



DEPARTMENT OF TELECOMMUNICATION AND MEDIA INFORMATICS  
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

ROUTING IN OPTICAL NETWORKS BASED ON PHYSICAL EFFECTS

By  
Szilárd Zsigmond

Ph.D. Thesis Summary

Supervised by

Dr. Tibor Cinkler  
Department of Telecommunications and Media Informatics

High Speed Networks Laboratory  
Budapest University of Technology and Economics

Budapest, Hungary  
2010

# 1. Introduction

New generation services brought by the incredible expansion of the internet traffic has indicated several new problems for the telecommunication service providers. The wavelength division multiplexing (WDM) networks have successfully solved the capacity issues in metro-core networks, but the continuously changing traffic still causes serious problems for the operators. In the very early stage it was realized that the static configurable point-to-point optical links are not suitable to support the ever changing demands. 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 situation is not simpler in case of dynamically reconfigurable optical networks. The combination of the ever-increasing demand for capacity, the generalization towards meshed network topologies, and widespread availability of dynamic optical switching, leads to severe constraints on quality of service (QoS) provisioning. These result from the difficulty in maintaining a uniform and acceptable quality for any optical path across a transparent optical network comprising multiple fiber types, signal formats and data rates [1]. Furthermore, the quality of each optical path is often correlated with the other optical paths due to optical impairments such as crosstalk, limited amplifier output power, or transients in optical amplifiers, among others. In this scenario, newly emerging unforeseen demands often cannot be satisfied without modifying the network design, which is costly and time consuming.

A solution for the interoperability issues among network layers based on the introduction of dynamic management and control capabilities must cope with the escalating complexity inherent to the deployment of more reliable transparent networks. The need to achieve higher performance levels and to enhance the network reconfiguration capability and autonomy is also spreading from core to metro and access networks [2].

In communication networks, routing generally performs the identification of a path (route), per connection request, between a source and a destination node, across the network. In optical networks, the particular wavelengths along the path should also be determined. The resulting problem is often designated as routing and wavelength assignment (RWA) problem in literature [3]. The existing RWA proposals can be classified into two main categories: (a) considering the effects of impairments on network performance and (b) network design without impairment consideration. Although this is a widespread research topic, for transparent networks the incorporation of physical impairments in the RWA problem is still to be explored in full width.

The aim of the dissertation is to give a good compromise to the RWA problem, to be able to take into account the most accurate way the specifics of optical networks.

For investigating the performance of optical networks I have used analytical calculations. The accuracy of the models were verified by numerical simulations and where it was possible also measurements were done. These calculations were built in the proposed RWA methods. The results are classified in two areas which are strongly correlated.

In the first group of thesis the modeling of physical effects is presented. Based on the already published models, these methods are extended or even in some cases restricted. I also present new calculation methods which fulfill the requirements of the RWA algorithms. For every physical effect I have developed a method which is able to characterize the effect in a quantitative way i.e., to calculate its effects onto the bit error ratio measured at the receiver.

In the second group of thesis the aim is to give a solution to the RWA problem which takes into account the physical effects. As it is well known, two main cases are distinguished in configuration of optical networks, the static and the dynamic configuration. For both cases I have developed new methods which fulfill the physical constraints. The advantages of these methods are presented by simulations.

All the algorithms and solutions of this dissertation are strongly motivated by the telecommunication industry. They can equip the switches of the future optical networks to be able to handle the requirements of the physical impairments.

The obtained results are supported by 10 journal and 10 conference paper, a book chapter and an international patent.

## **2. Research objectives**

The background of the research was that the routing and wavelength assignment algorithms either do not, or in a very simple way take into account the performance of the physical layer. Firstly my research was focus on the physical impairments occurring in WDM based optical networks. The goal was to develop a fast calculation method which is able to determine the signal quality in a real time environment. Beside the short calculation time, also accuracy of the method was important.

To increase the correctness of the model I did research on the nonlinear behavior of the optical fiber. The unsolved practical problems, and the results obtained by modeling the fiber nonlinearities, leads me to clarify the issues of the optimal signal power. For the sake of network design, the goal was to present results which can be used in practice. While knowing the main parameters of the network, based on the calculation results, the optimal output signal power of the optical amplifiers can be obtained.

The reconfigurable optical network offers the possibility to grow services between sites with no advanced engineering or planning, and without disrupting services. The technology called reconfigurable optical add-drop-multiplexer (ROADM) represents a real breakthrough for WDM networks by providing the flexibility and functionality

required in present complex networking environments. Due to the optical layer flexibility several new problems have appeared. In case of fix point-to-point optical links in one optical fiber the WDM channels had the same physical parameters. Due to ROADM deployment in today's optical networks this is not true anymore. So far the limitations of the optical layer were relatively easy to handle, however now due to reconfiguration this becomes a very serious problem. Since WDM channel has different distortions, per channel monitoring and compensation techniques had to be introduced. In the one hand this has triggered the evolution of optical components while on the other hand new routing and wavelength assignment algorithms have been also proposed. These challenges led me to develop new algorithms which consider the physical impairments while routing and are also suitable for a dynamic optical layer. The goal was to develop an algorithm, which is able to present the real constraints of optical layer, like the signal distortions, and also the features of multilayer networks such as traffic grooming and wavelength conversion.

The technological feasibility and the research done in fiber nonlinearities has oriented my interest onto the signal power based routing. I have proposed a new configuration method for optical networks, which outperforms the traditional schemes.

Beside the issues presented before I did research in most of the topics which is related to interoperability of multilayer networks based on physical layer performance.

### **3. Research Methodology**

The telecommunication networks are modeled by graphs. To solve the problems well known graph algorithms are used such as Dijkstra's algorithm [4][5]. Integer Linear Programming (ILP) [6] is used to formulate NP-hard problems and commercially available softwares were used to solve them, such as CPLEX [7]. The validation of the proposed algorithm was done by a network simulation program developed at the Technical and Economical University of Budapest, Department of Telecommunications and Media Informatics [8]. The ILP based algorithms were validated by the simulation software implemented by my colleagues and myself.

The modeling of the physical layer was done by analytical calculations. The results were in most cases compared and validated by commercially available software VPI Transmission Maker [9]. The results regarding the fiber nonlinearities were compared with the results of the research group of Athens Information Technology. In many cases also measurements were carried out, where analytical, simulation and measurement results were compared and a very good match was found [T1].

## 4. New Results

The new scientific results are classified in two areas. The first area is the modeling of physical impairments while the second are the RWA methods that consider physical impairments.

### ***4.1 Thesis group 1: Modeling the physical impairments in WDM optical networks***

In the last fifteen-twenty years the optical technology has been widespread in the telecommunication networks. Various technologies were developed for each segment of the network. In the access part of the network short range passive optical networks were proposed. In the metro networks the DWDM and Coarse WDM (CWDM) was deployed together with all-optical nodes. In the core and long haul networks low noise figure amplifiers, Raman amplifiers, accurate dispersion mapping is used. And all this technologies with various modulation formats and bitrates. Thus, to make a calculation method of the impairments which is valid in each segment of the network is impossible. The only solution is to distinguish between the certain technologies and to define the main impairments which have the most influence onto the signal quality.

