Novel Statistical OSNR Budgeting for Optically Amplified DWDM Circuits With Polarization-Dependent Loss

June-Koo Kevin Rhee, *Member, IEEE*

***Abstract*—Polarization-dependent loss of optical components used in all-optical network circuits may introduce fast power fluctuations and bursts of high bit-error-rate (BER) impairment at a receiver. The power fluctuation in amplified circuitry manifests as statistics of both power and optical-signal-to-noise-ratio (OSNR) penalty at the receiver. Importantly, the power and OSNR statistics are not directly correlated in a long chain of amplifiers and the impact to BER is rather complicated. We propose the corresponding statistic model for budgeting OSNR to guarantee the probabilistic system availability.**

***Index Terms*—Communication system performance, communication system reliability, optical amplifiers, optical fiber communication, optical fiber polarization.**

I. Introduction

OPTICAL power fluctuation in amplified transmission systems and circuits is a very common problem in designing optical network systems. One of the main causes of the power change is an impact of concatenated polarization-dependent loss (PDL), as well as others including transmitter laser output power instability, amplifier gain instability, and filter function instability. PDL is one of the critical impairments that is not avoidable even with the state-of-the-art optical component technologies. When PDL is coupled with the random state of polarization (SOP), the optical signal power changes arbitrarily, introducing instantaneous bit-error-rate (BER) performance degradation. Because of the relatively slow changes of the SOP in field-installed fibers on the order of 10 ms [1], [2] compared with the bit rate, bit errors happen as bursts of errors. This regime of the system behavior must be treated as short-term failure of system availability.

In an optically amplified system, such as by an erbium-doped fiber amplifier (EDFA), Raman amplifier, and semiconductor optical amplifier, the power changes have a two-fold impact in the system performance: optical-signal-to-noise-ratio (OSNR) degradation [3], [4] and receiver power degradation [5]. The latter is rather simple to associate with BER performance as a function of the receiver input power due to PDL statistics [6] and the former has been reported with some limitations in the analysis. The combination of the two effects is not straightforward to apply to a system performance analysis [7]. Such penalties are mitigated by passive budgeting and active control. A passive budgeting is achieved by OSNR margin requirements, while an active control is achieved by fast per-channel dynamic gain equalization [8] in the middle of optical transmission and automatic gain control in the receiver circuitry with millisecond response times. However, choice between the two becomes the techno-economic matter of available low-cost technologies, while the passive budgeting approach seems to be more reliable and a lower cost approach at the time of this publication.

This letter reports the statistical behavior between power and OSNR performance measures and the corresponding system performance statistics. Polarization-dependent gain (PDG) of an optical amplifier has the same system performance impact and is treated in the same manner as PDL in this letter. The result will provide a guide to component PDL requirements.

II. OSNR Model Under Power Deviations

An optical noise added by an amplifier, namely the amplified spontaneous emission (ASE), can be modeled conceptually quite simply if we consider a gain-normalized ASE power equivalent to an imaginary noise input entering the amplifier along with the input optical signal. Here the gain-normalized ASE power is defined by down scaling the ASE output power by the factor of the gain. Surprisingly, this input-equivalent virtual ASE power is independent from the gain or the input power, i.e., $\tilde{P}_N \cong n_{\rm sp} h\nu B_R \cong {\rm NF} \times 1.59$ nW at 1550 nm for a 0.1-nm ASE noise bandwidth at 1550 nm, when the gain G is practically large [9]. Here, $h\nu$ is the photon energy. The spontaneous emission factor $n_{\rm sp}$ and the amplifier noise figure NF have a relation of ${\rm NF} = 2n_{\rm sp}$. Consider an optical signal entering an amplifier with a finite ${\rm OSNR}^{\rm in}$. Defining noise-to-signal ratio $\rho = {\rm OSNR}^{-1}$, we find the input optical noise power $P_N^{\rm in} = \rho^{\rm in} P_{\rm ch}^{\rm in}$, where $P_{\rm ch}^{\rm in}$ is the optical input channel power. The noise-to-signal ratio at the output is then given

$$\rho_1^{\rm out} = G\left(P_N^{\rm in} + \tilde{P}_N\right) \Big/ {\rm GP}_{\rm ch}^{\rm in} = \rho^{\rm in} + \tilde{P}_N \Big/ P_{\rm ch}^{\rm in}. \quad (1)$$

For a chain of n amplifiers, we find $\rho^{\rm out} = \rho^{\rm in} + \sum_{k=1}^{n} \tilde{P}_N / P_{{\rm ch},k}^{\rm in}$.

