Modeling of Penalties on Chains of Optical Amplifiers with Equalizing Filters

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***Abstract*—A mathematical model for the calculation of optical signal-to-noise ratio (SNR) on cascades of erbium doped fiber amplifiers (EDFA's) with interposed equalizing filters in the fiber spans is presented. The model enables to simulate different types of cascade, whether the filters are placed after each amplifier or after any group of amplifiers. Criteria for the design of the optimal filter are presented for a typical configuration. The relation between preemphasis and penalty on SNR is studied, and for the first time to our knowledge it is shown that some asymmetry may arise when using in line optical filters. A study of the sensitivity of penalty at receiver toward preemphasis at transmitter based on the model is presented.**

***Index Terms*—Amplifiers, equalizers, erbium, filters, optical amplifiers, optical propagation, optical repeaters, wavelength-division multiplexing (WDM).**

I. Introduction

In recent years erbium-doped fiber amplifiers (EDFA's) have played an increasing role in telecommunications, for applications in wavelength-division multiplexing (WDM) systems. The problem of self filtering, which arises when chaining a great number of amplifiers, is especially important for the design of long-haul links such as submarine systems: to overcome the reduction of the available optical bandwidth, or of the total number of transmittable optical channels, many solutions have been suggested. As preemphasizing the power of transmitted optical channels must be limited to reduce consequent penalty on signal-to-noise ratio (SNR) at receiver [1], different approaches have been proposed. Some works focus on the variation of gain flatness versus inversion level of the EDFA's [2], by alternating high inversion and moderate inversion amplifiers; many works focus on the design of the doped fiber [3], [4]. Passive equalizing components from different technologies have been introduced and studied, based either on doped [5] or on grating fiber [6]; their performance in a chain of amplifiers [7], [8] is also described. Formulas to calculate optical SNR in WDM systems have also been given in [9] and [10]. Our purpose here is to introduce a mathematical formalism to describe the presence of equalizing filters in WDM EDFA's chains through a closed form matrix which, given the characteristics of the amplifiers and filters at the channel wavelengths, completely describes (by means of its eigenvectors and eigenvalues) both the power preemphasis at the transmitter and the SNR penalty at the receiver. It has been shown [1] that the equalized optical SNR at the output of a chain of erbium-doped amplifiers can be derived from the following eigenvalue/eigenvector problem:

$$\Gamma P = \frac{\mathrm{SNR}_o}{\mathrm{SNR}_e} P \tag{1}$$

where SNR_e is the equalized signal to noise ratio at the output of the link, SNRo is the signal to noise ratio at the output of the link assuming all amplifiers have ideally flat gain shapes, the ratio SNRo/SNRe is the penalty, P is an eigenvector containing the power of each channel injected into the line, and Γ is a square matrix defined as follows:

$$\Gamma_{c,\,q} = \frac{1}{N_a N_p} \sum_{k=1}^{Na} (\frac{g_q}{g_c})^{k-1} c, \quad q = 1, \ldots, p \tag{2}$$

$$g_i = \alpha\, G_i$$

with

- N_a number of amplifiers in the link;
- N_p total number of transmitted channels;
- G_i gain of the ith channel;
- α attenuation of fiber spans.

Notation (1) has been introduced [1] for links where all amplifiers have the same gain versus wavelength, and the span attenuation is the same along the whole link. We would like to show how that same notation can be used also in a more generalized way, that is in the case of links where blocks of amplifiers can have different gain shapes, and also some filters are regularly interposed between groups of amplifiers. Penalty and preemphasis can still be calculated from an eigenvalue/eigenvector problem: matrix Γ in (2) is defined according to link type.

II. Two Groups of Amplifiers

First, we would like to focus on the problem of a link which is based on two different types of amplifiers: a first block of N_1 amplifiers with gain of the ith channel G_i^1, followed by a second block of N_2 amplifiers with gain of the ith channel G_i^2. The schematic of the link is described in Fig. 1. The assumption on amplifiers both of first and of second block is that their total output power is automatically controlled and held constant at the total value P_o. The attenuation of all spans between any two consecutive amplifiers is α; any possible spectral dependency of the attenuation $\alpha(\lambda)$ can be included in (2).

