

# Adapting the Transmission Reach in Mixed Line Rates WDM Transport Networks

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**Abstract**—We consider the problem of planning a mixed line rates (MLR) wavelength division multiplexing (WDM) transport optical network. In such networks, different modulation formats are usually employed to support the transmission at different line rates. Previously proposed planning algorithms, have used a transmission reach limit for each modulation format/line rate, mainly driven by single line rate systems. However, transmission experiments in MLR networks have shown that physical layer interference phenomena are more significant between transmissions that utilize different modulation formats. Thus, the transmission reach of a connection with a specific modulation format/line rate depends also on the other connections that co-propagate with it in the network. To plan a MLR WDM network, we present routing and wavelength assignment (RWA) algorithms that take into account the adaptation of the transmission reach of each connection according to the use of the modulation formats/line rates in the network. The proposed algorithms are able to plan the network so as to alleviate interference effects, enabling the establishment of connections of acceptable quality over paths that would otherwise be prohibited.

**Keywords**- *Wavelength Division Multiplexing (WDM), Mixed line rates (MLR), Routing and Wavelength Assignment (RWA), planning (offline) phase, transmission reach.*

## I. INTRODUCTION

Optical networks using Wavelength Division Multiplexing (WDM) technology modulate multiple channels over a single fiber. The most common architecture utilized for establishing communication in WDM optical networks is *wavelength routing* [1], where the communication between a source and a destination node is done by setting up optical channels (lightpaths) between them. The problem of selecting appropriate paths and wavelengths for a set of requested connections is called Routing and Wavelength Assignment (RWA), and has objective the minimization of the network resources used, and of the network cost, or the maximization of the traffic served for a given set of resources [1].

Given the increasing growth of traffic, the available bandwidth of many core networks has to be upgraded. While the industry wants to move quickly to higher capacity optical transport networks and enhance the 10Gbps systems currently employed, there are a number of technology issues that need to be addressed. Transmission performance, price, space and power dissipation per bit have to be improved over 10Gbps, to make the use of 40 and 100Gbps DWDM transport a candidate solution. As the technology of higher data rates matures and becomes more efficient, 40 and 100Gbps connections will be incorporated in existing 10G networks [3]-[5]. Thus, a transport network will end up managing a variety of channel

data rates, what is usually named a mixed line rates (MLR) system (Fig. 1).

Signal transmission is significantly affected by physical limitations of fibers and optical components [2]. Transmission reach is the distance an optical signal can travel before the signal quality and the bit-error-ratio (BER) degrade to an unacceptable level and the communication is considered infeasible. Many factors affect the transmission reach: the launched power of the signal, the modulation format, the bit rate, the type of the amplification, the dispersion map, etc. To plan a single line rate WDM system, the transmission reach can be used in a coarse RWA planning algorithm. More accurate physical layer models that take into account interference effects among the lightpaths can give better and more sophisticated algorithmic solutions [11].

Typically, for a given modulation format, higher bit rate transmissions have a shorter reach than lower bit rate transmissions, due to higher impairments [2]. This may become impractical and is the main reason that we have to consider different and improved modulation techniques with a better reach-rate product. Note that 10Gbps systems utilize ON/OFF keying (OOK) modulation. To move to higher rate transmissions more advanced modulation formats with higher spectral efficiency and more tolerance to impairments, such as duobinary or phase shift keying modulation techniques, have to be employed [3]-[5]. Even with these advanced modulation techniques, transmission reach will decrease as we move from a 10 Gbps transmission to a 40 Gbps and from a 40 Gbps to a 100 Gbps transmission.

When planning a WDM network the main objective is to minimize the cost. Planning a network so as to use MLR, that is, planning a system that supports more than one rates, (e.g. 10/40/100 Gbps, possibly with different modulation techniques), can reduce the cost of the network by exploiting the heterogeneity in MLR transmissions. For example, some long-distance low-bit-rate connections could be served with inexpensive low-rate and long reach (10 Gbps) transponders, while short-distance high-bit-rate connections could be served with more expensive but fewer in number high-rate connections using improved modulation format transponders, so as to have the lowest possible total cost. The cost could be defined as the sum of the products of the number of transponders of each type required to serve the traffic multiplied by the cost of the corresponding transponder.

