Mixed line rate virtual topology design considering non linear interferences between amplitude and phase modulated channels

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Abstract In the last years, the migration from 10 Gbps to 40/100 Gbps networks has been proposed as a solution to increase the capacity of transparent optical networks. Initially, the replacement of 10 Gbps legacy equipment was considered. Nowadays, some works point out that the deployment of mixed line rate (MLR) networks, where 10 Gbps and higher bit rate Gbps channels share the same fiber, could be more cost effective than the total replacement of 10 Gbps systems. In this paper, we investigate the planning of 10/40 Gbps MLR networks using the ITU 50 GHz grid, considering non linear interferences between 10 and 40 Gbps channels, which degrade the quality of transmission. This approach is novel in the literature. In addition, we conduct a set of tests normalizing the length of fiber links, to observe the trends in MLR planning for different network sizes.

Keywords *Virtual Topology Design · Transparent Optical Networks · Multi Rate · Mixed Line Rate · DQPSK · Non linear interactions · 10 Gbps · 40 Gbps · 100 Gbps*

1 Introduction

Wavelength division multiplexing (WDM) has been confirmed as the enabling technology for high-capacitated optical backbone networks [1, 2]. In WDM networks, traffic demands are routed on all optical connections, called lightpaths. A lightpath is set up between a pair transmitter/receiver (together referred as transceivers) at two different ending nodes, occupying a single wavelength channel in each traversed link between them. Since the traffic carried onto a lightpath is not processed electronically at intermediate nodes, savings with respect to electronic switching equipment are achieved.

The particular set of lightpaths established over the physical topology constitutes the so-called virtual topology. Virtual topology design (VTD) implies to solve a multilayer planning problem. In the upper layer, electronic traffic demands or electronic traffic flows (i.e. measured in Gbps) are routed on top of the lightpaths. In the lower layer, each lightpath in the virtual topology has to be routed over the physical topology and assigned a wavelength. This implies solving the Routing and Wavelength Assignment (RWA) problem [3].

Initially, the migration from traditional 10 Gbps based optical transmission systems to higher (40/100 Gbps) bit rates based ones was proposed as a clear strategy to increase the total capacity in WDM optical networks. Besides this capacity enlargement, the higher bit rate systems allow to support more lower bit rate services in one unique wavelength channel, decreasing the number of wavelengths entering a node and relaxing the wavelength switching requirements [1]. On the other hand, the expected cost for a non coherent 40 Gbps transceiver is only 2.5 to 3 times more than a 10 Gbps transceiver, what introduces a volume discount on the cost *per bps* for 40 Gbps transceiver: the cost per bps estimated for 40 Gbps transceivers is between 62.5% and 75% of the same cost for 10 Gbps transceivers [1, 4]. A similar volume discount on the *per bps* cost is expected for 100 Gbps transceivers however in this case the coherent technology might increase the price. Conversely, physical layer impairments affect more severely to higher bit rate signals. To illustrate that, in 40 Gbps channels with respect to 10 Gbps ones, the dispersion tolerance decreases (by a factor of 16 for Chromatic Dispersion, CD, and by 4 for Polarization Mode Dispersion, PMD), the OSNR has to be improved by 6 dB to maintain the same BER, and the non linear impairments become more relevant [4, 5]. The situation is very similar in case of 100 Gbps transmission. As a consequence, the maximum distance without electronic regeneration (transparent reach) is shorter for 40/100 Gbps than for 10 Gbps communications.

Summing up the above commented advantages and drawbacks, a tradeoff appears between the higher capacity and lower cost per bps (volume discount) of 40/100 Gbps transceivers and the longer transparent reach of 10 Gbps signals. Therefore, the deployment of mixed line rate systems taking advantage of the good qualities of both options can be more cost-effective than the pure migration to higher bit rates and replacement of the 10 Gbps transceivers [6, 7].

This paper is focused on the Mixed Line Rate Virtual Topology Design (MLR-VTD), a variant of the VTD problem when several transmission bit rates are considered for the optical connections. Namely, we study the MLR-VTD problem in a realistic scenario where 10 Gbps NRZ-OOK and 40 Gbps RZ-DQPSK lightpaths share a 50 GHz grid on the optical fiber spectrum. In this scenario, non linear impairments (particularly, cross phase modulation, XPM) induced by 10 Gbps (intensity modulated) channels affect seriously to neighboring 40 Gbps (phase modulated) ones [8, 9]. A solution to prevent these non linear interferences is to establish “guard-bands” between 10 and 40 Gbps channels. That will be detailed and justified in section 2.

We concentrate on 10 and 40 Gbps, excluding 100 Gbps systems, to stress the tradeoffs between low bit rate (10 Gbps) channels and higher bit rate (40/100 Gbps) channels. Anyway, many of the considerations for the 10/40 Gbps interferences are also valid for 10/100 Gbps ones.

