Crosstalk in WDM optical networks

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Abstract
The impact of linear and non linear crosstalk on the transmission performances of multi-wavelength optical transport networks is analysed. A performance evaluation of some relevant geographical networks is also reported.

I-INTRODUCTION

The transmission capacity and the network nodes throughput are expected to increase more and more, due to the increasing demand for new services, towards the advent of broadband communications. The optical technology provides the possibility of significantly increase the transmission capacity and, by the use of wavelength division multiplexing technique, also allows switching and routing functions to be accomplished directly in the optical domain, without the need to convert the high speed signals in electrical format. The possibility of achieving such function quite independently of the transmission format and the signal speed, provide the network the property of transparency, which is a significant feature for building flexible networks.

Different demonstrators and field trials have been realised [1,2]. In such experiments, it has been evidenced that the crosstalk, besides the node losses and the amplified spontaneous emission (ASE) noise due to optical amplifiers, represents the main limitation for the transmission performance of the network.

The aim of this work is to analyse the limitations imposed by crosstalk to the performances of the WDM optical transport network layer.

Optical Network Design and Modelling H. van As & A. Jukan (Eds.)

II-CROSSTALK ANALYSIS

Basically, it is possible to distinguish two types of crosstalk, depending on the nature of the effects that generate it: linear and non-linear crosstalk. Linear crosstalk originates in the optical cross-connecting node (OXC), while non-linear crosstalk arises from four-wave mixing in fibre (FWMF), which is generated in high speed-long distance WDM transmissions.

Linear crosstalk can be further categorised in two categories: hetero-wavelength crosstalk (HEC) and homo-wavelength crosstalk (HOC).

Hetero-wavelength crosstalk. This effect is generated by the spectra tails of the adjacent channels entering the bandwidth of the selected channel, and by non-ideal filtering (the filter transfer function is not rectangular). In a real network the spectrum of the channel is distorted by the transit through the OXC's due to the presence of non ideal filters. In particular, the spectra tails are attenuated and the total crosstalk contribution depends on the path followed by the interfering channels through the network. Moreover, it depends on the relative polarisation of the channels, on the relative phase of the optical carriers and on the relative phase of messages transmitted on different channels.

Considering that it is not possible to take rigorously into account all these elements, in the analysis we consider a worst case approach. It is assumed that the spectra of the interfering channels are not altered in the transit through the OXC before the crosstalk generation itself. As a matter of fact, crosstalk can be described as a random process generated by the sum of many independent contributions. This process can be regarded as an additive Gaussian noise, since the polarisations and the phases of the optical channels are uncorrelated each other. It is worth observing that if the overall optical bandwidth is roughly comparable with the bit rate, such a noise can be schematised as white noise. Its noise power can be expressed analytically as:

$$\sigma^2 = \int_{-\infty}^{+\infty} \left|H_s(\omega)\right|^2 \cdot \sum_{k=1}^{N} \left|H_x(\omega)\right|^{2(N+1-k)} \sum_{j=1, j\neq y}^{M} S(\omega + j d\omega)\, d\omega \quad (1)$$

where the selected channel is indicated with y, while $H_X(\omega)$ and $H_S(\omega)$ represent, respectively, the transfer function of the OXC and of the selection filter at the receiver. $S(\omega)$ is the power spectral density of one of the transmitted channels, N is the number of fiber links and M represent the number of channels belonging to the comb.

Homo-wavelength crosstalk. Homo wavelength crosstalk happens when a channel interferes at the OXC output with crosstalk components at the same wavelength. Such crosstalk contributions, that accumulate coherently along the transmission path, can be originated either by adjacent channels, and by the same channel that traversed the OXC along a spurious path: in particular they are generated every time the channels are WDM multiplexed by a passive combiner, as is shown in fig.1. The devices that generates HOC contributions are either optical filters and switch matrixes.

In fact, due to the non ideal filtering of the optical filters inside the OXC, and the imperfect behaviour of the switching matrices, spurious contributions, from other channels carried by the same wavelength of the considered channel, sum at the combiners (placed either at the OXC and at the matrix output). Such contributions can be regarded as in-band crosstalk and propagate together with the channel. Since this effect occurs in each OXC, this kind of crosstalk accumulate and cannot be eliminated. HOC generated by other channels at the same wavelength can be modelled similarly as the HEC. So it is possible to consider it as a noise and derive its noise power adopting the same model used for HEC. In particular equation (1) holds with $\Delta\omega=0$.

On the other hand, HOC originating from the replica of the same channels through different optical paths inside the OXC (self-interference), can't be modelled as a noise, due to its coherent nature. However this kind of HOC can be drastically reduced if wavelength conversion is adopted inside the OXC [3].

