Planning Mixed-Line-Rate WDM Transport Networks

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ABSTRACT
We consider the problem of planning a mixed line rates (MLR) WDM transport optical network. In a MLR network, the interference between different modulation format/line rate connections affect the transmission reach of these connections. We present algorithms to plan a MLR network that take into account the variation of the transmission reach according to the use of the modulation formats/line rates in the network.
Keywords: Mixed line rates WDM systems, routing and wavelength assignment, adaptive transmission reach.

1. 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 is performed by setting up transparent optical channels named lightpaths. The problem of selecting appropriate paths and wavelengths for a set of requested connections is called Routing and Wavelength Assignment (RWA) and its objective is to the minimize the network resources used for a given traffic, or maximize the traffic served for a given set of resources.

Signal transmission is significantly affected by physical limitations of fibers and optical components [1]. Transmission reach is the distance an optical signal can travel before its quality and the bit-error-ratio (BER) degrade to an unacceptable level. Many factors affect the transmission reach: the launched power, the modulation format, the bit rate, the type of the amplification, the dispersion map, etc. For a given modulation format, higher rate transmissions have a shorter reach. After a point, this may become impractical, and we have to consider different and improved modulation techniques with better spectral efficiency and reach-rate product. Note that 10 Gbps systems typically utilize ON/OFF keying. To move to higher rate transmissions more advanced modulation formats, such as duobinary or phase shift keying modulation techniques have to be employed [2-5]. Given the rapid increase of traffic, the available bandwidth of many core networks has to be upgraded. While the industry wants to move quickly to higher capacity networks and enhance the 10 Gbps 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 to justify the use of 40 and 100 Gbps DWDM transport over 10 Gbps transport. As the technology of higher data rates matures and becomes more efficient, 40 and 100 Gbps connections will be incorporated in existing 10G networks [2-3]. Thus, a transport network will end up managing a variety of channel rates, what is usually referred to as a mixed line rates (MLR) system. The total cost of the transponders can be reduced by exploiting the heterogeneity and flexibility available 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 40 or 100 Gbps transponders.

Recently, routing and wavelength assignment (RWA) algorithms for MLR systems have been proposed [5-7]. The authors in [5] investigate the bit-rate migration from 10 to 40 Gbps. In [6], the design of a multi-rate Ethernet optical network is examined, where nodes use electronic regeneration, with all wavelengths on a link running at the same rate, but different links having different rates. In [7] a cost-effective approach to plan a MLR network under transmission-reach constraints calculated by the modulation format that is used for each rate is proposed.

However, multiplexing wavelength channels with different modulation format/line rates in the same system introduces a number of additional technical issues. A field trial has been conducted to demonstrate the feasibility of accommodating 10, 40 and 100Gbps with standard 50-GHz channel spacing [3]. Simultaneously transmitted optical signals with different modulation formats can lead to considerable degradations in signal quality and, consequently, to reductions in the transmission reach up to 25% [5]. Taking this into account, [5] proposed a heuristic algorithm that follows a worst case approach, that is, using the decreased transmission reaches under worst case interference assumption, without considering the actual utilization state of the network.

In this paper we present RWA algorithms for planning MLR optical transport networks. As discussed in [2-5], 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. 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 among different rate connections, which we will call *cross-rate interference*. The proposed algorithms take into account the variation of the transmission reach of the connections according to the utilization state of the network, so as to avoid cross-rate interference, enabling transmission over paths that would otherwise be prohibited.

2. EFFECTIVE LENGTH

In what follows we present a way to formulate the variation of the acceptable transmission reach of a connection in accordance with the utilization state of the network. In particular, depending on the 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 lightpath, we adapt the effective lengths of the links that comprise the path followed by it in order to account for cross-rate interference.

