

# OSNR based routing in WDM optical networks

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*In this paper we propose new physical impairments based routing and wavelength assignment (ICBR) methods where the control plane has influence on the signal power of the Wavelength Division Multiplexed (WDM) channels in metro-optical networks. We give the exact integer linear programming (ILP) formulation of the method. Nowadays in nearly all kinds of reconfigurable optical add-drop multiplexers (ROADM) the signal power can be tuned via variable optical attenuators (VOA) from the control plane. The proposed algorithm can be used in existing WDM optical networks where the nodes support signal power tuning. The proposed method outperforms the traditional existing schemes.*

## 1. Introduction

WDM networks have successfully solved the capacity issues, but the continuously changing traffic still causes a serious problem for the operators. Emerging demands often cannot be satisfied without modifying the network design, which is quite costly and difficult, so operators try to avoid this situation whenever possible. There is a strong need for a system that can deliver the same capacity as WDM, with the design and provisioning flexibility of SONET/SDH. The solution must ensure flexibility for dynamically changing future demands.

The reconfigurable optical network offers the possibility to increase or change services between sites with no advanced engineering or planning, and without disrupting existing services. In the past, reconfigurable optical networking technology was too expensive or delicate to be widely deployed. With recently matured silicon-based integrated Planar Lightwave Circuit components, reconfigurable optical add/drop multiplexers (ROADMs) are now being installed by many operators. The technology called ROADM represents a real breakthrough for WDM networks by providing the flexibility and functionality required in present complex networking environments. Older, or fixed, OADMs cannot configure capacity at a node without manual reconfiguration and typically support reconfiguration of only a limited number of wavelengths. In contrast, ROADMs allow service providers to reconfigure add and drop capacity at a node remotely, reducing operating expenses by eliminating the time and complexity involved in manual reconfiguration.

ROADM by itself is not enough. Increased data management capabilities on individual wavelengths are also needed to exploit the benefits of ROADM in metro and backbone WDM networks. For instance, ROADM rings are very sensitive to topology changes and need strict monitoring and control of wavelength power to keep the system in balance. The real innovation lies in the system engineering related to the ROADM function, addressing

per-wavelength power measurement and management, and per-wavelength fault isolation. Almost every optical system vendor has commercial ROADM with wavelength monitoring functions (see e.g. [1-4]).

The next step towards a fully reconfigurable WDM optical network is the deployment of tunable Small Form-factor Pluggable (SFP) interfaces, where the wavelength allocation is modified according to the network changes. The tunable dispersion compensation elements mean another innovation. Nowadays these ready-made products can be purchased [5,6]. The evolution of optical networks seems to tend towards a fully reconfigurable network where the control and the management plane (CP and MP) have new functions, such as determining the signal quality, tuning the wavelength frequency, setting dispersion compensation units, and – by using variable optical attenuators – setting the channel powers. Of course traditional functions (such as routing) remain the main function of the CP and MP. Routing and Wavelength Assignment (RWA) play a central role in the control and management of optical networks. Many excellent papers deal with the design, configuration, and optimization of WDM networks (see e.g. [7-8]). However, they do not consider the physical parameters of the fully reconfigurable optical network in the RWA method at all.

In this paper we propose a new ILP based RWA algorithm where the control plane handles the routing and the signal power allocation jointly. Nowadays in nearly all types of ROADMs the signal power can be tuned with variable optical attenuators (VOA) from the management system.

In metro WDM networks the signal power of the optical channels is determined by Cross-Phase (XPM) modulation and Raman scattering and not by the Brillouin threshold. This means that the total power inserted in fiber and not the channel powers has an upper bound. In this case it is possible to increase the powers of some channels up to the Brillouin threshold and at the same time the other channel powers have to be decreased to

fulfill the XPM and Raman scattering constraints. The previously mentioned idea can be used while configuring lightpaths. Let us assume a very simple scenario, see Fig. 1 In this case we have two wavelengths  $\lambda_1$  and  $\lambda_2$ . In Case "A" due to physical constraints node A can only reach node C in all-optical way. If there is a demand between node A-D this can only be established with signal regeneration or in node B or in C. In case "B" it is possible to increase the signal power of  $\lambda_2$  to fulfill the OSNR request at the node D. in this way it is possible to establish an all-optical connection between nodes A-D.

The proposed method can be used in existing WDM optical networks where the nodes support signal power tuning. The method also finds global optimum if it exists.

