# Impact of Physical Layer Impairments on Optical Network Performance

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*Abstract* — **We theoretically estimate the on-line BER of a mesh and ring optical network, while taking into account the impact of crosstalk and amplifier noise generation along the signal propagation over assigned lightpaths.**

## I. INTRODUCTION

In a wavelength-routed optical network, any transmitted signal remains in the optical domain over the entire route (lightpath) assigned to it between its source and destination nodes. The optical signal may have to transverse a number of cross-connects switches (XCSs), fibre segments, and optical amplifiers (EDFAs). Thus, while propagating through the network, the signal may degrade in quality as it encounters crosstalk at the XCSs and also picks up amplified spontaneous emission (ASE) noise at the EDFAs. Since these impairments continue to degrade the signal quality as it progresses toward its destination, the received bit error rate (BER) at the destination node might become unacceptably high. Most previous work on the lightpath routing and wavelength assignment (RWA) problem assumed an ideal physical layer that causes no impairment to a transmitted signal [1]–[3].

In order to design efficient and low cost optical networks, the first step is the evaluation of physical impairments. Assuming signal power levels low enough, standard single-mode fibre links, and an appropriate channel spacing, fibre nonlinearities will have a minor impact on system performance. Under this assumption, the network scale will be primarily limited by node and link losses, chromatic dispersion, signal-to-noise ratio, filter concatenation, and crosstalk induced penalties. In our previous work [4], we have studied the impact of node and link losses, chromatic dispersion, and signal-to-noise ratio on the network size, assuming a linear transmission regime. Our goal was to obtain a maximum number of nodes the signal can pass through in order to keep the linear impairment penalties below 1 dB. However, the penalties associated to crosstalk are critical for the design of optical networks, since they impose limitation on the number of nodes, on the number of wavelengths in the network, and on the number of input/output ports in each node. The influence of crosstalk on these network parameters has been studied in long haul networks, both experimentally [5] and theoretically [6], [7].

In this paper, we are interested in evaluating network performance while taking into consideration the physical layer limitations. This will be used as part of the call admission phase in the control plane of the OMEGA (Optical Metro network for Emerging Gigabit Applications) test bed being assembled at CPqD Foundation [8], [9]. The model adopted here is based largely on that introduced by Ramamurthy et al. [10], which estimates the on-line BER on candidate routes and wavelengths before setting up a call. Note that the existence of other calls currently in progress, i.e., traffic variation, will affect the BER estimate (since they will affect the crosstalk in XCSs and the wavelength dependence and saturation of gains and ASE noise generation in EDFAs). For questions of computational efficiency, we only consider the impact of the crosstalk in XCSs and ASE noise generation in EDFAs along the signal propagation over the assigned lightpath. We are not considering the impact of chromatic dispersion when estimating the on-line BER. We believe that, for reasonably linear systems, this physical impairment can be adequately (but not optimally) compensated for on a per-link basis. Besides that, as the bit rate and node distances increase, dispersion compensation will not be optional but mandatory.

Since the BER on a lightpath would dynamically change with traffic variation (e.g., due the presence or absence of other co-propagating lightpaths), it is useful to test the on-line BER for each lightpath that is considered for a call request. Thus, RWA algorithms that consider such BER constraints are more pragmatic, and they may lead to more efficient network operation.

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## II. SIMULATION MODEL

### A. Network Architecture

A lightpath in a wavelength-routed network consists of a number of intermediate wavelength-routing nodes (WRN) between the source and destination nodes, interconnected by fibre segments. Fig. 1 presents a block diagram for a cross-connect switch (XCS). The WRN is composed by an XCS, a pair of EDFAs and optical power taps, on either side of the XCS at each port, for monitoring purposes. Each WRN also contains a transmitter array (Tx) and a receiver array (Rx), enabling add/drop of any of the wavelengths at any of the nodes. The WRNs are connected through single mode fibres that may employ in-line optical amplifiers for long-distance connectivity. Below, we describe the architecture of the XCS, and its representative loss and crosstalk models used in this work.

