D6.7 - GUIDELINES AND SOFTWARE TOOL FOR METRO NETWORK DESIGN BASED ON THE PASSION ARCHITECTURE

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EXECUTIVE SUMMARY

D6.7 of PASSION project provides a full description of the software tool for designing and planning networks employing PASSION hardware. The tool has been programmed in open-source R, making use of the igraph library for graph analysis. The tool is fed with the optical characterization of PASSION hardware (for OSNR calculations), hierarchical network topology and traffic matrix, and delivers as outputs, both primary and backup lightpaths, wavelength assignment per fiber link, and techno-economic metrics of the solution, including per-node design and inventory cost. The objective of the tool is exploiting the specific capability of PASSION to perform IP-offloading at intermediate hierarchical levels, as explained in section 2, by automatically computing paths to interconnect all optically all edge nodes (starting at hierarchical level 4) to the closest core nodes via disjoint primary and secondary paths. The computed deployment cost assumes a pay-as-you-grow business model where the operator is charged only for the licensed active VCSELs it is using.

In a nutshell, the planning tool receives as Inputs:

- Network topology characterized as files: nodesLabeling.csv and crossMatrix.csv. The first file shows the main features of each node. The second is a matrix that provides connectivity between the nodes (0 if not connected or a number of km if connected).
- Traffic matrix: this is included in nodesLabeling.csv as the amount of traffic injected (in Gb/s) to the MAN per HL4, HL3 and HL1/2 nodes.
- OSNR requirements for the support of 25, 40 and 50 Gb/s per wavelength, after crossing n HL4 nodes and m HL3/2/1, as files osnr_25_oh_fec.csv, osnr_40_oh_fec.csv and osnr_50_oh_fec.csv. This matrix needs to be computed through simulation.
- Normalized equipment cost (in Cost Units), provided in file PASSION_cost_components.csv.

And generates the following Outputs:

- lightpaths.csv includes the primary and backup paths from each HL4 towards the closest HL1/2. The backup path is both link and node disjoint if possible; if the topology connectivity does not allow it, the backup path shares the minimum number of links and nodes with the primary path. This file also includes details regarding the end-to-end OSNR, bitrate and route.
- FFlightpaths.csv provides a description of the wavelength and fiber allocation per lightpath.
- NodeDesign.csv contains the design of each node (number of ROADMs and S-BVTs) along with its cost in normalised CU.

The software code is open-source and downloadable from Github, URL:

https://github.com/josetilos/PASSION_WDM_planner/

and in PASSION Zenodo repository:

https://doi.org/10.5281/zenodo.4838021
https://zenodo.org/record/4838021#.YLFWN-vOOgA

1 INTRODUCTION TO THE PASSION WDM PLANNER

The techno-economic analysis of a Tb/s technology for the future MAN is a complex task given the large amount of uncertainties. There are multiple factors not easy to forecast (market demand, traffic demand, arousal of novel competing technologies, new services enabled by the technology, impact of the 5G momentum, etc).

Previous works (D2.4) remark that the fabrication cost of devices is one of the key factors in the commercial success of the technology, but the fabrication cost itself depends heavily on the amount of units demanded by the market, namely transponders/transceivers and switches. The study reveals that use cases requiring mass fabrication, involving as many network nodes as possible, are also the ones where PASSION technology provides techno-economic advantage w.r.t. existing technologies. These two big use cases are: IP offloading and 5G fronthaul/midhaul traffic transport. In this work, we focus on the former, given the fact that fronthaul traffic involves access technologies, out of the scope of PASSION. Furthermore, a generalized development of C-RAN in the next years, that may justify Tb/s capacities in the access, is still uncertain. Therefore, the short-term main application niche of PASSION is the metro aggregation, transit and core segments.

This deliverable provides the guidelines to design networks centered in S-BVT aggregation and distribution of traffic by-passing intermediate IP aggregation stages, and describes the tool developed by PASSION to exploit such capability. The idea is to design an agile powerful tool that allows to estimate very quickly the cost for a number of market and traffic growth assumptions on a target topology. It should be noted that standard spreadsheet-based tools can only estimate costs based on regular distributions of traffic, densities and distances. Therefore, they draw average high-level conclusions. This PASSION planner tool performs more precise calculations, making use of the actual topologies, computes the paths and maximizes their operation rate. Furthermore, it provides the primary and secondary paths for each HL4 node toward the core, so that its output can be represented on a map and serve as a guide for network provisioning.

The tool

The functionality of the tool designed to estimate this saving is outlined in Figure 1. The tool takes an input: (1) the network topology, (2) the traffic demands from every node towards the closest HL1/2, (3) the precomputed OSNR requirements for paths traversing n HL4 and m HL3/HL2/HL1 nodes to achieve 50G, 40G or 25Gb/s per lambda, and (4) a list of device's unitary costs.

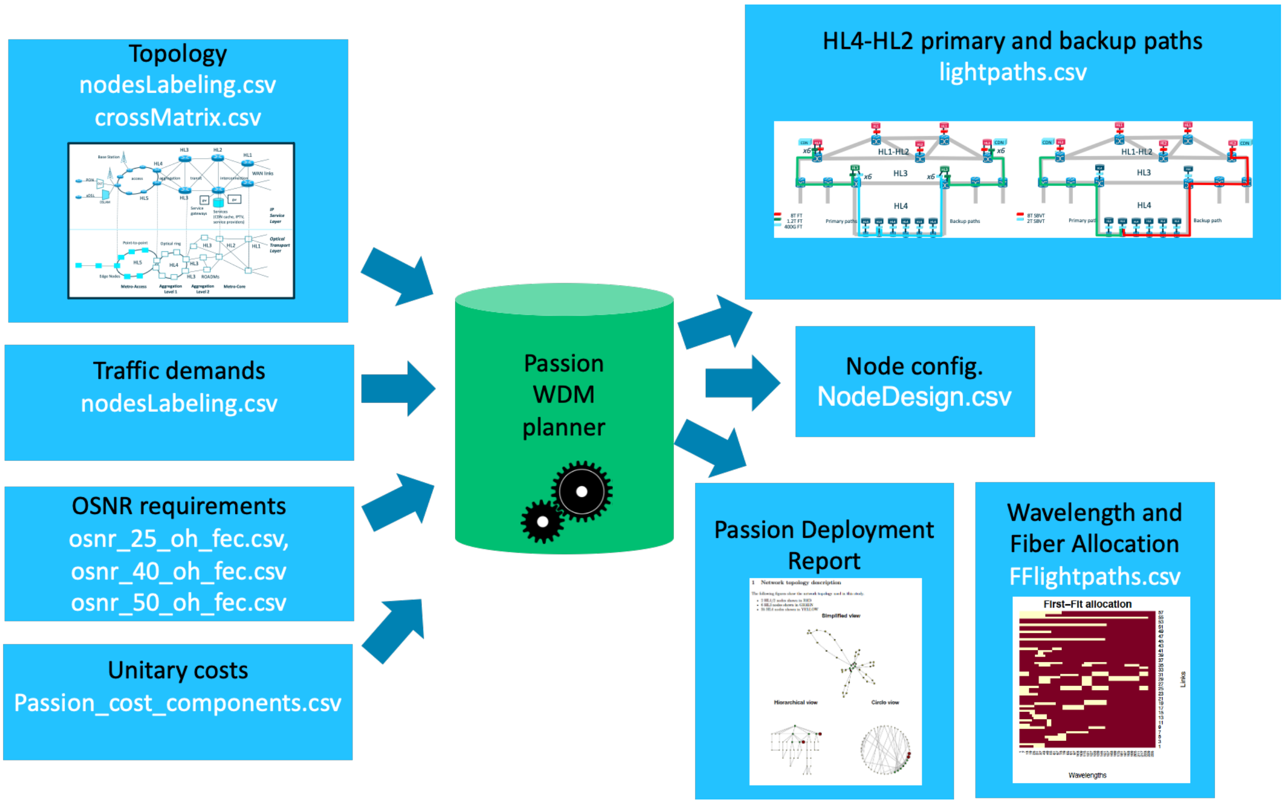

Figure 1. Tool and data used in the analysis cost of the different network planning strategy

The tool generates all the optical channels to be set up between each HL4 router and the closest HL1/HL2 (core) router required to fulfill the traffic demand HL4-core 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. The output can be further fed into a GIS tool in order to have a visual representation of nodes and paths on a map.

The deliverable is structured as follows. Section 2 provides an overview of the design guidelines for PASSION networks and describes the methodology employed for OSNR path estimation embedded in the WDP planner tool. Section 3 is a short User Manual for the tool and Section 4 overviews the cost assumptions used for the techno-economic studies. Finally, the annexes include the reports generated by the tool for the examples mentioned in the manual.

2 PASSION NETWORK DESIGN AND PATH COMPUTATION GUIDELINES

2.1 TARGET PATHS: ALL OPTICAL HL4-HL2 CHANNELS FEATURING HL3 IP OFF-LOADING

As estimated in D2.1 [D2.1], traffic in the MAN is expected to grow at an intense pace in the next decade toward 1Tb/s (peak rate) at large Central Offices (HL4). See Figure 2 for the relative place of HL4 in the reference MAN topology.

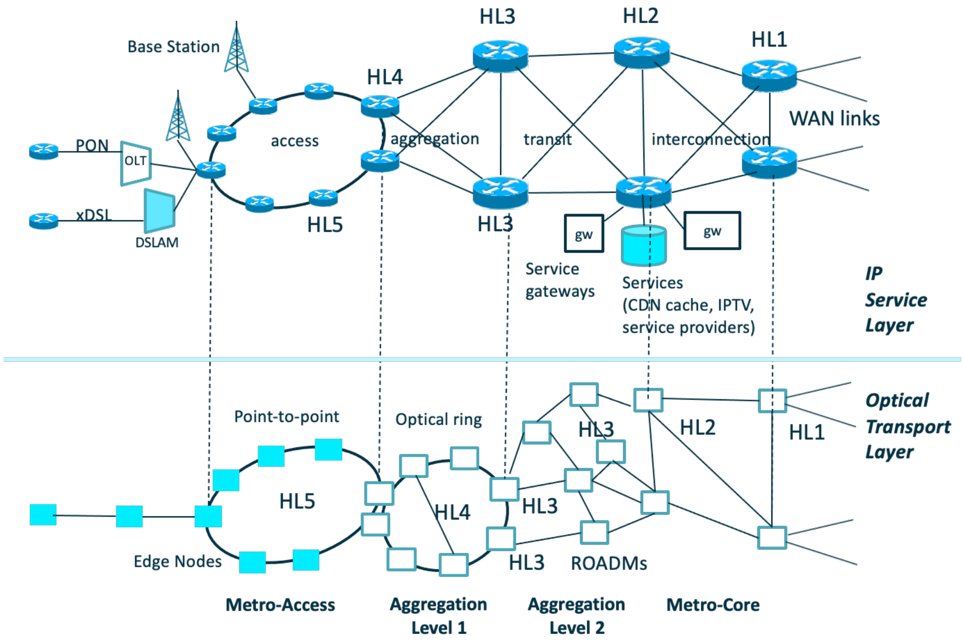

Figure 2. Hierarchical structure of PASSION reference MAN [D2.4]

Many factors like the development of 5G and the market trend to offer symmetric 1Gb/s FTTH are the main factors behind this growth. To cope with such traffic demand PASSION provides a choice of high-capacity WDM transmission and multiplexing technology. One of the most differential technologies provided by PASSION is the S-BVT. A comprehensive description of the architecture and functionality of this device can be found in [D3.1] [D4.1] [Svaluto2021].

The guidelines G*n* proposed by PASSION to exploit these technologies can be outlined as:

- **(G1)** Start using WDM technology at HL4 nodes and above. Access nodes (HL5) offer too little traffic (under 100Gb/s) to make a WDM cost effective and hence PASSION recommends employing packet-switched grooming and standard transmission long-reach transceivers (I.e. no ROADMs).
- **(G2)** HL4s should be equipped with 2T S-BVTs and HL1/2 should be equipped with either 8 or 16T S-BVTs (the latter considers exploiting dual-polarization multiplexing) that receive connections from remote nodes, including HL4s if possible.
- **(G3)** Use PASSION HL4-type ROADMs nodes if the available fibers and traffic demand allow to do it. Otherwise use HL3 ROADMs. HL4 ROADMs [Martinez2019], much simpler than HL3/HL2/HL1 nodes, can save costs and insertion losses at the HL4 hierarchical level. Since the focus of the tool is transceivers, we shall take into account the specific insertion impairments of HL4 nodes in the OSNR estimation but consider the same functionality and cost as any HL3/HL2/HL1 node (that of a commercial ROADM) for the sake of simplicity. Not using HL4s implies fewer fiber consumption but shorter paths.
- **(G4)** In the MAN scenario most traffic (90%) goes to and comes from the core (HL1/HL2 nodes) and PASSION S-BVTs feature aggregation and multipoint connectivity, as per the sliceability property. Thus, the network designer should try to set up aggregation and distribution multipoint connections rooted at the core preferably. Moreover, those paths should be as long as possible in order to prevent O/E/O conversions.
- **(G5)** In other words, the idea is that each HL4 router aggregates all the traffic from its HL5s and perform an all-optical transport lightpath from each HL4 nodes to the closest HL1/2 by-

passing HL3s at the optical layer. Further extension of light paths to other HL2/HL1 nodes is not recommended as aggregation ends in the first HL2/HL1 node. From that point on, the connections would be distributed to other HL2 nodes over the HL2/HL1 mesh if necessary. IP forwarding of packets at the first HL2 or HL1 is the recommended choice.

- **(G6)** The conclusion is that the **most important target of PASSION is supporting all-optical HL4-HL2/HL1 paths**. The reason for this is saving in: (a) intermediate O/E/O conversions, (b) high-end routers and (c) their corresponding transceivers (the most expensive deployment cost), as visually sketched in Figure 3, in addition to gaining a reduction of power consumption and packet delay and jitter.
- **(G7)** Install 8T/16T at HL1/HL2 nodes and exploit the sliceability property to perform statistical multiplexing of channels available at the root nodes on demand. Contention of access to those channels is solved by the SDN control plane. A smart process at the controller should deal with the potential fragmentation of bandwidth that may happen due to the dynamic nature of allocation.

