Algorithm for Accurate Numerical Eye Opening Evaluation

J.E.S. Machado[1,2], Armando Pinto[2, 3]

[1] PT Inovação, S.A. Rua Eng. José Ferreira Pinto Basto, 3810 - 106 Aveiro – Portugal
Phone: (+351) 234 403 200, Fax: (+351) 234 424 723
[2] Instituto de Telecomunicações - Polo de Aveiro, Campus Universitário de Santiago 3810-193 Aveiro – Portugal
3 Electronic and Telecommunication Department, University of Aveiro, Campus de Santiago, 3810-193 Aveiro - Portugal.
Emails: est-j-machado@ptinovacao.pt; anp@det.ua.pt

***Abstract* — This paper presents a reliable eye opening numerically evaluation algorithm. The algorithm is able to determine the eye aperture considering a user specified window even in the presence of strong signal degradation.**

***Keywords*- eye opening, eye opening evaluation**

I. Introduction

High-speed optical transmission systems suffer from various impairments that lead to signal degradation. The eye opening is a frequently used measurement to quantify the systems performance. Comparatively with other measurement techniques, like the Q-factor, the eye opening figure gives valuable results even in the presence of strong inter-symbolic interference. The evaluation of the eye opening directly from the eye diagram is a simple process. However, to automatically and accurately estimate the eye opening aperture in the presence of strong signal degradation is not a trivial process [1,2]. This task is normally accomplished manually, using “paper sheet and pencil”, being a time consuming and error prone process.

In this work a new algorithm is presented to accurately and automatically evaluate the eye aperture (*H*) over a predefined time window, see figure 1. The width of the time window is specified in order to take into consideration the limited accuracy of the receiver clock extraction circuit and other possible sources of timing jitter not include in the numerical model. Therefore the time window defines the time span from which the signal can be sampled in order to guarantee a given power margin.

The eye aperture (*H*) quantity is useful for signal assessment when inter-symbol interference (ISI) is present on the signal, and its analysis along a transmission link, can be translated on the eye open penalty (EOP) that is usually an asset on signal wave-shape distortion degradation evaluation [3,4], better then in the systems where signal dependent noise distortion dominates, from where bit error rate gives a reliable quantity of the signal quality in terms of Q-factor [5]. The separation of noise from distortion can also be an issue when evaluating high-speed optical fiber system impairments, and *H* can also be a critical numerical quantity looking forward to obtain reliable numerical models concerning the separate analysis of noise and distortion [6].

A brief overview on sources of waveform distortion for high bit-rate optical communication systems is presented in section II. The *eye opening* algorithm is explained in section III. In section IV the algorithm is applied to a set of signals suffering from strong degradation, and its performance is evaluated. Final conclusions and remarks are stated at section V.

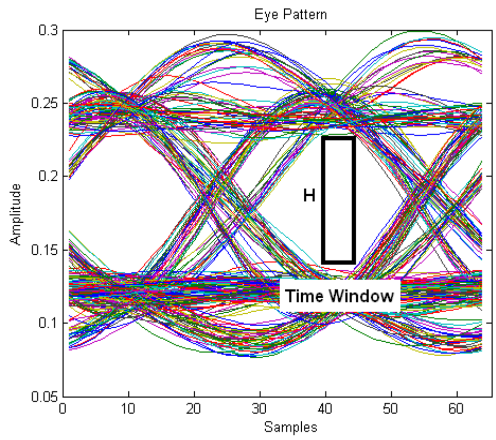


Figure 1 – Eye Opening Time Window

II. Short Overview on Sources of Waveform Distortion

Regarding to high-speed optical communication systems, we may point ISI, amplified spontaneous emission (ASE) noise and timing jitter as the main factors leading to bit error in the receiver.

ISI typically comes out due to chromatic dispersion (CD), polarization mode dispersion (PMD) and also from optical and/or electrical active filtering [7].

ASE noise, as other noise sources coming out from active optical network elements may also be relevant in terms of eye closure [8].

Timing jitter usually arises due to the quadratic detection at the optical receivers, which leads to signal to optical beating [8]. This time uncertainty can be enhanced if the optical

This work was in part supported by the ADI – Agência de Inovação, in the context of the “The Most – Transimpedance Highly Efficient Micro&milimetrewave Optical Smart Transceiver” project.

power transmitted is enough to make the nonlinear effects in the optical fibers relevant. The nonlinear effects can also cause signal distortion if the system is very long or if high levels of optical power are injected into the fiber [8].

