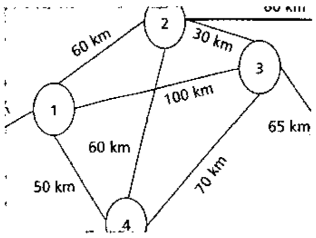

# PERFORMANCE ENGINEERING OF METROPOLITAN AREA OPTICAL NETWORKS THROUGH IMPAIRMENT CONSTRAINT ROUTING

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## ABSTRACT

We demonstrate the use of impairment constraint routing for performance engineering of transparent metropolitan area optical networks. Our results show the relationship between blocking probability and different network characteristics such as span length, amplifier noise figure, and bit rate,and provide information on the system specifications required to achieve acceptable network performance.

## INTRODUCTION

During the last decade, optical networks have evolved dramatically in terms of technology and architectures toward a more flexible and intelligent optical network layer based on the use of wavelength-division multiplexing (WDM), new optical switching technologies, and advanced control and management protocols.

In a wavelength routed network signal quality is subject to a variety of impairments introduced by the transmission line or switching equipment. Network designers may overcome the impact of signal impairments using per channel optoelectronic regenerators at selected network nodes. However, this solution is not cost effective since regenerators are expensive modules, and the number of regenerators used should be reduced to a minimum. Especially for metropolitan area optical networks, where cost is a major consideration, this goal becomes even more central. Performance engineering for metropolitan area networks (MANs) is a rather difficult task since the use of cost-effective devices (e.g., semiconductor optical amplifiers, SOAs, vs. Erbium doped fiber amplifiers, EDFAs) usually comes at the expense of device performance. Since metro networks cover a relatively small geographical area, as opposed to long-haul networks, it is anticipated that appropriate network engineering may result in acceptable overall system performance.

Impairment management techniques in metro optical networks can be implemented in line (e.g., through the use of dispersion compensating modules) or at the optical transponder interfaces (e.g., through the use of novel modulation formats). However, some of these approaches are still not sufficiently cost effective, and there is a tendency to add new features to the optical transport systems in order to eliminate all expensive impairment management equipment from the transmission line. It is expected that transmission-advanced modulation formats able to extend the uncompensated reach of 10 Gb/s systems to 300 km will eliminate all dispersion compensating modules (DCMs), making the system upgradeable, scalable, modular, and future-proof. We also mention that MANs typically support distances only up to 300 km (resulting in low launched power requirements for reasonable signal-to-noise ratio) and standard single-mode fiber (SMF) with high local dispersion ($D$ = 17ps/nm km) is commonly used. Hence, nonlinear effects such as four-wave mixing do not have significant impact on overall system performance.

In addition to advanced modulation formats and other similar techniques, the network designer may also use appropriate routing and wavelength assignment (RWA) algorithms that take into account the signal impairments. Such algorithms constrain the routing of wavelength channels so that it is consistent with the physical characteristics and limitations of the optical paths. Routing in communication networks generally involves the identification of a path for each connection request between the two end nodes. In opaque optical networks the signal is electrically regenerated at each node (i.e., any impairment of the signal can be eliminated). For this reason, routing in opaque networks assumes system engineering on a per link basis. In opaque networks, the RWA algorithm gives for each connection request a path that may use different wavelengths on different links of the path (opto-electronic wavelength conversion is available). Most routing approaches find a path that minimizes a certain cost parameter such as the number of hops or the fiber length of the connection. A very good and rich collection of RWA schemes and formulations that have been proposed to date is presented in [1]. The majority of these RWA algorithms assume that once the path and wavelengths have been identified, connection establishment is feasible. This is generally the case in opaque networks, but may not be true in transparent networks, where the signal quality degrades as it is transmitted through optical fiber and nodes. Hence, impairment constraint-based routing (ICBR) may be used in transparent networks as a tool for performance engineering with the goal of choosing feasible paths while minimizing the blocking probability for new connection requests. ICBR may also serve as a tool to provide QoS in the network. Different connection requests may have different requirements in terms of the quality of the received signal. Since this is strongly related to the constraints each impairment imposes, it is obvious that the ICBR can be incorporated in the routing mechanism to provide more "intelligence" for the routing of the connections, so that different levels of QoS can be supported. The topic of impairment constraint routing in optical networks recently regained attention and is discussed extensively in fora such as the Internet Engineering Task Force (IETF) [2].

In this article we demonstrate the use of an improved ICBR algorithm for performance engineering in a typical metro network architecture. Although most of the impairments are present in ultra-long-haul networks as well, due to the differences in the characteristics and requirements of each type of network, some impairments are dominant in backbone and others in MANs (e.g., chromatic dispersion). One reason is that backbone networks consider the use of impairment compensation modules (e.g., dispersion compensator module/dispersion maps). This is not the case, though, with metro networks. Important impairments are chromatic dispersion and filter concatenation; thus, these impairments have to be studied in order to increase a network's efficiency and have a more complete view of the system's actual performance. The study shows the dependence of the connection blocking probability on various physical network parameters, which gives the system/component specifications required for a given network behavior. Our results also provide performance engineering studies offering insight into the system parameters that support the use of cost-effective devices. For example, we present the conditions under which SOAs may be used for amplification instead of EDFAs. We also demonstrate that the use of advanced modulation formats (e.g., duobinary) may considerably reduce the blocking probability in unregenerated and uncompensated metro networks.