In most systems, $\rho^{\rm in} \cong 0$. If there are small-scale input power changes with respect to the nominal uniform input power $\bar{P}_{\rm ch}^{\rm in}$, i.e., $P_{{\rm ch},k}^{\rm in} = \bar{P}_{\rm ch}^{\rm in}(1 + \Delta_k)$, then $\rho = n(\tilde{P}_N / \bar{P}_{\rm ch}^{\rm in})(1 -$

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The author is with the School of Engineering, Information and Commnunications University (ICU), DaeJeon 305-732, Korea (e-mail: rhee.jk@ieee.org).

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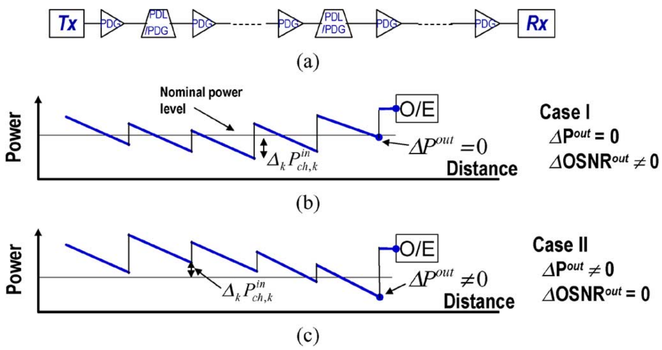

Fig. 1. (a) Reference optical circuit model. The number of spans varies up to 20 for 2000-km circuit length. Trapezoids represent OADMs. (b) and (c), representative cases that illustrate an OSNR penalty only and a received power penalty only, respectively.

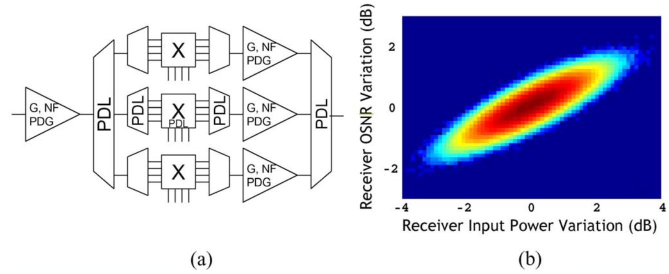

Fig. 2. (a) OADM node model and (b) joint probability density function of OSNR and received power changes after propagation through 20 fiber spans with 25 passive components. Shading is scaled to the log of the density. Trapezoids in (a) represent DWDM band splitters and de/multiplexers.

$(1/n)\sum_{k=1}^{n}\Delta_k)$. In the regime of small Δ_k, the OSNR (in the linear scale) after the last amplifier becomes

$$\mathrm{OSNR}^{\mathrm{out}} \cong \mathrm{OSNR}^{\mathrm{out}}_{\mathrm{nom}}\left(1+\frac{1}{n}\sum_{k=1}^{n}\Delta_k\right) \quad (2)$$

i.e., $\Delta\mathrm{OSNR}^{\mathrm{out}} \cong \mathrm{OSNR}^{\mathrm{out}}_{\mathrm{nom}}\overline{\Delta_k}$, where $\mathrm{OSNR}^{\mathrm{out}}_{\mathrm{nom}} \equiv \bar{P}^{\mathrm{in}}_{\mathrm{ch}}/n\tilde{P}_N$ is the nominal output OSNR. The corresponding output power change with respect to the nominal power is $\Delta P^{\mathrm{out}} = P^{\mathrm{out}}_{\mathrm{nom}}\Delta_n$. In the analysis, we considered an equal amount of noise powers for both parallel and perpendicular noise polarization with respect to the signal polarization as discussed in [8]. Polarization hole burning is not considered as the channel spacing of dense wavelength-division multiplexing (DWDM) is narrower than the spectral width of the hole burning.