Amplitude jitter due to intra-channel nonlinear interaction is another source of degradation that can contribute for the eye closure [8].

III. Eye Opening Algorithm

The *eye opening* algorithm that will be next presented is intended to evaluate the eye opening (*H*) over a predefined *time window* in which the signal can be sampled with the same noise margin. By looking at figure 1, we find that it is not that hard to point the maximum window height, *H*, just only by using our own eyesight. By the other side it is not that easy to numerically and accurately evaluate it, especially when strong waveform distortion is present along the communication system.

For accurate *H* evaluation, the receiver should first have knowledge about the original incoming binary sequence. This condition is met in a simulation environment by feeding the receiver directly with a copy of the transmitted sequence. It worth point out, that this same procedure is needed in the laboratory to perform bit error rate measurements. Pseudo-random sequences are usually used in such procedures.

To estimate the eye opening we need to define the number of symbols that we use to draw the eye diagram (*NumSym*). This number must be large enough to consider also possible combinations of bits with relevance for ISI. Therefore the receiver is fed with two signals. One of them is the transmitted signal - in the numerical model we use a set of samples per symbol (*SampSym*) to represent this signal. For the example in figure 2, the transmitted signal comes as *sig(c)*, being c the number of signal samples. Also for the example in figure 2, we state *NumSym* = 4 and *SampSym* = 6. The other one is a logical signal, which in the considered example is 0101. The first thing to do is to expand the logical signal in order to have the same number of samples per symbol, *ref*(c). Two functions must also to be defined *High(c)* and *Low(c)*. For definition of the Low(c) and High(c) variables, a simple algorithm is next presented. Low(c) was assumed to be previously initialized with zero values and High(c) with a value greater or equal to max(sig(c)).

```
WIN = NumSym*SampSym;
for c=1:WIN
  for aux1=1:SampSym:WIN
    case ref(c+aux1-1)
      0: Low(c) = max(Low(c), sig(mod(c+aux1-1,WIN));
      1: High(c) = min(High(c), sig(mod(c+aux1-1, WIN));
    end
  end
```

The difference between *High(c)* and *Low(c)* for each sample will be another function that states for the eye opening aperture according with the decision time, see *eyeopen* in figure 3 (a). The maximum of this function is the maximum eye opening that we can achieve when considering an ideal decision time. In order to account for uncertainties at the decision time, a time window is needed that guaranty a minimum margin over a time interval. A typical value for this window is 20% of the time bit [3]. Wider windows show robustness to timing jitter. H is the maximum eye aperture for the considered time window, see figure 3(b). Figure 3 (b) is the result of a 3-sample time window applied over the *eyeopen* function presented in figure 3 (a). See hereafter a simple algorithm to clearly understand time window procedure. *WindowSamp* is the number of time window samples, which is directly obtained from the specified time interval and the sampling frequency used in the numerical model.

```
for k = 1:(length(eyeopen)- WindowSamp +1),
  Hmax(k) = min(eyeopen(k: WindowSamp +k-1));
end
```

Note that wider the window width, larger would be the receiver timing jitter tolerance and consequently more margin we are accounting for, however the eye aperture will be smaller.