This article is organized as follows. We present the modeling of each impairment as it is incorporated in the ICBR scheme. We present simulation results for a typical metro network, where each of the impairments is considered for signal degradation. Finally, we present the conclusions of our work.

## IMPAIRMENT CONSTRAINT ROUTING

The difficulties of the ICBR approach stem from the diverse nature and variety of limitations that have to be considered in order to minimize the blocking probability in the network. On one hand there are physical impairments (e.g., chromatic dispersion, polarization mode dispersion, amplifier spontaneous emission, crosstalk, nonlinearities); on the other hand there are network-related performance parameters (e.g., blocking probability, end-to-end delay, throughput) that capture and describe the overall performance of the WDM optical network. All these heterogeneous parameters have to be modeled in a unified way under a properly designed framework that will provide the setting for the RWA problem.

Recently there has been intensive research on constraint-based routing, and the way physical constraints are modeled and taken into account in the routing process in WDM optical networks. Crosstalk (XT) and amplifier spontaneous emission (ASE) were the impairments considered in [3], where the candidate lightpaths were determined by the bit error rate (BER) value of the path. Polarization mode dispersion (PMD) has also been examined [4, 5] in terms of the quality of the links of the network and the number of regenerators needed to ensure establishment of all connections. The impact of the optical switch, amplifier, and multiplexer/demultiplexer characteristics on network performance were also included in [6]. A novel model for dynamic resource allocation that takes into account signal transmission impairments and differentiated service classification considerations was presented in [7]. In a very recent study PMD and optical signal-to-noise ratio (OSNR) signal characteristics were included in a new constraint-based routing algorithm [8]. Today, none of the proposed ICBR takes into account chromatic dispersion (CD) and filter concatenation (FC), although they are often considered important performance degrading effects in transparent uncompensated metropolitan area networks. To the best of our knowledge, the proposed ICBR is the first one that takes into account these two impairments. After showing their importance in MANs we illustrate some performance engineering studies by comparing two different modulation formats.

Routing algorithms find the paths for existing connection requests that minimize the cost function. This cost function can be distance, number of hops, or something else. The various impairments degrade the quality of the signal in different ways as it propagates through the links, so they are associated with a specific link cost. Higher cost for a link implies more severe signal degradation due to a particular impairment while the signal is transmitted through this link, whereas lower link cost indicates that the link is more immune to this impairment, thus favoring the routing through this link. Existing ICBR schemes pay little attention to the overall efficiency of the network, since the metrics they incorporate refer only to aspects of the physical layer of the network (BER, OSNR, etc.) and do not take into account the performance in the network layer. Sometimes a path is selected that does not necessarily have the best BER, but a BER within acceptable boundaries, and its selection would be more suitable if it would cause less congestion in the upper layers, thus increasing the overall throughput of the network. For this reason, the metric we choose to use and optimize is blocking probability, which is the only parameter that can capture the true performance of a network. By properly modeling and incorporating in the routing algorithm the various physical impairments, we manage to tightly couple the constraints of the physical layer with the overall network performance as described by the blocking probability.

Next, we provide some information on the variety of physical impairments an ICBR scheme should consider and their association to the link cost. Special attention will be paid to CD and FC, which are more severe in metro networks and have not been covered in previous ICBR schemes.

**Polarization mode dispersion**: The constraint posed by PMD is that the broadening of the pulse less than a fraction $a$ (usually 10 percent) of the bit duration, $T = 1/B$, where $B$ is the bit rate [2]. The link cost related to PMD is the product of the square root of the PMD parameter of the link $D_{PMD}(k)$ with the link length $L(k)$, that is, $D_{PMD}(k) \, x \, \sqrt{L(k)}$.

**Amplified spontaneous emission (ASE) noise**: OSNR reduction is one source of system penalty in WDM systems introduced by the ASE noise generated through the presence of optical amplifiers used to compensate for any losses in the system. The OSNR of the received signal should be greater than or equal to a given minimum acceptable threshold, $\text{OSNR}_{\text{min}}$, which is a design parameter. The use of forward error correction (FEC) techniques may relax the OSNR requirements for error-free transmission. Therefore, different $\text{OSNR}_{\text{min}}$ limits may be considered. For example, if FEC is not used, the minimum acceptable OSNR may be $\text{OSNR}_{\text{min}} =$ 20 dB, whereas if FEC providing coding gain of 6 dB is used, the OSNR threshold value will be reduced to $\text{OSNR}_{\min} = 14$ dB. The link cost associated [3] with the ASE impairment has been specified as the number of amplifiers along the particular link.

