Case study: Gaussian Channel Crosstalk versus Realistic Statistical Crosstalk

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Overview

- Purpose: Illustrate that a Gaussian noise assumption is a conservative estimate of performance when the crosstalk noise factors are not Gaussian distributions
- Outline
  - Motivation
  - Experiment
  - Overview of Statistical Simulation Principles
  - Quick PDF Estimate
  - PDF and CDF (eye diagram) Results
  - Non-Gaussian Example Designs
  - Summary

Motivation

- Channels with loss of 33 dB for PAM-4 and 35 dB for NRZ (patel_01_0312) can create significant challenges for device and interconnect design.
  - This is 10+ dB more loss than considered in ‘ap’ and ‘ba’ .
- Frequency domain masks and integrated power sums have channel guard band to ensure performance.
- Channel guard band refinements can help address design of devices and interconnect for the purpose of expanding broad market applicability.
- Reduction in guard band may start with a closer look at crosstalk noise modeling.
  - Crosstalk and ISI noise PDF (probability density function) generation is not difficult to calculate can be fast

Motivation: Prior Work

http://www.rle.mit.edu/isg/documents/Stojanovic_CICC03_slides.pdf

Slide 36: "Gaussian model only good down to 10-3 probability…
Way pessimistic for much lower probabilities"

http://eprints.soton.ac.uk/262972/1/D2.pdf

p. 82: "Our simulation results validate our analysis, suggesting that the widely used Gaussian approximation of the ICI is inaccurate and hence results in a pessimistic BER estimate."

http://www.pcb007.com/pdf/DesignCon_08_Gupta-Wong.pdf

p. 22: 'When using just the Gaussian PDF with the same σ to predict BER performance, a 23 % overestimation (pessimistic) of error rate occurred."

http://www.ieee802.org/3/bj/public/nov11/ran_01a_1111.pdf

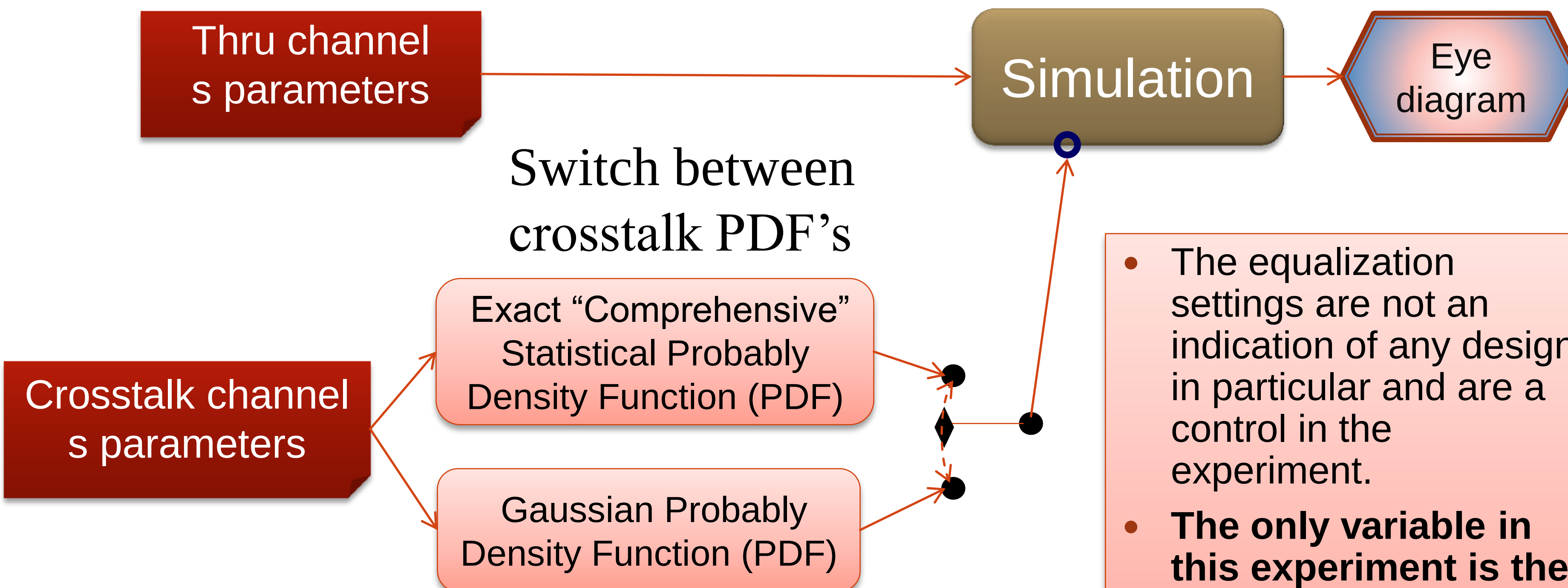
Slide 5: "Noise sources are uncorrelated to each other …
Can be summed by PDF convolution…
This analysis is much more accurate than power-summing and comparing SNRs"

