

# Modeling Physical-Layer Impairments in Multi-domain Optical Networks

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**Abstract**—The advantages of optical transparency are still confined to the boundaries of a domain, since the optical signals are subject to O/E/O conversions at the border nodes that separate two optical domains. The extension of transparent connections across domains requires advances both in the modeling of the impairments suffered by the optical signals as well as in devising strategies to exploit such models in practice. In this latter regard, one of the main challenges is to design information exchange models and protocols enabling optical bypass without disclosing detailed physical-layer information among domains. In this paper, we focus on the modeling and the exchange of impairment-related information between optical domains. We propose a model that conveniently captures the degradation experienced by an optical signal along a lightpath, and describe its use in the frontier between two neighbor domains. Our approach respects the privacy and administrative limits of carrier networks, while enabling the provision of transparent connections beyond domain boundaries. The model and strategies proposed in this paper generalize the contributions made by some of the most relevant works in the field, providing in this way a first attempt toward a unifying view and theory for quantifying the transmission impairments in DWDM optical networks.

## I. INTRODUCTION

In DWDM all-optical networks, traffic is transmitted entirely in the optical plane, i.e., without undergoing any optical-electronic-optical (O/E/O) conversion at transit nodes. Such networks are commonly referred to as “transparent” optical networks, in contrast to fully “opaque” settings where electrical regeneration is applied at every hop along a path. Transparent optical networks not only provide huge transmission and switching capacity, but also reduce the capital and operational expenses as well as the energy required by opaque network infrastructures. For instance, the cost of an optical port represents approximately only a 20% of the cost of an electrical port [1], and it has been shown that the potential savings both in operational costs and energy are also significant [2], [3].

In practice, the benefits of optical transparency are confined to the boundaries of an optical domain, since all traffic that leaves from or enters a domain undergoes an electronic conversion at the border nodes, regardless of its destination. The possibility of deploying transparent lightpaths beyond the

frontier between domains is gradually being supported by carriers, and thus is attracting increasing attention from the scientific community.

One of the major challenges in extending the reach of transparent optical circuits is that, the longer the distance, the lower the quality of the optical signal at the detection point. Current long-haul networks are mainly composed of optical nodes called optical crossconnects (OXC), Single Mode Fibers (SMFs), and optical amplifiers, each of which degrades at some extent the quality of an optical signal along its propagation path. The physical impairments introduced by these optical elements can be taxonomized into two categories, namely, linear and nonlinear impairments (see Fig. 1). When the degradation caused by an optical element does not depend on the power of the signals transported through the optical element, the impairment is said to be linear, and can be assessed independently for the different channels (wavelengths) transiting the element. Contrarily, nonlinear impairments depend on the power of the signals transported, and therefore, the level of degradation on each wavelength strongly depends on the intensity of the optical signals carried by other wavelengths transiting an optical element [1], [4].

The impairments caused by the different optical elements present in a transparent network have been the subject of study of a number of high quality articles and books in the past, such as [5]–[12], [1], and [4]. By analyzing the contributions in the literature, two important conclusions can be extracted. In the first place, there is not a single and widely accepted model that captures the main physical-layer impairments in a straightforward and compact way. Indeed, the works cited above provide different renditions covering in some cases the same physical phenomena, and surprisingly, there are considerable differences in the taxonomies employed, and

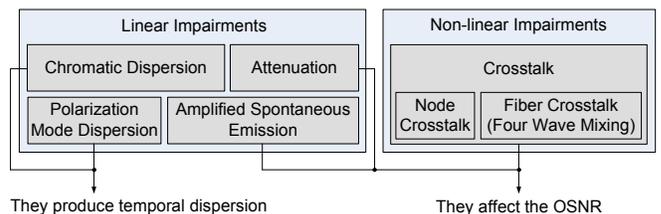


Fig. 1. Physical-layer impairments modeled in this paper.

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hence in the quantifications and models ultimately obtained. In the second place, the models developed so far mainly cover the impairments suffered by an optical signal within an optical domain. In other words, little progress has been made to extend the studies beyond domain boundaries.

In this context, this paper makes the following contributions. We provide a conciliatory model in an attempt to come up with a unifying and compact expression covering the most harmful effects in current transparent DWDM networks. In addition, we propose a strategy for the exchange of information between two neighbor domains, leveraging in this way the model developed in this paper without transgressing the privacy required by optical domains.