Moreover, HOC originating from self-interference can be considered uncorrelated with the signal itself and modelled as a noise, if it is assumed that the optical path between the demultiplexer and the optical combiner is longer than the length of coherence of the transmitters. This hypothesis is always verified if not all the OXC's devices are monolithically integrated.

Non-linear crosstalk. Non linear crosstalk is due to Four Wave Mixing arising during fibre propagation for the presence of Kerr non linearity. In order to schematise this crosstalk contribution, we adopt the same approach used for linear terms. In particular, FWMF spectral power density contributions are calculated as described in [3,5] where the validity of the Gaussian approximation is also discussed. It is worth noting that the non-linear crosstalk terms accumulate incoherently, since the channels at the same wavelength changes throughout the network.

Since any crosstalk contribution can be regarded as white Gaussian noise, the total crosstalk power can be evaluated by summing the different noise powers.

III-SIMULATION MODEL

To evaluate the transmission performances of the network, we consider a generic signal path through the network consisting in: an originating OXC, containing the transmitter, a chain of in-line OXC and a final OXC that contains the receiver. The transmitter is supposed to be composed by a single mode laser externally modulated by a Mach -Zender modulator. The receiver is constituted by a p-i-n diode, a Gaussian electric filter and a decision circuit. Optical amplifiers

(EDFA) are present in the fiber links in order to compensate for fiber losses. Different node architectures have been proposed in literature: here we consider the one proposed and realised in the RACE-MWTN project [1] and reported in fig.2. The realised simulator can evaluate the transmission performances (in terms of bit error rate) of a generic optical path through the transport network. It numerically simulates the evaluation of the signal up to the decision circuit of the receiver. Then the exact error probability is calculated applying the characteristic function method and the "Saddle Point Approximation"[3]. Besides all the distortion contributions, the obtained error probability takes into account the optical noise due to the accumulation of amplified spontaneous emission (ASE) of the optical amplifiers, the thermal noise and the crosstalk contributions.

The signal propagation in the fiber is simulated considering attenuation, chromatic dispersion, and Kerr effect (in particular self-phase modulation). In the numerical simulation of the signal through the network, the modelling of the crossed optical devices is taking into account, by their transfer functions or by theri phisycal modelling, according to the complexity of their behaviour.

Moreover, we develop a model that into account the matrix internal crosstalk and the ASE power generated by the semiconductor optical amplifier (SOA) used ad switching elements [6].

The overall error probability is evaluated by averaging the BER calculated for each bit of a random signal pattern, whose length is long enough to take into account memory effects of the transmission system, mainly due to chirping/dispersion.

IV-RESULTS AND DISCUSSION

In order to test our simulator we referred to a real network (SGN: Stockholm Gigabit Network) [7], realised in the framework of the RACE-MWTN project. In fact, our simulation results were compared with the experimental measures achieved on such a network. The OXC architecture is reported in fig.2. The channels discrimination is achieved by means of optical power splitters and tunable filters (double stage acousto-optic filters). The space switching is realised through optical switching matrices based on InP technology, and using optical amplifiers as switching elements. The OXC has four input fibres, each carrying a comb of four WDM channel. The transmission performances relating to 2.5 Gb/s channels, obtained either by simulation or by measures, are reported in fig. 3. The agreement between experimental and simulated results can be considered quite satisfactory.

To analyse the crosstalk effect in optical networks covering much wider geographic areas we considered, as an example, a possible Italian optical transport network. In particular we referred to a transmission path 1650 km long.

As far as 10 Gb/s systems is concerned, we accoplished several simulations in order to evaluate how non ideal optical filtering, inside the OXC's, influences the transmission performances. In particular we consider the following types of optical filters:

- single and double stage Fabry-Perot filter,
- single and double stage acousto-optic filter,
- apodized acousto-optic filter,
- interference filter.

The OXC is supposed to have four input fibres each carrying a comb of four WDM channels, 4 nm spaced. The optical filter one side bandwidth is 200 GHz, while the optical selection filter and the receiver electric filter bandwidths are respectively 2R and R (R=10 Gb/s). Moreover the selection filter in front of the receiver is assumed to be single Fabry Perot. The main parameters adopted in the simulations are reported in table 1. The fibre links are realised by a dispersion shifted fibre with dispersion coefficient D=4 ps/nm/km and an attenuation of 0.25 dB/km. In line EDFAs are 50 km spaced and, after each EDFA, a dispersion compensating fiber is placed.