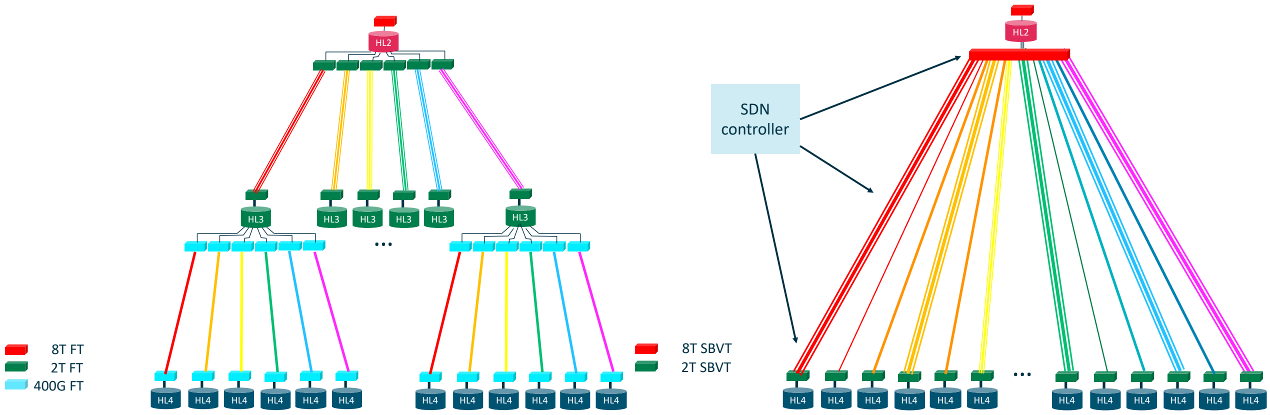

Figure 3. IPoverWDM vs HL3 IP-Offloading [D2.4]

- **(G8)** HL4-HL4 or HL4-HL3 connectivity is also supported at all. As a matter of fact, this non-hierarchical traffic can be carried without the need for additional transceivers. That is, in the tool we shall not make use of the sliceability property of S-BVTs that may be used to interconnect neighboring-HL4s or for HL4-HL3 links to carry non-hierarchical as illustrated in Figure 4, because according to TID 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 [D2.4].

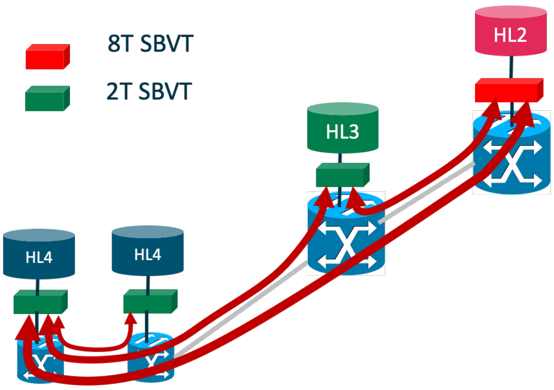

Figure 4 Connectivity options from an HL4 node.

- **(G9)** Exploit the new possibilities opened by longer primary and secondary paths. Rather than the classic ring connectivity protection, PASSION enables inter-level connectivity protection, exploiting the benefits of horseshoe and mesh topologies. The services must be designed in such a way (by means of service replication) that the services located at a given HL2 site (CDN cache, telephony gateway, etc) can be run by another HL2 node, so that the system can protect from both link failures, node-path failures and HL1/HL2 node failure. If this is not the case, the connectivity to the serving node is obtained through the HL1/HL2 mesh (Figure 5).

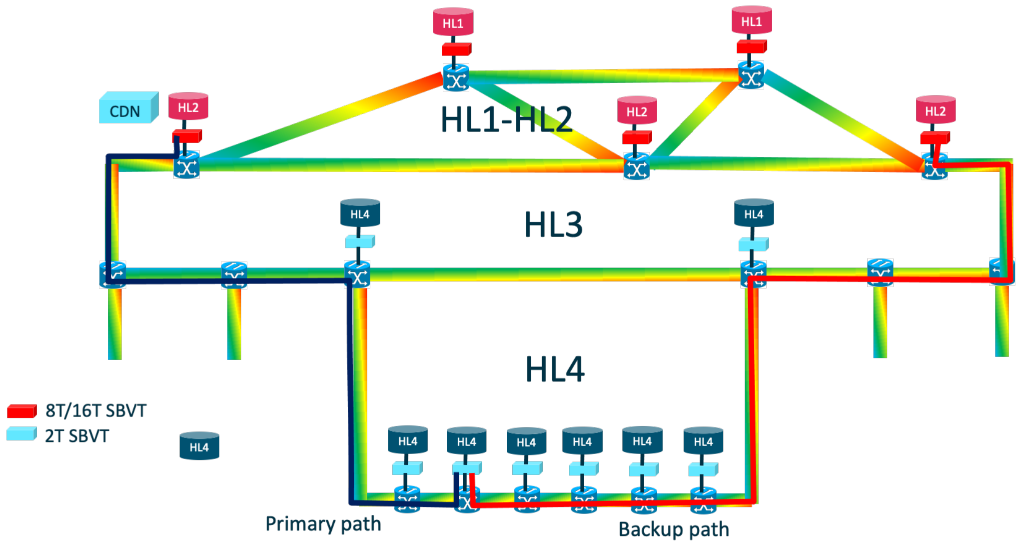

Figure 5. Concept of PASSION primary and backup paths to the MAN core

2.2 CHARACTERIZING THE OPTICAL PATHS

In order to ensure that the PASSION technology is able to provide the intended functionality via direct end-to-end light paths, we need to assess the suitability of the solution for the particular set of paths in a given topology. To do so, the OSNR requirements are first computed by means of simulation, taking into account the effects of the fiber propagation, the optical amplification, and the traversal of a node. As a result, we obtain an estimation of the needed OSNR to achieve a certain Bit Error Rate (BER) or a given capacity per channel. Namely, thorough simulations have been performed for the 50, 40, and 25 Gb/s cases [Parolari2018]. The simulations have been partially validated in experimental environments [Svaluto2021]. Among its features, it is worth highlighting that it considers the S-BVT characteristics (chirp, VCSEL linewidth, electrical modulation, frequency responses, etc) and outputs the impact of filtering and crosstalk between adjacent channels.

Tables 1 and 2 show the relationship between the number of traversed nodes and the required OSNR to provide the service considering HL4 and HL3/2/1 S-BVTs, respectively. Note that the HL3 nodes pose stricter OSNR requirements than the HL4 nodes due to the narrower filter bandwidth. It is worth mentioning that crossing an HL4 node actually reduces the OSNR threshold thanks to the vestigial sideband filtering.

Table 1. Required OSNR for 25, 40, and 50 Gb/s while traversing 4 HL3 nodes for different number of HL4 hops.

Number of HL4 nodes / Target capacity	1	2	3	4	5
25 Gb/s	24.5 dB	24.2 dB	24 dB	23.8 dB	23.6 dB
40 Gb/s	32.5 dB	32.5 dB	32.3 dB	32.3 dB	32.1 dB
50 Gb/s	39.6 dB	39.6 dB	39.6 dB	39.4 dB	39.4 dB

Table 2. Required OSNR for 25, 40, and 50 Gb/s while traversing 2 HL4 nodes for different number of HL3 hops.

Number of HL3 nodes / Target capacity	1	2	3	4	5
25 Gb/s	22.8 dB	24.7 dB	23.5 dB	24.2 dB	25.7 dB
40 Gb/s	29.6 dB	32.6 dB	31.6 dB	32.5 dB	33.2 dB
50 Gb/s	33.1 dB	39 dB	37.7 dB	39.6 dB	47 dB

On the other hand, Tables 3, 4 and 5 present the OSNR minimum threshold to support paths that are combinations of a given number of HL3s and HL4s, for 25, 40, and 50 Gb/s. At least one HL3 node is needed so as to select the transmission channel. For simplicity, only combinations of up to 5 HL3 and 5 HL4 nodes are shown.

Table 3. Minimum OSNR for 50 Gb/s depending on the number and type of traversed nodes.

Target OSNR for 50 Gb/s [dB]		Number of HL3				
		1	2	3	4	5
Number of HL4	0	33.5	39.2	37.8	39.6	47
	1	33.3	39	37.8	39.6	47
	2	33.1	39	37.7	39.6	47
	3	33.1	39	37.5	39.6	47
	4	33.1	38.8	37.4	39.4	46.9
	5	32.9	38.6	37.4	39.4	46.9

Table 4. Minimum OSNR for 40 Gb/s depending on the number and type of traversed nodes.

Target OSNR for 40 Gb/s [dB]		Number of HL3				
		1	2	3	4	5
Number of HL4	0	30	33	32	32.7	33.6
	1	29.8	32.8	31.8	32.5	33.4
	2	29.6	32.6	31.6	32.5	33.2
	3	29.4	32.4	31.4	32.3	33
	4	29.2	32.2	31.3	32.3	33
	5	29	32	31.1	32.1	32.8

Table 5. Minimum OSNR for 25 Gb/s depending on the number and type of traversed nodes.

Target OSNR for 25 Gb/s [dB]		Number of HL3				
		1	2	3	4	5
Number of HL4	0	30	33	32	32.7	33.6
	1	29.8	32.8	31.8	32.5	33.4
	2	29.6	32.6	31.6	32.5	33.2
	3	29.4	32.4	31.4	32.3	33
	4	29.2	32.2	31.3	32.3	33
	5	29	32	31.1	32.1	32.8

It is important to note that the 50 Gb/s capacities require an OSNR between 32.8 to 47 dB (37.80 dB on average). Also, 40 Gb/s demand between 28.50 and 37.20 dB (average of 31.67 dB), and 25 Gb/s requires between 21.00 and 27.30 dB (average of 23.55 dB).

As shown in Figure 6, these calculations assume that the transport infrastructure is made of single mode fiber with an attenuation of 0.25 dB/km along with 6dB-noise-figure-EDFAs. The HL3 node model assumes that switches are used for aggregate and disaggregate traffic and WSS that are traversed twice per node for adding and dropping of channels from the main flow. All the physical impairments are taken into account, assuming 18GHz VCSEL with 0dBm power and directly modulated with a 16-GHz DMT signal of 256 subcarriers. The amplification noise caused by the EDFAs is added at the end of the propagation path, by providing the appropriate OSNR level.

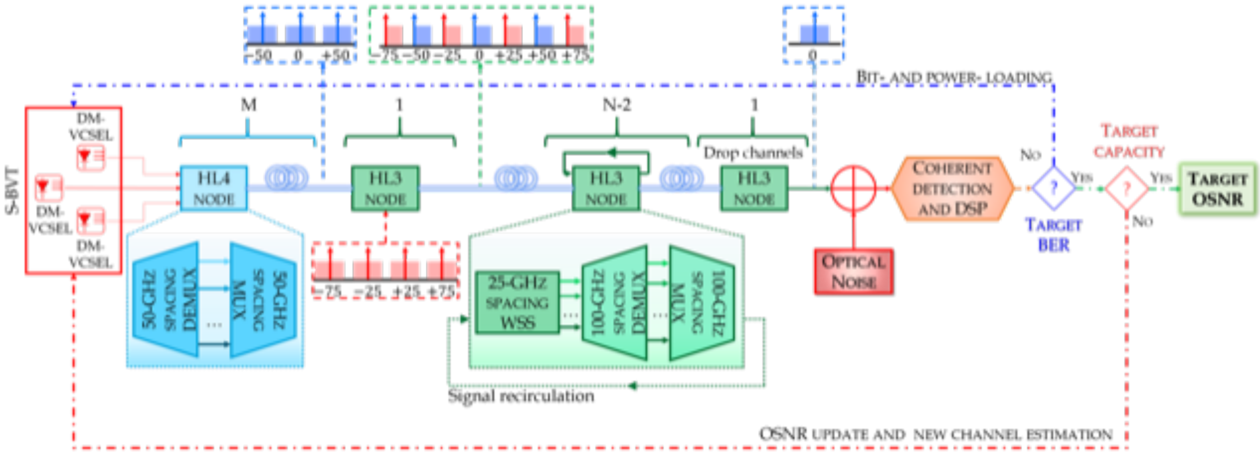

Figure 6 Simulation set up for OSNR calcuation.

The final step consists of estimating the OSNR budget for each possible primary and secondary (backup) path in the MAN of interest, in order to compare it with the above-mentioned OSNR requirements. We do this using the linear model shown in [ITUG680]. In the case of optical network elements (ONEs) that contain amplifiers, the OSNR of the optical signals at the output or drop ports will be lower than the OSNR at the input or add ports. The magnitude of this reduction can be calculated using following equation:

$$OSNR_{out} = \frac{1}{\frac{1}{OSNR_{in}} + \frac{1}{OSNR_{ONE}}}$$

where OSNR “out” stands for the linear OSNR at the output port of the ONE, OSNR “in” is the linear OSNR at the input, and OSNR “one” is the linear OSNR that we would see at the output port if the input signal were noise-free.

If the OSNR is defined in dB, the above equation can be rewritten as:

$$OSNR_{out} = -10\log(10^{-\left(\frac{OSNR_{in}}{10}\right)} + 10^{-\left(\frac{P_{in} - NF - 10\log(hv\nu_r)}{10}\right)})$$

where *Pin* is the channel power at the input port, *NF* is the noise figure of the path, *h* is the Planck’s constant, *v* is the optical frequency, and *Vr* is the reference bandwidth.