Multiplexing wavelength channels with different modulation format/line rates (10/40/100Gbps) in the same system, however, introduces a number of additional technical issues [8],[9]. A field trial has been conducted to demonstrate the feasibility of accommodating 10, 40 and 100Gbps with

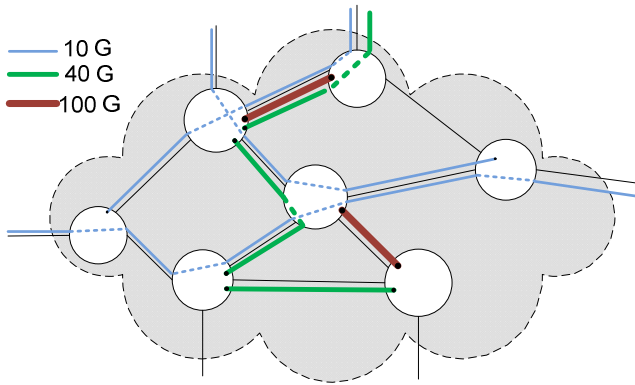


Figure 1: A part of a network that supports mixed line rates (MLR).

standard 50-GHz channel spacing [4]. Depending on the signal power and other physical characteristics, interferences of simultaneously transmitted optical signals with different modulation formats can lead to considerable degradations in signal quality and consequently to reductions in the transmission reach. This issue has to be considered when planning a MLR system, but has been ignored in previous works, except for [8].

Recently, routing and wavelength assignment (RWA) algorithms for MLR systems have been proposed [7]-[11]. The authors in [8] investigate the bit-rate migration from a networking point of view, by providing insight into the optimization of routing and aggregation in terms of overall capital expenditures (CapEx). 10G can be groomed into 40G channels or transmitted natively, reducing the reach of concurrently mixed 40G channels. For long-term migration, optimal network cost is achieved by early investments in 40G-only transmission systems. In [7], the design of an opaque MLR network is proposed, where each node has electronic regeneration (which can also support wavelength conversion, grooming, etc.). This work also assumed that all wavelengths on a link run at the same rate, but different links have different rates. Based on the distance it needs to travel, a lightpath is routed so as to use minimum regeneration. In [9], the authors considered MLRs that employ multiple modulation formats. The authors in [10] propose a cost-effective approach to plan a MLR network under transmission-range (TR) constraints. By intelligent assignment of channel rates to lightpaths, based on their TR constraint, the need for signal regeneration can be minimized, and a “transparent” optical network can be planned to support all-optical end-to-end lightpaths. The planning problem is formulated as an integer linear program (ILP), while a heuristic algorithm is also proposed. Taking a different approach, optical Orthogonal Frequency Division Multiplexing (OFDM) can be used as a new networking solution that can provide flexible bandwidth allocation to connections. A comparison study of the cost of a WDM and an OFDM-based network is presented in [11].

In this paper we present RWA algorithms for planning mixed line rates (MLR) optical transport networks. As discussed in [3],[4] and [8], the transmission reach of a lightpath at a given modulation format/rate, changes depending on the modulation format/rates of the connections that co-propagate with it in the network. For this reason in MLR networks it is not enough to consider a specific transmission reach for each modulation format/rate, but also the interactions between the connections and the modulation formats/rates they use. The proposed algorithms take into account the adaptation

of the transmission reach of the connections according to the utilization state of the network, so as to plan the network and avoid, to a certain degree, the interference effects, enabling the transmission of connections with acceptable quality over paths that would otherwise be prohibited

The rest of the paper is organized as follows. In Section II we introduce the planning problem for a mixed line rate (MLR) optical transport network. Next, in Section III, we describe the proposed reach adapting MLR algorithms. Performance results are presented in Section IV. Finally, in Section V we give our concluding remarks.

## II. NETWORK MODEL

In a single line rate system, given the modulation format and the rate that is going to be used, the network is designed to achieve high values for the transmission reach, using specifically designed amplification schemes, dispersion maps, etc. Typically, in an optical transport network that supports mixed line rates (MLR), different modulation formats are employed to support the transmissions at different rates. In such a MLR network the transmission reach of each modulation format/rate is not the same as the optimized reach in a corresponding single line system, but is somewhat reduced. Moreover, due to interference effects between the different modulation formats/rates used, the transmission reach of each modulation format/rate is affected by the other transmissions. For example, in the study presented in [8] the maximum transmission reach of a 40 Gbps network, using DQPSK modulation, is considered 1000 km in a single line rate system, and is reduced to 800 km when other transmissions of 10 Gbps co-propagate with the 40 Gbps signal.