Since the effects of the aforementioned non linear interactions are considered when planning the network in this paper, we name the investigated mixed line rate problem as MLR-VTD-uNLE (Mixed-Rate Virtual Topology Design under Non Linear Effects). As far as the authors know, this is the first time that the non linear impairments induced by 10 Gbps intensity modulated lightpaths over the 40 Gbps phase modulated ones are explicitly taken into account in a network planning problem. In general, mixed line rate problems have scarcely been explored in optical communications. In [10], a RWA algorithm called DIRWA (Dispersion-optimized Impairment-aware RWA) is proposed. DIRWA incorporates CD information to minimize the lightpath blocking rate in a multi-rate line dynamic case where the lightpath requests arrive randomly.

The MLR-VTD problem has been also studied in [6, 7], where non linear effects between neighboring channels are considered. In these studies, the transparent reach of a lightpath is computed through analytical models that compute the linear impairments. In [6], a unique modulation format (duobinary) is assumed; whilst, in [7], multiple modulation formats (duobinary and DQPSK) are considered. In both papers, the problem is modeled as an ILP formulation. A heuristic algorithm is proposed in [6].

Finally, network protection aspects in MLR planning are investigated in [11, 12]. In [11], Ethernet is used as transport technology over WDM for backbone networks, whereas [12] extends the study in [6] towards survivability considerations. In contrast to the present paper, these works also ignore possible interfering effects between adjacent wavelengths.

The rest of the paper is organized as follows. Section 2 justify the solutions applied to solve the

MLR networks issues. In Section 3 we provide an optimal MILP (Mixed Integer Linear Programming) formulation for the MLR-VTD-uNLE problem. Section 4 presents a heuristic algorithm. Results of exhaustive tests are presented in Section 5 . Finally, Section 6 concludes the paper.

2 Issues on MLR networks: spectral width and guard bands

The joint utilization of 10 Gbps and 40/100 Gbps channels on the existing infrastructure brings several challenges. The main issues to solve are related to: (i) the spectral width of the 40/100 Gbps signals and (ii) the non linear effects between 10 Gbps and 40/100 Gbps neighboring channels.

Nowadays, one of the most wide-spread grid spacing in optical communications is the ITU G.694.1 50 GHz grid. The spectral efficiency of the traditional 10 Gbps on-off keying (OOK) signals is 0.2 bits/Hz [4], what easily permits to fit them into the 50 GHz grid. Conversely, 40/100 Gbps OOK signals would need to be accommodated in a grid spacing even larger than 100 GHz. That forced the market to look for more spectral efficient modulation formats for 40/100 Gbps transceivers.

Several formats for 40 Gbps communications have been proposed. The most well-known candidates are phase shaped binary transmission (PSBT) [13, 14], differential phase shit keying (DPSK) [13, 15], partial DPSK (p-DPSK) [13, 15], return-to-zero differential quaternary phase shift keying (RZ-DQPSK) [13, 15]. In the last years thanks to the successful development of the coherent technology and digital signal processing (DSP) two other modulation formats has been proposed, namely polarization-division multiplexed quaternary phase shift keying (PDM-QPSK) [13, 15, 16] and polarization-division multiplexed binary phase shift keying (PDM-BPSK) [17].

In case of 100 Gbps transmission the situation is simpler, since the feasible only solution is the coherent transmission combined with DSP. Considering the modulation formats here the two candidates are: PDM-QPSK [16] and frequency division multiplexed PDM-QPSK (FDM PDM-QPSK) [18]

With the exception of 40 Gbps DPSK, that requires 100GHz spacing, most of the previously mentioned formats fit into 50 GHz grid, what solves the issue of the grid spacing in high bit rate signals.

Other limiting factor to use phase modulated channels together with OOK channels (e.g. 10 Gbps together with 40/100 Gbps), are the nonlinear effects. As it is well known the OOK channels highly deteriorates the quality of phase modulated channels due to the cross phase modulation (XPM). Several papers have been published investigating the nonlinear tolerance of different modulation formats. In [19] the performance of 40 Gbps channel DPSK, p-DPSK, RZ-DQPSK and coherent PDM-QPSK surrounded by 10Gbps are compared. In [20] it was shown that the closer is the symbol rate of 40 Gbps channels to 10 Gbps the higher is the nonlinear penalties due to XPM. In case of polarization multiplexed channels besides the XPM also the cross-polarization modulation (XPolM) limits the optical transmission [21, 22]. In [22] it was shown that for dispersion managed networks the XPolM has higher impact on the signal quality than the XPM.

It is technically possible to have 10 Gbps and 40 Gbps channels in 50 GHz spacing. However in this case an extra OSNR penalty for the 40/100 Gbps channels must be considered. The amount of the OSNR penalty depends on the modulation format, launch power of the channels and guard bands [23]. In most of the deployed networks it is not possible to change the modulation format as well as the launch powers. Therefore, in these cases the only option is to use guard bands between 40/100 Gbps and 10 Gbps channels, to have the optimal working conditions.