Since the dissertation is based on impairment aware routing in WDM optical networks the calculation of the physical constraints has the following assumption:

- CWDM or DWDM metro-core network
- high performance, externally modulated distributed feedback lasers (DFB) for transmitters
- amplitude modulated non-return-to-zero (NRZ) or return-to-zero (RZ) signals
- direct detection receiver, PIN or Avalanche APD photodiode
- bit rate up to 10 Gbit/s
- channel spacing 50 or 100 GHz

As it can be seen these assumptions are not severe assumptions, nearly all types of nowadays (2010) deployed WDM systems fulfill these requirements. However, it has to be mentioned that several companies have 40 Gbit/s bit-rate phase modulated systems. In this case the proposed calculation method must be improved.

#### **4.1.1 Claim 1.1: Analytical method of Q-factor estimation**

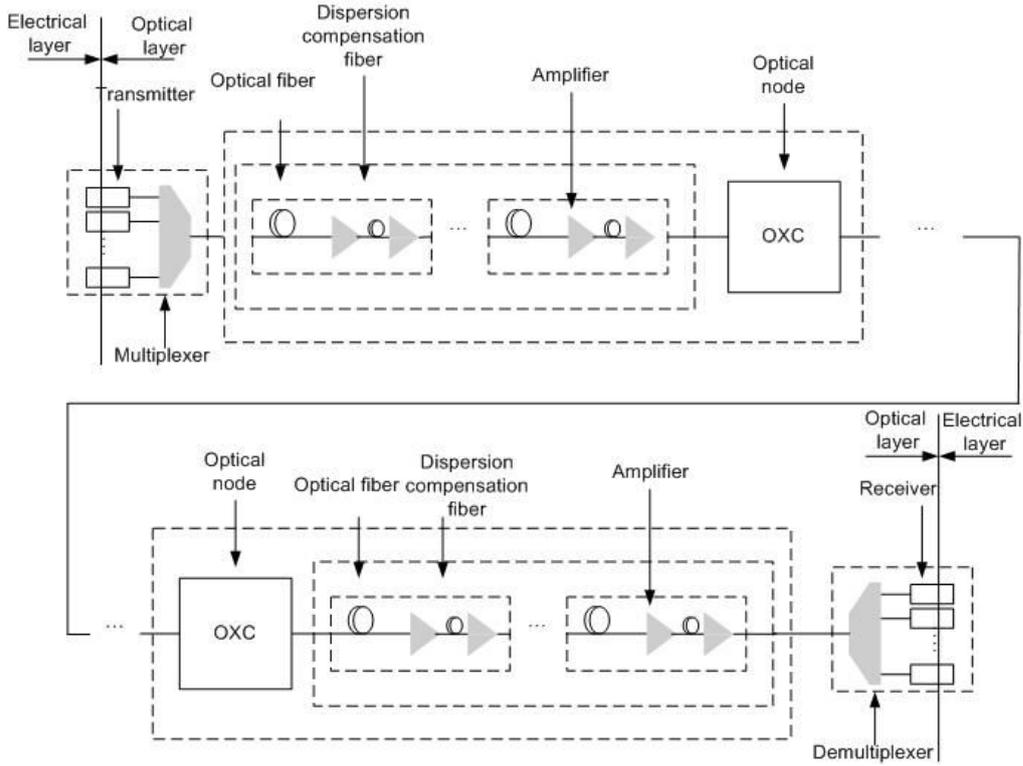
*Claim 1.1: "I have proposed an analytical signal quality calculation method, which has low computation requirements while it still takes into account the main degrading effects of intensity modulated direct detection 10 Gbit/s bit-rate wavelength division multiplexed all-optical networks."*

Claim 1.1 describes an analytical method to calculate the Q-factor. Several methods have been proposed in the literature so far [10][11][12][13][J7] and it is quite hard to distinguish between them, since the basic method is to calculate the variance of the noise at the receiver side [10][14][15]. The method presented in this dissertation also calculates the variance of the noise however it has two main advantage comparing to the already published ones.

The first difference is that it is able to calculate nearly all physical effects which occur in WDM optical networks, concerning the assumptions defined in section 4.1. To the best of the authors knowledge this is the first method which can handle erbium doped fiber amplifier (EDFA) noise, node crosstalk, fiber nonlinearities: like four-wave mixing (FWM), stimulated Raman scattering (SRS), cross-phase modulation (XPM) and also the effects of polarization mode dispersion (PMD) simultaneously. These effects are the most limiting effects in case of nowadays deployed backbone networks.

The other very important issue of the proposed calculation method is that the original problem is divided to sub problems. Considering a point-to-point connection where a chain of optical elements (fibers, EDFA, optical nodes, etc.) are used the proposed method is reduced to several sub calculations where each of the calculations can be done separately. The advantage of the proposed method, is the it can be incorporated into impairment routing schemes.

An optical link consists of several optical elements in chain as presented in Figure 1. An accurate calculation method to determine the signal quality must handle all of these elements simultaneously.



**Figure 1 Optical link elements**

Using the definition of Q-factor and with a simple mathematical rearranging as shown in equation 1 it is possible to calculate the Q-factor after one optical element ( $Q_{end}$ ) while knowing the input Q-factor ( $Q_{start}$ ) and the degradation effects of the element. Using the previously presented method it is possible to calculate Q-factor of a signal that passes through the network.

$$\begin{aligned}
 Q_{end} &= \frac{\mu_{1end} - \mu_{0end}}{\sigma_{1end} + \sigma_{0end}} = \left( \frac{\mu_{1end} - \mu_{0end}}{\mu_{1start} - \mu_{0start}} \right) \times \left( \frac{\sigma_{1start} + \sigma_{0start}}{\sigma_{1end} + \sigma_{0end}} \right) \times \left( \frac{\mu_{1start} - \mu_{0start}}{\sigma_{1start} + \sigma_{0start}} \right) = \\
 &= \left( \frac{\mu_{1end} - \mu_{0end}}{\mu_{1start} - \mu_{0start}} \right) \times \left( \frac{\sigma_{1start} + \sigma_{0start}}{\sigma_{1end} + \sigma_{0end}} \right) \times Q_{start} = (\text{Eye Penalty}) \times (\text{Noise Penalty}) \times Q_{start}
 \end{aligned} \tag{1}$$

As presented in equation 1 a “system-overall” Q-factor can be determined by the calculation of each element physical degradation i.e. the eye and noise penalty. The eye related penalties are the dispersion related penalties such as chromatic dispersion (CD) and polarization mode dispersion (PMD). The Noise related penalties are the amplifier spontaneous emission (ASE) and crosstalk.

The CD in nowadays metro-core optical networks is compensated. Since the CD has wavelength dependency the residual dispersion can deteriorate the signal quality. However it does not have high influence on the signal quality in case of nowadays used C or L band and just several hop numbers and less than 20 compensation points.

The situation is different in case of PMD. Since in nowadays used networks the PMD is not compensated thus even for 10 Gbit/s systems it can have high influence onto the signal quality [J7].

The noise related penalties include ASE noise from EDFA, the crosstalk from the nodes and also the nonlinearities in the optical fiber. Here it is assumed that the

influence of each phenomena to the others is negligible, i.e., it result in a larger or smaller perturbation around the mean value of a channel. The phenomena under consideration (ASE, crosstalk (XT), FWM, XPM, and SRS) are treated as statistically independent, and their overall contribution to the Q-factor is approximated by a Gaussian variable.