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 and in the simulation results that $r = \{10, 40, 100\}$Gbps, and each link consists of a single fiber. However, the proposed algorithms are general and can work for different and more rates. Assume a lightpath (p, w, r), that is, the lightpath utilizes path p and wavelength w and uses rate r. Assume a link l of length D_l that is crossed by path p, so that $l\in p$, and consider another lightpath (p', w', r') that also crosses link l. We will say that lightpath (p', w', r') *cross-rate* interfere to (p, w, r), if these lightpaths utilize different rates, $r' \neq r$, they cross the same link l and their spectrum distance is within a given distance, $|w - w'| \leq I^{r,r'}$, where $I^{r,r'}$ is the interfering distance threshold in wavelengths. The effective length of the fiber link l of lightpath (p, w, r) that is subject to interference from lightpath (p', w', r') is denoted by $D^{r,r'}_{l,w} = D_l + m^{r,r'} \cdot D_l = (1 + m^{r,r'}) \cdot D_l$, that is, it is equal to the physical length D_l of the link, increased by a factor $m^{r,r'}$. Similarly, we can define the effective length of the link l for lightpath (p', w', r') to be $D^{r',r}_{l,w'} = (1 + m^{r',r}) \cdot D_l$. In general, we can have different effective length factors for different directions of the interference, $m^{r',r} \neq m^{r,r'}$, and we can also have different wavelength interfering distance thresholds $I^{r',r} \neq I^{r,r'}$. We define the *effective length* of link l for lightpath (p, w, r) as

$$D^r_{lw} = D_l + \sum_{r':\exists(p',w',r')\text{ and } l\in p' \text{ and } |w-w'|\leq I^{r,r'}} m^{r,r'} \cdot D_l = \left(1 + \sum_{r':\exists(p',w',r')\text{ and } l\in p' \text{ and } |w-w'|\leq I^{r,r'}} m^{r,r'}\right) \cdot D_l . \quad (1)$$

Note that, even if two or more lightpaths of rate r' are within interfering distance $I^{r,r'}$, we increase the effective length of the link just once. Also note, that the actual wavelength distance $|w - w'|$ is not taken into account. In this context the effective length factor $m^{r,r'}$ corresponds to the worst case interference effect of rate r' on rate r. A more accurate model that would consider the exact number and distance of the cross-rate interfering lightpaths could be used, as done for single line rate systems in [8]. However, we argue that the above model is quite realistic and gives us enough flexibility to use the wavelength domain to avoid cross-rate interference.

Consider a lightpath (p, w, r) and assume that we know the rate utilization of the interfering wavelength channels on all the links $l_1, l_2, \ldots, l_n$, comprising path p. We can then use Eq. (1) to calculate $D^r_{l_i w}$, for all links $l_i = l_1, l_2, \ldots, l_n$. Then, the effective length of lightpath (p, w, r) is given by

$$D^r_{pw} = D^r_{l_1 w} + D^r_{l_2 w} + \ldots + D^r_{l_n w} . \quad (2)$$

For the example of Fig. 2, the effective length for path p_{ABC} for wavelength w_1 at rate 10Gbps is $D^{10}_{pw_1} = D^{10}_{lw_1} + D^{10}_{l'w_1} = (1.1)\cdot D_l + D_{l'}$, assuming that $m^{10,40} = 0.1$ and $I^{10,40} = 2$. In comparison, the effective length for wavelength w_5 is $D^{10}_{pw_5} = D^{10}_{lw_5} + D^{10}_{l'w_5} = D_l + D_{l'}$. The difference is due to the 40 Gbps lightpath on wavelength w_2 that interfere with the lightpath that utilizes w_1 and not with the one that utilizes w_5.

In our model, we assume that a lightpath of rate r has, in the absence of any cross-rate interference, a maximum transmission reach D^r. This maximum transmission reach accounts for all other kinds of physical layer impairments a connection of rate r is subject to. This limit is used as an upper bound on the effective length (instead of the physical length) of all connections of rate r in the MLR system. If the effective length of the lightpath (p,w,r) is higher than the given bound (i.e., $D^r < D^r_{pw}$) then the lightpath has unacceptable quality of transmission and cannot be utilized.