In the following sections we will consider only 40 Gbps RZ-DQPSK modulation. The RZ-DQPSK (Return to Zero Differential Quadrature Phase Shift Keying) is one of the candidates for 40 Gbps signaling [7, 15], since its spectral efficiency of 0.8 bits/Hz is sufficient to allocate 40 Gbps channels on 50-GHz grids, and presents a tolerable OSNR resilience and a good dispersion tolerance [4, 13, 15]. The counterpart is that is strongly impacted by XPM induced by 10 Gbps intensity modulated channels [8, 9]. For this reason, we adapt the network planning to prevent that 10 Gbps and 40 Gbps channels sharing a fiber link, are allocated neighboring wavelengths.

3 MILP Formulation

In this section, the MLR-VTD-uNLE problem is characterized as a MILP (Mixed Integer Linear Programming) formulation. In the sequel, we name this model as OPT-MR-uNLE.

Let $G(N,E)$ be the graph of the physical topology being N the set of nodes and E the set of unidirectional fiber links. We denote as $a(e)$ and $b(e)$ the initial and end nodes of fiber $e \in E$, respectively. We assume that a common wavelength grid is used in all the network links, being W the set of wavelengths channels. We denote as D the set of traffic demands, and $a(d)$ and $b(d)$ denote the initial and end nodes of demand $d \in D$, respectively. For each demand d, $h(d)$ represents the volume of the demand in bit rate units (Gbps).

Nodes are equipped with two types of transceivers which we denote as r_{10} and r_{40}. r_{10} represents the 10 Gbps transceiver type that uses NRZ-OOK modulation; and r_{40}, the 40 Gbps transceiver type that uses RZ-DQPSK modulation. The set $R = \{r_{10}, r_{40}\}$ represents the two available types of transceivers. For each transceiver type $r \in R$, BR_r denotes its bit rate in Gbps (that is, $BR_{r10} = 10$, $BR_{r40} = 40$), and c_r represents the cost of a transmitter plus a receiver of that type.

We denote as P the set of paths p that can support a lightpath meeting the Quality of Transmission (QoT) requirements, i.e., a QoT feasible lightpath. This set can be precomputed in different fashions depending on how the planner decides to estimate the lightpaths' QoT. In this work, a path p is included in set P, if the sum of the lengths of the fibers traversed in the path p does not exceed the transparent reach. Then, any lightpath following this route would be QoT feasible. However, the approach followed in the paper is compatible with any other form of defining set P. For instance, the set P can be defined using a linear QoT estimator [24] that collects the physical layer impairments to determine the signal quality. This type of QoT estimator computes explicitly the linear impairments (e.g. ASE noise), whereas, it overestimates the non linear ones (e.g. XPM) and accumulates them to the linear ones. By doing so, the QoT estimation of a lightpath would not depend on the copropagating lightpaths, and thus could be precomputed. A lightpath over a path $p \in P$ would be QoT feasible if the value of its QoT value is lower than a given threshold associated to a given bit error rate.

In our case, since we have two transceivers types with two different transparent reaches, two subsets of paths according to QoT considerations are defined: (i) P_{r10} and (ii) P_{r40}, corresponding lightpaths equipped with transceivers r_{10} or r_{40}, respectively. The set of paths traversing fiber $e \in E$ is denoted as P_e. The initial and end nodes of path $p \in P$ are referred to as $a(p)$ and $b(p)$, respectively. Finally, the set of paths initiated and ending at node $n \in N$ are named as $\delta^+(n)$ and $\delta^-(n)$, respectively.

The decision variables of the problem are:

- $x_{dpw} \in [0,\infty)$: fraction of the traffic volume associated to demand $d \in D$ carried onto a lightpath established on $p \in P$ using wavelength $w \in W$.
- $y_{pwr} = \{0,1\}$. y_{pwr} takes the value 1 if a lightpath is established on $p \in P$ using wavelength $w \in W$ and transceiver type $r \in R$.

Then, the problem can be formulated as:

$$\text{Minimize} \sum_{p\in P, w\in W, r\in R} c_r y_{pwr} \tag{1a}$$

Subject to

$$\sum_{\substack{p\in\delta^+(n),\\ w\in W}} x_{dpw} - \sum_{\substack{p\in\delta^-(n),\\ w\in W}} x_{dpw} = \begin{cases} h_d, & \text{if } n = a(d) \\ -h_d, & \text{if } n = b(d) \\ 0 & \text{otherwise} \end{cases} \quad d \in D, n \in N \tag{1b}$$

$$\sum_{d\in D} x_{dpw} \le \sum_{r\in R} BR_r y_{pwr}, \qquad p \in P, w \in W \tag{1c}$$

$$\sum_{p\in P_e, r\in R} y_{pwr} \le 1, \quad e \in E, w \in W \tag{1d}$$

$$\sum_{r\in R} y_{pwr} \le 1, \qquad p \in P, w \in W \tag{1e}$$

$$y_{pwr} = 0, w \in W, r \in r_{10}, p \notin P_{r_{10}} \quad (1f)$$
$$y_{pwr} = 0, w \in W, r \in r_{40}, p \notin P_{r_{40}}$$

$$\sum_{p \in P_e} \left[y_{pwr_{10}} + y_{p(w+1)r_{40}} \right] = 0, \quad e \in E, w \in W - \{w_{|W|}\} \quad (1g)$$
$$\sum_{p \in P_e} \left[y_{pwr_{10}} + y_{p(w-1)r_{40}} \right] = 0, \quad e \in E, w \in W - \{w_1\}$$