Using the equations for a p-i-n photodiode in the receiver and the previously stated assumptions, the Q-factor is approximately given by [J1]:

$$Q_i = \mu_{SRSi} \frac{\mu_{1i} - \mu_{0i}}{\sigma_{0\text{ASE}i} + \sqrt{\sigma_{1\text{ASE}i}^2 + (\sigma_{XPMi}^2 + \sigma_{FWMi}^2 + \sigma_{SRSi}^2)}} \quad 2$$

Where  $\sigma_{0\text{ASE}i}$ ,  $\sigma_{1\text{ASE}i}$  are the noise variances excluding the nonlinear effects,  $\mu_{0i}$ ,  $\mu_{1i}$  are the mean values of the marks/spaces voltages or currents, and  $\sigma_{XPMi}$ ,  $\sigma_{FWMi}$ ,  $\sigma_{SRSi}$  are the induced optical power deviations due to the respective effect at  $i^{\text{th}}$  channel.  $\mu_{SRSi}$  is the SRS-caused signal level deviation normalized by the output power.

Combining the equation 1 and 2 it is possible to calculate the performance of an optical link containing a chain of optical fibers and different elements such as optical switches, EDFAs, etc. The detailed sub-calculation of each phenomena can be found in the dissertation.

The calculation method presented in Claim 1.1 is a highly complex method using several sub calculations. The validation of it, is a difficult task. As first step the calculation presented for ASE and PMD was compared with the results obtained with a commercially available softer VPI Transmission Maker [9] where very similar results were obtained. In case of nonlinearities this is not possible since in case of higher total power where the nonlinearities have influence ( $> 18$  dBm) the calculation time increase drastically (several weeks even months). Here I compared the optimal signal power (see claim 1.2) using the previously presented method, and the commercially available products EDFA output power like the Cisco and Huawei ones. Here I again found very good mach. In case of nonlinearities it was also compared the results with a commercially available simulation softer OptiSystem [16] in case of CWDM systems where the calculation time is much less than in case of DWDM systems. The results were published in [J4]. Also these calculations used in [T1]-[T3] where the results were compared with real measurements, simulation performed with VPI Transmission Maker and the analytical calculation based on previously presented method. Here, again very good match was found between the different methods..

As conclusion the presented analytical calculation method for Q-factor estimation gives accurate results for systems of up to 10Gb/s channel bit rate OOK modulation and direct detection, i.e. the nowadays mostly deployed systems.

#### **4.1.2 Claim 1.2: Calculation of optimal signal power for WDM optical networks**

*Claim 1.2: "I have calculated for different network scenarios the optimal signal power for intensity modulated direct detection 10 Gbit/s point-to-point wavelength division multiplexed optical systems."*

In Claim 1.1, a model to calculate analytically the signal quality deterioration due to physical impairments was presented. In claim 1.2, based on simple network scenario and the method mentioned before, the exact value of the optimal signal power is calculated. In this case the optimum means that if the signal power is increased, better optical signal to noise ratio (OSNR) is received. However, due to fiber nonlinearities, while increasing the signal power the nonlinear distortion is also increasing. The optimum means the maximum signal power while tolerating a well defined nonlinear distortion. As a result the exact values are given for the optimal signal power at the transmitter point, or at the output of the inline amplifiers for 10 Gbit/s WDM On-Off-keying (OOK) direct detection (DD) systems.

In the last twenty years the WDM technology had an incredible evolution. Nearly all physical effects can be compensated in an all-optical way. The only effect that cannot be compensated is the noise. Clearly there are techniques to decrease the noise distortion such as bandwidth filters; however the total eraser is very difficult to be done all-optically. Thanks to technology evolution low-noise amplifier techniques have appeared, such as Raman or parametric amplifiers, or even EDFA and SOA with low noise figures. The crosstalk of the nodes is drastically decreasing as the technology evolves and the noise of the transmitters can be very low as well.

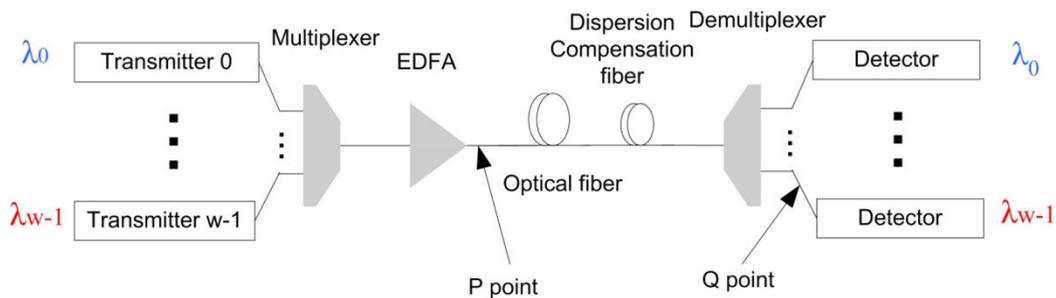
The only phenomena that still limit the optical networks are the nonlinear effects. Although, there are optical fibers with low nonlinear coefficients, it is commercially nearly impossible to replace the already deployed fibers with them. The only solution is to maximize the signal power inserted into the optical fiber. To increase the size of the optical networks the maximization of the signal power is needed. Moreover the nonlinear effects highly depend on the network bit rate. While increasing the bit rate from 2.5 Gbit/s to 10 or 40 Gbit/s or even higher the maximally allowed signal power in one optical fiber is decreasing and therefore the size of the all-optical network is decreasing as well.

Nowadays in case of optical networks system designers have very strict rules regarding the optical power inserted into optical fibers in order not to reach the nonlinear region of them. A model of the nonlinear behavior would lead to a more accurate system design. Using the proposed scheme it is possible to determine a signal power range where the signal quality deterioration due to nonlinear effects is tolerated. This way it is possible to maximize the signal power used in optical fibers, to increase the size of the optical network or to minimize the number of inline amplifiers. It has to

be mentioned that there are other existing techniques like the use of other modulation formats, or dispersion mapping which decrease the influence of nonlinearities onto the signal quality [17]-[19]. Best results can be reached combining these techniques and maximizing the signal power.

Using the model presented in Claim 1.1 it is possible to calculate the optimal signal powers of the transmitters and inline amplifiers in typical optical networks. The main strength of it is, that for network designers, it gives the maximum signal power which can be used for different network scenarios. The results are also compared with the Brillouin threshold. The Brillouin threshold is the signal power limit for one channel due to Brillouin scattering.

In Figure 2 the used model is depicted. The goal of the calculation was to increase the total power at point P, after the EDFA and calculate the signal quality at point Q. This way the optimal signal power for a point-to-point WDM optical network can be obtained.



**Figure 2: Model used for calculating the optimal signal powers in WDM optical networks**

The results can be extended to multiple amplified systems since the optimal signal power will not change in case of using more EDFAs, only the signal quality will decrease. The signal quality was also compared for every nonlinear effect with the signal quality obtained when only the ASE noise is taken into consideration. As it was expected while increasing the gain of the amplifier the ASE noise is increasing that leads to a decreased OSNR. This results in a decreased signal quality when only the ASE is taken into account. See in Figure 3 the solid line marked with *ASE*. In these figures the total input power inserted in the fiber is plotted versus the Q-factor. The curve corresponding to *\*\*\*+ASE* means the respective nonlinear effect and the effects of ASE onto the signal quality, where *\*\*\** is the corresponding nonlinear effect. *XPM* means the cross-phase modulation, *FWM* means the four-wave mixing and *SRS* means the stimulated Raman scattering. The curve signed with *TOTAL* was obtained when all the nonlinear effects were taken into account.

