How to do unbundling in PON

Proposals for unbundling in optical access network using WDM

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Review 0.2

Contents

Foreword

Several different types of bandwidth-hungry applications and services, including multimedia oriented applications such as high-definition television (HDTV), are rapidly being deployed in the access network. Hence, telecommunication operators are driven to upgrade their access networks to provide broader bandwidth for their subscribers [1].

The growing demand of bandwidth requires the deployment of a new optical access network, but it places several questions of different nature, first of all: "Who will sustain costs". This question probably does not still have answer today in Italy, but fortunately it is out of our purposes. Instead an interesting question is "How to share the network among operators", in other word, how to approach unbundling problem in optical network. This document tries to answer this question.

Framework

Before entering in the unbundling proposals details, this section shows the assumptions made.

Complete passive optical network

Various optical access architectures, such as point-to-point (P2P) dedicated fiber or active optical networks have been proposed and even tried in various deployments but recently passive optical network (PON) has emerged as the most flexible, scalable, and future-proof optical access technology. The flexibility of PON lies in its simple point-to-multipoint topology, low-cost implementation, and relative ease of deployment [2]. For this reason, unbundling proposals are based upon the architecture depicted in Figure 1.

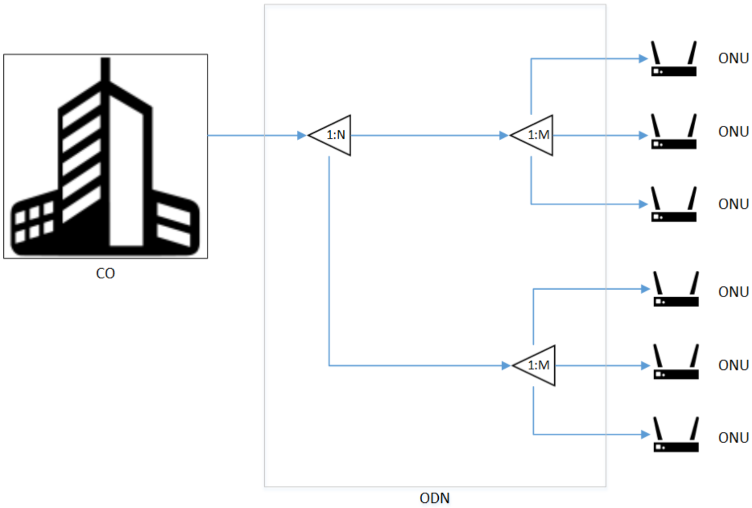

FIGURE 1 - COMPLETE PASSIVE OPTICAL NETWORK ARCHITECTURE

This architecture only uses passive components in ODN. Alternative solutions with AWGs will be evaluated in future works.

PON greenfield scenario

The ROAD-NGN project includes, as a case-study, the new optical access network of the historical downtown L'Aquila, which still is to be rebuilt after the destructive earthquake of April 6th 2009. In this scenario, the requirement of coexistence with legacy PONs could be not necessary.

FIGURE 2 - ROAD-NGN LOGO [3]

An area where PON had not been previously deployed is referred to as "PON greenfield" [4].

Full-spectrum fiber

Historically, conventional single mode fiber had high attenuation at 1383 nm (commonly referred to as the water-peak) and nearby wavelengths making transmission in this part of the spectrum challenging. The increased attenuation results from absorption of OH ions during the manufacturing process. The International Telecommunication Union standard (ITU-T G.652.D) sharply limits attenuation at/near the water-peak, extending the range of possible transmission signals. The industry commercially refers to these fibers as "reduced-water-peak (RWP) fibers", "low-water-peak fibers" or "full spectrum fibers" [5].

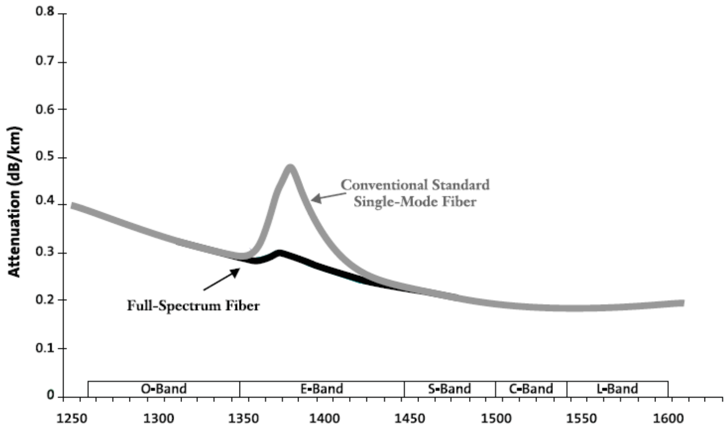

FIGURE 3 - COMPARISON OF CONVENTIONAL AND FULL-SPECTRUM SINGLE-MODE FIBER [6]

Unbundling proposal is based upon this type of fiber.

Transmission technologies

G-PON and EPON are right now the dominant deployed optical access systems in the world. This fact comes from the very low cost of the TDM-PON technology and architecture. The optical fiber plant is the most cost effective possible, and the opto-electronic equipment has been cost-reduced to levels that are really quite remarkable. The growth of demand will eventually outstrip the gigabit technologies and require an upgrade of the network. So, interested groups such as FSAN, IEEE, and ITU SG-15 have begun standardization efforts to contemplate what comes next (Figure 4).

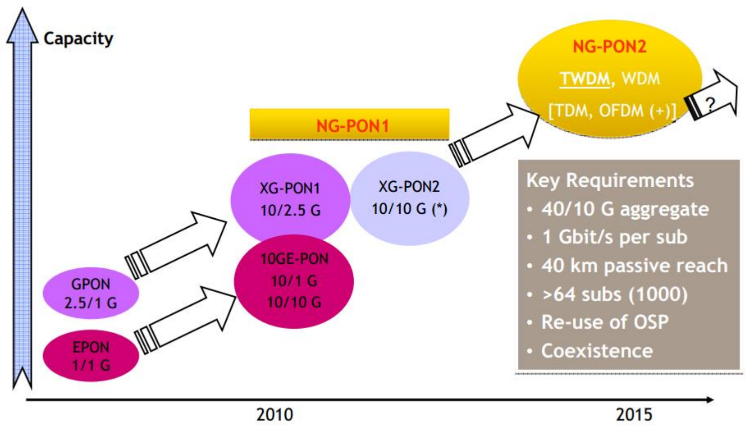

FIGURE 4 - PON STANDARDIZATION ROADMAP [7]

The first crop of replacement systems were 10GE-PON and XG-PON, with efforts starting around 2006 and culminating in standards about 2009. Close on the heels of this work, FSAN has carried on with a study effort named NG-PON2 [8]. The standardization of this new system is currently in process. The first document (ITU-T G.989.1) has released since the end of 2013.

	XG-PON1	NG-PON2
Multiplexing	TDM	TWDM (TDM+WDM)
wavelength DS	1575-1580 nm	4, 8 or 16 wavelenghts
wavelength US	1260-1280 nm	4, 8 or 16 wavelenghts
Feeder capacity DS **User capacity DS**	10 Gbit/s 10 Gbit/s	40 Gbit/s (up to 160 Gbit/s) 10 Gbit/s
Feeder capacity US **User capacity US**	2.5 Gbit/s 2.5 Gbit/s	10 Gbit/s (up to 80 Gbit/s) 10 Gbit/s
Split ratio	Up to 1:256	Up to 1:256
Maximum fibre distance	Up to 60 km	Up to 60 km
Standard	ITU-T G.987 series	ITU-T G.989.1

FIGURE 5 - COMPARISON OF XG-PON1 AND NG-PON2

XG-PON1 and NG-PON2 (also known with TWDM-PON) are essential building block for the proposals in next section. Figure 5 shows a comparison of these two technologies.

