node

In past preliminary analysis this use case was regarded as medium impact. However, the detailed cost analysis which follows reveals that this use case has a high economic impact due to the savings in intermediate FTs at HL3. The methodology designed to estimate this saving is outlined in Figure 7. The procedure makes use of the Passion techno-economic tool to be released in Passion deliverable D6.7 *Guidelines and software tool for Metro network design based on the PASSION architecture*. This tool takes an input: (1) the network topology, (2) the Year-0 (Y0) traffic demand plus a forecasted yearly growth rate , (3) a list of device's unitary costs and (4) a deployment/planning strategy (*IPoverWDM*, *IPoWDM_bp* and *Passion*, as defined below). In our comparison, we shall use the PASSION reference topology [D2.1] assuming an unlimited number of fibers among nodes, will assume a demand in Y0 with a normal distribution across HL4 nodes and will use current market price estimates for operators.

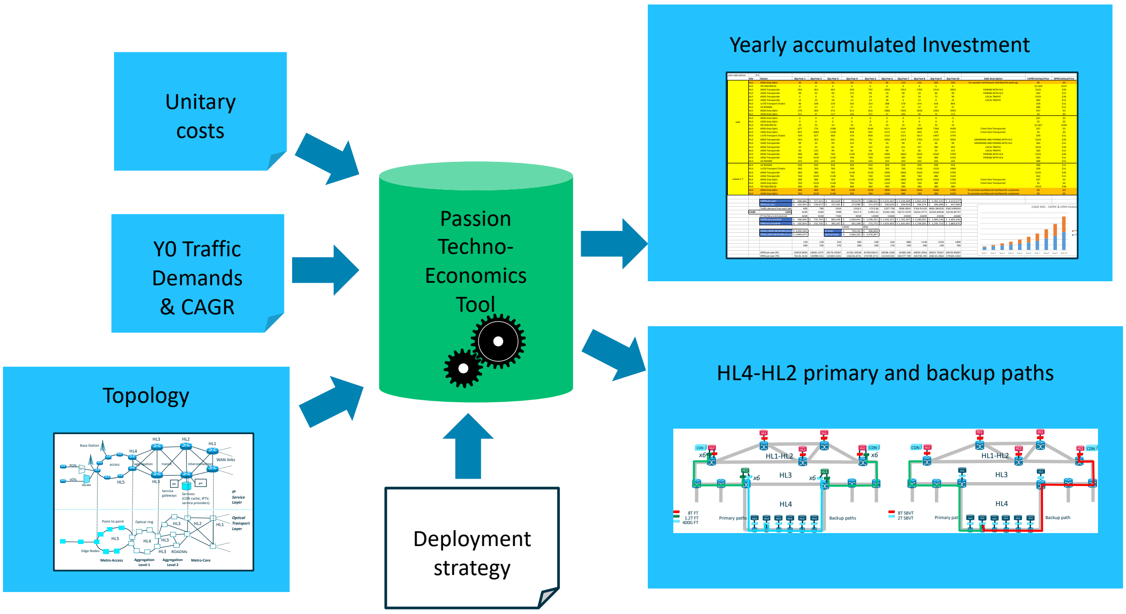


Figure 7 Tool and data used in the analysis cost of the different network planning strategy

The tool generates all the optical channels between each HL4 router and the closest HL1/HL2 router required to fulfill the traffic demand and provides an inventory of devices to be deployed according to the selected planning strategy, and a cost breakdown for the accumulated investment through the years.

PASSION MAN topology review

It is worth recalling the hierarchical structure of PASSION Metro topology of reference, organized into three main levels, namely HL4, HL3 and HL1/2 with the following features:

- 6 HL1/2s, with average nodal degree of 6.0
- 33 HL3s, with average nodal degree of 3.42
- 380 HL4s, with average nodal degree of 2.50

Essentially, there is one HL1/2 per 5.5 HL3 and 63.33 HL4s on average. Also, there is one HL3 per 11.51 HL4s.

Network planning strategies

In order to show the economic feasibility and benefits of the PASSION solution, this will be compared with two classical network dimensioning strategies. In concrete, the scenarios under study consider:

1) IPoverWDM strategy with 400G Fixed Transponders (FT) and IP traffic grooming at the HL3 nodes (IPoWDM_gr).

In this scenario, HL4 nodes are equipped with small IP routers and connected with 400G Transponders toward the next hierarchical layer, i.e. HL3. Here, all HL4 traffic is collected and aggregated together to further be forwarded toward the HL1/2 layer. Such HL3 traffic grooming is employed by medium-size IP routers at the HL3 nodes. In addition, 1/2 traffic oversubscription is assumed thanks to the statistical multiplexing benefits of traffic aggregation.

This dimensioning strategy applied to the PASSION topology implies that each HL3 node collects the traffic of 11.51 HL4 nodes on average (plus its local traffic) and uses IP grooming to forward only 50% of the peak traffic towards the next hierarchical level HL1/2. Each HL1/2 node receives on average the amount of traffic of 5.5 HL3 nodes. Essentially, the IP routers at the HL3 and HL1/2 must have sufficient capacity to handle about 11-12x the traffic of an HL4 IP routers and about 32x the traffic of an HL4 IP router (one HL1/2 per 64 HL4 nodes with 50% oversubscription at HL3). In addition, both HL4, HL3 and HL12 nodes are dimensioned to be equipped with sufficient 400G FT to cover with peak traffic values.

2) IPoverWDM strategy with 400G Fixed Transponders and optical-bypassing at the HL3 nodes (IPoWDM_bp).

In this scenario, HL4 nodes are equipped with small IP routers and connected with 400G FT directly toward the HL1/2 nodes, thus by-passing all-optically intermediate HL3 nodes. HL3 nodes are then equipped with small IP routers acting as HL4 nodes, sending their traffic directly toward the HL1/2.

This dimensioning strategy applied to the PASSION topology implies that each HL1/2 receives the peak traffic of about 63-64 HL4s and another 5.5 HL3s. Cost savings are expected with respect to solution #1 since HL3 nodes are a lot simpler than the previous case, both in terms of IP routers and number of downstream and upstream transponders at the HL3s.

3) PASSION solution with 2T-8T-16T S-BVTs with 50Gb/s lambda granularity and optical-bypassing at the HL3 nodes (PASSION).

This scenario considers the PASSION solution whereby all nodes are equipped with multi-Tb/s S-BVTs in a pay-as-you-grow fashion, that is, only the necessary number of 50G channels (VCSELs) are activated to fully cover the traffic requests of the lightpaths. Intermediate HL3 nodes are all-optically by-passed like in strategy #2; these HL3s are dimensioned as HL4 nodes again, with smaller IP routers and less transponders.

This dimensioning strategy applied to the PASSION topology implies that each HL1/2 receives the peak traffic of about 63-64 HL4s and another 5.5 HL3s. Cost savings are expected with respect to solution #1 since HL3 nodes are a lot simpler than the previous case, both in terms of IP routers and number of downstream and upstream transponders at the HL3s. In addition, extra cost-savings are expected thanks to the pay-as-you-grow strategy where peak traffic is provided in steps of 50G capacity units rather than 400G units as it is the case of FTs. In addition, the cost of grey optics is avoided in this third solution since the S-BVTs are directly plugged to the IP routers.

Traffic assumptions and cost estimates

Two traffic scenarios are assumed for a 10-year period CAPEX analysis:

- Year 0 (Y0) traffic of 150G offered per HL4 and 40% Compound Annual Growth Rate (CAGR)
- Year 0 (Y0) traffic of 600G offered per HL4 and 15% CAGR

Concerning traffic costs, Table 5 summarizes the numbers used in the analysis regarding optical equipment, IP routers, transponders and grey optics. Normalised cost units (CU) have been assumed for privacy reasons. The value of 1 CU is equal to the cost of a 10G grey transceiver, in line with the techno-economic studies of other past projects (e.g. 5G PPP H2020 Metrohaul).

Table 5 Equipment used for the techno-economic studies and their cost.

Item	**Description**	**Normalised Cost Units (CU)**
IP Routers		
Small	Intended for HL4 nodes (and HL3 nodes in bypass scenarios)	250.00
Medium	Intended for HL3 nodes in IP grooming scenarios	1666.67
Large	Intended for HL1/2 nodes	2500.00
Photonic mesh		
1D-ROADM	ROADM degree node. A node with degree 6 must multiply this amount with 6x	88.96
WDM Transponders		
Chassis	Can allocate up to 4 transponders	28.66
100G FT	Fixed transponder	62.50
400G FT	Fixed transponder	100.56
2T S-BVT	Passion’s VCSEL-based SBVTs. Cost estimated as twice the cost of a 400G Fixed Transponder	201.11
Grey optics		
100G grey transceiver		3.33
400G grey transceiver		36.96

Figure 8 shows the comparison between the three strategies on a 10-year period. As shown, the PASSION architecture achieves large cost savings, not only the first year Y0, but also on the other ones too. In particular, the TCO is 0.22 Million CU for Passion on Y0, while classical IPoverWDM implementations with 400G FT comprises 0.41 MCU and 0.34 MCU respectively. Even larger CAPEX savings are observed in Y9, where the cost of Passion architecture is between 1/3 and ¼ than that of classical IP over WDM strategies. Essentially, the cost savings are achieved thanks to the 50G granularity traffic dimensioning in the pay-as-you-grow license model for the S-BVTs, but other important savings are obtained thanks to the no-need for grey optics and lighter IP routers in the HL3s (IP offloading). Interestingly, while traffic increases by 40% each year, CAPEX increases 15.20% and 13.72% for the two classical IPoverWDM with grooming and bypassing respectively. The PASSION solution only increases at a CAPEX rate of 7.6% in this scenario.

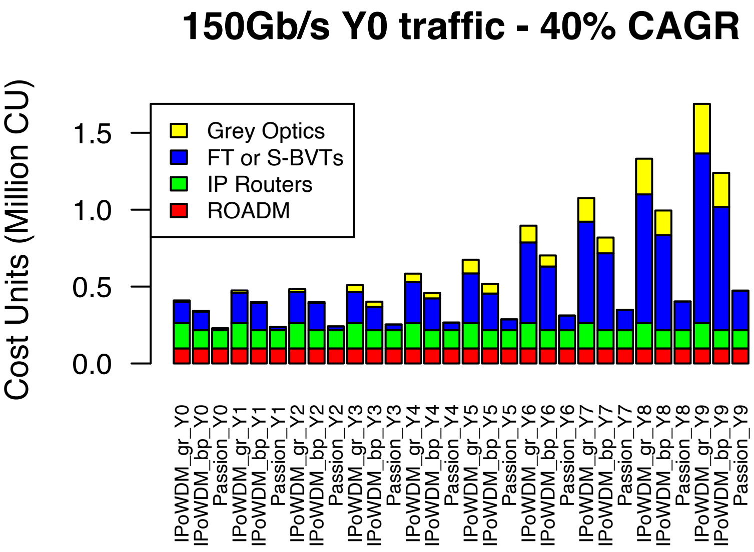


Figure 8 Scenario #1 with 150Gb/s Y0 traffic per HL4 and CAGR = 40%

Figure 9 shows the second scenario where Y0 offered peak traffic is 600 Gb/s per HL4 node and the annual traffic growth is 15%. As shown, again the PASSION architecture is a lot cheaper in all cases than the two classical IPoverWDM dimensioning cases. In particular, the TCO is 0.26 Million CU for PASSION on Y0, while classical IPoverWDM implementations with 400G FT comprises 0.59 MCU and 0.46 MCU respectively. Larger CAPEX savings are observed in Y9, where the cost of PASSION architecture is between 1/2 and 1/3 of the one of the classical IP over WDM strategies. Again, cost savings are mainly achieved thanks to the 50G granularity traffic dimensioning in the pay-as-you-grow license model for the S-BVTs, but savings are also obtained thanks to the no-need for grey optics and lighter IP routers in the HL3s (IP offloading). Again, while traffic increases by 15% each year, CAPEX increases 7.8% and 7.4% for the two classical IPoverWDM with grooming and bypassing respectively. The PASSION solution only increases CAPEX at a rate of 4% in this scenario of 15% traffic annual growth.

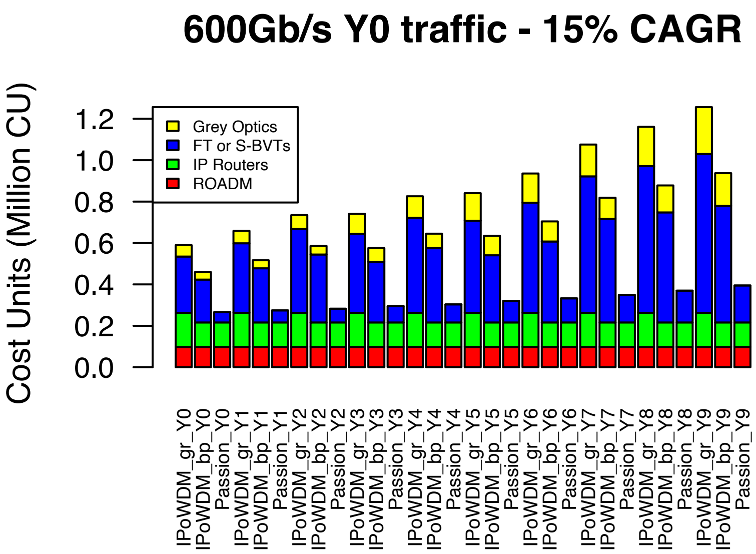


Figure 9 Scenario #2 with 600Gb/s Y0 traffic per HL4 and CAGR = 15%

In conclusion, the PASSION architecture is feasible from a techno-economic perspective as it achieves the objective of 40% CAPEX reductions to justify a technology shift from the classic paradigm. Also, it shows scalability in terms of moderate cost increase per year for different traffic growth cases (15% and 40% CAGR). In outline:

Table 6 KBB#2 impact

KBB	**Operator perspective**	**Vendor perspective**	**Overall impact**
UseCase#2: Cost-effective ultra-broadband transport and expansion in a large Metropolitan Area Network: Dynamic capacity adaptation and HL3 IP off-loading	Very High impact IP offloading can yield savings of tens of 10Tb/s routers per big city. However, the saving in FTs both downlink and uplink at HL3 is very high.	High impact. Tens of HL3s per large city. 380 2T SBVTs and HL4 nodes per large city.	High impact The cost reduction of IP equipment does not justify the investment in PASSION S-BVTs per-se, but the saving in FTs does. 40% CAPEX reduction achieved. Great scalability: moderate cost increase with traffic growth. Potential massive deployment.

