Impact of linear transmission impairments on a metropolitan optical network scale

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ABSTRACT

Possible Metropolitan Area Networks (MAN) length scales and node spacing are analyzed considering standard single mode fiber linear impairments. This is accomplished by the evaluation of loss budget, dispersion and amplifier noise-induced penalties through simple analytical expressions. Dispersion-induced penalties are the main limitations to the network scalability. Strategies for planning the scale of cost-effective MANs, in terms of transparency length and number of nodes, are presented.

1. INTRODUCTION

The multiplicity of services and protocols in the metropolitan area networks requires a transport technology which can accommodate all these traffic types. All optical networks, operating with WDM technology, appear to be an appropriate choice for this application, considering the possibility of having network transparency, configurability and scalability [1].

In order to design efficient and low cost optical MANs, the first step is the evaluation of physical impairments. Assuming signal power levels low enough, standard single-mode fiber links, and an appropriate channel spacing, fiber 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. Our present goal is to discuss some restrictions imposed by the first three impairments above.

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 [2] and theoretically [3],[4].

The scalability of a network can be defined with respect to the capacity (number of wavelength channels, bit rate per wavelength and number of input/output ports per node) [1],[5], and to the network size (number of node and node separation) [6]. In this paper, we study the impact of node and link losses, chromatic dispersion, and signal-to-noise ratio, in a linear transmission regime, on the network size. Given a node separation, our goal is to obtain a maximum number of nodes the signal can pass through, in order to keep the linear impairment penalties below 1 dB.

The scalability of the network in terms of its size depends on the bit rate and number of wavelength channels. The analysis presented here takes into account three bit rates and a single channel in the optical network. In this first paper we will not consider multichannel effects, such as amplifier gain spectrum profile, noise variation with wavelength [6], dispersion slope, and spectral clipping due to filter concatenation [7].

This paper is organized as follows. Section 2 contains a description of an optical MAN node, able to operate at multiple wavelengths and to provide some management functions for circuit switching connections. It also presents some typical values for the devices, necessary for our analysis. Section 3 presents the network loss budget and evaluates the maximum node distance limited by device losses and EDFA gain. Section 4 analyzes the signal to noise ratio. In Section 5 the dispersion penalty is analyzed for both direct and external modulations. Finally, a summary of this study is presented in Section 6.

2. NODE DESCRIPTION

One of the main objectives of our work is to discuss the restrictions imposed by physical impairments and to point out strategies for planning cost-effective MANs. In order to achieve such a goal, we plan to assembly a five-node mesh network test bed. Figure 1 illustrates the basic configurable transversal all-optical node considered in this project. It consists of three optical wavelength demultiplexers, which receive up to 8 WDM channels from three fiber links. Each demultiplexer is connected to eight 4 x 4 thermal-optical switches, which are responsible for establishing circuit-based connections.

The fourth input/output port of every switch is dedicated for adding/dropping data to/from the network. The remaining three output ports of each switch are connected to three optical multiplexers. Signals that emerge from the multiplexers are amplified by an EDFA, before being sent to the fiber link. Optionally, a pre-amplifier may be placed at the input of each node.

The switches are computer-controlled in order to configure the nodes with a dynamical wavelength switching operation. This way, any wavelength in a given input port can be switched to any output port. However, when these nodes are inserted into a network, the availability of free output ports will depend on traffic demand. A proper management algorithm must control this situation.

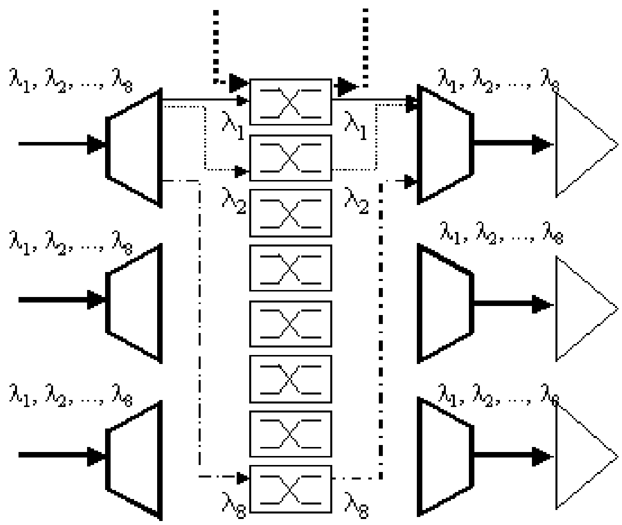

Figure 1. Node (optical crossconnect with add/drop) configuration. For clearness, only connections from/ to the first switch are illustrated.

