Simulation of ASE Noise Accumulation in a Wavelength Add–Drop Multiplexer Cascade

N. Antoniades, *Student Member, IEEE,* I. Roudas, R. E. Wagner, and S. F. Habiby

***Abstract*— This letter presents a computer simulation of a cascade of wavelength add–drop multiplexers (WADM's) each consisting of optical amplifiers, a multiplexer/demultiplexer pair, gain equalizing attenuators and 2 $\times$ 2 optical switches. It is shown that one of the eight wavelengths can propagate through more than 50 equidistant WADM's in a wavelength-division multiplexed (WDM) optical network before its optical signal-to-noise ratio (SNR) drops below acceptable levels. These simulations indicate that a national scale transparent WDM network is feasible.**

***Index Terms*—Noise, optical amplifiers, optical networks, simulation, system performance, wavelength-division multiplexing.**

I. Introduction

IN RECENT YEARS, significant research efforts have been devoted to the design of high-capacity, flexible, cost effective, reliable, transparent, and scalable multiwavelength optical networks [1], [2].

The multiwavelength optical networking (MONET) program's goal is to demonstrate the feasibility of a transparent multiwavelength optical network of national scale [3]. The MONET optical transport layer is composed of seven different types of network elements (NE's) [3], that provide all the necessary network functionalities. A wavelength add–drop multiplexer (WADM) is one of the key NE's which is used for selectively dropping and inserting optical signals into the wavelength-division multiplexed (WDM) network. The WADM that was used in this work consists of a preamplifier, a multiplexer/demultiplexer (MUX/DMUX) pair, 2 $\times$ 2 optical switches for signal adding/dropping, servo-controlled attenuators for power equalization and a booster amplifier [Fig. 1(a)]. Fig. 1(b) shows a basic multiwavelength optical network topology, where eight channels ranging in frequency from 192.100 to 193.500 THz in steps of 200 GHz [3] propagate through a cascade of equidistant WADM's. Channels are added and dropped at each WADM according to a specific add–drop plan. Amplified spontaneous emission (ASE) noise due to the erbium-doped fiber amplifiers (EDFA's) is filtered inside each WADM by the MUX/DMUX pair. However, the part of amplified spontaneous emission (ASE) noise inside the passband of the MUX/DMUX pair accumulates and eventually degrades the optical signal-to-noise ratio (SNR) at the drop location.

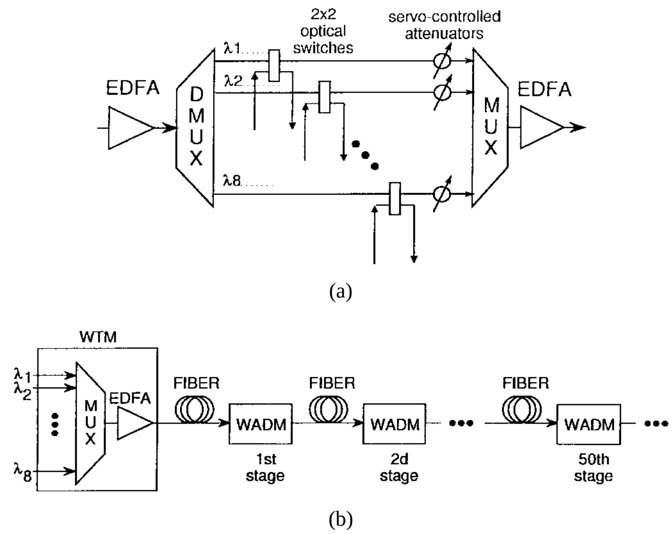

Fig. 1. (a) Block diagram of a WADM. (b) Block diagram of a cascade of WADM's.

In this letter, computer simulation techniques are used to study the optical SNR degradation due to the accumulation of ASE noise in a cascade of 50 WADM's, each separated by span loss of 17 dB. This number of NE's is chosen to represent a transparent national scale WDM optical network. Our goal is to determine if the above effect poses a significant constraint for the size of such networks. It is shown that more than 50 WADM's can be cascaded before optical SNR deteriorates to unacceptable limits. The impact of other physical effects such as laser/filter misalignment, chromatic dispersion, nonlinearities, crosstalk, polarization dependent loss or polarization dispersion are beyond the scope of this study and are neglected.