The rest of this paper is structured as follows. Section II models the physical-layer impairments shown in Fig. 1 in the context of a single optical domain. Section III describes the strategy for the exchange of information between two neighbor domains, with the aim to exploit the model developed in Section II. Finally, Section IV, concludes the paper.

## II. PHYSICAL-LAYER IMPAIRMENT MODEL INSIDE AN OPTICAL DOMAIN

Figure 2 depicts the transmission model of a typical DWDM optical network [1], [9]. On the left-hand side, the optical node  $n$  (the source node) is equipped with a pool of parallel optical channels that are multiplexed, amplified, and transmitted over a SMF fiber. The DWDM line systems that interconnect two adjacent nodes consist of two SMF fibers, one for transmission and another for reception (Fig. 2 only shows one direction). Each fiber is composed of a set of concatenated spans, where a fiber span corresponds to the segment of a link between two line amplifiers. Each line amplifier contains an Erbium Doped Fiber Amplifier (EDFA) and a Dispersion Compensation Module (DCM), which are necessary to passively recover the propagation losses and to compensate for the Chromatic Dispersion (CD), respectively. In a typical DWDM transmission system, the span length is  $\approx 80$  km. In addition, optical amplifiers are used both at the input and output of the switching nodes. Each optical node is composed of a non-blocking and all-optical switching fabric that is able to switch an optical signal from an input port to an output port without electrical processing. The optical nodes are equipped with a DWDM wavelength multiplexer (Mux) and a de-multiplexer (De-Mux). The Mux inputs are

connected to the lasers and modulators located in the output ports of the switch fabric, whereas the outputs of the De-Mux are connected to the photo-detectors and demodulators located in the input ports of the switch fabric. As shown on the right-hand side of Fig. 2, a pool of regenerators can be optionally connected at dedicated ports of the switching fabric, but its use would clearly break the optical transparency.

We now model the impairments introduced by the different elements present in a DWDM transmission system. We focus on modeling the impairments shown in Fig. 1, addressing in first place the linear impairments and then the nonlinear ones.

### A. Linear Impairments

The linear impairments modeled in this paper are Attenuation, Amplified Spontaneous Emission (ASE), Chromatic Dispersion (CD), and Polarization Mode Dispersion (PMD). The first two degrade the Optical Signal-to-Noise Ratio (OSNR) at the detection point, whereas the latter two produce temporal dispersion in the optical signal.

1) *Attenuation*: The optical signals are attenuated both by the optical nodes and by the fiber spans along a path. To model these effects, consider the example illustrated in Fig. 3, which shows a set of interconnected optical nodes inside a domain or Autonomous System (AS). Let  $N$  be the number of nodes (hops) in the path from the border node OXC  $B$  (the source) to the destination node OXC  $N$ . The number of links between OXC  $B$  and OXC  $N$  is  $N$ , so the total number of spans along the path is  $M \geq N$ . Let  $L_{span}$  be the maximum admissible length of a span ( $\approx 80$  km), and  $L_n$  denote the length of the  $n$ -th link of the path,  $n = 1, \dots, N$ . Hence, the total number of spans  $M$  along the path is:

$$M = \sum_{n=1}^N \lceil \frac{L_n}{L_{span}} \rceil = \sum_{n=1}^N S_n \quad (1)$$

where  $S_n$  denotes the number of spans along link  $n$ .

Let  $e^{-\alpha_n(\lambda_l)}$  denote the attenuation (loss) for wavelength  $\lambda_l$  due to the  $n$ -th node in the path, and  $e^{-\beta_m(\lambda_l)L_m}$  denote the loss due to the  $m$ -th span of link  $n$  (note that the exponent is proportional to the length of the span  $L_m$ ) [5], [9]. Moreover, let  $G_m(\lambda_l)$  be the gain of the line amplifier located in span  $m$ . By recursion as in [9], it is easy to observe that the power at the output of node  $n$  for wavelength  $\lambda_l$  is:

$$P_n(\lambda_l) = P_{n-1}(\lambda_l) e^{-\alpha_n(\lambda_l)} \prod_{m=1}^{S_n} e^{-\beta_m(\lambda_l)L_m} G_m(\lambda_l) \quad (2)$$