In general, this equation can be used to compute the OSNR of any end-to-end path in an optical network as

$$OSNR_{out} = -10\log(10^{-\left(\frac{P_{in1} - NF_1 - 10\log(hv\nu_r)}{10}\right)} + 10^{-\left(\frac{P_{in2} - NF_2 - 10\log(hv\nu_r)}{10}\right)} + \cdots + 10^{-\left(\frac{P_{inN} - NF_N - 10\log(hv\nu_r)}{10}\right)})$$

where Pin1, Pin2, …, PinN are the channel power at the inputs of each amplifier in the path, and NF1, NF2, …, NFN are the noise figures of the amplifiers in the path. Once we obtain the OSNR budget for a candidate path, we compare it to the OSNR thresholds in the previous tables to know whether these are feasible or not and to give a final answer on what the optimal primary and backup paths are for a given source, destination, traffic demand, and state of the network.

3 USER MANUAL

3.1 REQUIREMENTS AND HOW TO INSTALL THE PASSION TOOL

The PASSION network planning tool is based on the R programming language for obtaining the network configuration, in particular, the igraph library, version 0.9.3 [igraph]. Following the URL description, "igraph, the network analysis package, is a collection of network analysis tools with the emphasis on efficiency, portability and ease of use; igraph is open-source and free, and can be programmed in R, Python, Mathematica and C/C++".

In this sense, the easiest way to use the tool is by installing R (v 3.0.1+) and Rstudio IDE (v 1.4+), available for MAC OS, Linux and Windows systems. The easiest way to install them is by following the instructions in [Rstudio].

Once these are installed and configured, the latest version available of the igraph package is needed to be installed, using install.packages("igraph",dependences=TRUE)

Finally, the software tool is programmed in files:

- R_passion_tool2.R (main R code)
- PASSION_tool.Rmd (Rmarkdown file)

The former contains all the code and logic for designing the PASSION network, while the later uses the information provided by the main R code to produce techno-economic reports in PDF format.

To execute the main R code, only a click to Source button in Rstudio is needed. To generate the techno-economic PDF file using the Rmd code, only a click to Knit button in Rstudio is necessary.

The code is open-source and downloadable from Github:

https://github.com/josetilos/PASSION_WDM_planner/

and in PASSION Zenodo repository:

https://doi.org/10.5281/zenodo.4838021

3.2 HOW THE SOFTWARE TOOL OPERATES:

The PASSION planning tool receives a hierarchical network topology (with HL1/2, HL3 and HL4 nodes), traffic demands from all HL4 and HL3 nodes toward the closest HL1/2 and PASSION OSNR specifications for traversing the nodes, all in CSV format.

The topology is specified in two files: nodesLabeling.csv and crossMatrix.csv (separation of values is defined with semicolon symbol ";"), and can be edited with a simple text editor or csv editor like Microsoft Excel. For instance, nodesLabeling comprises three columns, including node name, type and traffic demand (in Gb/s) toward the closest HL1/2, see for instance for the Tokyo MAN in Figure 7.

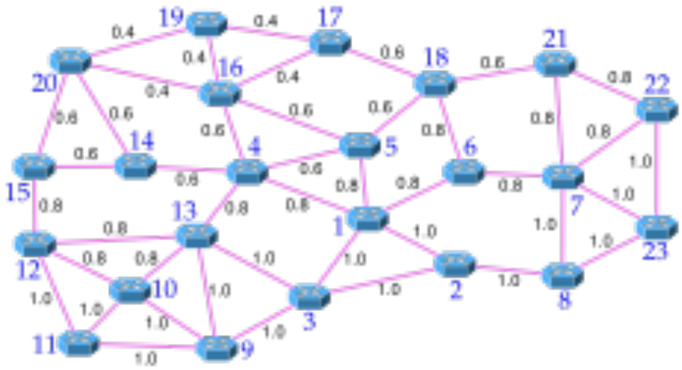

Figure 7 Tokyo MAN topology overview

The crossMatrix.csv file relates the interconnection between nodes (I.e. the links) including the physical distance in KM (0 for no connectivity), see for instance Figure 8.

Tokyo_01	HL2	1200
Tokyo_02	HL4	1000
Tokyo_03	HL4	350
Tokyo_04	HL2	800
Tokyo_05	HL2	750
Tokyo_06	HL4	2000
Tokyo_07	HL3	1500
Tokyo_08	HL4	900
Tokyo_09	HL4	200
Tokyo_10	HL4	100
Tokyo_11	HL4	850
Tokyo_12	HL4	1300
Tokyo_13	HL3	1900
Tokyo_14	HL4	500
Tokyo_15	HL4	1600
Tokyo_16	HL3	800
Tokyo_17	HL4	900
Tokyo_18	HL4	1000
Tokyo_19	HL4	900
Tokyo_20	HL4	1600
Tokyo_21	HL4	300
Tokyo_22	HL4	900
Tokyo_23	HL4	150

0	1	1	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0.6	0	0	0	0	0	0	0	0.8	0.6	0	0.6	0	0	0	0	0	0	0
0.8	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0.6	0	0	0	0	0
0.8	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	0
0	0	0	0	0	0.8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	1
0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	1	0.8	0.8	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.8	1	0	0.8	0	0.8	0	0	0	0	0	0	0	0
0	0	1	0.8	0	0	0	0	1	0.8	0	0.8	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0.6	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0.8	0	0.6	0	0	0	0	0	0.6	0	0	0
0	0	0	0.6	0.6	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0.4	0.4	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0.6	0.4	0	0	0	0
0	0	0	0	0.6	0.8	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0.6	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0	0	0.4	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.6	0.4	0	0	0.4	0	0	0	0
0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0.8	0
0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	1
0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Figure 8. Tokyo topology: nodes labelling (left) and crossMatrix (right) CSV screenshots

In addition, three files regarding the OSNR requirements (overviewed in the previous section) are provided to the tool, see for instance the OSNR requirements for 25 Gb/s per wavelength for multiple combinations of HL3 and HL4 node traversal (Figure 9).

index	hl3_0	hl3_1	hl3_2	hl3_3	hl3_4	hl3_5	hl3_6	hl3_7	hl3_8	hl3_9	hl3_10
hl4_0	1000	23.6	25.6	24.2	24.7	26	26.8	28	28.2	28.6	29.1
hl4_1	1000	23.1	25.1	23.8	24.5	25.9	26.6	27.8	28.1	28.5	28.8
hl4_2	1000	22.8	24.7	23.5	24.2	25.7	26.4	27.7	27.9	28.3	1000
hl4_3	1000	22.4	24.1	23	24	25.5	26.2	27.5	27.7	1000	1000
hl4_4	1000	22.2	23.9	22.7	23.8	25.3	26.1	27.3	1000	1000	1000
hl4_5	1000	21.9	23.6	22.5	23.6	25.2	26	27.1	1000	1000	1000
hl4_6	1000	21.6	23.4	22.3	23.6	25	26	27.1	1000	1000	1000
hl4_7	1000	21.4	23.2	22.1	23.5	24.8	26	1000	1000	1000	1000
hl4_8	1000	21.2	23	21.9	23.4	24.8	26	1000	1000	1000	1000
hl4_9	1000	21	22.8	21.8	23.2	24.8	26	1000	1000	1000	1000
hl4_10	1000	20.8	1000	1000	1000	1000	1000	1000	1000	1000	1000

Figure 9 OSNR requirements for 25 Gb/s (CSV screenshot)

Here, each value represents the OSNR requirement in dB, while value 1000 implies that a lightpath with such configuration is not possible. Two more tables for 40 and 50 Gb/s are also provided to the tool as input.

Finally, one last csv file regarding network cost is provided to the software tool for computing the cost per node and total network cost (Passion_cost_component.csv), with values normalized in cost units (CU), as shown in Figure 10.

ROADM_degree	88.96
HL12_Router	2500
HL3_Router	1667
HL4_Router	250
SBVT	201.11

Figure 10 PASSION_cost_components CSV screenshot

With this information, the tool creates a network graph object, called gPass, and uses function get.shortest.paths to obtain the closest list of nodes and links from every HL4 and HL3 nodes to all HL1/2. Then it selects the shortest path in terms of hop count as the primary path. Secondly, the tool removes the nodes and links participating in the primary path to obtain a secondary path, totally disjoint from the primary one. If this is not possible because removing links and nodes leads to disconnection, then the software tool computes a secondary path discouraging the use of links and nodes participating in the primary path (setting routing cost metrics to very high values).

Once both primary and secondary lightpaths are selected, the tool records the characteristics of the lightpath, i.e. source node, destination node, type_of_path, distance in km and hops, OSNR and whether or not 25G, 40G and 50G bitrate per wavelength is supported. This is recorded in csv file lightpath.csv, see Figure 11.

Source	Destination	prim_sec	distance_KM	distance_hops	N_HL5s	N_HL4s	N_HL3s	N_HL12s	OSNR_e2e	OSNR_req50G	OSNR_req40G	OSNR_req25G	Can_50G	Can_40G	Can_25G	FullPath
Tokyo_02_HL4	Tokyo_01_HL12	Primary_path	1	1	0	1	0	1	51.75	33.3	29.8	23.1	TRUE	TRUE	TRUE	Tokyo_02_HL4++++Tokyo_01_HL12
Tokyo_02_HL4	Tokyo_04_HL12	Secondary_path_totally_disjoint	2.8	3	0	2	1	1	46.995390240827	36.5	32.6	24.7	TRUE	TRUE	TRUE	Tokyo_02_HL4++++Tokyo_03_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_03_HL4	Tokyo_01_HL12	Primary_path	1	1	0	1	0	1	51.75	33.3	29.8	23.1	TRUE	TRUE	TRUE	Tokyo_03_HL4++++Tokyo_01_HL12
Tokyo_03_HL4	Tokyo_04_HL12	Secondary_path_totally_disjoint	1.8	2	0	1	1	1	48.7646280879734	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_03_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_06_HL4	Tokyo_01_HL12	Primary_path	0.8	1	0	1	0	1	51.8	33.3	29.8	23.1	TRUE	TRUE	TRUE	Tokyo_06_HL4++++Tokyo_01_HL12
Tokyo_06_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1.4	2	0	2	0	1	48.8146280879734	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_06_HL4++++Tokyo_18_HL4++++Tokyo_05_HL12
Tokyo_08_HL4	Tokyo_01_HL12	Primary_path	2	2	0	2	0	1	48.7397000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_08_HL4++++Tokyo_02_HL4++++Tokyo_01_HL12
Tokyo_08_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	3.2	4	0	3	1	1	45.7792561759469	36.3	32.4	24.1	TRUE	TRUE	TRUE	Tokyo_08_HL4++++Tokyo_07_HL3++++Tokyo_06_HL4++++Tokyo_18_HL4++++Tokyo_05_HL12
Tokyo_09_HL4	Tokyo_01_HL12	Primary_path	2	2	0	2	0	1	48.7397000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_09_HL4++++Tokyo_03_HL4++++Tokyo_01_HL12
Tokyo_09_HL4	Tokyo_04_HL12	Secondary_path_totally_disjoint	1.8	2	0	1	1	1	48.7646280879734	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_09_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_10_HL4	Tokyo_04_HL12	Primary_path	1.6	2	0	1	1	1	48.7897000433602	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_10_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_10_HL4	Tokyo_01_HL12	Secondary_path_totally_disjoint	3	3	0	3	0	1	46.9787874528034	33.1	29.4	22.4	TRUE	TRUE	TRUE	Tokyo_10_HL4++++Tokyo_09_HL4++++Tokyo_03_HL4++++Tokyo_01_HL12
Tokyo_11_HL4	Tokyo_01_HL12	Primary_path	3	3	0	3	0	1	46.9787874528034	33.1	29.4	22.4	TRUE	TRUE	TRUE	Tokyo_11_HL4++++Tokyo_09_HL4++++Tokyo_03_HL4++++Tokyo_01_HL12
Tokyo_11_HL4	Tokyo_04_HL12	Secondary_path_totally_disjoint	2.6	3	0	2	1	1	47.0120567438567	36.5	32.6	24.7	TRUE	TRUE	TRUE	Tokyo_11_HL4++++Tokyo_10_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_12_HL4	Tokyo_04_HL12	Primary_path	1.6	2	0	1	1	1	48.7897000433602	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_12_HL4++++Tokyo_13_HL3++++Tokyo_04_HL12
Tokyo_12_HL4	Tokyo_01_HL12	Secondary_path_totally_disjoint	3.8	4	0	4	0	1	45.7418462235086	33.1	29.2	22.2	TRUE	TRUE	TRUE	Tokyo_12_HL4++++Tokyo_10_HL4++++Tokyo_09_HL4++++Tokyo_03_HL4++++Tokyo_01_HL12
Tokyo_14_HL4	Tokyo_04_HL12	Primary_path	0.6	1	0	1	0	1	51.85	33.3	29.8	23.1	TRUE	TRUE	TRUE	Tokyo_14_HL4++++Tokyo_04_HL12
Tokyo_14_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1.6	3	0	2	1	1	47.095390240827	36.5	32.6	24.7	TRUE	TRUE	TRUE	Tokyo_14_HL4++++Tokyo_20_HL4++++Tokyo_16_HL3++++Tokyo_05_HL12
Tokyo_15_HL4	Tokyo_04_HL12	Primary_path	1.2	2	0	2	0	1	48.8397000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_15_HL4++++Tokyo_14_HL4++++Tokyo_04_HL12
Tokyo_15_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1.6	3	0	2	1	1	47.095390240827	36.5	32.6	24.7	TRUE	TRUE	TRUE	Tokyo_15_HL4++++Tokyo_20_HL4++++Tokyo_16_HL3++++Tokyo_05_HL12
Tokyo_17_HL4	Tokyo_04_HL12	Primary_path	1	2	0	1	1	1	48.8646280879734	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_17_HL4++++Tokyo_16_HL3++++Tokyo_04_HL12
Tokyo_17_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1.2	2	0	2	0	1	48.8397000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_17_HL4++++Tokyo_18_HL4++++Tokyo_05_HL12
Tokyo_18_HL4	Tokyo_05_HL12	Primary_path	0.6	1	0	1	0	1	51.85	33.3	29.8	23.1	TRUE	TRUE	TRUE	Tokyo_18_HL4++++Tokyo_05_HL12
Tokyo_18_HL4	Tokyo_01_HL12	Secondary_path_totally_disjoint	1.6	2	0	2	0	1	48.7897000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_18_HL4++++Tokyo_06_HL4++++Tokyo_01_HL12
Tokyo_19_HL4	Tokyo_04_HL12	Primary_path	1	2	0	1	1	1	48.8646280879734	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_19_HL4++++Tokyo_16_HL3++++Tokyo_04_HL12
Tokyo_19_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1.6	3	0	3	0	1	47.095390240827	33.1	29.4	22.4	TRUE	TRUE	TRUE	Tokyo_19_HL4++++Tokyo_17_HL4++++Tokyo_18_HL4++++Tokyo_05_HL12
Tokyo_20_HL4	Tokyo_04_HL12	Primary_path	1.2	2	0	2	0	1	48.8397000433602	33.1	29.6	22.8	TRUE	TRUE	TRUE	Tokyo_20_HL4++++Tokyo_14_HL4++++Tokyo_04_HL12
Tokyo_20_HL4	Tokyo_05_HL12	Secondary_path_totally_disjoint	1	2	0	1	1	1	48.8646280879734	36.5	32.8	25.1	TRUE	TRUE	TRUE	Tokyo_20_HL4++++Tokyo_16_HL3++++Tokyo_05_HL12

Figure 11 Lightpath information screenshot

Finally, the tool also assigns wavelengths to individual traffic demands taking into account the traffic demand and the maximum bitrate supported. For instance, if the traffic demand is 180 Gb/s and the maximum bitrate supported is 50G, then 4 wavelengths are needed; however, if the maximum bitrate supported is 40G, then 5 wavelengths are needed. These wavelengths are assigned to the links in a First-Fit fashion subject to the wavelength continuity constraint. This is recorded in file FFlightpaths.csv, see Figure 12.