Unbundling proposal

Unbundling proposal here presented uses similar concepts mobile network has already used several time, for example in LTE technology as shown in Figure 6.

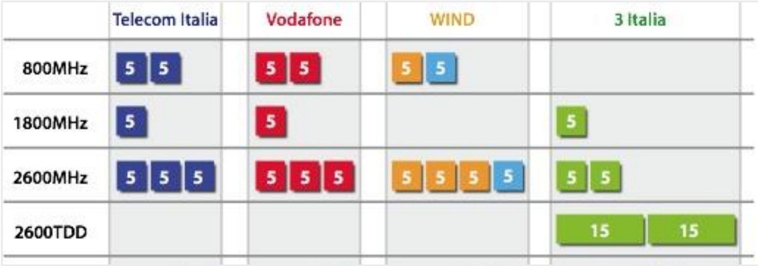

FIGURE 6 - LTE FREQUENCY ALLOCATION TO ITALIAN OPERATORS [9]

The unbundling proposal consists in three steps:

- Bandwidth characterization: to characterize fiber bandwidth with a cost for each wavelength;
- Bandwidth partitioning: to partition fiber bandwidth in slot;
- Bandwidth assigning: to assign several slot to the operators following fairness constraints.

Bandwidth characterization

The characterization of the fiber bandwidth is an essential step to create an allocation process with fairness requirements.

Bandwidth characterization builds a cost index in $[dB]$. For each wavelength, cost index takes into account three effects

$$C(\lambda) = c_a(\lambda) + c_d(\lambda) + c_s(\lambda)\ [dB]$$

EQUATION 1 - COST INDEX FOR FIBER CHARACTERIZATION

where c_a represents distance attenuation effect, c_d represents chromatic dispersion effect and c_s represents receiver sensitivity.

Distance attenuation

The primary specification of optical fiber is the attenuation. Attenuation means a loss of optical power. The attenuation of an optical fiber is expressed by the attenuation coefficient which is defined as the loss of the fiber per unit length, in dB/km [10].

Figure 7 shows a typical full-spectrum attenuation curve.

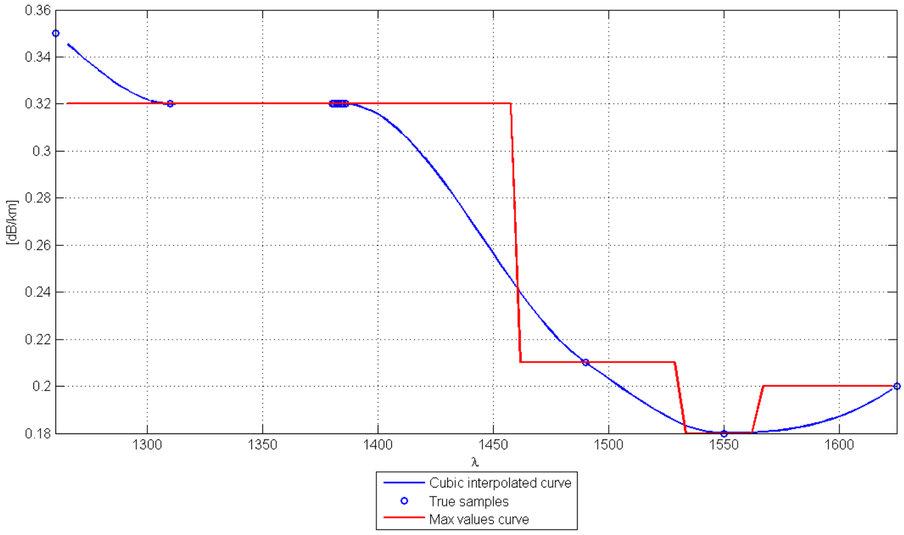

FIGURE 7 - ATTENUATION CURVE FOR FULL-SPECTRUM SINGLE MODE FIBER (VALUES FROM CORNING SMF-28UOF DATASHEET)

Figure 8 shows $c_a(\lambda)$ curves for several target distances.

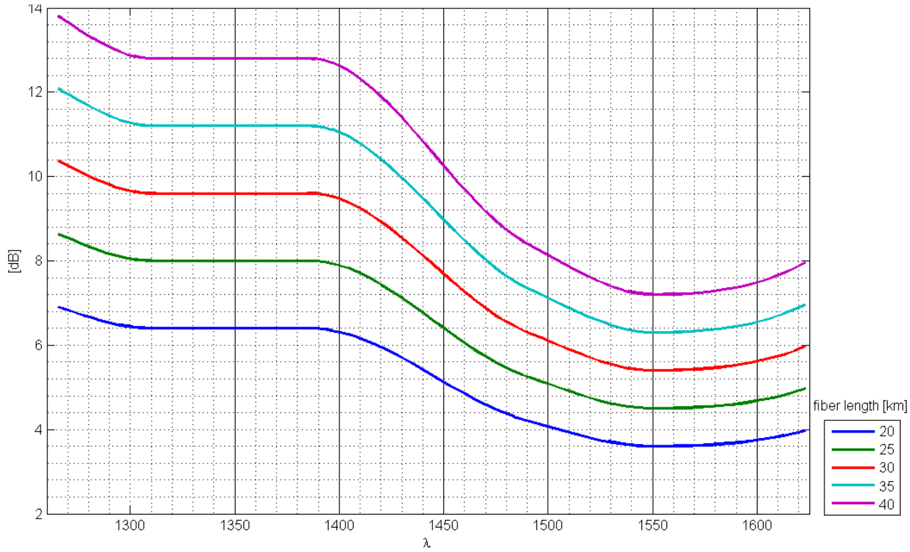

FIGURE 8 - $c_a(\lambda)$ CURVES FOR FIBER LENGTH FROM 20 TO 40 KM

Chromatic dispersion

Chromatic dispersion (CD) is caused by the fact that single mode glass fibers transmit light of different wavelengths at different speeds [11].

Figure 9 shows typical chromatic dispersion curve for full-spectrum wavelength.