The output SNR for channel c will be

$$\mathrm{SNR}_C = \frac{\alpha P_o}{N_F F N_p (N_1 + N_2)}$$

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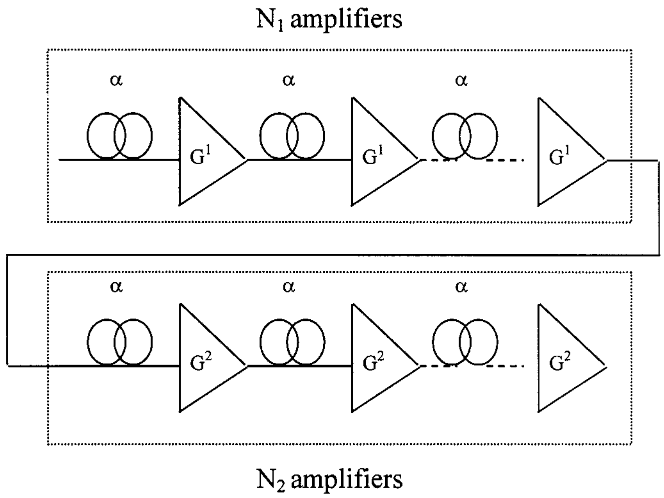


Fig. 1. Cascade of two groups of amplifiers.

$$\cdot \frac{P_c^{\text{in}}}{[(\frac{N_1}{N_1+N_2}\Gamma^1 + \frac{N_2}{N_1+N_2}\Gamma^{2'})P^{\text{in}}]_c} \tag{3}$$

where

N_F	noise figure of the optical amplifiers;
F	$h\nu_c B$ (B: resolution bandwidth);
N_p	total number of transmitted channels;
P^{in}	(N_px1): power of the Np channels into the link;
α	attenuation of each span;
P_o	total ouput power of each amplifier;
N_1	number of amplifiers in the first group;
N_2	number of amplifiers in the second group;
$[..]_c$	component c of vector.

The matrix Γ^1 in (3) is the same as in (2), and is related to the first block of N_1 amplifiers

$$\Gamma^1_{\text{c,q}} = \frac{1}{N_1 N_p} \sum_{k=1}^{N1} \left(\frac{g_q^1}{g_c^1}\right)^{k-1}. \tag{4}$$

The matrix $\Gamma^{2'}$ is related to the second block of N_2 amplifiers, and is defined as

$$\Gamma^{2'}_{c,q} = \frac{1}{N_2 N_p} \left(\frac{g_q^1}{g_c^1}\right)^{N_1} \sum_{k=1}^{N2} \left(\frac{g_q^2}{g_c^2}\right)^{k-1} \tag{5}$$

$g_i^{1,2} = \alpha G i^{1,2}$.

Matrix $\Gamma^{2'}$ is obtained from the same general expression (2), but with an additional multiplying factor which takes into account the presence before the second block of one group of amplifiers with different gain shape (first block). It is worth noticing that the SNR for a chain of $N_1 + N_2$ ideally flat amplifiers is first term in (3)

$$\text{SNR}_o = \frac{\alpha P_o}{N_F F N_P (N_1 + N_2)}$$

The problem of determining the equalized SNR_e at the output of this type of link, the related penalty and the preemphasis of the launched channel powers can be solved by means of the eigenvalues and eigenvectors of the new system matrix

$$\Gamma^{2\text{ groups}} = \frac{N_1}{N_1+N_2}\Gamma^1 + \frac{N_2}{N_1+N_2}\Gamma^{2'} \tag{6}$$

where matrices $\Gamma^{2'}$ and Γ^1 are weighted according to the number of amplifiers they represent. Matrix $\Gamma^{2\text{groups}}$ in (6) can be generalized to represent any cascade of more than two groups of amplifiers, but an even more general definition is possible, to take into account the introduction of in line equalization filters, whose purpose is to compensate for possible mismatches in the different gain shapes of the various groups of amplifiers.