3. 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. We are also given the actual (physical) lengths D_l of all links $l\in E$. Each fiber is able to support a set $C=\{1,2,\ldots,W\}$ of W distinct wavelengths, and a set $R=\{r_1,r_2,\ldots,r_M\}$ of M different bit rates. For each rate r, we are given the interfering wavelength distance threshold $I^{r,r'}$ and the effective length factor $m^{r,r'}$, for all $r'\in R$. We are also given the transmission reach bounds D^r and the corresponding transponder costs C^r. We assume an a-priori known traffic scenario given in the form of a matrix Λ, called the traffic matrix. Then, Λ_{sd} denotes the requested bandwidth from source s to destination d. The objective for planning a MLR system is to serve all traffic, described in Λ, and minimize the total cost of the transponders, related to the number and type of the transponders used. Moreover, each lightpath has to satisfy an adaptive transmission reach constraint, modelled through the use of the effective lengths of the links that vary according to the utilization state of the network and the modulation formats/rates used. In this study, we consider the planning of transparent MLR networks, which do not support regeneration and all connections are established end-to-end through transparent lightpaths. The proposed algorithm pre-calculates for each requested source-destination pair (s,d) a set of k-shortest paths P_{sd}.

x^r_{pw}: Boolean variable. Equals to 1 if wavelength w with rate r over path $p\in P_{sd}$, that is, transparent lightpath (p,w,r), is used to serve the connection (s,d).

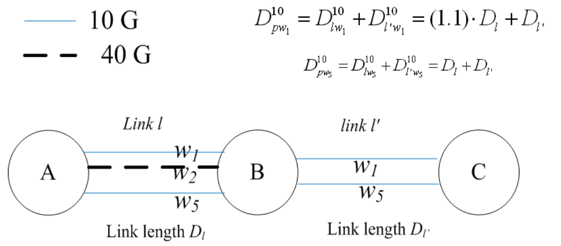

Figure 2a. Calculation of the effective length of a lightpath, taking into account the cross-rate interference.

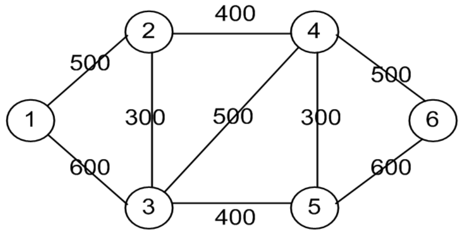

Figure 2b. Small 6-node network used in simulation experiments.

$u^{r,r'}_{lw}$: Boolean variable. Equals to 1 if at least one connection with rate r' is transmitted over link l in wavelengths $[\max(0,w-I^{r,r'}),\min(w+I^{r,r'},W)]$.

Objective: minimize: $\sum_p \sum_w \sum_r C^r \cdot x^r_{pw}$, subject to the following constraints:

for all $s,d\in V$, $\sum_{p\in P_{sd}} \sum_w \sum_r r\cdot x^r_{pw} \geq \Lambda_{sd}$; (C1)

for all $l\in E$, for all $w\in W$, $\sum_{p:l\in p} \sum_r x^r_{pw} \leq 1$; (C2)

for all $l\in E$, for all $w\in W$, for all $r,r'\in R$, $\sum_{\max(0,w-I^{r,r'})\leq w'\leq \min(w+I^{r,r'},W)} \sum_{p:l\in p} x^{r'}_{pw'} \leq B\cdot u^{r,r'}_{lw}$, (C3)

where B is a large constant, e.g. B=1000;

for all $s,d\in V$, $p\in P_{sd}$, for all $w\in W$, for all $r\in R$, $\sum_{l\in p} D_l \cdot x^r_{pw} + \sum_{r'\in R} \sum_{l\in p} m^{r,r'}\cdot D_l \cdot u^{r,r'}_{lw} < D^r$. (C4)

Constraints (C1) ensure that the lightpaths chosen to serve an end-to-end demand should have higher capacity than the requested demand. Constraints (C2) prohibit the assignment of a wavelength to more than one lightpaths. Constraints (C3) identify cross-rate interfere among lightpaths so as to set accordingly the corresponding $u^{r,r'}_{lw}$ variables. To do so, constraints (C3) take into account the utilization of the lightpaths of the network. Then, variables $u^{r,r'}_{lw}$ are used in constraints (C4) to calculate the effective lengths of the lightpaths based on the effective lengths of the links that comprise them, using Eq. (2).