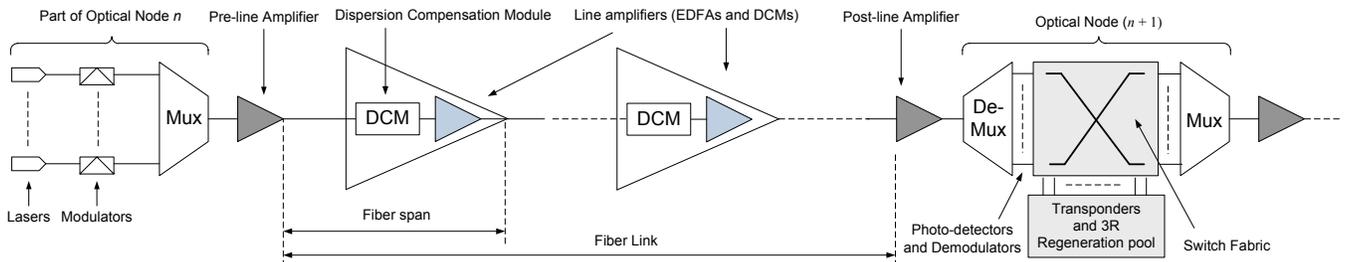


Fig. 2. Main optical elements in a DWDM transmission system between two adjacent nodes; direction: from node  $n$  to node  $(n + 1)$ .

Given that the output power at the border node OXC  $B$  is  $P_0 = P_B(\lambda_l)$ , the power in detection can be obtained by solving the recursion, yielding:

$$P_D(\lambda_l) = P_B(\lambda_l) \underbrace{\prod_{n=1}^N e^{-\alpha_n(\lambda_l)} \prod_{m=1}^M e^{-\beta_m(\lambda_l)L_m} G_m(\lambda_l)}_{\text{Total attenuation factor } A(\lambda_l)} \quad (3)$$

2) *Amplified Spontaneous Emission (ASE)*: The ASE noise is due to the spontaneous emission of photons produced by the EDFAs. The amount of noise accumulated at the detection point for wavelength  $\lambda_l$  will depend on the gains of cascading EDFAs  $G_m(\lambda_l)$ , the bandwidth of the optical filters  $B_0$ , the photon energy  $h\nu$  ( $h$  is Planck's constant), and the spontaneous emission factor  $\eta_m$  of the line amplifiers located in the spans,  $m = 1, \dots, M$  [5], [9]. More specifically, the ASE noise power added by the EDFA at the end of the  $m$ -th span is:

$$N_{ASE}^{(m)}(\lambda_l) = 2h\nu B_0 \eta_m (G_m(\lambda_l) - 1) \quad (4)$$

Hence, the ASE noise power at the output of span  $m$  can be expressed by recursion as follows:

$$N_m(\lambda_l) = N_{ASE}^{(m)}(\lambda_l) + N_{m-1}(\lambda_l) e^{-\beta_m(\lambda_l)L_m} G_m(\lambda_l) \quad (5)$$

In practice,  $G_m(\lambda_l) \gg 1$  for spans larger than 40 km [5], so without loss of generality we can assume that  $N_{ASE}^{(m)}(\lambda_l) \simeq K \eta_m G_m(\lambda_l)$ , with  $K = 2h\nu B_0$ . Since  $N_0(\lambda_l) = 0$ , the ASE noise power in detection can be obtained by solving the recursion, yielding:

$$N_D^{ASE}(\lambda_l) = K \left[ \eta_M G_M(\lambda_l) + \sum_{m=1}^{M-1} \eta_m G_m(\lambda_l) a_m(\lambda_l) \right] \quad (6)$$

$$a_m(\lambda_l) = \prod_{j=m+1}^M e^{-\beta_j L_j} G_j(\lambda_l)$$

3) *Chromatic Dispersion (CD)*: This is one of the temporal dispersions suffered by the optical signals as they propagate through SMFs. The dispersion occurs because of the different group velocities of the spectral components present in an optical signal. The negative effect of CD is that the different spectral components arrive at the receiver at different time, thus producing inter-symbol interference (ISI) [1], [8]. The impairments caused by CD are wavelength-dependent, and also depend on the bit-rate, the modulation technique, the fiber used, and the quality of the compensation obtained through the Dispersion Compensation Modules (DCMs) located in the line amplifiers (see Fig. 2). Overall, the CD is considered one of the most harmful effects within the category of linear impairments.

