Efficient and accurate computation of eye diagrams and bit error rates in a single-channel CRZ system

R. Holzlöhner,[1] C. R. Menyuk,[1,2] V. S. Grigoryan,[1] and W. L. Kath[3,1]

[1] *Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County, TRC 201 B, 1000 Hilltop Circle, Baltimore, MD 21250*
tel: 410-455-3318, fax: 410-455-6500, email: holzloehner@umbc.edu
http://www.photonics.umbc.edu/

[2] *PhotonEx Corporation, 200 MetroWest Technology Park, Maynard, MA 01754*

[3] *Department of Engineering Sciences and Applied Mathematics, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208*

Abstract: We use linearization to compute the noise evolution in a 10 Gb/s single-channel chirped RZ system over 6,100 km, transmitting 32 bits. The linearization allows us to efficiently and accurately compute eye diagrams and error rates without the use of Monte Carlo simulations.

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1 Introduction

Bit error rates and eye diagrams in optical transmission systems are commonly estimated by running Monte Carlo simulations and extrapolating the results [1]. This method is time consuming and not always reliable. In this work, we report on the application of linearization [2, 3] to calculate the eye diagrams and bit error rate in a single-channel chirped return-to-zero (CRZ) system propagating over 6,100 km. We focused on this system because it is well-characterized in simulations [4, 5] and it is similar to a single one of the channels in some commercial WDM submarine systems [6].

Our simulated transmission line consists of 34 dispersion maps of length 180 km each, or 6,120 km in total. Each map contains a normal span of 160 km and dispersion $D_n = -2.5$ ps/nm-km and an anomalous span of 20 km and $D_a = 16.5$ ps/nm-km. We use pre- and post-compensating fibers with a total dispersion of 920 ps/nm. The loss is compensated by an EDFA every 45 km with a spontaneous emission factor of $n_{\mathrm{sp}} = 2.0$. The signal pulses are co-polarized and have a FWHM duration of 28 ps with a chirped raised-cosine shape and an initial peak power of 1 mW before the pre-compensation. We transmit a pseudorandom bit sequence of $2^5 = 32$ bits, exhausting all possible bit patterns of length 5.

As we did previously [3], we calculate the linearized evolution of the noise around the noise-free signal without the use of Monte Carlo simulations. The new contribution here is that we remove the phase jitter from the covariance matrix at each amplifier, which allows us for the first time to deal with strings containing many overlapping bits. The optical noise at the receiver is multivariate Gaussian-distributed after the phase jitter is removed from the noise [2, 3]. Each pulse in the signal can have a different phase, which must be separately removed. In a system in which pulses do not overlap, such as a soliton system, the phase jitter can be easily removed for each pulse individually. In the present system, however, the maximum pulse duration is about 500 ps, leading to a significant pulse overlap. We find that the phase jitter can still be removed in the simulation after linearly recompressing the pulses by compensating the amount of total accumulated dispersion. This procedure separates the pulses, is fully reversible, and was used previously to measure pulse distortion in CRZ systems [5]. After the phase jitter is removed, the opposite dispersion is used to restore the signal shape. We find that timing jitter is small and does not have to be removed. We verified that the probability density functions (pdfs) of the narrow-band filtered receiver voltage in the marks and the spaces of our linearized approach, averaged over all 32 bits, agree with the histogram obtained from a traditional Monte Carlo simulation, as displayed in Fig. 1. Even in the absence of noise, our simulation shows that inter-symbol interference leads to significant amplitude jitter. Hence, bit pattern effects are important. In Fig. 2, we compare the averaged pdf of the marks in Fig. 1 with the separate contributions to the pdf of the lowest (worst) and highest (best) noise-free mark, and we do the same for the spaces. We see that near the