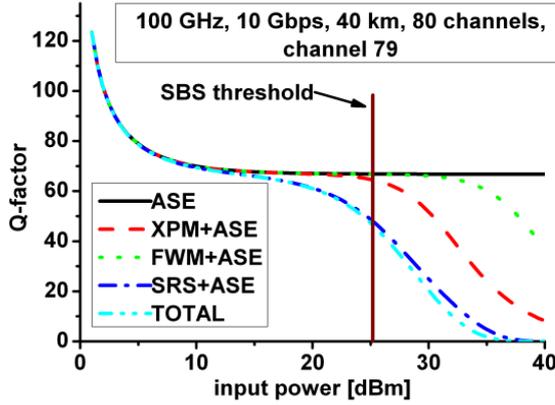


Figure 3: Q-factor as function of the input power for a 40-km transmission line using 100-GHz channel spacing taking into account ASE noise and nonlinear effects

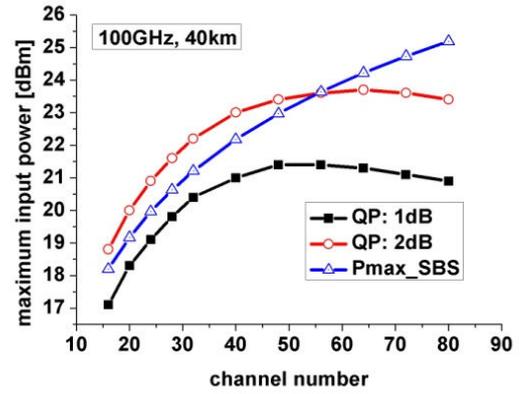


Figure 4: Optimal signal power in case of 100 GHz channel spacing 40 km fiber length

To define the optimal signal power, I introduced the Q-factor penalty of the nonlinear effects. The Q-penalty of the nonlinearities can be obtained as follows:

$$QP = \frac{Q_{ASE}}{Q_{TOTAL}} \quad 3$$

Where  $Q_{ASE}$  is the Q-factor when only the ASE is taken into account as described in previous section and  $Q_{TOTAL}$  is the Q-factor when the effects of nonlinearities are taken into account besides the effect of ASE. I defined for the  $QP_{dB}$  two margins, 1 and 2 dB. These are the typical margin values at which the influences of the certain physical effects are tolerated. The results can be seen in Figure 4. As a comparison I also plotted the curve corresponding to Brillouin threshold. The results were obtained as follows:

- I calculated the Q-factor of the ASE and the nonlinearities as presented in previous section for different channel number.
- I took the worst channel and calculated the signal power corresponding to 1 or 2

$$QP_{dB}$$

In claim 1.2 the dependency of the nonlinear effects on the signal power was presented. By analytical calculations the optimal signal powers for different network scenarios were defined. I also demonstrate for different network scenarios the most limiting nonlinear effects. These results are useful tools for network designers for improving their optical network or even redesigning their power budget calculations. The results were published in [J1][J4][J8][J9].

## **4.2 Thesis group 2: Physical impairments based routing**

The accelerating growth of data traffic is motivating the research for more efficient, flexible and intelligent optical network architectures. In this direction, IP over WDM is becoming accepted as one of the most promising candidates to fulfill these ever-increasing bandwidth demands. On the other hand, there is a global industry consensus to consider the generalized multi-protocol label switching (GMPLS) protocol suite [20] to be an integral part of next-generation transport networks, especially as enabler for the automatic switched optical network (ASON) [21] control plane, because it renders optical networks intelligent. However, the huge transport capacity of WDM technology is accepted to not be fully used by current optical networks [22]. Such inefficiency on the bandwidth utilization is due to the use of optical-electrical-optical (OEO) transponders, which originates the well-known electronic bottleneck. These opaque networks have important advantages such as electronic signal regeneration as well as the capability of intrinsic wavelength conversion, or grooming, on every hop of the connection. However, opaque networks also present important drawbacks: a complex layered structure, sensitive to signal format and data rate, elevated capital and operational costs (capex and opex), and suboptimal use of WDM's capacity. As a consequence, future optical networks are expected to overcome these limitations and take full advantage of the WDM technology. This will be achieved using all-optical switches (e.g., reconfigurable optical add drop multiplexers, ROADMs, and/or optical crossconnects, OXCs) which allow to switch/route entirely an optical connection (lightpath) over the optical domain (i.e., transparent networks). Thus, the introduction of transparency in optical networks eliminates the need for expensive OEO transponders (reducing capex) during the switching of a lightpath. However, this also results in losing the electrical regeneration of signals, which in turn makes the optical signal to the accumulation of the impairments due to fiber transmission (attenuation, dispersion, nonlinearities, etc.), optical amplification (ASE) and insertion losses and crosstalk introduced by optical elements such as switches, filters or mux/demux in ROADMs and OXCs.

Several excellent papers deal with the RWA problem [10][23][24][25][26][27][28]. Usually in these papers the optical network is modeled by an ideal graph, where the RWA problem is deduced to a path computation problem. While the signal passes through the network its quality deteriorates. Several papers have been already published that consider these effects beside the path computation [10][29][30][31].

In this section the focus is on the utilization of intelligent routing algorithms which take into account physical layer attributes as input parameters (i.e., constraints) for the path computation, with the aim to achieve quality-enabled services. Such routing algorithms are known in the literature as impairment aware RWA (IA-RWA) or in some cases physical impairment constrain routing (PICR).

### 4.2.1 Claim 2.1: Dynamic IA-RWA algorithm

*Claim 2.1: "I have proposed a novel dynamic IA-RWA algorithm which can take into account the physical constraints of the optical layer considering a multilayer network environment."*

In both, metropolitan optical networks (MON) and long haul optical networks (LHON) the signal quality is often influenced by the physical impairments, therefore a proper impairment based routing decision is needed. In the absence of all-optical 3R regenerators, the quality of transmission has a strong impact on the feasibility of all-optical transmission. It is assumed that signal regeneration can be done only in electrical layer. Once the signal is in electrical layer there are some features supported e.g. the traffic grooming. I shown that by taking into account both, the physical impairments characterized by the Q-factor, as I propose in claim 1.1, and the features of electrical layer, will have a strong impact onto the routing that is based on impairment constraints. The claim 2.1 presents a method for that. In this thesis a novel algorithm is presented for the IA-RWA which also takes into account the features of multilayer networks. The results have been published in [B1][C4][C6].

The setup of the algorithm can be split in two main parts. The first one is the routing part, based on Dijkstra's algorithm [4][5] and the second one is the calculation of physical impairments (CPI), (Figure 5). The communication between these two parts is as follow: The routing algorithm chooses an optimal route, between the source and destination node and it sends the description of the route to CPI. The description of the route contains the lengths of the optical fibers between the nodes. The CPI calculates the signal quality based on the calculation presented in Claim 1.1, [C5] and if it is adequate it sends a message back to the routing part, that the connection can be established. If the signal quality is not adequate the CPI determines the maximum reachable node (MRN) along the path and sends this information back to the routing model. The routing model establishes the connection between the source and the MRN, than chooses another route between the MRN and the destination node. If the MRN is the source node e.g. there is no possible connection due to the physical layer, the route is blocked [C6].