The objective function (1a) minimizes the total transceiver network cost. The flow conservation constraints (1b) ensure that all the traffic volume of demands $d \in D$ is carried. The lightpath capacity constraints (1c) guarantee that traffic allocated in a lightpath does not exceed the bit rate of the transceivers. The wavelength clashing constraints (1d) prevent assigning the same wavelength to different lightpaths sharing the same fiber. The fact that one unique transceiver type can be assigned to a lightpath is considered in (1e). Constraints (1f) forbid that a lightpath exceeds the transceiver transparent reach. Finally, XPM interferences between adjacent NRZ-OOK and DQPSK modulated channels are avoided by leaving unused a guard channel between them in constraints (1g).

4 Heuristic approach

Clearly, the MLR-VTD-uNLE problem is NP-hard, as the general VTD problem [25]. According to our results, it becomes intractable even for moderate sized instances (e.g. $|N| = 4$, $|W| = 6$). In this section, we propose a heuristic algorithm, named Heur-MR-uNLE, to solve large size instances of the problem.

4.1 General Algorithm Structure

In this subsection, we describe the general structure of the heuristic. The algorithm has an iterative operation. A pseudocode illustrating the steps in the main algorithm loop is shown in Fig. 1. The algorithm processes sequentially the demands $d \in D$, attempting to carry the maximum possible volume of them in each iteration. The algorithm finishes when all the demands are totally served or when it is not possible to allocate more traffic.

The algorithm receives as input parameters the graph $G(N,E)$, the wavelength channel set W, the demand set D and the transceivers set R. In the initialization stage, the virtual topology is created as empty, and the demand set D is set as the so-called *remaining demand set D'*, that stores the demand volumes (Gbps) pending to be carried.

At the beginning of each iteration, the remaining demands (demands $d' \in D'$) are resorted in descending order of their volumes $h(d')$ pending to be carried. Then, the demand d' with higher pending traffic is selected, and a path for connecting the ending nodes $a(d')$ and $b(d')$ is searched for. This path consists of a sequence of lightpaths between $a(d')$ and $b(d')$. The ILP formulation (2), described in the subsection 4.2, is used to determine the lightpaths in terms of (i) their routing and wavelength assignment, and (ii) their bit rate, which can be different for different lightpaths in the sequence. Guard bands between 10 Gbps and 40 Gbps channels are enforced by (2).

If formulation (2) for d' results infeasible and no lightpaths are allocated, the algorithm attempts it again with the next demand in set D'. If infeasibility repeats for all demands in D', the traffic pending to be carried is considered as blocked, and the algorithms terminates.

If model (2) is able to find a lightpath sequence between nodes $a(d')$ and $b(d')$, the new lightpaths are added to the virtual topology and the algorithm advances to a *flow allocation stage*. In this stage, as much pending traffic as possible from set D' is carried onto the updated virtual topology. Every demand with zero pending traffic is removed from set D'. The *flow allocation stage* is detailed in subsection 4.3.

Algorithm:
Input: *G*(*N*,*E*), *W*, *D*, *R*
Initialize
Virtual Topology *VT*←{}
Pending Demand Set *D'*←*D*
while *D'* is not empty **do**
  Step 1: Sort demands *d in D'* in descending order of *h*(*d*).
  Step 2: Select as *d'* the first demand in set *D'* .
  Step 3: Search a sequence of lightpaths between *a*(*d'*) and *b*(*d'*) solving **ILP formulation (2)**
  if sequence of lightpaths is found, **do**
    Step 4.a.i: Add found lightpaths to *VT*.
    Step 4.a.ii: Carry onto *VT* as much traffic from *D'* set as possible by ***Flow Routing Stage*** and remove from *D'* demands with null pending traffic.
  else if *d'* is last demand in *D'*,
    break.
  else
    Step 4.b: Select as *d'* the next demand in set *D'* and **go to Step 3.**
  end if
end while
Return *VT*

Fig. 1 Pseudocode of the general structure of the heuristic

4.2 Lightpath sequence determination

This subsection describes the ILP formulation to obtain a lightpath sequence between the initial and end nodes of demand *d*'. The input parameters to the formulation are the same as (1) and, additionally:

- $z'_{pwr} = \{0,1\}$. z'_{pwr} takes the value 1 if one lightpath was previously established on $p \in P$ using wavelength $w \in W$ and transceiver type $r \in R$.
- ξ_{pwr}: Virtual cost assigned to establishing a lightpath on $p \in P$ using wavelength $w \in W$ and transceiver type $r \in R$.

The decision variables are:

- $z_{pwr} = \{0,1\}$. z_{pwr} takes the value 1 if a lightpath is established on $p \in P$ using wavelength $w \in W$ and transceiver type $r \in R$.