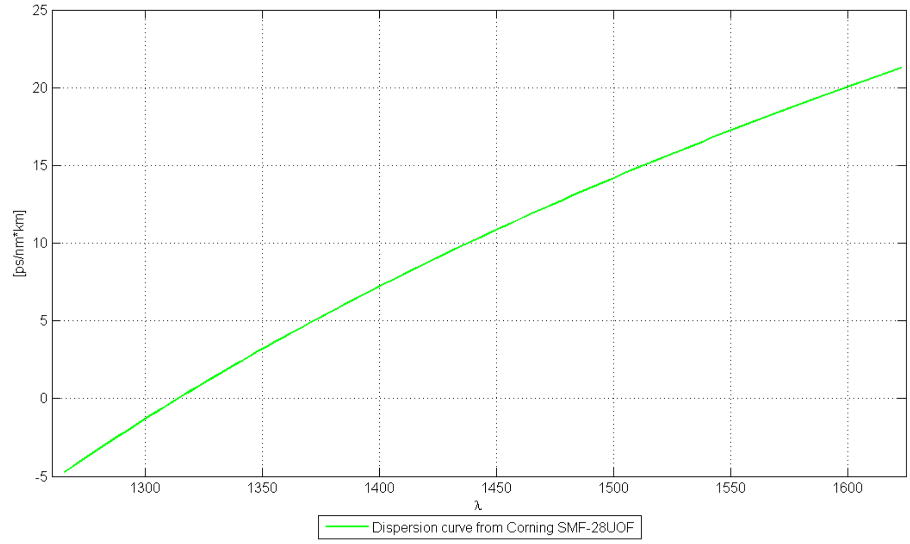

FIGURE 9 - CHROMATIC DISPERSION CURVE (VALUES FROM CORNING SMF-28UOF DATASHEET)

The measurement unit of chromatic dispersion is $\left[\frac{ps}{nm}\cdot km\right]$ while the cost index need a power penalty in $[dB]$. The conversion of chromatic dispersion effect in power penalty is known as "Dispersion power penalty problem".

Dispersion power penalty

Dispersion penalty is defined as *"the increase in the receiver input power needed to eliminate the degradation in the BER caused by fibre dispersion"* [12].

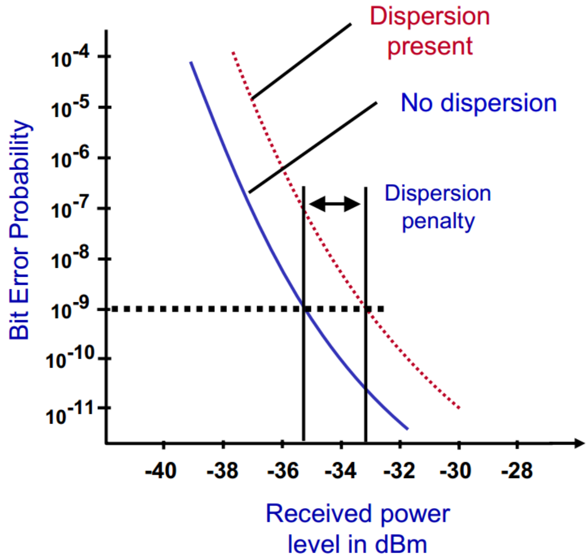

FIGURE 10 - DISPERSION POWER PENALTY VISUALIZED [12]

Figure 10 shows a graphical representation of dispersion penalty.

An analytical rules for dispersion calculation is the *Agraval's formula* (IEEE uses it in IEEE802.3av – 10GEPON).

$$\boldsymbol{c_d(\lambda) = 5\,log_{10}[(1 + 8C\beta_2 B^2 L)^2 + (8\beta_2 B^2 L)^2]}, \qquad with\ \beta_2 = -\frac{\lambda^2}{2\pi c}D$$

EQUATION 2 – AGRAVAL'S FORMULA [13]

In Equation 2, C is the chirp parameter (laser dependent), L is the transmission distance in $[km]$, B is the bit rate in $[Tbaud]$ and D is the dispersion coefficient in $\left[\frac{ps}{nm}\cdot km\right]$.

Unfortunately, chirp parameter 'C' in the Equation 2 is very difficult to predict, but there are several works estimating this parameter for different lasers (for directly modulated DFB see [14]).

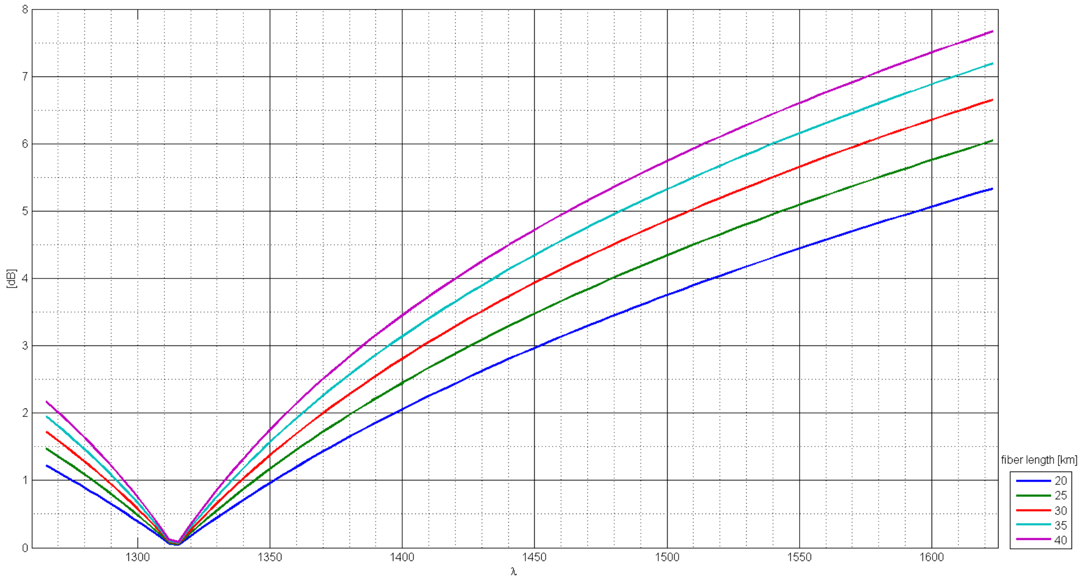

FIGURE 11 – $c_d(\lambda)$ DISPERSION PENALTY CURVES FOR FIBER LENGTH FROM 20 TO 40 KM CHIRP PARAMETER $C = -5$ ($\boldsymbol{DFB\ laser}$ [13]) AND $\boldsymbol{B = 0.01\,Tbaud\,(10\frac{Gbit}{s})}$

Figure 11 shows $c_d(\lambda)$ curves for a DFB laser with line rate of 10 Gbit/s.

Receiver sensitivity

Optical receiver in digital communication system typically contains of Photo Detector, Trans-impedance Amplifier (TIA), and Post Amplifier then followed by decision circuit (Figure 12).

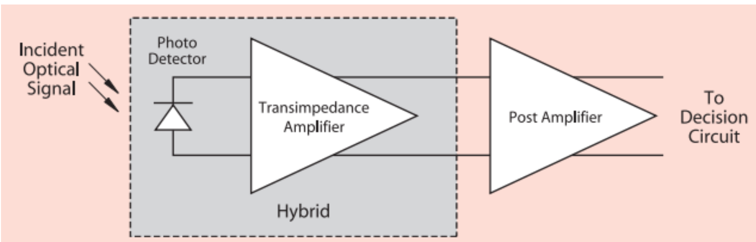

FIGURE 12 - FUNCTIONAL BLOCK DIAGRAM OF AN OPTICAL RECEIVER [15]

Photo Detector (PD), typically PIN or Avalanche Photo Diode (APD), produces photocurrent proportional to the incident optical power. Trans-impedance amplifier converts this current into voltage signal and then Post Amplifier bring this voltage to some standard level, so Post Amplifier output signal can be used by decision circuit.

Number of errors at the output of decision circuit will determine the quality of the receiver and of course the quality of transmission system. Bit-error-rate (BER) is the ratio of detected bit errors to number of total bit transmitted. Sensitivity S of the optical receiver is determined as a minimum optical power of the incident light signal that is necessary to keep required Bit Error Rate. Sensitivity can be expressed in terms of Average Power $[dBm]$, sometimes $[\mu W]$) with given Extinction Ratio ($[dB]$).