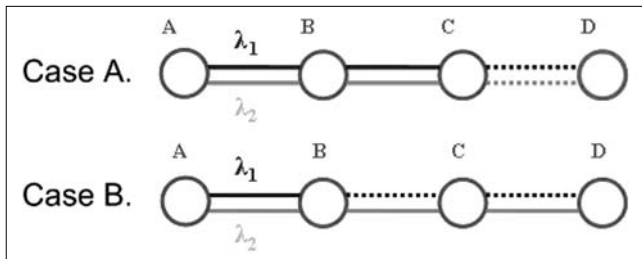


Figure 1. The difference of OSNR based routing and traditional routing schemes

### 2. Physical feasibility

As mentioned before, our proposed algorithms use different channel powers in the same optical fiber. This approach introduces many new problems related to physical feasibility. All physical effects were already investigated using equal channel power allocation. The only difference in our case is that the impacts of the effects are different for each channel, since the signal powers are different. In case of linear effects the signal power has no influence on the dispersion and its compensation schemes. The only linear effect which has signal power dependency is the crosstalk in the nodes. We assume that using the well-known power budget design process the effects of the crosstalk can be eliminated.

More interesting question is how the EDFAs react to the use of different channel power allocations. For this purpose we made simulations using the VPI TMM/CM Version 7.5 simulation tool [9]. We assumed a system with 8 channels which are multiplexed and then amplified using EDFA rate propagation modules. We aimed at investigating the difference between the uniform and the adaptive channel power allocations. These results lead us to the conclusion that the so far deployed EDFAs behave similarly in case of both uniform and non-uniform channel power allocations in a single optical fiber.

The other interesting question is about the nonlinear effects, since these effects

highly depend on the used signal powers. The only solution is to limit the signal power inserted in one optical fiber. This must be done in both allocation schemes. Another problem is the maximum allowed difference between the maximum and the minimum channel powers. In our case this is an input parameter of the algorithm. Determining this value is a hard task and is out of the scope of this paper. Finally to conclude: according to the results adaptive signal power allocation scheme can be implemented in optical systems deployed so far. Moreover, the authors know existing WDM optical networks operating without any error, where different channel powers – though not intentionally – are used, since the power tuning was not performed for the inserted channels in the ROADMs.

To investigate the relation between the signal power and the maximum allowed distance, we consider a noise limited system where other physical effects can be taken into account as power-penalty. It is possible to prove by analytical calculations that there is a linear relationship between the channel power and the maximum allowable distance of an all-optical link [10,11]:

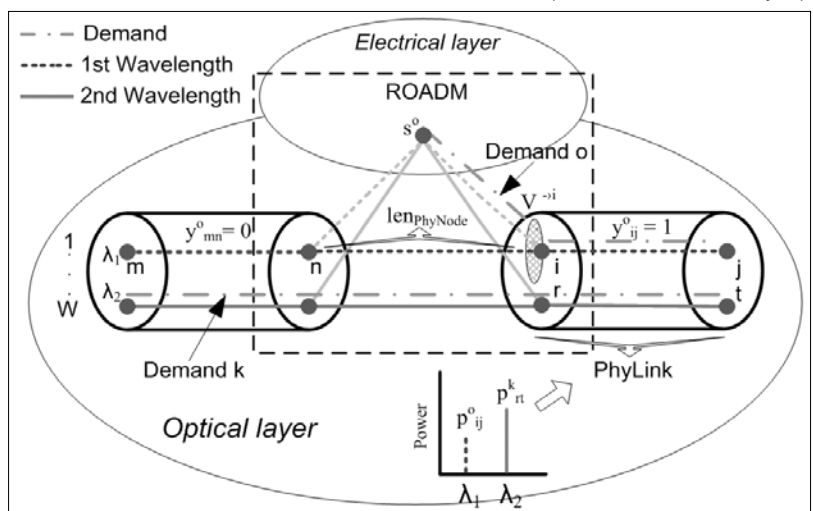
$$L = L_c \cdot P_{mW} \tag{2.1}$$

where  $P_{mW}$  is the input power in mW,  $L$  is the maximum allowable distance, and  $L_c$  is the linear factor between it. For typical constant values, used in telecommunications,  $L_c$  is between 500 and 2000.

### 3. Network and Routing Model

We applied the wavelength graph (WL graph) modeling technique. The WL graph (which can be regarded as a detailed virtual representation of the network) is derived from the physical network considering the topology and the switching capabilities of the devices (nodes). The technique allows arbitrary mesh topologies, different types of nodes and joint optimization of multiple layers. A simpler version of the model has been first proposed in [12].

