

Statistical Measurements of BER Fluctuations due to PMD in 10-Gb/s Optical Transmissions

Alexandre Bessa dos Santos, Marcelo R. Jimenez, Jean Pierre von der Weid, *Member, IEEE*, and Anders Djupsjöbacka

Abstract—Polarization-mode dispersion induces signal fading and fluctuating power penalties in optical systems. The intrinsic uncertainty of the bit error rate (BER) measurements combined to the time needed to perform power adjustments for a power penalty measurement can completely distort the statistics of the as-measured power penalties. We show that measuring the BER statistics and using the receiver sensitivity power dependence gives a better measurement of the power penalty statistics. The influence of the statistics of error detection in the measurements must be considered in order to define the correct measuring time for each situation.

Index Terms—Fluctuations, optical communications, polarization, polarization-mode dispersion.

I. INTRODUCTION

THE POLARIZATION-MODE DISPERSION (PMD) of a transmission fiber, which can be regarded as an overall fluctuating birefringence with a variable differential group delay (DGD), causes dual path propagation in the fiber. In high-capacity long-distance communications systems, PMD imposes a potential limit in the maximum bit rate—distance product of the system contributing to bit error rate (BER) deterioration, performance fluctuations, or system fading even in the moderate bit rate—distance product regime [1]. Combined with PDL or multipath interference noise (MPI) even the smallest PMD fiber will give rise to fading effects related to the fluctuations of the polarization state. The phenomena become stochastic and the related power penalties random variables, which must then be treated statistically.

The power penalty is the system designer parameter, and most of the PMD work use the statistics of the power penalty to evaluate the impact of the PMD in a system [2]–[5]. However, when an experiment is performed the quantity which directly measured is not the power penalty, but the number of errors after a certain number of bits is transmitted, i.e., the BER. If the power penalty is to be determined, the received power must be adjusted in order to attain a given BER, this power being then compared to the back-to-back sensitivity. Because the measurement of the

BER also involves a statistics, the number of measured errors defines the interval within which the error probability will be for a given confidence level. Hence, the adjustment of the power to lock the BER at a given level is an operation full of uncertainties, which takes a long time to be performed mainly due to the low levels of error rates involved. The measurement of the BER statistics at a fixed received power level is much more precise because the received power is a deterministic quantity, which can be adjusted and kept fixed at the millisecond time scale even if polarization-dependent losses are present. The power penalty statistics can then be extracted combining the BER statistics with the receiver sensitivity curve, which can be measured with arbitrary precision. Because both the BER measurements and the PMD are stochastic phenomena, two questions arise when dealing with their statistical measurements. 1) How fast should one measure the BER in order to be sure that the stochastic process was unaltered during this measurement? 2) What is the admitted error in a BER measurement, which would still allow one to verify its fluctuations due to the relevant parameter statistics? In this letter, we address these questions in the framework of PMD distortion effects.

II. THEORETICAL CONSIDERATIONS

Let $\{x_i\}$ be a collection of N independent random variables such that $x_i = 0$ if there was no error at the i th received bit and $x_i = 1$ if there was an error at that bit. Then x_i are random Bernoulli variables, where $P(x_i = 1) = p$ is the error probability. The expected value of x_i is

$$E(x_i) = 0 \cdot (1 - p) + 1 \cdot p = p. \quad (1)$$

The number of errors will then be given by

$$N_e = \sum_{i=1}^N x_i \quad (2)$$

which is a random binomial variable with parameters N and p . The BER can be written as

$$\text{BER} = \frac{N_e}{N} = \frac{1}{N} \sum_{i=1}^N x_i \quad (3)$$

and is also a random variable with expected value given by

$$E(\text{BER}) = \frac{1}{N} \sum_{i=1}^N E(x_i) = \frac{1}{N} \sum_{i=1}^N p = p. \quad (4)$$

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A. B. dos Santos, M. R. Jimenez, and J. P. von der Weid are with the do Rio de Janeiro, Rio de Janeiro, 22453-900 RJ, Brazil (e-mail: vdweid@cetuc.puc-rio.br).

A. Djupsjöbacka is with Ericsson Telecom AB Optical Networks Research Laboratory, S-126 25 Stockholm, Sweden (e-mail: etxdjup@kk.etx.ericsson.se).