To estimate the sensitivity of PD/TIA at certain BER, we need to find required SNR and then calculate average power using Equation 3.

$$S = \frac{SNR \cdot I_{N,RMS}}{2R} \cdot \frac{(r_e + 1)}{(r_e - 1)}$$

EQUATION 3 - SENSITIVITY

In Equation 3, $I_{(N,RMS)}$ is the input equivalent RMS noise current of TIA, r_e is the extinction ratio and R is photodetector responsivity.

The responsivity of a photodiode is a measure of the sensitivity to light, and it is wavelength dependent [15].

Figure 13 shows a typical responsivity curve for a photodiodes made on InGaAs/InP material.

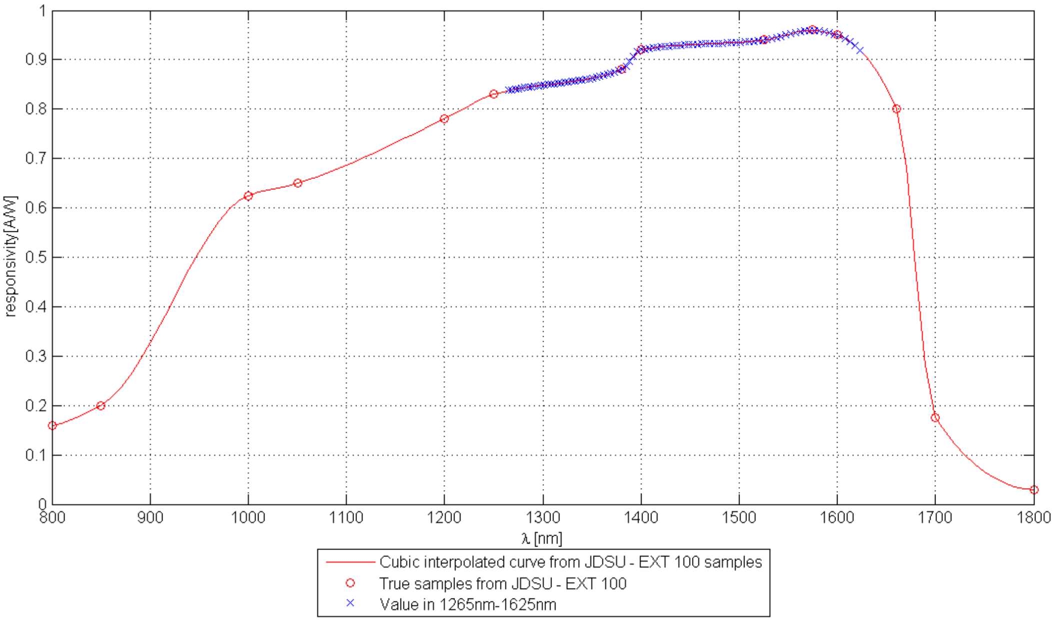

FIGURE 13 – $R(\lambda)$, TYPICAL RESPONSIVITY SPECTRAL RESPONSE AT 23°
(VALUES FROM JDSU-EXT100 DATASHEET)

At this point, calculation of c_s is easy as shown in Equation 4.

$$\boldsymbol{c_s(\lambda) = S(\lambda) - S_{min}}, \qquad with\ S_{min} = \min_{\lambda} S(\lambda)$$

EQUATION 4 - POWER PENALTY DUES TO RECEIVER SENSITIVITY

Figure 14 shows c_s curve when $SNR = 14{,}06$[1], $I_{N,RMS} = 0{,}5\ [\mu A]$ and $r_e = 7{,}94$.

[1] It represents SNR value for $BER = 10^{-12}$ with two level modulation and NRZ coding

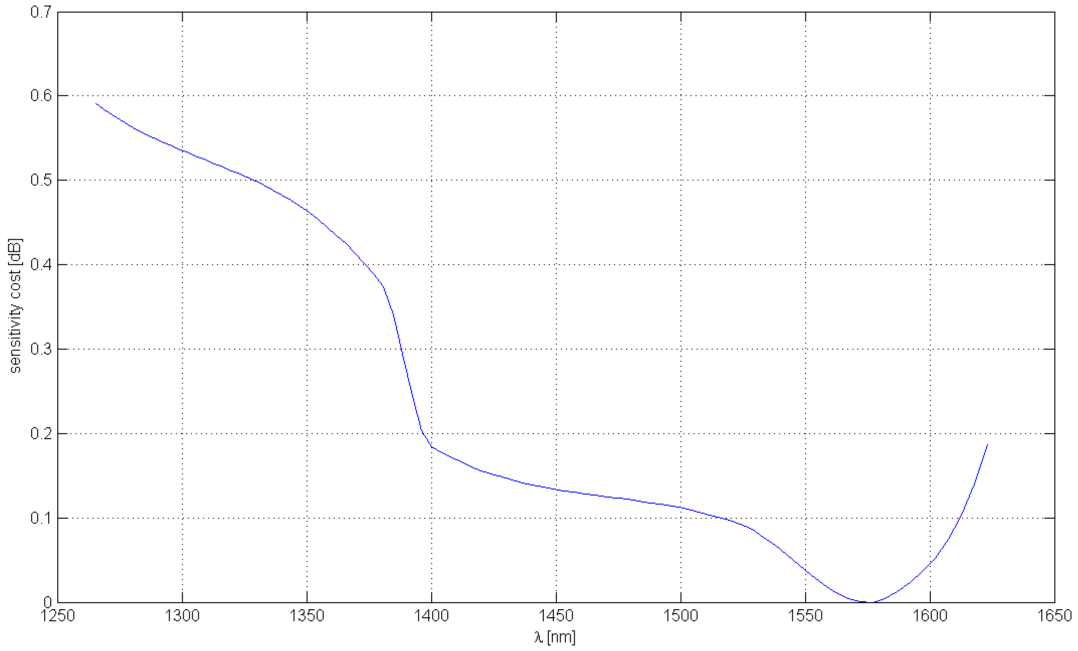

FIGURE 14 - c_s CURVE

Bandwidth partitioning

Two types of partition:

- CWDM grid partition;
- DWDM grid partition.

CWDM grid partition

This type of bandwidth partition uses the CWDM wavelength grid. ITU-T recommendation G.694.2 (12/2003) specifies the CWDM grid. Metro applications uses CWDM grid. This solution gives18 slots with centre-band wavelength spaced $\boldsymbol{20nm}$ apart as shown in Figure 15.

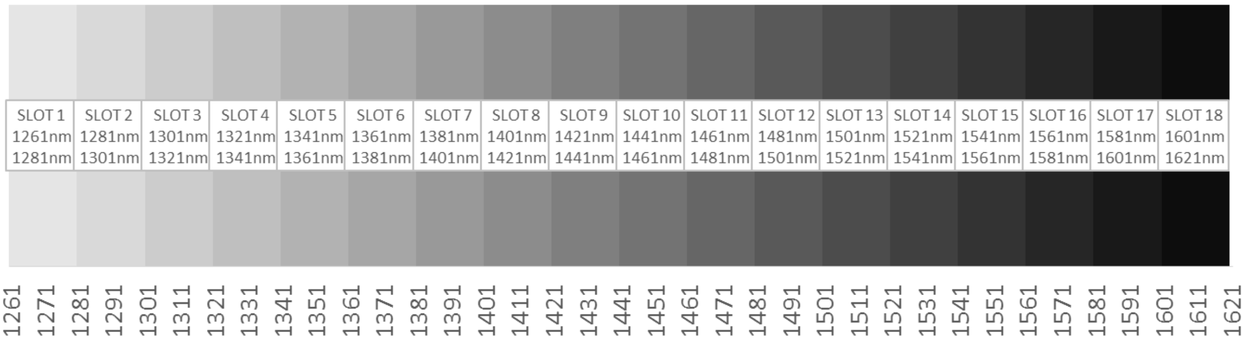

FIGURE 15 - CWDM WAVELENGTH GRID

Pros of this solution are:

- Transceiver, filter and any other hardware are available.

