Error Probability of Transparent Optical Networks With Optical Multiplexers/Demultiplexers

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***Abstract*—This letter presents an accurate model for the evaluation of the error probability of transparent multiwavelength optical networks with cascaded optical multiplexers/demultiplexers (MUX/DMUXs). The error probability evaluation takes into account arbitrary pulse shapes, arbitrary optical MUX/DMUX and electronic lowpass filter transfer functions, intersymbol interference, and the accurate (non-Gaussian) noise probability density function at the output of the optically preamplified direct-detection receiver. As an example, the model is used to study the cascadability of arrayed waveguide grating routers in conjunction with nonreturn-to-zero pulses.**

***Index Terms*—Error analysis, optical filters, optical receivers.**

I. Introduction

OPTICAL multiplexers/demultiplexers (MUX/DMUXs) present nonideal amplitude transfer functions (i.e., insertion loss, passband curvature, tilt, and ripple) and nonlinear phase transfer functions. Consequently, optical MUX/DMUX concatenation can severely degrade the performance of transparent multiwavelength optical networks, e.g., [1]–[4].

Previous theoretical studies of the cascadability of different optical MUX/DMUX types either used the noiseless eye opening at the output of the direct-detection receiver as a qualitative criterion of the network performance [1] or calculated the error probability with various degrees of accuracy, assuming Gaussian noise probability density function (pdf) at the output of the direct-detection receiver [2]–[4].

This letter presents an accurate semi-analytical model for the evaluation of the error probability of transparent multiwavelength optical networks with cascaded optical MUX/DMUXs. The error probability evaluation takes into account arbitrary pulse shapes, arbitrary optical MUX/DMUX and electronic LPF transfer functions, ISI, and the accurate (non-Gaussian) noise pdf at the output of the optically preamplified direct-detection receiver.

To illustrate the model, the concatenation of conventional arrayed waveguide grating (AWG) routers with round passband in a chain optical network is studied. It is shown that, contrary to common wisdom, optical MUX/DMUX concatenation can lead to performance improvement, when the bandwidth of the individual optical MUX/DMUXs is much larger than the signal spectral occupancy. The concatenation limit of optical MUX/DMUXs can be increased indefinitely, at least in principle, at the expense of spectral efficiency.

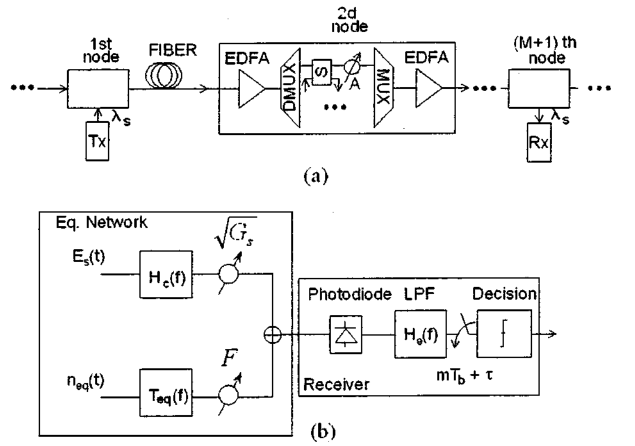

Fig. 1. (a) Chain network topology. (Symbols: Tx: Transmitter; Rx: Receiver; λs: signal's nominal carrier wavelength 2×2 optical switch; A: servo-controlled attenuator). (b) Simplified block diagram of the network topology shown in (a) (Symbols: $E_s(t)$: input signal; G_s: signal power gain; $H_c(f)$: transfer function of the signal channel; $T_{\rm eq}(f)$: equivalent transmittance of the ASE noise channel; F: excess noise factor; $n_{\rm eq}(t)$ = equivalent input ASE noise; T_b: bit period; τ: propagation group delay).

II. Theoretical Model

Consider optical signal propagation through $M+1$ equidistant transparent optical nodes, e.g., wavelength add-drop multiplexers (WADMs) [5] [see Fig. 1(a)]. Without loss of generality, the architecture of reconfigurable WADMs [5] proposed in the multiwavelength optical networking (MONET) project is assumed. In each WADM, the optical signal at wavelength λ_s passes through two erbium-doped fiber amplifiers (EDFAs), an optical MUX/DMUX pair, a 2×2 optical switch fabric for signal adding/dropping, and a servo-controlled attenuator for optical power equalization.

For the purpose of this study, it is assumed that the network is approximately linear. Although this assumption is not always valid, the following study provides an upper bound for the cascadability of optical MUX/DMUXs.

A linear optical network can be represented by two equivalent channels for the optical signal and the ASE noise, respectively, [see Fig. 1(b)]. The reason for such a representation can be intuitively understood since the ASE noise is generated in a

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distributed fashion throughout the optical network, so the optical signal and ASE noise are filtered by a different number of optical MUX/DMUXs.