Figure 2. Model of switching device with optical and electronic switching capabilities, grooming and 3R regeneration (in the electronic layer)



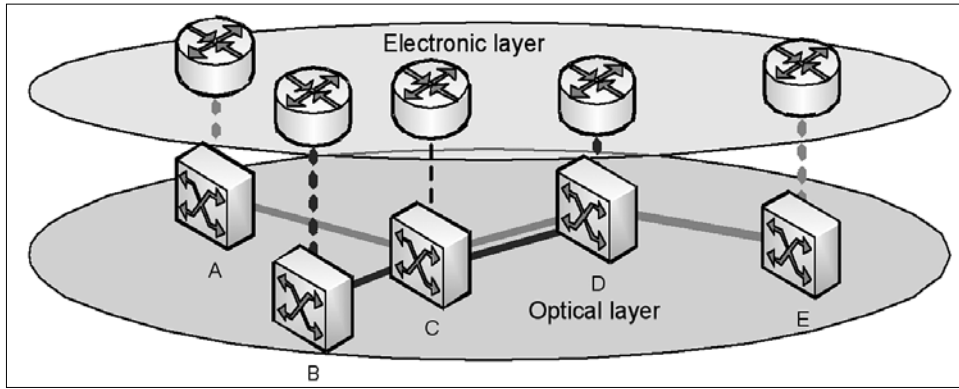


Figure 3. End-to-end lightpaths are assigned to each demand. In this example there are two demands (A-E and B-D). Two lightpaths (A-E, B-D) are allocated, no grooming is allowed on link C-D.

The model of an ROADM switching device assumed in our simulations is shown in Fig. 2. The device can perform optical switching and – through the electronic layer – wavelength conversion, grooming and 3R signal regeneration. The device is illustrated in Figure 2 has an input and an output interface with a *physical link* (or fiber) connected to each. Each physical interface supports two *wavelengths* ( $W=2$ ), marked by dark dashed and solid lines. The signal powers of the wavelengths in the right hand side physical link are different – as shown by the small subfigure. The example also comprises two demands (indicated by dash-dotted line): *demand k* passes through the switch in the optics, while *demand o* originates in this device in the electronic layer ( $s^o$ ). A certain length of fiber ( $len_{PhyNode}$ ) is assigned to each internal edge, e.g., edge  $(n, i)$ , which corresponds to the amount of signal distortion that the switching functionality introduces in the demand path. The edges representing O/E or E/O conversion are marked by grey color.

In routing we assume that WL conversion, grooming and signal regeneration are possible only in the electronic layer, and that the *noise and the signal distortion accumulate along the lightpath*. Actually, re-amplification, re-shaping and re-timing – which are collectively known as 3R regeneration – are necessary to overcome these impairments. Although 3R optical regeneration has been demonstrated in laboratories, only electronic 3R regeneration is economically viable in current networks.

The constraints of maximum input power in each fiber, and maximum allowed distance as a function of the input power of the lightpath have to be met.

In addition we differentiate between two routing cases and propose an ILP formulation for each (presented in Sections 4 and 5).

In the first case (referred to as *single-layer network*) we assume that a whole lightpath is assigned to each demand from source to destination node. The signal enters into the optical layer at the source node and leaves it at the destination node. Wavelength conversion, grooming or regeneration is not allowed elsewhere along the path.

In the second case (referred to as *multilayer network*) the path of a demand may consist of several lightpaths, i.e. it can enter and leave the electronic layer multiple times if necessary and efficient. In addition, in the second case grooming is also applicable.

## 4. ILP formulation of OSNR based routing in single layer networks

In this section we introduce the ILP formulation of OSNR based routing for single-layer networks (Fig. 3).

### 4.1 Constants

The WL graph contains nodes ( $V$ ) and edges ( $A$ ). Edge  $(i, j)$  represents one edge in the WL graph.  $V^{i \rightarrow}$  and  $V^{i \leftarrow}$  represent incoming and outgoing edges of node  $i$ , respectively. Symbol  $A^{sw}$  denotes the set of edges in the WL graph representing switching function inside a physical device; other edges represent wavelengths of a physical link ( $A^{pl}$ ). The set of demands in the network is denoted by  $O$ .

$$P_{pl}^{max} = 4-20 \text{ dBm, typically } 10 \text{ dBm} \quad (4.1)$$

Constant  $P_{pl}^{max}$  means the upper limit of total power in physical link  $pl$  in dBm.  $P_{pl}^{max}_{lin}$  the same in mW.

$$len_{ij} \quad (4.2)$$

Constant  $len_{ij}$  is the length of the physical link which the wavelength belongs to.

$$len_{PhyNode} = 90 \text{ km, typically} \quad (4.3)$$

Constant  $len_{PhyNode}$  corresponds to the length of the fiber a switching device induces to the path of the demand.