In what follows we present a way to formulate the adaptation of the acceptable transmission reach of a connection as a function of the utilization state of the network. In particular, depending on the types of modulation formats/rates transmitted over a link we calculate what we call the “effective length” metric of that link. Instead of decreasing the transmission reach of a connection, we adapt the effective lengths of the links that comprise the path over which the connection is established. For example, given a connection with specific modulation format/rate and another connection that uses an interfering modulation format/rate that share a common link, instead of decreasing their transmission reach we increase by some amount the effective length of their common link.

We assume a MLRs network that supports a number of different rates  $r$ . For the sake of being specific, we will assume in this section that  $r=\{10,40,100\}$ Gbps, and that a link consists of a single fiber. Under the above assumption, we can distinguish seven different “types” of fiber, according to the rates of the lightpaths that are transmitted over it:  $t=\{\{10\}, \{40\}, \{100\}, \{10,40\}, \{10,100\}, \{40,100\}, \{10,40,100\}\}$ .

Assume a link  $l$  of length  $D_l$ . According to the type of fiber  $t$  and the transmission rate  $r$  of a specific connection using it (by the definition, the rate  $r$  must be supported by the type of fiber  $t$ ), the effective length of the fiber link is denoted by  $D_l^{r,t} = m^{r,t} D_l$ , that is, the length  $D_l$  of the link, multiplied by a factor  $m^{r,t}$ . Multiplier  $m^{r,t} \geq 1$  expresses the increase of the length of the link, due to interference effects generated by the other rates concurrently transmitted over the fiber of type  $t$ . Clearly, when a fiber is used only by connections of a certain rate  $r$ , its effective length is equal to its real length, thus,  $m^{r,r}=1$ .

Assuming that for all the links  $l_1, l_2, \dots, l_n$ , of a path  $p$  we know the corresponding fiber types  $t_1, t_2, \dots, t_n$ , the effective length of the path  $p$  at rate  $r$  is given by

$$D_p^r = D_{l_1}^{r,t_1} + D_{l_2}^{r,t_2} + \dots + D_{l_n}^{r,t_n}.$$

For the example of Fig. 2, the effective length for path  $p_{ABD}$  at rate 10Gbps is  $D_{ABD}^{10} = m^{10,\{10,40\}} \cdot D_{AB} + m^{10,\{10\}} \cdot D_{BD}$ , and the effective length for path  $p_{ACB}$  at rate 10Gbps is  $D_{ACB}^{10} = m^{10,\{10\}} \cdot D_{AC} + m^{10,\{10\}} \cdot D_{CB}$ .

Moreover, depending on the transmission rate, a lightpath has a maximum transmission reach that is translated to a maximum effective length bound  $D^r$ . If the effective length of the lightpath that uses path  $p$  is beyond the given bound (i.e.,  $D^r < D_p^r$ ) then the lightpath has unacceptable quality of transmission and cannot be used as part of the solution.

Finally, we assume that each modulation format/line rate is associated with a transponder, and the cost of the transponder is higher for higher transmission rates. Since the transmission reach of a modulation format/rate decreases as we move from a 10Gbps to 40 and 100 Gbps transmission, there should be a cost benefit of using higher rates. Thus, the ratio of the transmission rate over the cost of the transponder (which is the per bit transmission cost) should be higher for higher rates, or otherwise there would be no cost benefit of using higher rates.

Note that in the above model, we adapt the effective length of a link based on the modulation formats/rates of the connections transmitted over it, irrespectively of the wavelengths used by these connections. Since interference among lightpaths is more severe when the utilized wavelengths are neighboring (or at least close to each other), instead of using per-link variables, we could use link and wavelength related variables similar to [12]. This more accurate and sophisticated model would considerably complicate the proposed algorithms and is left for future work.

### III. REACH ADAPTING MLR ALGORITHM

We are given a network  $G=(V,E)$ , where  $V$  denotes the set of nodes and  $E$  denotes the set of (point-to-point) single-fiber links. Each fiber is able to support a set  $C=\{1,2,\dots,W\}$  of  $W$  distinct wavelengths, and a set  $R=\{r_1,r_2,\dots,r_M\}$  of  $M$  different bit rates. Each bit rate is associated with a certain modulation format. Each fiber is characterized by a type  $t$  based on the bit rates that is able to support. In particular,  $t \in T = \{\mathcal{P}(R) - \{\emptyset\}\}$ , that is the power set of  $R$ , excluding the empty set. Moreover, each type  $t$  has a multiplier factor  $m^{r,t}$  for every rate  $r$  that it supports, that can be used to compute the effective length  $D_l^{r,t}$  of link  $l$  for rate  $r$ . We are also given transmission reach bounds  $D^r$  for all the rates that are supported in the network and single transponder costs  $C^r$  again for all supported rates.