Cons of this solution are:

- 18 slots aren't enough to build an optimization process with fairness constraints;
- It is not fair in frequency terms:
  - SLOT 01: 1261 – 1281, 20nm and 3.71 THz;
  - SLOT 18: 1601 – 1621, 20nm and 2.31 THz.

DWDM grid partition

ITU-T recommendation G.694.1 specifies the DWDM grid.

DWDM grid supports a variety of fixed channel spacing ranging from 12.5 GHz to 100 GHz and wider (integer multiples of 100 GHz). For channel spacing of 100 GHz or more on a fibre, the allowed channel frequencies (in THz) are defined by: 193.1 + n × 0.1 where n is a positive or negative integer including zero [16].

Interesting values for channel spacing can be derived from the following considerations:

- XG-PON laser requires about 0.6 THz channel spacing;
- NG-PON2 laser requires about 0.1 THz channel spacing.

DWDM grid partition has much more slots than CWDM-grid solution.

For example, using XG-PON channel spacing, DWDM grid solution gives 88 slots with centre-band wavelengths spaced 0.6 THz apart between 184.5 THz and 237.9 THz (Figure 16).

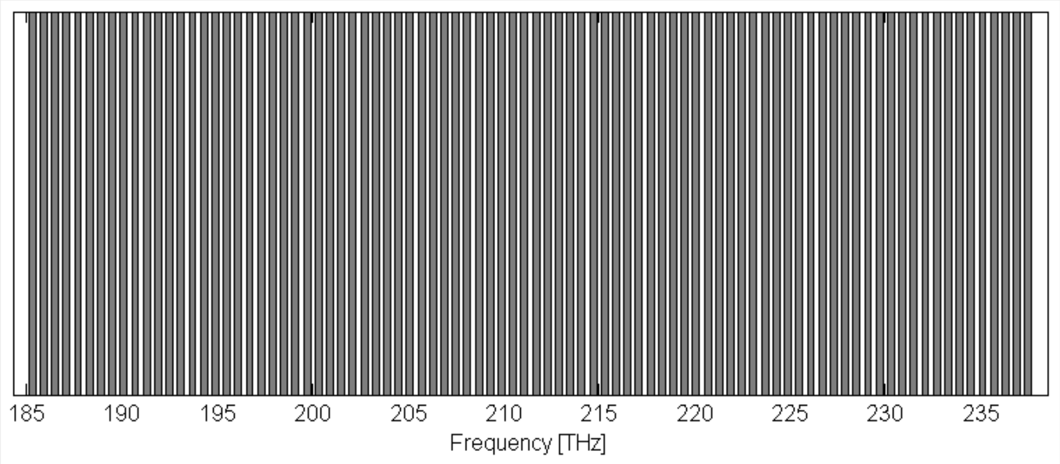

FIGURE 16 – DWDM EXTENDED GRID WITH 0.6 THZ OF CHANNEL WIDTH 88 AVAILABLE SLOT

DWDM grid partitions are essentials to build an appropriate optimization process for slot assignment to the operator.

Channel spacing (THz)	Number of slot
0.1	534
0.6	88
1	52

TABLE 1 - CHANNEL SPACING AND SLOT NUMBER

Bandwidth assigning

The bandwidth assigning is the solution of an optimization problem.

General requirements are the follow:

- Input requirements
  - Bandwidth characterization (the cost index);
  - Bandwidth partition (the channel spacing);
  - Number of operators;
  - Number of wavelengths requested by each operator;
- Output requirements
  - Wavelengths allocation plan.

General requirements can be satisfied by different formulations of the optimization model.

Minimum cost

The goal of this model, is to allocate the best available bandwidth portion of the fiber. In other word, this model builds bundles of slot to have minimum allocation cost.

Introduction

- A set W of available wavelengths
- A set P of operators
- The cost c_j associated to each wavelength $j \in W$
- The number of wavelength nso_i requested from each operator $i \in P$
- Goal: minimizing the total cost of wavelength selection.

Decision variables

- $x_{ij} \in \{0,1\},\ \forall i \in P, \forall j \in W :\ x_{ij} = 1$ if the wavelength j is assigned to operator i

Objective function

$$min \left\{ \sum_i x_{ij} \cdot c_j \right\}$$

Constraints

- To assure that operators requests will be satisfied

$$\sum_j x_{ij} \geq nso_i , \qquad \forall i \in P$$

- To assure that each wavelength will be assigned only one time

$$\sum_i x_{ij} \leq 1 , \qquad \forall j \in W$$

- Variables domain

$$x_{ij} \ \in \ \{0,1\}, \qquad \forall i \in P, \forall j \in W$$

$$z \geq 0 \ \in \ \Re$$

Maximal fairness

The goal of this model, is to obtain a fair bandwidth allocation between operators. In other word, this model assigns bundles of slot to operator in such a way the operators have a portion of bandwidth very similar to each other.

Introduction

- A set W of available wavelengths
- A set P of operators
- The cost c_j associated to each wavelength $j \in W$
- The number of wavelength nso_i requested from each operator $i \in P$
- Goal: minimizing the maximum allocation cost difference between operators, i.e. minimizing the worst assignment.

Decision variables

- $x_{ij} \in \{0,1\},\ \forall i \in P, \forall j \in W : x_{ij} = 1$ if the wavelength j is assigned to operator i
- $z \geq 0$: maximum cost difference

Objective function

$$min\{z\}$$

Constraints

- To assure that operators requests will be satisfied

$$\sum_j x_{ij} \geq nso_i\,, \qquad \forall i \in P$$

- To assure that each wavelength will be assigned only one time

$$\sum_i x_{ij} \leq 1\,, \qquad \forall j \in W$$

- To assure maximum fairness

$$\boldsymbol{z \geq (x_{ij} \cdot x_{kl}) \cdot |c_j - c_l|}, \qquad \forall i, \forall k \in P, i \neq k \ and \ \forall j, \forall l \in W, j \neq l$$

- Variables domain

$$x_{ij} \ \in \ \{0,1\}, \qquad \forall i \in P, \forall j \in W$$

$$z \geq 0 \ \in \ \Re$$

Proximity constraint

Both maximal fairness and minimum cost models don't generate a contiguous wavelength assignment. To have a contiguous wavelength assignment for each operator is required an additional constraint named proximity constraint.

$$(x_{ij} \cdot x_{kl}) \cdot |f_j - f_l| \leq (nso_i - 1) \cdot cw, \qquad \forall i, \forall k \in P, i \neq k \ and \ \forall j, \forall l \in W, j \neq l$$

Proximity constraint requires the function f_j and the scalar cw. Function f_j represents the frequency value associated to each wavelength $j \in W$ and the scalar cw is the channel width value, both in THz.