5 KBB#3: ECONOMIC IMPACT OF USE CASE #3: INTERCONNECTION FOR DISTRIBUTED COMPUTATION SITES WITHIN THE MAN: EFFICIENT CDN RESTAURATION SCHEMES AND TRAFFIC OVERFLOW

The analysis of this KBB is the most advanced one, so we include more detail than in other KBBs. Two sub use cases are considered in this KBB, whose purpose is saving IT and communication resources: (1) Management of overflow traffic of Edge Computing in the MAN with PASSION technology, and (2) Optical Interconnection of CDN (Content Delivery Networks) Caches with SBVTs featuring Restoration.

5.1 MANAGEMENT OF OVERFLOW TRAFFIC OF EDGE COMPUTING IN THE MAN

Dense metropolitan areas are responsible for the majority of the traffic growth in telecom operators. The focus of PASSION is to develop new photonic technologies for supporting agile metro networks and enabling capacities of Tb/s per channel to deal with such traffic increment.

Scaling the deployment of edge computing to all Central Offices (Cos) to support ultra-low latency applications is complex and costly. Dimensioning data centers(DCs) to meet blocking probabilities as low as 10^{-6} [Arno2012] requires taking full advantage of state-of-the-art distributed computing capabilities over the MAN to keep a high CPU utilization. To this end, several DC interconnection strategies are feasible. However, a strict control of latency is required in order to achieve service response times within the limits imposed by the target applications.

One way to reduce latency is by offloading edge computing traffic from IP and using direct optical channels to interconnect DCs according to the demand. The switching and multiplexing technology developed by PASSION aims to enable such low-latency jitter-free inter-data center communication, among other applications. Since many MANs have edge-to-core distances below 40 Km (i.e. 200 µs of one-way latency over optical fiber) the distribution of edge computation beyond the Central Office (CO) over other MAN DCs can be acceptable for most applications. This makes it possible to use several strategies.

The new metro network infrastructure defined for the PASSION project has two key components: (1) the Sliceable Bandwidth Variable Transceivers (S-BVT) and (2) Pb/s optical switches. The effort is devoted to the development of the essential photonic building blocks, but at the same time is looking for a solution that fits within the network operator. Due to space and cost constraints the CO is envisaged to host a limited amount of resources and resort to other data centers within the latency budget to provide very low blocking probabilities. Providing an optical solution based on SDN programmability, an S-BVT can provide a dynamic multi-destination Tb/s flows that can be adapted to deal with the computing demands overflown from the edge data centers are feasible by using a single transceiver per node.

Pairing same-level DCs (i.e. pair-wise strategy A in Figure 10), has three relevant advantages over hierarchical (strategy B): (1) the latency for overflown traffic is not substantially larger than for locally served traffic; (2) the amount of optical channels is fewer in A (N/2) vs (N) in B, where N is the amount of Cos; (3) the optical channels required to interconnect two DCs are also shorter in A than in B. These advantages make, in principle, A preferable to B. However, strategy A considers the provisioning of permanent physical infrastructure to cope with the overflow traffic. Conversely, Sliceable Bandwidth Variable Transceivers (S-BVT) can change this situation since dynamic temporal circuits can be provisioned for the overflown traffic over already existent links. The flexigrid channels are set up by means of an SDN control plane yielding sub-second control of switches [Martinez2019] and enabling end-to-end set up times in the order of units of seconds.

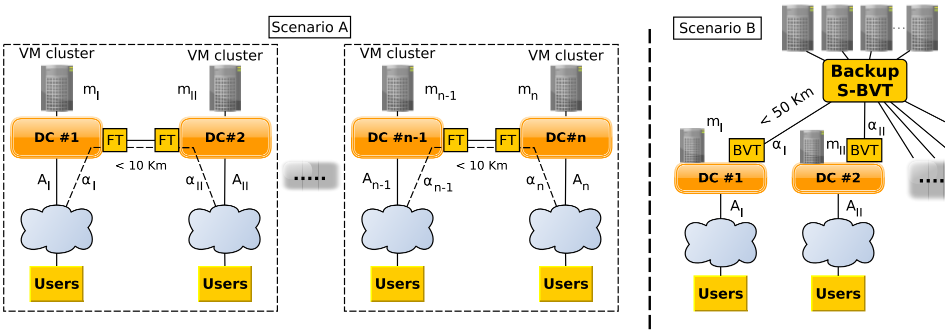


Figure 10 Overflow strategies: Pairwise (A) and Hierarchical (B)

The methodology is based on queuing theory. Consider the two approaches for the target use case depicted in Figure 10. **Strategy A** represents a group of n DCs located at n metropolitan districts (approximately 200000 inhabitants). These implement a pair-wise protection system where both can send overflow traffic to one another. **Strategy B** shows a centralised backup system in which a S-BVT copes with the overflow traffic from all the local DCs.

Strategy A: consider that 1% of the population (2000 inhabitants) are subscribed to a service that is active 4 times a week per user, e.g., immersive live sports streaming, generating $2000 \cdot 4 = 8000$. Assuming exponentially distributed service times with a mean of 60 mins, the total offered traffic to each local DC is $A_i = 47.619$ Erlangs for $i = \mathrm{I}, \mathrm{II}, \dots, \mathrm{n}$. Considering Poissonian arrival times, the i-th local DC's blocking probability is given by the Erlang B expression $B_i = E(m_i,\ A_{Total})$, where m_i is the maximum number of available resources, e.g., virtual machines or processing units, at the local DC i ,and A_{total} is the aggregated offered traffic to each DC. This is the combination of the city users' traffic (A_i) and the overflow traffic coming from the paired fixed transceiver (FT) of a neighbor city (α_j) (see Figure 10 left). Note that A_i is poissonian while α_j follows an interrupted Poisson Process (IPP) and the blocking probability experienced by the aggregated 20entraliza greater than it would be if a Poissonian source was assumed. Consequently, we shall use the *Fredericks-Hayward* approximation to characterize the aggregated traffic and scale it by its peakedness factor. Let r be the peakedness factor of one blocked arrival process, defined as the variance ν to mean α ratio of the occupancy: $r = \frac{\nu}{\alpha} = \frac{\sum_i \nu_i}{\sum_i \alpha_i}$, where α_i and ν_i are the amount and variance of the overflow traffic, respectively. Then, the blocking probability for each local DC follows

$$\boldsymbol{B_{LocalCDN} \approx E\left(\frac{m_i}{r}, \frac{A_{Total}}{r}\right)} \quad (1)$$

Accordingly, the variance of each blocked flow can be computed via the Riordan's formula:

$$\boldsymbol{\nu_i = \alpha_i \cdot \left(1 - \alpha_i + \frac{A_i}{m_i + 1 - A_i}\right)} \quad (2)$$

Focusing on DC pair $1 - 2$ in Scenario A, we know that $A_{I,Total} = A_I + \alpha_{II}$. Also:

$$\boldsymbol{\alpha_{II} = B_{A_{II}} \cdot A_{II,total} = B_{A_{II}} \cdot (A_{II} + \alpha_I)} \quad (3)$$

Targeting a total blocking probability $B_{total} = 10^{-6}$ (considering that we want a similar service availability as a tier 4 DC) and assuming that the overflow probability is equally distributed between the members of the pair, we get $B_{A_I} = B_{A_{II}} = \sqrt{B_{Total}} = 10^{-3}$. Substituting in Eq. (3) the target blocking probability and assuming $A_I = A_{II} = 47.619$ Erlangs, the overflow 21entraliza $\alpha_{II} = \alpha_I = 0.00477$ Erlangs. Therefore, the total offered traffic to each DC is $A_{I,Total} = A_{II,Total} = 47.6667$ Erlangs and the blocking probability is

$$\boldsymbol{1 \cdot 10^{-3} = E\left(\frac{m_i}{r}, \frac{47.6667}{r}\right)} \quad (4)$$

which is a two-variable equation in r and the number of resources m_i. Solving via bisection method, we obtain a peakedness factor of $r = 1.0021$ and a number of resources at each local DC of $m_i = 70$.

Strategy B: blocked traffic from the local DCs is steered towards the backup DC located at the MAN core. We target the same overall blocking probability, i.e., $B_{Total} = 10^{-6}$ but now it is distributed in a different way. Since in this case we have a backup infrastructure, we relax the blocking probability at the local DCs to be $B_{LocalCDN} = \sqrt[3]{B_{Total}} = 10^{-2}$. Assume that the backup DC driven by the S-BVT is hopefully more reliable than the local DCs, achieving a blocking probability of $B_{Backup} = \frac{B_{Total}}{B_{LocalCDN}} = 10^{-4}$.

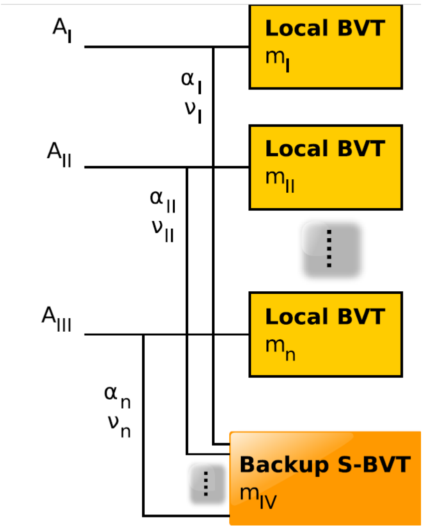


Figure 11 Traffic overflow in Scenario B

Since now the only offered traffic to each local DC is the poissonian traffic, the blocking probability is: $B_{LocalCDN} = 10^{-2} = E(m_i, 47.619) \leftrightarrow m_i \geq 61$. That is, we need only 61 resources to guarantee the same blocking probability as in Scenario A. The intensity of the overflow traffic, i.e., the blocked 21entraliza each local DC can be expressed as $\alpha_i = B_i \cdot A_i = 0.4762$. Assuming a number of cities of $N_C = 30$, the total overflow 21entraliza given by $A_{Overflown} = N_C \cdot \alpha_i = 14.286$ Erlangs. Since all of the overflow 21entraliza non poissonian, we shall apply again Eq. (1) and (2) so as to find the number of resources needed to achieve the target overall blocking probability. After computing the peakedness 21entraliz $r = \frac{N_C \cdot \nu_i}{N_C \cdot \alpha_i} = 3.7289$, the blocking probability is

$$\boldsymbol{B_{Backup,SBVT} = E\left(\frac{m_{S-BVT}}{3.7289}, \frac{14.286}{3.7289}\right) = 10^{-4}}, \quad (5)$$

yields $m_{S-BVT} = 53$. We now compare the cost of both approaches for the same offered traffic to each local DC and the same overall blocking probability. Let C_{Local} and C_{Core} be the cost of a resource in a local DC and in the core DC driven by the S-BVT, respectively. Then, the total cost of each scenario in terms of computational resources are

$$\boldsymbol{Cost_A = C_{Local} \cdot N_C \cdot m_{iA} = C_{Local} \cdot 2100} \quad (6)$$

$$\boldsymbol{Cost_B = C_{Local} \cdot N_C \cdot m_{iB} + C_{Core} \cdot m_{S-BVT} = C_{Local} \cdot 1830 + C_{Core} \cdot 53} \quad (7)$$

(left) plots the total cost of both scenarios, for different target blocking probabilities, assuming a normalized cost of resources $C_{Core} = C_{Local} = 1$. Additionally, we show the relationship between the costs of both 22entralizati: $(Cost_A - Cost_B)/Cost_A$ (see right axis green line with circles). Continuing our numerical example, total saving percentage for our target blocking probability is 8%. It is important to note that the conclusion drawn is only true for certain values of the total blocking probability. Close inspection of Figure 12 (left) reveals that Scenario B is better than Scenario A in terms of cost, for total blocking probabilities below $12.7 \cdot 10^{-3}$. Conversely, Scenario A remains better for blocking probabilities above that threshold. Finally, Figure 12 (right) shows that both the gap between the cost of both approaches and the threshold that makes Scenario A or B a better choice are hugely dependent on how the blocking probabilities are divided between tiers. While Figure 12 (left) represents the case in which the backup DC has a lower blocking probability, (right) shows the behaviour of the system when $B_{LocalCDN} = B_{Backup} = \sqrt{B_{Total}}$. In this case, the achieved savings with Scenario B are never above 1%.