We assume an a-priori known traffic scenario given in the form of a matrix of aggregated demands  $\Lambda$  in Gbps, called the traffic matrix. Then,  $\Lambda_{sd}$  denotes the requested bandwidth from source  $s$  to destination  $d$ .

The objective of the RWA algorithm for planning a MLR system is to serve all traffic, described in  $\Lambda$ , and minimize the cost of the network, related to the number and type of the transponders of different line rates used. Moreover, each lightpath selected in the solution has to satisfy an adaptive transmission reach constraint. The adaptive transmission reach is modelled through the use of the effective lengths of the links

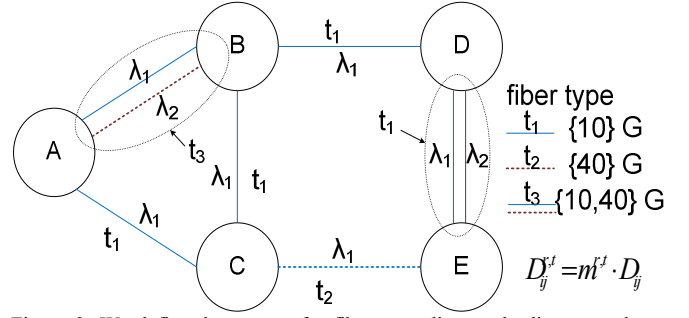


Figure 2: We define the type  $t$  of a fiber according to the line rates that are transmitted over it. We associate each fiber type  $t$  with a set of multipliers  $m^{r,t}$  that help us calculate the effective length  $D_l^{r,t}$  of the link for a transmission of a given rate  $r$ .

that vary according to the utilization state of the network and the modulation formats/rates used.

In the following we present two algorithms to solve the planning problem of MLR systems. We start by describing a combinatorial optimization algorithm that is based on an Integer Linear Programming (ILP) formulation. Since this formulation cannot be solved efficiently for large input instances, we also propose a heuristic algorithm that solves the planning MLR problem by sequentially serving one-by-one the connections. The order in which connections are considered plays an important role in the performance of the heuristic algorithm. We propose and evaluate two ordering policies and also use a simulated annealing meta-heuristic to find good orderings that yield near-optimal performance.

#### A. ILP algorithm

For each requested source-destination pair  $(s,d)$  we pre-calculate  $k$ -shortest paths  $P_{sd}$ . We also pre-calculate the real lengths of these paths using the physical lengths of the links. As the effective lengths of the links change according to the modulation formats/rates used in the network, the effective lengths of the paths change accordingly. The effective lengths of the links or paths are always higher than their corresponding real lengths, since the effective length multipliers are always higher than or equal to 1. So, the real lengths of the paths correspond to the best possible case, and we can reject the rates that cannot be supported over these paths.

#### Variables

- $x_{pw}^r$ : Boolean variable. Equals to 1 if path  $p \in P_{sd}$  and wavelength  $w$  are used to serve the connection  $(s,d)$  with rate  $r$ .
- $f_l^t$ : Boolean variable. Takes the value of 1 if type  $t$  is used for link  $l$ .
- $u_l^r$ : Boolean variable. Takes the value of 1 if at least one connection with rate  $r$  is transmitted over link  $l$ .
- $y_p^r$ : Boolean variable. Takes the value of 1 if path  $p$  cannot be used for a transmission of rate  $r$ .

#### Objective

$$\text{minimize: } \sum_p \sum_w \sum_r C^r \cdot x_{pw}^r$$

subject to the following constraints:

- Incoming traffic constraints

$$\text{For all } (s,d), \sum_{p \in P_{sd}} \sum_w \sum_r r \cdot x_{pw}^r \geq \Lambda_{sd} \quad (1)$$

- Single wavelength assignment constraints

$$\text{For all } l, \text{ for all } w, \sum_{p:l \in p} \sum_r x_{pw}^r \leq 1 \quad (2)$$

- Link-rate utilization constraints

$$\text{For all } l, \text{ for all } p:l \in p, \text{ for all } w, \text{ for all } r, x_{pw}^r \leq u_l^r \quad (3)$$