As it is shown in fig.4, neither the use of Fabry Perot filters nor the use of single stage acousto optic filters, allow satisfactory transmission performances to be achieved. On the other hand, if channel spacing is large enough, as in the considered case, double stage acousto optic filters and apodized acousto optic filters assure good performances. In particular a suppression of the side lobes from -9 dB to -15 dB is achieved, using apodized acousto optic filters instead of simple double stage ones.

Optimum results can be obtained using interference filter. This kind of filters is characterised by a flat transfer function and by the absence of side lobes; however there are not yet tunable filter available. Their use inside the optical cross connects reduces the flexibility of the network. In table 2 we report the signal to homowavelength contribute ratio obtained with different kind of filters.

In the crosstalk analysis we also consider high density WDM systems (8 channels per fibre, 1.5 nm spaced). In this case, the optical filter onr side bandwidth inside the OXC is 130 GHz.

The simulation results are reported in fig.5. It is worth noting that, also in this kind of systems, the best performances are achieved if interference filters are used. In table 3 we report either the signal to homowavelength contribute ratio and the signal to heterowavelength contribute ratio, that become significant for the selected value of $\Delta\lambda$.

V-CONCLUSIONS

Linear crosstalk, and in particular homo-wavelength crosstalk, imposes significant limitations to the performances of WDM optical transport networks. This limitation can drastically reduce if highly selective filters (high roll-off factor), and switch elements with high ON/OFF ratio are utilised in the cross connect. Non linear crosstalk, due to Four Wave Mixing in Fibre is not significant if national transport network is analysed. However it become determinant if international geographic link (beyond 2000 km) is considered.

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Transmitter extinction ratio	20 dB
Receiver sensitivity	-29 dBm
Optical amplifier noise factor	2.6

Table 1. System Parameters

TYPE OF FILTER	SNR-HOC (dB)
Single stage F-P	9.31
Double stage F-P	12.32
Single stage A-O	17.23
Double stage A-O	24.14
Apodized double stage A.O	27.59
Interference Filters	33.09

Table 2: Signal to HOC contribution ratio (SNR-HOC) for different kind of optical filter: 4 channels per fibre 4 nm spaced.

TYPE OF FILTER	SNR-HOC (dB)	SNR-HEC (dB)
Double stage A-O	21.14	26.23
Apodiz. double stage A-O	23.21	26.21
Interference	30.75	26.11

Table 3: Signal to HOC contribution ratio (SNR-HOC) and signal to HEC contribution ratio (SNR-HEC) for different kind of optical filter: 8 channels per fibre 1.5 nm spaced.

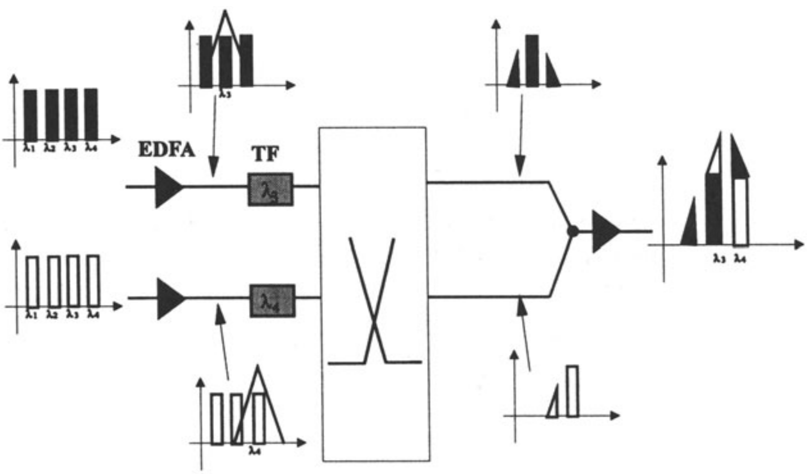

Figure 1. Homowavelength contribution generated in the channel selection.