III. In Line Equalization Filters

We focus on the problem of the chain shown in Fig. 2, where one first group of N_1 amplifiers is followed by a fiber span which besides the fiber contains one compensating filtering unit, then followed by a second group of N_2 amplifiers. The length of the fiber span where the filter is allocated can be reduced to compensate for the additional attenuation of the filter itself, generally calculated from the spectral transfer function as the minimum insertion loss plus half the contrast; this length compensation is typical for real links, as the erbium doped amplifier gain shape does vary when the total input power is changed. By ensuring the same total optical power injected into an amplifer, we guarantee at first order the same type of gain shape versus wavelength. In the calculations shown here the gain of each amplifier G is allowed to be multiplied by a factor γ, which can vary according to the specific amplifier, and is needed to obtain for every amplifier a total output power equal to a constant P_o, as in [1]. The effective spectral gain of an amplifier will be then $\gamma\, G$. The attenuation α' of the span containing the filter will appear in the calculation. So the expression for SNR at the output of the line in Fig. 1 is of the same type (6) as the one previously obtained for two groups of amplifiers without filter in between, that is

$$\text{SNR}_c = \frac{P_c^{\text{in}} \alpha P_o}{F N_F N_p (N_1 + N_2)} \bullet \frac{1}{\left\{\left[\frac{N_1}{N_1+N_2}\Gamma^1 + \frac{N_2}{N_1+N_2}\Gamma^{2\prime}\right] P^{\text{in}}\right\}_c}. \tag{7}$$

The difference between (7) and (6) is the definition of matrix $\Gamma^{2'}$:

$$\Gamma^{2'}{}_{cq} = \frac{1}{N_2 N_p} \left[\left(\frac{g_q^1}{g_c^1}\right)^{N_1} \frac{L_q}{L_c}\right] \left[\sum_{k=2}^{N_2} \left(\frac{g_q^2}{g_c^2}\right)^{k-1} + \frac{\alpha}{\alpha'}\right] \tag{8}$$

where L_i is the filter linear insertion loss for the ith channel. The effect of placing a filter before the second block of amplifiers is thus to have as a new multiplication factor the ratio of insertion losses of channels c and q for the calculation of element $(c,\, q)$ of the block matrix. The maximum eigenvalue of matrix $\Gamma^{2\prime}$ represents the SNR penalty with respect to a link where all amplifiers have flat spectral gain, and all fiber spans have the same nominal attenuation α.

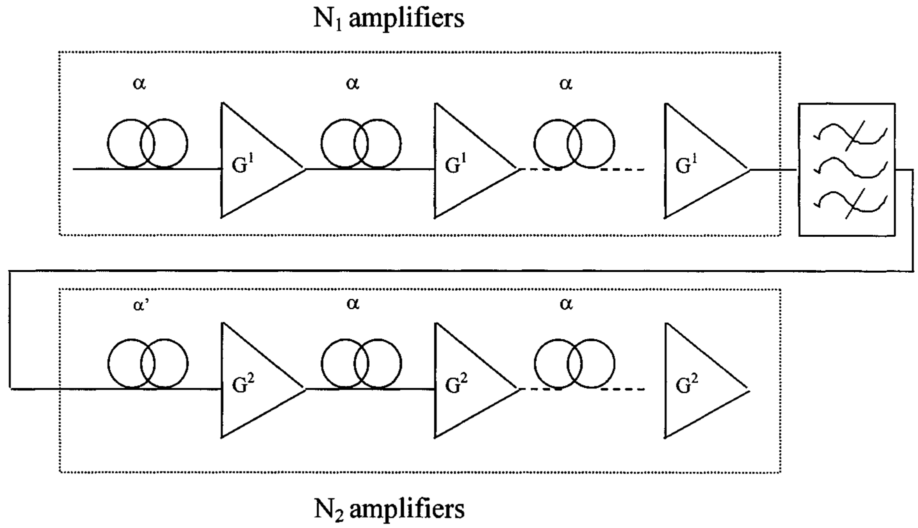


Fig. 2. Cascade of two groups of amplifiers with equalizing filter.