Table 1 lists typical characteristics for each element assembled in the optical node, necessary for the discussions in the next sections.

Table 1. Typical characteristics of the node devices.

Optical Device	**(dB)**
Demux loss, $Loss_{demux}$	3
Switch loss, $Loss_{sw}$	8
Mux loss, $Loss_{mux}$	3
Connector loss, $Loss_{con}$	0.5
EDFA gain, G_{EDFA}	15 to 25

3. LOSS BUDGET

A signal is inserted in the network and collected after N hops. Assuming that all links are equally spaced by l km, the total power loss is given by:

$$Loss_{out} = N\left(Loss_{demux} + Loss_{mux} - G_{EDFA} + a\,l\right) + (N+1)Loss_{sw} + (8N+2)Loss_{con} \tag{1}$$

where α is the fiber loss expressed in dB/ km, $Loss_{demux}$, $Loss_{sw}$, $Loss_{mux}$, and $Loss_{con}$ represent, respectively, the average loss given by the demultiplexers, switches, multiplexers, and connectors at each connection. G_{EDFA} is the Erbium Doped Fiber Amplifier gain. All losses and gains are expressed in dB.

Figure 2 illustrates the dependence between $Loss_{out}$ and N, for different link lengths (losses of the devices are listed in Table I). Three values of G_{EDFA} (15, 20 e 25 dB) were chosen to show its influence on $Loss_{out}$.

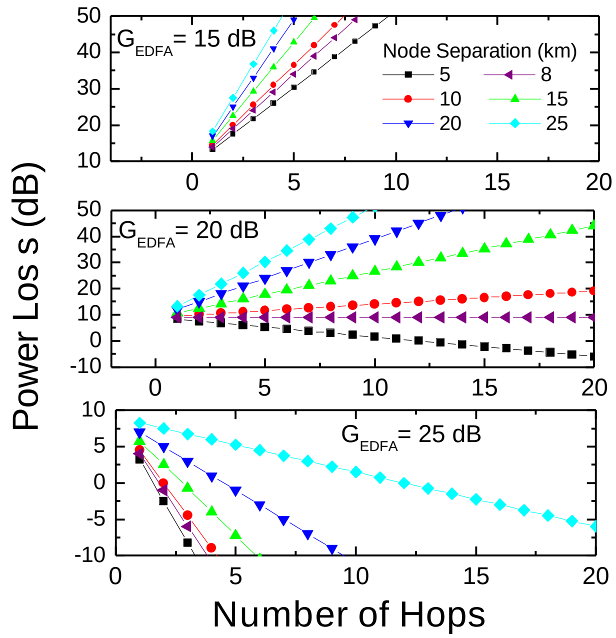

Figure 2. Loss budget as a function of the number of hops, for a node separation from l = 5 to l = 25 km. Each set of curves is plotted for G_{EDFA} = 15, 20, and 25 dB.

It is clear that, for a given detector sensitivity, the power loss limits the maximum number of hops. For each EDFA gain, there is a fiber length at which the output optical power is constant, independently of the number of hops, as illustrated for the case G_{EDFA} = 20 dB . Such a length is achieved for an EDFA gain that exactly compensates the node and link losses, and is called *transparency length* [2], where

$$G_{EDFA} = \sum_{i=1}^{\substack{Number\ of \\ Devices}} Loss_i + a\,l\,. \qquad (2)$$

The summation in (2) is extended to all node devices and connections pointed out in (1).