II. Simulation Model

The simulation block diagram is shown in Fig. 1(b). Wavelength domain simulation is used and the values of the simulation parameters are chosen taking into account current technology limitations of the optical components. For example, laser and receiver arrays used in MONET [1, pp. 967–976] impose input and output power level range requirements at the add–drop sites of the WADM's. The two EDFA's in the WADM's are assumed to be identical single-stage forward-pumped amplifiers that include an ASE blocking filter for ASE

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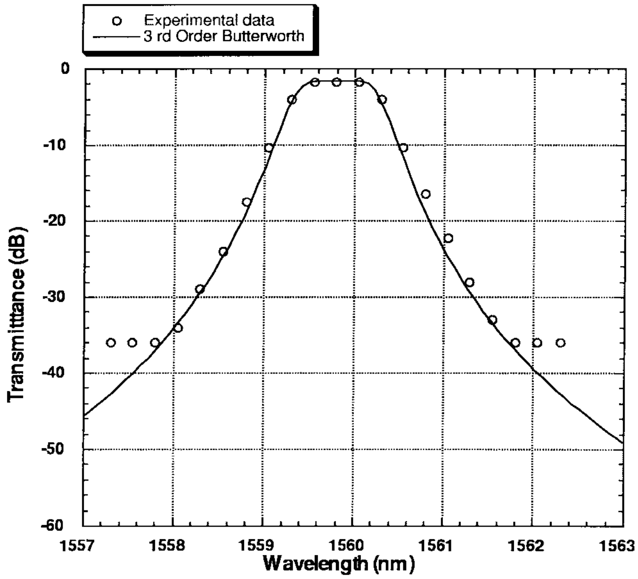
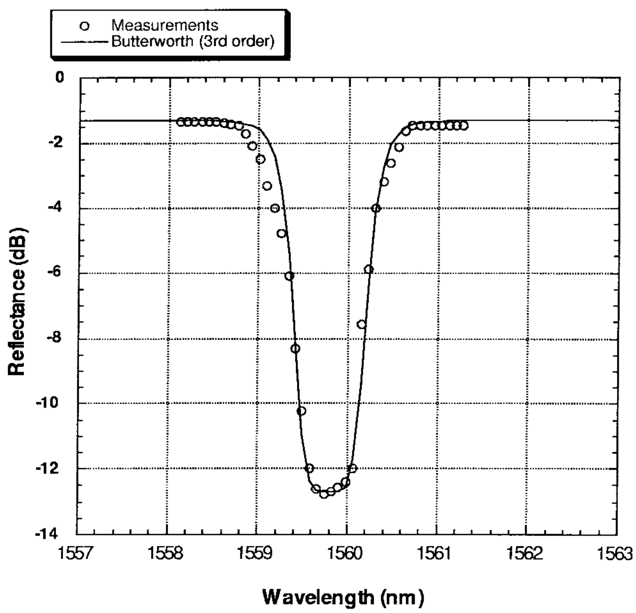


(a)



(b)

Fig. 2. (a) Transmittance of MI filter. (b) Reflectance of MI filter.