In order to quantify its effects, let  $\Delta t_B^{(CD)}$  denote the CD at the output of the border node OXC  $B$  in Fig. 3, and let  $D_m$  and  $\Delta \lambda_l$  be the CD parameter of the  $m$ -th span, and the width in nanometers of the optical signal spectra, respectively. The compensation factor of the DCM present in span  $m$  is denoted as  $C_m$ , and the length of the compensation is denoted as  $L_m^c$ .

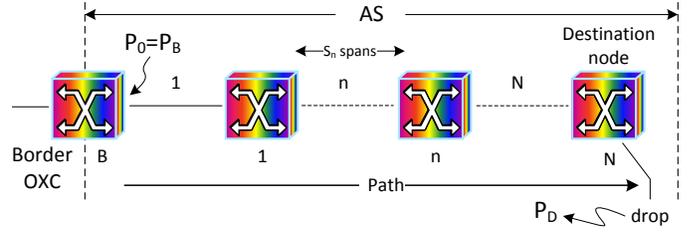


Fig. 3. A transparent lightpath between the border node OXC  $B$  and an internal node OXC  $N$ .

By including compensation, the expression in [8] for the CD in the detection point can be generalized as follows:

$$\Delta t_D^{(CD)}(\lambda_l) = \Delta t_B^{(CD)}(\lambda_l) + \sum_{m=1}^M (D_m \Delta \lambda_l L_m - C_m L_m^c) \quad (7)$$

The compensation is said to be perfect when the summation on the right-hand side of (7) is zero.

4) *Polarization Mode Dispersion (PMD)*: PMD is caused by imperfections in the circularity of the fibers cross-section. External forces applied on the fiber, irregularities, or even heating, are all potential sources of PMD. The slight ovality of the core makes that the refractive index of the glass differs for the two orthogonal polarization modes that compose the optical pulses. This phenomenon is called birefringence, and causes that the two polarization modes travel at different speeds in the fiber, resulting in the broadening of the optical pulse. The dispersion introduced by PMD does not depend on the wavelength, and even though it is smaller in magnitude than that of CD, it is more difficult to compensate. The dispersion increases with the distance, and its value in detection can be expressed as follows [4], [8]:

$$\Delta t_D^{(PMD)} = \sqrt{\left(\Delta t_B^{(PMD)}\right)^2 + \sum_{m=1}^M P_m^2 L_m} \quad (8)$$

where  $\Delta t_B^{(PMD)}$  is the PMD at the output of the border node in Fig. 3, and  $P_m$  is the PMD parameter of the  $m$ -th fiber-span expressed in picoseconds per square root of km ( $\frac{ps}{\sqrt{km}}$ ).

## B. Nonlinear Impairments

The challenge in modeling nonlinear impairments lies in that the noise power on each channel depends on the utilization and power levels of the rest of the channels transiting an optical element. In this paper, we focus on crosstalk, which is one of the main impairments in this category. There are basically two sources of crosstalk, node crosstalk and fiber crosstalk (see Fig. 1). Node crosstalk is caused by imperfect isolation of the switching elements, especially, by non-ideal wavelength de-/multiplexing and processing within the switch fabric. These imperfections induce power leakage from other DWDM channels on a given channel and vice versa. Fiber crosstalk, on the other hand, can be split into two groups: one that encompasses the Kerr effects, namely, the Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM), and another that covers the stimulated

scattering effects [1], [4]. With current technology, the most penalizing crosstalk in fibers is the FWM effect [1], [6], [10], [12], and therefore, it is the one that will be considered in this work. It is worth highlighting that both the power and the spectral separation of the channels are critical factors when modeling crosstalk, since the severity of the node and FWM crosstalk depend on the wavelength spacing and the optical power level carried on each wavelength [4], [6], [10], [12].

We now proceed to model the node and FWM crosstalk, in an attempt to provide a unifying and more general view of the models proposed in [7], [8], [9], [10], [11] for the node crosstalk, and in [6], [12] for the FWM effect.