$$L_c = 1200 \quad (4.4)$$

Constant  $L_c$  is the factor of the linear relation between the input power of a demand (in mW) and the maximum distance the signal is allowed to reach.

$$\alpha \quad (4.5)$$

Constant  $\alpha$  expresses tradeoff between optimization objectives: minimal routing cost or minimal power.

$$s^o, t^o \quad (4.6)$$

Symbols  $s^o$  and  $t^o$  represent source and target of demand  $o$ .

$$\beta = \frac{n}{W} \cdot P_{pl}^{max}_{lin} \quad (4.7)$$

Constant  $\beta$  is the maximum allowed signal power for one channel in mW. Here  $n$  is integer a real number between 1 and  $W$ , and  $W$  is the number of wavelengths in a fiber.

## 4.2 Variables

$$p^o \in \left[ 0, \frac{\beta}{P_{pl}^{max}} \right], \forall o \in O \quad (4.8)$$

Variable  $p^o$  denotes the input power of demand  $o$  divided by  $P_{pl}^{max}$ .

$$p_{ij}^o \in \left[ 0, \frac{\beta}{P_{pl}^{max}} \right], \forall (i, j) \in A, \forall o \in O \quad (4.9)$$

Variable  $p_{ij}^o$  means the power of demand  $o$  on edge  $(i, j)$  divided by constant  $P_{pl}^{max}$ .

$$y_{ij}^o \in \{0, 1\}, \forall (i, j) \in A, \forall o \in O \quad (4.10)$$

Variable  $y_{ij}^o$  tells whether demand  $o$  uses edge  $(i, j)$  or not. (E.g., variable  $y_{mn}^o = 0$  in Fig. 2, since demand  $o$  does not pass through edge  $(m, n)$ , which represents the first wavelength. On the other hand, variable  $y_{ij}^o = 1$ , because demand  $o$  does use edge  $(i, j)$ .)

## 4.3 Objective function

Minimize:

$$\alpha \cdot \sum_{\forall o \in O} \sum_{\forall (i, j) \in A/\Lambda_{sw}} y_{ij}^o + (1-\alpha) \cdot \sum_{\forall o \in O} p^o \quad (4.11)$$

The objective function expresses that the sum of the used edges should be minimized together with the sum of input powers of demands. If we want to minimize the total cost of the routing, constant cost factors should be assigned to each edge.

Constant  $\alpha$  decides whether optimization emphasis is on minimal routing cost ( $\alpha$  is close to 1) or on minimal input power ( $\alpha$  is close to zero).

## 4.4 Constraints

$$\sum_{\forall o \in O} \sum_{\forall (i, j) \in pl} p_{ij}^o \leq 1, \forall pl \in \text{PhysLinks} \quad (4.12)$$

$$p_{ij}^o \leq y_{ij}^o, \forall (i, j) \in A, \forall o \in O \quad (4.13)$$

$$\sum_{\forall j \in V^{-in}} p_{ji}^o - \sum_{\forall k \in V^{+out}} p_{ik}^o = \begin{cases} -p^o & \text{if } i = s^o \\ 0 & \text{if } i \notin \{s^o, t^o\}, \\ +p^o & \text{if } i = t^o \end{cases}, \forall i \in V, o \in O \quad (4.14)$$

$$\sum_{\forall j \in V^{-in}} y_{ji}^o - \sum_{\forall k \in V^{+out}} y_{ik}^o = \begin{cases} -1 & \text{if } i = s^o \\ 0 & \text{if } i \notin \{s^o, t^o\}, \\ +1 & \text{if } i = t^o \end{cases}, \forall i \in V, o \in O \quad (4.15)$$

$$\sum_{\forall o \in O} y_{ij}^o \leq 1, \forall (i, j) \in A \quad (4.16)$$

$$\sum_{\forall (i, j) \in A^{sw}} y_{ij}^o \cdot \text{len}_{\text{PhysNode}} + \sum_{\forall (i, j) \in A^{pl}} y_{ij}^o \cdot \text{len}_{ij} \leq L(p^o) = L_c \cdot p^o \cdot P_{pl}^{max}, \forall o \in O \quad (4.17)$$

## 4.5 Explanation

Constraint (4.12) expresses that the sum power of demands traversing a physical link (fiber) cannot exceed

the maximum allowed power of that link. Constraint (4.13) tells that if the power of demand  $o$  in edge  $(i, j)$  is larger than zero, then edge  $(i, j)$  is used by demand  $o$ . Constraints (4.14) and (4.15) express the flow-conservation constraint of the power and of the  $y$  decision variables, respectively, for every demand. Constraint (4.16) guarantees that a given edge can be used by only one demand. Constraint (4.17) ensures that the total length of demand  $o$  should be less than the distance allowed by the input power of demand  $o$ .