IV. Generalization

The next step is to generalize expression (8) for a chain of N_g groups of amplifiers, where each group is made of amplifiers with the same gain shape, but different groups are related to different gain shapes; a filter is placed between any two subsequent groups, and filters can have different spectral transfer function (insertion loss versus wavelength). In practice, what happens in real systems is that filters are defined to have all the same nominal characteristics; nonetheless the formulas which are proposed here enable to solve any type of general problem of filters interposed between groups of optical amplifiers. The only constraints in the following formulas are that gain shapes of amplifiers have to be the same for all amplifiers inside one same group and that noise figure and total output power (held constant through automatic power control) of each amplifier is the same for all amplifiers in the groups. The equalized SNR for channel c at the output of the link described in Fig. 2 is

$$\mathrm{SNR}_c = \frac{P_c^{\mathrm{in}}\alpha P_o}{FN_F N_p\left(\sum_{k=1}^{N_g} N_k\right)} \frac{1}{\left\{\left[\sum_{i=1}^{N_g}\left(\frac{N_i}{\sum_{k=1}^{N_g} N_k}\Gamma^{i\prime}\right)\right] P^{\mathrm{in}}\right\}_c} \tag{9}$$

where the same notation as in (3) is used and

- N_g number of groups of amplifiers;
- N_i number of amplifiers in ith group;
- Γ^i matrix for ith group.

Again the matrix in square brackets in (9) is the generalized Γ matrix

$$\Gamma^{\text{system}} = \sum_{i=1}^{N_g}\left(\frac{N_i}{\sum_{k=1}^{N_g} N_k}\Gamma^{i\prime}\right).$$

The maximum eigenvalue of Γ^{system} represents the SNR penalty at the link output, and the related eigenvector contains the power of each channel injected into the line; the first ratio in (9) represents the SNR for ideally flat amplifiers. The generalized Γ matrix is obtained as the summation of the matrices of the groups, and each group matrix is weighted according to the number of amplifiers of that group. The matrices of different groups are defined in ascending order as follows:

- $\Gamma^{1'}$ same as in (2), N_a replaced by N_1;
- $\Gamma^{2'}$ same as in (8)

$$\Gamma^{3\prime} = \frac{1}{N_3 N_p}\left[\left(\frac{g_q^1}{g_c^1}\right)^{N_1}\frac{L_q^1}{L_c^1}\left(\frac{g_q^2}{g_c^2}\right)^{N_2}\frac{L_q^2}{L_c^2}\right] \bullet \left[\sum_{k=2}^{N_3}\left(\frac{g_q^3}{g_c^3}\right)^{k-1} + \frac{\alpha}{\alpha_3'}\right]$$

and so forth; then for the general ith matrix:

$$\Gamma^{i\prime} = \frac{1}{N_i N_p}\prod_{k=1}^{i-1}\left[\left(\frac{g_q^k}{g_c^k}\right)^{N_k}\frac{L_q^k}{L_c^k}\right]\left[\sum_{k=2}^{N_i}\left(\frac{g_q^i}{g_c^i}\right)^{k-1} + \frac{\alpha}{\alpha_i'}\right] \tag{10}$$

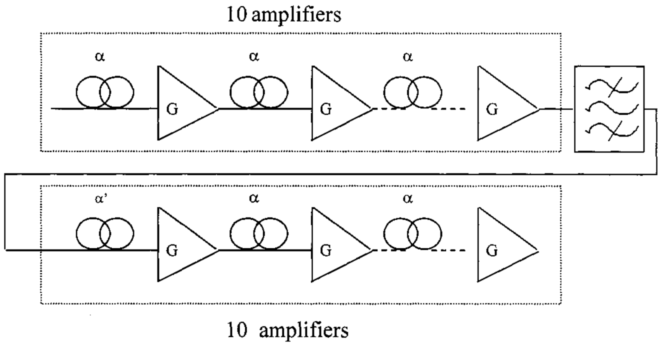
where the same notation as (9) is used and

- g_c^k $= \alpha G_c^k$;
- G_c^k nominal gain of amplifiers in group k, channel c;
- L_c^k insertion loss of filter between groups k and $k+1$, channel c;
- $\alpha_i{}'$ attenuation of fiber span containing filter $(i-1)$.