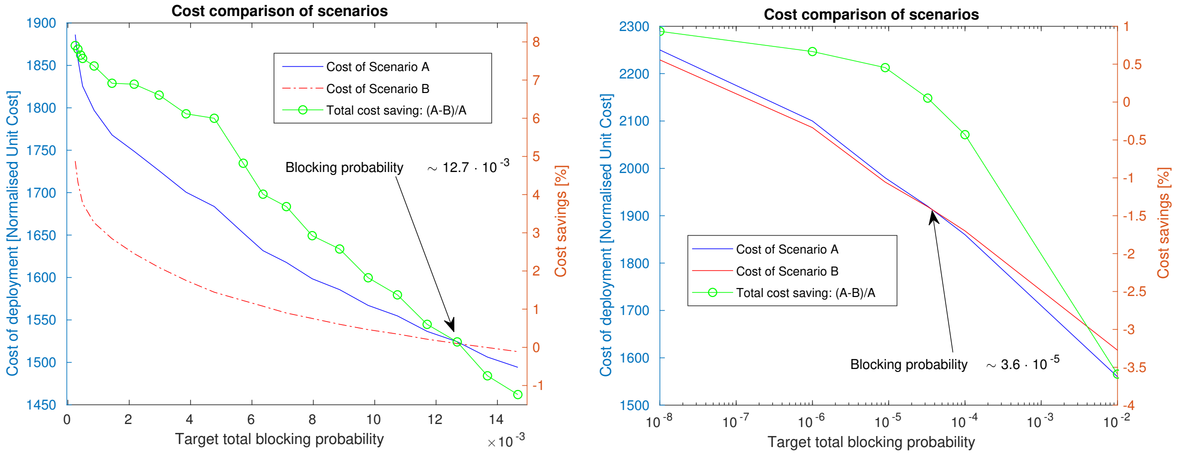


Figure 12 Cost simulation for different values of the target blocking probability. Left: unbalanced A, Right: balanced A

The figures reveal that a proper distribution of computing resources in the centralized overflow approach can reduce the IT infrastructure cost of a distributed strategy, requiring smaller DCs in Cos. However, the condition for the saving is not straightforward and a careful analysis of the system to achieve a relevant IT cost saving for a target blocking probability is required. The simulation shows that the distribution of blocking probabilities between the edge data centers and the central data center is very relevant.

Obviously, the unbalanced situation is the target one: the more processors are installed in edge data centers, the more the maintenance costs. 1% to 8 % of CPU savings is desirable, but it is unlikely that the use of longer optical paths of strategy A is justified by this saving. Therefore the impact of this KBB is regarded low.

5.2 OPTICAL INTERCONNECTION OF CDN CACHES WITH SBVTS FEATURING RESTORATION

Telecommunications operators are concerned about the cost and scalability of the upcoming multiple edge computing capabilities such as CDN (Content Delivery Networks) caching, MEC (Mobile Edge Computing) or NFV (Network Function Virtualization) schemes running on edge cloud architectures such as CORD (Central Office Re-Architected as a Data Center, (https://opencord.org/)). However, providing carrier-grade data center services means upgrading the numerous edge facilities of a telecom operator with costly redundant computing, storage and communication equipment, as well as dual power supply and air conditioning. Given the large amount of network edges, the only scalable solution for high service availability seems to be making remote data centers backup other data centers of usually lesser reliability. This is the case of hierarchical CDN caching, although the use case is generalizable to any other edge computing service that needs low-latency communication with another server (e.g. augmented reality). A CDN cache can save a lot of traffic in the core but it needs a certain permanent connectivity for edge cache update from a cache at a higher hierarchical level, which may also take over the role of the edge cache in the event of data center outage. It should be noted, that backing up a whole data center with another assumes that the communication equipment necessary to switch the traffic over to another data center has its own protection mechanisms and remains up and running while the local data center is down. Recently, a field of study is that MAN data centers, within the latency budget, act as a backup for other local data centers of lesser reliability. Given the low latency target of caching, the optical layer is the preferred option to interconnect caches. However, carrying the backup traffic from one data center (DC) to another with a permanent optical circuit based on Fixed Transceivers (FT) features low utilization and no statistical multiplexing gain on the path, which makes the backup network resources costly. In this study we compare several approaches to implement this scenario with dynamic circuits, considering both inter-cache and backup traffic with FTs featuring both permanent and switched optical circuits, and with the Tb/s sliceable bandwidth-variable transceivers (S-BVT). As we show, S-BVTs can be key devices to improve backup network scalability in terms of IT resources and transceivers, thanks to their capability to adapt to the actual traffic demand and to obtain multiplexing gains at the optical layer.

One way to deal with both inter-cache traffic and backup traffic is the IP layer. However, using IP routers equipped with fixed transceivers (FT) to move the whole data traffic of a CO from one point to another may not be the most effective approach, given the low utilization of the backup capacity and the additional queuing latency. Given the ultralow latency targets of caching and other edge computing services, the optical layer is the preferred technical option to interconnect caches. On the other hand, carrying the backup traffic from one data center (DC) to another with a permanent optical circuit based on Fixed Transceivers (FT) features ultralow latency but low utilization and no statistical multiplexing gain on the path, which makes the backup network costly.
In this use case, we compare several approaches to implement this scenario, considering both inter-cache and backup traffic with FTs featuring both permanent and dynamic connections, and PASSION S-BVTs, which have the capability to real-time adapt to the current traffic demand and to obtain multiplexing gains at the optical layer.

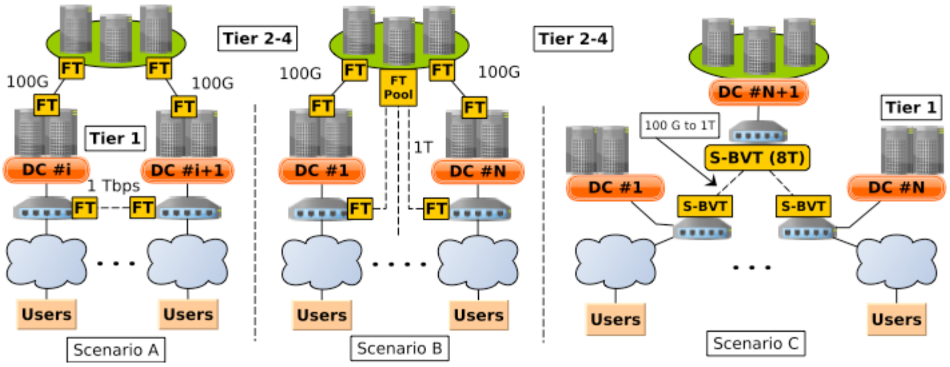


Figure 13 MAN CDN cache interconnection scenarios supporting restoration under analysis

we compare the benefits and drawbacks of three different architectures for handling DC downtimes/failures and show how S-BVTs can bring significant improvements by using dynamic circuits that are set up in the event of a DC failure. The network is structured in two levels such that local DCs can serve most of the traffic (assumed to be 1 Tb/s as a target case) using local caching. This target traffic corresponds to 70,000 active subscribers of individual IPTV contents watching a 15Mb/s 4K-video (Netflix recommended reservation rate) attached to the edge node, accessing content available at their local cache. On the other hand, caches are connected to a higher hierarchical level that serves the contents not available locally (assumed to be 100 Gb/s in our target example).

The first one is a pair-wise backup system (**Scenario A**). The traffic of each metropolitan area is served by a local cache running at the CO's DC on a first attempt. In case of a failure, demands can be satisfied using the IT available resources (i.e., VMs, storage, etc) in the paired DC. These can be satisfied using the IT resources available in the paired DC over a
1 Tbps dynamic circuit. If the latter is not possible due to a failure in the backup DC, the traffic is lost, as not enough capacity is provisioned toward the core for the complete traffic demand, that is, no 1Tbps connectivity is foreseen from edge to core and only 100 Gbps of would be supported. This option provides low latency but comes at a high cost in terms of IT resources as each local DC needs to provision resources to handle the failure of its pair.

In the second approach, **Scenario B**, each local DC has its backup on a central DC, using an independent dynamic connection that is set up upon a DC failure. This however implies a larger latency. From the cost point of view, this scenario benefits from statistical multiplexing and can significantly reduce the IT resources needed to support the backup as discussed in the following. However, a major drawback is that a large number of optical circuits and transceivers are needed when fixed transceivers are used. The third option in Figure 4, **Scenario C**, also implements a backup to a central node but using S-BVTs. This enables significant reduction of both optical circuits and transceivers, as well as flexibility to assign additional bandwidth to DCs when needed.

We analyze the probability of failure for the three options and compare the IT and optical resources needed to show the advantages of the S-BVTs centralized architecture. Let us next use the Tier classification of DCs [Arno2012] fostered by the Uptime Institute, the data center classification standard most adopted by IT industry. For the sake of cost, we shall assume that edge DCs are the simplest data center infrastructure considered by this standard: Tier 1, and the most sophisticated DC technology is in place in the core, i.e., Tier 4. Let $P_{failureT1}$ be the failure probability of a Tier 1

DC estimated as the unavailability of a Tier 1 DC (99.671%). Then, the probability of not being able to serve the traffic of any city of the pair in Scenario A is $P_{No} service\ A = P^2_{failureT1}$. Considering a number of N cities and $\frac{N}{2}$ pairs of DCs, we would need to double the resources at each DC $\#i, \forall i \in [1, N]$, in order to have enough resources to cope with the traffic of two cities, just in case one of the DCs in the pair fails.

On the other hand, Scenarios B and C (see Figure 13 middle and right) represent a centralized backup architecture. Here, when a local DC fails, the traffic demand is directed to a higher tier DC. This applies to every single local DC in the lower tier. Let $P_{failutre\ T1}$ and $P_{failutre\ T4}$ be the failure probabilities of a Tier 1 and Tier 4 data center, respectively. In this context, the probability of being unable to find available resources for user's requests of any city in Scenario B can be expressed as $P_{No\ service\ B,C} = P_{failure\ T1} \cdot P_{T4\ Not\ available}$, where $P_{T4\ Not\ available}$ can be computed as

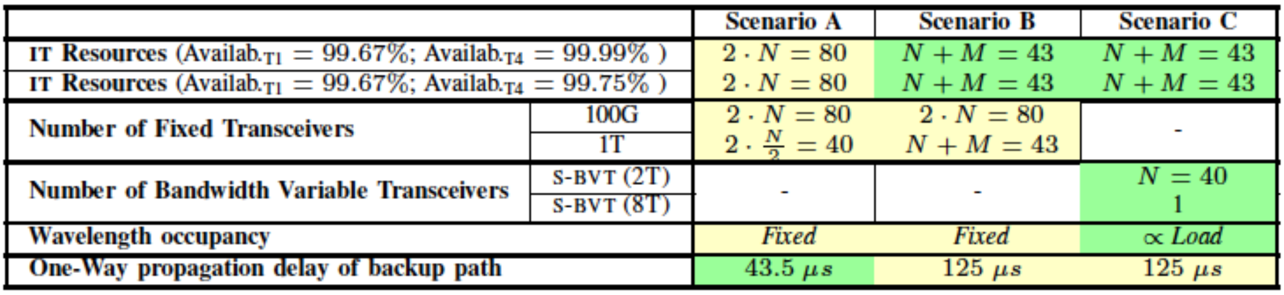
$$P_{T4\ Not\ available} = P_{failure\ T4} + P_{Not\ enough\ resources\ T4} - P_{failure\ T4} \cdot P_{Not\ enough\ resources\ T4}.$$

In order to compute $P_{Not\ enough\ resources\ T4}$, we need to have in mind that N Tier 1 DCs can potentially fail. Also, we assume that a given number of IT resources (M) are available to cope with the incoming traffic, each one equivalent to the resources of one Tier 1 DC. Substituting the appropriate expressions and rearranging them we get:

$$P_{No\ service\ B,C} = P_{failure\ T1}[P_{failure\ T4} \sum_{i=M+1}^{N} P^i_{failure\ T1} \left(1 - P_{failure\ T1}\right)^{N-i} (1 - P_{failure\ T4})]$$

From here, we may compute how many resources (M) we need in the Tier 4 DC in order to achieve the same overall service availability as that of Scenario A by solving $P_{No\ service\ B,C} = P_{No\ service\ A}$. Let us consider that the Tier 1 DC's availability is 99.67% and that of a Tier 4 DC is 99.99% [Arno2012]. Also, assume that we want to dimension both scenarios to support N = 40 metropolitan areas. Turning aforementioned availability times into no service probabilities by using $P_{No\ service} = 1 - (\frac{Availability}{100})$, and solving $P_{No\ service\ B,C} = P_{No\ service\ A}$ we get that the number of resources that we need at the Tier 4 DC driven by the S-BVT is $\mathrm{M} = 3$. Therefore, in Scenario A, we would need a total number of $2 \cdot N = 80$ IT resources while, in scenarios B and C, we would need $N + M = 43$ IT resources (i.e., DC's resources). This represents a total saving of ≃ 46% in the required resources. The same reasoning applies to the number of transceivers in the central DC. Table 3 summarizes the comparison between the two architectures, regarding the amount of required IT resources and the needed fixed and variable bandwidth optical transceivers.

Table 7 Comparison of resources for optical connectivity + restoration architectures for N=40 edge CDN caches.