In this situation, the residual optical loss corresponds to the loss necessary to insert and to drop out the signal of the network. This can be easily verified in (1) and occurs because the EDFA does not compensate the loss imposed to the signal that enters the network through the switch.

The main advantage of working on the transparency length is that the optical output power is the same, irrespective to how far the node that sent information is. Also, reasonable launched optical powers will not be limited by the detector sensitivity.

Figure 3 illustrates this situation for the devices listed in Table I. A residual power loss of 9 dB is due to one switch and two connectors, used to insert and to drop out the signal.

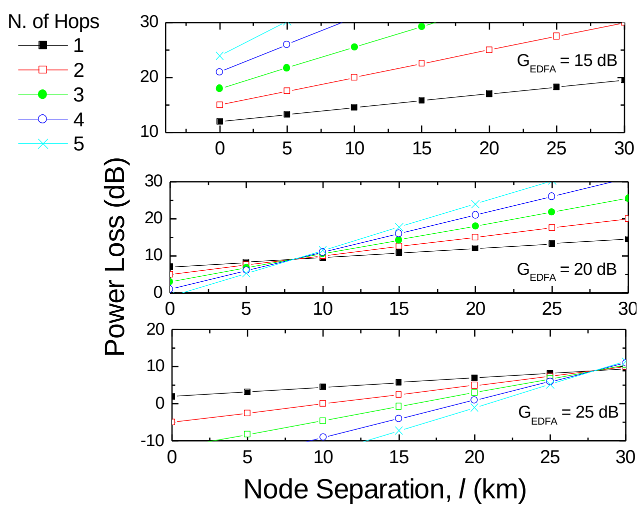

Figure 3. Power loss as a function of the node separation, for the number of hops, N, from 1 to 5.

Finally, assuming a loss per node equal to (G- $Loss_{Node}$), where

$$Loss_{Node} = \\ Loss_{demux} + Loss_{mux} + 8\,Loss_{con} + Loss_{sw} \qquad (3)$$

the maximum node separation will be determined by the detector sensitivity. Figure 4 presents such a separation, for an input power of 4 dBm, and typical sensitivities for 2.5, 10, and 40 Gbits/s. The node separation ranges from l = 5 to l = 25 km.

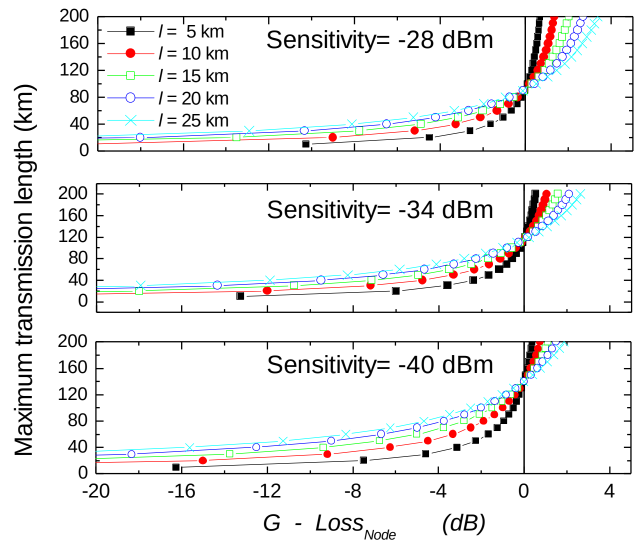

Figure 4. Maximum transmission length, L, limited by the node loss and the detector sensitivity. Input power P_{in} = 0 dBm.

For simplicity, the next sections will treat the case in which the nodes are equally spaced. However, it is interesting to note that one can operate in the transparency length condition even if the distance between nodes is not constant. For this sake, it is only necessary to adjust G_{EDFA} in a way to compensate for the respective link loss:

$$G_{EDFA,i} = \sum_{i=1}^{\substack{Number\ of \\ Devices}} Loss_i + a\ l_k \qquad (4)$$

where k stands for the k-th network link.