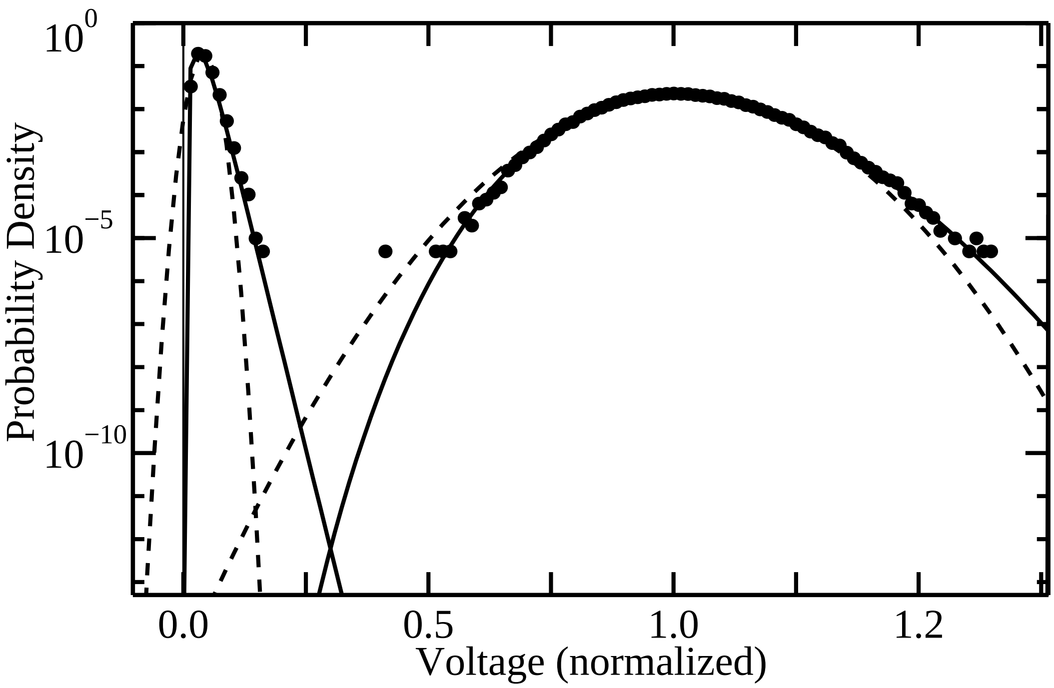

Fig. 1. Histogram of a traditional Monte Carlo simulation (dots) with Gaussian fits of the data points in the marks and spaces based on their mean and variance (dashed lines) and the pdf of the linearization method (solid line). All data are averaged over 32 bits.

intersection of the pdfs, the average pdfs are dominated by the worst bits. Thus it is possible to estimate the BER by focusing on the worst bits. Fig. 3 shows the corresponding eye diagram of all 32 bits.

In conclusion, we find that the critical part of the deterministic noise linearization method [3], the removal of the phase jitter, can still be carried out in a system with strong noise and multiple pulses that strongly interfere. In the future, we will apply the noise linearization method to WDM CRZ systems.