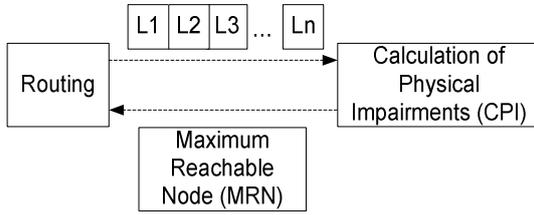


Figure 5: Set-up of the algorithm

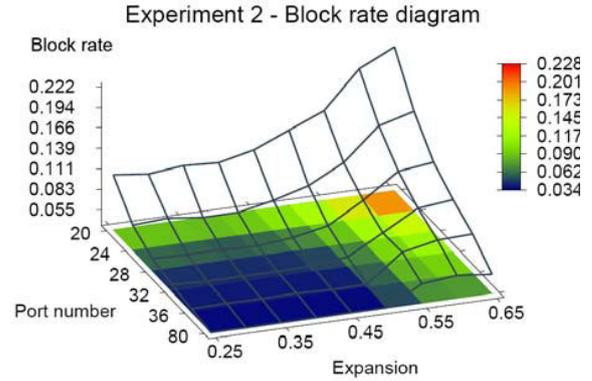


Figure 6: Blocking ratio dependency from the network parameters

The used network scenario is the basic topology proposed by COST 266 project [32]. The used bit rate is 10Gbit/s per wavelength. All traffic samples were created using a Poisson-like birth process having geometrically distributed inter-arrival times with a mean of 10 time units; the source and destination nodes were distributed uniformly among the possibilities with the exclusion of calls whose endpoints are the same. The bandwidth requested by each call followed a binomial distribution of a mean of 100, 1000 or 5000 Mbit/s, while the holding times had, again, a geometric distribution with an average obtained to have 0 blocking in case of 80% network load.

As first step I have defined there parameters to investigate:

The first one is the scale of the network. This parameter has high influence onto the signal quality, i.e., the blocking ratio due to physical effects. In the following simulations to get comparable results a scale between 25% to 65% was used.

The other important parameter is the average bandwidth of the demands. This parameter has high influence onto the grooming capability of the network. Each link contains 16 wavelengths. An average 60% network load was considered. Assuming that every wavelength operates at 10 Gbit/s, I generated 3 traffic samples, a 10 Mbit/s, a 1 Gbit/s, and a 5 Gbit/s as mean value for the bandwidth of the demands. These values represent very low bandwidth request, an average bandwidth request, and a very high bandwidth request for the demands respectively. Each traffic sample contains around 200 000 demands. For comparison reasons to fulfill the 60% network load for all three traffic samples the holding time has been changed.

The last important parameter was the number of optical-electronic-optical (O/E/O) converters within the switch. It was assumed that all the nodes in the network are OXCs.

Figure 6 shows the blocking ratio of the simulations. The figures show the expected tendencies. If the length of the links increases, the blocking grows, because the physical effects will not allow connections. If only a few converters are used, the blocking grows, because the network nodes cannot perform enough wavelength conversion, and traffic grooming to allow the new calls into the system. A very

important conclusion can be made regarding the required O/E/O regenerations based on the blocking ratio. Defining a tolerable blocking ratio of the network as it is to be seen, it is possible to determine the number of O/E/O regenerators in the node.

#### 4.2.2 Claim 2.2: Adaptive configuration method

*"I have proposed an adaptive configuration method, where the signal powers are tuned based on OSNR requirements in metro WDM networks. I have shown that it gives in every case the same or better configurability than the traditional methods."*

In claim 2.2 I propose a novel network configuration method where the control plane has influence on the signal powers of the channels [P1][J5][C8]. The basic idea is to tune the signal power of each channel separately, according to the OSNR requirements at the receiver side. I also present that the nowadays used metro WDM optical networks support such thing and the proposed idea can be implemented in routing schemes.

Let us assume a very simple scenario, Figure 7. 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 nodes A-D this can only be established with signal regeneration either in node B or in node 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.

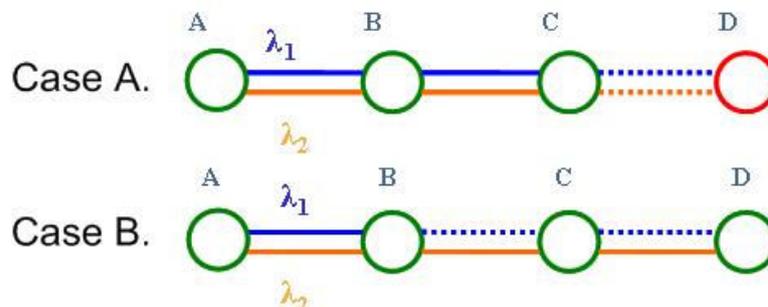


Figure 7 The difference of OSNR based routing and traditional routing schemes

Currently the power of certain channels within a fiber is set to equal levels. This is one of the remaining practices of point-to-point optical networks. Naturally using this kind of channel power allocation is a technical simplification. The other reason for using the same channel powers are the nonlinear effects which in this case have the smallest impact on the signal quality. The idea is to use different channel powers according to the length of the path of the connection request to fulfill the optical signal to noise ratio (OSNR) to achieve bit-error free detection. E.g. for a long distance connection we can increase the signal power of the dedicated wavelength, while for a short distance connection lower wavelength power is satisfactory.

Partly the same idea has been already implemented in an Alcatel-Lucent product [33]. The difference between the proposed scheme and the product of Alcatel-Lucent

is that in [33] just the minimal signal power for point to point wavelength links is set up, and the signal power of the links is not optimized. The similarity is that both deal with different channel powers in optical fibers.

The linear effects occurring in optical fibers such as insertion loss or dispersion do not depend on the signal power however, since the nonlinear effects highly depend on the used dispersion mapping thus the dispersion has to be considered as a bottleneck of the proposed scheme. In case of metro WDM networks where due to short distances dispersion mapping is not used the method can be useful. In case of long haul networks where well balanced power budget and accurate dispersion maps are used the proposed method cannot be used. The other interesting question is about the nonlinear effects, since these effects highly depend on the used signal powers. 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 [J1]. This means that the total power inserted in fiber has an upper bound and not the powers of certain channels. 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.

#### **4.2.3 Claim 2.3 Heuristic RWA for the adaptive configuration scheme.**

*"I have proposed a heuristic routing method for the adaptive signal power based configuration method. The algorithm depending from the input parameters can give back the globally optimal solution, or the simplest shortest path routing solution, thus makes a trade-off between scalability and complexity of the method."*

In this claim a novel routing algorithm and its advantages are presented. This algorithm is able to handle the adaptive signal power configuration scheme [P1][J5][C8] and is also suitable to compare the proposed and traditional configuration schemes. Claim 2.2 gives a configuration method of the signal powers concerning the OSNR requirements and also shows the possibility of different channel powers. The claim 2.3 focuses on the routing part of such networks. This claim gives a routing algorithm for adaptive configuration scheme.

In recent years there have been a few publications which apply the same idea of different channel power allocation. This problem was considered in [31] where a general OSNR network model was developed and the OSNR optimization problem was formulated as a non-cooperative game between channels. A distributed iterative algorithm was also proposed. In this publication the focus is to find an equilibrium based on game-theory models to the overall network OSNR. Also as it was mentioned the newest Alcatel-Lucent WDM product [33] benefits from the advantage of different channel powers. As it is to be seen to use different signal power in one optical fiber can be done, moreover the author knows error free operation optical networks where the

signal powers differ from each other, although this wasn't done intentionally. In this specific case the tuning of signal power was not done in ROADMs.

To the best of the author knowledge to joint optimization of the routing and the signal power was presented in [C8] and extended in [J5], patented in [P1]. All the previously mentioned methods treats the RWA and the signal power allocation as two independent problems.