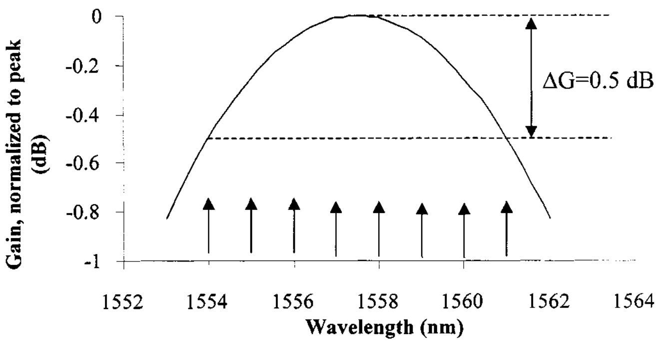
Notice that only the ratios of insertion loss of two channels appear in expression (10): the absolute insertion loss is taken into account only when determining the required attenuation α_i' of the fiber span containing the filter.

V. Equalization Filter Design

One interesting application from the analysis which leads to formulas (9) and (10) is related to the design of the optimal



(a)



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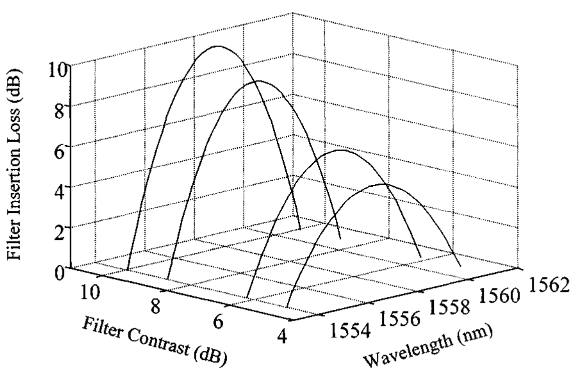

(c)

Fig. 3. (a) Cascade of two groups of amplifiers with one equalizing filter. Span attenuation: 20 dB (95.2 km). Amplifier total output power: +9 dBm (power per channel: 0 dBm). Transmission distance: 1906 km (for 10 dB filter), 1923 km (for 5 dB filter). (b) Spectral gain of EDFA's in the simulations: arrows show the channel location. (c) Simulated spectral insertion loss of equalizing filters (one every ten amplifiers). The plot shows how the Gaussian bandwidth is changed to increase the total contrast.

equalizing filter to be used in long-haul links. We assume here that all the amplifiers in a link have nominally the same spectral transfer function, and that some filters are placed regularly in the line, say one every N amplifiers, in order to overcome the problem of self filtering which reduces the overall bandwidth of the complete chain. The objective here is to create a calculation flow to design the optimal spectral insertion loss of the equalizing filter. With the above assumptions to place one filter every

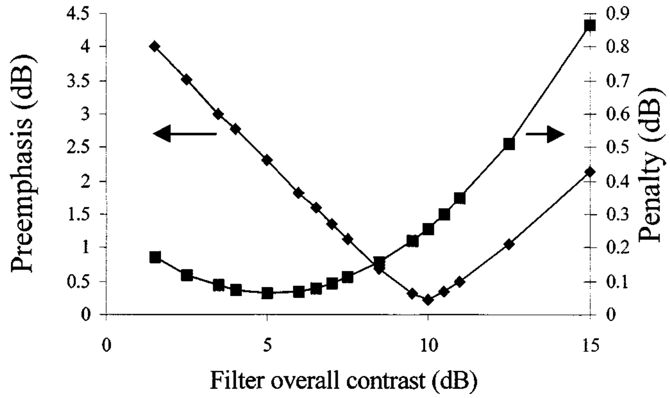

Fig. 4. Penalty and preemphasis versus filter contrast, for the system defined in Figs. 3(a), 3(b), and 3(c).