4. AMPLIFIER NOISE PENALTY

The penalty induced by amplifiers is dependent on their configuration at the nodes. In a first approach, each node may have only one EDFA, preceding the transmission fiber until the next node. A more complex configuration includes two EDFAs: one at the output, referred to as post-amplifier, and the other at the input of the node, known as pre-amplifier. In the transparency length, penalties for these configurations can be adapted from the expression indicated in [10] and are given by:

$$PEN_{POS} = 10\log\left[\frac{1}{1 - k_a Q_0^2 (m-1) P_{out}^{-1}}\right], \qquad (5)$$

$$PEN_{POS/PRE} = 10\log\left[\frac{1}{1-k_a Q_0^2 m(1+Loss_{Fiber}^{Linear} G_{EDFA}^{Linear})Loss_{Node}^{Linear} P_{out}^{-1}}\right], \quad (6)$$

where PEN_{pos} and $PEN_{pos/pre}$ are the power penalties for, respectively, the single and double amplifier configurations, m is the number of nodes, Q_0 is the Q parameter for a given BER, P_{out} is the output power, $Loss_{Fiber}^{Linear}$, $Loss_{Node}^{Linear}$ are, respectively, the linear losses (gains) at each fiber link and at the last node, and G_{EDFA}^{Linear} is the amplifier gain, assumed to be the same in pre- and post-amplifiers. The constant k_a is given by $k_a = 4n_{sp} hn B_e$, where n_{sp} is the population inversion parameter of the amplifier, h is the Planck constant, n is the light frequency, and B_e is the bandwidth of the electrical filter at the reception. It is assumed that post- and pre-amplifiers have the same gain.

Figure 5 plots the noise-induced penalty as a function of the maximum node separation. It is assumed that the total gain is the same for both configurations: without pre-amplifier and with post- and pre-amplifiers. A maximum tolerable BER= 10^{-9} (Q_0= 6) is adopted. This figure shows that for a penalty of 1dB, the amplifier noise degradation is relevant only when the pre-amplifier is not used. Even in this case, a reasonably large MAN, with length scales up to 150 km, will be limited by noise only if bit rates are comparable to or greater than 10 Gb/s.

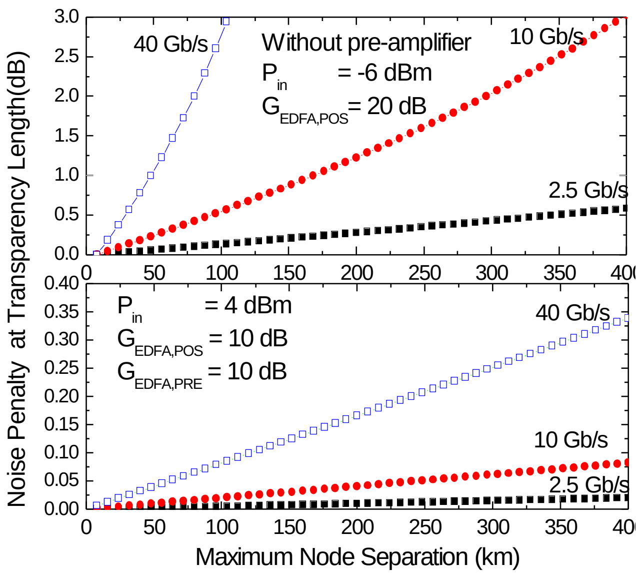

Figure 5. Noise induced penalty as a function of maximum node separation at a transparency length (node spacing) of 8 km.

5. DISPERSION PENALTY

The distortion caused by chromatic dispersion is one of the linear data degradations to be considered when designing transparent optical networks with large number of nodes – as it is the case in MANs. Modern transmission fibers offer a possible strategy to overcome the limitations imposed by dispersion in the most world wide installed fiber, i.e. the single-mode standard, STD, or conventional fiber. However, their higher cost may inhibit their implantation in a metropolitan environment. Also driven by the metro cost requirements, the use of high-bit rate directly modulated transmitters may impose severe dispersion penalties, made worse by the spectral broadening due to the frequency chirp originated from direct modulation, even in relatively short distances. Depending on the bit rate, the inclusion of external modulators may be necessary and, to further extend the transmission distance, some dispersion compensation technique must be indicated. Therefore, for a given fiber type and modulation technique, it is important to establish some criteria based on the maximum number of nodes (or transmission distance) for each option.