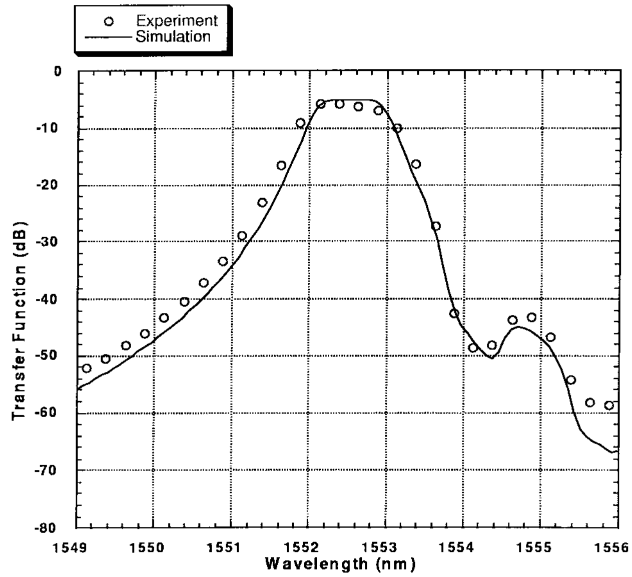


Fig. 3. Transmittance of MONET wavelength 3 through a MUX. As explained in [6], a MUX is a cascade of eight MI filters. ASE noise is inserted on input 3 (associated with wavelength 3) of the multiplexer and what is shown is the MUX output. We focus on transmittance at one wavelength.

peak rejection. They are modeled based on the steady-state EDFA model of [4], which is adequate for low-gain amplifiers (Gain $\leq$ 20 dB) [5]. The erbium doped fiber (EDF) length and pump power at 980 nm are adjusted so that each amplifier provides an average gain of 17 dB/channel to compensate for the span loss. Fiber spans are assumed to have 17-dB flat attenuation. Maximum gain variation between channels for an individual EDFA is equal to 0.5 dB and the noise figure of the EDFA's was calculated to be 4.2 dB at 1550 nm. The minimum WADM input power per channel needed to ensure a system optical SNR of 20 dB at each add–drop site is then −12 dBm.

The MUX/DMUX's in the WADM's are made of cascades of eight elementary multilayer interference (MI) filters [6]. The elementary MI filters are approximated by third-order Butterworth filters with full-width at half-maximum (FWHM) of 125 GHz. An extra factor has been added to the analytical formulas to account for the filter insertion losses.

The expressions for fitting the transmittance and reflectance of the MI elementary filters are:

$$H(f) = \frac{\alpha_1}{1 + \left(\dfrac{f - f_0}{f_c}\right)^{2n}} \tag{1}$$

$$R(f) = \alpha_2 \left(1 - \frac{\alpha_3}{1 + \left(\dfrac{f - f_0}{f_c}\right)^{2n}}\right) \tag{2}$$

where f_0 is the filter center frequency, f_c is half the 3-dB bandwidth and n is the filter order. The $\alpha_1, \alpha_2, \alpha_3, f_0$, and f_c are adjustable parameters.

Fig. 2 presents the transmittance and reflectance of an elementary MI filter centered at MONET wavelength λ_8. The solid curves represent the approximations (1) and (2), whereas the dots represent the measurements. Fig. 3 shows the transmittance for a MUX consisting of eight elementary filters in series, and compares simulation (solid curve) and measurements (points). The agreement between the simulated passband shape and the measured shape is excellent.

The insertion loss of a MUX/DMUX pair is calculated from simulation to be 6.6 dB per channel and the interchannel crosstalk is approximately −24 dB. Both are very close to the experimentally measured values.

The 2 × 2 switches are assumed to have 1-dB insertion loss/channel. Optical crosstalk in the switches can vary from −30 dB to −60 dB, depending on the switch technology, and is neglected for the present work. The servo-controlled attenuators are automatically adjusted to equalize the signal power at −12 dBm per channel at the input of the second EDFA. This

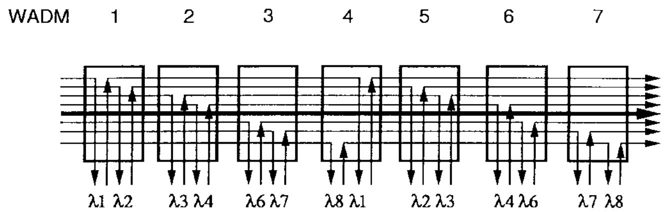
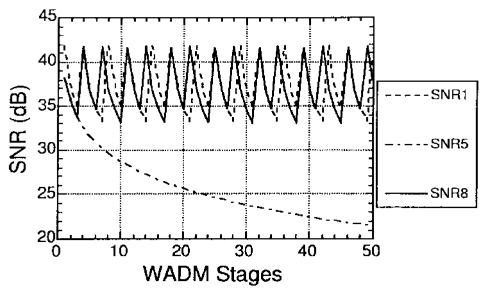
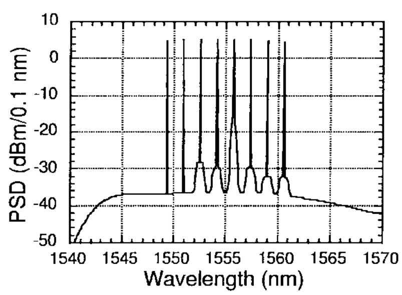