		Scenario A	Scenario B	Scenario C
IT Resources (Availab.$_{T1}$ = 99.67%; Availab.$_{T4}$ = 99.99%)		$2 \cdot N = 80$	$N + M = 43$	$N + M = 43$
IT Resources (Availab.$_{T1}$ = 99.67%; Availab.$_{T4}$ = 99.75%)		$2 \cdot N = 80$	$N + M = 43$	$N + M = 43$
Number of Fixed Transceivers	100G	$2 \cdot N = 80$	$2 \cdot N = 80$	-
	1T	$2 \cdot \frac{N}{2} = 40$	$N + M = 43$	
Number of Bandwidth Variable Transceivers	S-BVT (2T)	-	-	$N = 40$
	S-BVT (8T)			1
Wavelength occupancy		*Fixed*	*Fixed*	$\propto$ *Load*
One-Way propagation delay of backup path		43.5 μs	125 μs	125 μs

The number of required IT resources in Scenarios B and C to meet the same availability as in Scenario A is dramatically reduced by means of statistical multiplexing. We include an extra case where Scenarios B, C are supported by a lower Tier DC. Observe that having a Tier 4 DC in the upper level does not reduce the number of IT resources we need to provision compared to staying with a cheaper Tier 2 DC. Also, we show the required hardware to implement each scenario.

It is worth highlighting that the amount of needed transceivers does not scale well with the number of edge CDN nodes for Scenarios A and B. Conversely, we achieve savings in the number of needed transceivers for Scenario C by using N SBVTs at the local DCs and one S-BVT at the core. Furthermore, for the example considered, the S-BVT at the central site with 140 channels x 50 Gb/s /channel can provide 7 Tb/s and the S -BVT s at the edges can provide 1 Tb/s by enabling half of the VCSELs. The amount of required FTs vs SBVTs gives an idea of how much more costly an S - BVT can be with respect to a FT for Scenario C being a more cost-effective choice than B.

From the wavelength occupancy point of view, the S -BVT is the best choice as it can fit the real load of the network with finer granularity (50 Gb/s). Finally, the last row of Table 7 shows the expected latency for each option having in mind the average distances between levels of aggregation of the reference PASSION network [D2.1] and assuming a delay of 5 μs/Km. Although Scenarios B and C suffer from a higher delay, 125 μs is not a heavy burden for most CDN applications.

In summary, the only scalable solution for high service availability of low latency CDN caching is making other MAN data centers within the target latency budget backup other data centers of usually lesser reliability. In this study, we compared several approaches to implement this scenario using dynamic optical protection circuits, considering both inter-cache and backup traffic both with FTs and with the PASSION Tb/s sliceable bandwidth-variable transceivers (S-BVT) to build flexi-grid channels. As we showed, S-BVTs can be key devices to improve backup-network scalability in terms of IT resources and transceivers, thanks to their capability to adapt to the actual traffic demand and to obtain multiplexing gains at the optical layer. The advantage of sliceable variable allocation of bandwidth through the network is clear not only when there is a need to move the traffic from a failing data center to another backup node. It is also an essential capability to quickly populate the caches when they are first started or after a general storage failure, without having to devote a large amount of permanent capacity to interconnect edge and central caches. Once the caches are updated, the capacity of the network and the transceivers are released and are available for other purposes.

The overall saving in terms of transceivers for CDN interconnection is very important. The only question is whether all HL4s in a MAN will host caches or not. Thus, the impact is qualified as moderate.

As in previous KBBs, the operator's and vendor's perspective of the impact of this KBB are summarized in the next table.

Table 8 KBB#3 Impact

KBB	Operator perspective	Vendor perspective	Overall impact
UseCase#3.1: Management of overflow traffic of Edge Computing	Low impact PASSION enables strategies for dynamic sharing of IT resources.	High impact. Assuming that edge computing service becomes a commodity,	Low impact It can be considered an added value for the operator. May not justify the investment.

	Moderate saving of IT resources (around 10%)	necessary in all HL4s. 380 S-BVTs /city.	If edge computing is further pushed to the access (HL5), the impact could be very high for the vendor.
UseCase#3.2: Optical Interconnection of CDN Caches with S-BVTs	Medium impact Saving of transceivers can be big given the trend to edge computing	High impact. Edge computing assumed in HL4. 380 S-BVTs per big city.	Moderate impact. The deployment of caches in HL4s may be slow and not all HL4s may host CDN caches.

6 KBB#4: ECONOMIC IMPACT OF USE CASE #4: SUPPORT OF MASSIVE EVENTS: DRASTIC DYNAMIC RE-ALLOCATION OF CAPACITY NEAR THE ACCESS

This KBB deals with a use case addressing the support of a cultural or sport events where a crowd of 5G or Wi-Fi users are actively using communication services. Several projects have estimated the traffic figures for this scenario, 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 uplink(UL) and 7.5Tb/s Km2 downlink (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 m^2 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.

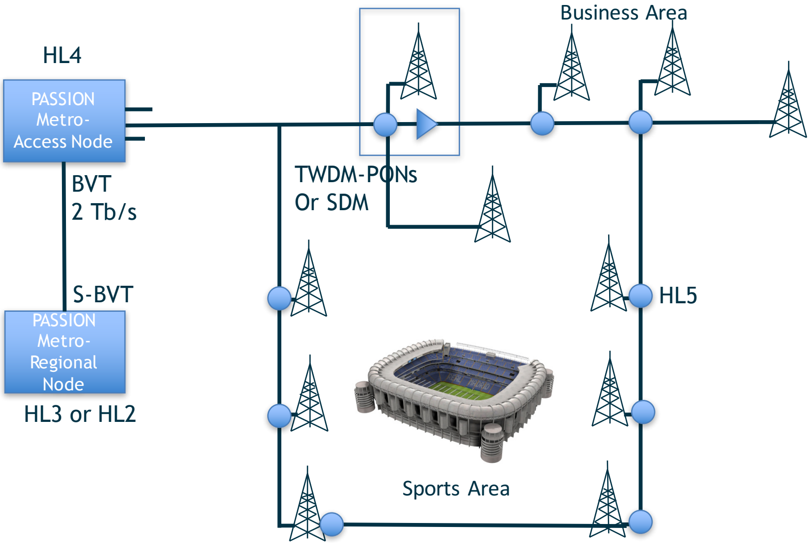


Figure 14 Support of massive events with PASSION

This use case requires to temporarily convert an HL5 node into an HL4 node (2Tb/s capacity) in order to support the traffic of a massive event (e.g., soccer match, concert) where a crowd with 5G use needs to access video streams, send video messages or access Augmented Reality services (i.e., 5G eMBB enhanced mobile broadband). The direct economic impact of this KBB is relatively low, unless the operator can generate revenue with pay-per-view services, given the duration of these type of events (most of the time the traffic is null).

Table 9 KBB#4 Impact

KBB	Operator perspective	Vendor perspective	Overall impact
UseCase#4: **Support of massive events: drastic dynamic re-allocation of capacity near the access**	Medium impact Potential new revenue sources from new event services. Intangible: brand name, attraction of new subscribers	Low impact. Not many stadiums and auditoriums to support in a city to equip like a Central Office. A few additional HL4 nodes and 2T S-BVT.	Low impact It is an important added value to use case #1. Just the cost of IP equipment may not justify the investment. Potential deployment in many massive hot spots in many cities may improve the weight of this KBB.

7 KBB#5: ECONOMIC IMPACT OF USE CASE #5: SEPARATE OPTICAL BACKHAUL/MIDHAUL/FRONTHAUL CONNECTIVITY WITH A SCALABLE FLEXIBLE N X 50GB/S SERVICE

Mobile network operators are facing challenges when choosing appropriate network deployments that minimize both capital and operational expenditures. Many operators have implemented, recently, small-scale test-beds following a centralized processing concept, specifically having in mind dense urban topologies. Adding new macro base stations in these scenarios is expensive or even an impossible task. Most of the times, these base stations require a huge capital expenditure (housing, signal processing equipment, adequate powering infrastructure, etc). In general, all research efforts are aware that the current network topologies are exhausted and unable to meet the envisioned future requirements.

C-RAN: The concept

Cloud Radio Access Network (C-RAN) architecture presented by China Mobile in 2014, introduces the idea of a cloud computing-based processing of radio signals on cellular networks. The concept was already introduced in [16] by IBM under the name of Wireless Network Cloud (WNC). The so-called Total Cost of Ownership (TCO) applied to cellular networks, comprises Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). The former refers to the cost of construction of a network. Network planning, site acquisition, purchase of hardware and software, installation of the powering and cooling are some examples that would be defined as CAPEX. The OPEX, refers to the costs that arise while operating the network. Among these, it is worth highlighting the cost of electricity, site rental, maintenance, etc. It seems obvious that, under traditional deployment schemes, the CAPEX and OPEX increase importantly as more stations are added to the network. This is due to the fact that base stations represent one of the most expensive elements in the network. Moreover, the authors of [C-RAN] claim that a huge percentage (~72%) of the total power consumption required to operate is at the cell sites. All these facts justify the convenience of deploying much simpler base stations at the expense of providing more network transmission resources.

This architecture, proposed as an implementation option for 5G Mobile Networks has shown, in several experiments, important Capital and Operation Expenditure (CAPEX/OPEX) savings to the network operator, while enhancing the cellular network's effective capacity by means of load balancing and combined processing of radio signals coming from several closely located base stations [checko2015, checko2016]. This concept represents large-scale centralized base station deployments, achieving significant cost reductions by separating the radio equipment of each base station from the elements that process the signals, which now are centralized and possibly virtualized.

One of the main selling points of C-RAN are the ability to exploit multiplexing gains as well as performing efficient resource sharing between areas that are active in different times of the day. For instance, the resources that are normally available to an office area during work time, can be used to serve residential areas while the first ones are idle at night-time or during the weekend. Among these resources, it is worth to mention the processing power CPU, RAM, etc. In a broader sense, we can also think of adaptability and scalability at higher levels, such as the service level. For example, various services hosted by different virtual machines can be instantiated or shut down depending on the real-time demands of the network at each particular time. This concept also opens up a world of possibilities regarding the implementation of self-organizing networks.

In C-RAN, lightweight Remote Radio Heads (RRHs) or Distributed Units (DUs) and Remote Radio Unit (RRUs), perform simple operations on the radio signals, digitize and forward them towards the remotely-located Baseband Units (BBUs) or Central Unit (CU), where the processing takes place, through the so-called front-haul (FH) network. In other words, these RRHs are in charge of radiating radio signals to the users as well as gathering and digitizing them back to the processing units by using appropriate transport protocols like eCPRI over IP or Ethernet [oteroJOCN]. Conversely, the BBUs (or CUs) are in charge of synthesizing the radio signal that will be sent to the RRHs. In the 3GPP 5G architecture, some of the radio processing functions may be realized in an additional intermediate node, the Distributed Unit (DUs). The network segment between DU and CU is usually called midhaul network. Up to the date, most C-RAN implementations for LTE use the CPRI (Common Public Radio Interface) specification [cpri].

Additionally, the processing functions performed by these distributed base stations are dependent on the particular deployment [ITU]. Moreover, since many of the processing tasks are no longer located at the remote radio heads, its hardware is simpler, cheaper and its maintenance cost is reduced. This network architecture obviously reduces the complexity and cost of the deployed base stations. Also, it supports more complex and smarter Coordinated Multi-Point (CoMP) services, better interference management, energy-efficient cooling and virtualization features that enable an agile and fast introduction of new services [rowel2014]. However, this scheme poses stringent latency requirements on the digitized data that must be met for the proper functioning of the network. The extreme requirements of this Digital Radio system, initially designed for intra-base-station communications, have pushed more efficient schemes.

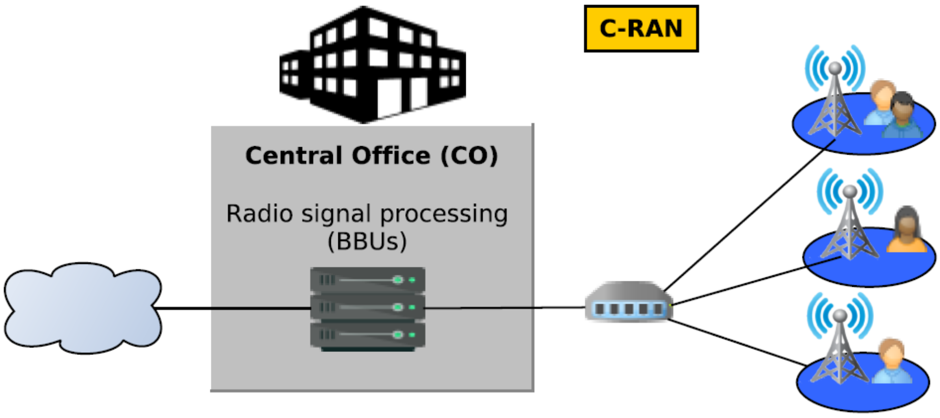


Figure 15. Typical deployment envisioned for Cloud Radio Access Networks

Figure 15 shows an example of a typical C-RAN deployment. The main idea of these deployments is to separate the gathering of the users' signals and their processing. On the right-hand side of the picture, we can see a light-weight deployment comprised by simpler and low-power cells that perform a minimal processing of the signals. On the other side, we find a centralized facility in charge of finishing the processing of the user's data.