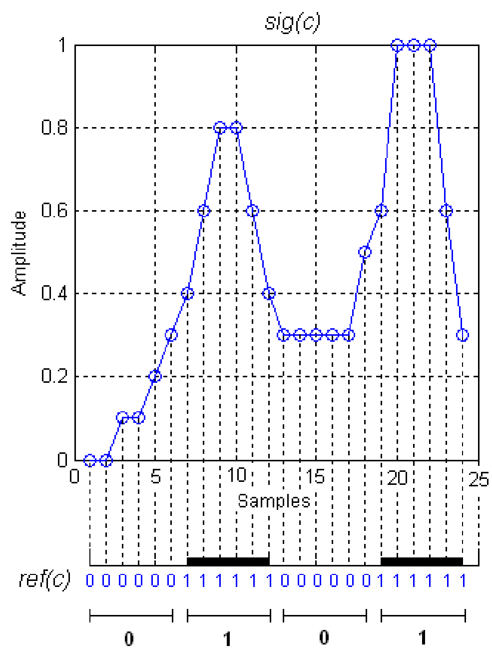
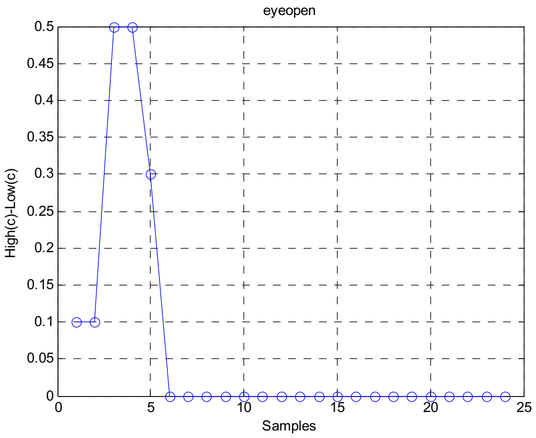
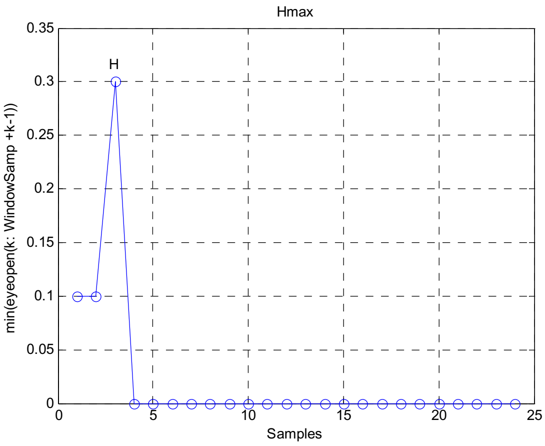


Figure 2 – Signals synchronization. Received signal vs reference signal (*NumSym* = 4, *SampSym* = 6)



(a)

Figure 3 – (a) *eyeopen* function presenting the eye aperture



(b)

Figure 3 – (b) eye opening after applying a 3-sample window width

In the example of figure 2 and 3, the received signal has an eye opening of H = 0.3, when considering a 3-sample window, corresponding to 50% of the bit period.

IV RESULTS FOR HIGHLY DISPERSIVE CHANNELS

We next present two eye pattern examples where severe signal distortions are shown.

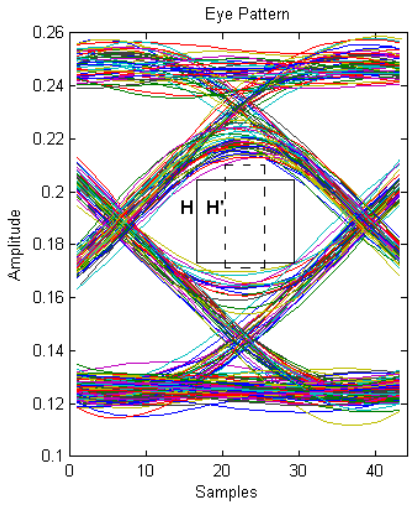
A 40Gbit/s non return-to-zero (NRZ) signal, after 5km of standard mono-mode fiber (SMF) optical channel with CD parameter equal to D=17ps/nm/km and a Differential Group Delay (DGD) set to $\Delta\tau$ =2ps is presented in Figure 4(a), while in Figure 4(b) the same channel is increased to 6km of fiber length and the CD and DGD parameters are set to D=21ps/nm/km and $\Delta\tau$ =18ps, respectively. In this last diagram, an adaptive fractionally spaced equalizer with nonlinear phase behavior was also placed at the receiving edge. For both signals data recovery may easily be an hard experience, being Q-Factor estimation a low reliable measurement quantity due to the strong inter-symbolic interference, which causes non-gaussian statistics for both ‘1’ and ‘0’ detection levels.

In figure 4, two possible window widths were enabled, giving rise to both different eye opening heights, H and H’, corresponding to wider and narrower values of window widths correspondingly.

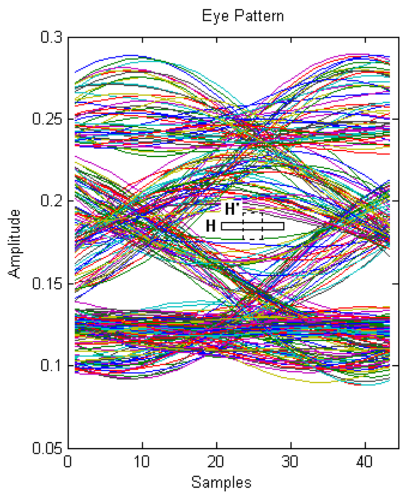
Eye opening (*H*) values in terms of the window width for both eye patterns of figure 4 are presented at figure 5. Note that the window width comes in percentage of the incoming time bit, which for 40 Gbit/s means 25ps.