- Fiber type constraints

$$\text{For all } l, \sum_t f_l^t = 1 \quad (4)$$

$$\text{For all } r, \text{ for all } t: r \notin t, \text{ and for all } l, f_l^t \leq 1 - u_l^r. \quad (5)$$

For the case of an MLR system with  $r=\{10,40,100\}$  Gbps, we have the following set of constraints

$$\text{For all } l, f_l^{t=\{40\}} \leq 1 - u_l^{r=10}, f_l^{t=\{100\}} \leq 1 - u_l^{r=10}, f_l^{t=\{40,100\}} \leq 1 - u_l^{r=10},$$

$$f_l^{t=\{10\}} \leq 1 - u_l^{r=40}, f_l^{t=\{100\}} \leq 1 - u_l^{r=40}, f_l^{t=\{10,100\}} \leq 1 - u_l^{r=40},$$

$$f_l^{t=\{10\}} \leq 1 - u_l^{r=100}, f_l^{t=\{40\}} \leq 1 - u_l^{r=100}, f_l^{t=\{10,40\}} \leq 1 - u_l^{r=100}.$$

- Effective length constraints

$$\text{For all } p, \text{ for all } r, \sum_{l \in p} \sum_t D_l^{r,t} \cdot f_l^t \leq D^r + B \cdot y_p^r, \quad (6)$$

where  $B$  is a large constant (e.g. greater than the length of the longer length path in the network).

$$\text{For all } p, \text{ for all } r, \text{ for all } w, x_{pw}^r \leq 1 - y_p^r. \quad (7)$$

Constraints (1) ensure that the lightpaths that would serve a connection have higher capacity than the one requested. Constraints (2) prohibit the assignment of a wavelength to more than one lightpaths. Constraints (3) define the utilization of different rates of a link, based on the lightpaths that are transmitted over that link. Constraints (4) and (5) define the type of fiber used for a link, based on the different modulation format/rates used over it. Constraints (6) enable or disable the use of a certain path for a certain rate based on the effective lengths of the links that comprise it (the effective lengths of the links are adapted based on the utilization of the network as determined by constraints (3)-(5)). Constraints (7) prohibit the utilization of lightpaths over paths that cannot be used for a transmission at certain rate (as defined by constraints (6)).

TABLE I. NUMBER OF VARIABLES AND CONSTRAINTS

Variables	$x$ $kN^2 \cdot W \cdot M$	$f$ $L \cdot 2^M$	$u$ $L \cdot M$	$y$ $kN^2 \cdot M$
Constraints	(1) $N^2$	(2) $L \cdot W$	(3) Less than $L \cdot kN^2 \cdot W \cdot M$	(4) $L$
	(5) $M(2^M-1) \cdot L$	(6) $kN^2 \cdot M$	(7) $kN^2 \cdot M \cdot W$	

Table I presents the number of variables and constraints required in the above ILP formulation. In this table we denote by  $N=|V|$  the number of nodes, by  $|E|=L$  the number of links, by  $|C|=W$  the number of wavelengths, by  $|R|=M$  the number of

different rates and by  $k$  the number of pre-calculated shortest paths per connection. The number of different fiber types can be calculated as  $|T|=2^M-1$ , which is the cardinality of the powerset of  $R$  excluding the zero set.

### B. Heuristic algorithm

Since the above ILP formulation cannot be solved efficiently for large networks, it is desirable to obtain efficient heuristic algorithms. The approach to be proposed uses a pre-ordering phase and then a heuristic algorithm designed for single demands, to sequentially serve the demands one-by-one.

#### 1) Single Demand Heuristic Algorithm

We assume that each link is characterized by a wavelength availability vector  $\overline{W}_l$  of physical length  $D_l$  and fiber type  $t_l$ . In what follows, we assume that we have enough wavelengths to satisfy the requested connections. Moreover, the network supports a set  $R=\{r_1, r_2, \dots, r_M\}$  of  $M$  rates. The cost of each transponder at rate  $r$  is equal to  $C^r$ .