1) *Node Crosstalk*: Figure 4 shows the different types of crosstalk introduced by an OXC considering all possible combinations of input and output ports and interfering wavelengths. As in most works in the literature, we shall only consider co-wavelength and adjacent wavelength interferences, since the crosstalk due to non-adjacent wavelengths is negligible in practice. According to the terminology introduced by Deng et al. [7], there are three types of node crosstalk: *co-wavelength crosstalk*, *neighbor port crosstalk*, and *self-crosstalk* (see Figs. 4(a), (b), and (d), respectively). To model these effects, we introduce:

- a square matrix of size  $W \times W$  that we call the “crosstalk matrix”  $X_n$  of optical node  $n$ ,  $n = 1, \dots, N$ , where  $W$  is the number of wavelength channels supported by each DWDM line system in the network;<sup>1</sup>
- and a vector of size  $W$  that we call the “channel utilization vector”  $U_n^p$ , being  $p$ ,  $p = 1, \dots, d_n$ , a port of node  $n$ , and  $d_n$  the outdegree of the node.

$$X_n = \begin{bmatrix} 0 & \gamma_n^a & 0 & \dots & 0 \\ \gamma_n^a & 0 & \gamma_n^a & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \gamma_n^a & 0 & \gamma_n^a \\ 0 & \dots & 0 & \gamma_n^a & 0 \end{bmatrix}, \quad U_n^p = \begin{bmatrix} u_{1n}^p \\ u_{2n}^p \\ \vdots \\ u_{Wn}^p \end{bmatrix} \quad (9)$$

The nonzero elements of matrix  $X_n$  are  $x_{l,l+1}^{(n)} = x_{l+1,l}^{(n)} = \gamma_n^a$ ,  $l = 1, \dots, W-1$ , wherein  $\gamma_n^a$  represents the penalization factor

<sup>1</sup>For simplicity in the exposition, the wavelength combs are assumed to have the same number of channels  $W$ .

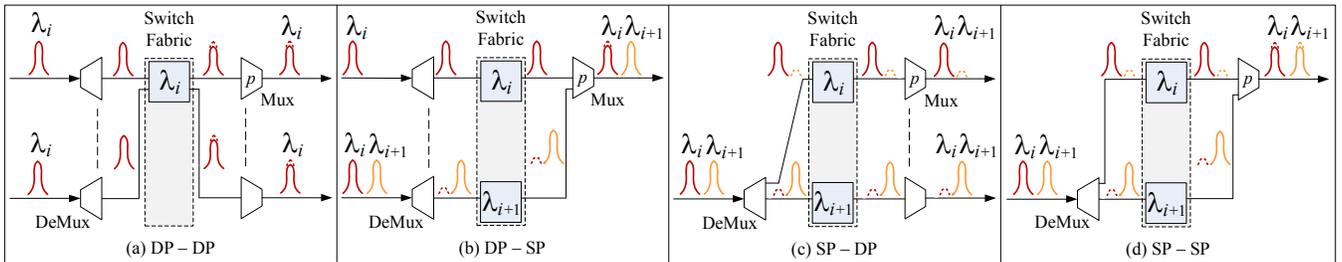


Fig. 4. Types of crosstalk depending on the combination of input and output ports for interfering optical signals in an OXC. Different Ports (DP) means that the signals ingress to or egress from the OXC through different ports, whereas Same Port (SP) indicates that the signals share a port in the OXC; (a) Co-wavelength crosstalk; (b) Neighbor port crosstalk; (c) does not produce crosstalk; (d) Self-crosstalk (figure inspired in Deng et al. [7]).

due to non-perfect isolation of adjacent channels during the demultiplexing and multiplexing stages in node  $n$  (cases (b) and (d) in Fig. 4). In addition, each component of vector  $U_n^p$  in (9) is a binary function, such that  $u_{ln}^p = 1$  if wavelength  $\lambda_l$ ,  $l = 1, \dots, W$  is occupied on output port  $p$  of node  $n$ , and zero otherwise. Moreover, let  $\gamma_n^s$  be the penalization factor due to interference in the switch fabric of node  $n$  (case (a) in Fig. 4). As mentioned above, the higher the optical power carried on each wavelength, the greater the values of  $\gamma_n^a$  and  $\gamma_n^s$ . By using  $X_n$  and  $U_n^p$ , the different types of crosstalk shown in Fig. 4 can be expressed as vectors of size  $W$ , such that the  $l$ -th component of each of these vectors quantifies the level of impairment (i.e., the penalization) on wavelength  $\lambda_l$ . Indeed, it can be easily shown that the co-wavelength crosstalk produced in the  $p$ -th port of node  $n$ ,  $C_n^p$  (case (a) in Fig. 4), can be expressed as:

$$C_n^p = \gamma_n^s \sum_{j=1, j \neq p}^{d_n} U_n^j \quad (10)$$

where the  $l$ -th component of vector  $C_n^p$  represents the penalization on wavelength  $\lambda_l$ , for the (node, port) pair  $(n, p)$ . Observe that neighbor port crosstalk and self-crosstalk end up inducing the same interference effect at the output port  $p$ , so their penalization vectors can be respectively expressed as  $N_n^p = S_n^p = X_n U_n^p$  [7], [9]–[11]. And given that the penalization cumulates linearly along the nodes in the path [11], the total penalization vector at the detection point is:

$$X_D^{(nodes)} = \sum_{n=1}^N \left( 2X_n U_n^p + \gamma_n^s \sum_{j=1, j \neq p}^{d_n} U_n^j \right) \quad (11)$$