As larger the window width, lower the *H* value is, like it can also be seen in figure 5. We may evaluate signal timing and amplitude jitter robustness by looking at the x-axis and y-axis, figure 5, correspondingly.

This trade off between window width and eye opening height may also be seen as a relevant concern for receiver design.



(a)



(b)

Figure 4 – Eye Patterns showing up with two eye apertures, H and H’, for different window widths (a) After 5km of SMF (D = 17ps/nm/km, $\Delta\tau$ = 2ps) (b) After 6km of SMF (D = 21ps/nm/km, $\Delta\tau$ = 18ps) and nonlinear phase filter

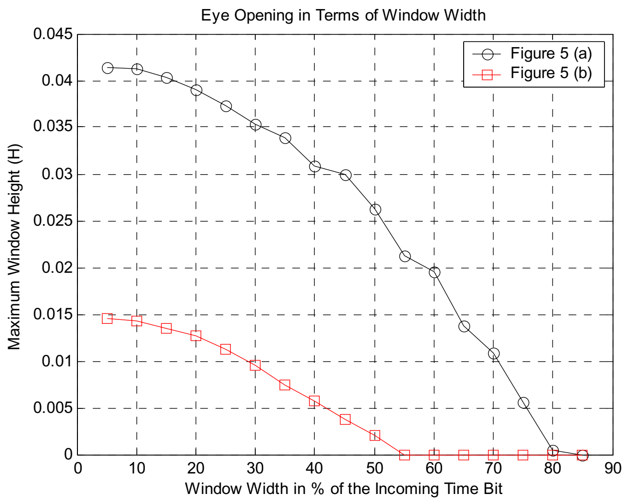


Figure 5 – Eye Opening in Terms of Maximum Window Height according to Figure 4 (a) and (b) Eye Patterns

V. CONCLUSION

The proposed *eye opening* algorithm is a reliable solution for numerical eye opening evaluation, even when data signal is affected by strong waveform distortions. The robustness of this algorithm is intended to make it suitable for new approaches in signal quality evaluation, especially under very high bit rate optical channels, where chromatic dispersion and polarization mode dispersion can turn ISI a dominant effect.

REFERENCES

[1] Seije Norimatsu, Masanori Maruoka, "Accurate Q-Factor Estimation of Optically Amplified Systems in the Presence of Wafeform Distortions", *IEEE Journal of Lightwave Technology*, Vol. 20, No. 1, pp. 19-27, January 2002.

[2] Hiroshi Nishimoto, Tadashi Okiyama, Naoki Kuwata, Yasunari Arai, Akira Myauchi, Takashi Touge, "New method analyzing eye patterns and its application to high-speed optical transmission system", *IEEE Journal of Lightwave Technology*, Vol. 6, No. 5, pp. 678-685, May 1988.

[3] Elbers, P; Farbert A.; Scheerer C.; Glingener C.; Fischer G., "Reduced model to describe SPM-limited fiber transmission in dispersion-managed lightwave systems", *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 6, No. 2, pp. 276-281, March/April 2000.

[4] Pizzinat, A.; Schiffini, A.; Alberti, F.; Matera, F.; Pinto, A.N.; Almeida, P. "40-Gb/s systems on G.652 fibers: comparison between periodic and all-at-the-end dispersion compensation". *IEEE Journal of Lightwave Technology* Vol. 20, No. 9, pp. 1673- 1679, September 2002.

[5] Marcuse, D. "Derivation of analytical expression for the bit error probability in lightwave systems with optical amplifiers", *IEEE Journal of Lightwave Technology*, Vol. 8, Issue. 12, pp. 1816-1823, December 1990.

[6] Hui R.; Vaziri M.; Zhou J.; O'Sullivan M., "Separation of noise from distortion for high-speed optical fiber system link budgeting", *IEEE Photonics Technology Letters*, Vol. 11, No. 7, July 1999.

[7] J. E. S. Machado, A. N. Pinto, J. M. Santos, P. M. Monteiro, M. Violas, L. M. R. Teixeira, "Transversal Filter Model for High Bit Rate Optical Channel Equalization", *II Symposium on Enabling Optical Networks*, 14th of June 2004, Oporto – Portugal.

[8] Govind P. Agrawal, "Fiber-Optic Communication Systems", *Wiley Series in Microwave and Optical Engeneering,* New York, 2002.