Use of Wavelength- and Time-Domain Simulation to Study Performance Degradations due to Linear Optical Crosstalk in WDM Networks

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Abstract

As optical networks become larger and more complex, optical crosstalk can develop into an important performance impairment factor. A new simulation methodology is used for the study of performance degradations due to linear optical crosstalk in WDM optical networks. It is based on a combination of wavelength- and time-domain simulation that provides for calculation of error probabilities and system margins in complex WDM network architectures. Such simulations can be used as an effective tool for setting crosstalk performance criteria for individual components as well as switch architectures. It was found that for a relatively complex Wavelength Selective Cross-connect (WSXC) mesh topology with dilated switching fabrics, individual crosstalk levels better than -14.7 dB are necessary to achieve an acceptable Bit Error Rate (BER) of 10^{-9}.

Index Terms: Crosstalk, optical amplifiers, optical networks, Wavelength Selective Cross-Connects, simulation, wavelength-division multiplexing.

Introduction

In recent years, significant research efforts have been devoted to the design of high-capacity, flexible, cost-effective transparent and scalable multiwavelength optical networks. As the size and complexity of these networks increases, analytical performance evaluation becomes very difficult. As part of the Multiwavelength Optical Networking (MONET) program [1], a wavelength-domain simulation tool has been developed [2] for the study and design of the optical transport layer. It is intended for local exchange networks with thousands of individual components and it is thus essential for it to utilize a computationally efficient simulation technique that will reduce simulation time. This computational efficiency is achieved by undersampling the signal and Amplified Spontaneous Emission (ASE) noise spectrum and propagating only their optical powers ignoring phase information [2]. This significantly increases the simulation speed and allows for complex network architectures to be simulated. The wavelength-domain simulator can evaluate the signal, ASE noise [3], and linear optical crosstalk powers at every point in the network. Linear optical crosstalk due to imperfections in the optical switches and the optical filters within the (de)multiplexers (MUX/DMUXs) can lead to significant performance degradations in the form of Bit Error Rate (BER) floors and can impose strict requirements on the components [4],[5].

It was shown that when studying optical crosstalk, phase, polarization and optical frequency of the signal and crosstalk play an important role in determining the performance degradation imposed on the system; the interference of the underlying fields of the signal and the interferers must be studied for this purpose [6]. In our wavelength-domain approach the phase and polarization information is not propagated during the simulation and thus optical crosstalk can not be entirely studied in the wavelength-domain. The solution is to use the wavelength-domain simulation first to simulate the entire network and effectively collect the powers of all the crosstalk interferers in the network. Then we select a specific path through the network and run time-domain simulations in that path to determine the effects of crosstalk on the performance [2].

This paper applies the above methodology to a specific WDM network architecture (Fig. 1), which is a mesh of Wavelength Selective Cross-connects (WSXCs) and Wavelength Add/Drop Multiplexers (WADMs) [1], to study the accumulation of common-channel crosstalk (or intraband crosstalk). Common-channel crosstalk is generated when signals of the same nominal wavelength interfere at the receiver. This happens due to imperfections on the elementary optical switches within the WADMs and WSXCs. Multipath-homodyne crosstalk is a special case of common-channel crosstalk that is generated from either the MUX/DMUX pairs or the switching fabrics when signals from the same source interfere at the receiver. Adjacent-channel crosstalk is rather small in our example and in general can be controlled by optical filtering and is thus neglected. The resulting performance degradations due to common-channel crosstalk impose component crosstalk-level constraints as well as switch fabric architecture constraints [7]. Thus, the above simulation methodology can serve as a powerful network level tool for setting crosstalk performance selection criteria for components and switch architectures providing an elegant extension to individual component studies [4],[5].