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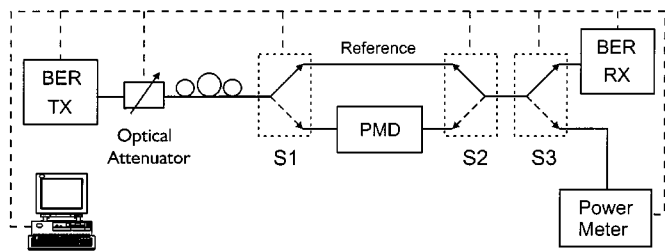


Fig. 1. Experimental setup for the measurements of the BER statistics.

The variance of the BER will be

$$\begin{aligned}
 V(\text{BER}) &= \frac{1}{N^2} \sum_{i=1}^N V(x_i) = \frac{1}{N^2} \sum_{i=1}^N p(1-p) \\
 &= \frac{p(1-p)}{N}.
 \end{aligned} \tag{5}$$

Hence, the standard deviation of the BER, which is the square root of its variance, is proportional to the inverse square root of the total number of transmitted bits during the BER measurement

$$\text{SD}(\text{BER}) = \sqrt{\frac{p(1-p)}{N}}. \tag{6}$$

In PMD-related evaluation measurements, there is another random variable which is the power penalty induced by the signal distortion or power fluctuations. Now p becomes itself a random quantity, varying as the DGD and higher distortion levels vary with time. The best way to evaluate the impact of PMD in the system is to measure the statistics of p by measuring repeatedly the BER while the polarization effects evolve with time. Hence, we are evaluating p and its statistics through a number of BER measurements and (4).

III. EXPERIMENTAL ANALYSIS

In order to answer the questions 1) and 2) above, one must perform a comparison between the statistics of the BER for different number of bits N and compare a reference path (without PMD or any other signal distortion source) with the test path. The experimental setup is presented in Fig. 1, and is essentially the same as described in [6]. Two optical switches (S1 and S2) commute the measuring system between the test and reference optical paths. A variable attenuator adjusts the optical power transmitted through the test and reference paths to be the same for each measurement. A third switch (S3) commutes the signal between the power meter and the 10-Gb/s BERT receiver, which uses a pin detector with no optical preamplification. The power reproducibility of the switches was tested to be 0.006 dB over a set of 2000 repeated measurements. A pseudorandom bit sequence of $2^{31} - 1$ bits of the BERT was used. Angular polished connectors were used to avoid interferometric noise and for each test path measurement a new reference point was measured. Two PMD emulators (12 and 28 ps) with 20 sections of Hibi fibers were used, both emulating first order PMD and also second-order PMD to some extent [7]. The temperature of the

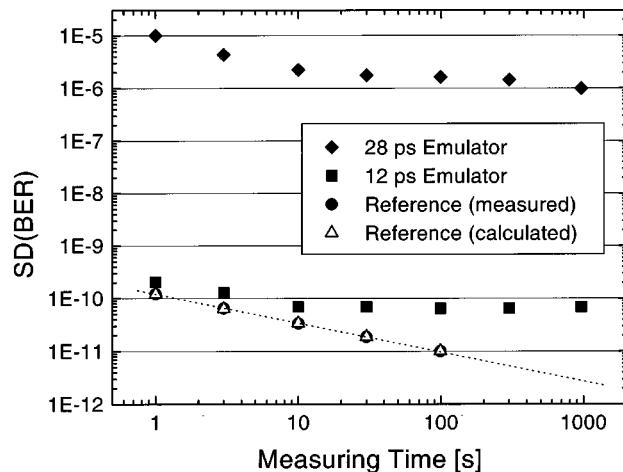


Fig. 2. Standard deviation of the BER as a function of the BER measuring time for a 28-ps PMD emulator (diamonds), a 12-ps PMD emulator (squares), and the reference path (circles) compared to the calculated standard deviations for the reference path (triangles).

emulators was forced to randomly vary during the experiments, the statistics being obtained with a set of ~ 1000 measurements.

