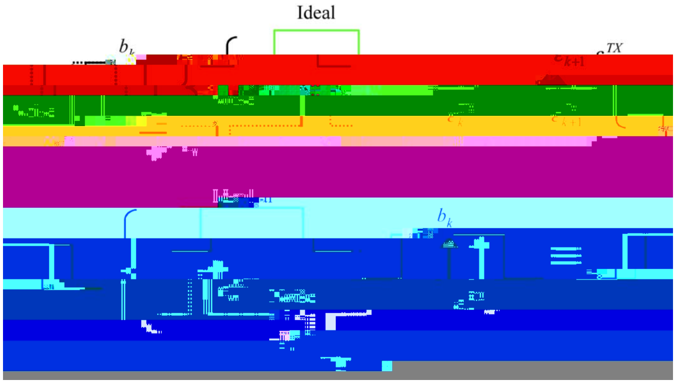


Fig. 1. Transmitter and receiver jitter models.

Note that ε_m^{RX}

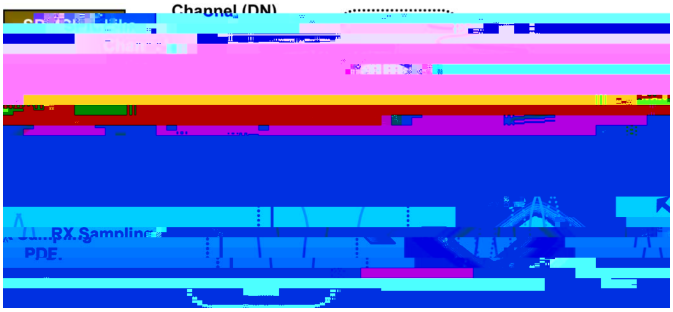


Fig. 2. Flowchart of BER calculation using statistical eye.

The overall process of BER calculation is illustrated in Fig. 2. First, the effects of ISI, jitter, and other noise sources are separated. Assuming random input data patterns and symmetric rising and falling edges [1]–[5], [8], the ISI PDF is calculated by convolving ISI components in the SBR. This approach features fast computation and accurate results. For more general systems that do not satisfy the random pattern and symmetric edges assumptions, a fast time-domain simulation technique such as multiple edge response is needed to estimate the ISI distribution [8]. Once the ISI PDFs have been calculated for each phase, they are convolved with the effective voltage noise to generate the BER eye diagram. The link BER is then calculated based on the BER eye diagram and CDR phase distribution.

III. TRANSMITTER AND RECEIVER JITTER

where $\vec{\varepsilon}_W$

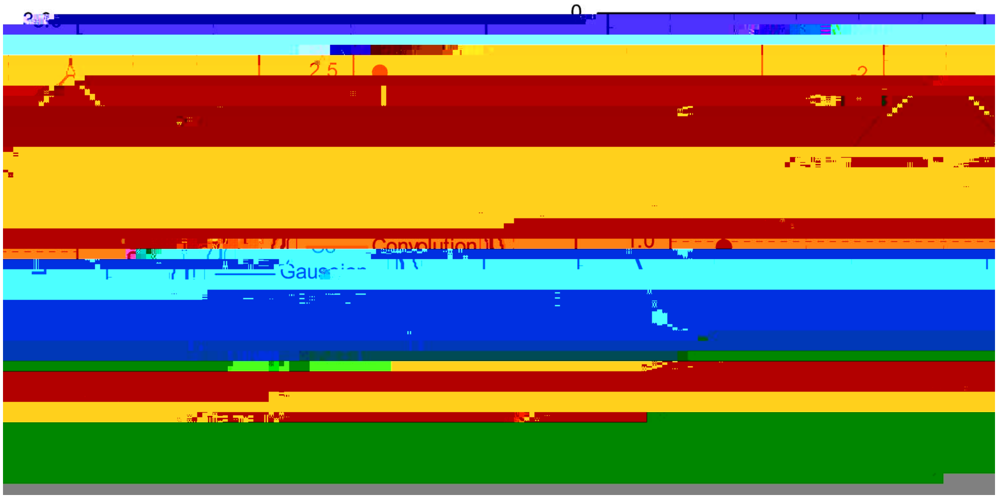


Fig. 4. (a) Distribution of λ_n and (b) PDFs of effective voltage noise using different methods at the eye center phase.