Since the above ILP formulation cannot be solved efficiently for large networks, we also developed a heuristic approach that consists of three phases. In the first phase, the algorithm breaks the demands into end-to-end connections of specific rates. For each demand we calculate k-shortest paths and define the rates that can be used over these paths. We then break the transmission in these supported rates so as to minimize the cost of the transponders that are required. In the second phase the demands are ordered according to some criterion. We employed a specific policy, the *Highest Demand First* (*HDF*) policy, and we also used simulated annealing (SimAn) to obtain even better orderings. Then, in the third phase, a heuristic algorithm designed to serve single demands is used, to sequentially serve the connections one-by-one. We maintain the utilization state of the network in terms of links-wavelengths-rates that have been utilized up to that point. For each demand we establish the lightpaths with the rates that were identified in the first phase of the algorithm. For each rate we examine the paths that can support that rate. For an available wavelength over a path, we calculate the effective length of the defined lightpath (the lightpath is defined by the path-wavelength-rate choice), taking into account the utilization state of the network up to that point and applying Eq. (1) and (2). We also calculate again the effective lengths of the established lightpaths to check if the introduction of the new lightpath turns some of them previously established connections infeasible. If all checks are passed we establish the lightpath and update the utilization state of the network. After searching all available wavelengths, the algorithm returns the number of lightpaths that were not served with the given number of supported wavelengths in the network.

4. PERFORMANCE RESULTS

We carried out a number of simulation experiments in order to evaluate the performance of the proposed adaptive length MLR algorithms. We assumed that the network supports three transmission rates, and in particular 10, 40 and 100 Gbps, using e.g. OOK, QPSK and DQPSK, respectively. The transmission reaches D^r were taken equal to 2500, 1500 and 800 km, and the relative costs of the transponders were set to 1, 2.5 and 5.5, respectively. Note that, as we move to higher rate transmitters the cost per bit decreases, but also the transmission reach decreases. In these simulations we set the effective length factor $m^{r,r'}$=0.1, and the wavelength interfering distance thresholds $I^{r',r} = 2$, for all $r'\neq r$. We performed experiments assuming a simple 6 node topology shown in Fig. 2. We randomly created traffic matrices. In particular, for a given traffic load, we created 10 traffic matrices, where the capacity for each (s, d) pair was given by an exponential random variable with average the given traffic load.

Table 1. Performance results for the 6-node network topology.

Load (Gbps)	10			25			40			55			70			85			100		
Algorithm	cost	w	time	cost	w	time	cost	w	time	cost	w	time	cost	w	time	cost	w	time	cost	w	time
HDF	44.05	4.90	0.08	69.10	5.70	0.11	95.85	6.90	0.12	119.60	7.40	0.13	145.15	9.40	0.19	170.90	10.30	0.26	196.00	11.90	0.27
SimAn (100 iter)	44.05	4.70	0.16	69.10	5.10	0.42	95.85	6.30	0.27	119.60	7.20	0.40	145.15	8.60	0.91	170.90	9.70	0.99	196.00	11.10	1.13
SimAn (1000 iter)	44.05	4.60	0.31	69.10	5.10	0.41	95.85	6.30	0.24	119.60	7.10	2.29	145.15	8.40	8.81	170.90	9.50	9.95	196.00	10.70	20.91
ILP	44.05	4.60	3.57	69.10	5.10	2.69	95.85	6.30	3.43	119.60	7.10	4.45	145.15	8.40	10.17	170.90	9.40	12.12	196.00	10.70	78.38
best	44.05	4.60	2.29	69.10	5.10	2.55	95.85	6.30	3.11	119.60	7.10	4.07	145.15	8.40	4.27	170.90	9.40	6.17	196.00	10.70	11.40
worst	44.45	5.00	2.25	71.10	6.60	2.66	98.95	8.50	3.61	124.10	10.30	3.64	150.90	12.80	4.76	178.40	14.60	5.93	204.60	16.90	9.12