ULL solutions

Using the cost curve derived in bandwidth characterization, the partitions proposed in bandwidth portioning and the models proposed in bandwidth assigning, this sections shows several example of solutions for ULL.

Matlab scripts are used for the bandwidth characterization and partitioning. AMPL and Gurobi are used to solve the optimization problems.

Scenario 1 – [CDWM-grid + XGPON-based]

This first scenario use CWDM-grid and transceiver characteristics derived from XGPON standard. It has the following requirements

- Four different operators
- Upstream
    - One wavelength at 2.5 Gbit/s for each operator
    - DM-DFB laser
- Downstream
    - One wavelength at 10 Gbit/s for each operator
    - DM-DFB laser
- Target distance 20 km
- Optimization model
    - Minimum cost with proximity constraint

Using minimum cost algorithm

Figure 17 shows a graphical representation of the solution. Blue curve and red curve are the upstream cost curve and the downstream cost curve, respectively. The red line is higher than the blue one due to the dispersion penalty effect that depends of line rate.

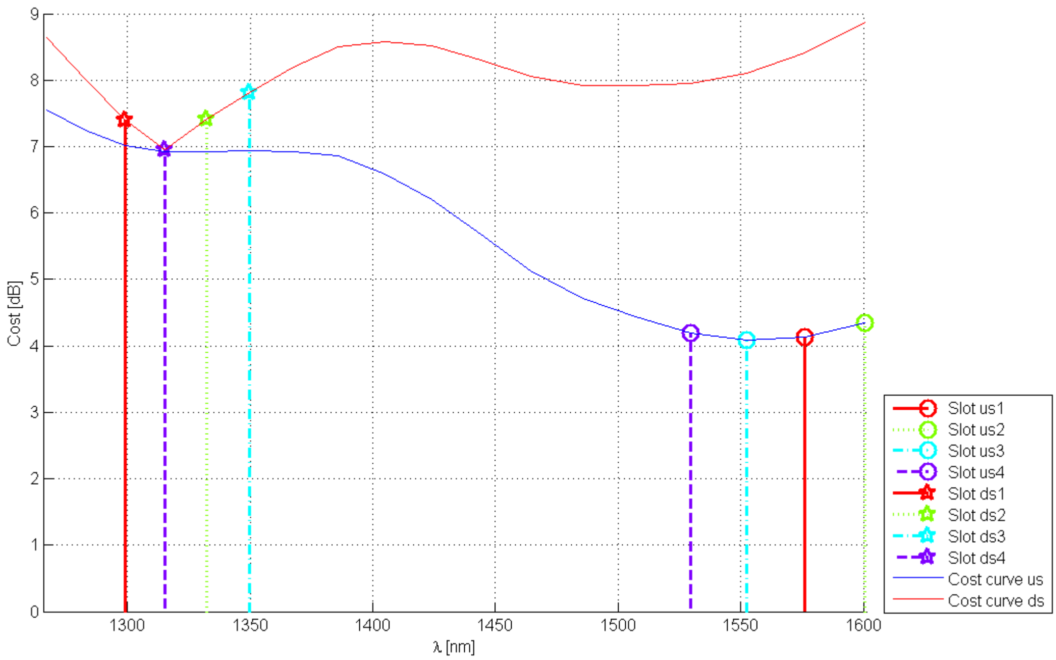

FIGURE 17 – SPECTRAL PLAN FOR SCENARIO 1 USING MINIMUM COST ALGORITHM

Table 2 shows the complete wavelength plan.

Operator	Stream	Center lambda (nm)	Channel width (nm)	Center frequency (THz)	Channel width (THz)	Cost (dB)
1	us	1576.20	15.9	233.70	2.9	4.1
2	us	1600.60	15.5	236.60	2.9	4.4
3	us	1552.52	16.3	230.80	2.9	4.1
4	us	1529.55	16.7	227.90	2.9	4.2
1	ds	1298.93	23.3	193.10	2.9	7.4
2	ds	1332.41	22.0	198.90	2.9	7.4
3	ds	1349.81	21.4	201.80	2.9	7.8
4	ds	1315.46	22.6	196.00	2.9	7.0

TABLE 2 - WAVELENGTH PLAN FOR SCENARIO 1 USING MINIMUM COST ALGORITHM

Using maximum fairness algorithm

Figure 18 shows a graphical representation of the solution. Blue curve and red curve are the upstream cost curve and the downstream cost curve, respectively. Maximum fairness upstream privileges the flatness part or the curve.

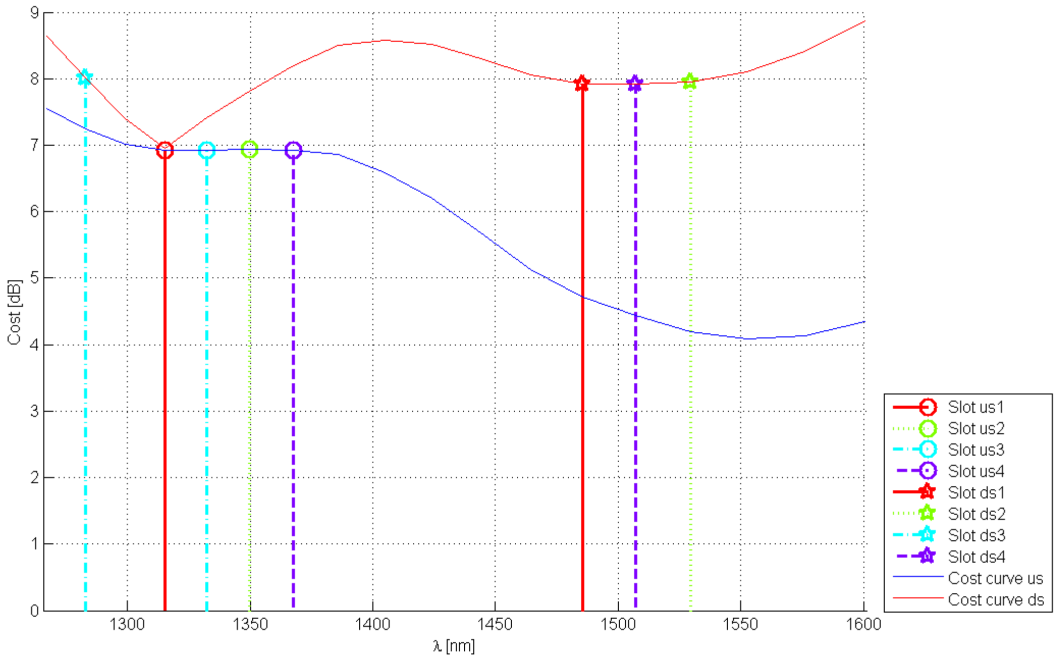

FIGURE 18 - SPECTRAL PLAN FOR SCENARIO 1 USING MAXIMUM FAIRNESS ALGORITHM

Table 3 shows the complete wavelength plan.