The routing algorithm of Claim 2.3 is an integer linear programming (ILP) based method which gives the globally optimal solution. Since the ILP as it is in its name, is a linear programming method the main difficulty in the routing algorithm was to give a linear relationship between the channel power and maximum distance.

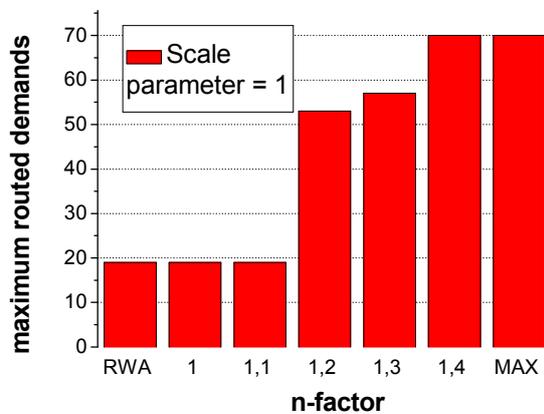
The other issue was that the ILP formulation is an NP-hard problem, thus the scalability of the algorithm is very poor, usually for networks of practical size eight wavelengths is the limit. To improve the scalability a pre-filtering technique has been proposed, to decrease the number of variables, i.e. to decrease the complexity of ILP. This is done by preprocessing the variables before solving the ILP based algorithm. The algorithm has the following steps:

- for every demand calculate the shortest path
- determine a previously defined *maximum deviation*
- calculate for every demand and every edge that if the demand goes through the edge how much will be the total length of the route
- if the route length is higher than the shortest path plus the *maximum deviation* than this variable is excluded from the ILP description, thus decreasing the number of variables.

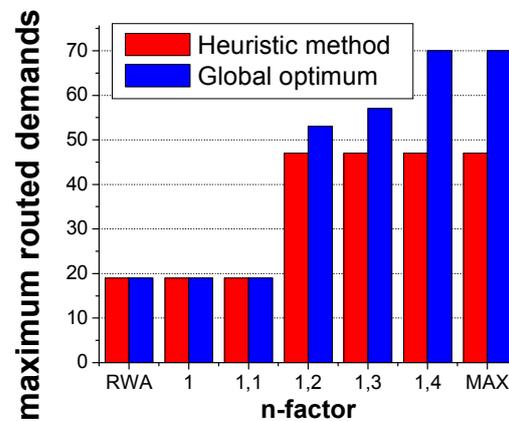
The heuristic presented before has several advantages. In the one hand if the *maximum deviation* is infinite or high enough, the heuristic method gives back the globally optimal solution, in the other hand, if the *maximum deviation* is zero than we got a shortest path routing for adaptive configuration method, which scales well with the number of wavelengths. Of course by changing the input parameter *maximum deviation* it is possible to make a trade-off between the calculation complexity and the scalability.

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 tuneability of the signal power. I have compared the proposed algorithm with the traditional RWA algorithm, (Figure 8). Here in this case the *maximum deviation* parameter was infinite, i.e. it is solved the ILP which gives the globally optimal solution. On the y-axis the maximum number of routed demands is depicted, while on the x-axis the used routing schemes. *RWA* means

that the traditional routing scheme is used, where each channel has the same signal power. It has to be mentioned that the n-factor parameter gives the maximum possible deviation between the channel powers. 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 I 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 I changed the lengths of the used network link by multiplying the original lengths with the scale parameter. In Figure 8 the scale is 1, i.e., the original link lengths (geographical distances decreased to 25% to get metro-WDM sized network, as presented in dissertation) are used.



**Figure 8: Maximum number of routed demands versus n-factor parameter in case of COST 266 topology**



**Figure 9: The performance of the heuristic method in case of globally optimal solution and shortest path routing**

In Figure 9 the performance of the method is presented in case of networks with eight wavelength links. Two extreme cases are compared when the maximum allowable distance is zero, i.e. all demands are routed in shortest path, and when the maximum allowable distance is infinite, i.e. the globally optimal solution. As it is to be seen, in case of low n-factor values the two methods are the same but while increasing the tune-ability of the signal powers, as it was expected, the globally optimal solution performs better than the shortest path routing. The main goal is, that even for the simplest shortest path routing, if it is allowed to tune the signal power, much more demands can be route in all-optical domain than in case this is not allowed.

## **5. Application of the Results**

The calculation method presented in Claim 1 has been several times used to configure real optical networks [T1]. These calculations have high importance due to fast calculation time and can give a good prediction of the feasibility of an optical network.

The method presented in Claim 1.1 is suitable to determine the signal quality of an optical connection. In many cases I have used the mentioned calculation method to decide the need of an optical element in the network [T1]-[T3].

The goal of the claim 1.2 is also an important industrial question arriving from network designers. How much should be the output power of the inline EDFA? The results are useful tools for network designers for improving their optical network or even redesigning their power budget calculations.

The importance of the algorithm presented in the second claim will prove true when the migration from point to point optical networks to all-optical mesh network will happen. The claim 2.1 gives an RWA method to such kind of networks.

Claim 2.2 proposes a novel network configuration method which gives better performance in every case, than the traditional configuration schemes. The proof of applicability is that Ericsson has patented the method [P1].

In Claim 2.3, based on the idea presented in claim 2.2, a heuristic RWA algorithm is given which makes a tradeoff between the performance of the algorithm and the scalability of the networks.

In my research work one of the main goals was the applicability of the results. I hope my dissertation reflects it.

## **6. Acknowledgement**

I would like to thank to my supervisor Tibor Cinkler, whose help was essential in becoming a researcher in the field of telecommunications.

I would also like to thank to Géza Paksy for every day discussions, and his deliberate advices which made my research more adequate and useful. It was my honor to work with him.

My work was done in the research cooperation framework between Ericsson and the High-Speed Networks Laboratory (HSNLab) at the Budapest University of Technology and Economics. I am grateful to Tamás Henk and Robert Szabó for their continuous support.

## 7. Reference

- [1] K. L. Chen, H. M. Cheung, K. C. Chan, "From optical performance monitoring to optical network management: research progress and challenges (Invited)", ICOCN 2004
- [2] M. Saleh, J. M. Simmons, "Evolution toward the next-generation core optical network", *IEEE/OSA. J. Lightwave Technology*. 24(9), 3303–3321, 2006. doi:10.1109/JLT.2006.880608
- [3] H. Zang, J.P. Jue, B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks.", *SPIE/Baltzer Opt. Netw. Mag.* 1(1), 47–60, 2000
- [4] E. W. Dijkstra, "A note on two problems in connexion with graphs", *Numer. Math.*, vol. 1, pp. 269–271, 1959.
- [5] U. Meyer, "Single-source shortest-paths on arbitrary directed graphs in linear average-case time", in *SODA: ACM-SIAM Symposium on Discrete Algorithms*, pp. 797–806, 2001.
- [6] L. A. Wolsey, "Integer Programming.", Wiley-Interscience, 1998.
- [7] "CPLEX.", <http://www.ilog.com/products/cplex/>.
- [8] J. Szigeti, P. Hegyi "IDRSIM (Intra-Domain Routing Simulator)", Department of Telecommunications and Media Informatics, Budapest University of Technology and Economics, 2004–2007
- [9] "VPI Transmission Maker" <http://www.vpisystems.com/>
- [10] B. Ramamurthy, D. Datta, H. Feng, J. P. Heritage, B. Mukherjee, "Impact of Transmission Impairments on the Teletraffic Performance of Wavelength-Routed Optical Networks", *IEEE/OSA J. Lightwave Tech.*, vol. 17, no. 10, Oct. 1999, pp. 1713–23.
- [11] I. Neokosmidis et al., "New techniques for the suppression of the fourwave mixing-induced distortion in nonzero dispersion fiber WDM systems", *IEEE/OSA J. Lightw. Technol.*, vol. 23, no. 3, pp. 1137–1144, Mar. 2005
- [12] A. Cartaxo, "Impact of modulation frequency on cross-phase modulation effect in intensity modulation–direct detection WDM systems", *IEEE Photon. Technol. Lett.*, 10( 9):1268–1270, 1998
- [13] K. Inoue, K. Nakanishi, K. Oda, H. Toba, "Crosstalk and Power penalty due to fiber four-wave mixing in multichannel transmission", *IEEE J. Lightwave Technol.*, 12(8):1423-1439, 1994
- [14] Y. Huang, J. P. Heritage, B. Mukherjee, "Connection Provisioning With Transmission Impairment Consideration in Optical WDM Networks With High-