**Crosstalk**: Crosstalk is introduced in WDM systems when leakage of optical signals generated through muxing/demuxing, switching, and other optical components interferes with the data channels, imposing power penalties in the system. Two types of XT arise in WDM systems: interchannel and intrachannel. The former is when the XT interference is on a different wavelength than the signal, the latter when the interference is on the same wavelength with the signal. This impairment presupposes that the routing and wavelength assignment have already taken place, which means that a link cost parameter for the XT impairment cannot be computed in advance. For this reason XT is examined together with ASE at the end of the routing process in order to make sure that the selected paths meet the requirements imposed on the received signal quality. The switch architecture used for the XT study is based on that proposed in [3], and different signal-to-noise ratio values were considered.

**Chromatic dispersion**: Chromatic dispersion has been considered for many years the most serious linear impairment for systems operating at bit rates higher than 2.5 Gb/s, and for this reason has been acknowledged as the main limiting constraint for metropolitan area optical networks. Dispersion compensation modules (DCMs) can be used at the optical add/drop multiplexers (OADMs)/optical crossconnects (OXCs) or amplifier sites to cancel out the accumulated CD. In our analysis the effects of the laser frequency chirp and fiber dispersion have been taken into account [9] in a simple phenomenological model that is able to predict the dispersion/chirp-induced eye closure penalty (ECP). Similar to PMD, the link cost related to CD is the product of the CD parameter of the link $D_{CD}(k)$ with the link length $L(k)$, that is, $D_{CD}(k) \times L(k)$. The ECP induced by CD should be less than a predefined threshold (e.g., 2 dB). This penalty depends on a number of different parameters, such as bit rate, modulation format, and the use or nonuse of DCMs at intermediate nodes. Specifically, the use of the appropriate modulation format may have a significant impact on CD and, as a result, on the performance of the network. For this purpose two different modulation formats, non-return to zero (NRZ) and low-pass filter-based duobinary (LPF) [10] are evaluated. The performance of a point-to-point link using standard single-mode fiber is assessed, and the 2 dB penalty limit appears at about 50 km for the NRZ and at about 140 km for the LPF modulation format [10].

**Filter concatenation**: The degradation of the signal caused by FC is due to the narrowing of spectral width the signal undergoes after traversing a set of filters in its path [10]. As in the case of XT, the penalty induced by FC depends on the selected paths and the number of intermediate nodes the signal traverses before it reaches the final destination. Therefore, the validity of the computed paths under the filter concatenation constraint is examined at the end, after the RWA has been solved, and if a computed path satisfies the filter concatenation constraint, it is established; otherwise, it is rejected. The penalty, which depends on the type of modulation as in the case of CD, should be less than a predefined threshold (e.g., 0.5 dB). Based on simulation results using the VPI simulation tool, we calculated the power penalty induced by FC as a function of the number of nodes the signal traverses before it arrives at the final destination for both NRZ and LPF modulation formats. LPF modulation offers greater tolerance to FC effects. It is worth mentioning that when using LPF modulation, the 1 dB penalty quite often used as a typical value for the power penalty due to FC is reached when the signal has traversed 12 intermediate nodes, while for NRZ modulation the corresponding number of nodes is only 6. As in the case of XT, the penalty induced by the FC effect cannot be computed in advance since this is strongly dependent on the selection of the path through which the optical signal is routed and the number of hops it comprises.

The ICBR algorithm we propose consists of three phases. The first is a preprocessing phase where all the information related to network characteristics and traffic demands is collected. This *network information* includes network topology, equipment (type of node, wavelength conversion capabilities, etc.), infrastructure, modulation format, link capacity, fiber characteristics (CD parameter, PMD parameter, amplifier gains, amplifier spontaneous emission, launched power per channel for each node, span length, the attenuation factor of each span, the signal-to-crosstalk ratio of each amplifier, the ability to use regenerators and/or DCMs). The *traffic characteristics* include information such as the number of demands, end nodes, and bit rate. Based on these parameters, the link costs that will be considered when finding the paths are computed. Computation of the link costs depends on the impairment types we desire to take into account each time and has been done based on the way we described previously. The second phase is initiated once the link costs have been found. This phase assigns paths and wavelengths to all the demands. One of the advantages of this model is the joint optimization of routing and wavelength assignment. The exact formulation we used for the RWA problem to assign the most suitable paths and wavelength to the connection requests is described in detail in the Appendix. For each connection request a set of $k$ shortest paths is identified, and a linear optimization problem is solved with the objective to minimize the cost induced by all flows in the network. The impairment constraint routing phase (which is the focal point of the effort in this article) checks the validity of the lightpaths delivered by the second (RWA) phase. A path is established if the proposed lightpath satisfies all the constraints that are determined by the impairments taken into account each time. If the proposed lightpath does not accomplish the impairment requirements, the path is deleted from the set of $k$ shortest paths and a new path from the set $k$ is taken. If none of the $k$-shortest paths satisfies the impairment constraints, the connection is blocked.