Wavelength-Domain Simulation Approach

The wavelength-domain simulation block diagram (Fig.1) consists of nine nodes: three eight-wavelength 4x4 WSXCs, four WADMs and two Wavelength Terminal Multiplexers (WTMs) [1] forming two inteconnected bi-directional WADM rings. The duplex fiber links between the nodes have a 17 dB loss. The WTMs are used for adding/dropping the eight wavelengths which are equally spaced by 200 GHz in the range of 1549.31-1560.60 nm [1]. For simplicity all channels are present on all the links and routing is such that all nodes are connected. Each 4x4 WSXC, shown in Fig.2, consists of pre-amplifiers, MUX/DMUXs, eight layers of a 4x4 switching fabrics, servo-controlled attenuators for signal power equalization and booster-amplifiers. The amplifier pump power and EDF length are adjusted so that they provide an average gain of 17 dB, with maximum gain variation among the channels of 0.5 dB and with a noise figure of 4.2 dB at 1550 nm [3]. The MUX/DMUXs are modelled as cascades of Multilayer Interference (MI) filters [3]. The WADMs, shown in Fig. 3, are used for adding/dropping signals [3]. Their adjacent channel crosstalk is 39 dB below the signal level for a 200 GHz channel spacing.

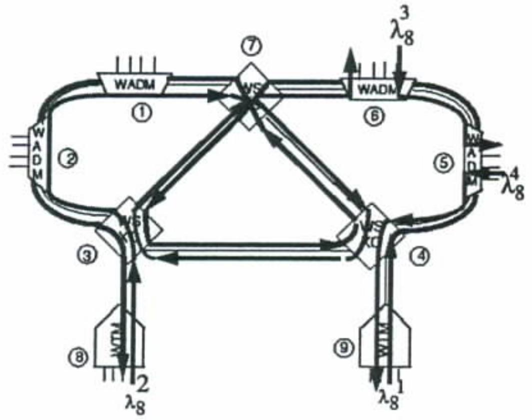

Fig. 1. Wavelength-domain simulation block diagram.

Fig. 1 shows the routing diagram for wavelength 8. There are four lasers transmitting at nominal frequency 8, and they are denoted by λ_8^i with $i = 1, ..4$. We will focus on λ_8^1 which is added at WTM 9 and goes through all nodes, and some of them twice, before being dropped at WTM 8. Thus 9-4-5-6-7-3-4-7-1-2-3-8 is our main signal path and although our simulation tool calculates all possible crosstalk terms generated in the mesh, we focus on crosstalk that accumulates on the above worst case path. While this is a rather improbable path in a real network, it is designed to provide an insight on the most severe crosstalk penalties possible. All four lasers will be contributing in terms of crosstalk, with crosstalk generated at the optical switches of both the WSXCs and WADMs. However, in these simulations, common-channel crosstalk can only en-

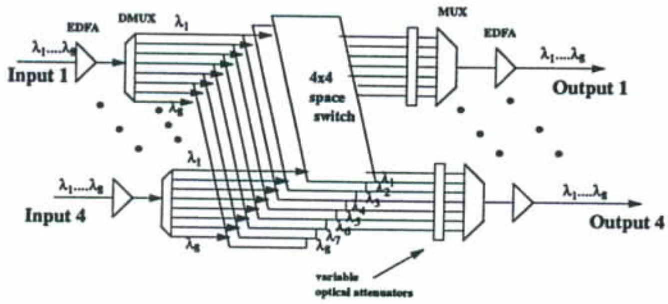

Fig. 2. Block diagram of 4x4 Wavelength Selective Cross-connect (WSXC).

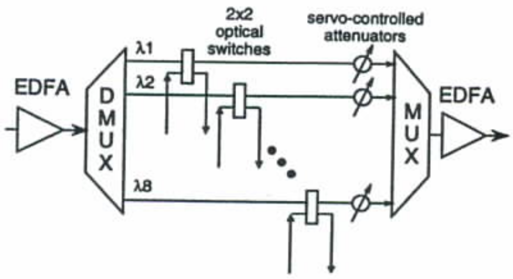

Fig. 3. Block diagram of Wavelength Add-Drop Multiplexer (WADM).