V1	V2	V3	V4
lightpath++Tokyo_02_HL4++Tokyo_01_HL12	lightpath++Tokyo_02_HL4++Tokyo_01_HL12	lightpath++Tokyo_02_HL4++Tokyo_01_HL12	lightpath++Tokyo_02_HL4++Tokyo_01_HL12
lightpath++Tokyo_03_HL4++Tokyo_01_HL12	lightpath++Tokyo_03_HL4++Tokyo_01_HL12	lightpath++Tokyo_03_HL4++Tokyo_01_HL12	lightpath++Tokyo_03_HL4++Tokyo_01_HL12
NA	NA	NA	NA
NA	NA	NA	NA
lightpath++Tokyo_06_HL4++Tokyo_01_HL12	lightpath++Tokyo_06_HL4++Tokyo_01_HL12	lightpath++Tokyo_06_HL4++Tokyo_01_HL12	lightpath++Tokyo_06_HL4++Tokyo_01_HL12
NA	NA	NA	NA
NA	NA	NA	NA
NA	NA	NA	NA
NA	NA	NA	NA
NA	NA	NA	NA
lightpath++Tokyo_10_HL4++Tokyo_04_HL12	lightpath++Tokyo_10_HL4++Tokyo_04_HL12	lightpath++Tokyo_10_HL4++Tokyo_04_HL12	lightpath++Tokyo_10_HL4++Tokyo_04_HL12
lightpath++Tokyo_14_HL4++Tokyo_04_HL12	lightpath++Tokyo_14_HL4++Tokyo_04_HL12	lightpath++Tokyo_14_HL4++Tokyo_04_HL12	lightpath++Tokyo_14_HL4++Tokyo_04_HL12
lightpath++Tokyo_17_HL4++Tokyo_04_HL12	lightpath++Tokyo_17_HL4++Tokyo_04_HL12	lightpath++Tokyo_17_HL4++Tokyo_04_HL12	lightpath++Tokyo_17_HL4++Tokyo_04_HL12
NA	NA	NA	NA
lightpath++Tokyo_18_HL4++Tokyo_05_HL12	lightpath++Tokyo_18_HL4++Tokyo_05_HL12	lightpath++Tokyo_18_HL4++Tokyo_05_HL12	lightpath++Tokyo_18_HL4++Tokyo_05_HL12
NA	NA	NA	NA
NA	NA	NA	NA

Figure 12. Wavelength allocation screenshots

The tool finally computes the number of fibers needed to input/output each node, along with the number of VCSEL required to satisfy each node demand, generating a new file with the node configuration and its cost. This is included in file NodeDesign.csv, as shown in Figure 13.

	node_name	nlambdas	deg	degRoadm	cost
Tokyo_02_HL4	Tokyo_02_HL4	24	3	2	637.546
Tokyo_03_HL4	Tokyo_03_HL4	20	4	4	706.395
Tokyo_06_HL4	Tokyo_06_HL4	7	3	4	641.03425
Tokyo_08_HL4	Tokyo_08_HL4	16	3	1	597.324
Tokyo_09_HL4	Tokyo_09_HL4	15	4	3	681.25625
Tokyo_10_HL4	Tokyo_10_HL4	40	4	1	806.95
Tokyo_11_HL4	Tokyo_11_HL4	30	3	1	667.7125
Tokyo_12_HL4	Tokyo_12_HL4	18	4	1	696.3395
Tokyo_14_HL4	Tokyo_14_HL4	4	3	3	536.991
Tokyo_15_HL4	Tokyo_15_HL4	2	3	1	526.9355
Tokyo_17_HL4	Tokyo_17_HL4	17	3	1	602.35175
Tokyo_18_HL4	Tokyo_18_HL4	26	4	3	736.5615
Tokyo_19_HL4	Tokyo_19_HL4	38	3	1	707.9345
Tokyo_20_HL4	Tokyo_20_HL4	10	4	1	656.1175
Tokyo_21_HL4	Tokyo_21_HL4	32	3	1	677.768
Tokyo_22_HL4	Tokyo_22_HL4	16	3	1	597.324
Tokyo_23_HL4	Tokyo_23_HL4	18	3	1	607.3795
Tokyo_07_HL3	Tokyo_07_HL3	24	5	4	815.466
Tokyo_13_HL3	Tokyo_13_HL3	20	5	4	795.355
Tokyo_16_HL3	Tokyo_16_HL3	7	5	4	729.99425
Tokyo_01_HL12	Tokyo_01_HL12	170	5	5	3799.5175
Tokyo_04_HL12	Tokyo_04_HL12	156	5	5	3729.129
Tokyo_05_HL12	Tokyo_05_HL12	58	4	2	3147.4495

Figure 13. Node Configuration CSV screenshot

3.3 Summary Report of the Software Tool

In addition to the csv files summarizing the PASSION dimensioning for a given network topology and traffic matrix, the software tool also dynamically generates a PDF file with the following table of contents:

- Section 1: Network topology description
- Section 2: Optical lightpaths
    - Demand matrix
    - Lightpath characterization
    - Primary paths
    - Secondary paths
    - First-fit wavelength allocation
- Section 3: Node configuration and cost
- Appendix

The appendices include the execution of the software tool for different network topology use cases, including the Milano and Tokyo MAN topologies depicted in Figure 14.

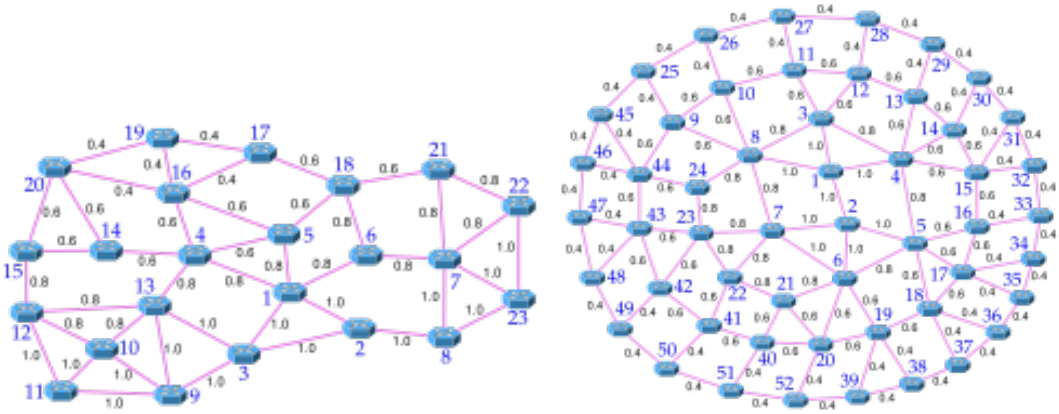

Figure 14 Tokyo (left) and Milano (right) reference topologies.

4 COSTS INCLUDED BY THE TOOL AND COST ASSUMPTIONS

The PASSION WDM planner provides an inventory of transmission (S-BVTs) and switching (routers and ROADMs) resources and their configuration required to carry a given MAN traffic. In addition, **the tool provides an estimation of cost associated to that inventory**. That is the limit of the cost calculation available in this tool, focused on planning. This is because techno-economic analysis realized in PASSION and other EU projects like Metrohaul revealed that most of the deployment bill corresponds primarily to transceivers; secondly, to switching devices. Thus, the design target of the planning tool is the accounting of transceivers as well as switching elements.

However, there are other terms of costs in the TCO that have been excluded intentionally, which should be added in a complete deployment budget. One of these costs is the cost of optical fiber. As stated in D2.4, PASSION is a product intended to be deployed in scenarios where there is plenty of fiber owned by the operator. Thus, 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 (what we have named *hired*field), to very high fiber deployment cost (greenfield) where ducts and trenches need to be made). Therefore, although the number of required optical fibers is accounted, its cost is not included in the deployment bill. An operator should add the fiber cost effect for its specific scenario as the tool is open source. The second simplification is the cost of switches. In order to not introduce too many free variables, we decided to include the cost of commercial ROADMs, rather than estimating a target cost for PASSION HL4 and HL3/HL2/HL1 switches. Therefore, the OSNR computation takes into account the respective insertion impairment of HL4 and HL3 ROADMs but their cost is homogeneous and corresponds to commercial switches. Further prospect on the saving in PASSION switches can be realized, although it is expected to yield to further benefit for the PASSION solution.

The current 2Tb/s S-BVT cost is set to a target price of twice the price of a 400G FT, and the cost per VCSEL license (50Gb/s carrier) is set to 1/40 of the whole S-BVT cost. The current cost settings assume pay-as-you-grow for operators as proposed by PASSION. This can be changed to make the operator assume the cost of the whole S-BVT when deployed or a different intermediate business model (e.g. pay 1/3 of the price on installation and then on a per-lambda basis). There are also two possible points of views; the operator needs to estimate how much it can save with PASSION and the vendor wants to ship as many units as possible. The tool helps PASSION vendors to estimate the number of S-BVTs required for a MAN and allows operators to estimate the economic saving of deployment and upgrade of the infrastructure as traffic grows. The tool made available computes the wavelength planning and cost for a single year. A multi-year analysis like the one made in D2.4 requires multiple executions of the tool. A target saving of 40% is claimed as necessary to cause a technology shift toward the adoption of PASSION by operators. OPEX costs are not included either as the focus of the tool is CAPEX (switching and transmission equipment), and OPEX can simply be modelled as a fixed yearly rate of 12%-15% of the CAPEX. However, it should be noted that S-BVT and remote license activation has implicit OPEX savings.

Table 6 summarizes the numbers used in the tool regarding optical equipment, IP routers, transponders and grey optics. Normalized 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). This information is included in PASSION_cost_component.csv of the software tool.

Table 6 Equipment used for the techno-economic studies and their cost [D2.4]

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

5 Conclusions

This deliverable has provided a set of design guidelines and the description of the software tool to perform WDM planning of MAN networks with PASSION hardware according to those guidelines. The tool has been programmed in open-source R, making use of the igraph library for graph analysis. The tool is fed with the optical characterization of PASSION hardware (for OSNR calculations), hierarchical network topology and traffic matrix, and delivers as outputs, both primary and backup lightpaths, wavelength assignment per fiber link, and techno-economic metrics of the solution, including per-node design and inventory cost. The objective of the tool is exploiting the specific capability of PASSION to perform IP-offloading at intermediate hierarchical levels as described in the guidelines section.

6 References

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7 ACRONYMS

AWG	Arrayed Waveguide Grating
BVT	Bandwidth-Variable Transceiver
CAGR	Compound Average Growth Rate
C-RAN	Cloud Radio Area Network
CAPEX	Capital Expenditure
CDN	Content Delivery Network
CO-Rx	Coherent Receiver
CU	Cost Unit
FT	Fixed Transceiver
HLn	Hierarchy Level n
InP	Indium Phosphide
IPTV	IP Television
KBB	Key Building Block
MA	Margin Adaptive
MAN	Metropolitan Area Network
OPEX	Operational Expenditure
OSNR	Optical Signal-to-Noise Ratio
PD	Photodiode
PDM	Polarization-Division Multiplexing
PSM	Photonic Switching Module
QoT	Quality of Transmission
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
TCO	Total Cost of Ownership
VCSEL	Vertical-Cavity Surface-Emitting Laser
VPN	Virtual Private Network
VR	Virtual Reality
WDM	Wavelength-Division Multiplexing
WSS	Wavelength Selective Switch

8 APPENDICES

PASSION planning and dimensioning tool

PASSION WP6 Research Team

2021-05-28

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Appendix **8**

Summary report

This Rmd file is a tool for planing MAN networks using PASSION technology. This tool receives a hierarchical network topology (with HL1/2 - HL3 - HL4 nodes), traffic demands from all HL4 nodes toward the closest HL1/2 and Passion's OSNR speficiations for traversing the nodes, all in CSV format. The output comprises the optical lightpaths (both primary and backup) from every HL4 node to the closest HL1/2 nodes, including the WDM physical attributes of the lightpath (i.e. end-to-end OSNR and bitrate supported 25/40/50 Gb/s), wavelenght allocation (First-Fit heuristics), hardware node configuration and techno-economics of the solution.