- Speed Channels”, IEEE/OSA Journal of Lightwave Technology, col. 23, no. 3, pp. 982-993, March 2005.
- [15] R. Cardillo, V. Curri, M. Mellia, ”Considering transmission impairments in wavelength. routed networks”, in Proc. of the 9th Conference on Optical Network Design and Modelling (ONDM), Milan (Italy), 2005
- [16] OptiSystem <http://www.optiwave.com/>
- [17] R. A. Saunders, B. L. Patel, H. J. Harvey and A. Robinson, “Impact of crossphase modulation for WDM systems over positive and negative dispersion NZDSF and methods for its suppression”, Electron. Lett., 32, (24), (1996), pp. 2206-2207.
- [18] H. J. Thiele, R. I. Killey and P. Bayvel, “Influence of transmission distance on XPM-induced intensity distortion in dispersion-managed, amplified fibre links”, Electron. Lett., 35, (5), 1999, pp. 408-409
- [19] I. Neokosmidis *et al.*, “New techniques for the suppression of the fourwave mixing-induced distortion in nonzero dispersion fiber WDM systems”, IEEE/OSA *J. Lightw. Technol.*, vol. 23, no. 3, pp. 1137–1144, Mar. 2005
- [20] E. Mannie *Ed.*, “Generalized Multi-Protocol Label Switching (GMPLS) Architecture“, RFC 3945, Oct. 2004.
- [21] Recommendation G.8080/Y.1304, “Architecture for the Automatically Switched Optical Network (ASON)“, ITU-T, Tech. Rep., Nov. 2001.
- [22] Z. Zhang, *et al.*, “Lightpath routing for intelligent optical networks“, IEEE Network, vol. 15, no. 4, July-Aug. 2001
- [23] A. Djupsjöbacka, G. Jacobsen, B. Tromborg ”Dynamic Stimulated Brillouin Scattering Analysis”, IEEE/OSA Journal of Lightwave Technology, vol. 18, no. 3, March 2000
- [24] G. Wilfong, P. Winkler, ”Ring routing and wavelength translation”, in SODA: ACM-SIAM Symposium on Discrete Algorithms, 1998.
- [25] N. Wauters, P. Demister, ”Design of the Optical Path Layer in Multiwavelength Cross-Connected Networks”, IEEE Journal on Selected Areas in Communications, vol. 14, no. 5 pp. 881-892, June 1996.
- [26] D. Banerjee, B. Mukherjee, ”A practical Approach for Routing and Wavelength Assignment in Large Wavelength-Routed Optical Networks”, IEEE Journal on Selected Areas in Communications, vol. 14 no. 5 pp. 903-908, June. 1996
- [27] Y. Liu, D. Tipper, P. Siripongwutikorn, ”Approximating optimal spare capacity allocation by successive survivable routing,” in IEEE INFOCOM, (Anchorage, Alaska), pp. 699–708, 2001.

- [28] L. Gargano, U. Vaccaro, "Routing in all-optical networks: Algorithmic and graph-theoretic problems", *Numbers, Information and Complexity*, pp. 555–578, February 2000.
- [29] I. Tomkos "Performance Engineering of Metropolitan Area Optical Networks through Impairment Constraint Routing", *OptiComm*, August 2004.
- [30] M. Ali, D. Elie-Dit-Cosaque, L. Tancevski, "Enhancements to Multi-Protocol Lambda Switching (MPIS) to Accommodate Transmission Impairments", *GLOBECOM '01*, vol. 1, 2001, pp. 70–75.
- [31] L. Pavel, "OSNR optimization via end-to-end power control: A central cost approach", *IEEE INFOCOM*, pp. 1095–1105, 2005
- [32] "COST 266 reference network basic topology (BT) "
- [33] Alcatel-Lucent 1626 Light Manager <http://www.alcatel-lucent.com/wps/portal>
- [34] R. Ramaswami, K.N. Sivarajan, "Routing and Wavelength Assignment in All-Optical Networks", *IEEE Transaction on Networking*, vol. 3 no. 5 pp. 489-500, Oct. 1995.
- [35] J. Tapolcai, "Routing algorithms in survivable telecommunication networks", PhD thesis, Budapest University of Technology and Economics, Budapest, Hungary, 2004.
- [36] W. Zeiler, F. Di Pasquale, P. Bayvel, J.E. Midwinter, "Modeling of Four-Wave Mixing and Gain Peaking in Amplified WDM Optical Communication Systems and Networks", *IEEE/OSA J. Lightwave Technol.*, 14(9):1933-1942, 1996
- [37] K.-P. Ho, "Statistical Properties of Stimulated Raman Crosstalk in WDM Systems", *IEEE/OSA J. Lightw. Technol.*, 18(7):915-921, 2000
- [38] "Cisco 15454 ROADM module"  
[http://www.cisco.com/en/US/prod/collateral/optical/ps5724/ps2006/ps5320/product\\_data\\_sheet0900aecd803fc52f.html](http://www.cisco.com/en/US/prod/collateral/optical/ps5724/ps2006/ps5320/product_data_sheet0900aecd803fc52f.html)
- [39] G. P. Agrawal, "Nonlinear Fiber Optics", 2nd ed. New York: Academic, 1995
- [40] T. Antony, A. Gumaste, "WDM Network Design", Cisco Press Feb 7, 2003

## 8. Publication (34)

### Book Chapter (1,5)

- [B1] I. Tomkos, Sz. Zsigmond et al, "Towards Digital Optical Networks" Chapter 1. Springer ISSN: 0302-9743(Print) 1611-3349 (Online <http://www.springer.com/computer/communications/book/978-3-642-01523-6>) Volume:5412/2009, DOI:10.1007/978-3-642-01524-3 (6/4=1,5)

### International Patent (1)

[P1] Sz. Zsigmond, M. Perényi, T. Cinkler "Signal Power Based Routing In WDM All-Optical Networks" European Patent Office, PCT/EP2008/056579, submitted by Ericsson (2/2=1)

**Journal Publication (with peer review)(10,4)**

[J1] D. Mazroa, Sz. Zsigmond, T. Cinkler, "Determining the Maximum Signal Power in 10 Gbit/s WDM Optical Networks", Photonic Network Communications Vol. 18 Issues 1, 2009, pp 77. (6/2=3)