## 5. ILP formulation of OSNR based routing in single layer networks

In this section we introduce the ILP formulation of Signal Power based Routing for multilayer networks, which can provide optimal solution for the joint problem of RWA with grooming and of determining the signal powers of lightpaths (Fig. 4).

### 5.1 Variables and constants

The symbols are similar to those introduced in 4.1. In addition the set of lightpaths is denoted by  $L$ . A path in the WL graph is considered as a lightpath if it goes only in the optical layer without going up to the electronic layer. A lightpath does not traverse through any electronic node except for the source and destination nodes.

$$p_{EF} \in \left[ 0, \frac{\beta}{P_{pl}^{max}} \right], \forall (E, F) \in L \quad (5.1)$$

Variable  $p_{EF}$  denotes the input power of lightpath  $(E, F)$  divided by constant  $P_{pl}^{max}$ .

$$p_{ij}^{EF} \in \left[ 0, \frac{\beta}{P_{pl}^{max}} \right], \forall (i, j) \in A, (E, F) \in L \quad (5.2)$$

Variable  $p_{ij}^{EF}$  means the power of lightpath  $(E, F)$  on edge  $(i, j)$  divided by constant  $P_{pl}^{max}$ .

$$x_{ij}^{EF} \in \{0, 1\}, \forall (i, j) \in A, o \in O, (E, F) \in L \quad (5.3)$$

Variable  $x_{ij}^{EF}$  expresses whether demand  $o$  uses lightpath  $(E, F)$  on edge  $(i, j)$  or not.

$$y_{ij}^{EF} \in \{0, 1\}, \forall (i, j) \in A, (E, F) \in L \quad (5.4)$$

Variable  $y_{ij}^{EF}$  indicate whether lightpath  $(E, F)$  uses edge  $(i, j)$  or not.

$$y_{ij} \in \{0, 1\}, \forall (i, j) \in A \quad (5.5)$$

Variable  $y_{ij}$  expresses whether edge  $(i, j)$  is used by the routing or not.

We use the same constants and calculated constants defined in 4.1.

### 5.2 Objective function

$$\text{Minimize: } \alpha \cdot \sum_{\forall (i, j) \in A} y_{ij} + (1-\alpha) \cdot \sum_{\forall (E, F) \in L} p_{EF} \quad (5.6)$$

The objective function expresses that the routing cost (including network resources) should be minimized together with the total of signal powers. If we want to minimize

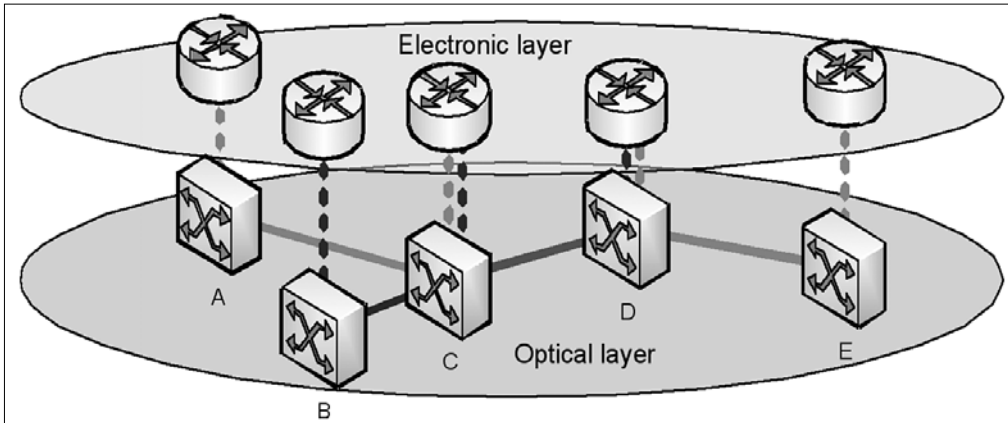


Figure 4.  
There are two demands (A-E and B-D).  
Altogether 4 lightpaths (A-C, B-C, C-D and D-E) are allocated.  
Grooming is applied on lightpath C-D.

the sum cost of the routing, constant cost factors should be assigned to each edge. Constant  $\alpha$  decides whether optimization emphasis is on minimal routing cost ( $\alpha$  is close to 1) or on minimal signal power ( $\alpha$  is close to zero).