An important notion of this result is that an OSNR change is proportional to the average of input power changes at every amplifier, and thus independent from the output power from the last amplifier, as depicted in Fig. 1. A simple assumption that the system penalty is a function of only the output power can lead to an over-generalization error in a system performance analysis, as the OSNR penalty is independent from the output power penalty but a function of the average of the power evolution history, as depicted in Fig. 1(b) and (c). However, there is strong correlation between the output power changes and OSNR changes because the final output power and the average power have certain correlation when the number of amplifiers is small.

In order to investigate such correlation quantitatively, we apply the proposed model to a system with power fluctuations due to PDG of an amplified transmission line with 20 fiber spans with 15 EDFA nodes and five optical add–drop multiplexer (OADM) nodes. Each OADM node consists of two EDFAs and five passive components with a nominal PDL of 0.3 dB Fig. 2(b). We assume that all EDFAs have a nominal PDG of 0.3 dB. Due to fast evolutions of the SOP in hundreds of kilometers of fibers, the polarization state of the transmitter optical data launched from an EDFA is randomized so that the EDFA PDG and OADM PDL cause the output powers of EDFA and OADM nodes randomized [5]. Using Monte Carlo methods, the SOP difference between the input optical field and the PDG/PDL elements are randomly chosen so as to generate statistics of the input power at every node. As a result, the random variable $\Delta\mathrm{OSNR}^{\mathrm{out}}$ is then merely the average of Δ_k, where Δ_k is a pseudorandom walk process. In this way, we obtain joint statistics of the instantaneous OSNR and the instantaneous receiver input power, as shown in Fig. 2. The joint density shows correlation with a correlation coefficient of 0.86 between $\Delta\mathrm{OSNR}^{\mathrm{out}}$ and ΔP^{out}. A regression of $\Delta\mathrm{OSNR}^{\mathrm{out}} = \Delta P^{\mathrm{out}}/2$ is found because $\Delta\mathrm{OSNR}^{\mathrm{out}}$ is the average of Δ_k. The correlation increases, for a small number of PDL elements, or if there exist only few dominant PDL components. The joint statistics correlates less as the number of PDL elements increases.

Depending on the statistics, a burst of errors occurs occasionally, when the SOPs of all PDL components happen to be aligned in-phase. The system availability in this simulation is counted against such burst failures with respect to total number of investigated cases. In order to estimate both OSNR and power changes, our simulation traces the optical power evolution of a channel rather than that of the insertion loss in contrast to the prevailing approaches taken by other studies.

III. System Penalty Model

At the receiver, both lower power and lower OSNR increase system penalty. The latter is a fundamental impairment that cannot be fixed at the receiver. A typical optical-to-electrical converter, or the photoreceiver, has an adaptive gain and threshold control with response time characteristics of hundreds of milliseconds. For a meaningful power control should be combined with a delicate threshold control whose response time is often limited to the speed of the BER detection time in the low BER limit. However, the SOP in an installed fiber rotates with characteristic time faster than tens of milliseconds [1], [2], so we can assume that the receiver has a fixed gain and threshold as a slowly varying approximation, and thus the power decrease degrades the BER performance immediately.

Fig. 3 shows such compound BER estimation for a 10-Gb/s system based on the Gaussian PDF model with a fixed gain and threshold receiver model. The left-hand side of the V-shaped contour is mainly the manifestation of non-optimum threshold level of the receiver data recovery, when the receiver input power changes rapidly. The outage rate due to the instantaneous burst BER is then estimated by the area integral of the PDF in Fig. 2(b) over the area below the BER requirement in Fig. 3. If a gain control is employed, but not with fast enough a