[J2] A. Teixeira · L. Costa · G. Franzl · S. Azodolmolky · I. Tomkos · K. Vlachos · S. Zsigmond · T. Cinkler · G. Tosi-Beleffi · P. Gravey · T. Loukina · J. A. Lázaro · C. Vazquez · J. Montalvo · E. Le Rouzicet "An integrated view on monitoring and compensation for dynamic optical networks: from management to physical layer", Photonic Network Communications Accepted 2008 waiting for publication. DOI 10.1007/s11107-008-0183-5 (6/15=0,4)

[J3] Á. Szabó, Sz. Zsigmond, T. Cinkler, "Impact of Physical Effects onto the Optimal Signal Power in CWDM Optical Networks", Mediterranean Journal of Electronics and Communications (MEDJEC) under acceptance (6/2=3)

[J4] Á. Szabó, Sz. Zsigmond, "Determining the Optimal Signal Power Based on Physical Effects in CWDM Optical Networks", Híradástechnika, vol. LXIII., 2008/7, pp. 55-59, (4/2=2)

[J5] Sz. Zsigmond, M. Perényi, T. Cinkler, "OSNR Based Routing in WDM Optical Networks", Híradástechnika, vol. LXIII., 2008/7 pp. 47-54, (4/2=2)

**Journal Papers in Hungarian:(6)**

[J6] Sz. Zsigmond, B. Megyer, T. Cinkler, "Optikai virtuális magánhálózatok kialakítása a fizikai szint korlátainak figyelembevételével", Magyar Távközlés Jun. 2004 XV/2, (2/2=1)

[J7] Sz. Zsigmond "Polarizációs Módus Diszperzió és kompenzációs lehetőségei WDM hálózatokban ", Híradástechnika, vol. LXI., pp. 11-16, 2006 (2/1=2)

[J8] D. Mazroa, Sz. Zsigmond, "Maximális optikai jelszint meghatározása DWDM rendszerekben", Híradástechnika, vol. LXII., pp. 26-34, 2007 (2/2=1)

[J9] Á. Szabó, Sz. Zsigmond, "Optikai jelszint meghatározása CWDM optikai hálózatokban a fizikai hatások figyelembevételével", Híradástechnika, vol. LXIII., pp. 43-48, 2008 (2/2=1)

[J10] Sz. Zsigmond, M. Perényi, T. Cinkler, "Jel/zaj viszonyon alapuló útvonalválasztás WDM hálózatokban", Híradástechnika, vol. LXIII., pp. 35-42, 2008 (2/2=1)

**Invited Papers: (2,5)**

[C1] T. Cinkler, Sz. Zsigmond, M. Perényi, "Traffic Grooming and Power Level Tuning for Physical Impairment Constrained Routing", ICTON 2008 June 22-26 2008-Athens Greece (3/2=1,5)

[C2] T. Cinkler, Sz. Zsigmond, M. Perényi D. Gál, "Physical aspects of end-to-end optical routing", IWO 2008: 3rd International Workshop on OPS & OCDMA. Shanghai, Kína, 2008.10.23-2008.10.25. (3/3=1)

**Conference Proceedings Publications (with peer review) (12,1)**

[C3] Sz. Zsigmond B. Megyer T. Cinkler "Design of Optical VPNs with Simulating Physical Limitations", Eunice Short Paper 2004 Tampere Finland, Session 2 - Lower Layer Issues (3/2=1,5)

[C4] Sz. Zsigmond B. Megyer, Sz. Ákos, T. Cinkler "Design of Traffic Grooming Optical VPNs Obeying Physical Limitations", The Second IEEE and IFIP International Conference on Wireless and Optical Communications Networks WOCN 2005 marc. 6-8 Dubai (3/3=1)

[C5] Sz. Zsigmond, A. Szodenyi, B. Megyer, T. Cinkler, A. Tzanakaki, I. Tomkos "A New Method for Considering Physical Impairments in Multilayer Routing", COST291/GBOU ONNA workshop on Design of Next Generation Optical Networks: from the physical up to the network level perspective Gent, Belgium, February 6, 2006 (3/5=0,6)

[C6] Sz. Zsigmond, G. Németh, T. Cinkler "Mutual Impact of Physical Impairments and Grooming in Multilayer Networks", ONDM 2007 Greece (3/2=1,5)

[C7] Sz. Zsigmond, M. Perényi, T. Cinkler "Cross-Layer Optimization of OSNR-Constrained RWA in WDM Optical Networks", COST 291 workshop on The role of optical networking in the future Internet Vilanova i la Geltrú, Catalonia, Spain, March 11, 2008 (3/2=1,5)

[C8] Sz. Zsigmond, M. Perényi, T. Cinkler "ILP formulation of Signal Power Based Routing for Single and Multilayer Optical Networks", BROADNETS 2008 September 8-11 2008 London (3/2=1,5)

[C9] Á. Szabó, Sz. Zsigmond, T. Cinkler "Impact of Physical Effects onto the Optimal Signal Power in CWDM Optical Networks", 6th CSNDSP - 23-25 July 2008, Graz University of Technology, Graz, Austria (3/2=1,5)

[C10] Sz. Zsigmond, H. Furukawa, N. Wada, T. Miyazaki "Modulation Formats Comparison in a Prototype 640Gbit/s/port Optical Packet Switching System" 14th OptoElectronics and Communications Conference (OECC 2009) No: WB3, 13-17 July 2009, Hong Kong (4/2=1)

[C11] Sz. Zsigmond, H. Furukawa, N. Wada, T. Miyazaki "Scalability Study of a Prototype 640Gbit/s/port Optical Packet Switch for Network Applications" 35th

European Conference on Optical Communication (ECOC 2009) 20-24 September 2009, Wien Austria (4/2=1,5)

[C12] Sz. Zsigmond, H. Furukawa, N. Wada "Scalability Study of SOA Based Optical Switch for Optical Packet Networks" International Conference in Photonics in Switching (PS 2009) 15-19 September 2009, Pisa Italy (3/2=1,5)

[C13] H. Furukawa, Sz. Zsigmond, N. Wada "Network scalability of 640 Gbit/s/port Wide-colored Optical Packet Switch" 4<sup>th</sup> International Workshop on OPS and OCDMA (IWOOC 2009) 17-18 November 2009, Tokyo Japan (3/2=1,5)

#### **Conference Proceedings Publications in Hungarian (0,5)**

[C14] Sz. Zsigmond "10 Gbit/s sebességű optikai átvitel fizikai korlátainak modellezése", 15. Távközlési és Informatikai Hálózatok Szeminárium és Kiállítás 2006. október 11-12-13. EGER (1/2=0,5)

#### **Additional Publications:**

[T1] Paksy Géza, Zsigmond Szilárd: "A DWDM gerinchálózatokban használható nagysebességű jelek alkalmazhatóságának elméleti és gyakorlati méréseken alapuló", Készült a PKI Távközlésfejlesztési Intézet megbízásából BME-TMIT által teljesítve, 2006.

[T2] Megyer Balázs, Paksy Géza, Szödényi Ákos, Zsigmond Szilárd: "Optikai crossconnect-ek (OXC) alkalmazása a transzportálózatokban", Készült a PKI Távközlésfejlesztési Intézet megbízásából BME-TMIT által teljesítve, 2005.

[T3] Paksy Géza, Mazroa Dániel, Zsigmond Szilárd: "SFP és XFP modulok alkalmazásai feltételeinek vizsgálata számítógépes szimulációval", Készült a PKI Távközlésfejlesztési Intézet megbízásából BME-TMIT által teljesítve, 2007.