Automated eye diagram analysis with a bit-error-rate tester

P. Mégret, I. Rondou[1], V. Moeyaert, M. Blondel

Advanced Research in Optics, Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique de Mons, 31 Boulevard Dolez, B-7000, Mons, Belgium
Tel: +32 (65) 374194; Fax: + 32 (65) 374199; E-mail: Megret@telecom.fpms.ac.be
[1] Now with GTS, Terhulpesteenweg 6A, 1560 Hoielaart - Belgium

By using a bit-error-rate tester with variable decision threshold and variable time delay, we have experimentally measured the eye diagrams of optical links without reference to a classical digital scope. By this technique, we can thus simultaneously estimate the bit-error-rate and the eye contours which are the loci in the plane decision threshold - decision time of constant bit-error-rate. This technique has been applied to several links and the results will be presented and compared with results obtained by a scope.

Introduction

The bit-rates and number of WDM channels used in optical digital links increase drastically and tend towards Tbit/s [1]. It is thus very important for the design phase as well as for the maintenance of the networks to measure the link quality with a high degree of precision and as quickly as possible. To do this, we can measure the bit-error-rate (BER) with BER-meter which computes the ratio of the errored bits and the total transmitted bits in some measuring time or we can measure the eye diagram with a digital scope from which the Q factors can be computed to have an *estimate* of the BER. To be significant, the measuring time with a BER-meter has to follow some rules and can be very long if we want a high precision [2]. On the other hand, it can be shown [3,4] that the Q factors computed from the eye diagram traces on the scope are relatively poor estimators of low BER. To avoid these difficulties, Bergano et al [5] have developed a method based on the so-called *variable decision threshold* which allows to compute the Q factors and thus the BER with a bit-error-rate meter with a high degree of accuracy in a relatively short time.
In this paper we explain the method proposed by HP [3] to record the eye diagram with a bit-error-rate tester by using the Bergano's method and add some new functionalities.

Theory

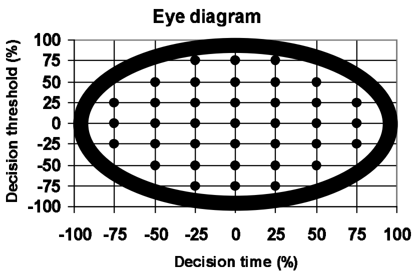

Figure 1: Schematic eye diagram normalized to the bit-rate and to the peak-to-peak signal

Figure 1 shows a schematic normalized eye diagram obtained from a scope trace. To get an image of this eye diagram with a BER-meter, the BER must be measured in function of the decision threshold E (vertical axis on Fig. 1) and of the decision time t_d (horizontal axis on Fig. 1). By correctly choosing the grid inside the eye diagram and the measuring time of each point (•), it is possible to obtain BER points from which BER constant contours can be interpolated to give an idea of the shape of the eye diagram. It is

important to point out that these BER measurements do not rely on any hypothesis about the noises and are very accurate as soon as the measuring time for each point is long enough. The total measuring time to get the eye diagram can thus be very long as soon as we want the constant low BER contours.
It is therefore interesting to find a way to reduce the total measuring time to obtain the eye diagram and this can only be done by introducing some hypothesis.
Under the *gaussian* approximation of the noises corrupting the ones and the zeroes and assuming that the probabilities of emitting a '1' and a '0' are equal to 1/2, one can write [3,4,5] the BER at the decision time t_d and with the decision threshold E, as:

$$BER(E,t_d)=\frac{1}{4}\left[erfc\left(\frac{E-\mu_0(t_d)}{\sqrt{2}\sigma_0(t_d)}\right)+erfc\left(\frac{\mu_1(t_d)-E}{\sqrt{2}\sigma_1(t_d)}\right)\right] \quad (1)$$

where erfc(x) is the (classical)[1] complementary error function [6] and $\mu_i(t_d)$ and $\sigma_i(t_d)$ are the means and variances for a '1' (i=1) and a '0' (i=0).
The technique developed by Bergano consists of measuring, for a given t_d, the BER versus E and to limit these measurements on BER values which can be obtained quickly with a high precision. For each t_d, E is first fixed to $\mu_0(t_d)$ and increased by a fixed or variable amount. $BER(E,t_d)$ is then measured until E is too far from $\mu_0(t_d)$ to give an accurate measurement in a reasonable time. Then E is fixed to $\mu_1(t_d)$ and the same procedure is done by decreasing E until again the measurement precision requires a too long time.
When E is slightly above $\mu_0(t_d)$, the errors mainly occur on the zeroes and the second term of relation (1) is negligible. The opposite is true when E is slightly below $\mu_1(t_d)$:

$$BER^{(0)}(E,t_d)=\frac{1}{4}erfc\left(\frac{E-\mu_0(t_d)}{\sqrt{2}\sigma_0(t_d)}\right)=f(y^{(0)}) \quad \text{(a)} \qquad \text{with } y^{(0)}=\frac{E-\mu_0(t_d)}{\sqrt{2}\sigma_0(t_d)} \quad \text{(b)} \quad (2)$$

$$BER^{(1)}(E,t_d)=\frac{1}{4}erfc\left(\frac{\mu_1(t_d)-E}{\sqrt{2}\sigma_1(t_d)}\right)=f(y^{(1)}) \quad \text{(a)} \qquad \text{with } y^{(1)}=\frac{\mu_1(t_d)-E}{\sqrt{2}\sigma_1(t_d)} \quad \text{(b)} \quad (3)$$

At the end of the measurement procedure, we obtain two series $x_m^{(0)}=BER^{(0)}(E_m,t_d)$ and $x_n^{(1)}=BER^{(1)}(E_n,t_d)$ where m and n are respectively the measurement index the BER dominated by errored zeroes (Eq. 2) and by errored ones (Eq. 3). From the first series and with relation (2a), one can obtain $y_m^{(0)}=f^{-1}(x_m^{(0)})$ from which it is possible to extract the mean $\mu_0(t_d)$ and the variances $\sigma_0(t_d)$ by a linear regression because (2b) is a linear function between E_m and $y_m^{(0)}$. The same procedure is repeated for the second series to give $\mu_1(\ )$ and $\sigma_1(\ )$. Knowing the two means and the two variances it is now possible to compute BER for any E by the relation (1).