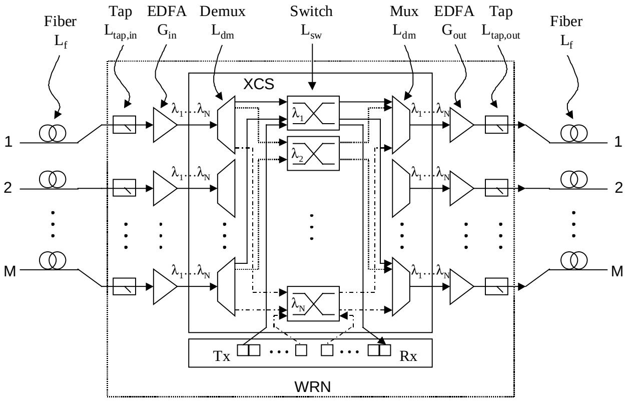


Fig. 1. Components and their loss/gain parameters in a wavelength routing node (WRN).

All the demultiplexed signals on a given wavelength, say $\lambda_1$, are directed to the same optical switch (WRS-$\lambda_1$). The switch routes the signal toward the desired output port. Finally, the multiplexers combine the optical signals on all wavelengths and pass them on to the desired output fibre. The number of optical switches in an XCS equals the number of incoming wavelengths, and each switch has at least M input/output ports, where M is the number of input/output fibres. Signals can interfere with one another when they co-propagate through the same switch, leading to crosstalk generation.

### B. Call Admission Procedure

Our approach to call admission is to establish a call on any lightpath with a BER lower than a certain threshold (e.g., $10^{-12}$); if no such lightpath is found, the call is blocked. In this approach, the BER of a candidate lightpath is computed during the admission phase of a call. Once the call has been set up in the network, its BER could vary slightly depending on the instantaneous traffic in the network – ignoring transient effects, the BER of an existing call in the network may increase slightly when a new call is established and it may decrease slightly when another ongoing call leaves the network. Transient effects, such as EDFA gain transients, are not considered in this paper.

The block diagram for the call admission is shown in Fig. 2. For each call request, the RWA algorithm begins looking for a free wavelength on an available route. The route is chosen according to a predetermined method, e.g., shortest-path routing. If there is no route from the source to the destination or if no wavelengths are free along a chosen route, the call is blocked (i.e., dropped).

If a free wavelength is available, the lightpath is identified and passed to the on-line BER evaluation. Then, the losses and gains in the network components traversed along the lightpath are determined, and the noise and crosstalk generated in the EDFAs and switches are computed. Finally, using the received signal, noise, and crosstalk powers at the destination, the BER model estimates the receiver BER. Thereafter, a decision is made to admit or block the call depending on whether the BER estimate exceeds the upper limit of BER.

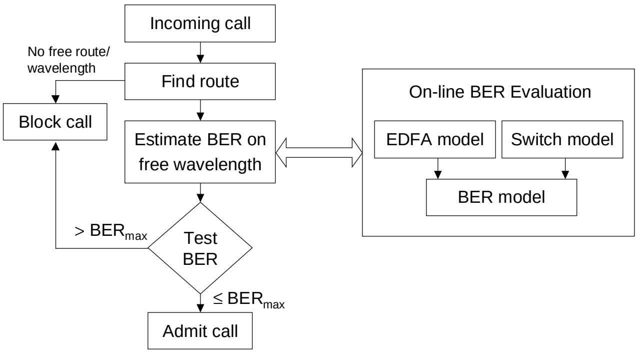


Fig. 2. Block diagram for the call admission.