ter the signal path through the WSXCs where signals from different inputs can combine due to imperfections in the 4x4 switching fabrics. Multipath-homodyne crosstalk can be generated in two ways: either due to the architecture; crosstalk from a signal (i.e. λ_8^1) can leak through the WSXC's 4x4 switching fabrics (see Fig. 1) and combine with itself (main signal path), or within the WADMs because of imperfections in the MUX/DMUX filters. In the latter, a signal can have seven other multipath crosstalk contributions which we denote as MUX/DMUX multipath crosstalk terms. Since we are focusing on λ_8 (at edge of band), there is only one dominant MUX/DMUX multipath crosstalk term which is 78 dB below the signal. The 4x4 switching fabric used within each WSXC is a 4x4 dilated binary tree architecture [8]. Proper setting of the unused switches in this architecture will create only one *second-order* dominant crosstalk term per switch output which is the result of leaking through two stages of optical switches. Wavelength-domain simulation is used to collect the powers of all the crosstalk terms in the above network. In this case 20 iterations of the above mesh topology were obtained to allow signals to circulate and crosstalk to be generated and reach steady state where the derived signal and noise levels changed by less than 0.1 dB. The dominant crosstalk terms are 6 second-order terms due to the optical switches. Again there are several higher-order terms due to the MUX/DMUX pairs, the optical switches or hybrids (combinations of both). There are a total of more than 150 crosstalk contributions for the above path. In [7] different 4x4 switching fabrics were simulated and the crosstalk power penalties were calculated using an approximate worst-case model frequently used in the literature.

Time-Domain Simulation Approach

During the second step of our simulation methodology, conventional time-domain simulation is used to study the performance of the selected path shown in Fig. 1, so instead of doing a time-domain simulation of the entire network (with prohibitively long computation time), we construct the simulation block diagram shown in Fig. 4. The 6 dominant second-order crosstalk terms are treated as signals, and are assigned phases, optical frequencies and polarizations all of which are randomly distributed with respect to the signal. At 10 Gbps per signal, external modulation of the lasers is used to eliminate effects associated with chirp. Phase noise is included and the linewidth of the lasers is assumed at 20 MHz. Time-domain simulations were performed using a pseudo-random data sequence of 2^{12} bit-length which was rotated from channel to channel to produce uncorrelated sequences for the crosstalk terms. The combined fields are incident on a photodetector which is followed by a Butterworth lowpass filter with cutoff frequency 0.65 R_b. There are several methods for the calculation of the Bit Error Rate (BER) using simulation: Monte Carlo method, modified Monte Carlo based on importance sampling and BER computation based on extreme-value theory [9]. To minimize the computation time of our simulations we adopt the quasi-analytical (QA) technique [9] where we use noiseless time-domain simulations (Fig. 4) to simulate the signal waveforms throughout the selected optical path and then we superimpose an analytically calculated noise at the receiver. It is assumed that the noise is additive with a known probability distribution at the receiver and that it does not experience non-linear distortions throughout the path. The noise after the photodetector is composed of contributions from shot noise, thermal noise, ASE-ASE and signal-ASE beating terms as well as contributions from the higher-order crosstalk terms that have not been simulated. These higher-order crosstalk terms are assumed to have Gaussian statistics which is fairly accurate when their number is large [10]. The overall photocurrent statistics are then assumed Gaussian and the BER is obtained [11]:

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \tag{1}$$

where Q is evaluated to be:

$$Q = \frac{|D - D_s|}{\sigma} \tag{2}$$

The decision threshold D is assumed half-way between space and mark, D_s is the sampled value after the receiver lowpass filter and the noise variance σ^2 is based on Ref. [12] modified to include the contributions of signal beating with higher order crosstalk terms. The following parameters were varied statistically and Monte Carlo time-domain simulations were performed: optical frequencies of the signals were assumed uniformly distributed in [-10 GHz, 10GHz] around the carrier frequency for channel 8 (192.100 THz), polarizations based on a given polarization alignment factor [13] and phase through the random delays in the crosstalk paths (Fig. 4). These delays were assumed to be random non-integral multiples of one bit and thus despite the slow variations in the phase, crosstalk and signal combine incoherently at the detector.

Simulation Results

The crosstalk level of the elementary optical switches within the switching fabrics of the WSXCs and within the WADMs is varied from -17 dB to -11 dB, which are typical crosstalk values for $LiNbO_3$ or polymer technology switches. Monte Carlo simulations are performed and the BER is calculated using the QA method described in the previous section. We base our performance impairment calculation on the power penalty imposed by crosstalk