### 5.3 Constraints

$$\sum_{\forall(i,j) \in pl} \sum_{(E,F) \in L} p_{ij}^{EF} \leq 1, \forall pl \in \text{PhyLinks} \quad (5.7)$$

$$x_{ij}^o \leq y_{ij}^{EF} \leq y_{ij}, \forall o \in O, i, j \in V, (E, F) \in L \quad (5.8)$$

$$y_{ij}^{EF} \leq \sum_{\forall o \in O} x_{ij}^o, \forall (i, j) \in A, (E, F) \in L \quad (5.9)$$

$$y_{ij} \leq \sum_{\forall (E,F) \in L} y_{ij}^{EF}, \forall (i, j) \in A \quad (5.10)$$

$$p_{ij}^{EF} \leq y_{ij}^{EF}, \forall i, j \in V, (E, F) \in L \quad (5.11)$$

$$\begin{aligned} & \sum_{\forall j \in V^{in}} p_{ji}^{EF} - \sum_{\forall k \in V^{out}} p_{ik}^{EF} = \\ & = \begin{cases} -p_{EF} & \text{if } i = E \\ 0 & \text{if } i \notin \{E, F\}, \\ +p_{EF} & \text{if } i = F \end{cases} \quad (5.12) \end{aligned}$$

$$\begin{aligned} & \sum_{\forall j \in V^{in}} \sum_{\forall (E,F) \in L} x_{ji}^o - \sum_{\forall k \in V^{out}} \sum_{\forall (E,F) \in L} x_{ik}^o = \\ & = \begin{cases} -1 & \text{if } i = s^o \\ 0 & \text{if } i \notin \{s^o, t^o\}, \forall i \in V, o \in O \\ +1 & \text{if } i = t^o \end{cases} \quad (5.13) \end{aligned}$$

$$\sum_{\forall (E,F)} y_{ij}^{EF} \leq 1, \forall (i, j) \in A \quad (5.14)$$

$$\sum_{\forall o \in O} \sum_{(E,F) \in L} x_{ij}^o \cdot b^o \leq B, (i, j) \in A \quad (5.15)$$

$$\begin{aligned} & \sum_{\forall (i,j) \in A_{sw}} y_{ij}^{EF} \cdot \text{len}_{\text{PhyNode}} + \sum_{\forall (i,j) \in A_{pl}} y_{ij}^{EF} \cdot \text{len}_{ij} \leq \\ & \leq L(p_{EF}) = L_c \cdot p_{EF} \cdot p_{pl, \text{lin}}^{\max}, (E, F) \in L \quad (5.16) \end{aligned}$$

### 5.4 Explanation

Constraint (5.7) explains that the total power of lightpaths traversing a physical link or fiber (denoted by  $pl$ ) cannot exceed the maximum allowed power of that link.

In constraint (5.7) we calculate sum of the power of lightpaths going through those edges that belong to physical link  $pl$ . Constraint (5.8) is straightforward: it expresses that edge  $(i, j)$  is used by lightpath  $(E, F)$  if any of the demands – multiplexed into lightpath  $(E, F)$  – uses that edge. Similarly it also tells that edge  $(i, j)$  is used by the routing if any of the lightpaths use that edge. Constraint (5.9) states that edge  $(i, j)$  is used by lightpath  $(E, F)$  only if it is used by at least one demand. I.e., lightpath  $(E, F)$  does not use unnecessarily edge  $(i, j)$ . Similarly constraint (5.10) expresses that edge  $(i, j)$  is used by the routing only if it is used by at least one lightpath, i.e., a lightpath is not created unnecessarily. Constraints (5.9) and (5.10) are optional, since these rules are implicitly expressed by the objective function. Constraint (5.11) simply means that if the power of a lightpath on an edge is greater than zero, then that edge is used by the lightpath. Constraint (5.12) assures that the signal power of a lightpath is the same along the whole path. Constraint (5.13) expresses flow conservation constraint for demands. Constraint (5.14) assures that each edge is used by at most one lightpath. Constraint (5.15) expresses the grooming constraint, i.e., the sum bandwidth of multiplexed demands cannot exceed wavelength capacity. Constraint (5.16) expresses the relation between the physical distance traversed by the lightpath and the signal power of the lightpath.

## 6. Benefits of the algorithm

It is a very hard task to illustrate the efficiency of the algorithm since it gives obviously better results than the traditional RWA algorithms. This is due to the additional degree of freedom, namely, the tunability of the signal power. In this section we illustrate some of the benefits of the algorithm having in mind that for different input parameters the results would be slightly different.