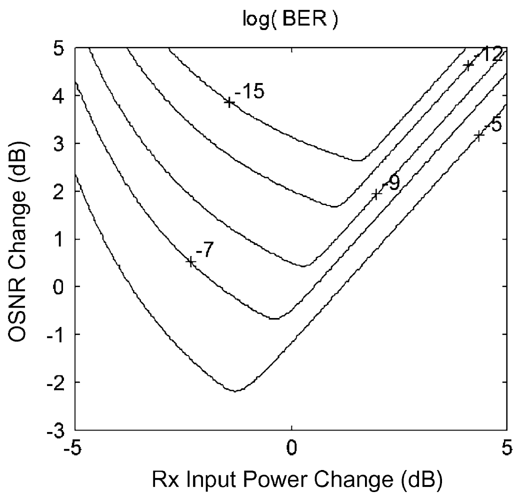

Fig. 3. BER as a function of received power change and OSNR change. Values of $\log_{10}$ (BER) are marked on equi-BER contours. In this example, the nominal OSNR in 0.1 nm is 13.4 dB as used in the RAN case of Fig. 4.

TABLE I
OPTICAL SYSTEM MODEL PARAMETERS

	Fiber span (km)	OADM span (km)	Longest circuit length (km)
RAN	100	200	800
ULH	100	500	2,000

response time, the outage due to the left-hand side of V-shaped contour will be reduced to a lower probability of the cases that such large power change and fast SOP evolution jointly happen. In the following analysis, we assume that the system fails when BER increases above 10^{-5} (i.e., the area below the log (BER) curve of "-5" in Fig. 3), which is a typical criterion for forward error correction.

IV. SYSTEM REQUIREMENT OF PDL

The requirements for PDL of two types of optical network models are investigated: regional area network (RAN) and ultralong haul (ULH) network. The system design parameters are shown in Table I. We assume the OADM node model [10] of Fig. 2(a), with a nominal PDG of 0.3 dB for EDFAs. The PDL of passive components in OADM is varied from 0.1 to 0.4 dB in order to understand an OSNR margin requirement due to PDL. Consequently, combined PDG-PDL components are 39 and 51, in the regional and ULH systems, respectively. The transmitters and receivers in OADMs transmit and terminate 10-Gb/s optical channels, respectively.

Fig. 4 shows the OSNR margin requirement for regional and ULH networks as a function of component PDL requirement in reference to outage probability of 10^{-5}, or the availability of 99.999%. The outage is defined when the BER estimation is greater than 10^{-5}, considering a typical requirement for a transceiver with forward error correction. If it were not for PDL contributions from passive components, i.e., a point-to-point system

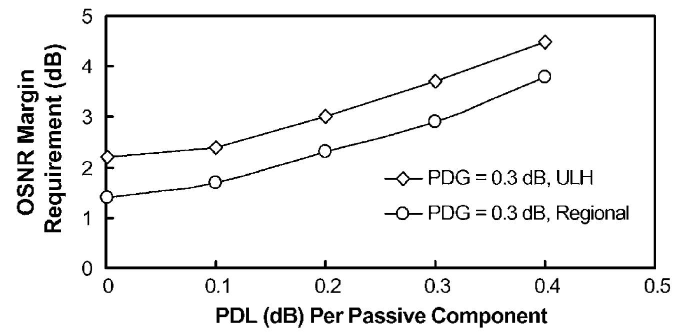

Fig. 4. Examples of OSNR margin requirements against PDL tolerance per passive component for 99.999% availability. The nominal 0.1-nm OSNR is 12 dB.

with no OADM, the OSNR margin requirements would be 1.4 and 2.2 dB for RAN and ULH systems, respectively, due to the 0.3-dB PDG penalty of 14 and 26 EDFAs. The OSNR margin requirement increases approximately at the rate of 0.7 dB per 0.1-dB PDL increase in 25 passive components. Note that this relation will be different for different nominal OSNR requirements.

V. SUMMARY

We have investigated the system impact of OSNR statistics correlated with the received power taking into account the PDL effect, to estimate the OSNR margin requirement due to PDL. For regional and ULH optical network systems with 8 and 20 fiber spans, OSNR margins of 1.4 and 2.2 dB, respectively, are required to guarantee an availability of 99.999% for EDFAs with a 0.3-dB PDG. The extra OSNR margin requirements due to additional passive components with PDL are also presented.

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