Although it is interesting to consider the use of dispersion compensation as a mean to extend the transmission limits, due to economic factors, it is not a better approach for a MAN, where the ideal option is to employ direct modulation schemes [1]. Adding to the high price of dispersion compensation modules, one must keep in mind that their use will alter the results of the previous analysis presented in this paper since the most typically used compensator, the dispersion compensation fiber, DCF, exhibits a high insertion loss. Modern long haul optical networks tend to adopt a solution that solves that problem by employing erbium-doped fiber amplifiers with two stages, separated by a mid-stage. Such a scheme provides a low noise figure amplifier in a way that the DCF, placed at the mid-stage, configures a nearly lossless compensator [2]. An alternative approach is the use of Raman amplification within the DCF, equally leading to a lossless, or even amplifier, compensator [3]. Unfortunately, both technical solutions do not follow the low cost criteria, imperative in metropolitan networks. Therefore, the dispersion analysis should follow a step-by-step choice, starting from the cheapest one. Assuming propagation through a STD fiber, at first we must find a maximum distance and bit rate for employing direct modulation. Beyond that, with external modulation, the problem will be to find the maximum distance before adopting the use of DCF modules.

Although precise calculation of the penalty due to dispersion would require computer simulation, good estimations can be obtained if we consider that pulse spreading should not exceed a fraction *e* of the bit period. Following this assumption, transmission with external and direct modulations are respectively limited by [4]:

$$|D| L B(\Delta l) < e \qquad (6)$$

$$B l \sqrt{|D| \frac{L}{2 p c}} < e \qquad (7)$$

In the preceding equations, D stands for the fiber chromatic dispersion at the operating wavelength l, L is the fiber length (or the sum of several shorter fibers of length l), B is the bit rate, Δl is the spectral width of the transmitted signal, and c is the speed of light.

The dependence between e and chromatic dispersion induced penalty, PEN_{CD}, is indicated in literature [11] for some given penalties and can be approximated, through a fitting, by:

$$e \cong 0.3665\, PEN_{CD} - 0.0605\, PEN_{CD}^{2} . \qquad (6)$$

Taking this into account, Figures 6 and 7 show the chromatic dispersion penalty as a function of a STD fiber length, respectively, for direct and external modulations. They highlight a strong dependence on the maximum transmission distance and the bit transfer rates.

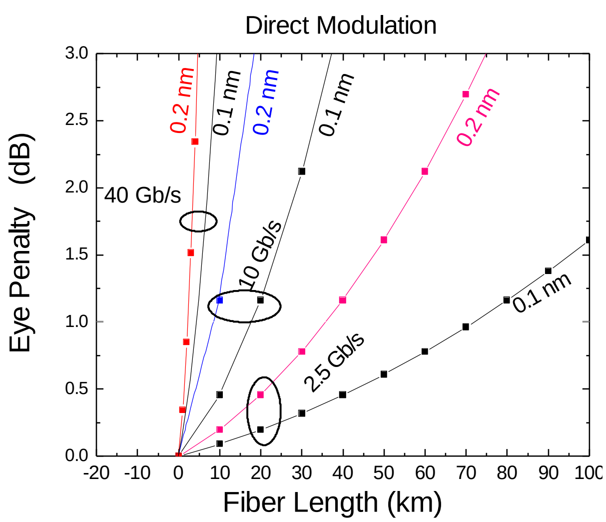

Figure 6. Chromatic dispersion induced penalty as a function of the maximum transmission distance, in a direct modulation transmission, where 0.1 nm and 0.2 nm are the spectral widths of the transmitted signal.

Since typical MAN lengths scale up to 100 ~ 200 km, for a maximum tolerable penalty of 1 dB, even 2.5 Gb/s networks will be limited by dispersion in systems with direct modulation.