In these networks, both fronthaul and backhaul traffic coexist. The possibility of aggregating fronthaul and backhaul flows in the same optical circuits will be a must. Recently, a combination of C-RAN and heterogeneous networks (HetNets), known as Heterogeneous Cloud Radio Access Network (H-CRAN) [hcran1, otero2020], has emerged featuring several types of base stations. Compared to C-RAN, H-CRAN makes use of LTE-A and WiFi to alleviate the burden on the fronthaul links and support offloading through different technologies. In this context, a careful design of the network becomes paramount to ensure that both C-RAN and non-C-RAN/backhaul data can coexist while meeting the requirements for both. Moreover, there exists the desire of going beyond this coexistence and achieving the convergence of technologies that brings us the best of both architectures and services.

Potential multiplexing gains

The dramatic increase of the traffic load in cellular network, has forced the designers to come up with smarter and more dynamic ways of planning and utilize the available resources in the network. Cloud computing conveniently captures some of these ideas by enabling the implementation of both statistical multiplexing and dynamic provisioning of resources.

Several studies show the gains achieved by multiplexing resources, induced from user load and traffic heterogeneity and dynamism. The authors of [Multiplexing2013] study the multiplexing gains obtained when pools of baseband units are used in 4G to process the devices' signals. Obviously, the multiplexing gains are not limited to a particular protocol, technology or resource. In general, multiplexing gains can be achieved whenever a pool of resources is shared by a given group of users. The main idea is that even though the summation of all user's requests would require an amount of resources that exceeds the available pool, these requests happen at different points in time. In other words, since the users' requests are not concurrent, their requested peak data rates will be located at different times. Thus, we are able to instantiate a pool of resources that is smaller than the total aggregate workload. It is worth noting that these smaller pools of resources translate into a cost reduction for network operators because, roughly speaking, we are serving the same number of users with less equipment. The less resources the operator deploys to give service to a network, the lower the resulting capex. Consequently, with a lower number of deployed resources, the power consumption will be smaller (OPEX). However, since now there are not enough resources to serve all users at the same time, from the user perspective the service performance is not guaranteed. Here is where the concept of Quality of Service (QoS) arises.

In [checkoPhD], a compact definition of multiplexing and pooling gains is given. In general, understood for any type of resource, the multiplexing gain can be defined as the ratio between the summation of single resources and the aggregated resources. This gives us an idea of how many times fewer resources we need to meet the users' requests if they are aggregated. On the other hand, the Pooling Gain can be defined as the power, processing or computational resources savings obtained by centralizing them.

The main points that support the introduction of C-RAN are: the traffic intermittent patterns, i.e., its burstiness, and the so-called tidal effect, that is, the inherent traffic changing conditions depending on the time of the day. Particularly, the last one is of great interest for operators. In order to illustrate the potential multiplexing gains that the C-RAN approach is able to provide, let us examine the following daily traffic pattern previously used in this project. In [D2.1], we considered five different types of regions, depending on the predominant kind of traffic in each one. We do this by using real-world data from [trafficPatterns]. In that study, the authors analyze the data from 9,600 cellular towers, concluding that the traffic of any of the 9,600 cells can be explained with a linear combination of four human activities. These are translated into the generation of different kinds of traffic: residential, cellular, transport, and business traffic. The five basic time-domain traffic patterns, obtained by means of a machine learning clustering algorithm are:

1. **Residential area**: 40% of the cells handle the predominant residential traffic, while only 20%, 22%, and 18% account for the cellular, transport and business traffics, respectively.

2. **Transport area**: only 10% handle residential traffic, 22% cellular, 44% transport, 22% business.

3. **Business area**: 15% residential, 18% cellular, 29% transport, and 37% business, now the biggest group.

4. **Cellular area**: 11% residential, 39% cellular, 28% transport, 23% business.

5. **Comprehensive area**: 29% residential, 23% cellular, 21% transport, 26% business. This represents a homogeneous traffic combination for this region.

In addition to these quantitative numbers, the temporal dimension must be added to scene in order to get the overall picture of the network. Taking the values of the daily peaks and valley of a real topology as in [trafficPatterns] and interpolating the data we get the temporal patterns shown in Figure 16, for each one of the described areas.

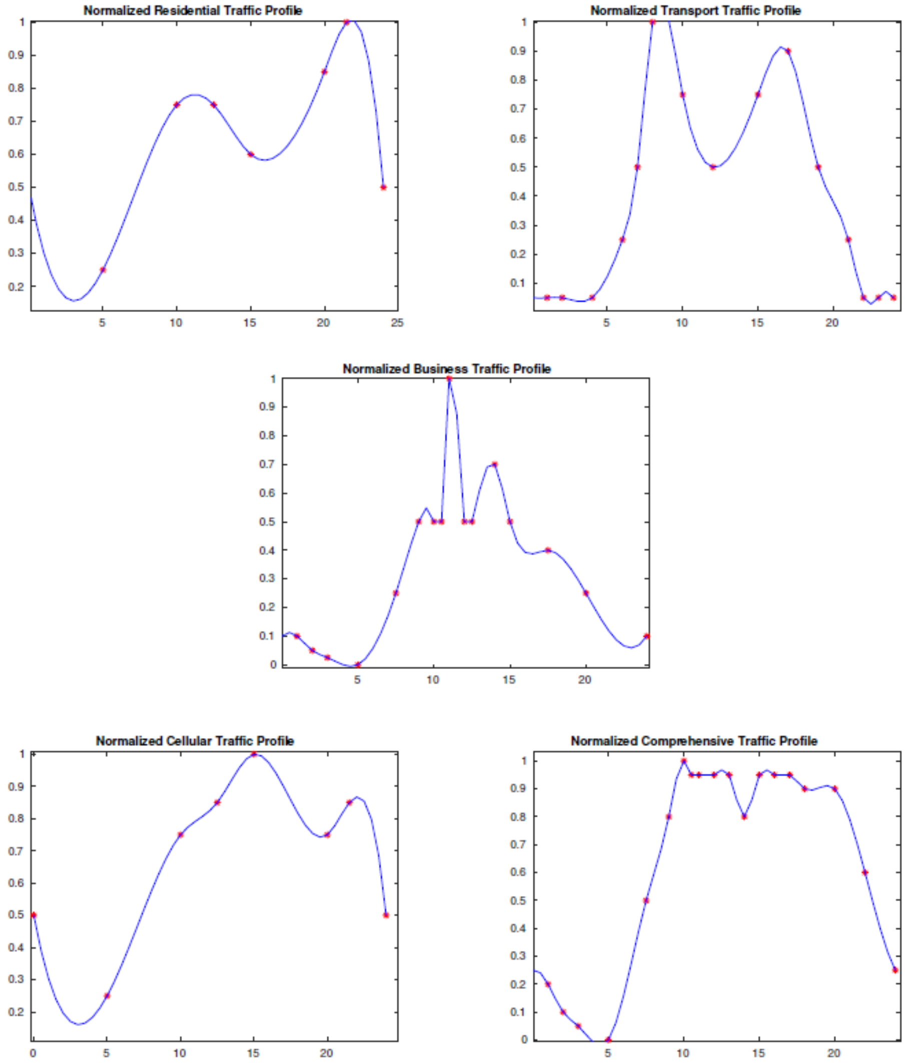


Figure 16. Normalized daily pattern for the different area types.

Table 10. Detail of the peak and valley times for each area.

Region	Residential	Transport	Business	Cellular	Comprehensive
Peak time	21:30	8:00/18:00	10:30	15:00	Not periodic
Valley time	3:00 – 5:00	3:00 – 5:00	5:00	3:00 – 5:00	5:00

Table 10 summarizes the values of the peaks and valleys for each type of region. It is worth noting how all of the regions have, at least, one valley in a 24-hour span. In particular, the transport area (see the top right plot) has one noticeable extra valley around noon that represents, roughly, a 50% reduction in the traffic demand with respect to the peak of the day. It is also interesting how the residential area achieves its maximum demand as we get closer to night-time.

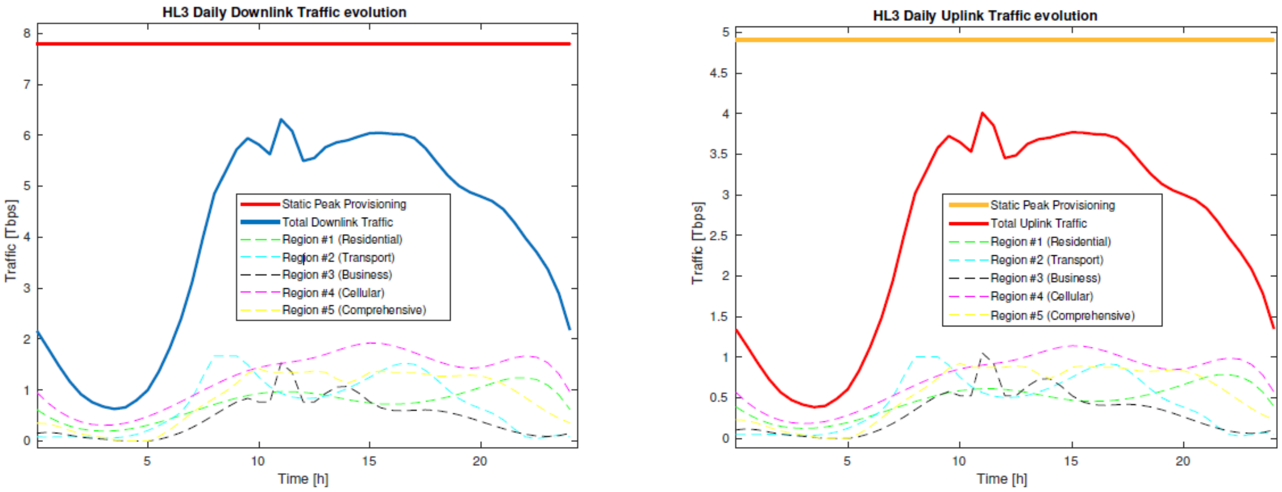


Figure 17. Evolution of the downlink and uplink traffic.

We use these normalized traffic patterns to weight the uplink and downlink traffic defined for future access networks. Namely, the assumptions are as follows:

- **Cellular traffic**: peak rate per cell [ITU/M.2410] 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.

Then, we just have to add up all the contributions from all the different zones to see what the aggregate traffic looks like. Figure 17 shows the result of the aggregation of the traffic demands coming from all suburbs, for downlink and uplink. The two figures we plot both the aggregated traffic and, as flat lines, the hypothetical static provisioning needed to cope with all the demands. These are a result of the summation of the peak traffic values of all the areas, assuming that we cannot predict where these peaks are going to meet and, more importantly, assuming that we cannot change the total amount of provisioned resources.

Closing the gap between the static provisioning and the actual aggregated traffic, that is, being able to adapt to the tidal effects, is what C-RAN aspires to do. Of course, all these ideas come at the expense of installing and maintaining a centralized infrastructure as C-RAN proposes.

In Use case #1, all these end-user traffic in a MAN were considered: residential, business and 5G. In particular, for the latter ITU-R report M.2410 [ITU/M.2410] set the minimum requirements for technical performance for IMT-2020 radio interfaces, which determine the throughput goals for 5G. This includes the recommendation of downlink/uplink peak data rates of 20/10 Gbit/s (along with other relevant performance targets like: user experienced data rates 100/50Mb/s (Dl/UL), <1ms of user plane latency for URLLC and <3ms for eMBB). This 20G/10G gives a target reference for 5G backhaul data rate of a 5G gNB (base station) that we used in Use Case #1 (KBB#1) to define a worst-case traffic situation with all MAN cells at full load.

In that scenario, fronthaul traffic is left aside because it is considered an access technique, given the fact that low level functional splits (below MAC layer) are subject to strict network latency constraints.

In particular, eCPRI considers functional splits I_D/II_D and I_U (see Figure 18) to reduce the rate requirements of CPRI (equivalent to split E in the figure). The one-way network latency budget of eCPRI is 100 μs. This allows for up to 20Km of fiber propagation time in the case of point-to-point fiber links but the expected distribution of this budget is about 10Km for propagation and 50 us for transport based on packet switching (for queuing, packet processing delay, etc).

In principle, the operator prefers to centralize baseband processing as much as possible in order to improve the utilization of the pools of BBUs shared by as many cells in the MAN as possible. However, the latency budget foreseen by eCPRI and IEEE 802.1cm would not enable such setting given the distances involved in a MAN. Hence fronthaul would be constrained to the access segment (HL5).

Given this limitation, 3GPP is considering the use of multiple splits in the path. The Distributed Unit (DU) within 20Km from the Remote Units (RU) would deal with low-level splits (baseband processing Figure 18's splits I_D,II_D,I_U) and a second level of resource sharing could be carried out at so-called Central Units (CU) that would deal with high-level functions like PDCP encapsulation/de-encapsulation (Figure 19 3GPP option 2 or 3 as the recommended choices). DU/RU may be co-located at the gNBs generating midhaul, and CU/DU may be co-located generating fronthaul. This RAN's distributed deployment option is being studied by operators. Although the economic advantages of midhaul over backhaul are not yet clear PASSION decided to include this additional traffic source as a new use case #5.