Fig. 1(b) shows a simplified block diagram of the network topology in Fig. 1(a). The input signal $E_s(t)$ and equivalent input ASE noise $n_{\mathrm{eq}}(t)$ are propagating through different channels, which are represented by the transfer function $H_c(f)$ and the equivalent ASE noise transmittance $T_{\mathrm{eq}}(f)$, respectively. The equivalent input ASE noise $n_{\mathrm{eq}}(t)$ is defined here as a fictitious white Gaussian noise source that if placed at the input of the network, will produce the same noise at the receiver input as the one provided by all the optical amplifiers in the network.

Signal attenuation arises from the insertion loss and the band-limiting operation of the optical MUX/DMUXs (the latter defined as excess loss). The attenuation is automatically compensated by an adjustment of the insertion loss of the servo-controlled attenuators and an increase of the gain of the EDFAs in the network. The overall signal power gain coefficient necessary to compensate the action of optical MUX/DMUXs is denoted by G_s. At the same time, this gain causes an additional ASE noise amplification. This effect is described by an excess noise factor F.

The direct-detection receiver in Fig. 1(b) consists of a photodiode, an electronic lowpass filter (LPF) with transfer function denoted by $H_e(f)$, a sampler that samples the signal at integer multiples of the bit period T_b, and a decision device, whose threshold is automatically set to minimize the error probability. It is worth noting that the EDFA and optical DMUX at the input of the $(M+1)$th network element are playing the role of the receiver optical preamplifier and optical bandpass filter (BPF), respectively.

The quantities $H_c(f)$, $T_{\mathrm{eq}}(f)$, G_s, F, for the two equivalent channels can be calculated analytically as a function of the optical MUX/DMUX transfer functions.

For the evaluation of the error probability, we use essentially the formalism of ideal square-law detection, see e.g., [6] and more recently [7], [8], with some minor modifications in order to take into account the fact that the optical signal and ASE noise are filtered by different transfer functions.

In summary, the evaluation of the error probability is based on a semi-analytic method [9], which allows for accurate evaluation of the ISI, the signal-ASE, and ASE-ASE noise pdfs. The semi-analytic method involves several steps: 1) evaluation of the signal waveform at the output of the receiver by noiseless simulation; 2) analytical evaluation of the ASE noise power spectral density at the photodiode; 3) analytical evaluation of the characteristic function of the noise at the output of the receiver for each bit, using an expansion of the ASE noise impingent upon the photodiode in Karhunen–Loève series [6]–[8]; 4) asymptotic evaluation of the conditional error probability for each bit from the corresponding characteristic function using the method of steepest descent [6], [8]; 5) evaluation of the mean error probability by averaging over the conditional error probabilities for all bits; and 6) numerical minimization of the mean error probability by optimization of the decision threshold.

III. Study Case: AWG Router Cascadability

For illustrative purposes, the model is used to study the cascadability of AWG routers. This subject was partly studied previously by [3], [4] for 10-Gb/s nonreturn-to-zero (NRZ) transmission. Here, we highlight some interesting aspects of the problem that remained unnoticed.

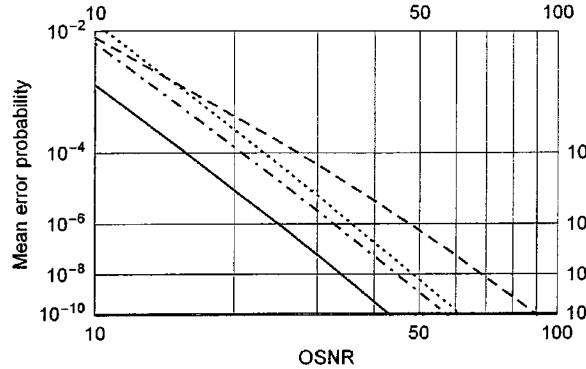

Fig. 2. Mean error probability as a function of the received OSNR measured in a resolution bandwidth equal to the bit rate for one (dotted line), three (dashed–dotted line), and twelve (dashed line) fiber spans, in the presence of polarizer at the receiver (condition: $B_o = 4\ R_b$, $Be = 0.7 R_b$). Solid line: Matched filter receiver.

To isolate the impact of the AWG router filtering from other transmission effects, the following network parameter set is used in this study: ideal NRZ pulses with infinite extinction ratio, zero chirp, and phase noise; perfectly aligned, identical AWG routers represented by Gaussian transfer functions with linear phase [10]; absence of fiber chromatic dispersion and nonlinearities; ASE noise-limited direct-detection receiver; negligible shot and thermal noises; a fourth-order Bessel electronic with a 3-dB cutoff frequency $B_e = 0.7\ R_b$ at the receiver, where R_b is the bit rate. The performance of the actual network is compared to an optically preamplified direct-detection receiver with matched optical BPF, and an optical polarizer aligned along the received signal polarization [11].