The complexity of the proposed ICBR scheme has been shown to be polynomial with respect to the number of network nodes $n$: $O(n^4)$. A more detailed description is given in the Appendix.

## METRO NETWORK SIMULATIONS

This section presents performance results for the ICBR algorithm in a transparent metropolitan area reference network architecture. Performance engineering is accomplished and system specifications are extracted by minimizing the blocking probability.

The architecture used as a reference network is shown in Fig. 1. It consists of 10 nodes interconnected by 16 bidirectional links. Each link is able to support up to 80 wavelengths, which is a typical value for the number of wavelengths a modern optical network can provide. The link lengths cover a range of 20–100 km long, with an average link length of 70 km. Such a distribution of lengths is quite realistic for a typical large MAN. Link fibers have a PMD factor of either 0.1 ps/km$^{1/2}$ or 0.5 ps/km$^{1/2}$, corresponding to newer or older fibers, respectively. The CD parameter is taken to be equal to 8 ps/nm.km for newer fibers and 17 ps/nm.km for older fibers. The attenuation coefficient is assumed to be 0.25 dB/km. The percentage of new fibers in the network is given by the parameter $\alpha$. Since the majority of existing metro networks were installed a few years ago, the infrastructure may be quite old.

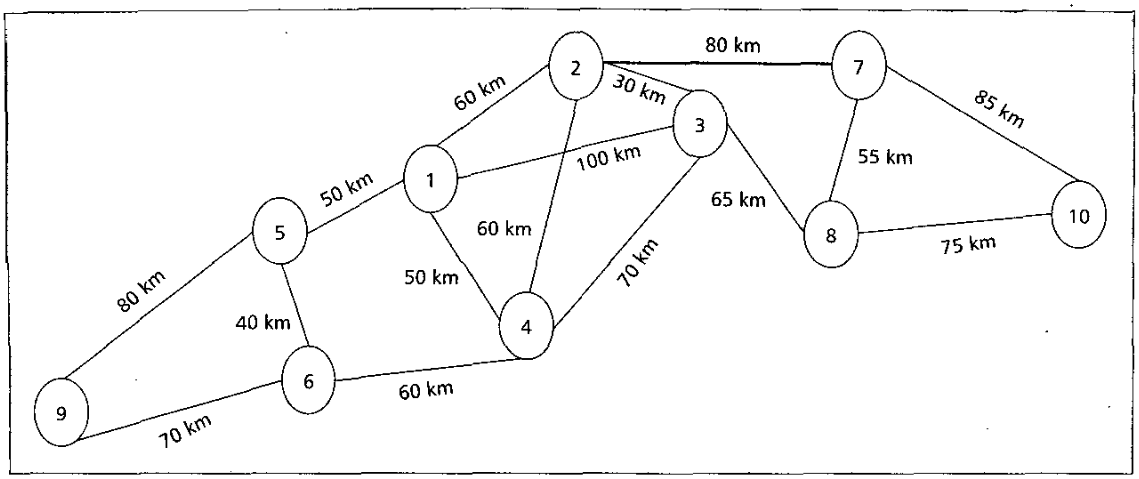

**FIGURE 1.** The topology of the reference metro optical network.

For this reason the value of the percentage α was selected to be less than 0.5, with the default value being 0.1.

In this reference network, a static traffic scenario has been considered. Each node of the network requests for a connection with each other node of the network for a total of 90 end-to-end connections. Connections can carry different bit rates (10 or 40 Gb/s). This scenario is quite reasonable since providers prefer to set up long-term connections between the various nodes of the network, based on traffic models describing the expected traffic in the network and estimating the bulk of data that are exchanged between different pairs of nodes. This static scenario has been used in previous work [4–6]. We have considered the following types of impairments; PMD, ASE, XT, CD, and FC. In what follows we present for simplicity a set of simulations where each of the impairments is considered each time as the dominant one. In all the simulation results the blocking probability has been computed as the ratio of established connections over the total amount of end-to-end connections requests. The value $k$ for the number of $k$-shortest paths has been chosen equal to 3.

## POLARIZATION MODE DISPERSION STUDIES

We studied the dependence of the blocking probability on the bit rate of the connections parameterized by the percentage of newer fibers. The value of the PMD parameter of the fiber span is chosen to be equal to the value of the PMD parameter of a newer fiber with probability α and equal to the value of the PMD parameter of an older fiber with probability $1 - \alpha$. In other words, a binomial distribution of probability α is used to determine the value of the PMD parameter of each fiber span. The results obtained for different values of α are shown in Fig. 2. The PMD becomes more dominant with increasing bit rates, which deteriorates the blocking performance of the network. For a 10 Gb/s bit rate, the performance of the network is not affected at all by the PMD, even when all the links use old-type fibers. The PMD starts limiting network performance at a rate on the order of 20 Gb/s. Significant improvements can be achieved for a specific bit rate when using newer fibers. For example, at 40 Gb/s and a network consisting exclusively of fibers of the old type ($\alpha = 0$), all the connections are blocked. However, if just half of the links comprise fibers of lower PMD factor ($\alpha = 0.5$), the blocking probability reduces to 60 percent.