Then, problem can be formulated as:

$$\text{Minimize} \sum_{p\in P, w\in W, r\in R} \xi_{pwr} z_{pwr} \quad (2a)$$

Subject to

$$\sum_{\substack{p\in\delta^+(n)\\ w\in W\\ r\in R}} z_{pwr} - \sum_{\substack{p\in\delta^-(n)\\ w\in W\\ r\in R}} z_{pwr} = \begin{cases} 1, \text{if } n = a(d) \\ -1, \text{if } n = b(d), \quad n \in N \\ 0 \text{ otherwise} \end{cases} \quad (2b)$$

$$\sum_{p\in P_e, r\in R} z_{pwr} \le 1, \quad e\in E, w\in W \quad (2c)$$

$$\sum_{r\in R} z_{pwr} \le 1, \quad p\in P, w\in W \quad (2d)$$

$$z_{pwr_{10}} = 0, w\in W, p \notin P_{r_{10}} \quad (2e)$$
$$z_{pwr_{40}} = 0, w\in W, p \notin P_{r_{40}}$$

$$\sum_{p\in P_e} \left[z_{pwr_{10}} + z_{p(w+1)r_{40}} \right] = 0, \quad e\in E, w\in W - \{w_{|W|}\} \quad (2f)$$
$$\sum_{p\in P_e} \left[z_{pwr_{10}} + z_{p(w-1)r_{40}} \right] = 0, \quad e\in E, w\in W - \{w_1\}$$

$$z_{pwr} = 1, \ (p,w,r) / z'_{pwr} = 1 \quad (2g)$$

The lightpath sequence conservation constraints (2b) guarantee that the set of lightpaths established composes a path on the physical topology connecting the demand ending nodes *a*(*d*) and *b*(*d*). The constraints (2c)-(2f) are the equivalent to the constraints (1d)-(1g) by replacing the decision variables y_{pwr} for z_{pwr}. The constraints (2g) tie to one the decision variables corresponding to lightpaths set up in previous iterations.

The objective function (2a) minimizes the virtual cost of the sequence of lightpaths. The particular values used for the cost coefficients ξ_{pwr} becomes critical in the algorithm performance. We have tested the two options given in (3a) and (3b):

$$\xi_{pwr} = \frac{c_r}{BR_r}, \ p\in P, w\in W, r\in R \quad (3a)$$

$$\xi_{pwr_{10}} = M, \xi_{pwr_{40}} = 1, \ p\in P, w\in W \quad (3b)$$

In (3a), the relative cost per bps of the transceiver is used as the objective function. Whilst, in (3b), a large cost value *M* (e.g. $M = |W||P|$) is chosen so that 40 Gbps lightpaths are always preferred. The performed experiments reveal us that the algorithm generates solutions with lower network costs when (3a) cost function is used. However, for some of these experiments under high traffic loads, solutions presented blocked traffic. The heavy loaded cases were repeated by using the values (3b) as coefficient costs, obtaining solutions with null blocking rate, but paying a higher network cost than before for weights (3a). The rationale behind this algorithm behavior is that high bit rate transceivers are in these cases the only choice to reduce the traffic blocking, because of its higher capacity.

Finally, the new lightpaths to add to current virtual topology are computed as the difference $z_{pwr} - z'_{pwr}$ for each $p \in P, w \in W, r \in R$.

Flow Routing Stage:
Input: *d', D', VT*
Step 1: Put demand *d'* in the first position in set *D'*.
for *d* ∈ *D'*, starting with the first demand **do**
  Step 2: Solve **Max Flow Problem** onto *VT* for demand *d* and subtract carried traffic from *h*(*d*).
  if *h*(*d*) = 0, *D'*← *D'* - {*d*}; **end if**
end for
Return *D'*

Fig. 2 Pseudocode of Traffic Flow Routing Phase

4.3 Flow allocation stage

This algorithm stage aims at carrying as much pending traffic as possible onto the upgraded virtual topology design. The pseudocode in Fig. 2 illustrates the steps of the algorithm. The input parameters to this stage are: (i) a demand *d'*, (ii) the *remaining demand set D'* and (iii) the established virtual topology *VT*. First of all, the demand *d'* is moved from its current position to the top in the *set D'*, that was previously sorted in descending order of demand volumes. The demands are sequentially fed to an instance of the *MaxFlow* [26] problem, following the order in *D'*. For each demand *d*, the *MaxFlow* problem intends to carry as much traffic as possible (but limited to *h*(*d*)) using the available capacity in the lightpaths of the *VT*. The Gbps successfully carried in the *MaxFlow* solution are subtracted from the volume *h*(*d*) pending to route in *D'*. Finally, before continuing on next demand, those demands $d \in D'$ for which $h(d) = 0$ are removed from set *D*'.

5 Results

5.1 Network scenario

We investigate the MLR planning using as a case of study the Abilene network ($|N| = 9$ nodes) [27] using 80 wavelengths per fiber and a grid spacing of 50 GHz. The algorithms have been implemented in MATLAB code, integrated and tested in the MatPlanWDM tool [28], which links to the TOMLAB/CPLEX solver [29]. The network cost to minimize is given by the sum of the cost of the transceivers. We assumed the following costs and maximum transparent reaches of the transceivers as shown in Table 1.