Fig. 2 shows the mean error probability as a function of the received optical signal-to-noise ratio (OSNR) measured in a resolution bandwidth equal to the bit rate for one (dotted line), three (dashed–dotted line), and twelve (dashed line) fiber spans, in the presence of polarizer at the receiver. The equivalent noise bandwidth of individual AWG routers in this graph is assumed $B_o = 4\ R_b$. (For example, for a bit rate $R_b = 10$ Gb/s, this assumption implies an AWG router equivalent noise bandwidth equal to 40 GHz, which is quite reasonable for commercially available devices for 100-GHz channel spacing). For comparison, the error probability for the matched filter receiver is also shown (solid line). For one fiber span, 1.54 dB of additional power compared to the matched filter receiver are required to achieve an error probability of 10^{-9}. When the number of spans increases, initially the sensitivity is improved, because the optical bandwidth narrowing reduces the power of the ASE noise without essentially distorting the signal. A maximum sensitivity is achieved after three fiber spans, where there is only 1.22-dB power penalty compared to the matched filter receiver. As the number of spans continues to increase, the power penalty slowly increases due to the increase of ISI. It is observed that the slope of the error probability curves changes as a function of the number of fiber spans. This is due to the fact that AWG filtering changes the properties of the ASE noise at the input of the direct-detection receiver.

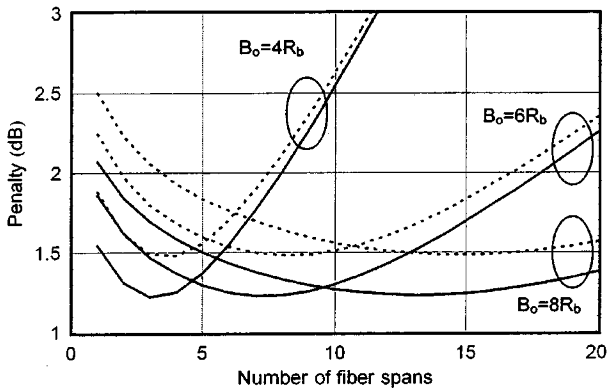

Fig. 3. Optical power penalty compared to the matched filter receiver, at an error probability of 10^{-9} as a function of the number of fiber spans, for three individual AWG router equivalent noise bandwidths, i.e., $B_o = 4, 6, 8\ R_b$, in the presence (solid lines) or absence (dotted lines) of polarizer, respectively.

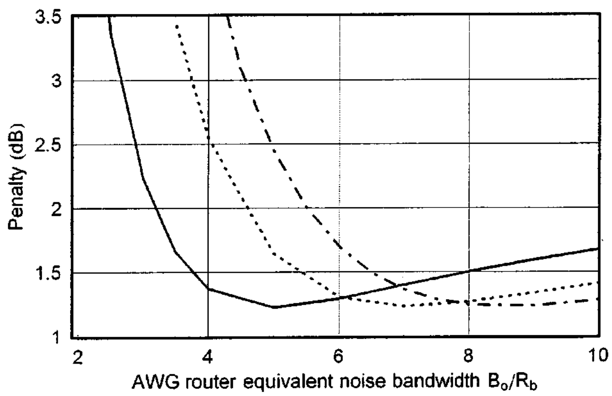

Fig. 4. Optical power penalty compared to the matched filter receiver, at an error probability of 10^{-9} as a function of the equivalent noise bandwidth of the individual AWG routers for five (solid line), ten (dotted line), and fifteen (dashed–dotted line) fiber spans, in the presence of polarizer at the receiver.

From Fig. 2, it is possible to evaluate the optical power that is necessary to achieve a desired error probability as a function of the number of fiber spans. Fig. 3 shows the optical power penalty compared to the matched filter receiver at an error probability of 10^{-9} as a function of the number of fiber spans, in the presence (solid lines) or absence (dotted lines) of polarizer at the receiver. Three individual AWG router equivalent noise bandwidths B_o are considered. These results indicate that it is possible to increase indefinitely, at least in principle, the number of concatenated AWG routers by increasing the equivalent noise bandwidth B_o of individual AWG routers for fixed bit rate R_b at the expense of spectral efficiency defined roughly as R_b/B_o. In addition, the role of the polarizer is more important for larger individual AWG router equivalent noise bandwidths and smaller number of fiber spans.

For a given number of fiber spans, maximization of the performance of the network requires optimization of the optical MUX/DMUX equivalent noise bandwidth. Fig. 4 shows the optical power penalty at an error probability of 10^{-9} compared to the matched filter receiver, as a function of the equivalent noise bandwidth of the individual AWG routers for five (solid line), ten (dotted line), and fifteen (dashed-dotted line) fiber spans, in the presence of polarizer at the receiver. For all cases, there is a broad minimum, whereas the sensitivity degrades sharply for narrower than the optimum equivalent noise bandwidths. If the optical signal may be rerouted through all aforementioned paths during the network's lifetime (depending on traffic demands, equipment failures, and so forth), a possible compromise is to choose the AWG router equivalent noise bandwidth equal to $B_o = 7\ R_b$, which guarantees an optical power penalty less than 1.5 dB in all cases.

IV. Conclusion

An accurate model for the evaluation of the network performance degradation due to the concatenation of optical MUX/DMUXs is presented. The model can be used to derive specifications for arbitrary optical MUX/DMUXs in order to achieve a prescribed power penalty in conjunction with different modulation formats.

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