To serve a new connection  $(s,d)$  requiring capacity  $\Lambda_{sd}$ , the algorithm first splits this capacity into the available bit rates of the network, while minimizing the cost of the required transponders. For example, in case of a MLR system with two bit rates  $r=\{10,40\}$  Gbps and the relative cost of transponders to satisfy the inequality  $2 \cdot C^{10} < C^{40} < 4 \cdot C^{10}$ , we split the capacity  $\Lambda_{sd}$  into two different rates (sub-demands)  $r_1=10$  and  $r_2=40$  such that  $10x_1+40x_2 \geq \Lambda_{sd}$ , where  $x_1$  and  $x_2$  are integers, and  $x_i$  is the number of required lightpaths at rate  $r_i$ . We find  $x_1$  and  $x_2$  as follows:  $\alpha = \lfloor \Lambda_{sd} / 40 \rfloor$ ,  $b = \text{mod}(\Lambda_{sd} / 40)$ . If  $b \leq 10$ , then  $x_1=1$ ,  $y=0$ , else if  $b \leq 20$  then  $x_1=2$ ,  $y=0$ , else if  $b \leq 30$  then  $x_1=0$ ,  $y=1$ , else if  $b \leq 40$  then  $x_1=0$ ,  $y=1$ . Finally,  $x_2=\alpha+y$ . The same procedure can be followed for a system that supports three or any other number of rates. Note that finding the optimal split of  $\Lambda_{sd}$  to the available rates is a difficult problem and the above heuristic is used to maintain the running time at low levels.

The single demand algorithm works as follows. As previously, we pre-calculate in a pre-processing phase a set  $P_{sd}$  of  $k$  paths for each source destination pair  $(s,d)$ . We then establish the lightpaths for each of the sub-demands  $x_i$ . The demands  $x_i$  of  $\Lambda_{sd}$  are routed through 10G lightpaths. The fiber types of all links comprising the path are updated based on the candidate 10G lightpath and the already established lightpaths. If there are only 10G channels established in some links, the fiber type of these links is not changed. From the  $k$  paths the algorithm chooses the one that has minimum impact on the established connections. If the newly established lightpath affects any previously established lightpath of higher rate, the affected lightpaths are rerouted through lower rate connections. The demands  $x_2$  of  $\Lambda_{sd}$  are routed through 40G lightpaths using a similar logic. The only difference is what happens when other lightpaths are affected. In this case, the  $x_2$  demands of 40G are routed through lower rate (10G) lightpaths. The same stands for higher rate demands.

The above described algorithm is a quick and efficient greedy algorithm that finds for each new connection demand the lowest possible cost to. Pre-calculation of paths is used for speeding up the procedure, especially in the simulated annealing variation of the algorithm, to be described shortly.

## 2) Ordering the demands and Simulated Annealing

The heuristic algorithm described above serves the demands in the traffic matrix, one-by-one, in some particular order. The ordering in which the requested connections are served is quite important in this process, and different orderings result in different planning solutions. Two such ordering policies that we have evaluated are the following:

- *Highest Demand First (HDF)* ordering: We order the connection demands according to their requested rate, and serve first the demand that requires the highest rate.
- *Longest Path First (LPF)* ordering: We order the connection demands according to the number of links on their shortest paths, and serve first the demand whose shortest path utilizes the largest number of links.

In order to find good orderings, we also use a simulated annealing (SA) meta-heuristic, which works as follows. We start with the HDF ordering and calculate its cost (viewed as “energy” in the SA setting) by serving the connections one-by-one, using the single demand heuristic algorithm described in subsection III.B.1 (this is the “fitness function”). For a particular ordering  $((s_1, d_1), (s_2, d_2), \dots, (s_M, d_M))$  of  $M$  demands, we define its neighbor as the ordering where  $(s_i, d_i)$  is interchanged with  $(s_j, d_j)$  for some  $i$  and  $j$ . To generate a random neighbor we choose pivots  $(s_i, d_i)$  and  $(s_j, d_j)$  uniformly among the  $M$  demands. We use this random neighbor creation procedure and the single demand heuristic as the fitness function in a typical simulated annealing iterative procedure.

## IV. PERFORMANCE RESULTS

We carried out a number of simulation experiments in order to evaluate the performance of the proposed adaptive MLR algorithms. We have implemented both the ILP and the heuristic algorithm in Matlab. We used ILOG CPLEX to solve the corresponding ILP problems and Matlab’s built in simulated annealing tool. Our results were obtained for the generic Deutsche Telekom network topology consisting of 14 nodes and 46 directed links. The average shortest path length of this network is 450 km. We used a realistic traffic matrix consisting of traffic prediction for 2009 (please refer to deliverable D2.1 in [www.diconet.eu/deliverables.asp](http://www.diconet.eu/deliverables.asp)). In this traffic matrix the capacity requirements among the connections range from 4.5 up to 47 Gbps, with an average of 15 Gbps. We scaled up this realistic traffic matrix to obtain traffic matrices up to 8 times larger than the reference matrix, corresponding to the expected traffic growth in the following few years. For all the algorithms we used  $k=3$  shortest paths.