2) *Four-Wave Mixing (FWM)*: FWM occurs when three optical signals with different frequencies  $f_i, f_j, f_k$  propagate simultaneously on a fiber, giving rise to a new signal, called an idler of frequency  $f_l$ , with  $l = i + j - k$  ( $i, j \neq k$ ) and  $i, j, k = 1, \dots, W$ . The noise power produced by the idler at the output of a path that traverses  $N$  fibers (see Fig. 3) can be expressed as:

$$N_D^{FWM}(\lambda_l) = \sum_{n=1}^N \sum_{\substack{k=1 \\ k \neq j}}^W \sum_{\substack{j=1, l \neq j \\ 1 \leq l-j+k \leq W}}^W N_{(l-j+k)jk}^{(n)} \quad (12)$$

where  $N_{(l-j+k)jk}^{(n)}$  is the FWM power generated by the three frequencies  $i, j, k$  along the  $n$ -th fiber of the path, with  $i = l - j + k$ , and is given by:

$$N_{(l-j+k)jk}^{(n)} = A_{(l-j+k)jk}^{(n)} P_{l-j+k}^{(n)} P_j^{(n)} P_k^{(n)} e^{-\alpha_n L_n} \quad (13)$$

where  $\alpha_n$  is the attenuation of fiber  $n$ ,  $L_n$  is the length of the fiber,  $P_{l-j+k}^{(n)}$ ,  $P_j^{(n)}$ , and  $P_k^{(n)}$  are the input powers of the optical signals  $i, j$ , and  $k$ , respectively, and:

$$A_{(l-j+k)jk}^{(n)} = (d_{(l-j+k)jk}^{(n)} \gamma L_{eff}^{(n)})^2 \eta_{(l-j+k)jk}^{(n)} \quad (14)$$

where the terms  $d_{(l-j+k)jk}^{(n)}$ ,  $\gamma$ ,  $L_{eff}^{(n)}$ , and  $\eta_{(l-j+k)jk}^{(n)}$  are, the degeneracy factor, the nonlinear coefficient, the effective length of the fiber, and the efficiency of the fiber, respectively. For a detailed description of these terms and their calculation, the reader is referred to [6], [12].

We now address the integration of all these impairments and describe its use in the frontier between two neighbor domains.

### III. INFORMATION EXCHANGE MODEL BETWEEN ADJACENT OPTICAL DOMAINS

Consider the scenario shown in Fig. 5, wherein two adjacent domains,  $AS_{i-1}$  and  $AS_i$ , have an agreement to foster the set up of transparent optical circuits between them. Our goal is to provide an information exchange model enabling optical bypass at the frontier between  $AS_{i-1}$  and  $AS_i$ , while preserving the confidentiality of the physical-layer information managed by each domain. To this end, let  $S \in AS_{i-1}$  be the source node, and  $B_i$  and  $D$  be the ingress (border) node and the destination node in  $AS_i$ , respectively (see Fig. 5). Let  $P_S$  denote the power level at the optical signal launch in node  $S$ , and  $P_D$  denote the power of the optical signal at the detection point in node  $D$ . Moreover, let  $O_{x'x}$  and  $\Delta T_{x'x}$  be two vectors of size  $W$  that we call the OSNR and dispersion vectors for the segment of a path between the nodes  $x'$  and  $x$  ( $x' \rightarrow x$ ), which we define as follows:

$$O_{x'x} = \begin{bmatrix} o_{x'x}^{(\lambda_1)} \\ \vdots \\ o_{x'x}^{(\lambda_l)} \\ \vdots \\ o_{x'x}^{(\lambda_W)} \end{bmatrix}, \quad \Delta T_{x'x} = \begin{bmatrix} \Delta t_{x'x}^{(\lambda_1)} \\ \vdots \\ \Delta t_{x'x}^{(\lambda_l)} \\ \vdots \\ \Delta t_{x'x}^{(\lambda_W)} \end{bmatrix} \quad (15)$$