Table 1 Transceivers Parameters

Bit Rate (Gbps)	Modulation Format	Transparent Reach (km)	Cost of one transceiver pair
10	NRZ-OOK	2000	1
40	RZ-DQPSK	600	2.5

As a novelty, we study how the MLR systems behave if the lengths of the links in the network are varied. By doing so, we observe the trends in the network characteristics for different network sizes (e.g. metro, continental network...). Different network sizes are generated by tuning the values of the so-called "link length factor" β. The factor β of a network is computed as the quotient between the longest link length and the transparent reach of 40 Gbps transceivers (600 km, see Table 1). Thus, reference factor $\beta_{ref} = 1$ corresponds to a network where the longest link is 600 km. We employ six distance factors β = {0.25, 0.5, 0.75, 1, 2, 3}. In the real link length case, the β factor of Abilene Network is 2.84.

5.2 Network throughput

First, we are interested on investigating how the maximum network throughput is affected by the link length in MLR networks. In this paper we define the maximum network throughput as the maximum traffic which can be carried, according to the Heur-MR-uNLE algorithm, with null traffic blocking. A traffic normalization process is required for this aim. In our tests, a reference traffic matrix T_{BASE} is initially computed by using the distance-population traffic model detailed in [30]. Then, we find the highest factor α_{MAX} for which the traffic matrix $T_{MAX} = \alpha_{MAX} \cdot T_{BASE}$ can be supported with null traffic blocking. The maximum network throughput is then the total volume summing up the coordinates of the matrix T_{MAX}. Naturally, these values are different for different network size factors β, since larger networks may force the use of 10 Gbps equipment with longer transparent reach but lower capacity. Table 2 collects the results obtained.

Table 2 Maximum network throughput (Tbps)

β	Throughputs	Upper Bound (UB)	Gap (%)
0.25	27.24	27.42	0.67%
0.5	27.24	27.42	0.67%
0.75	27.24	27.42	0.67%
1	26.53	27.42	3.24%
2	7.40	8.93	17.16%
3	6.76	6.84	1.23%

As can be observed in Table 2, there is an abrupt reduction in the network throughput for those networks with size factor β > 1. That is because for these networks some of the links are too long to allow a 40 Gbps lightpath to traverse them. For increasing values of β, more links have a length higher than 600 km (the transparent reach for 40 Gbps transceivers considered), and thus fall into this limitation.

The *Upper Bound* column computes an upper bound to the maximum network throughput. This upper bound is of interest, to assess the quality of the Heur-MR-uNLE algorithm according to its ability to find solutions with null traffic blocking. The upper bound is calculated (i) relaxing the MILP formulation by eliminating the wavelength assignment constraints (1d) and (1g), and then (ii) finding the T^{MAX} matrix for which a solution to the relaxed problem is found. The *Gap* column in Table 2 shows the optimality gap between the maximum throughput computed by the heuristic and the upper bound. Results reveal that a very small gap is obtained in most of the occasions, confirming the quality of the algorithm to find solutions without traffic blocking.

5.3 Network cost

A second set of experiments is devoted to evaluate the evolution of the network cost in MLR networks. Fig. 3 collects the results, showing the cost of the network planned with the Heur-MR-uNLE algorithm, as a function of the carried traffic volume. We repeat the tests for ten traffic loads corresponding to fractions of size ρ = {0.1, 0.2, ..., 1} of the maximum network throughput 27.24 Tbps (best case, for link-length factor β = 0.25).

Only the cases for which a null lightpath blocking is found, are included. According to Table 2, this means that networks with factor β > 1 have only cost values for traffic loads < 30%. Observing Fig. 3, we note that the network cost grows with the traffic volume in a predictive almost linear manner in all the cases. The slope in the cost variation is significantly steeper for higher network sizes. This result is interesting, since it shows that all the non linear interactions that are introduced in the network plan (RWA constraints, mixed-line-rates, effect of the interferences), still produce an almost perfect linear growth of the cost with the traffic.

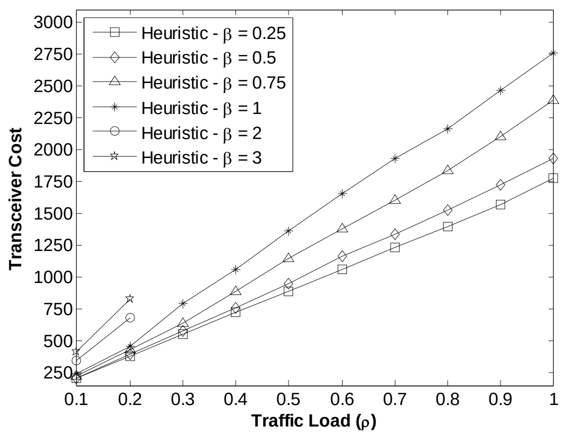

Fig 3 MLR Case. Network Cost.