We assumed that the network supports two line rates, 10 and 40 Gbps, implemented using OOK and DQPSK transmitters, respectively. Thus, there are three types of fibers, and in particular  $T = \{\{10\}, \{40\}, \{10,40\}\}$ . The relative cost of the 10 and 40 Gbps transmitters was taken to be  $C^{10}=1$  and  $C^{40}=2.5$ , respectively, and the transmission reach is  $D^{10}=2500$  and  $D^{40}=800$  km, respectively. Note that as previously discussed, the cost per bit of the 40 Gbps connection is lower than the corresponding cost per bit of the 10 Gbps, but the transmission reach is reduced for the 40 Gbps connection.

The transmission reach of the 10 Gbps connections is high for the network under study, and thus the effective length multipliers  $m^{r=10,t}$ ,  $t \in T$ , related to the 10 Gbps rate would have no effect, unless they take large values (e.g. values higher than 2). Thus, we only have to consider the effective length multiplier for 40 Gbps, that is  $m^{r=40,t}$ ,  $t \in T$ . Recall that by

TABLE II: NETWORK COST FOR THE  $m^{40,\{10,40\}} = 1.25$  CASE

Load	Algorithms				
	ILP	HDF	SA -1000 iterations	Lower Bound ( $m=1$ )	Upper Bound ( $D_a^{40}$ )
1	342	342	342	342	343
2	507	512	507.5	505	512
3	666	684	669	661	680
4	848	887	855	837	863
5	1037	1137	1056.5	1024	1057
6	1197	1356	1220.5	1184	1224
7	1379	1608	1408.5	1361	1413
8	1564	1878	1636.5	1540	1600

TABLE III: TYPE OF FIBERS USED BY ILP ALGO. IN  $m^{40,\{10,40\}} = 1.25$  CASE

Type \ Load	1	2	3	4	5	6	7	8
{10}	5	4	2	0	1	2	1	1
{40}	7	7	8	8	8	10	10	10
{10,40}	34	35	36	38	37	34	35	35

definition  $m^{40,\{40\}}=1$  and  $m^{40,\{10\}}$  does not exist, since fiber type {10} does not support rate  $r=40$ . Thus, the sole effective length multiplier affecting the performance of the system is  $m^{40,\{10,40\}}$ , corresponding to the case of a 40 Gbps connection transmitted over a link that serves also 10 Gbps connections (fiber of type  $t=\{10,40\}$ ). In our simulation experiments we have used three different values for  $m^{40,\{10,40\}}$ , and in particular,  $m^{40,\{10,40\}}=1$ , 1.25 and 1.5. Note that the case where  $m^{40,\{10,40\}}=1$  corresponds to a MLR system that does not adapt its transmission reach, and other planning algorithms from the literature could be used. This case has been included for comparison purposes and can be used to find the lower bound of the network cost. The  $m^{40,\{10,40\}}=1.25$  case seems more realistic (similar to [8]), while the  $m^{40,\{10,40\}}=1.5$  case exaggerates the interference phenomena between 10 and 40 Gbps connections.

In addition to the above described scenarios we also present results for the case of a MLR system with  $m^{40,\{10,40\}}=1$  and (a) transmission reach of 40 Gbps connections  $D_a^{40}=800/1.25$  km, or (b) transmission reach of 40 Gbps  $D_b^{40}=800/1.5$  km. These cases correspond to the planning of a network under the worst case interference assumption and are used to obtain upper bounds on the network cost for the scenarios with  $m^{40,\{10,40\}}=1.25$  and  $m^{40,\{10,40\}}=1.5$ , respectively.

Table II presents the results for the case of  $m^{40,\{10,40\}}=1.25$ . Comparing the lower and upper bounds we can see the cost difference of planning the network with  $D^{40}=800$  km and  $D_a^{40}=800/1.25=640$  km. An MLR algorithm that plans the network by adapting the transmission reach would have performance in-between these two bounds.