In a nutshell, the planning tool receives as inputs:

- Network topology characterised as files: nodesLabeling.csv and crossMatrix.csv. The first file shows the main features of each node. The second is a matrix that provides connectivity between the nodes (0 if not connected or a number of km if connected).
- Traffic matrix: this is included in nodesLabeling.csv as the amount of traffic injected (in Gb/s) to the MAN per HL4, HL3 and HL12 nodes.
- OSNR requirements for the support of 25, 40 and 50 Gb/s per wavelength, as files osnr_25_oh_fec.csv, osnr_40_oh_fec.csv and osnr_50_oh_fec.csv.
- Normalised equipment cost (in Cost Units), provided in file Passion_cost_components.csv.

Output:

- lightpaths.csv includes the primary and backup paths from each HL4 towards the closest HL1/2. The backup path is both link and node disjoint if possible; if the topology connectivity does not allow it,

the backup path shares the minumum number of links and nodes with the primary path. This file also includes details regarding the end-to-end OSNR, bitrate and route.

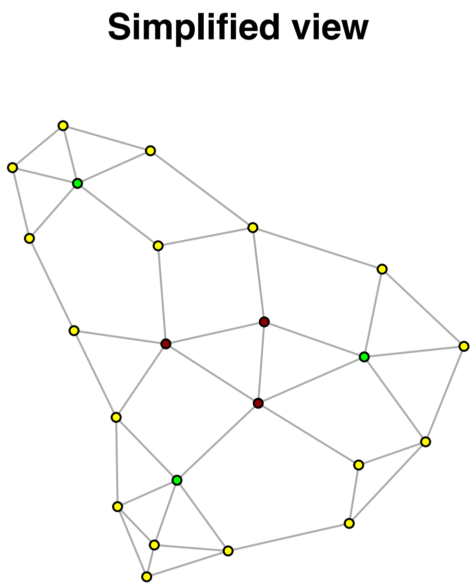
- FFlightpaths.csv provides a description of the wavelength allocation per lightpath
- NodeDesign.csv

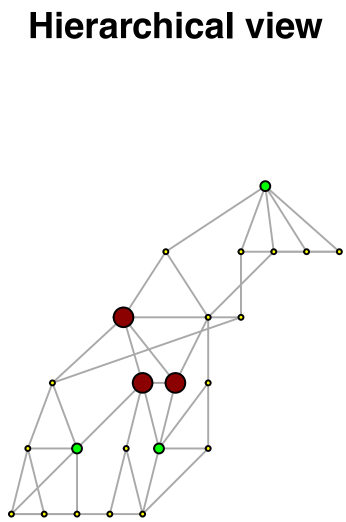
It is worth remarking that this is an R Markdown document, a simple formatting syntax for authoring and dynamically generate PDF documents using R code. For more details on using R Markdown see http://rmarkdown.rstudio.com.

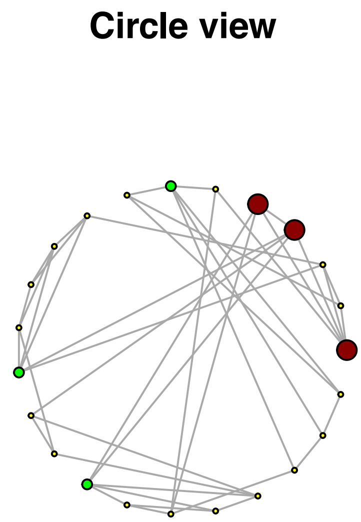
1 Network topology description

The following figures show the network topology used in this study.

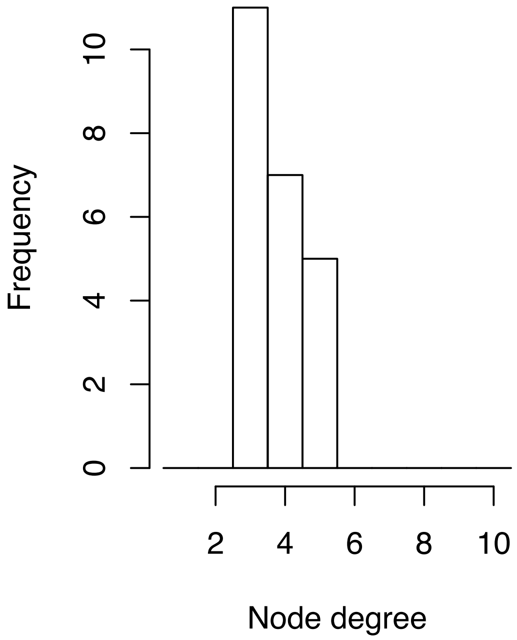
- 3 HL1/2 nodes shown in RED
- 3 HL3 nodes shown in GREEN
- 17 HL4 nodes shown in YELLOW

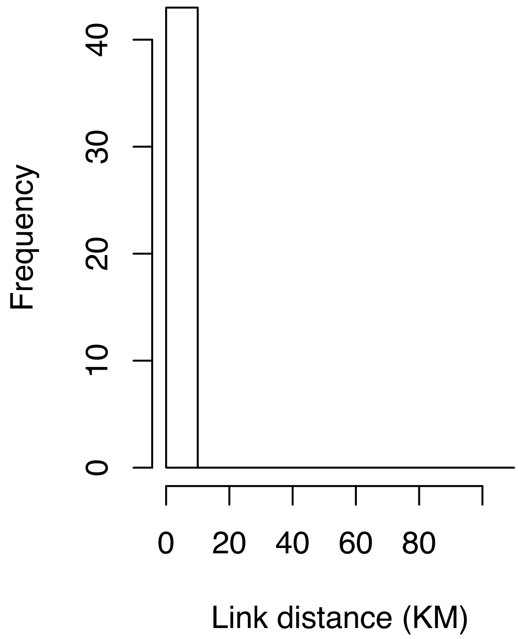






The next figures show a summary of the link lengths and degree per node:





Other properties of the topology are:

- The edge density is 0.1699605
- Average distance is 2.8735178

The following table provides a short summary of the first 10 nodes in the topology:

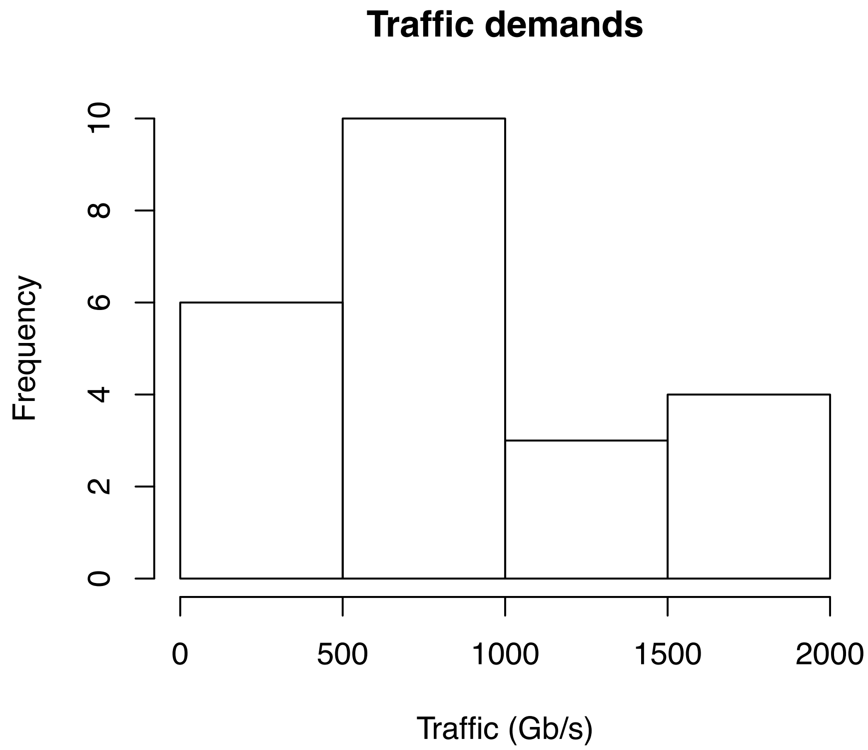
Table 1: Some Nodes (name, type and offered traffic)

	Nodes	Types	Traffic
Tokyo_01_HL12	Tokyo_01	HL12	1200
Tokyo_02_HL4	Tokyo_02	HL4	1000
Tokyo_03_HL4	Tokyo_03	HL4	350
Tokyo_04_HL12	Tokyo_04	HL12	800
Tokyo_05_HL12	Tokyo_05	HL12	750
Tokyo_06_HL4	Tokyo_06	HL4	2000
Tokyo_07_HL3	Tokyo_07	HL3	1500
Tokyo_08_HL4	Tokyo_08	HL4	900
Tokyo_09_HL4	Tokyo_09	HL4	200
Tokyo_10_HL4	Tokyo_10	HL4	100

2 Optical lightpaths

2.1 Demand matrix

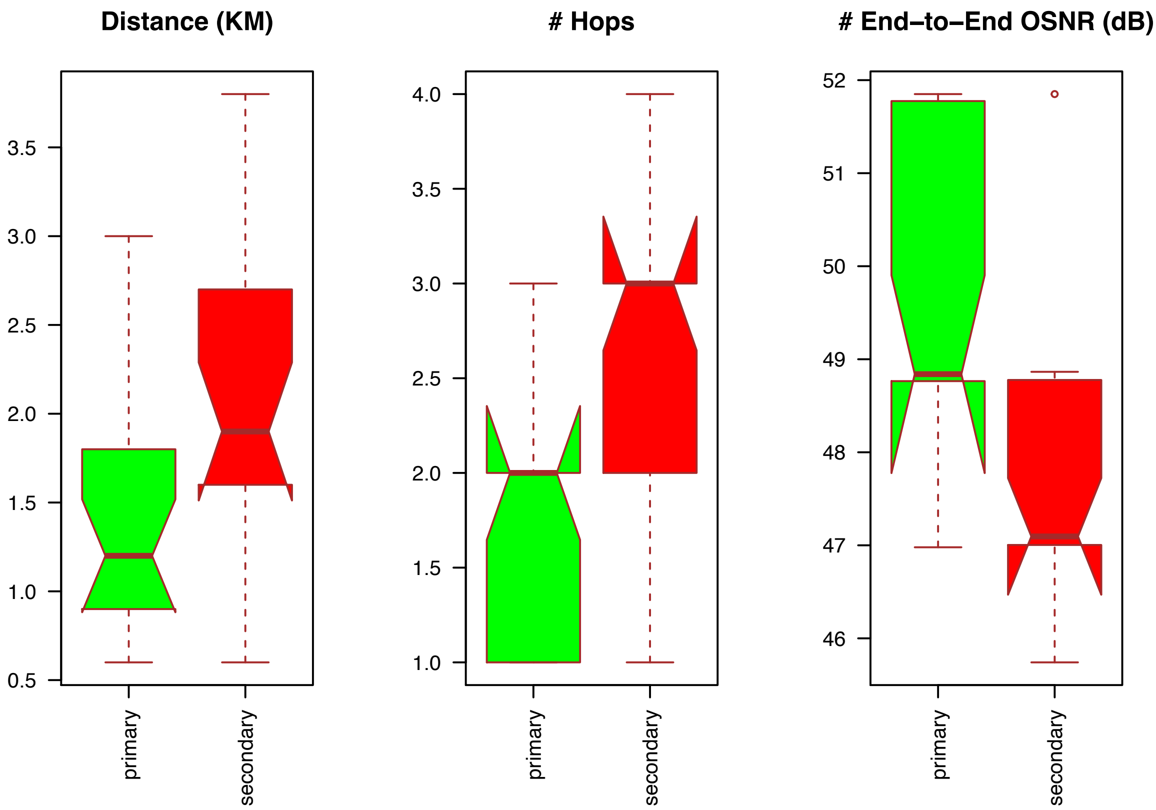
The traffic matrix for the experiment is summarised in the following histogram:



with a mean of 934.7826087 Gb/s.

2.2 Lightpath characterisation

The output file named lightpaths.csv provides the final description of every HL4-HL1/2 lightpath in the network topology. This includes both the route (sequence of links and nodes traversed) for both primary and secondary path, along with other characteristics, like the distance in hops and KM, end-to-end OSNR and whether or not the OSNR is good enough to support the transmission at 25, 40 and 50 Gb/s. The following boxplots provide a summary of the main distance metrics (hops and KM) of all lightpaths (primary in green, secondary in red), as well as the final end-to-end OSNR per lightpath:



2.3 Primary paths

Concerning primary paths, the average distance is 1.39 km and 1.8 hops. The selected distination HL1/2 are:

Table 2: Destination HL1/2 node

	Destination
Tokyo_01_HL12	9
Tokyo_04_HL12	9
Tokyo_05_HL12	2

and the percentage of lightpaths supporting each Bitrate is:

Table 3: Bitrates supported (primary lightpath)

	Percentage
Can_25G	100
Can_40G	100
Can_50G	100

2.4 Backup paths

Concerning backup paths, the average distance is 2.05 km and 2.7 hops. Their characterisation is

Table 4: Backup path type

	Backup_type
Secondary_path_totally_disjoint	20

The selected distination HL1/2 are:

Table 5: Destination HL1/2 node

	Destination
Tokyo_01_HL12	5
Tokyo_04_HL12	4
Tokyo_05_HL12	11

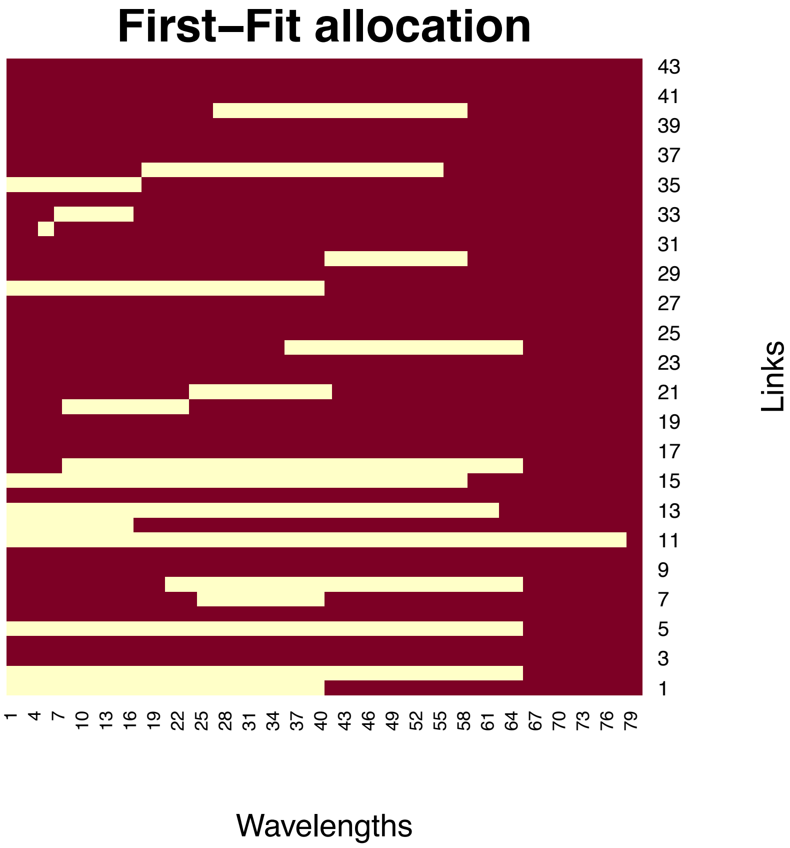
and the percentage of lightpaths supporting each Bitrate is:

Table 6: Bitrates supported (sec lightpath)

	Percentage
Can_25G	100
Can_40G	100
Can_50G	100

2.5 First-Fit wavelength allocation

Finally, First-Fit wavelength allocation of traffic demands heatmap, where occupied wavelengths are displayed in yellow, and empty ones are in red:



A CSV output file names FFlightpaths.csv is created with the wavelength allocation per lightpath.