Operator	Stream	Center lambda (nm)	Channel width (nm)	Center frequency (THz)	Channel width (THz)	Cost (dB)
1	us	1315.46	22.6	196.00	2.9	6.9
2	us	1349.81	21.4	201.80	2.9	6.9
3	us	1332.41	22.0	198.90	2.9	6.9
4	us	1367.67	20.7	204.70	2.9	6.9
1	ds	1485.59	17.6	222.10	2.9	7.9
2	ds	1529.55	16.7	227.90	2.9	8.0
3	ds	1282.81	24.0	190.20	2.9	8.0
4	ds	1507.25	17.2	225.00	2.9	7.9

TABLE 3 – WAVELENGTH PLAN FOR SCENARIO 1 USING MAXIMUM FAIRNESS ALGORITHM

Scenario 2 – [DWDM-grid 0.6 THz + XGPON-based]

This second scenario use DWDM-grid with 0.6 THz of channel spacing instead of CWDM-grid used in scenario 1 and transceiver characteristics derived from XGPON standard. It has same requirements exposed in scenario 1.

This scenario uses a 0.6 THz of minimum bandwidth gap between wavelengths assigned to different operators.

Using minimum cost algorithm

Figure 19 shows a graphical representation of the solution. Blue curve and red curve are the upstream cost curve and the downstream cost curve, respectively.

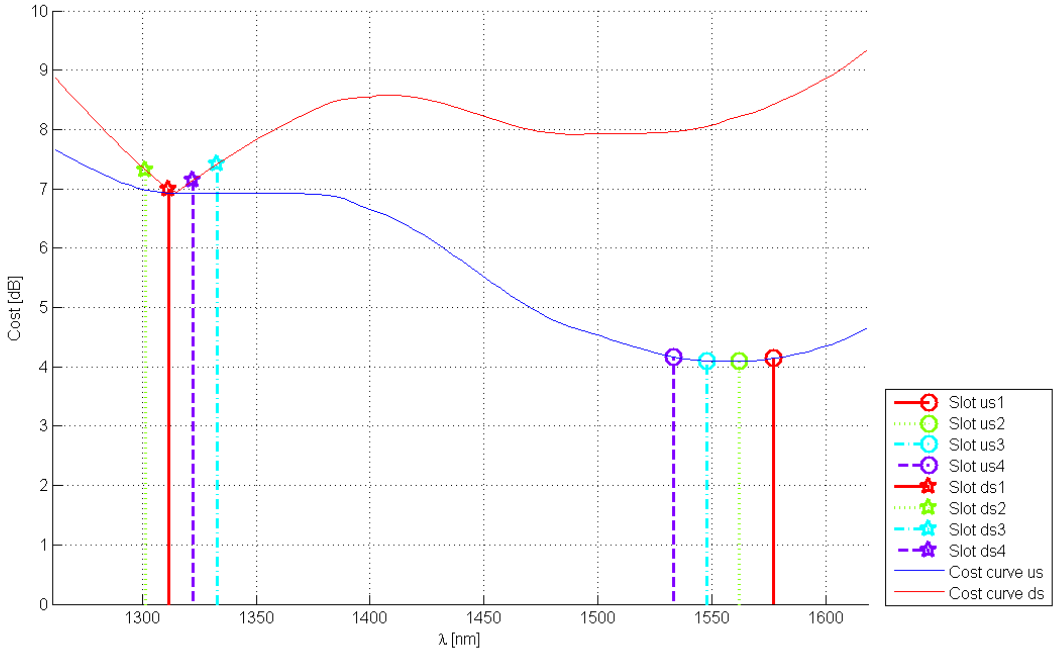

FIGURE 19 – SPECTRAL PLAN FOR SCENARIO 2 USING MINIMUM COST ALGORITHM

Table 4 shows the complete wavelength plan.

Operator	Stream	Center lambda (nm)	Channel width (nm)	Center frequency (THz)	Channel width (THz)	Cost (dB)
1	us	1577.07	3.3	232.77	0.6	4.1
2	us	1562.25	3.4	230.96	0.6	4.1
3	us	1547.71	3.4	229.16	0.6	4.1
4	us	1533.43	3.5	227.36	0.6	4.2
1	ds	1311.66	4.8	194.30	0.6	7.0
2	ds	1301.40	4.9	192.50	0.6	7.3
3	ds	1332.69	4.6	197.91	0.6	7.4
4	ds	1322.09	4.7	196.10	0.6	7.1

TABLE 4 – WAVELENGTH PLAN FOR SCENARIO 2 USING MINIMUM COST ALGORITHM

Scenario 3 – [DWDM-grid 0.6 THz + NGPON2]

This third scenario use DWDM-grid with 0.6 THz of channel width and transceiver characteristics derived from NGPON2 standard. It has the following requirements

- Four different operators
- Upstream
    - Four wavelengths at 2.5 Gbit/s for each operator
    - DM-DFB laser
- Downstream
    - Four wavelengths at 10 Gbit/s for each operator
    - EML laser
- Target distance 20 km
- Optimization model
    - Minimum cost with proximity constraint

This scenario uses a 0.6 THz of minimum bandwidth gap between wavelengths assigned to different operators.

Using minimum cost algorithm

Figure 20 shows a graphical representation of the solution. Blue curve and red curve are the upstream cost curve and the downstream cost curve, respectively. The downstream cost curve is different from previous scenarios because of EML laser.

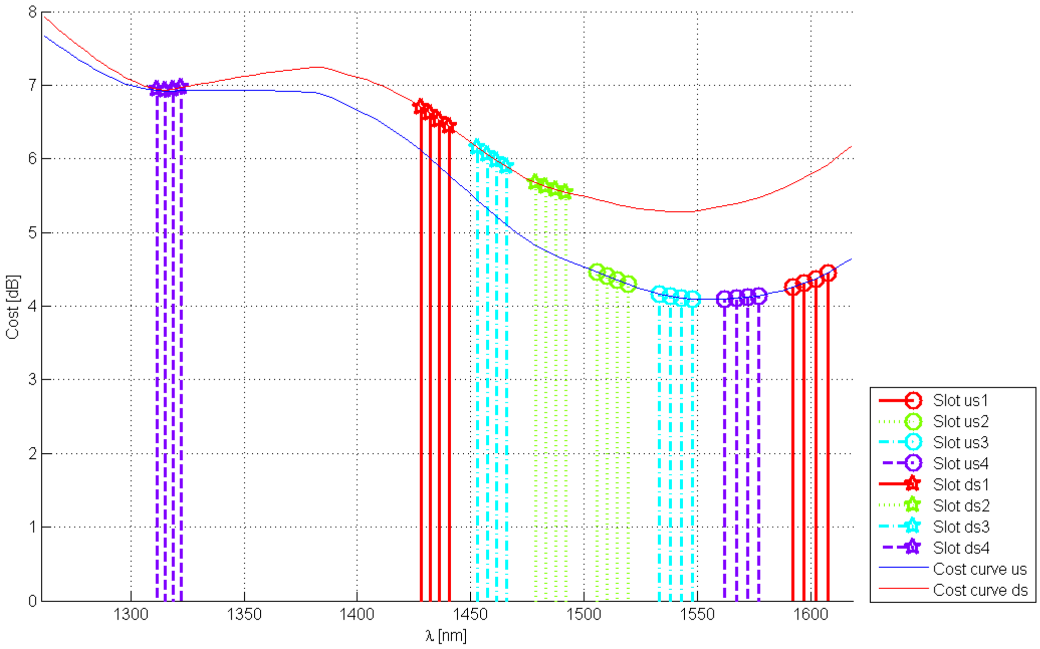

FIGURE 20 – SPECTRAL PLAN FOR SCENARIO 3

Table 5 shows the complete wavelength plan.