### C. On-Line Ber Evaluation

The computation of received power levels along the lightpath, during call admission, requires (a) the enumeration of all the events of signal, crosstalk, and ASE noise generation, and (b) their subsequent losses and gains at each node along the lightpath. Consider that a lightpath is to be established on wavelength $\lambda_i$ between nodes 1 and N in a network. The outbound powers of the signal ($p_{sig}(k,\lambda_i)$), ASE noise ($p_{ase}(k,\lambda_i)$), and crosstalk ($p_{xt}(k,\lambda_i)$) at the output of the $k$th node on wavelength $\lambda_i$ can be obtained using the following recursive equations:

$$p_{sig}(k,\lambda_i) = p_{sig}(k-1,\lambda_i)L_f(k-1,k)L_{tap,in}G_{in}(k,\lambda_i)L_{dm}(k)L_{sw}(k)L_{mx}(k)G_{out}(k,\lambda_i)L_{tap,out} \tag{1}$$

$$\begin{aligned} p_{sig}(k,\lambda_i) = {} & p_{ase}(k-1,\lambda_i)L_f(k-1,k)L_{tap,in}G_{in}(k,\lambda_i)L_{dm}(k)L_{sw}(k)L_{mx}(k)G_{out}(k,\lambda_i)L_{tap,out} \\ & + 2n_{sp}[G_{in}(k,\lambda_i)-1]h\nu_i B_0 L_{dm}(k)L_{sw}(k)L_{mx}(k)G_{out}(k,\lambda_i)L_{tap,out} \\ & + 2n_{sp}[G_{out}(k,\lambda_i)-1]h\nu_i B_0 L_{tap,out} \end{aligned} \tag{2}$$

$$p_{xt}(k,\lambda_i) = p_{xt}(k-1,\lambda_i)L_f(k-1,k)L_{tap,in}G_{in}(k,\lambda_i)L_{dm}(k)L_{sw}(k)L_{mx}(k)G_{out}(k,\lambda_i)L_{tap,out} + \sum_{j=1}^{J_k} X_{sw}p_{in}(j,k,\lambda_i)L_{sw}(k)L_{mx}(k)G_{out}(k,\lambda_i)L_{tap,out} \tag{3}$$

where $p_{sig}(0,\lambda_i) = P_t$ is the signal input power at first node, $p_{ase}(0,\lambda_i) = p_{xt}(0,\lambda_i) = 0$, $B_0$ is the optical filter bandwidth, $h$ is Planck's constant, $\nu_i$ is the optical frequency at $\lambda_i$, and $n_{sp}$ represents the spontaneous emission factor for the EDFAs (which can be obtained from the EDFA's noise figure using $NF(dB) = 10.log\,(2n_{sp})$ ). In the above equations, in order to guarantee the correct calculations of the outbound powers of a given lightpath we must set $L_f(0, 1) = L_{tap,in} = G_{in}(1,\lambda_i) = L_{dm}(1) = 1$ for the first node ($k = 1$) and $L_{mx}(N) = G_{out}(N,\lambda_i) = L_{tap,in} = 1$ for the last node ($k = N$). The loss and gain variables for various network components used above (generically, $L_x(k)$ for losses, and $G_x(k,\lambda_i)$ for gains) are indicated in Fig. 2. Further, $p_{in}(j,k,\lambda_i)$ is the power of the $j$th co-propagating signal at the switch shared by the desired signal (i.e., the switch, WRS-$\lambda_i$, for wavelength $\lambda_i$) at the $k$th node contributing to a first-order homo-wavelength crosstalk (switch crosstalk ratio = $X_{sw}$) with $J_k$ being the total number of such crosstalk sources at the $k$th node, and is given by

$$p_{in}(j,k,\lambda_i) = p_{sig}(j,m-1,\lambda_i)L_f(m-1,k)G_{in}(k,\lambda_i)L_{dm}(k)L_{tap} \tag{4}$$

where $p_{sig}(j,m\text{-}1,\lambda_i)$ is the outbound powers of the $j$th co-propagating signal at the output of the $m$th-1 node on wavelength $\lambda_i$ and can be calculated using Eq. 1. The inclusion of the index $m$ is to take in account that the $k$th node of the lightpath under consideration is not necessarily the $k$th node of the $j$th co-propagating signal.