We created matrices for loads ranging from 10 to 100 Gbps, with a 15 Gbps step. Table 1 reports the average cost, the average number of wavelengths, and the average running time for the different load values and different algorithms. We examined the performance of the ILP algorithm for transparent networks, the heuristic algorithm, using the HBF ordering policy and also using simulated annealing (SimAn) with 100 and 1000 iterations. We also report what we call the "best" and "worst" cases for these experiments. In the best case, we assumed that the network is not subject to cross-rate interference and thus the transmission reach of the connections does not change and remain always equal to 2500, 1500 and 800 km, for 10, 40 and 100 Gbps, respectively. To obtain the results for the best case we assumed $m^{r,r'} = 0$, and/or $I^{r',r} = 0$. In the worst case, we assumed that worst case cross-rate interference is always present, irrespective of the utilization state of the network. To obtain the results for the worst case we divided D^r by 1.2, which is equal to the worst case increase of the effective length of the lightpaths.

From Table 1 we can observe that the optimal ILP algorithm was able to track solutions with average times up to a few seconds (78 s for load = 100 Gbps). The performance of the heuristic is quite good, and we can see that in all case the heuristic was able to find solutions with equal transponder cost to the optimal ILP solution. This has to do with the first phase of the heuristic algorithm that succeeds in dividing the connections to the optimal number of lightpaths. These lightpaths are then established in the third phase of the algorithm, using the available wavelengths. We can see that the heuristic algorithm requires different number of wavelengths to find zero blocking solutions, depending to the ordering that is used. When using simulated annealing (SimAn) with 1000 iterations (1000 is the number of different orderings that are examined), the number of wavelengths required to find zero blocking solutions were almost equal to that of the ILP algorithm expect for one case. However, the running time SimAn with 1000 iterations is comparable to that of the ILP algorithm. As the number of SimAn iterations decreases, the number of wavelengths required to find zero blocking solutions increases. The case that we use only one ordering, HBF, without employing SimAn, has obviously the worst wavelength performance. On the other hand, the running time of the heuristic algorithm decreases as the number of SimAn iterations decreases. Thus, using SimAn we have a tradeoff between the running time and the wavelength performance, but at least for this small network, the results show that even with 100 SimAn iterations we can obtain performance quite close to the optimal solution found by the ILP. Also in Table 1 we can observe that the cost and the number of wavelengths reported for the ILP algorithm are equal to the corresponding values reported for the "best" case, where no cross-rate interference is present. Thus, the proposed ILP algorithm utilizes the wavelengths effectively to absorb cross-rate interference. On the other hand, as can be seen by the results reported for the "worst" case, the number of wavelengths required to solve the problem assuming worst-case cross-rate interference is quite high, and also the transponder cost is increased. This has to do with the fact that in the worst case the transmission reaches are decreased and many paths in the network cannot be used.

5. CONCLUSIONS

In MLR systems the transmission reach can differ significantly from those typically used in single rate systems, according to the utilization of the different modulation formats/rates in the network. We modeled cross-rate interference among lightpaths in a MLR system by defining the effective length metric and used it in order to formulate algorithms that account for the variation of the transmission reach of the connections. Our results indicate that the proposed algorithms plan the network and avoid the cross-rate interference effects, enabling the transmission of connections with acceptable quality over paths that would otherwise be prohibited.

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