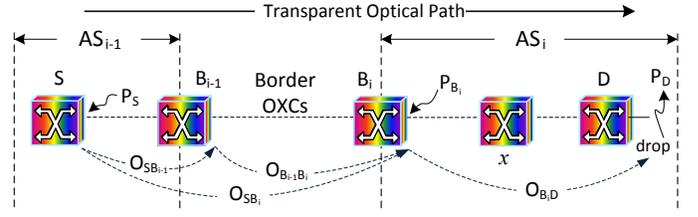


Fig. 5. Optical bypass between two neighbor domains.

and by using equations (3), (6), (7), (8), (11), and (12), it can be easily shown that when  $x$  represents a node inside  $AS_i$ , and  $x' = B_i$ , i.e., an ingress node to  $AS_i$ , the components of vectors  $O_{x'x}$  and  $\Delta T_{x'x}$  can be expressed as (16) (see Figs. 3 and 5 jointly).

Furthermore, let  $o_{\min}$  and  $\Delta t_{\max}$  be the minimum acceptable OSNR and the maximum admissible dispersion at detection, respectively, so that a lightpath can be established between the source and destination—note that these bounds are technology dependent, and thus will vary depending on the nodes and fibers used within an optical domain. Assuming that the admission control policy in  $AS_i$  is satisfied, then, the set up of a new lightpath between  $S$  and  $D$  through  $B_i$ , could be provisioned transparently using wavelength  $\lambda_l$  when:

$$\begin{cases} o_{SD}^{(\lambda_l)} = \left( \frac{1}{o_{SB_{i-1}}^{(\lambda_l)}} + \frac{1}{o_{B_{i-1}B_i}^{(\lambda_l)}} + \frac{1}{o_{B_iD}^{(\lambda_l)}} \right)^{-1} > o_{\min} \\ \Delta t_{SD}^{(\lambda_l)} < \Delta t_{\max} \end{cases} \quad (17)$$

Clearly, both inequalities must be satisfied in order to allow optical bypass at the border node  $B_i$  in  $AS_i$ . It is also worth noting that in the first inequality in (17):

- $o_{SB_{i-1}}^{(\lambda_l)}$  can be estimated using (16), and thus it can be used by an impairment-aware RWA algorithm prior to the path set up process;
- a nominal value characterizing the OSNR for the inter-domain link ( $o_{B_{i-1}B_i}$ ) can be either advertised between  $AS_{i-1}$  and  $AS_i$  or be estimated prior to the path set up process.

Thus, the term  $o_{SB_i}^{(\lambda_l)}$  in (17) can be reasonably estimated by  $AS_{i-1}$ , and, using the same line of reasoning, it is easy to observe that the dispersion between  $S$  and  $B_i$  can be estimated

$$o_{x'x}^{(\lambda_l)} = \left( \frac{P_{x'}(\lambda_l) A(\lambda_l)}{N_x^{ASE}(\lambda_l) + N_x^{XT}(\lambda_l) + N_x^{FWM}(\lambda_l)} \right) = \left( \frac{N_x^{ASE}(\lambda_l)}{P_{x'}(\lambda_l) A(\lambda_l)} + XT_x^{(\text{nodes})}(\lambda_l) + \frac{N_x^{FWM}(\lambda_l)}{P_{x'}(\lambda_l) A(\lambda_l)} \right)^{-1} \quad (16)$$

$$\Delta t_{x'x}^{(\lambda_l)} = \Delta t_{x'}^{(CD)}(\lambda_l) + \sum_{m=1}^M (D_m \Delta \lambda_l L_m - C_m L_m^c) + \sqrt{\left( \Delta t_{x'}^{(PMD)} \right)^2 + \sum_{m=1}^M P_m^2 L_m}$$

as well. On this basis, we propose to extend the budget-based approach introduced by Yang et al. [8] as follows. By operating in (17) we obtain the inequalities that  $AS_{i-1}$  must satisfy so that  $AS_i$  allows optical bypass in  $B_i$ :