For the case of $\alpha = 0.1$ (10 percent of the fibers are new), and for 40 Gb/s and 10 Gb/s systems, it has been found that fibers with PMD values of 0.135 and 0.542 ps/km$^{1/2}$, respectively, are required to be able to successfully route all the demands.

## AMPLIFIER SPONTANEOUS EMISSION

In metro networks the signal traverses shorter distances and goes through fewer amplifiers, which may have high noise figures (NFs). Amplifiers are used to compensate for span losses: longer span lengths need higher amplifier gain. Apart from the inline amplifiers used at the spans, amplifiers are also located at OADMs/OXCs to boost the signal before demultiplexing and before launching the signal into the fiber. Metro networks may use EDFAs and/or SOAs. The cost and size of EDFAs is larger than those of SOAs. Typical EDFA NF values range from 4.5 to 7 dB, whereas SOA NF values may be in the range of 6 to 10 dB. Our study covers NF values from 4.5 dB to 10 dB. The impact of the amplifier NF to the blocking probability of the network with respect to various amplifier gains corresponding to different span lengths is shown in Fig. 3.

For a given NF and for increasing $G$ (equal to the span loss) the OSNR is reduced, leading to larger blocking probability. It can also be observed that higher amplifier NF values give rise to a higher ASE impairment effect and an increase of blocking probability. Depending on the span length, the blocking probability may start increasing from lower values of NF (e.g., NF = 5 dB for span = 80 km and corresponding amplifier gain 20 dB) to higher values (e.g., NF = 8.5 dB for span = 60 km and corresponding amplifier gain 15 dB). It is worth mentioning that this graph also gives information on the conditions under which low blocking probability could be

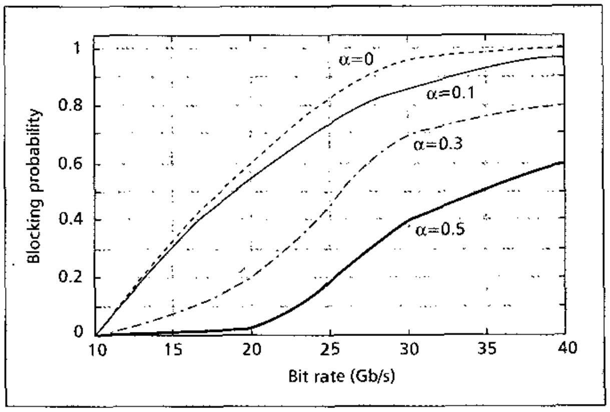

**FIGURE 2.** Blocking probability vs. bit rate for different percentages (α) of the newer type of fibers in the network.

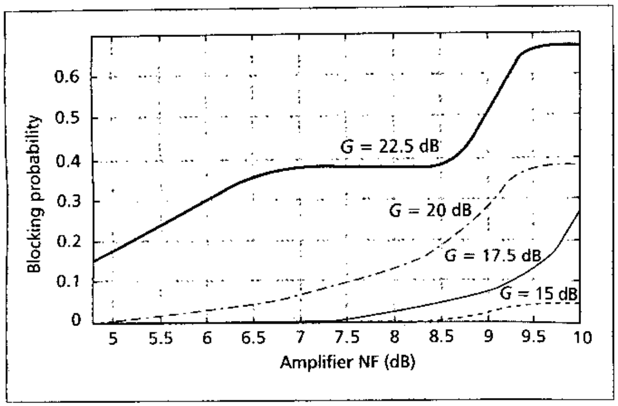

**FIGURE 3.** Blocking probability vs. amplifier noise figure (i.e., different amplifier types such as EDFA vs. SOA) for different amplifier gains.

maintained where low-cost SOAs are used instead of EDFAs. It can be observed that for low gains (15 and 17.5 dB), EDFAs offer very low blocking probabilities, whereas SOAs can have up to 27 percent blocking probabilities. For higher gains (on the order of 22.5 dB), SOAs give a prohibiting blocking probability (around 40 percent or more depending on the NF), whereas EDFAs with NF of 5 dB offer a more acceptable blocking probability of 16 percent. It should be noted, however, that the performance of SOAs in practical WDM metro systems will be limited not only by their NFs but also by other effects not analyzed in this work, such as cross-gain modulation.

## CROSSTALK

This section examines the effect of intrachannel XT in a transparent metro network scenario, since its effects are much more severe than those of interchannel XT [10]. The effect of XT is studied in conjunction with ASE noise, since both impairments have an impact on the inband optical signal-to-noise ratio. The amount of energy that leaks to neighboring wavelengths is described by the signal-to-XT ratio (*Xsw*).