The algorithm that accounts for the adaptive transmission reach would assign paths and rates to the connections so as to be able to control the interference. Cost gains would be obtained by maintaining acceptable transmission reach for capacity demanding connections. For example, consider a high capacity connection that would benefit from using a 40 Gbps transmission. Assume that for this transmission it can use a path whose length is between 800 and 640 km. The adaptive reach MLR algorithm would select to establish the connections

TABLE IV: NETWORK COST FOR THE  $m^{40,\{10,40\}} = 1.5$  CASE

Load	Algorithms				
	ILP	HDF	SA -1000 iteration	Lower Bound ( $m=1$ )	Upper Bound ( $D_b^{40}$ )
1	343	344	343	342	345
2	512	528	514	505	533
3	675	718	695	661	719
4	860	970	900.5	837	912
5	1049.5	1284	1113.5	1024	1120
6	1217	1582.5	1294.5	1184	1303
7	1402.5	1939	1476	1361	1507
8	1586.5	2021	1740.5	1540	1707

in the network so that 10 Gbps lightpaths do not interfere with it at every intermediate link (that would reduce the transmission reach of the connection down to the worst case - 640 km). The proposed ILP reach adaptive algorithm manages to plan the network and avoid interference. To do so it has certain links that support only 10 Gbps and only 40 Gbps connections. For example, for load 1 it finds a solution with 5 links of type {10}, 7 links of type {40} and the remaining links support both 10 and 40 Gbps connections. This information is presented in Table III, where we observe that even at high loads the ILP algorithm manages to have a high number of links that support only 40 Gbps connections, and whose effective length does not increase at all (remember that  $m^{40,\{40\}}=1$ ). Using this mechanism, we can observe in Table II that the ILP algorithm is able to plan the network with a cost that is close to the lower bound (corresponding to the planning of the network with  $D^{40}=800$  km). The sequential heuristic algorithm has decent performance, which is greatly improved when using simulated annealing. The HDF and LPF orderings produce good results for light load (only the best performing HDF is presented in Table II), but as the load increases and more connections can utilize 40 Gbps links, the problem becomes more complicated and the performance deteriorates. Simulated annealing (SA) was able to improve the performance and obtain good results in all cases, except for load=8, below the upper bound. Note that although the results reported were taken using 1000 iterations for SA, we also tested SA for a higher number of iterations. We found that the performance was only slightly improved for a higher number of SA iterations while the running times were, naturally, higher.

Regarding the running times, the ILP algorithm was able to solve these medium size problems within a few hours (note that we have used an enhanced version of the ILP formulation presented in Section III.A with a reduced number of variables and constraints so that only connections that would use 40 Gbps transmission over paths between 640 and 800 km are considered). In contrast, the average running time of the heuristic with a single ordering policy was a few seconds, and SA ran for a couple of minutes. As long as we were able to obtain solutions with the ILP, its performance was superior (as seen in Table II), but for larger networks and heavy traffic the heuristic algorithm is the only feasible solution.

Table IV presents results for the case where the interference between 10 and 40 Gbps connections is higher ( $m^{40,\{10,40\}}=1.5$ ). As expected, the difference between the lower and upper bounds in this case are larger, since the lower bounds remain

the same (as in Table II) while the upper bounds correspond to a network planned for a lower 40 Gbps transmission reach ( $D_b^{40}=800/1.5=534$  km). The ILP algorithm was again able to give solutions that are superior to those obtained by the other methods. We can observe that the ILP is able to plan the network with a cost close to the lower bound and the gains are more pronounced here than in the case of  $m^{40,\{10,40\}}=1.25$ , presented in Table II. Again the heuristic algorithm has acceptable performance when using simulated annealing.

Note that the algorithms presented in this paper can be used in networks that support any given number of rates (higher than two). In our simulations, we have used a network that supports only two rates as a proof of concept, and to obtain a better understanding of the effects of the parameters involved.

## V. CONCLUSIONS

We presented algorithms for planning a mixed line rates (MLR) optical transport network. In MLR systems the transmission reach can differ significantly from those typically used in single rate systems. We modeled the interference due to the different modulation formats/rates used in a MLR system by defining an effective length metric that helps us adapt the transmission reach of the connections according to the utilization state of the network. We used effective length constraints to solve the MLR adaptive planning problem. We initially presented an optimal ILP algorithm for the MLR planning problem. We also gave a sequential heuristic algorithm and examined two ordering policies and a simulated annealing variation. Our results indicate that important cost benefits can be obtained by planning the network using algorithms that account for the adaptation of the transmission reach, as the ones proposed here, compared to planning the network under the worst transmission reach assumption.

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