$$\begin{cases} o_{SB_i}^{(\lambda_i)} > \frac{o_{\min}}{1 - o_{\min} \cdot (o_{B_i D}^{(\lambda_i)})^{-1}} = o_{\text{Budget}}^{(\lambda_i)} \\ \Delta t_{SB_i}^{(\lambda_i)} < \Delta t_{\max} - \Delta t_{B_i D}^{(\lambda_i)} = \Delta t_{\text{Budget}}^{(\lambda_i)} \end{cases} \quad (18)$$

where  $o_{B_i D}^{(\lambda_i)}$  and  $\Delta t_{B_i D}^{(\lambda_i)}$  are computed by  $AS_i$  using (16). As in (15), we define two budget vectors of size  $W$ , namely,  $O_{\text{Budget}}$  and  $\Delta t_{\text{Budget}}$ , such that each component of these vectors is given by the right-hand side of the first and second inequality in (18), respectively.

In this framework, the budget vectors  $O_{\text{Budget}}$ , and  $\Delta t_{\text{Budget}}$ , represent the information that  $AS_i$  will associate to destinations  $D$  within its own domain, and for which  $AS_i$  is willing to provide transparent transit. Accordingly, the budget vectors are the information that  $AS_i$  will advertise to  $AS_{i-1}$ . In case that the local OSNR in  $AS_i$  is below the minimum admissible OSNR,  $o_{\min}$ , or the local dispersion surpasses  $\Delta t_{\max}$  for a given (path, wavelength, destination) tuple, the budgets advertised for the tuple are set to infinite, and zero, respectively.

It is important to note that, in our information exchange model, detailed physical-layer information is never disclosed between  $AS_i$  and  $AS_{i-1}$ , since only two scalar values are exchanged per (path, wavelength) pair toward any given destination  $D$ . Another important issue is the distinction between linear and nonlinear impairments and their role during admission control. Observe that since the dispersion is a linear impairment, the temporal constraint needs to be applied only on the desired wavelength. However, the presence of nonlinear impairments makes that the set up of a new circuit affects the OSNR of the already established connections and vice versa, since these latter will affect the OSNR of the new connection at the detection point. Thus, the set up of a new lightpath between  $S$  and  $D$  through  $B_i$ , is subject to the following constraint, which should be used by domain  $AS_i$  as part of its admission control policy:

$$OSNR_{(\text{new})}^{x \rightarrow d} > O_{\text{Budget}}^{x \rightarrow d} \quad \forall x = \{B_i, \dots, D\} \quad (19)$$

where  $x$  represents each of the transit nodes along the sub-path between  $B_i$  and  $D$  (see Fig. 5). The term  $OSNR_{(\text{new})}^{x \rightarrow d}$  represents an estimation of the new state of the OSNRs for the optical signals at the output ports of node  $x$ , upon the set up of the lightpath between  $S$  and  $D$ .<sup>2</sup> And,  $O_{\text{Budget}}^{x \rightarrow d}$  is the budget required to reach the destinations  $d$  for the lightpaths traversing node  $x$ —this means that all the circuits through node  $x$  must have sufficient budget to reach their corresponding detection points. As mentioned above, the constraint in (19) should form part of the admission control phase in  $AS_i$ , and as such, it should be checked before even considering (17).

<sup>2</sup> $OSNR_{(\text{new})}^{x \rightarrow d}$  could be estimated beforehand, and could even be assessed only over the most critical lightpaths traversing node  $x$  (i.e., on those showing the most critical budget).

## IV. CONCLUSION

In this paper, we have developed a physical-layer impairment model that encompasses both linear and nonlinear impairments, including, attenuation, Amplified Spontaneous Emission (ASE), Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), node crosstalk, and one of the main crosstalk effects on fibers, namely, Four Wave Mixing (FWM). As far as our knowledge, the work started in this paper is the first attempt toward the development of a conciliatory model, capable of unifying the substantially different taxonomies and proposals offered in the literature.

Based on this, we have described an information exchange model between adjacent optical domains. Our proposal extends the budget-based approach introduced by Yang et al. in [8], and could be used by an inter-domain RWA protocol with the aim to enable optical bypass in the frontier between neighbor domains. Our information exchange strategy preserves the administrative limits of domains, in the sense that sensitive physical-layer information is never disclosed between carrier networks.

Many issues remain to be resolved, including:

- the integration of other physical-layer impairments;
- the design of impairment-aware RWA protocols in order to efficiently exploit these models in practice;
- the integration with admission control;
- and the challenge of optimizing the overall translucent set up of connections involving the two optical domains.

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