To assess the quality of the Heur-MR-uNLE algorithm in terms of cost of the solutions provided, we compare the network cost with a lower bound (LB) to the network cost computed. To compute this cost LB, we make use of the same relaxation, described in section 5.2, of the problem formulation (1). In some cases, the CPLEX solver is not able to find a solution to the relaxed problem. However, in all the situations the solver is capable of providing a dual cost to the relaxed problem, which acts as a lower bound on the network cost. Then, we use this dual cost as the lower bound to the original problem. Table 3 plots the optimality gaps of the algorithm for the tested cases. Interestingly, the optimality gap is small (2-10 %) in the large majority of the cases, validating the quality of the algorithm. The exceptions occur in some experiments corresponding to middle network loads (ρ) and network size factors β between 0.5 and 1. At the end of the next subsection, we elaborate a possible explanation to this effect. This explanation will suggest that the larger gaps are caused by the slackness of the LB, and not by the quality of the algorithm.

Table 3 Optimality Gap on Total Cost (%)

β / ρ	**0.25**	**0.5**	**0.75**	**1**	**2**	**3**
0.1	9.7%	9.0%	8.0%	8.2%	9.2%	4.1%
0.2	7.1%	5.6%	6.2%	5.1%	8.0%	4.5%
0.3	6.2%	5.1%	5.1%	18.8%	-	-
0.4	4.5%	3.9%	9.3%	17.0%	-	-
0.5	3.7%	4.6%	11.1%	16.5%	-	-
0.6	3.0%	6.3%	9.6%	13.5%	-	-
0.7	2.6%	5.1%	8.2%	10.3%	-	-
0.8	2.3%	3.5%	7.6%	6.3%	-	-
0.9	2.0%	3.4%	7.5%	5.5%	-	-
1	4.0%	3.6%	7.5%	3.9%	-	-

5.4 Usage ratio of 10 Gbps vs 40 Gbps

The usage ratio of 10 Gbps vs 40 Gbps transceivers is analyzed in this subsection. In Fig. 4 we show the fraction of the number of 40 Gbps lightpaths in the network, with respect to the total number of lightpaths. These results are extracted from the same experiments (ρ, β) studied in the previous subsection.

Interesting conclusions can be drawn. First, for a given network (fixed β size factor), the use of 40 Gbps transceivers always increases with the traffic load ρ. That means that as traffic grows, the relative number of 10 Gbps decreases due its lower capacity to carry larger demands. Secondly, we can distinguish clearly two different situations depending on the network size factor β. For β values lower than one, it is always possible to find a high capacity virtual topology solely based on 40 Gbps transceivers. This is because in these networks all the links are within the 40 Gbps transparent reach (the 40 Gbps optical connectivity is guaranteed). As a consequence, the 40 Gbps transceivers usage is intense. Naturally, this usage is more intensive for lower β factors, since the availability of 40 Gbps QoT feasible lightpaths is larger (for β = 0.2, the 40 Gbps transceivers utilization is always close to 100%). Besides, the network planning can profit from the volume cost discount (10 Gbps relative cost per bps is 1, 40 Gbps relative cost per bps is 0.625). Conversely, for β values higher than one, the 10 Gbps transceivers dominate the virtual topology due to the shortage of 40 Gbps paths shorter than its transparent reach (600 km).

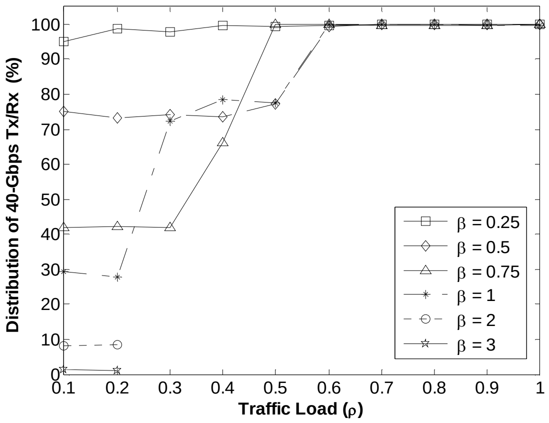

Fig 4 Distribution of 40 Gbps Transceivers (Percentage with respect the total number)

Finally, the joint analysis of Fig. 3 and Fig. 4 permits us to guess an explanation on the larger optimality gaps in network cost detected for medium loads. These values appear when the 40 Gbps transceivers utilization is abruptly increased. Moreover, the sharper the 40 Gbps utilization increment is, the worse the optimality gaps are. This abrupt increment cannot be just explained for a major need of higher bit-rate transceivers to face larger traffic loads, and probably is also caused by an extra increment of the number of 40 Gbps lightpaths to avoid to mix them with interacting adjacent 10 Gbps ones. Therefore, this degradation on the gap quality is something expected, since the lower bound is based on a relaxation of the MILP formulation (1) that ignores interferences constraints relative to non linear interactions between 10 Gbps amplitude modulated channels and 40 Gbps phase modulated channels.