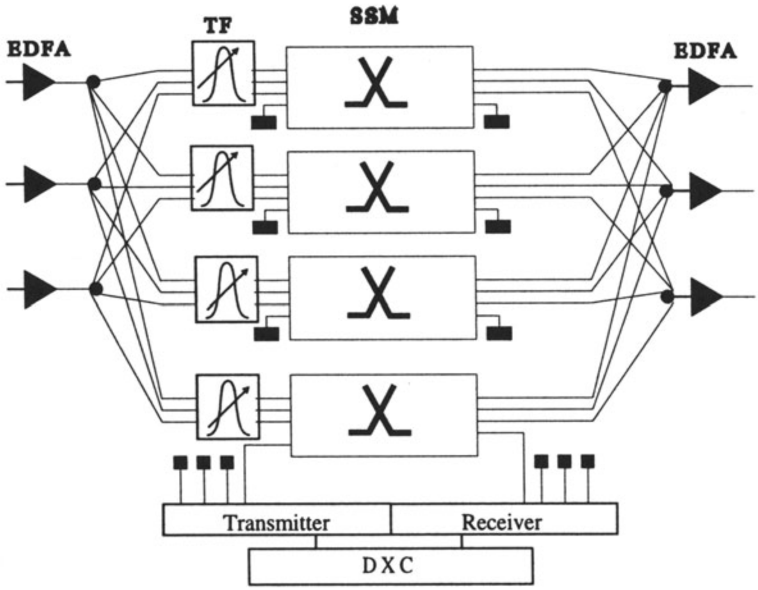

Figure 2. Block scheme of the optical cross-connect. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; SSM: Space Switch Matrix; DXC: Digital Cross Connect.

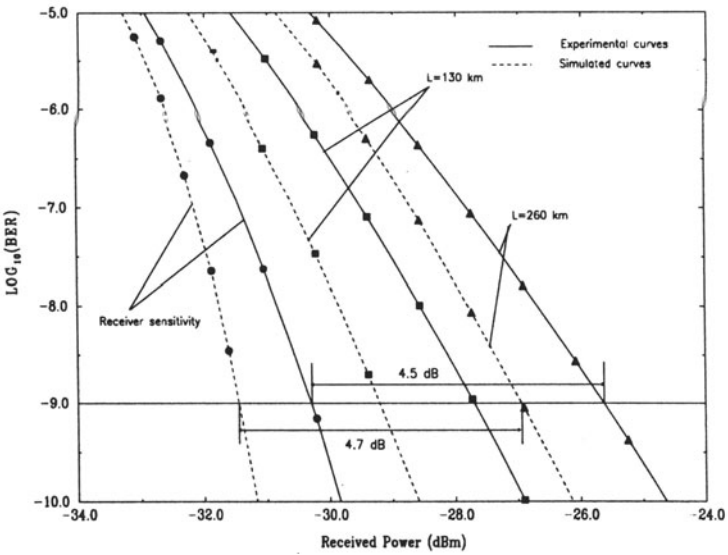

Figure 3. Transmission performances, regarding the Stockholm Gigabit Network, obtained experimentally and with the simulator.

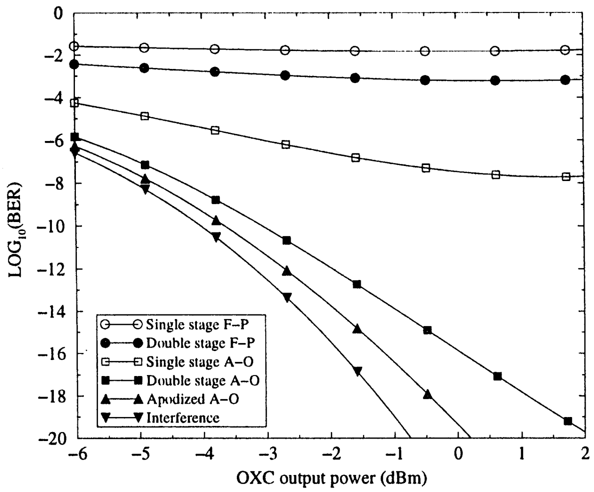

Figure 4. Transmission performances of low density WDM systems (4 channels 4 nm spaced) with different kind of optical filters.

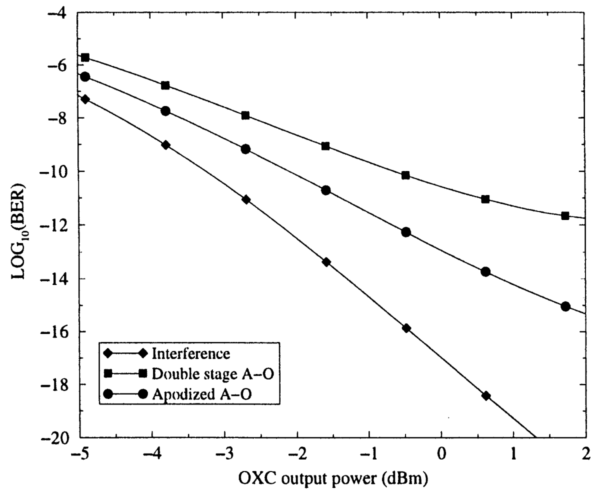

Figure 5. Transmission performances of high density WDM systems (8 channels 1.5 nm spaced) with different kind of optical filters.