Figure 4 presents the blocking probability with respect to the span length for various signal-to-XT ratios. The graph shows that *Xsw* significantly affects the blocking performance of the network. A 15 dB difference in *Xsw* can reduce the blocking probability from around 82 percent (for *Xsw* = –30 dB) to around 27 percent blocking probability (for *Xsw* = –45 dB) for 70 km span length, an improvement of 67 percent. This graph also shows the significant decrease of blocking probability observed when FEC techniques are used. For example, when we have *Xsw* = –40 dB and require a minimum $\text{OSNR}_{\text{min}}$ = 20 dB, the blocking probability is higher than 50 percent. However, when FEC techniques are used the $\text{OSNR}_{\text{min}}$ drops to 14 dB, and the blocking probability reduces to less than 5 percent. By comparing the blocking probabilities for different *Xsw* for $\text{OSNR}_{\text{min}}$ = 20 dB, we can observe that the blocking probability drops to 50 percent when the *Xsw* decreases by 10 dB (e.g., from *Xsw* = –40 dB to *Xsw* = –50 dB). This drop is due to the decrease in the number of XT terms considered [3].

## CHROMATIC DISPERSION

This section presents the dependence of blocking probability on the CD parameter, under two scenarios: with and without dispersion compensation. In the first scenario where dispersion compensation is used, the DCMs are placed at each OXC of the network compensating for the CD accumulated through the last link. A connection is blocked if the threshold of 2 dB power penalty is reached at some point of the selected path. The performance in terms of CD for the two modulation formats (NRZ and LPF) is compared in Fig. 5a. Similarly, Fig. 5b compares the two modulation formats when no DCM is used in the network. Both graphs show a significant performance improvement when LPF is used. When no compensation is used, the blocking probability for 8 and 17 ps/ns-km CD is 97 and 63 percent, respectively. On the other hand, when compensation is used it can be observed that for *Dcd* of up to 16 ps/nm-km zero blocking probability can be achieved. For 17 ps/nm-km and with LPF modulation format the blocking probability is 2 percent, whereas with NRZ modulation it is as high as 89 percent. This corresponds to a 98 percent difference for the two cases.

From the two graphs it can be deduced that dispersion compensation can greatly assist in reducing the blocking probability of the network. When NRZ modulation is used, this holds for values of CD lower than 15 ps/nm-km. For example, for 8 ps/nm-km CD the blocking probability drops from 62 to 16 percent, a blocking performance improvement of 74 percent. For a typical value of 17 ps/nm-km, the two schemes yield the same blocking probability, which indicates that in such a case dispersion compensation is not adequate to alleviate the negative effects of the impairment on the overall performance of the network. On the other hand, when LPF modulation format is used, dispersion compensation improves e blocking probability throughout the range of values that have been considered for the CD parameter. Even for a 17 ps/nm-km CD parameter the blocking improvement is 93 percent.

## FILTER CONCATENATION

This section presents the evaluation of the penalty induced by the FC to the eye closure of the signal and its impact on the blocking performance of the network. A connection is blocked whenever the power penalty of the signal measured at every node of the path exceeds the specified threshold value. The maximum allowed power penalty due to C varies from 0.1 to 1.5 dB. Connections routed through paths that at some intermediate noise exhibit a signal power penalty more than this value are blocked. The results are shown in Fig. 6. When using LPF modulation, all the connections can be routed when they introduce a penalty less than a maximum allowable of 0.5 dB, whereas the corresponding penalty value for NRZ modulation is 0.9 dB. For 0.5 dB maximum allowable penalty and NRZ modulation, 30 percent of the connections are blocked. It is obvious that the type of modulation format used can also contribute significantly to the efficiency of the rout-

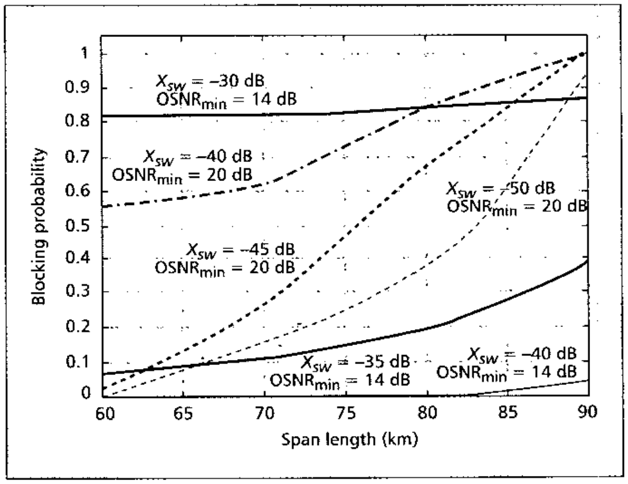

**FIGURE 4.** Blocking probability vs. span length under the ASE and XT impairments for different values of $\text{OSNR}_{\text{min}}$ and signal-to-XT ratio (*Xsw*).

