Direct calculation of the noise evolution in a highly nonlinear transmission system using the covariance matrix

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Abstract: We compute the complete statistical properties of the noise evolution in a dispersion-managed soliton system at 10 Gb/s over 24,000 km using covariance matrices. The method is fully deterministic and computationally efficient.

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Amplifier spontaneous emission (ASE) noise sets the lower limit on the allowed system power in current optical fiber communications systems [1, 2]. During the optical propagation, ASE noise distorts the signal shape and leads to amplitude and timing jitter, deteriorating the bit error rate (BER). The ASE noise spectrum of each optical amplifier is white over the spectral width of one channel. However, due to the nonlinearity of the optical fibers, the noise beats with the signal, resulting in a modified noise spectrum. The traditional computation of the probability distribution function (pdf) of the electrical signal in the receiver, based on Monte Carlo simulations, only works for a limited range of BERs beyond which the BER has to be extrapolated [3].

In this work, we report for the first time the successful direct calculation of the covariance matrix $\mathcal{K}$, that characterizes the noise propagation, in a dispersion-managed soliton (DMS) system at 10 Gb/s over a distance of 24,000 km [4]. We transmit the 8-bit sequence 11101000 in a time window of 800 ps in a single channel; all pulses are co-polarized. The calculation that we present here is completely deterministic in contrast to our earlier work in which we reported the calculation of $\mathcal{K}$ based on Monte Carlo simulations [5]. This deterministic approach requires substantially less CPU time while producing a much higher level of accuracy. For example, in the case considered here, the approximation of the covariance matrix with 5,000 Monte Carlo realizations required 72 hours of CPU time, while our present method required only 5 hours of CPU time on a 400 MHz Pentium III PC. The propagation length is 400 times the nonlinear scale length $1/(\gamma P_{\text{peak}})$, where γ is the nonlinear coefficient and P_{peak} is the peak power. Hence, the present system is a stringent test of our approach.

We showed earlier [5] that in order for the linearization to remain valid in this highly nonlinear system, it is necessary to remove the phase and timing jitter from $\mathcal{K}$. When using Monte Carlo simulations to infer $\mathcal{K}$, we could carry out this separation at the end of the optical fiber propagation. By contrast, in the deterministic approach presented here, it is necessary to separate the contributions to the phase and timing jitter at each EDFA. This way, $\mathcal{K}$ only describes the part of the noise that does not rotate the phase of the signal or shift its central time. At the same time, we track the variance of the timing jitter. When the final eye diagram of the receiver voltage after square-law detection is computed, phase jitter is irrelevant, while the amount of timing jitter that was removed can be reintroduced. When transmitting multiple pulses, as in the present simulation, the phase and timing jitter must be removed from each pulse separately. Fig. 1 compares the pdf in the marks and spaces of the narrow-band filtered receiver voltage from our linearization method with the histogram of a standard Monte Carlo simulation. Fig. 2 shows the corresponding eye diagram.

In summary, we present a fast and deterministic way of computing the linearized noise evolution in a highly nonlinear transmission system. We are able to describe the complete statistical properties of the accumulated