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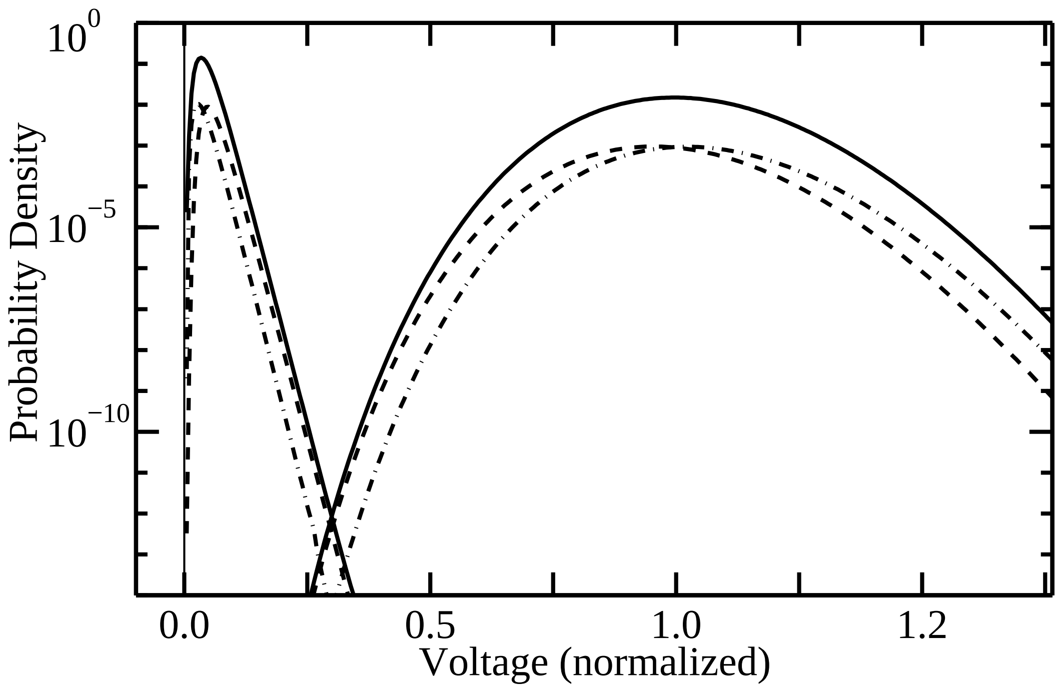

Fig. 2. Average pdfs (solid lines), compared with the contributions to the pdfs of the worst (dashed lines) and best (dash-dotted lines) mark and space.

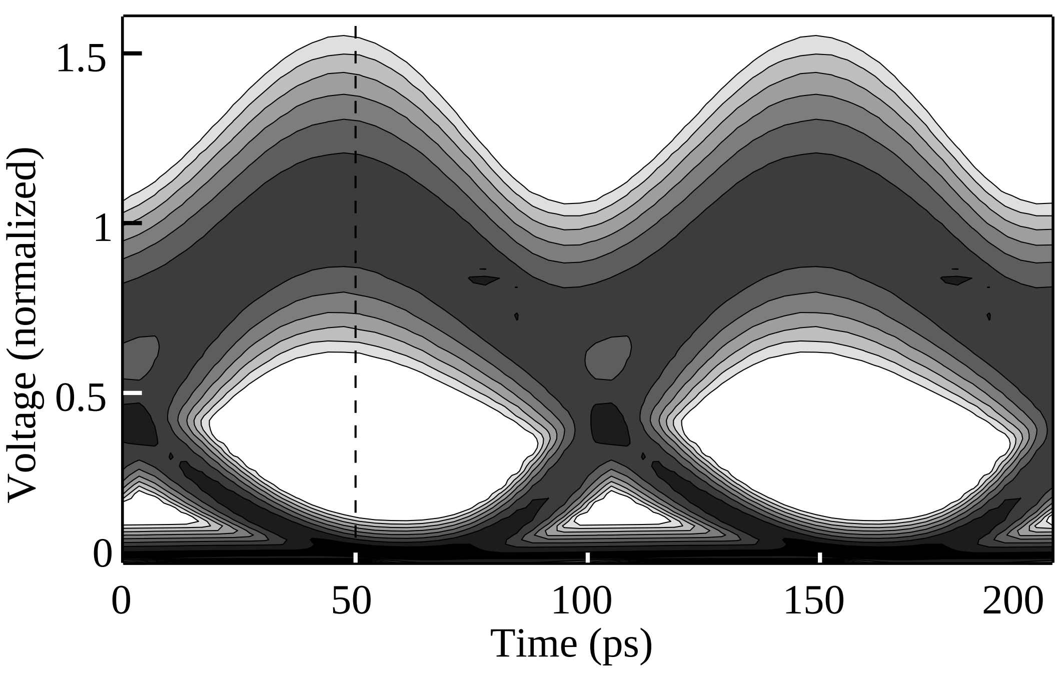

Fig. 3. A contour plot of the logarithm of the pdf as a function of time showing the eye diagram. The pdfs in Fig. 1 where taken at $t = 50$ ps (dashed line).