Fig. 4. Simulation add–drop scheme indicating the exact WADM where each channel pair is dropped and then added. Channels correspond to frequencies from 192.100 THz (for channel 8) to 193.500 THz (for channel 1) in 200-GHz steps. The add–drop scheme is periodically repeated after every seven WADM's.



(a)



(b)

Fig. 5. (a) Optical SNR in 0.1 nm resolution bandwidth as a function of the number of WADM's traversed. SNR varies between 34 dB at the drop site and 42 dB just after addition for all wavelengths except λ_5 whose SNR drops to 21.8 dB. (b) Power spectral density (PSD) in dBm/0.1 nm after the 50 WADM cascade.

efficient equalization scheme prevents any power variations between channels from accumulating during the propagation through the WADM cascade, and allows a uniform power per channel to be maintained for any arbitrary dropping plan.

In a chain of K WADM's, there are $8K$ 2×2 switches. The number of possible add–drop configurations is, thus, very large (2^{8K}) and is impossible to perform an exhaustive study of all possible configurations, therefore we limit our interest to an add–drop configuration that is a reasonably difficult case for a national scale network of the above size: at least one wavelength (Wavelength 5) propagates through the whole chain of WADM's and all the other wavelengths are periodically added and dropped in pairs at successive WADM's as shown in Fig. 4. In a realistic network, hardly any channel propagates through the entire WADM cascade without being dropped, thus the above will represent a difficult configuration (limit case), because that channel will have to cope with all the accumulated ASE noise. Other configurations might introduce worse performances in terms of SNR, however owing to the cross-saturation of the EDFA's and the presence of the servo-controlled attenuators it is impossible to deduce the case with the absolutely worse performance unless trying the prohibitively large number of configurations.

III. Simulation Results

Fig. 5(a) presents the optical SNR of selected channels measured in a 0.1-nm resolution bandwidth as a function of the number of WADM's traversed. The optical SNR of wavelength λ_5, that traverses all WADM's, drops to 21.8 dB, which is above the acceptable level necessary to achieve a bit-error-rate (BER) lower than 10^{-9} at 10 Gb/s (approximately 20 dB) [5]. For all other wavelengths, the optical SNR varies between 34 dB at the drop location, and 42 dB just after the addition of the signal.

Fig. 5(b) shows the power spectral density (PSD) after 50 WADM stages. No significant power variation between the eight wavelengths is observed. Irregularities of the ASE noise level are due to the specific add–drop configuration of Fig. 4. For example, from our add–drop configuration, we observe that wavelength 1 and 2 are added at the 50th stage so they have the lowest ASE noise level, wavelengths 7 and 8 are added at the 49th stage so they have higher ASE noise level than 1 and 2 but lower ASE noise than the rest of the wavelengths.

IV. Conclusion

The above simulations show that a WDM network with more than 50 WADM stages in cascade and with 850 dB of total fiber loss is feasible. The use of an efficient equalization scheme within the WADM's prevents any power variations from accumulating therefore one of the $8 - \lambda$s can propagate through the whole chain before its optical SNR drops below acceptable levels. This conclusion is based exclusively on the study of the interaction between the optical filter passband shapes and the ASE noise produced by the EDFA's in the WADM's, so it must be considered rather as an upper limit. Other phenomena (e.g., nonlinearities, dispersion) can further limit the size of the network.

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