In our simulations we used the well-known COST 266 reference network (Fig. 5). Since this network is a long haul network we have decreased the lengths of the links by 25% to get a metro size optical network. The nodes are fully optical nodes and the signal can not be 3R regenerated or converted into the electronics once it is in the optical layer. To demonstrate the advantage of the



Figure 5.  
COST 266 European reference network topology

proposed method we have introduced the concept of “maximum routed demands”. This means that we have randomly generated a certain number of demands, a traffic matrix. If these demands could be routed, we increase the number of demands, e.g. the size of the traffic matrix, and route it again. This process continues until it is not possible to route more demands anymore. This way it is possible to find the maximum number of demands which can be routed. The bandwidths of the demands were equal with the capacity of one channel. The source and destination pairs were chosen randomly. We used the single layer routing scheme. The constants of the routing algorithm were as described in Section 4.

The absence of solution can have two reasons: the RWA does not succeed or the distance between the source and destination node is too long i.e. the signal quality will be inadequate. It has to be mentioned that the proposed algorithm finds the global optimum of the routing problem which is an NP-hard problem. Therefore in some cases to find the maximum demands which can be routed takes long time, approximately one week for the COST 266 network with 8 wavelengths ( $W=8$ ) and  $n=8$ , where  $n$  means the maximum allowed deviation of signal power from the traditional power allocation scheme (see Equation (4.7)).

The “maximum routed demands” means the number of successfully routed demands from a randomly generated demand set. If a certain number of demands could be routed, we increase the number of demands and route it again. This process continues until it is not possible to route more demands anymore. This way it is possible to find the maximum number of demands which can be routed. The bandwidths of the demands were equal to the capacity of one channel. The source and destination pairs were chosen randomly. This timescale problem is not a significant drawback of the proposed algorithm since in real networks this kind of routing prob-

lem will not occur. Finding the global optimum (e.g., for COST 266 network with 8 wavelengths,  $n=1.5$  and 60 demands), takes approximately 10 minutes, which is a really fast RWA solution.

We compared the proposed algorithm with the traditional RWA algorithm (Fig. 6 and 7). On the y-axis the maximum number of routed demands is depicted, while on the x-axis the used routing schemes. RWA means that we used the traditional routing scheme where each channel has the same signal power. The  $n=1$  routing scheme is similar to the RWA routing scheme. The only difference is that in case of  $n=1$  the channel powers can be lower than the average of the powers. In RWA case this variation is not allowed. In  $n>1$  cases we used the proposed routing algorithm with  $n$  equal to the depicted numbers.

The result marked as “MAX” is the number of maximum routed demands in case when physical effects are neglected. The *scale parameters* mean that we changed the lengths of the used network link by multiplying the original lengths with the scale parameter. In Fig. 6 the scale is 1, i.e., we used the original link lengths (geographical distances). In Fig. 7 the scale parameter is 1.25.

In Fig. 6-7 it can be seen that the traditional RWA algorithm can route 19 and 1 demands, respectively. While by increasing the  $n$ -factor more and more demands can be route until we reach a limit, where the RWA problem is infeasible in itself (without considering physical effects).

The results lead us to a conclusion that just a small amount of  $n$ -factor increases highly increase the number of maximally routed demands. In Table 1 we have depicted the corresponding channel powers for different  $n$ -factor values in mW and dBm. As it is to be seen these values are much lower than the Brilluoin-threshold.

To investigate the dependency of the proposed method on the number of wavelengths we made simulations using the COST266 network topology and different wavelength numbers (see Fig. 8). The figure shows that while increasing the number of channels the maximum number of routed demands is increasing. This behavior is as expected when solving the RWA problem. The interesting property is that if we double the number of wavelengths and the  $n$ -factor is high enough, the maximum number of routed demands is more than double in each case. This behavior is due to the way how the proposed algorithm works.

If we have more wavelengths, there are more possible variations how the signal power can be allocated. Consequently, if the number of wavelengths is increased, the performance of the proposed algorithm will improve. However, as it was mentioned before, for higher number of wavelengths (32-64) to find the maximum number of demands which can be routed takes very long time, since it needs many tests to find the exact number of demands which can be routed. The other timescale problem occurs when the number of demands is very close to the maximum number of demands which can be route. This kind of simulations can have long running time, more than

	fix	1	1,2	1,4	1,6	1,8	Brillouin threshold
Pimax (mW)	1,25	1,25	1,5	1,75	2	2,25	~ 5
Pimax (dBm)	0,96	0,96	1,76	2,43	3,01	3,52	~ 7

Table 1. n-factor values in mW and in dBm respectively

a week. In other cases the running time of the algorithm has a timescale of minutes even for higher number of wavelengths.

### 7. Conclusion

In this paper we presented new RWA algorithms where the power of WDM channels can be adjusted. Our proposed algorithms perform joint optimization of routing (RWA) and of determining signal powers of WDM channels. The proposed methods can be used in existing WDM optical networks where the nodes support signal power tuning.