Operator	Stream	Center lambda (nm)	Channel width (nm)	Center frequency (THz)	Channel width (THz)	Cost (dB)
1	us	1592.17	3.3	234.57	0.6	4.3
1	us	1597.27	3.3	235.17	0.6	4.3
1	us	1602.40	3.2	235.77	0.6	4.4
1	us	1607.56	3.2	236.37	0.6	4.4
2	us	1505.66	3.6	223.75	0.6	4.5
2	us	1510.22	3.6	224.35	0.6	4.4
2	us	1514.81	3.6	224.95	0.6	4.3
2	us	1519.42	3.5	225.55	0.6	4.3
3	us	1533.43	3.5	227.36	0.6	4.2
3	us	1538.16	3.5	227.96	0.6	4.1
3	us	1542.92	3.4	228.56	0.6	4.1
3	us	1547.71	3.4	229.16	0.6	4.1
4	us	1562.25	3.4	230.96	0.6	4.1
4	us	1567.16	3.4	231.56	0.6	4.1
4	us	1572.10	3.3	232.16	0.6	4.1
4	us	1577.07	3.3	232.77	0.6	4.1
1	ds	1428.07	4.0	212.93	0.6	6.7
1	ds	1432.17	4.0	213.53	0.6	6.6
1	ds	1436.30	3.9	214.13	0.6	6.5
1	ds	1440.44	3.9	214.74	0.6	6.4
2	ds	1478.88	3.7	220.14	0.6	5.7
2	ds	1483.28	3.7	220.75	0.6	5.6
2	ds	1487.70	3.7	221.35	0.6	5.6
2	ds	1492.15	3.7	221.95	0.6	5.5
3	ds	1453.03	3.8	216.54	0.6	6.2
3	ds	1457.28	3.8	217.14	0.6	6.1
3	ds	1461.55	3.8	217.74	0.6	6.0
3	ds	1465.84	3.8	218.34	0.6	5.9
4	ds	1311.66	4.8	194.30	0.6	6.9
4	ds	1315.12	4.7	194.90	0.6	6.9
4	ds	1318.60	4.7	195.50	0.6	6.9
4	ds	1322.09	4.7	196.10	0.6	7.0

TABLE 5 – WAVELENGTH PLAN FOR SCENARIO 3

Scenario 4 – [DWDM-grid 0.1 THz + NGPON2]

This third scenario use DWDM-grid with 0.1 THz of channel width and transceiver characteristics derived from NGPON2 standard. It has same requirements exposed in scenario 3.

Using minimum cost algorithm

Figure 21 shows a graphical representation of the solution. Blue curve and red curve are the upstream cost curve and the downstream cost curve, respectively. This solution uses a bandwidth gap between wavelengths assigned to different operators.

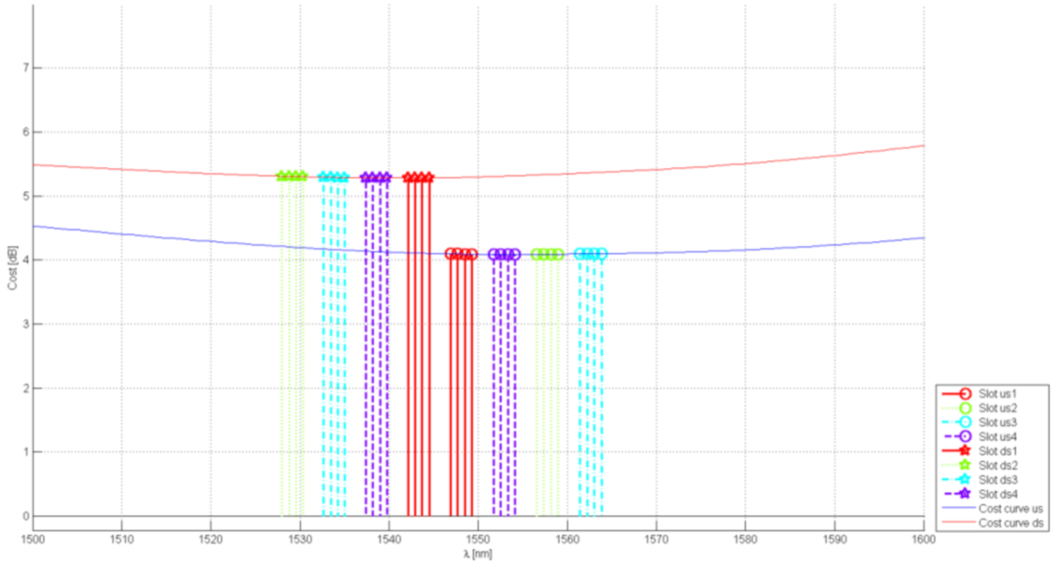

FIGURE 21 – SPECTRAL PLAN FOR SCENARIO 4
X-AXIS FROM 1500NM TO 1600NM

Table 6 shows the complete wavelength plan.

Operator	Stream	Center lambda (nm)	Channel width (nm)	Center frequency (THz)	Channel width (THz)	Cost (dB)
1	us	1546.92	0.6	228.70	0.1	4.1
1	us	1547.72	0.6	228.80	0.1	4.1
1	us	1548.51	0.6	228.90	0.1	4.1
1	us	1549.32	0.6	229.00	0.1	4.1
2	us	1556.55	0.6	229.90	0.1	4.1
2	us	1557.36	0.6	230.00	0.1	4.1
2	us	1558.17	0.6	230.10	0.1	4.1
2	us	1558.98	0.6	230.20	0.1	4.1
3	us	1561.42	0.6	230.50	0.1	4.1
3	us	1562.23	0.6	230.60	0.1	4.1
3	us	1563.05	0.6	230.70	0.1	4.1
3	us	1563.86	0.6	230.80	0.1	4.1
4	us	1551.72	0.6	229.30	0.1	4.1
4	us	1552.52	0.6	229.40	0.1	4.1
4	us	1553.33	0.6	229.50	0.1	4.1
4	us	1554.13	0.6	229.60	0.1	4.1
1	ds	1542.14	0.6	228.10	0.1	5.3
1	ds	1542.94	0.6	228.20	0.1	5.3
1	ds	1543.73	0.6	228.30	0.1	5.3
1	ds	1544.53	0.6	228.40	0.1	5.3
2	ds	1527.99	0.6	226.30	0.1	5.3
2	ds	1528.77	0.6	226.40	0.1	5.3
2	ds	1529.55	0.6	226.50	0.1	5.3
2	ds	1530.33	0.6	226.60	0.1	5.3
3	ds	1532.68	0.6	226.90	0.1	5.3
3	ds	1533.47	0.6	227.00	0.1	5.3
3	ds	1534.25	0.6	227.10	0.1	5.3
3	ds	1535.04	0.6	227.20	0.1	5.3
4	ds	1537.40	0.6	227.50	0.1	5.3
4	ds	1538.19	0.6	227.60	0.1	5.3
4	ds	1538.98	0.6	227.70	0.1	5.3
4	ds	1539.77	0.6	227.80	0.1	5.3

TABLE 6 – WAVELENGTH PLAN FOR SCENARIO 4

Future works

Future works will follow several directions among which:

- To remove pon-greenfield scenario hypothesis, in other word to add constraints at bandwidth assigning optimization model in order to support PON brownfield scenario;
- To study the impact of AWG in the ODN.

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