N amplifiers, the system matrix Γ calculated from (9) and (10) is

$$\Gamma_{c,\,q} = \frac{1}{N+1} \bullet \left\{ \Gamma^1_{c,\,q} + (\Gamma^1_{c,\,q} + \frac{\frac{\alpha}{\alpha'} - 1}{NN_p}) \sum_{i=1}^{N_F} \left(L_{c,\,q} \left(r_{c,\,q} \right)^N \right)^i \right\} \tag{11}$$

where

N	number of amplifiers in each segment;
$N_{\rm FILT}$	total number of in line filters;
$L_{c,q}$	ratio L_q / L_c;
$r_{c,q}$	ratio g_q / g_c.

Γ^1 is as usual the matrix of a single segment of N amplifiers (all blocks are now of same type)

$$\Gamma^1_{c,\,q} = \frac{1}{NN_p} \sum_{k=1}^{N} \left(\frac{g_q}{g_c} \right)^{k-1}.$$

The engineering problem of designing the optimal filter translates into defining $L_{c,q}$ in (11) in order to minimize the maximum eigenvalue of system matrix Γ, or SNR penalty. This can be achieved by forcing all the elements of matrix (11) to be equal to $1/N_p$. This is because the system matrix for an ideal link with a chain of all flat ampliers, from (4), has all elements equal to $1/N_p$. So we force also the new system matrix (11) to be as close as possible to the matrix of the link with ideal amplifiers. The polynomial equation to be solved is then of N_F order in $L_{c,q}$

$$(\Gamma^1_{c,\,q} + \frac{\frac{\alpha}{\alpha'} - 1}{NN_p}) \left[\sum_{i=1}^{N_{\rm FILT}} \left(L_{c,\,q} \left(r_{c,\,q} \right)^N \right)^i \right] + \Gamma^1_{c,\,q} - \frac{N_{\rm FILT}+1}{N_p} = 0. \tag{12}$$

Equation (12) has to be solved iteratively for $L_{c,q}$, as the value of attenuation α' is related to the final solution of the equation. So an initial assumption must be made for α'; after the first calculation for $L_{c,q}$ the new value for parameter α' is introduced in (12); solutions for $L_{c,q}$ and α' are generated iteratively until the result stabilizes.

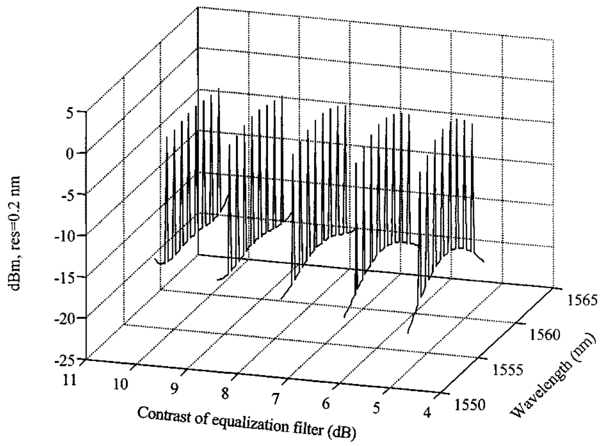

Fig. 5. Output spectra from the chain of 20 EDFA's Fig. 3(a): for all four curves the optical SNR's of the channels are equalized. The spectra have been simulated using a full spectrally resolved model. The spectrum on the right (lower contrast) corresponds to minimum penalty; the spectrum on the left (higher contrast) corresponds to minimum preemphasis.

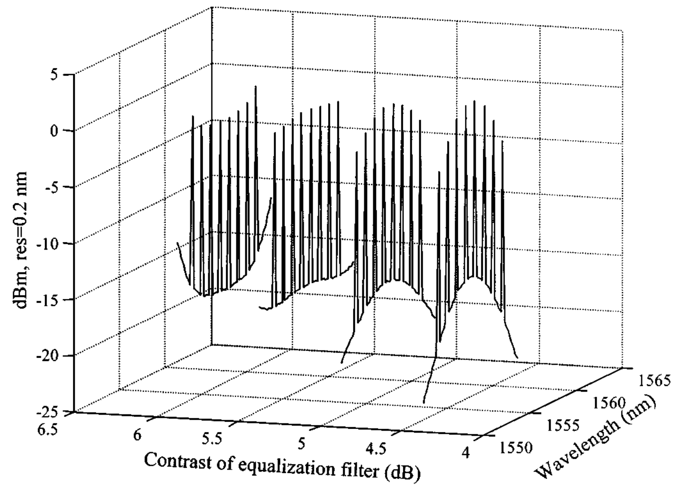

Fig. 7. Output spectra from the chain of 100 EDFA's: for all curves the optical SNR's of the channels are equalized. Same model as in Fig. 5 is used. The spectrum corresponding to minimum penalty is the second from right; the spectrum corresponding to minimum preemphasis is the second from left.