Fig. 2 presents the standard deviation of the measured BER values in the two emulators and the reference path as a function of the measuring time from 1 to 1000 s, corresponding to a total number of bits ranging from 10^{10} to 10^{13} bits at 10 Gb/s. The power was set to -19.5 dBm in all measurements. Because the number of detected errors is a random variable, the width of the reference path distribution depends on the measuring time according to (6), even if the error probability p is fixed. This is the case of a fixed thermal noise level at the receiver and the agreement of the experimental and calculated standard deviations confirms this statement. On the other hand, p is itself a random variable in the test path, so that the width of the corresponding BER values distribution will increase accordingly. A precise evaluation of the PMD-induced BER statistics will require the sharpest test path distribution so that the BER uncertainties due to the finite number of detected errors do not affect the measurements of the BER fluctuations due to the DGD and other stochastic variables related to PMD. From Fig. 2, we see that the small number of bits affects the measurements for very short times (< 10 s), even dominating the width of the BER distribution in the 12-ps emulator. For measuring times above 10 s, the standard deviations corresponding to the emulator path stabilize whereas the back-to-back path keeps decreasing with the square root of the total number of bits used for the evaluation of the BER. This means that between 10 and ~ 100 s, the PMD evolution is slow enough to present its fluctuations and display the correct statistics, thus answering questions 1 and 2 above. For longer measurement times, the standard deviations stabilize, indicating that although the PMD evolves during the BER measurement the corresponding time is not long enough to average out the PMD fluctuations. In the case of the 28-ps emulator we note, however, a decrease at long measurement times indicating that this process is already taking place. In any case, at 30-s measuring times the BER statistics correctly reflects the power penalty statistics for both emulators.

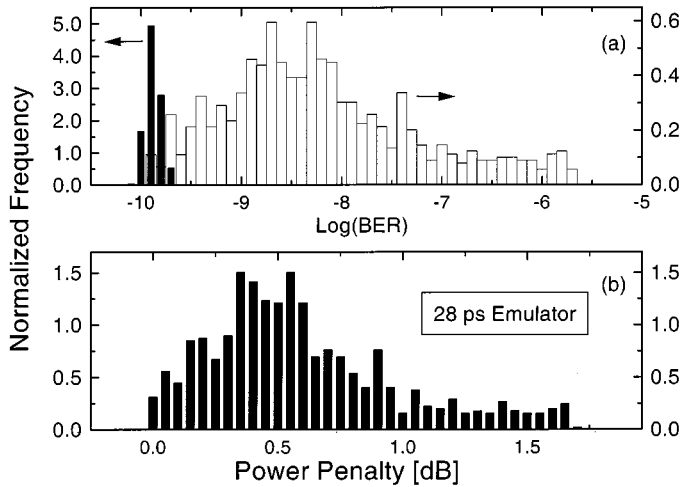


Fig. 3. (a) Statistical distribution of the BER at 10 Gb/s measured for the reference path (black columns) and for the 28-ps PMD emulator (hollow columns). The corresponding power penalty distribution is shown in (b).

In order to get the power penalty statistics, we measured the receiver sensitivity, which is described by a second order polynomial with a good approximation

$$\text{Log}(\text{BER}) = -219 - 18.2 \cdot R - 0.386 \cdot R^2 \quad (7)$$

where R is the received power in dBm. Then the power penalty statistics can be obtained from the statistics of p and solving (7) for R . Fig. 3(a) presents the distribution of the BER of the 28-ps PMD emulator and the reference path determined with 30-s measuring times at a fixed received power of -19.5 dBm, corresponding to a mean BER of 10^{-10} in the reference path. The corresponding power penalty distribution is displayed in Fig. 3(b), with 0.6-dB mean power penalty and 0.4-dB standard deviation. It is clear that a system with this level of PMD would never perform without a compensator. In the 12-ps emulator, the measured mean power penalty (0.1 dB) and standard deviation (0.04 dB) are much smaller, so that it would perform with a total power penalty smaller than 1 dB.

IV. CONCLUSION

The statistics of the BER fluctuations due to PMD was investigated with PMD emulators at 10 Gb/s. The fluctuating signal distortion due to the statistics of the PMD process gives rise to a fluctuating power penalty. Although the power penalty is the

significant parameter for the system designer, its measurement is harder and longer than for the BER statistics. This is due to the fact that the direct power penalty measurement requires the lock of the BER at a given value, and this involves the intrinsic errors due to the detected errors statistics. On the other hand, locking the received power at a given level is a direct and deterministic process, which can be performed in the millisecond scale. The most precise way to access the power penalty statistics is to measure the BER statistics and use the receiver sensitivity power dependence to reach the power penalty statistics. Of course, the receiver sensitivity will depend on the type of detector used in the front-end, a p-i-n diode in our case, and can be quite different for a receiver with signal dependent noise such as an APD. The BER statistics will depend on the receiver or on the use of optical preamplification, but once the detector is chosen, the statistics of the power penalties is determined and the method is self-adjusted for the receiver type. In any case, the influence of the statistics of error detection in the measurements must be considered in order to define the correct measuring time for each situation. This feature is particularly important in accelerated tests of system robustness using PMD emulators.

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