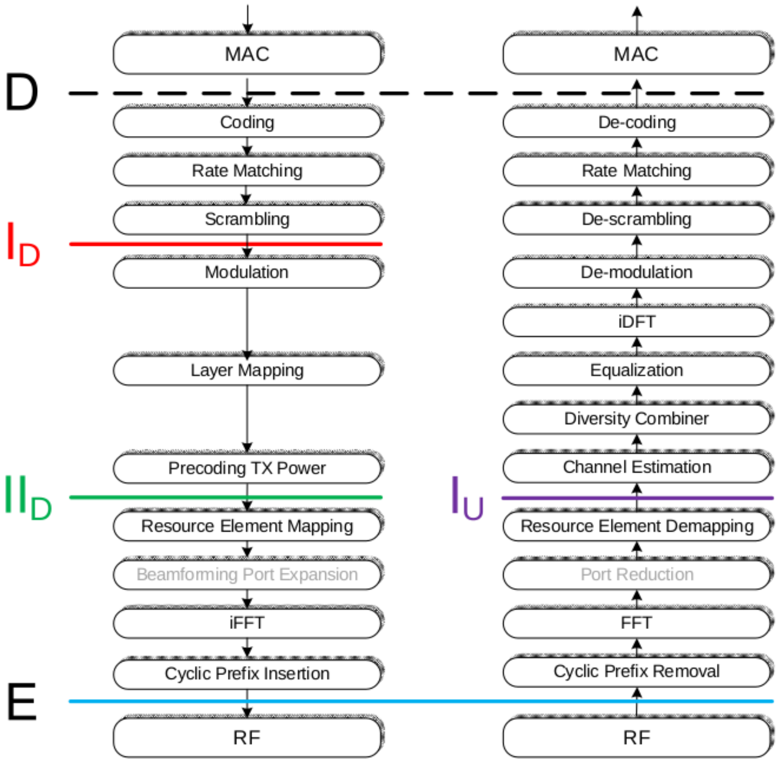


Figure 18 Functional splits considered by the eCPRI specification

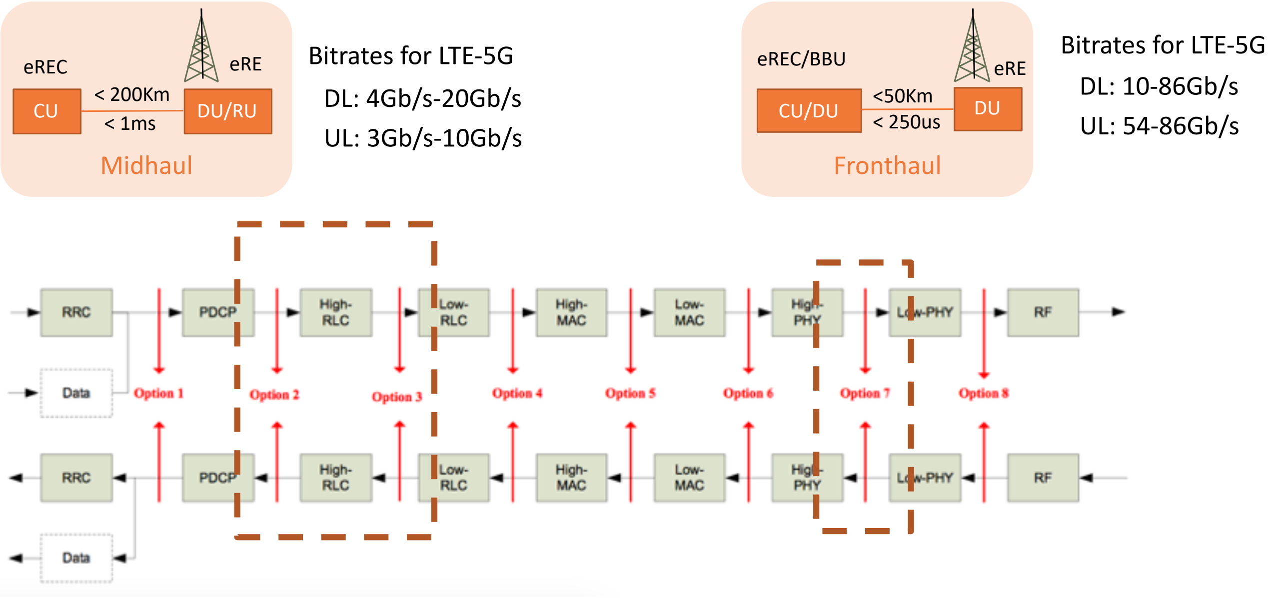


Figure 19 Functional splits under the focus of 3GPP and some reference bitrates

Figure 20 outlines the traffic offered at each level of the hierarchy, assuming that the DUs are placed at all HL4 nodes in PASSION reference topology, and Cus are located at HL1/HL2 nodes. As a conclusion, for 5G the HL2 level would process 53 Tb/s of backhaul traffic, roughly 4Tb/s per HL1/HL2 node at 100% load. **Each HL4 aggregation node generates up to 140 Gb/s of backhaul or midhaul traffic at 100%.** Proliferation of small cells is expected to boost this figure 10 times.

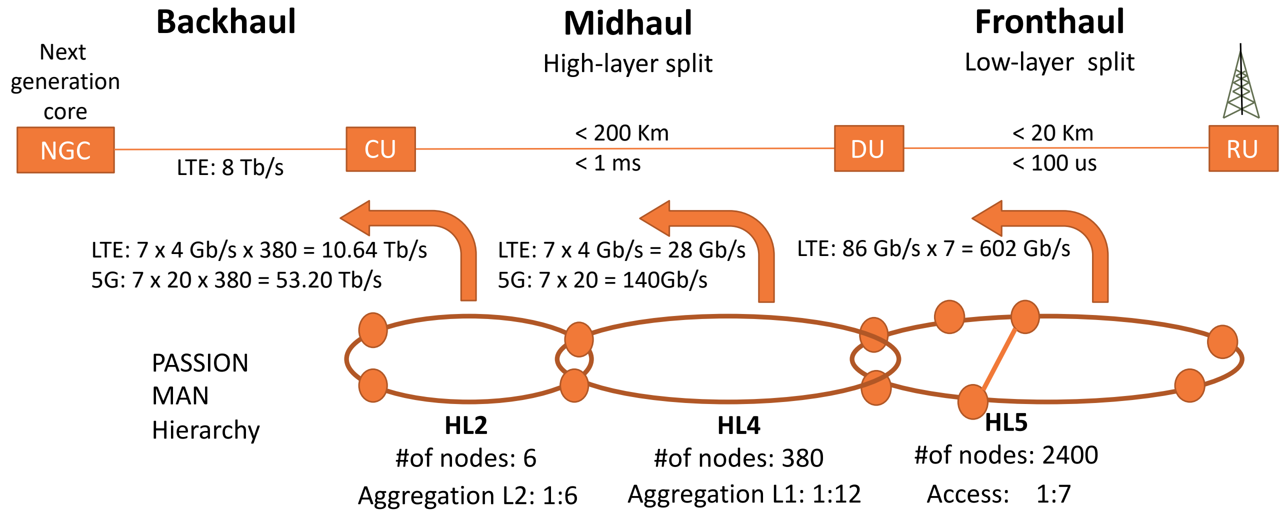


Figure 20 Maximum aggregated LTE and 5G rates in the target MAN topology

The operators have the dilemma between: (A) integrate backhaul/midhaul traffic with corporate/residential at IP or ethernet layer or (B) or keep cellular traffic at optical layer and isolated. An advantage of (A) is reduced CAPEX. Advantages of (B), the choice supported by PASSION, include:

- keeping **transport latency** << 1ms and ultra-low jitter, to fulfill **5G latency target** (5G KPI and **Tactile Internet** targets)

- **reducing traffic management complexity** (reduce **OPEX**)
- Avoiding large number of elephant HPF (High Priority Fronthaul) flows on highly loaded links
- Making **network slicing** easier, **IP offloading (reduce CAPEX at IP layer)**, etc.

Transporting Fronthaul through the MAN

At the time of writing this milestone report, it is not clear if operators will actually deploy DUs or regular BBUs (combined CU/DU function) and transport regular backhaul traffic from the HL4s. In fact, there is not a great difference of traffic between backhaul and midhaul. However, in addition to the convenience of transporting backhaul and midhaul at the optical layer, there is chance that the fronthaul traffic also crosses the MAN if instead of IEEE/eCPRI latency budget, the network budget is extended according to 3GPP budget in 3GPP TR 38.801 [TR338.801] of 250 μs. Therefore, the transport of fronthaul traffic deeper into the MAN is not completely discarded. If this latency budget is finally approved, the distances would extend the scope of fronthaul to 50Km. This can be very relevant technically and has an important economic impact. In our target 2400-node MAN topology it would be doable: Average path: 4 hops from HL4 to closest HL2/HL1 (36 Km) plus 5 hops in the access HL5-HL4 (7Km).

However, this time the amount of traffic to transport through the MAN (backhaul/midhaul plus fronthaul, where distance permits) will be difficult to deal with if there is not a proper affordable transmission technology like PASSION in place. Latest eCPRI and 3GPP splits are more efficient than split E ($R_{split\ E} = 2\ f_s\ \ N_{bits}\ N_{ant}$ where f_s is the subcarrier spacing, N_{bits} the number of bits per sample and N_{ant} the number of antennas, whereas $R_{split\ I_U} = \ N_{sc}\ \ 0.9\ (\ T_s)^{-1}\ \ \eta\ \ 2\ N_{bits}\ \ N_{ant}$ that depends on the load η (% of radio resource utilization) but still produces very high fronthaul rates. **Even with eCPRI splits I_U and II_D FH traffic may saturate 100G or 400G very soon**. Thus, it will make no sense to keep on performing packet switching (all is aggregate traffic toward the core) in the rest of the path. On average: 4 hops, maximum: 8 full channel hops where switches do not provide added value, only jitter and latency.

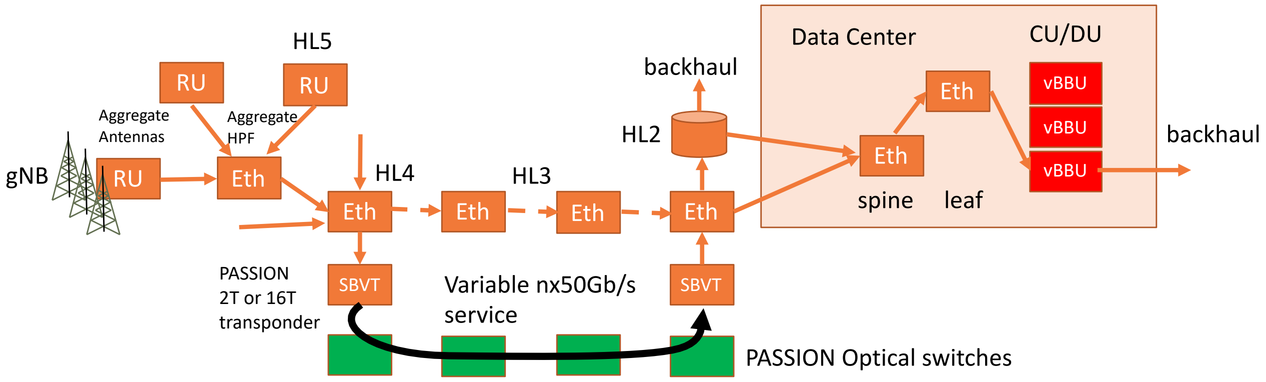


Figure 21 Optical layer transport of fronthaul

Figure 21 shows the solution proposed by PASSION to transport FH traffic. FH over Ethernet using IEEE 802.1cm and IEEE 1914.3 provides encapsulation, synchronization, packet scheduling, time stamping, latency normalization, etc of IQ samples. More importantly, Ethernet switches are used to aggregate the traffic of multiple antennas at the RU (RRHs), then to aggregate the traffic from a number of RUs (on average 7) before the traffic reaches the closest HL4. The aggregation of flows from multiple Rus is expected to provide a high statistical mux gain given that the cells may have very different loads. Once in HL4, if the traffic is above a given threshold, it may by-pass layer 2 through a tunnel (for instance, a Mac in Mac tunnel from layer-2's perspective) that actually is a PASSION super-channel with a rate that depends on the current demand. Once in HL2, the Ethernet layer is employed again to forward the FH flow to the right vBBU in the data center.

Two slicing granularities are enabled by this approach: on the one hand the fine bandwidth granularity provided by the packet switching technology in place (< 50Gb/s) and on the other, the 50Gb/s granularity provided by PASSION SBVTs.

The added value of PASSION Optical Layer awareness for layer 2 is the capability to deal with large aggregates of FH flows, zero-jitter transport in a large part of the path, slicing support with granularity: n x 50 Gb/s, perfect isolation of network slices, optical path protection, etc. It should be noted that this scheme is suitable for a centralized approach (BBUs at HL2 nodes), not for Distributed BBU allocation near the edge, as the amount of traffic involved would not justify PASSION rates at this part of the network. Fortunately, C-RAN aligns with this centralization approach since it seeks the processing of the user signals in a centralized location, to leverage the statistical multiplexing gains.

The economic impact of this Use Case KBB is very high as it implies the deployment of as many 2Tb/s SBVTs (and HL4 ROADMs) as HL4 nodes. However, the case is not simple: (1) BBU redundancy is required, and secondary paths are longer, (2) not all primary path cases can be reached with a 50Km budget. Thus, a combined centralized primary BBU – distributed secondary may be required, involving additional IT resources.