Figure 6. Maximum number of routed demands vs. n-factor parameter in case of COST 266 topology

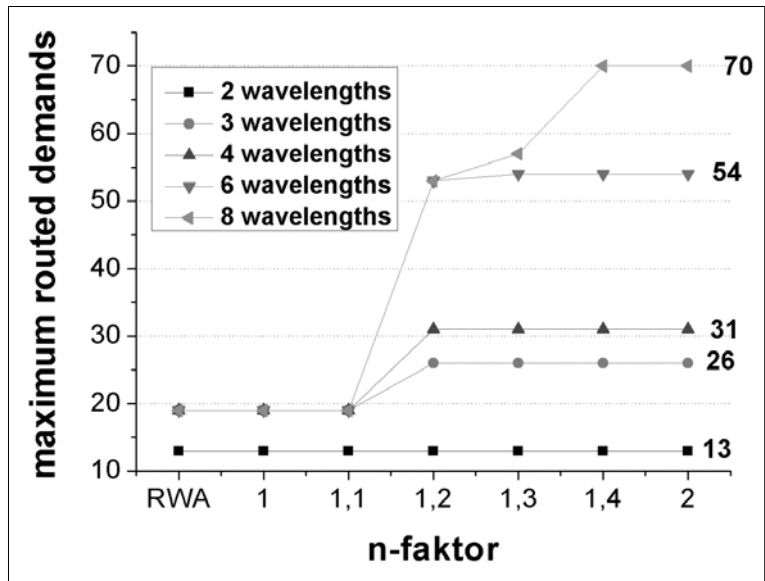


Figure 8. Maximum number of routed demands versus n-factor parameter in case of COST 266 topology, for different wavelength numbers

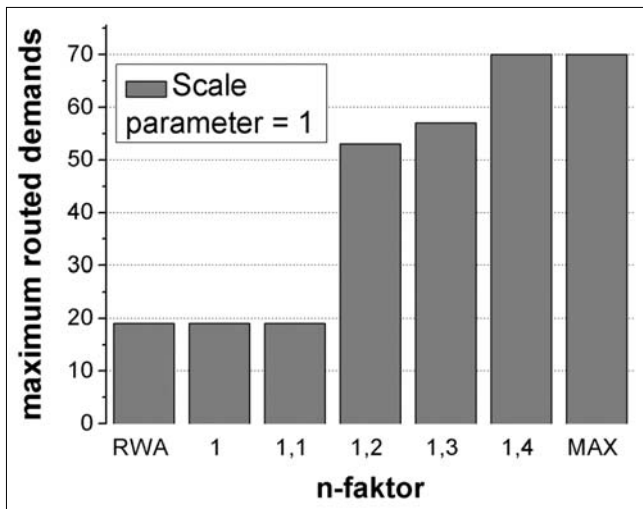
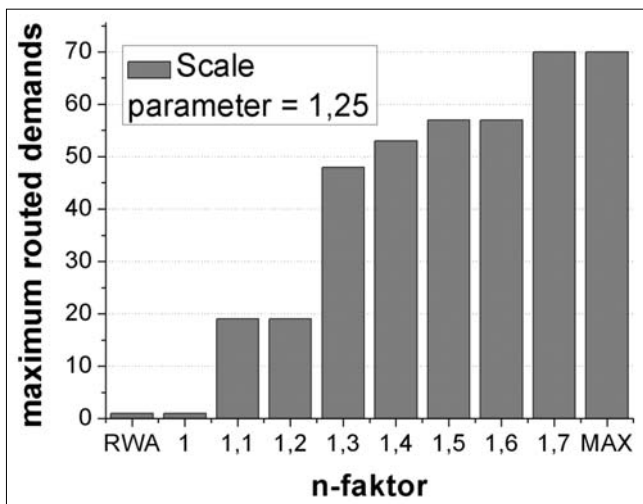


Figure 7. Maximum number of routed demands vs. n-factor parameter in case of COST 266 topology, scale 1.25



We gave the exact ILP formulation of the problems to find the global optimum. In the simpler single layer case it is not allowed to use the electronic layer at all along a path, except for the source and destination nodes, while in the more complex multilayer case electronic layer can perform 3R regeneration, grooming and wavelength conversion.

In the second case we carry out full joint optimization of RWA with grooming (according to a given demand set) and with determining the power of lightpaths (observing physical constraints). The multilayer optimization proved to be too complex for even small networks, while the single layer ILP formulation is practically applicable for moderate size networks.

However it is still worth looking for fast heuristic approaches. For such heuristic methods our ILP based optimal solutions can be regarded as a baseline for comparison.

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