3 Node Configuration and Cost

The following tables show the final configuration of each HL4 and HL1/2 node, including ROADMs, and Passion S-BVTs:

Table 7: HL4 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
Tokyo_02_HL4	24	50	2	637.5460
Tokyo_03_HL4	20	50	4	706.3950
Tokyo_06_HL4	7	50	4	641.0343
Tokyo_08_HL4	16	50	1	597.3240
Tokyo_09_HL4	15	50	3	681.2563
Tokyo_10_HL4	40	50	1	806.9500
Tokyo_11_HL4	30	50	1	667.7125
Tokyo_12_HL4	18	50	1	696.3395
Tokyo_14_HL4	4	50	3	536.9910
Tokyo_15_HL4	2	50	1	526.9355
Tokyo_17_HL4	17	50	1	602.3518
Tokyo_18_HL4	26	50	3	736.5615
Tokyo_19_HL4	38	50	1	707.9345
Tokyo_20_HL4	10	50	1	656.1175
Tokyo_21_HL4	32	50	1	677.7680

	nlambdas	speed	degRoadm	cost
Tokyo_22_HL4	16	50	1	597.3240
Tokyo_23_HL4	18	50	1	607.3795

Table 8: HL3 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
Tokyo_07_HL3	24	50	4	815.4660
Tokyo_13_HL3	20	50	4	795.3550
Tokyo_16_HL3	7	50	4	729.9942

Table 9: HL1/2 HW configuration and cost (in CU)

	nlambdas	degRoadm	cost
Tokyo_01_HL12	170	5	3799.517
Tokyo_04_HL12	156	5	3729.129
Tokyo_05_HL12	58	2	3147.450

Finally, the total cost of ownership of the Passion solution applied to this topology is:

Table 10: Total Cost (in CU)

TCO
24100.83

Appendix

Software code developed with R Studio v. 1.4.1103.

- Open-source software: R version 3.6.3 (2020-02-29) and igraph library

PASSION planning and dimensioning tool

PASSION WP6 Research Team

2021-05-28

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2.2 Lightpath characterisation . . . 4
2.3 Primary paths . . . 5
2.4 Backup paths . . . 6
2.5 First-Fit wavelength allocation . . . 6

3 Node Configuration and Cost **7**

Appendix **9**

Summary report

This Rmd file is a tool for planing MAN networks using PASSION technology. This tool receives a hierarchical network topology (with HL1/2 - HL3 - HL4 nodes), traffic demands from all HL4 nodes toward the closest HL1/2 and Passion's OSNR speficiations for traversing the nodes, all in CSV format. The output comprises the optical lightpaths (both primary and backup) from every HL4 node to the closest HL1/2 nodes, including the WDM physical attributes of the lightpath (i.e. end-to-end OSNR and bitrate supported 25/40/50 Gb/s), wavelenght allocation (First-Fit heuristics), hardware node configuration and techno-economics of the solution.

In a nutshell, the planning tool receives as inputs:

- Network topology characterised as files: nodesLabeling.csv and crossMatrix.csv. The first file shows the main features of each node. The second is a matrix that provides connectivity between the nodes (0 if not connected or a number of km if connected).
- Traffic matrix: this is included in nodesLabeling.csv as the amount of traffic injected (in Gb/s) to the MAN per HL4, HL3 and HL12 nodes.
- OSNR requirements for the support of 25, 40 and 50 Gb/s per wavelength, as files osnr_25_oh_fec.csv, osnr_40_oh_fec.csv and osnr_50_oh_fec.csv.
- Normalised equipment cost (in Cost Units), provided in file Passion_cost_components.csv.

Output:

- lightpaths.csv includes the primary and backup paths from each HL4 towards the closest HL1/2. The backup path is both link and node disjoint if possible; if the topology connectivity does not allow it,

the backup path shares the minumum number of links and nodes with the primary path. This file also includes details regarding the end-to-end OSNR, bitrate and route.

- FFlightpaths.csv provides a description of the wavelength allocation per lightpath
- NodeDesign.csv

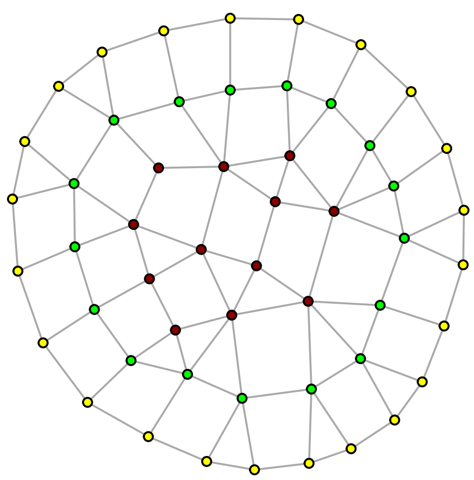
It is worth remarking that this is an R Markdown document, a simple formatting syntax for authoring and dynamically generate PDF documents using R code. For more details on using R Markdown see http://rmarkdown.rstudio.com.

1 Network topology description

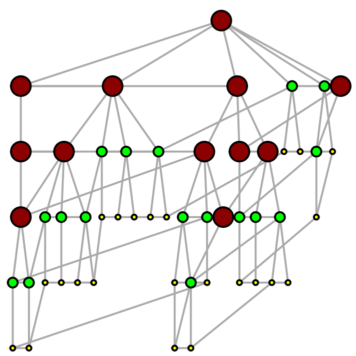
The following figures show the network topology used in this study.

- 12 HL1/2 nodes shown in RED
- 17 HL3 nodes shown in GREEN
- 23 HL4 nodes shown in YELLOW

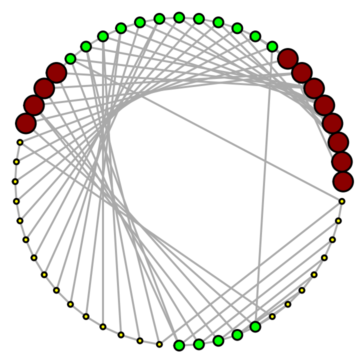
Simplified view



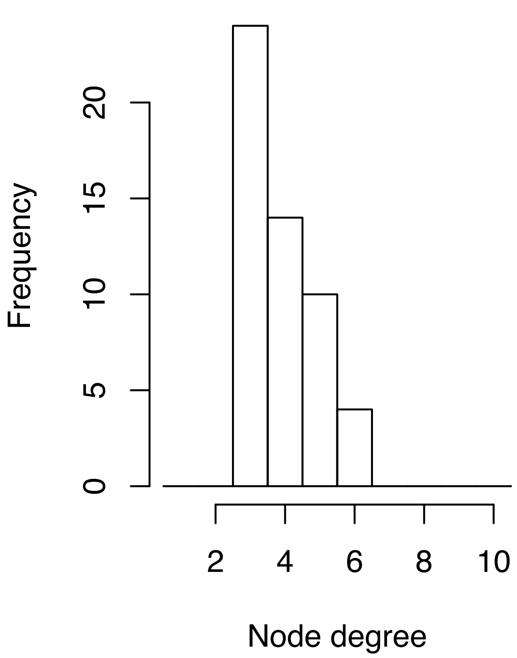
Hierarchical view

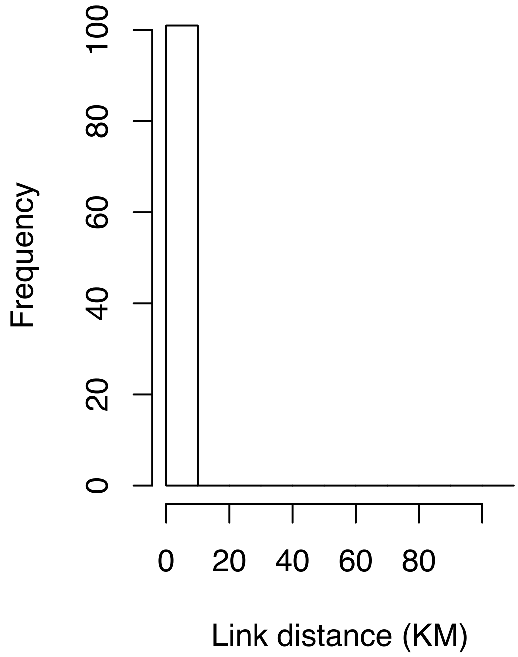


Circle view



The next figures show a summary of the link lengths and degree per node:





Other properties of the topology are:

- The edge density is 0.0761689
- Average distance is 4.0316742

The following table provides a short summary of the first 10 nodes in the topology:

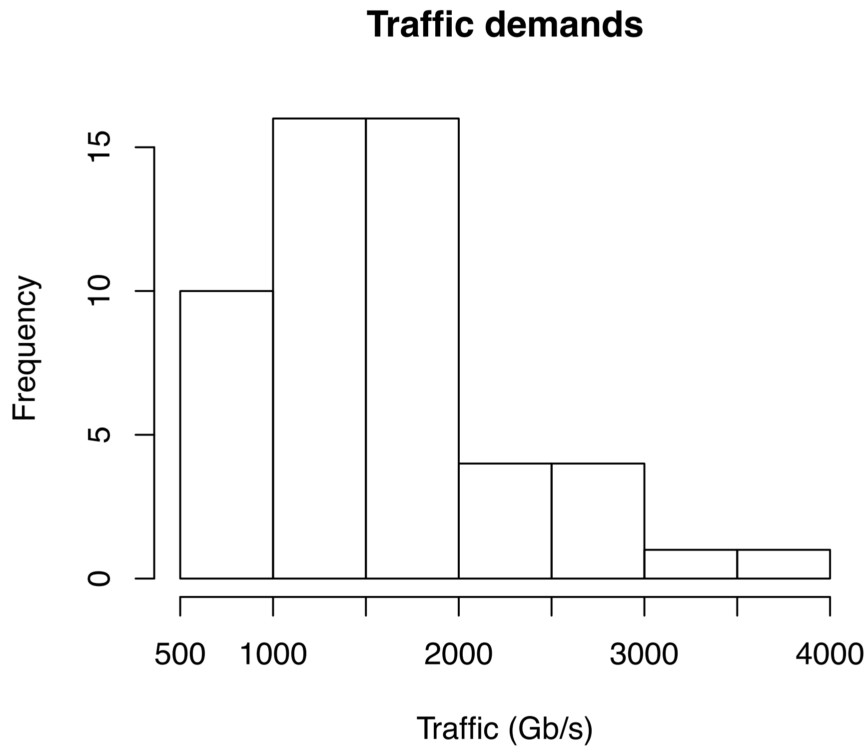
Table 1: Some Nodes (name, type and offered traffic)

	Nodes	Types	Traffic
Node1_HL12	Node1	HL12	1200
Node2_HL12	Node2	HL12	3000
Node3_HL12	Node3	HL12	2000
Node4_HL12	Node4	HL12	2700
Node5_HL12	Node5	HL12	4000
Node6_HL12	Node6	HL12	1500
Node7_HL12	Node7	HL12	1900
Node8_HL12	Node8	HL12	3100
Node9_HL3	Node9	HL3	2000
Node10_HL3	Node10	HL3	2200

2 Optical lightpaths

2.1 Demand matrix

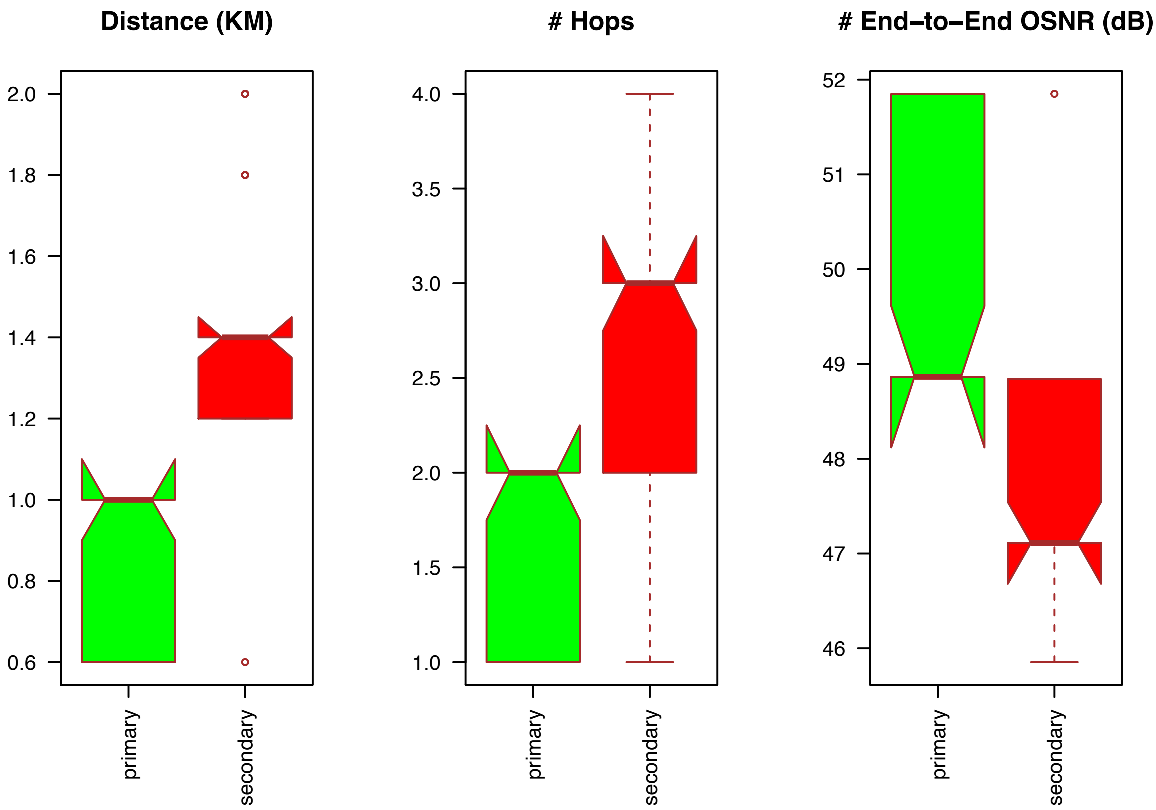
The traffic matrix for the experiment is summarised in the following histogram:



with a mean of 1642.3076923 Gb/s.