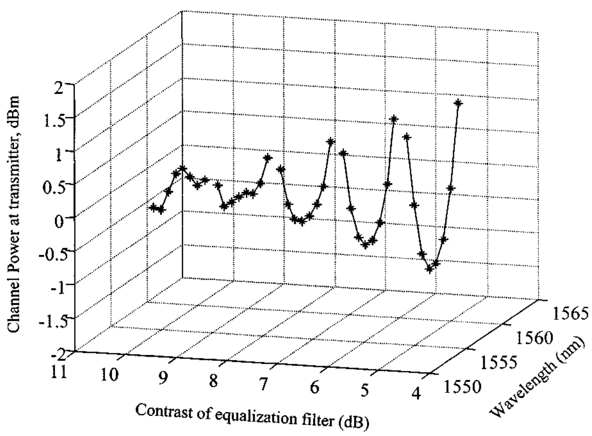

Fig. 6. Preemphasis for channel powers at transmitter (stars), corresponding to output spectra shown in Fig. 5. These results are in good agreement with those presented in Fig. 4, obtained from models (9) and (10).

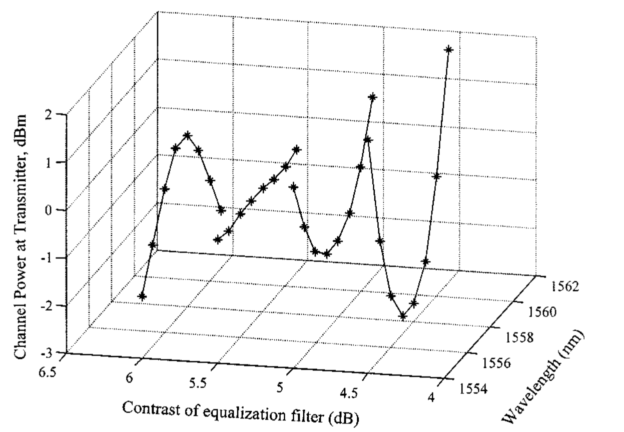

Fig. 8. Preemphasis for the eight channel powers at transmitter (stars), corresponding to output spectra shown in Fig. 7. These results are in good agreement with those presented in Fig. 9, obtained from model equations (9) and (10).

VI. Some Applications

System matrix (11) has been used to study preemphasis and related penalty of some examples. A first case of a chain of 20 amplifiers with a filter in the middle of the link has been evaluated, and is represented in Fig. 3(a). In this example span loss α is 20 dB (interamplifier span distance: 95.2 km). For the amplifiers: total output power is +9 dBm; noise figure NF is 6 dB; gain shape and bandwidth are shown in Fig. 3(b). Total transmission distance ranges from 1906 km (for 10 dB-contrast filter) to 1923 km (for 5-dB contrast filter). The SNR at the output of the system is equalized for all channels and is about 15.5 dB (0.2 nm resolution bandwidth). Total number of channels is 8, the channels are symmetrically distributed around the gain peak from 1554 to 1561 nm step 1 nm, as shown by arrows in Fig. 3(b). Fig. 3(c) defines the spectral insertion loss of the equalizing filter used in the simulations in terms of its total contrast. The shape of the filter is held gaussian, and is centered to the gain peak of the amplifiers. Fig. 4 represents the results obtained for total preemphasis and related penalty as a function of the overall contrast of the filter (as defined in Fig. 3(c).