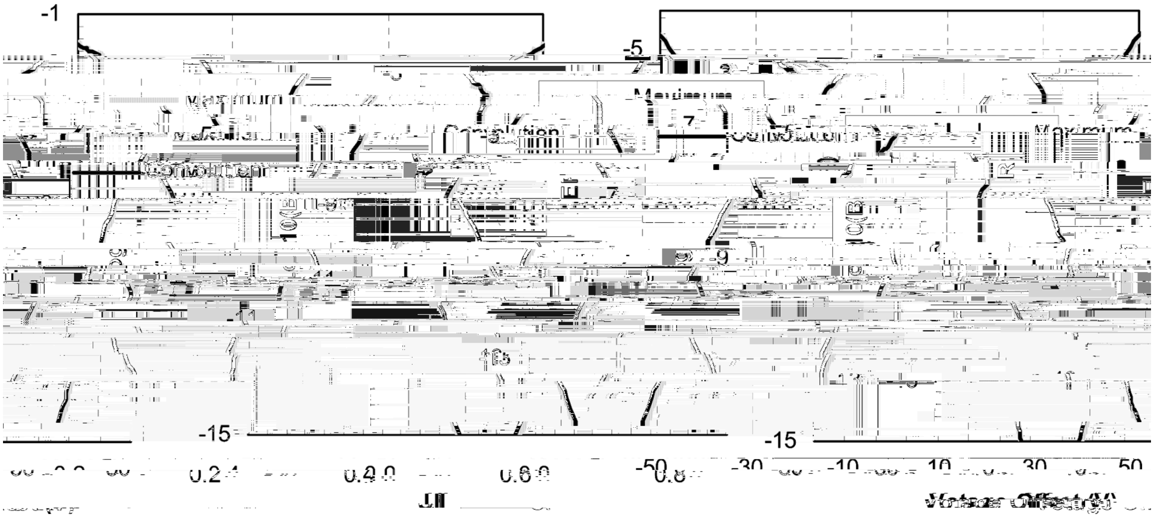


Fig. 5. Timing and voltage bathtubs calculated using different PDFs in Fig. 4.

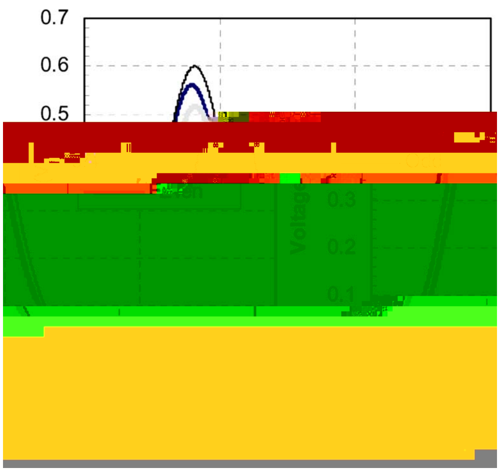


Fig. 6. Single bit responses with 10% TX DCD.

separately computing the SBRs for odd and even bits. Fig. 6 shows the SBR for a sample channel with 10% transmitter DCD.

Using the odd and even bit responses, the received signal is calculated by simply shifting and adding the corresponding single bit responses. For example, the channel response to an input sequence b_k with b_0 bit at the even bit time is obtained by

$$y_m = \sum_{2k-1} b_{2k-1} p^{\mathrm{odd}}((m-2k-1)T) + \sum_{2k} b_{2k} p^{\mathrm{even}}((m-2k)T) \quad (16)$$

where p^{odd} and p^{even} are the odd and even bit responses, respectively. Equation (16) shows that the ISI contribution from the other bits on the current bit is interleaved among odd and even bits. Therefore, the ISI PDFs for odd and even bits are computed by first interlacing odd and even ISIs in time and then computing the PDFs as usual. Fig. 7 shows the ISI PDFs for an odd bit, an even bit (10% transmitter DCD), and an ideal bit (no DCD).

In the presence of DCD, the receiver sees two different eyes, one for odd bits and the other for even bits. After computing individutter

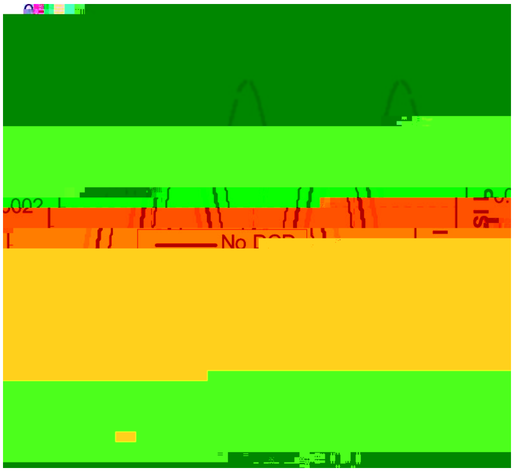


Fig. 7. ISI PDFs in presence of DCD and an ideal bit (cyan) without DCD.

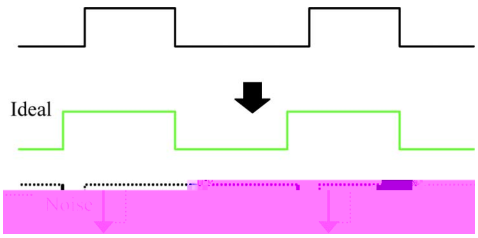


Fig. 8. Simple model of DCD.