Note that the XCSs in a wavelength-routed network can generate two different types of crosstalk, viz., hetero-wavelength (interchannel) crosstalk in multiplexing and demultiplexing devices, and homo-wavelength (in-band) crosstalk in the space switches. In practice, the cumulative effect of homo-wavelength crosstalk causes the dominant impairment at the receiver as compared to its hetero-wavelength counterpart [11]. Therefore, we consider only the effect of homo-wavelength crosstalk. For simplicity, the EDFA gains, $G_{in}(k,\lambda_i)$ and $G_{out}(k,\lambda_i)$, for each node at all wavelength are assumed be equal and constant. We do not take in account physical phenomena in EDFAs, such as gain saturation and wavelength-dependent gain induced by traffic-dependent signal channels.

Once obtained the powers of the signal, crosstalk, and ASE noise at the destination node, one can compute the powers of the composite electrical noise for binary zero and one receptions, which include the receiver thermal and shot noise components and the electrical noise components resulting from the signal-crosstalk and signal-ASE beats (here we are considering that the ASE-ASE, crosstalk-ASE and crosstalk-crosstalk beats are negligible; however, the ASE-ASE beat can become important in a long cascade of EDFAs). The composite electrical powers and the received photocurrent are then used to evaluate the BER by using a Gaussian model for the receiver:

$$P_b = 0.25\left[ erfc\left( \frac{I_{s1} - D}{\sqrt{2}\sigma_1} \right) + erfc\left( \frac{D}{\sqrt{2}\sigma_0} \right) \right] \tag{5}$$

where $I_{s1} = R_\lambda\, 2p_{sig}(N,\lambda_i)$ is the signal component of the photocurrent for the bit 1, $R_\lambda$ is the responsivity of the photodetector. The noise variance of the data bit ($i$=1 or 0) being received is given by

$$\sigma_i^2 = \sigma_{sxi}^2 + \sigma_{sspi}^2 + \sigma_{shi}^2 + \sigma_{th}^2 \tag{6}$$

where the corresponding noise variances are given by

$$\sigma_{sxi}^2 = R_\lambda^2 b_i p_{sig}(N,\lambda_i) p_{xt}(N,\lambda_i) \qquad \textit{(signal-crosstalk beat)} \tag{7}$$

$$\sigma_{sspi}^2 = 4R_\lambda^2 b_i p_{sig}(N,\lambda_i) p_{ase}(N,\lambda_i) B_e / B_0 \qquad \textit{(signal-ASE beat)} \tag{8}$$

$$\sigma_{shi}^2 = 2qR_\lambda (b_i p_{sig}(N,\lambda_i) + p_{xt}(N,\lambda_i) + p_{ase}(N,\lambda_i)) B_e \qquad \textit{(shot)} \tag{9}$$