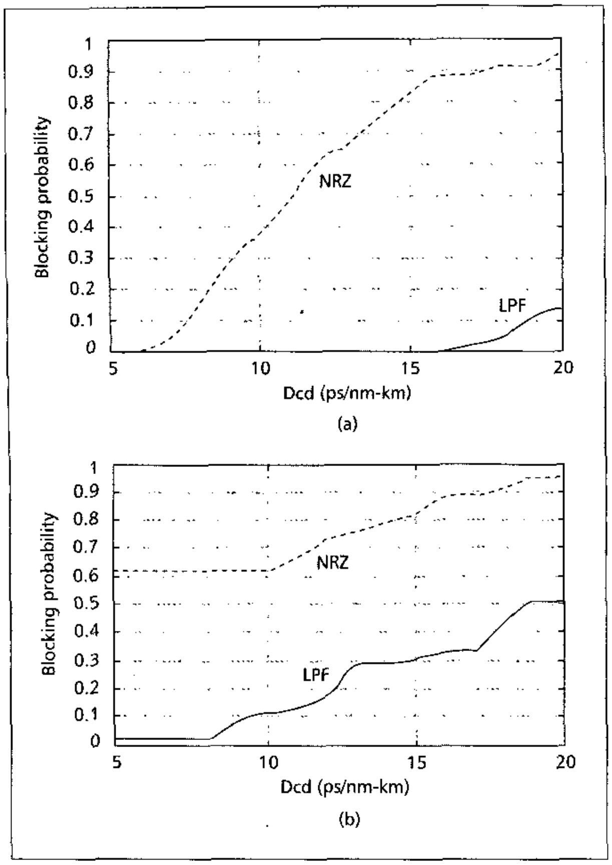

**FIGURE 5.** a) Blocking probability vs. CD factor: a)compensation at each node); b) no compensation.

ing and thus improve the performance of the network in the case of FC impairment.

## DISCUSSION AND FUTURE WORK ON THE INTEGRATION OF ALL THE IMPAIRMENTS

We have presented the effect that each of the impairments has on the network performance of a metro network. The network performance has been measured in terms of blocking probability and has allowed us to perform some performance engineering studies by comparing different types of equipment (e.g. amplifiers types) and modulation formats (e.g. NRZ and LPF). The presented studies allow network operators to see the equipment characteristics (NFs or gains for amplifiers, XT ration for crossconnects, etc.) that are required to achieve a certain blocking probability. An extension of our study can be the inclusion of the impact of all the impairments under a single cost parameter. In the following paragraph we discuss how this task can be performed.

The impairments we have just introduced can be classified into two classes:

- Link impairments (e.g., PMD)
- Node impairments (e.g., XT)

The former depend on the link characteristics, the latter on the other channels sharing the same node. In order to compute the signal degradation of a new demand due to node impairments we should know the routes of the other demands and identify the ones that will degrade the quality of the signal. The signal quality can be measured by the $Q$ factor [9], which could split it in two terms: $Q = Q_L x Q_N$. By this $Q$ factor, all the impairments could be considered within the signal degradation; thus, the overall performance behavior of all the impairments on the network could be studied. The improved ICBR will find in a first step the best path and wavelength, taking into account the link impairments (good $Q_L$ factor). When knowing all the paths, the node impairments for each path can be computed depending on the neighboring channels sharing the switches. If the path does not meet the signal requirements (low $Q_N$ factor), the path is discarded and the ICBR is run again so that a new path with its wavelength is proposed. The $Q$ factor will be checked again. The algorithm will run until paths and wavelengths for all the demands are found with acceptable $Q$ factor. This study, however, is beyond the scope of this article.

## CONCLUSIONS

In this article results related to the performance engineering of transparent metropolitan area optical networks through the use of an impairment constraint routing algorithm have been presented. These results show the relation between blocking probability and different network characteristics such as span length, amplifier noise figure, and bit rate, and give information on the system specifications required to achieve acceptable network performance. For example, the blocking probability for different types of amplifiers has been shown, as well as how we could maintain the throughput if SOAs are used instead of EDFAs due to their lower price. Increased throughput has been shown when LPF modulation is used instead of the well-known NRZ.

It is shown that the overall network performance can be significantly improved if impairment-aware routing is used to route the connections. Moreover, ICBR achieves significant cost savings by proper utilization of network resources and efficient usage of network infrastructure. By appropriately modeling the impairments and incorporating them in the routing algorithm, physical constraints can be alleviated and network efficiency increased.

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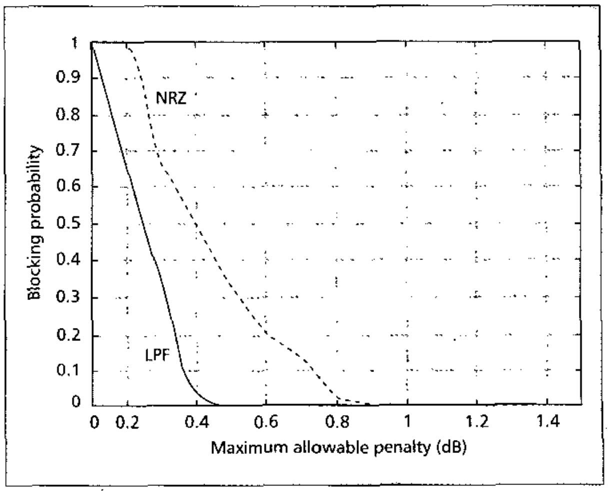

**FIGURE 6.** Blocking probability vs. maximum allowable penalty due to FC.

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# APPENDIX — RWA FORMULATION

## INPUT PARAMETERS:

The following parameters are considered to be known beforehand and are given as input to the algorithm for the routing and wavelength assignment of a given set of connections.