2.2 Lightpath characterisation

The output file named lightpaths.csv provides the final description of every HL4-HL1/2 lightpath in the network topology. This includes both the route (sequence of links and nodes traversed) for both primary and secondary path, along with other characteristics, like the distance in hops and KM, end-to-end OSNR and whether or not the OSNR is good enough to support the transmission at 25, 40 and 50 Gb/s. The following boxplots provide a summary of the main distance metrics (hops and KM) of all lightpaths (primary in green, secondary in red), as well as the final end-to-end OSNR per lightpath:



2.3 Primary paths

Concerning primary paths, the average distance is 0.83 km and 1.575 hops. The selected distination HL1/2 are:

Table 2: Destination HL1/2 node

	Destination
Node21_HL12	2
Node22_HL12	2
Node23_HL12	5
Node24_HL12	3
Node3_HL12	4
Node4_HL12	7
Node5_HL12	8
Node6_HL12	5
Node8_HL12	4

and the percentage of lightpaths supporting each Bitrate is:

Table 3: Bitrates supported (primary lightpath)

	Percentage
Can_25G	100
Can_40G	100

	Percentage
Can_50G	100

2.4 Backup paths

Concerning backup paths, the average distance is 1.41 km and 2.75 hops. Their characterisation is

Table 4: Backup path type

	Backup_type
Secondary_path_totally_disjoint	40

The selected distination HL1/2 are:

Table 5: Destination HL1/2 node

	Destination
Node21_HL12	5
Node22_HL12	3
Node23_HL12	1
Node24_HL12	4
Node3_HL12	6
Node4_HL12	6
Node5_HL12	5
Node6_HL12	6
Node8_HL12	4

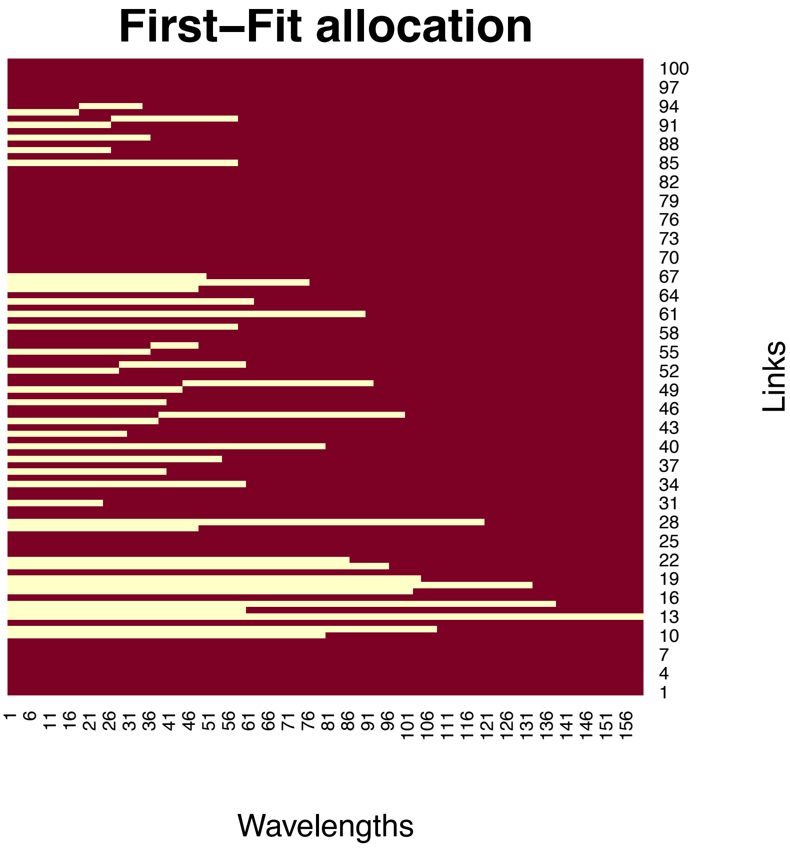
and the percentage of lightpaths supporting each Bitrate is:

Table 6: Bitrates supported (sec lightpath)

	Percentage
Can_25G	100
Can_40G	100
Can_50G	100

2.5 First-Fit wavelength allocation

Finally, First-Fit wavelength allocation of traffic demands heatmap, where occupied wavelengths are displayed in yellow, and empty ones are in red:



A CSV output file names FFlightpaths.csv is created with the wavelength allocation per lightpath.

3 Node Configuration and Cost

The following tables show the final configuration of each HL4 and HL1/2 node, including ROADMs, and Passion S-BVTs:

Table 7: HL4 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
Node25_HL4	24	50	1	637.5460
Node26_HL4	60	50	2	818.5450
Node27_HL4	40	50	1	717.9900
Node28_HL4	54	50	2	788.3785
Node29_HL4	80	50	2	919.1000
Node30_HL4	30	50	1	667.7125
Node31_HL4	38	50	1	707.9345
Node32_HL4	62	50	2	828.6005
Node33_HL4	40	50	1	717.9900
Node34_HL4	44	50	2	738.1010
Node35_HL4	48	50	2	758.2120
Node36_HL4	28	50	1	657.6570
Node37_HL4	32	50	1	677.7680
Node38_HL4	36	50	1	697.8790
Node39_HL4	12	50	1	577.2130

	nlambdas	speed	degRoadm	cost
Node45_HL4	18	50	1	607.3795
Node46_HL4	16	50	1	597.3240
Node47_HL4	26	50	1	647.6015
Node48_HL4	32	50	1	677.7680
Node49_HL4	36	50	1	697.8790
Node50_HL4	26	50	1	647.6015
Node51_HL4	58	50	2	808.4895
Node52_HL4	58	50	2	808.4895

Table 8: HL3 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
Node9_HL3	24	50	3	726.5060
Node10_HL3	60	50	5	996.4650
Node11_HL3	40	50	3	806.9500
Node12_HL3	54	50	5	966.2985
Node13_HL3	80	50	6	1185.9800
Node14_HL3	30	50	3	756.6725
Node15_HL3	38	50	7	1063.7745
Node16_HL3	62	50	4	917.5605
Node17_HL3	40	50	8	1162.7900
Node18_HL3	44	50	5	916.0210
Node19_HL3	48	50	5	936.1320
Node20_HL3	28	50	5	835.5770
Node40_HL3	32	50	5	855.6880
Node41_HL3	36	50	3	786.8390
Node42_HL3	12	50	3	666.1730
Node43_HL3	18	50	4	785.2995
Node44_HL3	16	50	4	775.2440

Table 9: HL1/2 HW configuration and cost (in CU)

	nlambdas	degRoadm	cost
Node1_HL12	0	0	2855.840
Node2_HL12	0	0	2855.840
Node3_HL12	188	5	3890.017
Node4_HL12	358	10	5189.534
Node5_HL12	338	10	5088.980
Node6_HL12	182	6	3948.811
Node7_HL12	0	0	2944.800
Node8_HL12	168	5	3878.422
Node21_HL12	90	3	3308.338
Node22_HL12	62	2	3167.561
Node23_HL12	124	4	3568.241
Node24_HL12	50	2	3018.267

Finally, the total cost of ownership of the Passion solution applied to this topology is:

Table 10: Total Cost (in CU)

TCO
75257.78

Appendix

Software code developed with R Studio v. 1.4.1103.

- Open-source software: R version 3.6.3 (2020-02-29) and igraph library

PASSION planning and dimensioning tool

PASSION WP6 Research Team

2021-05-28

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- OSNR requirements for the support of 25, 40 and 50 Gb/s per wavelength, as files osnr_25_oh_fec.csv, osnr_40_oh_fec.csv and osnr_50_oh_fec.csv.
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Output:

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- FFlightpaths.csv provides a description of the wavelength allocation per lightpath
- NodeDesign.csv

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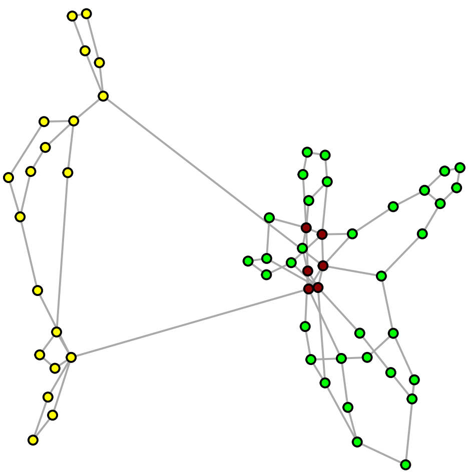
1 Network topology description

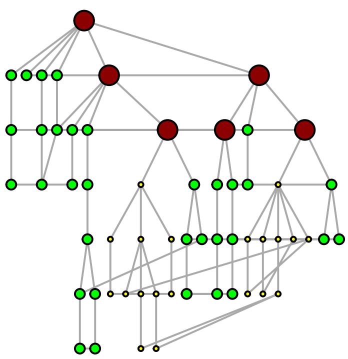
The following figures show the network topology used in this study.

- 6 HL1/2 nodes shown in RED
- 33 HL3 nodes shown in GREEN
- 20 HL4 nodes shown in YELLOW

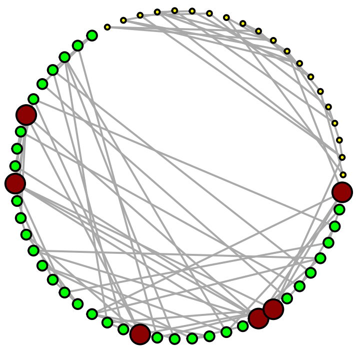
Simplified view



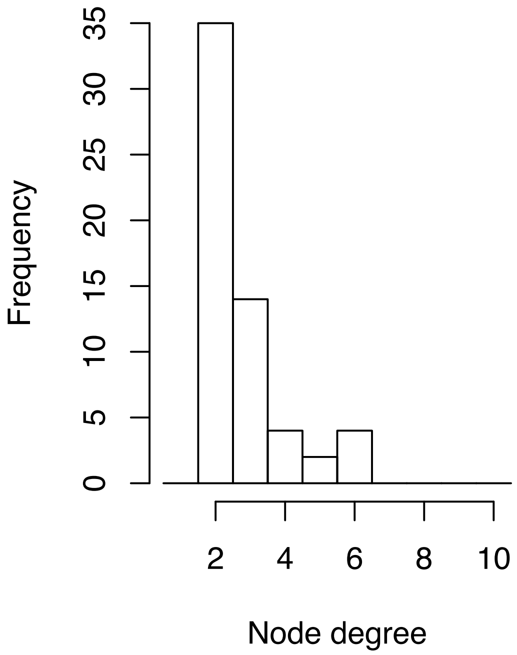
Hierarchical view

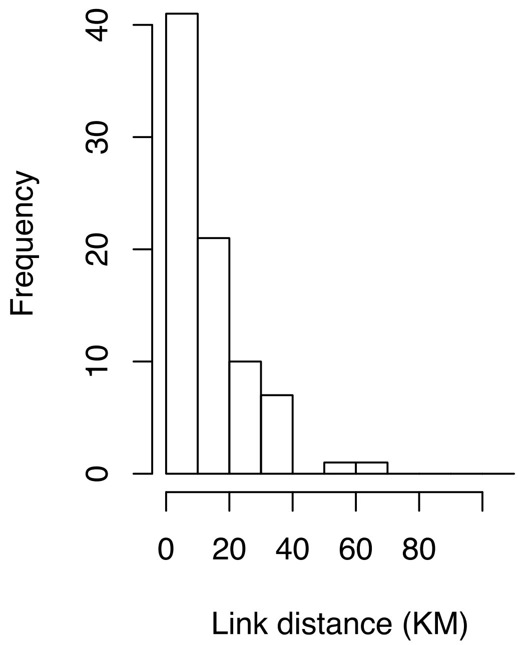


Circle view



The next figures show a summary of the link lengths and degree per node:





Other properties of the topology are:

- The edge density is 0.0473407
- Average distance is 4.4202221

The following table provides a short summary of the first 10 nodes in the topology:

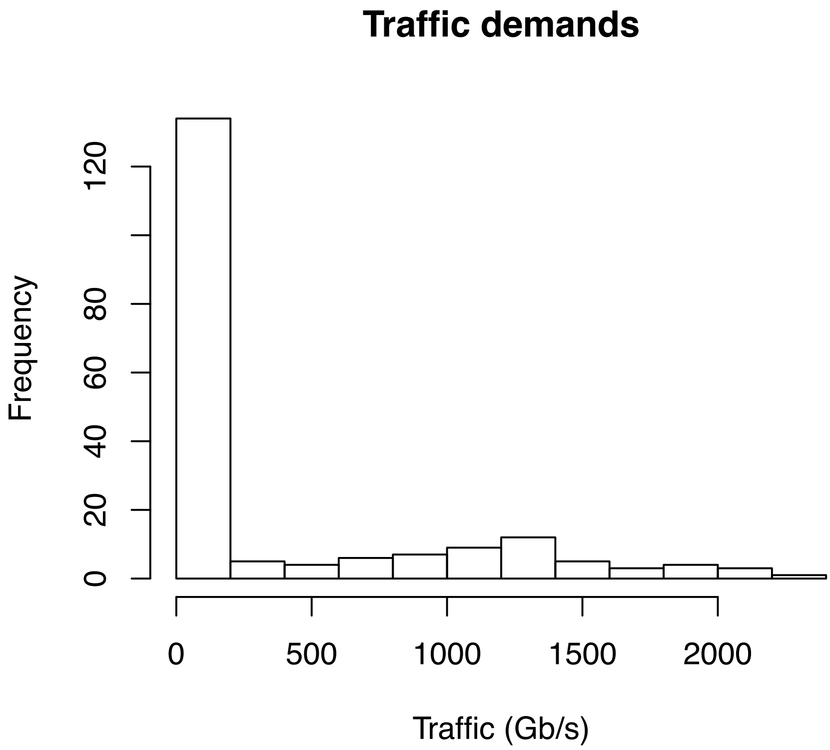
Table 1: Some Nodes (name, type and offered traffic)

	Nodes	Types	Traffic
02-00001_AN_1_HL5	02-00001_AN_1	HL5	150
02-00002_AN_1_HL5	02-00002_AN_1	HL5	150
02-00004_AN_1_HL4	02-00004_AN_1	HL4	450
02-00006_AN_1_HL5	02-00006_AN_1	HL5	150
02-00007_AN_1_HL5	02-00007_AN_1	HL5	150
02-00008_AN_1_HL5	02-00008_AN_1	HL5	150
02-00010_AN_1_HL5	02-00010_AN_1	HL5	150
02-00012_AN_1_HL5	02-00012_AN_1	HL5	150
02-00013_AN_1_HL5	02-00013_AN_1	HL5	150
02-00014_AN_1_HL5	02-00014_AN_1	HL5	150

2 Optical lightpaths

2.1 Demand matrix

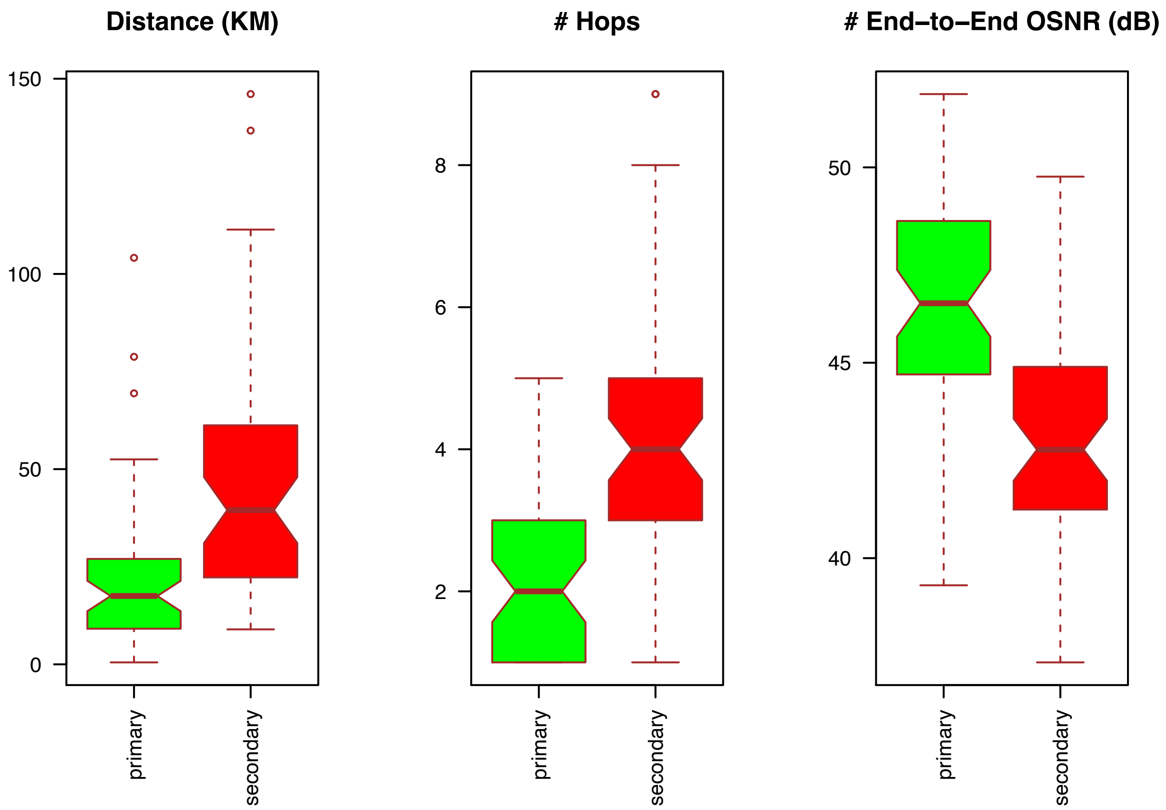
The traffic matrix for the experiment is summarised in the following histogram:



with a mean of 459.3264249 Gb/s.

2.2 Lightpath characterisation

The output file named lightpaths.csv provides the final description of every HL4-HL1/2 lightpath in the network topology. This includes both the route (sequence of links and nodes traversed) for both primary and secondary path, along with other characteristics, like the distance in hops and KM, end-to-end OSNR and whether or not the OSNR is good enough to support the transmission at 25, 40 and 50 Gb/s. The following boxplots provide a summary of the main distance metrics (hops and KM) of all lightpaths (primary in green, secondary in red), as well as the final end-to-end OSNR per lightpath:



2.3 Primary paths

Concerning primary paths, the average distance is 21.8249057 km and 2.1698113 hops. The selected distination HL1/2 are:

Table 2: Destination HL1/2 node

	Destination
09-00158_HL12	5
09-00207_HL12	11
09-00909_HL12	7
09-03381_HL12	1
09-03385_HL12	17
09-06005_HL12	12

and the percentage of lightpaths supporting each Bitrate is:

Table 3: Bitrates supported (primary lightpath)

	Percentage
Can_25G	100.00000
Can_40G	100.00000
Can_50G	94.33962

2.4 Backup paths

Concerning backup paths, the average distance is 46.4196226 km and 4.3584906 hops. Their characterisation is

Table 4: Backup path type

	Backup_type
Secondary_path_shared_1nodes0links	7
Secondary_path_totally_disjoint	46

The selected distination HL1/2 are:

Table 5: Destination HL1/2 node

	Destination
09-00158_HL12	4
09-00207_HL12	5
09-00909_HL12	8
09-03381_HL12	3
09-03385_HL12	19
09-06005_HL12	14

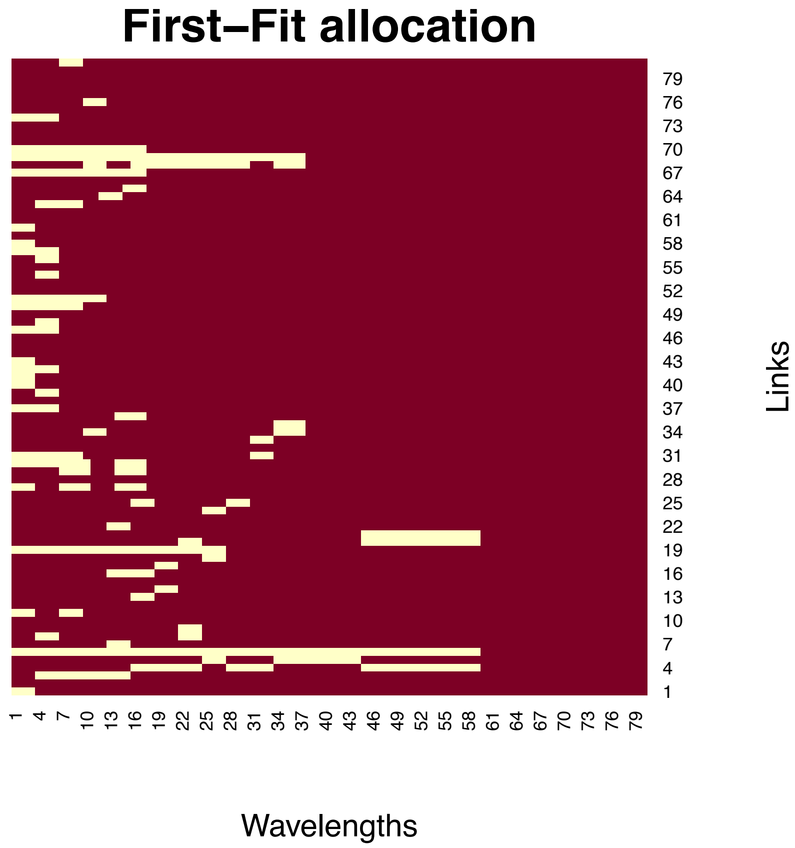
and the percentage of lightpaths supporting each Bitrate is:

Table 6: Bitrates supported (sec lightpath)

	Percentage
Can_25G	100.00000
Can_40G	96.22642
Can_50G	71.69811

2.5 First-Fit wavelength allocation

Finally, First-Fit wavelength allocation of traffic demands heatmap, where occupied wavelengths are displayed in yellow, and empty ones are in red:



A CSV output file names FFlightpaths.csv is created with the wavelength allocation per lightpath.

3 Node Configuration and Cost

The following tables show the final configuration of each HL4 and HL1/2 node, including ROADMs, and Passion S-BVTs:

Table 7: HL4 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
02-00004_AN_1_HL4	3	50	1	443.0032
02-00035_AN_1_HL4	3	50	5	709.8832
02-00038_AN_1_HL4	9	50	2	473.1698
02-00504_AN_1_HL4	3	50	2	443.0032
02-00505_AN_1_HL4	3	50	1	443.0032
02-00506_AN_1_HL4	3	50	2	443.0032
02-00902_AN_1_HL4	3	50	1	443.0032
02-00907_AN_1_HL4	3	50	1	443.0032
02-02201_AN_1_HL4	3	50	6	798.8433
02-02203_AN_1_HL4	3	50	2	443.0032
02-02214_AN_1_HL4	3	50	1	531.9633
02-02217_AN_1_HL4	3	50	2	443.0032
02-02247_AN_1_HL4	3	50	1	443.0032
02-02416_AN_1_HL4	3	50	1	443.0032
02-02422_AN_1_HL4	3	50	2	443.0032

	nlambdas	speed	degRoadm	cost
02-02430__AN__1__HL4	3	50	1	443.0032
02-02439__AN__1__HL4	3	50	4	620.9233
02-02440__AN__1__HL4	11	50	2	483.2253
02-02444__AN__1__HL4	3	50	1	531.9633
02-03021__AN__1__HL4	15	50	1	503.3363

Table 8: HL3 HW configuration and cost (in CU)

	nlambdas	speed	degRoadm	cost
09-00011__HL3	3	50	2	531.9633
09-00023__HL3	3	50	2	443.0032
09-00074__HL3	9	50	2	562.1297
09-00085__HL3	3	50	2	531.9633
09-00130__HL3	4	40	2	448.0310
09-00151__HL3	3	50	2	531.9633
09-00166__HL3	3	50	2	531.9633
09-00178__HL3	3	50	1	443.0032
09-00195__HL3	3	50	1	443.0032
09-00212__HL3	3	50	2	443.0032
09-00233__HL3	3	50	1	443.0032
09-00235__HL3	3	50	2	531.9633
09-00261__HL3	3	50	1	443.0032
09-00268__HL3	3	50	1	443.0032
09-00291__HL3	3	50	1	443.0032
09-00571__HL3	3	50	2	443.0032
09-00901__HL3	3	50	1	443.0032
09-00902__HL3	11	50	3	661.1453
09-00903__HL3	3	50	3	531.9633
09-00904__HL3	15	50	2	503.3363
09-00911__HL3	3	50	2	531.9633
09-00914__HL3	3	50	1	443.0032
09-03083__HL3	3	50	2	531.9633
09-03102__HL3	3	50	1	443.0032
09-03138__HL3	3	50	1	531.9633
09-03163__HL3	3	50	3	531.9633
09-03424__HL3	4	40	1	448.0310
09-03467__HL3	3	50	1	443.0032
09-03501__HL3	4	40	1	448.0310
09-03649__HL3	3	50	1	531.9633
09-03943__HL3	3	50	2	443.0032
09-03962__HL3	3	50	1	443.0032
09-04361__HL3	3	50	1	443.0032

Table 9: HL1/2 HW configuration and cost (in CU)

	nlambdas	degRoadm	cost
09-00158__HL12	15	4	3109.176
09-00207__HL12	33	4	3199.676
09-00909__HL12	23	2	3060.438

	nlambdas	degRoadm	cost
09-03381_HL12	3	1	2959.883
09-03385_HL12	96	3	3516.424
09-06005_HL12	44	2	3077.061

Finally, the total cost of ownership of the Passion solution applied to this topology is:

Table 10: Total Cost (in CU)

TCO
44902.36

Appendix

Software code developed with R Studio v. 1.4.1103.

- Open-source software: R version 3.6.3 (2020-02-29) and igraph library