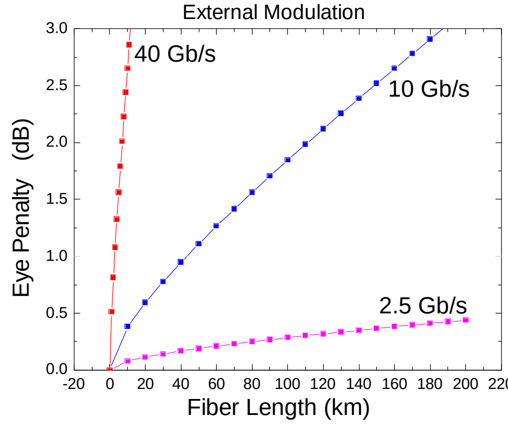

Figure 7. Chromatic dispersion induced penalty as a function of the maximum transmission length, for an external modulation transmission

Considering external modulation, dispersion will not severely affect the network performance for 2.5 Gb/s rates. However, in a 10 Gb/s MAN, without a dispersion compensation, the distance is limited to ~ 40 km.

Future networks, operating at 40 Gb/s, are the most susceptible ones to dispersion penalty limitations. At this rate, dispersion compensation should occur in distances inferior to 5 km, unless a different modulation format is used.

6. SUMMARY

The impact on a metropolitan optical network size, caused by node and link losses, signal-to-noise ratio, and chromatic dispersion, has been evaluated. Although the main concepts used here have been established a long ago, it is important to have them organized under the perspective of a WDM metropolitan network. In this scenario, cost is a significant aspect since it is shared by a smaller customer base, in comparison to a long-haul network. With the present study, we have proposed a methodology for scaling a network operating in a linear regime and employing lower-cost technologies such as standard singlemode fibers, directly modulated lasers, nodes without optical pre-amplifiers, and reduced need for regeneration. It starts with a power budget analysis, from which the transparency length can be inferred, followed by an optical noise study, performed by using two adapted expressions that includes two EDFAs per node: the post- and pre-amplifiers. To conclude, the dispersion effects evaluation establishes the final network scale.

To illustrate such a method, we based our analysis on a configurable transversal all-optical node, equipped with typical and low-cost optical components. Based on their insertion loss characteristics, a transparency length of 8 km (@ G_{EDFA} = 20 dB) has been determined. For such a node separation, the maximum number of nodes a signal can pass through, in order to keep the linear impairment penalties below 1 dB, has been found as a function of the bit rate, the optical amplifier noise accumulation (with and without pre-amplifier at each node), and the dispersion for two modulation schemes, i.e., direct or external. Table 2 summarizes the results of the analyzed example.

Table 2. Maximum transmission distance and number of nodes limited by dispersion, as a function of bit rate, modulation scheme, amplifier noise penalty, and transparency length.

Bit Rate (Gb/s)	Noise limited distance (km) / **Number of Nodes***		Dispersion limited distance (km) / **Number of Nodes***		
	No Pre-amplifier	Pre-amplifier	Direct modulation		External modulation
			$\Delta\lambda$=0.1nm	$\Delta\lambda$=0.2nm	
2.5	**	**	72 / **10**	36 / **5**	**
10	170 / **22**	**	16 / **3**	8 / **2**	42 / **6**
40	50 / **7**	**	4 / ***	2 / ***	4 / ***

* For a transparency length (node spacing) of **8 km**.
** Length scale beyond a MAN scope.
*** Dispersion compensation is required.

As expected, the results indicate that dispersion-induced penalties are the main linear limitations to the network scalability. A strategy to overcome these limitations and to design a cost-effective MAN must establish a tradeoff between routed wavelength architectures and those physical impairments.

In further studies we intend to perform a similar analysis that will consider nodes arbitrarily spaced, i.e. operating out of the transparency length. Moreover, they must include other important impairments, such as crosstalk, amplifier gain tilt, filter concatenation, and fiber nonlinearities (the later depending on the power level and channel spacing).

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