$$\sigma_{th}^2 = \eta_{th} B_e \qquad \textit{(thermal)} \tag{10}$$

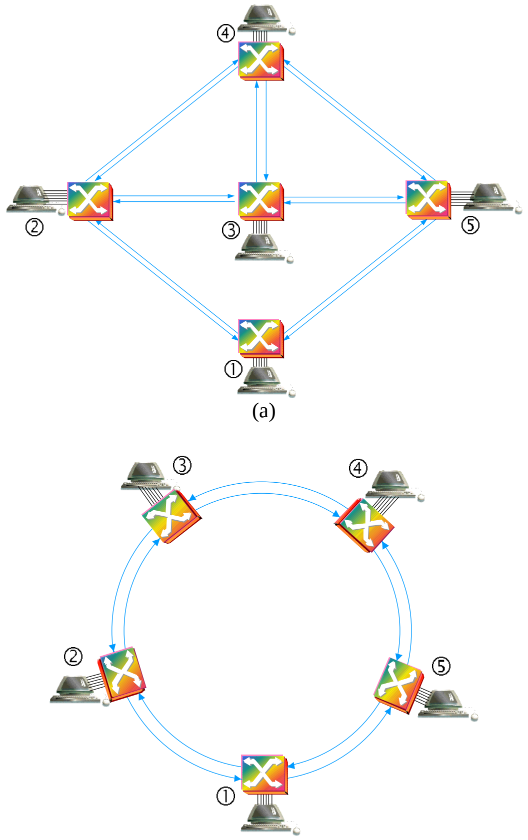
where $b_i = 2$ or 0 for $i = 1$ or 0, respectively, $B_0$ and $B_e$ represent the optical and electrical bandwidths of the receiver, and $\eta_{th}$ is the spectral density of the thermal noise current in the optical receiver. The receiver BER is evaluated with a given decision threshold choice, $D$. Assuming a perfect laser extinction (i.e., $b_0 = 0$, and hence $I_{s0} = 0$), we fix the receiver threshold $D$ at $I_{s1}/2$.

## III. NUMERICAL RESULTS

In this section, we show a comparative study of two different network topologies: mesh and ring. The main goal is present some examples of our simulation experiments employing the models of physical-layer phenomena and their impact on the blocking performance of networks. The mesh topology is our WRON test-bed (OMEGA-Crux) while the ring topology consists of 5 nodes connected by a pair of fibres (one in each direction) in a ring configuration. Fig. 3 shows the diagrams of both topologies used in our simulation.

For both topologies, we simulate three configurations: one that includes an EDFA located only in each input port of the node, other that includes two EDFAs – one in each input/output ports of the node, and a last one that includes an EDFA located only in each output port of the node. In Table I, we present the system/device parameters used in the simulations. Note that we have assumed conservative data for gain and insertion losses.

The dynamic performance of the network under several conditions was obtained (Fig. 4 and 5). In all cases, we assume the following: independent Poisson call arrivals for each node, exponential call holding time, uniform distribution of destinations for the calls in each node, and shortest-path routing of lightpaths. The BER threshold was set to $10^{-12}$, and forty thousand call requests for each node were simulated. We employ a wavelength-assignment algorithm called Least-Loaded algorithm where the first available wavelength in the least-loaded route among all shortest-path routes is chosen [12].



(a)

(b)

Fig. 3. Diagram of the mesh (a) and the ring (b) topology used in simulations.

From the results shown in Fig. 4 and 5, we observe that the blocking performances for both topologies (ring and mesh) are quite similar, being the ring network case slightly worst. This occurs because the ring network is less connected than the mesh network. We also note that when the switch crosstalk is increased to $X_{sw}$ = 25 dB, blocking in the network increases because of increased BER.

With regard to the EDFA positions at the network, we can observe that the blocking performance for the cases of EDFA only at the input port and at the input/output ports with $X_{sw}$ = 30 dB is practically the same to that for the ideal case, when BER constraints are ignored altogether. However, for the case of EDFA only at the output port, the blocking performance increases because the accumulation of ASE causes a more severe degradation in the signal-to-noise ratio (SNR) due to the low input power at the EDFA. The inclusion of EDFAs in the input ports of the nodes improves the SNR and consequently decreases the bit error rate.