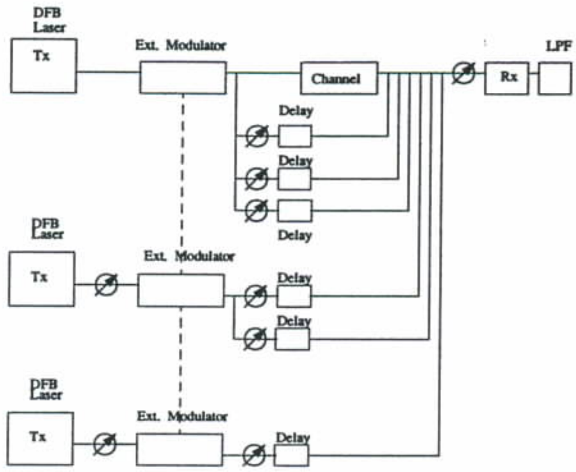

Fig. 4. Time-domain simulation block diagram.

at the receiver. To avoid the large flunctuations in the BER due to the Monte Carlo method, we focus on the calculation of the mean Q factor defined as: $Q_{dB} = 20\log(\overline{Q})$. Figure 5 shows the calculated mean Q factor versus the received optical power for several crosstalk levels of the individual switches. We assume aligned polarizations which is a worst case. Curve 1 shows the baseline with no crosstalk contributions. It is obtained by placing an attenuator before the photodiode and stepping through the received power. We observe an error floor due to the various noise components. Curve 2 corresponds to the case where the individual switch crosstalk levels are -17 dB. If we use a polynomial fit for the average Q values, we can obtain a power penalty of 0.4 dB at a BER of 10^{-9}. Curves 3 and 4 correspond to individual switch crosstalk levels of -14 dB, -13 dB. Their associated power penalties are: 1.6 dB and 2.8 dB respectively. Clearly curve 5 (-11 dB individual switch crosstalk) corresponds to the case where a BER floor below 10^{-9} exists. Figure 6 shows an output eye-diagram for the case corresponding to curve 4 in Fig. 5 (i.e. -13 dB individual crosstalk level) and -5.2 dBm received power corresponding to BER of 10^{-14}. The maximum eye-opening in the absence of crosstalk interferers is set equal to unity. Due to the effects of crosstalk-

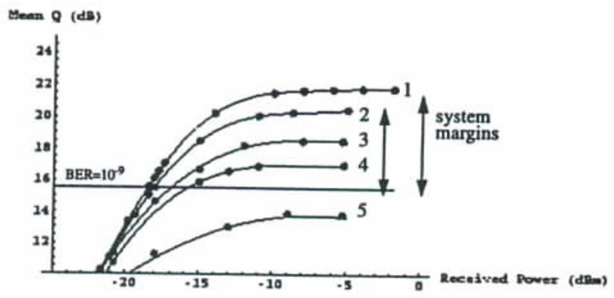

Fig. 5. Calculated Q factor versus received optical power for different individual switch crosstalk levels.

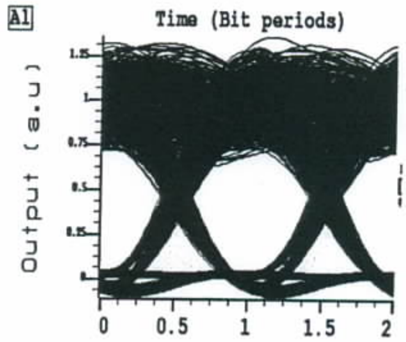

Fig. 6. Eye-diagram at the output of the direct-detection receiver for the case of -13 dB individual switch crosstalk level and -5.2 dBm received power.

induced interferometric noise that induces mostly amplitude noise the received waveform is distorted causing the observed eye closure. The thickening of the eye is due to the length of the data sequence. Based on Fig. 5 it was found that individual component crosstalk levels for the above architecture have to be ≤ -14.7 dB for a 1-dB power penalty at a BER of 10^{-9}. The system margin for the baseline case (no crosstalk) at maximum input power (-1.88 dBm) was calculated to be 5.5 dB and for the case of -14 dB individual crosstalk levels the system power margin at -5.3 dBm input power was calculated to be 2.9 dB (Fig. 5).

Conclusions

A new simulation methodology was used to study the effects of linear optical crosstalk on the performance of a WSXC mesh topology. It was shown that this methodology which is based on a wavelength- and time-domain simulation approach can be used efficiently to study realistic and complex architectures with thousands of components (2558 modules in the above example). It can be used to set crosstalk level requirements for switching fabrics used in large and complex WDM network topologies.

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