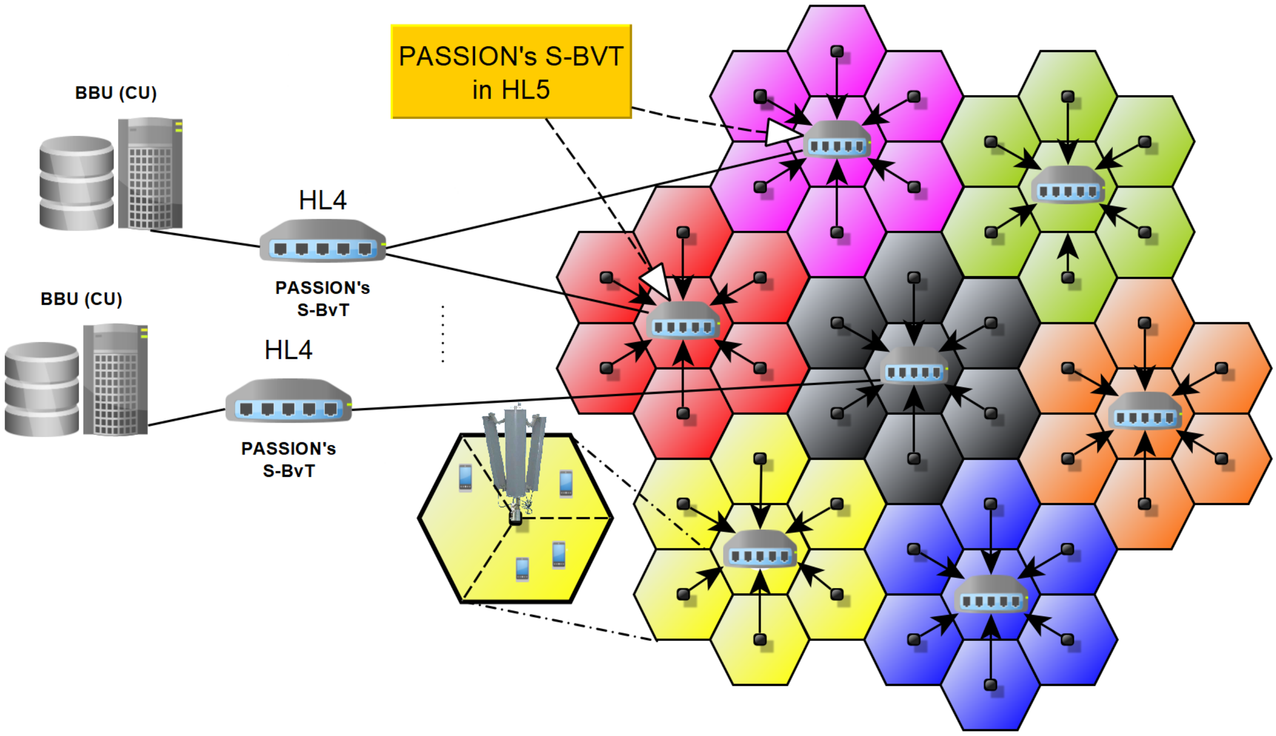


Figure 22. PASSION technology transporting fronthaul traffic.

Figure 22 gives the general overview of the PASSION technology aggregating the fronthaul traffic to be transported to the processing units. In the picture, a hexagonal cellular deployment is shown, where the traffic from the base stations is aggregated at the center of each hive. Each hive comprises seven cells with three antenna sectors each. PASSION S-BVTs are located in the HL5 level, at the center of each hive, in order to aggregate the fronthaul traffic coming from cellular base stations using a star topology. From there, each HL5 is connected to another PASSION S-BVT located in the HL4 aggregation level which will aggregate the traffic from one or more HL5 S-BVTs.

For this use case, we assume that the eCPRI functional split used for the transport of the fronthaul traffic is Split I_U. Table 11 summarizes the requirements of the 5G New Radio user plane fronthaul traffic. In particular, the subcarrier spacing, burst size and period, and the needed bitrate is show for different channel bandwidth for Splits E and I_U under full utilization.

Table 11. Functional splits traffic profiles for 5G New Radio user plane; 2 MIMO antennas, 15 bit/sample, 5% guardband.

	Split E		**Split I_U ($\eta = 1$)**			
Channel Bandwidth	50 MHz	100 MHz	50 MHz	100 MHz	200 MHz	400 MHz
Subcarrier Spacing	60 KHz	60 KHz	15 KHz	60 KHz	60 KHz	120 KHz
Burst Size [B]	120	240	23753	11880	23753	23753
Period [µs]	0.26042		66.6	16.6	16.6	8.3
Bitrate [Mb/s]	3686	7372	2851	5702	11401	22802

These numbers apply to a single RF channel to be transported using the eCPRI protocol. Since these requirements are too low to justify the use of a high-capacity S-BVT as the one developed in PASSION, we focus the study on the transport of 400 MHz channels and introduce the use of more demanding MIMO schemes (2, 8, 32, 64, and 128 antennas). This means that the required data rate in the fronthaul per RF Channel would be: 22.80, 91.23, 364.95, 729.90, and 1459,81 Gb/s, respectively. Considering base stations featuring three of these 400 MHz sectors, the data rate needed per base station would triple.

Now, we compare the cost of the deployment based on S-BVTs with an alternative one based on 100G and 400G fixed transceivers. We assume that we want to serve the 2432 HL5 nodes in our reference topology which are producing this kind of fronthaul traffic. We set the normalized cost of fixed transceivers and S-BVT's 50G lambdas as :

- 5 CU per 50G S-BVT lambda.
- 62.5 CU per 100G FT.
- 100 CU per 400G FT.

Table 12. Deployment cost CAPEX in Cost Units [CUs].

Number of antennas	**Data rate per BS/HL5 [Gbps]**	**Deployment CAPEX cost (CUs)**	
		With Fixed Transceivers	**With S-BVTs**
2	68.43	304000	48640
8	273.72	912000	145920
32	1094.86	1884800	535040

64	2189.72	3040000	1070080
128	4379.44	6080000	2140160

Table 12 shows the total CAPEX cost of the deployment for both options. Clearly, the solution based on S-BVTs is cheaper for all cases. It is worth highlighting that using S-BVTs with a granularity of 50G yields a cost reduction that spans from 84% for the lowest number of antennas per BS sector (2), to ~65% when massive arrays of antennas (128) are used.

Table 13 KBB#5 Impact

KBB	**Operator perspective**	**Vendor perspective**	**Overall impact**
UseCase#5: Optical Backhaul/Midhaul/Fronthaul connectivity with a scalable flexible n x 50Gb/s service	High impact PASSION makes available a huge capacity that flexibly adapts to cellular load. VCSEL license activation cost adapts to pace of deployment of 5G. It yields savings up to 84%, assuming license-based activation. CAPEX and OPEX savings from centralization of vBBU.	High impact. Mostl HL5s (thousands in our reference network) may require 2Tb/s transceivers and HL4s 8Tb/s transceivers. 380 2T SBVTs per large city.	High impact Potential massive deployment of S-BVTs in the access provided that there is a fiber per HL5 to HL4. Traffic of 5G new radio may justify the introduction of one 2Tb/s per HL5 if massive MIMO and C-RAN become global. It needs lots of owned fibers to spare in the MAN.

8 KBB#6: TECHNOLOGY EXPLOITATION AND NETWORK PLANNING STRATEGIES & TOOLS

The way PASSION technology is exploited (intelligence of the control plane to make efficient use of resources taking advantage of the dynamic) and appropriate network planning strategies and tools can save additional resources w.r.t. static optical networking systems or systems that rely on first-fit allocation. Although PASSION is not centered on the research of this smart networking and planning algorithms, its SDN control plane and dynamic reconfiguration capability make us list this feature as an additional KBB for PASSION.

A look at the state of the art allows to weigh the relative importance of this KBB:

The authors of [Xiong2018] present a solution based on triggered precomputation (FR-TP) that achieves fast failure recovery with minimal resource overhead in a flexi-grid elastic optical networks (EONs) driven by Software-Defined Networking (SDN). This FR-TP strategy computes backup paths before the failure of a link. With this information, they are able to compute layered auxiliary graph of spectrum window planes using a residual capacity matrix to change dynamically the width of the spectrum window planes (SWPs) to satisfy different service requests. Their results show that combining FR-TP and SWP reduces the recovery time by up to 30.4% without increasing the blocking probability.

In [Chen2015], the authors explore different alternatives to RSA (Routing and Spectrum Assigment) schemes that have as a drawback a high computational complexity. They propose a dynamic network resource evalutation method that takes into account both the distribution of traffic bandwidth and the spectrum blocks. Then, they include fragmentation-aware concepts into the RSA algorithm to compute load-balanced k-shortest paths. Their results show that, by adding this intelligence to the algorithm, the traffic concentration and spectrum fragmentation is improved by ~39% while reducing the computational complexity by 80%.

The study carried out in [Wang2008] presents a multi-path routing scheme for optical networks. The proposed algorithm adds intelligence to the path selection process by taking into account protection and restoration. The results show that the blocking probability as well as the utilization ratio are improved, proving that multi-path schemes can achieve much better results than sing-path ones. Particularly, their simulations show that the fraction of provisioned bandwidth can go from ~22% when considering a single path strategy to ~15% if we choose 2-4 paths. It seems clear that the dynamicity of PASSION S-BVTs to provision lambdas with 50G granularity could leverage these kind of multi-path algorithms to improve the network performance.

An overall view of the state of the art suggests that appropriate efficient heuristics close to optimal for resource allocation provide a potential saving estimated in <10% of used resources compared with direct allocation of resources. Thus, the impact of this KBB is considered medium.

Table 14 KBB#6 Impact

KBB	**Operator perspective**	**Vendor perspective**	**Overall impact**
Optimisation: PASSION technology exploitation and network planning strategies & tools	Medium impact Low-cost software tools can provide >10% cost saving	Low impact License of PASSION network planning software per operator.	Medium impact Extra 10% of resources made available from 41 entralizati for further exploitation

9 PASSION VISION ON FUTURE AGILE HIGH CAPACITY OPTICAL METRO NETWORKS

Traffic in the MAN is expected to grow at an intense pace in the next decade toward 1Tb/s (peak rates) at large Central Offices (HL4) as estimated in D2.1 [D2.1]. Many factors like the development of 5G and the market trend to offer symmetric 1Gb/s FTTH are the main factors behind this forecasted growth. To cope with such traffic demand in a scalable and cost-effective way, PASSION provides a set of high-capacity WDM transmission and multiplexing technology for MAN networks streamlined and optimized to take full advantage of the hierarchical structure of MAN networks (Figure 23). In this scenario most traffic goes to and comes from the core (HL1/HL2 nodes) and any technology optimized for massive aggregation and distribution has a chance to compete in the market and win.

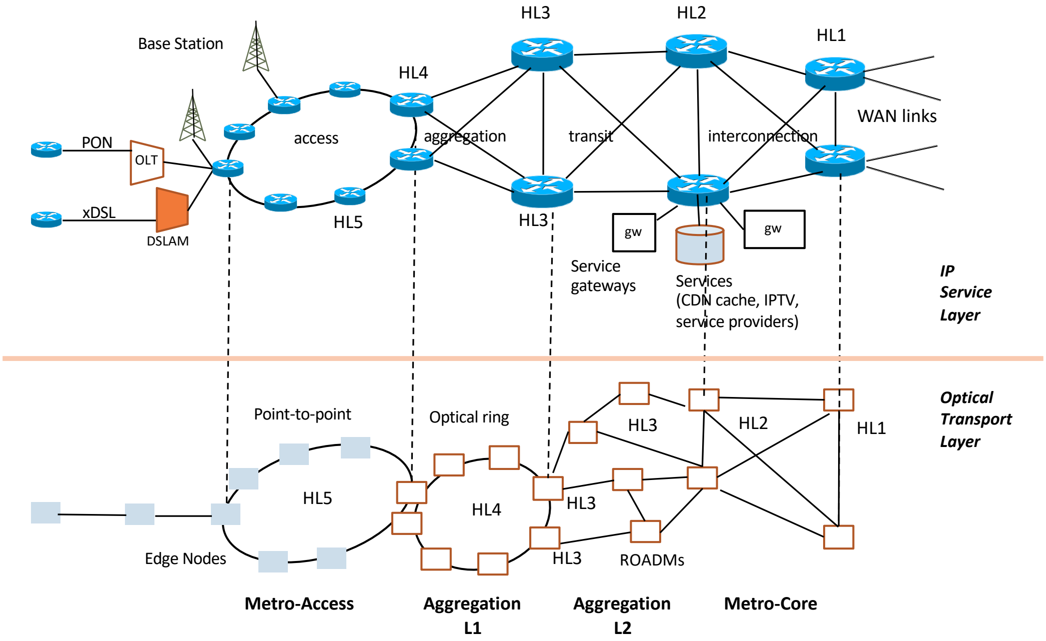


Figure 23 Hierarchical structure of PASSION reference MAN

Indeed, PASSION S-BVT is a solution that can save a huge number of FTs, which is the costliest part of the deployment bill. Furthermore, the extraordinary connectivity flexibility of S-BVT not only allows to save in terms of HL3 routers, as shown in section 4. Most of the saving comes from the fact that intermediate IP levels such as HL3 require, in classic IP/WDM approaches, many FTs downlink and uplink, whereas PASSION makes it possible to eliminate such intermediate optical-electronic-optical (OEO) conversion (as schematized in Figure 5). Furthermore, such intermediate IP layer of the classic solutions is an extra source of power consumption and packet delay and jitter. In this sense PASSION contributes to reduce the carbon footprint of MAN networks and to achieve ultra-low latency services. In addition, all aggregation and distribution functions are performed with a few hub high-capacity transceivers, thanks to its sliceability property (Figure 24).