5.5 SLR vs MLR

In this subsection, we repeat for 10 Gbps and 40 Gbps SLR cases (Single Line Rate), the experiments performed for the MLR case in section 5.3. In SLR cases, the Heur-MR-uNLE algorithm uses a unique single rate transceiver type. The intention is to compare the benefits of using MLR systems versus SLR ones in the scenarios under test. This type of comparisons has been already addressed in previous studies [6],[7]. The novelty of this paper is double: (i) the introduction of the guardband requirements between 10 Gbps and 40 Gbps channels, to mitigate the mutual interferences, and (ii) the comparative analysis for various network sizes.

Fig. 5 shows us the costs savings of the MLR approach with respect to the 10 Gbps and 40 Gbps SLR approaches. The savings are computed solely when the heuristic found null lightpath blocking rate solutions for both the MLR case and the SLR case. Obviously, pure 10 Gbps solutions are found just for low traffic loads (up to $\rho = 0.2$). In its turn, pure 40 Gbps solutions are found for short link length factors (up to $\beta = 1$).

From the observation of Fig. 5, it is easy to extract the conclusion that the deployment of MLR systems permits to obtain a lower total network transceiver cost than SLR solutions for low traffic loads. This idea is consistent with the results of previous works [6, 7]. But, in contrast with these studies where non mutual interfering modulation formats are considered; in our work, the requirement of leaving guard bands between 10 Gbps channels and 40 Gbps ones seems to reduce severely the cost savings achieved by mixed systems at middle and high traffic loads.

The magnitude of the MLR savings at low load seems to be very dependent on the network size (β): for pure 10 Gbps cases, it decreases with the growing of β; meanwhile, for 40 Gbps comparisons, increases. These different trends are explained by the tradeoffs between both transceivers types. Increasing the network size (β) means reducing the number of 40 Gbps QoT feasible paths, and using more 10 Gbps paths with longer transparent reaches. Then, MLR solutions become more "10 Gbps pure" and less "40 Gbps pure" on increasing the network size. The transceivers distribution rates shown in Fig. 4 witness this point. As we can expect, the benefits of MLR approaches are lower for those β cases where the MLR design is already basically a SLR one.

At medium and high traffic loads, the 40 Gbps approach is the unique SLR scenario able to find a network design without blocked traffic. In these cases, in comparison with the low load situations, the expected savings due to the presence of cheaper 10 Gbps transponders are negligible or inexistent. Even, in some cases, its presence provokes MLR solutions slightly worse than pure 40 Gbps solutions. This harmful use of lower bit rate transceivers is due to the heuristic nature of the algorithm.

The performance loss appearing in MLR networks for higher traffic loads is caused by higher occupation of the wavelength channels, that seriously limits the possibility of leaving unused guard channels between 10 Gbps and 40 Gbps lightpaths. In these cases, the unique choice to avoid the 10/40 Gbps interferences is utilizing only (or almost only) 40 Gbps lightpaths, becoming MLR designs into pure 40 Gbps SLR ones.

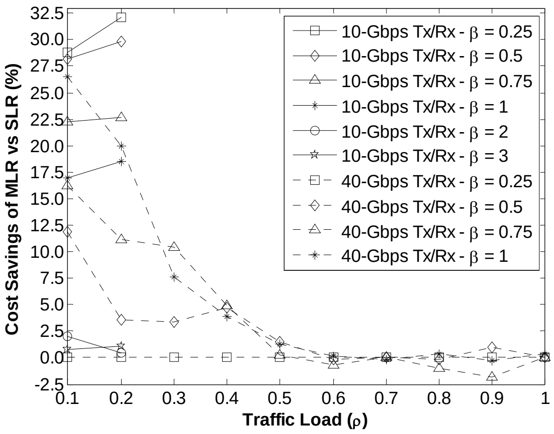

Fig 5 Abilene network. Cost Savings of the MLR approach with respect the SLR approaches

6 Conclusions

In this work, we investigated the planning of multilayer MLR (mixed line rate) optical networks, where 10 Gbps NRZ-OOK modulated signals must share the standard 50 GHz grid with 40 Gbps RZ-DQPSK modulated signals. In this scheme, the intensity modulated signals (10 Gbps) induces non linear impairments over the phase modulated signals (40 Gbps). To cope with this, the network planning should allocate empty wavelengths separating adjacent channels at different bit rates.

The resulting multilayer network planning problem is modeled through a MILP formulation. A heuristic algorithm, that can be easily adapted to any other modulation formats scenario, is presented. The quality of the algorithm has been confirmed by comparison with performance bounds. Finally, several experiments are conducted to analyze under this new light the tradeoffs between longer reach of 10 Gbps transceivers, versus higher capacity and better cost per bps of 40 Gbps transceivers in MLR networks. Results suggest that MLR networks are promising solutions to reduce the transceiver network cost in low loaded networks, where the intensity in the cost reduction is very sensitive with the network size. But, unfortunately, in heavy loaded networks, the interferences between 10 and 40 Gbps channels we have considered, dissuade to mix them, despite the possible benefits of using longer-reach 10 Gbps lightpaths.

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