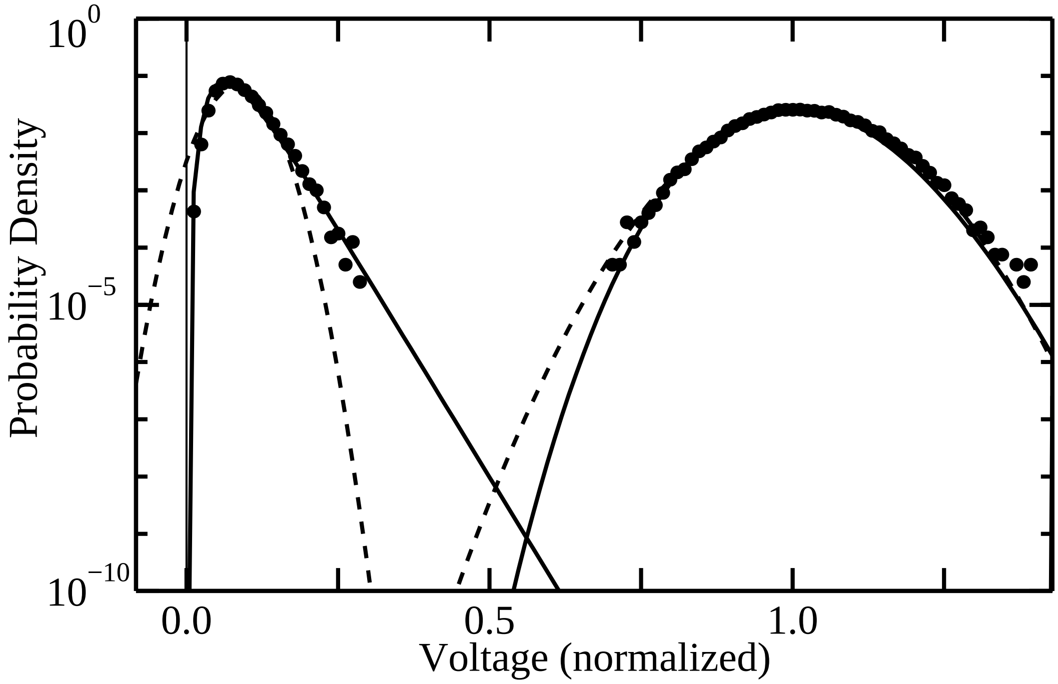

Fig. 1. Histogram from a traditional Monte Carlo simulation (dots) with Gaussian fits of the data points in the marks and spaces based on their mean and variance (dashed lines) and the result of the linearization method (solid line).

optical noise at any point along the propagation, as well as compute accurate error rates and eye diagrams.

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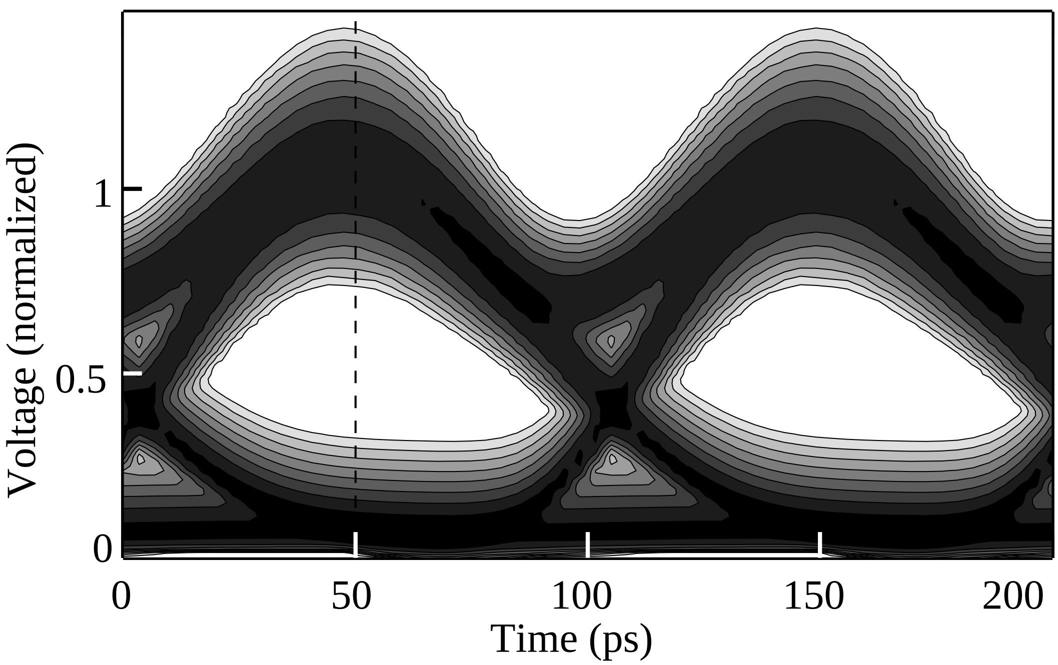

Fig. 2. A contour plot of the logarithm of the pdf as a function of time showing the eye diagram.