[1] In [5], another definition of the complementary error function is used. To be consistent with [6], this function should be called Q(x) and the link with the classical complementary error function erfc(z) is given by: $erfc(z)=2Q(\sqrt{2}z)$

In summary, the algorithm to measure the eye diagram is a three steps procedure for each decision time t_d :

1. Set E at $\mu_0(\quad)$ and measure $x_m^{(0)}$ as a function of increasing E until the measuring time become too long. Then set E at $\mu_1(\quad)$ and measure $x_n^{(1)}$ as a function of decreasing E until the measuring time become too long.
2. Compute $y_m^{(0)}$ and $y^{(1)}$ with the help of an analitycal function $y = f^{-1}(x)$ [5] or by a numerical inversion and estimate the means and the variances from linear regressions.
3. Compute BER for any E by the relation (1).

Experimental set-up

The experimental set-up (Fig. 2) consists of an optical link composed of an emitter, a fiber and a receiver. A PRBS signal is fed into the emitter and the error detector measures the BER as a function of the decision threshold and the decision time. To compare the estimated eye diagram, a sampling scope tracks the eye diagram in the same time.

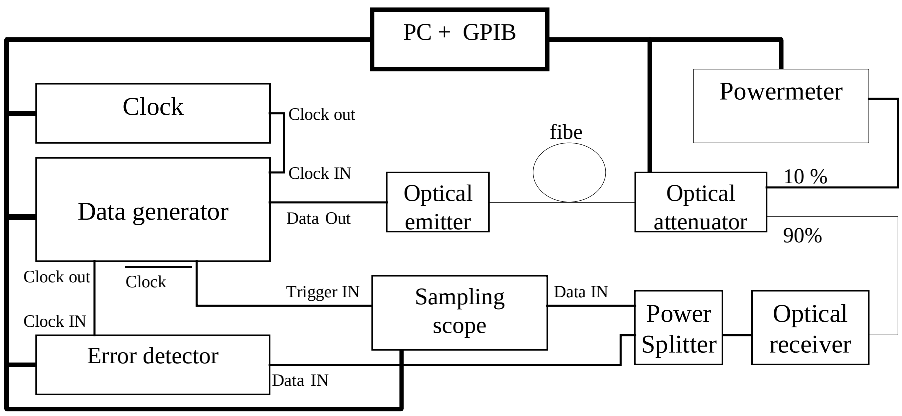

Figure 2: Experimental set-up

The results presented hereafter have been obtained on 25 km standard optical fiber with a DFB laser emitting at 1550 nm and with a high quality receiver. The bit-rate was 2.488 Gbit/s and we used a 2^{23}-1 PRBS. The grid has been divided into 11 decision times and 115 decision thresholds and each significant point has been measured during 5 minutes. Figure 3 shows the measured eye diagram obtained with a digital sampling scope from one output of the receiver whereas figure 4 shows the constant bit-error-rate contours from 10^{-2} to 10^{-16} computed from the BER measurements obtained from the second receiver output.

To obtain figure 4, we have proceeded in three steps as described above. As an example, for the central delay, we obtained from the errored zeroes $\mu_0 = -239.5$ mV and $\sigma_0 = 5.27$ mV and from the errored ones $\mu_1 = 202.6$ mV and $\sigma_1 = 3.83$ mV . From these means and variances, the data points at t_d=0 are computed and display. The BER we can expect if the decision threshold is set at the optimum is nearly zero because Q is of the order of 48.

In order to be able to test the different hypothesis, we have added the following functionalities: for each measured point on the grid we record the one-second time evolution and we measure the error count, the BER on ones, the BER on zeroes and the total BER. From the error count, we can test the BER precision and from the individual BER on ones and zeroes, we can verify when the errors are mainly dominated by the errored ones or errored zeroes and choose the data for the estimations of the means and the variances. From the time behavior, it is possible to test the absence of error bursts and thus have a better idea of the gaussian approximation.

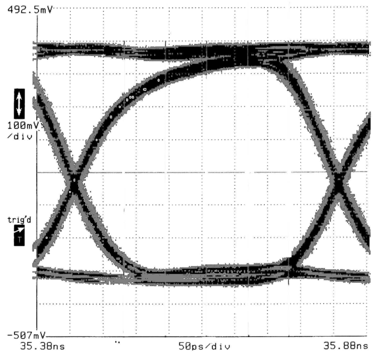

Figure 3: Measured eye diagram on the scope

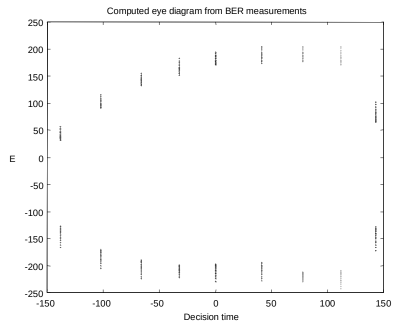

Figure 4: Eye diagram contours from 10^{-2} to 10^{-16} obtained from BER measurements.

Conclusions

We have developed an home-made program which allows to estimate the eye diagram from BER measurements. This package is device independent provided that the BER tester has variable decision threshold and variable decision time. We have added some new functionalities to be able to test the hypothesis used in the Bergano's method as well as to better understand the link behavior

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