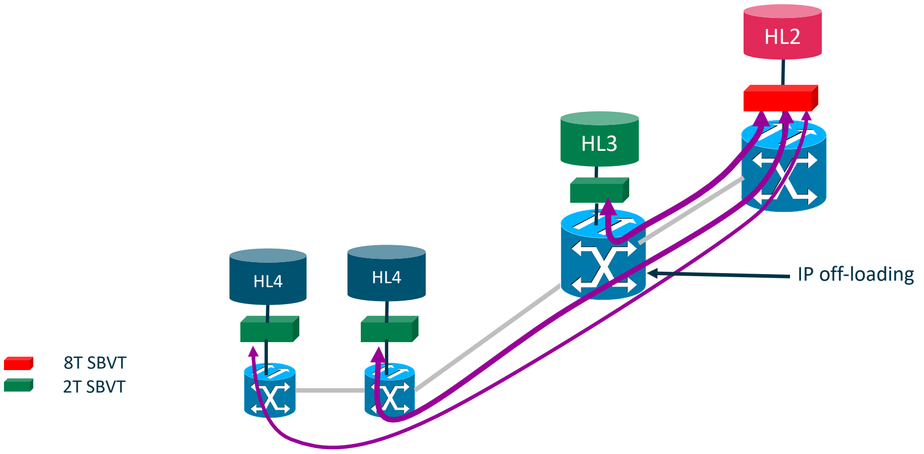


Figure 24 Illustration of the application of PASSION S-BVT slicing: traffic grooming and distribution at the optical layer

Regarding the metro-access segment, in PASSION's vision, taking WDM to the access may not be justified by the amount of traffic at HL5 nodes (about 100G peak traffic with high variance). Thus, HL5 traffic should either be aggregated with IP or ethernet switches or, in the case of scenarios with plenty of fibers, the connectivity of HL4 and HL5 should be implemented with a star topology (even if the duct-level topology is usually a ring). In PASSION's vision, this will enable in the future a scalable implementation of C-RAN, as deeply studied in section 7, and easy implementation of URLLC services without any ROADM. If the C-RAN approach becomes widely used in cellular networks, then a very high impact use case for the application of PASSION S-BVTs will be born as the rates required for 5G new radio fronthaul traffic with massive MIMO will soon exceed the capacity of most FTs. From HL4 and above levels, the use of WDM is properly justified.

This deliverable has developed the main KBBs for techno-economic analysis of PASSION technology that provides a use case-based PASSION vision. A summary of the KBBs, their relative impact, and methodology is shown in Table 15.

Table 15 Summary of Key Building Blocks for Techno-Economic Analysis and their Impact according to PASSION vision

KBB #	**KBB**	**Key Building Block (KBB) for Techno-Economic Analysis**	**Economic target**	**Economic Impact**	**Methodology Used to Quantify the Impact and Outline of Resulting Quantification**
0	HW	Hardware cost and associated ownership costs: design decisions	Show that it can be competitive when compared to alternative fixed transceiver DWDM solutions.	High: HL1..HL4 equipped with PASSION boards and switches especially if the fabrication cost per Gb/s attained is lower than with FTs.	Estimate cost of PASSION components & systems (at least identify all cost items in PASSION: transceivers, switches, packaging, etc). Massive production can indeed make PASSION approach cost-effective. A practical target is set as 2x the cost of a 400G fixed transponder for the 2T S-BVT.

1	UseCase#1	Cost-effective ultra-broadband transport and expansion in a large MAN: Pay as you grow	Pay-as-you-grow saving, and revenue increase associated to the growth of carried traffic. License-based business model (progressive activation of VCSELs) is paramount in the analysis of TCO in time.	High: HL1..HL4 equipped with PASSION boards and switches. License cost for per-VCSEL activation may adapt to competitor's costs to induce a technology shift by operators . 380 2T SBVTs per large city.	Estimation of traffic growth in 10 years (2025-2035) with license model on a large MAN topology under different assumptions. Analysed in UseCase#2 including HL3-offloading factor.
2	UseCase#2	Cost-effective ultra-broadband transport and expansion in a large Metropolitan Area Network: Dynamic capacity adaptation and HL3 IP off-loading	IP-offloading yields important saving in Tb/s routers and fixed transceivers w.r.t IP over WDM.	Very high: saving in HL3 IP level switch cost	Cost comparison with 100G/400G x 80c – 50GHz system in the target topology. The cost reduction of IP equipment does not justify the investment in PASSION S-BVTs per-se, but the saving in FTs does. 40% CAPEX reduction achieved. Great scalability: moderate cost increase with traffic growth. Potential massive deployment.
3	UseCase#3	Interconnection for distributed computation sites (e.g., CDN) within the MAN: efficient protection schemes	Saving in IT resources, transceivers and lambdas	Minor if Data Centers only in HL4. Medium if HL5 edge nodes are equipped with CDN caches and PASSION technology enters level HL5	Simulation of different traffic conditions and blocking probabilities for dimensioning. Potential savings of 50% in number of transceivers required to implement protection or traffic overflow with S-BVTs.
4	UseCase#4	Support of massive events: drastic dynamic re-allocation of capacity near the access	Enabling new services such as Augmented Reality (AR) to process sport events multimedia	Minor. Specific HL5s near to stadiums become eventually an HL4 nodes.	Simulation of different traffic conditions due to 5G traffic from audience lead to number of S-BVTs required: one 2Tb/s S-BVT in regular conditions should suffice.

5	UseCase#5	Optical Backhaul/Mid haul/fronthaul connectivity with a scalable flexible n x 50Gb/s service	OPEX saving in the implementation of an all-optical C-RAN for 5G. Energy saving.	Very High. All HL4 nodes. Dual SBVT boards directly from DU router or integrated with HL4 router.	Review existing analysis of C-RAN cost justification. Estimation of OPEX saving due to 45 centralization and CAPEX of multiplexed shared BBUs out of scope. Traffic of 5G new radio justifies the introduction of one 2Tb/s per HL5 if massive MIMO and C-RAN become global. BBU redundancy options needs additional techno-economic analysis.
6	Optimisation	Technology exploitation and network planning strategies & tools	Saving in transmission resources (fibers, wavelengths, transceivers)	Medium Over 10% resource saving estimated with tools tailored for PASSION	Certain exploitation strategies (RWA) can take advantage of PASSION technology and add cost savings (network resources). A technoeconomic tool for PASSION deployment (compares with 400G FTs with IP over WDM) has been developed and will be reported in WP6.

The main conclusions of the KBB-based analysis are:

- PASSION features a number of technical advantages that can justify per-se the adoption in future Tb/s-capable MANs, namely: (1) PIC modularity which will allow massive production of a single element of 2Tb/s that can be used everywhere in the network, even to build higher-order super-modules (8T/16T), (2) No need to match different rates, unlike with FTs, no inventory issues, (3) Disaggregation of transponders and ROADMs, a feature in the wish list of operators that estimate a saving of up to 50% of cost, (4) 5G compatibility thanks to the use of the same control and orchestration software, together with a data plane featuring low latency and jitter, (5) No capacity upgrade hardware cost (wavelength license pay-as-you-grow scheme), (6) No manual intervention cost for upgrades: lower OPEX, lower downtimes (7) Faster recovery from laser failures (other VCSEL gets activated upon a failure) and potential use of the same S-BVT for primary and backup paths, (8) Flexibility to tradeoff distance, rate (50G/40G/25G) and number of lambdas if necessary, (9) Extreme connectivity versatility with a single transceiver thanks to slicing: a-single-transceiver-multiple-circuits, (10) Smaller Form Factor than FTs, meaning lower space and presumably higher energy efficiency.
- Estimating the resulting force of all techno-economic factors is a complex task: many of technology aspects have cost implications that depend on market evolution, effect of new competing products, new services enabled by edge computing, etc, are hard to forecast. In particular, the advent of ultra-dense WDM products may become a strong competitor for PASSION in scenarios where the optical fiber is leased or scarce. For instance, 400G x 80c = 32Tb/s systems are not yet in current commercial portfolios, but they will provide higher spectral efficiencies than PASSION, so that their cost should be tracked in case they become affordable for the MAN context and competitive with PASSION. On the other hand, the 50Gb/s canonical granularity of PASSION solves the complexity of heterogeneous rate provisioning with FTs and provides important OPEX savings in rate upgrades, as these can

be performed remotely by software. However, it should be clearly noted that PASSION is a product intended to be deployed in scenarios where there is plenty of fiber owned by the operator. The cost of fibers has been excluded from the analysis. The reason for this is that the range of costs for this factor is extremely variable (from zero, in the case of already deployed owned fiber (brownfield), through country-dependent fiber leasing prices (*hired*field), to very high fiber deployment cost (greenfield) where ducts and trenches need to be made) and hence can blur the results of the analysis. An operator should add the fiber cost effect in its specific scenario.

- The **amount of 2Tb/s S-BVT to be fabricated** for each use case is the **decisive factor** driving the estimation of the relative impact of the KBB **from the transceiver maker perspective**, whereas the **economic saving of deployment and upgrade** of the infrastructure as traffic grows is the decisive impact **for operators**. A target saving of 40% is claimed as necessary to cause a technology shift to the adoption of PASSION by operators. This can be accomplished if the 2T module can be fabricated at a cost twice as much as a 400G module.
- The KBBs with the highest economic impact are use cases #1, #2 and eventually #5, as they require transceiver updates in current HL4 and HL5 nodes. As depicted in Figure 4, in a mid-size country like Spain, a telecom operator may need just tens of HL1/HL2 nodes but thousands of HL4s. **License-based commercialization is a must** to achieve pay-as-you-grow, and **HL3 offloading is envisioned to provide over 40% savings** in terms of FTs w.r.t. IP-over-WDM from year 0 if per-lambda license-based charging is in place and the target price of twice the 400G transceiver cost is achieved for 2Tb/s S-BVT. The rest of use cases provide added value but do not justify per se the investment of operators and vendors. Some cost results of some Use Cases have been developed in depth (CDN caching, edge computing, ...) but cause minor business impacts in terms of number of units for this market niche. Finally, the use of planning tools and smart applications to make efficient use of the optical channels throughout the whole topology making the most of the PASSION SDN platform is also a relevant KBB for the operator.

- The study was made for a timing 2025-2035 As described in the exploitation plan, PASSION commercial deployment could take place in two phases. The first phase could go along the deployment of 5G from 2025 to 2030:

  - 2Tb/s SBVT modules at HL4 and 16Tb/s modules at HL2/HL1
  - License-based "Pay as you grow" model based on gradual VCSEL activation
  - Partial optical disaggregation support so that optical channels from PASSION modules could be transported over existing optical DWDM networks.

The second phase from 2030 while massive deployment of 5G and ultra-low latency services

- Multiple 2 Tb/s and 16 Tb/s modules per HL4 and HL2/HL1 respectively
- Multiple fiber activation or introduction of Multi-Core Fiber.
- PASSION optical switching nodes deployment

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11 ACRONYMS

AWG	Arrayed Waveguide Grating
AR	Augmented Reality
BBU	Base-Band Unit
BL	Bit Loading
BTJ	Buried Tunnel Junction
BVT	Bandwidth-Variable Transceiver
CAGR	Compound Average Growth Rate
C-RAN	Cloud Radio Area Network
CAPEX	Capital Expenditure
CD	Chromatic Dispersion
CDN	Content Delivery Network
CO-Rx	Coherent Receiver
CRM	Coherent Receiver Module
CSI	Channel State Information
CU	Cost Unit or Central Unit
DBR	Distributed Bragg Reflector
DMT	Discrete Multitone
DSB	Dual Sideband
DSP	Digital Signal Processing
DM	Direct Modulation
EDFA	Erbium-Doped Fiber Amplifier
FEC	Forwarding Error Correction
FSR	Free Spectral Range
FT	Fixed Transceiver
FTTH	Fiber To The Home
HLn	Hierarchy Level n
InP	Indium Phosphide
IPTV	IP Television
KBB	Key Building Block
MA	Margin Adaptive
MAN	Metropolitan Area Network
MCS	Multicast switch

MQW	Multi Quantum Well
NRE	Non-Recurring Engineering
LO	Local Oscillator
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditure
OSNR	Optical Signal-to-Noise Ratio
PD	Photodiode
PDM	Polarization-Division Multiplexing
PIC	Photonics Integrated Chip
PL	Power Loading
PMF	Polarization-Maintaining Fiber
PRBS	Polarization Rotating Beam Splitter
PSM	Photonic Switching Module
QoT	Quality of Transmission
RA	Rate Adaptive
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RRH	Remote Radio Head
RSA	Routing and Spectrum Assignment
Rx	Receiver
RWA	Routing and Wavelength Assignment
S-BVRx	S-BVT Receiver
S-BVT	Sliceable-Bandwidth-Variable Transceiver
S-BVTx	S-BVT Transmitter
SC	Short-Cavity
SDM	Space-Division Multiplexing
SDN	Software Defined Networking
SMSR	Side Mode Suppression Ratio
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SOI	Silicon On Insulator
SSB	Single Sideband
SSMF	Standard Single-Mode FIber
SWT	Switch
TIA	Transimpedance Amplifier
TT	Tunable Transceiver
Tx	Transmitter
URLLC	Ultra-Reliable Low Latency Communications
VCSEL	Vertical-Cavity Surface-Emitting Laser
VPN	Virtual Private Network
VR	Virtual Reality
WDM	Wavelength-Division Multiplexing
WSS	Wavelength Selective Switch
YANG	Yet Another Next Generation