TABLE I

SYSTEM PARAMETER AND THEIR VALUES USED IN THE SIMULATIONS

| **Parameter** | **Value** |
|---|---|
| Maximum number of wavelengths | 8 |
| Channel spacing | 200 GHz |
| Bit rate per channel (r) | 2.5 Gb/s |
| Electronic bandwidth ($B_e$) | 0.7r |
| RMS thermal noise current Spectral density ($\eta_{th}$) | $2.8 \times 10^{-23}$ $A^2$/Hz |
| Fibre loss ($L_f$) | 0.25 dB/km |
| Signal input power ($P_t$) | +5.5 dBm (EDFA only in input port)<br>–4.5 dBm (EDFA in both input and output port)<br>–14.5 dBm (EDFA only in output port) |
| Input EDFA gain ($G_{in}$) | 20 dB (EDFA only in input port)<br>10 dB (EDFA in both input and output port)<br>0 dB (EDFA only in output port) |
| Output EDFA gain ($G_{out}$) | 0 dB (EDFA only in input port)<br>10 dB (EDFA in both input and output port)<br>20 dB (EDFA only in output port) |
| EDFA noise figure | 6 dB |
| Demultiplexer loss ($L_{mx}$) | 2.5 dB |
| Multiplexer loss ($L_{mx}$) | 2.5 dB |
| Switch loss ($L_{sw}$) | 10 dB |
| Input tap loss ($L_{tap,in}$) | 0 dB |
| Output tap loss ($L_{tap,out}$) | 0 dB |
| Switch crosstalk ratio ($X_{sw}$) | 25 dB, 30 dB |
| Optical filter bandwidth ($B_0$) | 0.8 nm |
| Internode distance ($L_f$) | 20 km |
| BER threshold | $1 \times 10^{-12}$ |

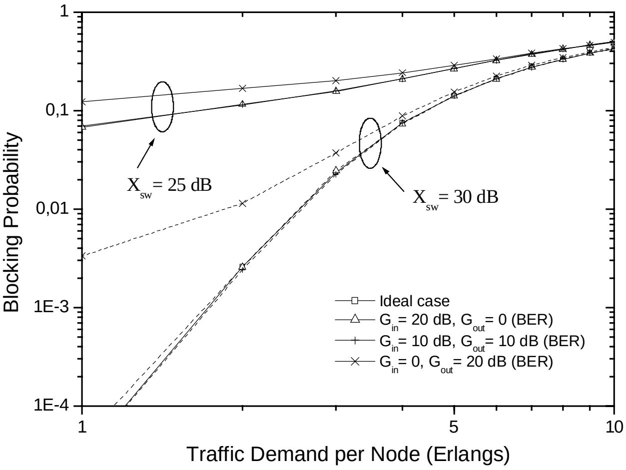


Fig. 4. Blocking probability versus traffic demand for the mesh network.

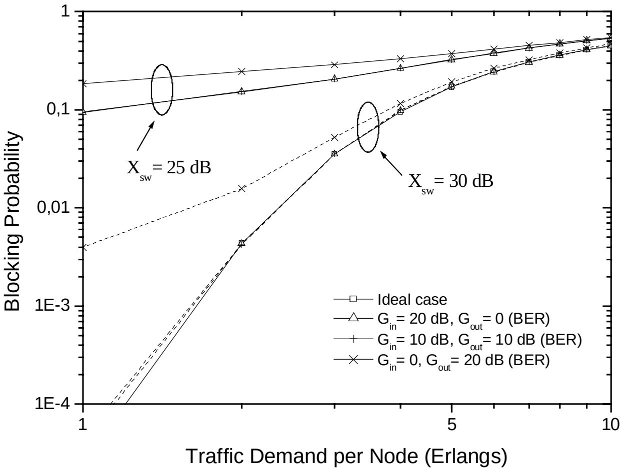


Fig. 5. Blocking probability versus traffic demand for the ring network.

## IV. CONCLUSIONS

This work investigated the impact of transmission impairments on the blocking performance of wavelength-routed optical networks. We compared three possible network configurations with respect the EDFA position in each node and concluded that using the EDFA only at the output port causes an increase in the blocking performance of the network. Although this is an initial investigation, it indicates that employing BER-based call-admission algorithms has a significant impact on the performance of realistic wavelength-routed optical network

## ACKNOWLEGMENTS

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