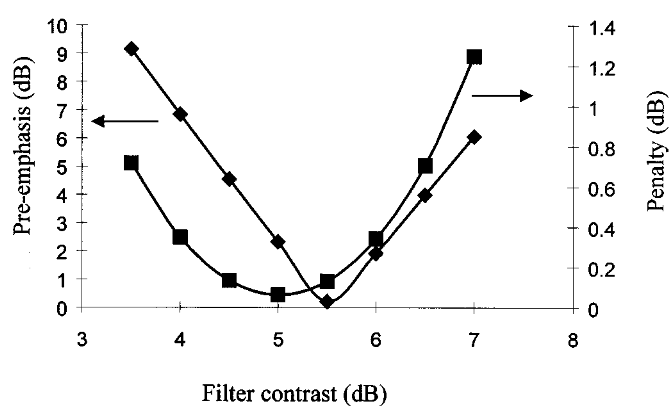

Fig. 9. Penalty and related preemphasis in the case of a chain of 100 amplifiers and nine filters along the line. Filters are placed every ten amplifiers. The result is in good agreement with that in Fig. 8.

The SNR penalty is related to the link with the same attenuation (α and α') along all the spans, but with spectrally flat amplifiers. Fig. 5 gives four spectra at the output of the chain of 20 amplifiers, calculated from a fully spectral resolved model: the four curves show how the spectrum evolves when contrast of the equalizing filter is increased from 5 dB to 10 dB; in particular the two spectra corresponding respectively to minimum penalty and minimum preemphasis are shown. Fig. 6 gives the preemphasis of the channel powers (input spectra) which generate the output spectra in Fig. 5: the agreement between the results from model [(9) and (10)], and the results from the full spectrally resolved simulation is excellent. Fig. 4 shows that the minimum of SNR penalty does not correspond to the minimum of the total preemphasis; moreover penalty has a minimum for a filter compensating exactly a single block chain (where preemphasis is about 2.7 dB); instead preemphasis has a minimum for a filter compensating exactly the complete chain of 20 amplifiers. The need to give preemphasis when SNR penalty has a minimum can generate other impairments from fiber nonlinearities. It is interesting to notice that a tradeoff between penalties coming from equalization and penalties coming from fiber nonlinearities exists; moreover, if the filter is designed to perform best penalty, as is usually the case, and if some errors have to be accepted on its overall contrast to make it feasible, it is better to have the errors in the direction of a higher rather than a lower contrast. The simulation has been extended also to the case of a chain of 100 amplifiers [gain bandwidth still as in Fig. 3(b)], with nine identical filters, one every ten amplifiers. The system characteristics for this example are the same as for previous example, with the exception of span loss (13 dB). The SNR's of the channels at the output of last amplifier are equalized in a range between 15–15.5 dB (resolution bandwidth: 0.2 nm), according to filter contrast. Fig. 7 show four spectra at the output of the chain of 100 amplifiers, calculated from a full spectrally resolved model: the four curves are given for a contrast of the equalizing filters between 4.5–6 dB. Fig. 8 gives the input spectra corresponding to output spectra in Fig. 7. The result in Fig. 9 is that the minimum penalty is for a filter compensating exactly the block of ten amplifiers, where the input preemphasis is still low. The difference with previous example is that curves are steeper versus filter contrast, and both preemphasis and penalty increase much more rapidly. It can be noticed that the overall penalty remains below 0.4 dB if the filter contrast is changed in a range of ± 1 dB. It appears that the minimum preemphasis is related to a filter shape that compensates the total number of amplifiers divided by the number of filters, while the minimum penalty is related to a filter shape compensating the number of amplifiers chained in every single block. For this example of a long chain of amplifiers, the contrast giving the minimum preemphasis is related anyway to a low penalty, less than 0.2 dB.

VII. Conclusion

A mathematical model to represent generalized WDM links has been defined; the formalism enables to study the performance of systems in terms of optical signal to noise ratio at receiver and preemphasis at transmitter, and two examples have been given to show that some asymmetry may arise between least penalty and best preemphasis when using filters to equalize unflatness of EDFA's. The formalism enables also to design in line optical filters in order to optimize the performance of the link. Spectral gain shapes of the amplifiers and spectral attenuation of the fiber can be taken into account in the model.

Acknowledgment

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