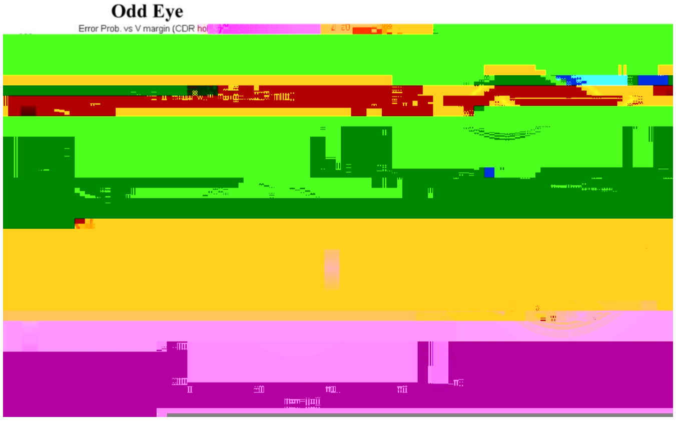


Fig. 9. BER calculation in the presence of DCD.

the odd and even eyes. As expected, the even eye is much worse than the odd eye, due to a smaller response and a larger ISI impact, and determines the final overall link performance in the example shown in Fig. 9.

V. VALIDATION

In order to validate the proposed statistical jitter modeling methodologies discussed above, we apply these models in LinkLab simulations. LinkLab is a state-of-the-art channel simulator that incorporates the complexities of both device behavior and channel characteristics in high speed links. Although other components within in LinkLab have already been validated, the simulation and lab measurement conditions are controlled to isolate the effects of jitter and CDR on system voltage and timing margins. The validation systems include a clock-forwarded Rambus parallel link called FlexIO™ [9], and a CDR-based Rambus serial link [3].

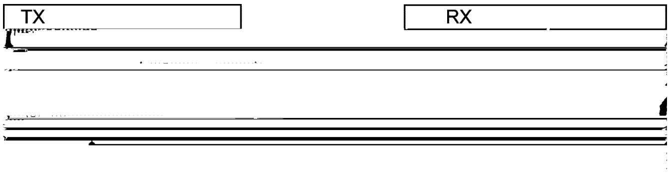


Fig. 10. FlexIO channel setup.

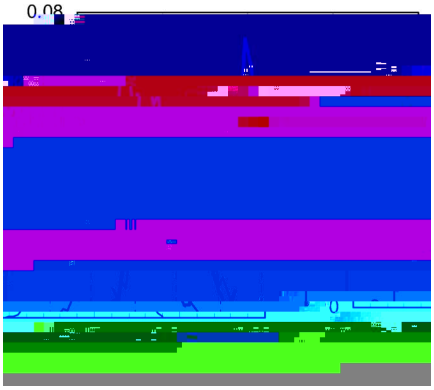


Fig. 11. FlexIO TX and RX timing measurements.

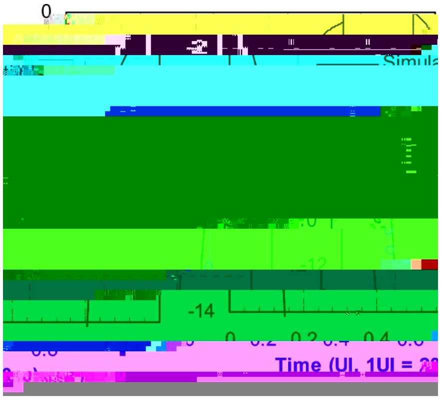
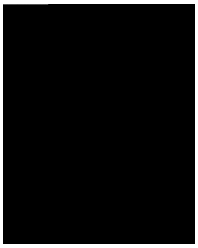


Fig. 12. FlexIO system-level correlation.

For the first system, FlexIO's clock-forwarding produces a synchronous system which simplifies the jitter analysis by removing CDR interactions. The simulation and laboratory environment comprises a 6-in PCB link on a socket-based system test board running at 5 Gbps, as shown in Fig. 10. Parameters for the transmitter jitter distribution are measured directly using an Agilent DCA-J. Parameters for the receiver jitter distribution are obtained by differentiating measured cumulative sampling distributions. The TX and RX jitter distributions are shown in Fig. 11. Since the test system is synchronous, the measured jitter for clock and data directly impact the final sampling distributions. Incorporating a previously correlated S-parameter channel model, the LinkLab simulation produced a reasonably good estimation of actual link performance, as seen in Fig. 12. The mismatch in high BER region of the bathtub curve may be



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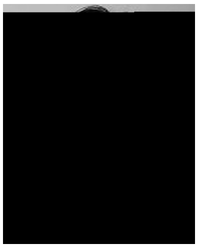

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