- **G(V,A)** a unidirectional graph, where $V$ is the set of vertices describing the nodes of the network and A the set of edges describing the links of the network.
- **N** = **|V|** the number of the nodes of the network
- **L** = **|A|** the number of the edges of the network
- **C** the set of the available wavelengths
- **W** = **|C|** the total number of the available wavelengths
- **R** the traffic matrix in units of lightpaths, i.e. $R_{12} = 2$ indicates that there are 2 connection/lightpath requests between nodes 1 and 2 of the network
- **U** the total number of the distinct source-destination pairs
- **k** the total number of paths (main and alternate/protection) that have to be selected for each request
- **P** the set of all paths (main and alternate/protection) of all the connections
- **Z** the set of all nodes that have wavelength conversion capabilities
- **Q** the set of all available wavelength conversions at all the nodes of the network
- $\mathbf{Q_i}$ the set of all available wavelength conversions at nodes $i$ of the network
- $\mathbf{T_i}$ the number of wavelength converters at node $i$
- **D** a properly chosen piecewise linear cost function. This function is a function of flow in every link and in its general form is a piecewise monotonically increasing convex function.
- **a** the number of the piecewise linear segments comprising the piecewise linear cost function, $1 \leq a \leq W$

## VARIABLES

We also introduce the following variables.

- $\lambda_{p,l}^{c}$ an *indicator variable* that has the value of 1 when path $\boldsymbol{p}$ occupies the link $\boldsymbol{l}$ and the wavelength $\boldsymbol{c}$ and 0 in all other cases
- $x_l = \sum_{\substack{p \in P \\ c \in C}} \lambda_{p,l} = \sum_{p \in P} \sum_{c \in C} \lambda_{p,l}$ the total flow in link $l$

The formulation of the problem is the following.

## OBJECTIVE

$$\min \sum_{l} D_l(x_l) \forall l \in A \tag{1}$$

**Subject to the constraints**

**1.** $$\sum_{p} \lambda_{p,l}^{c} \leq 1 \qquad \forall l \in A, c \in C \tag{2}$$

Each wavelength at a specific link can be used at most once.

**2.** $$\lambda_{p.l_i}^{c} = \lambda_{p.l_j}^{c} \qquad \forall p \in P, \text{ and } (l_i, l_j) \in p \text{ are successive links in } p \tag{3}$$

At nodes where no wavelength capabilities are available, passing lightpaths should be using at the egress the same wavelength as at the ingress so that the **wavelength continuity constraint** is satisfied.

**3.** $D_l \geq c_i x_l + \beta_i \quad \forall l \in A$ and $\forall i, 1 \leq i \leq a$ (4a)

In essence, the previous constraint is the mathematical expression of

$$D_l \geq \max\{c_i, x_l + \beta_i\}. \tag{4b}$$

**4.** $\sum_{\substack{c \\ p \in P_{sd}}} \lambda^c_{p,l_i} = R_{sd} \quad \forall l_i$ which is the first link in $p$ (5)

The sum of all lightpaths departing from node $s$ (source) to node $d$ (destination) has to be equal to the corresponding value $R_{sd}$ of the traffic matrix.

$$\sum_{\substack{c \\ p \in P_{sd}}} \lambda^c_{p,l_j} = R_{sd} \quad \forall l_j \text{ which is the last link in } p \tag{6}$$

The sum of all lightpaths originating from node $s$ (source) to node $d$ (destination) has to be equal to the corresponding value $R_{sd}$ of the traffic matrix.

**5.** $\sum_c \left|\lambda_{p,l_i} - \lambda_{p,l_j}\right| \leq 2T_i$ $\forall$ intermediate node $i$ that has wavelength conversion capabilities, where $(l_i l_j) \in p$ are successive links in **p**. (7a)

For nodes that have wavelength conversion capabilities, the number of lightpaths exiting in a different wavelength from the one they were using when entering the node must not exceed twice the number of the wavelength converters available at the specific node.

In essence, this constraint is equivalent to

$$\max\left\{\sum_c \pm\left(\lambda^c_{p,l} - \lambda^c_{p,lj}\right)\right\} \leq 2T_i. \tag{7b}$$

As can be shown, the total number of both optimization variables and the constraints of the formulation is on the order of $O(N^4)$, where $N$ is the total number of nodes. This is the worst case; in practice, though, it is much lower, since the topologies are seldom fully mesh, which is the assumption for $O(N^4)$.

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