http://ee.tamu.edu/~spalermo/ecen689/link_modeling_pda_casper_vlsi_2002.pdf

"Since sources such as intersymbol and cochannel interference have truncated distributions, the associated worst-case magnitudes can be directly calculated from the unit pulse responses of the system… We correlated our simulation results to actual measurements of a high-speed signaling system"

Experiment: Switch between Gaussian and Exact PDF Crosstalk

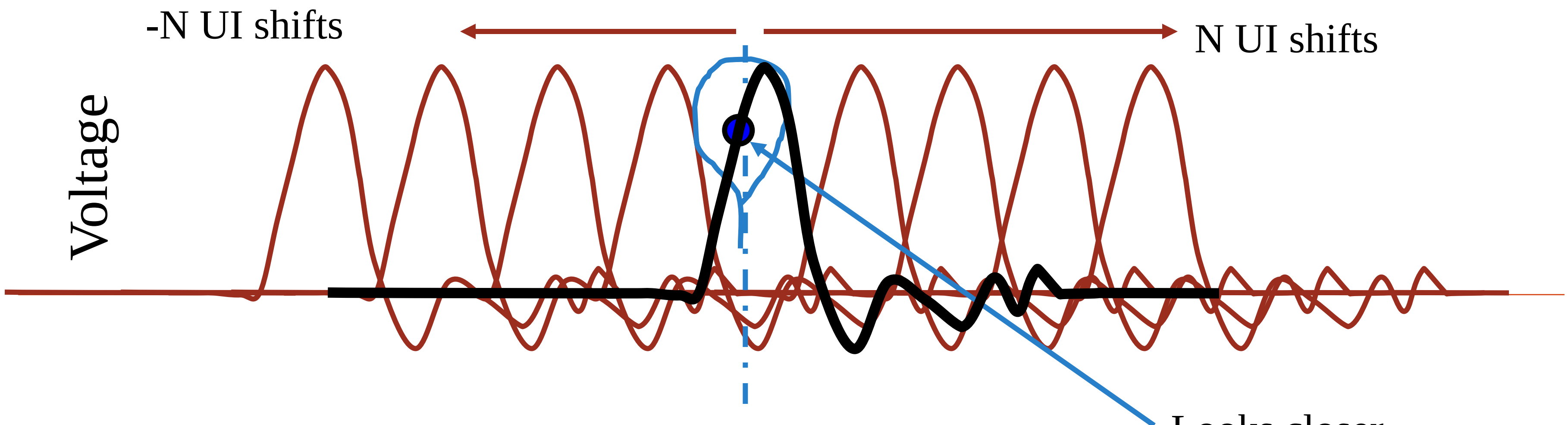
This is applicable to both NRZ and PAM-4



- The equalization settings are not an indication of any design in particular and are a control in the experiment.
- **The only variable in this experiment is the model for crosstalk**
- See backup for simulation details

Overview of Statistical Simulation: Regardless of line code (NRZ/PAM4)

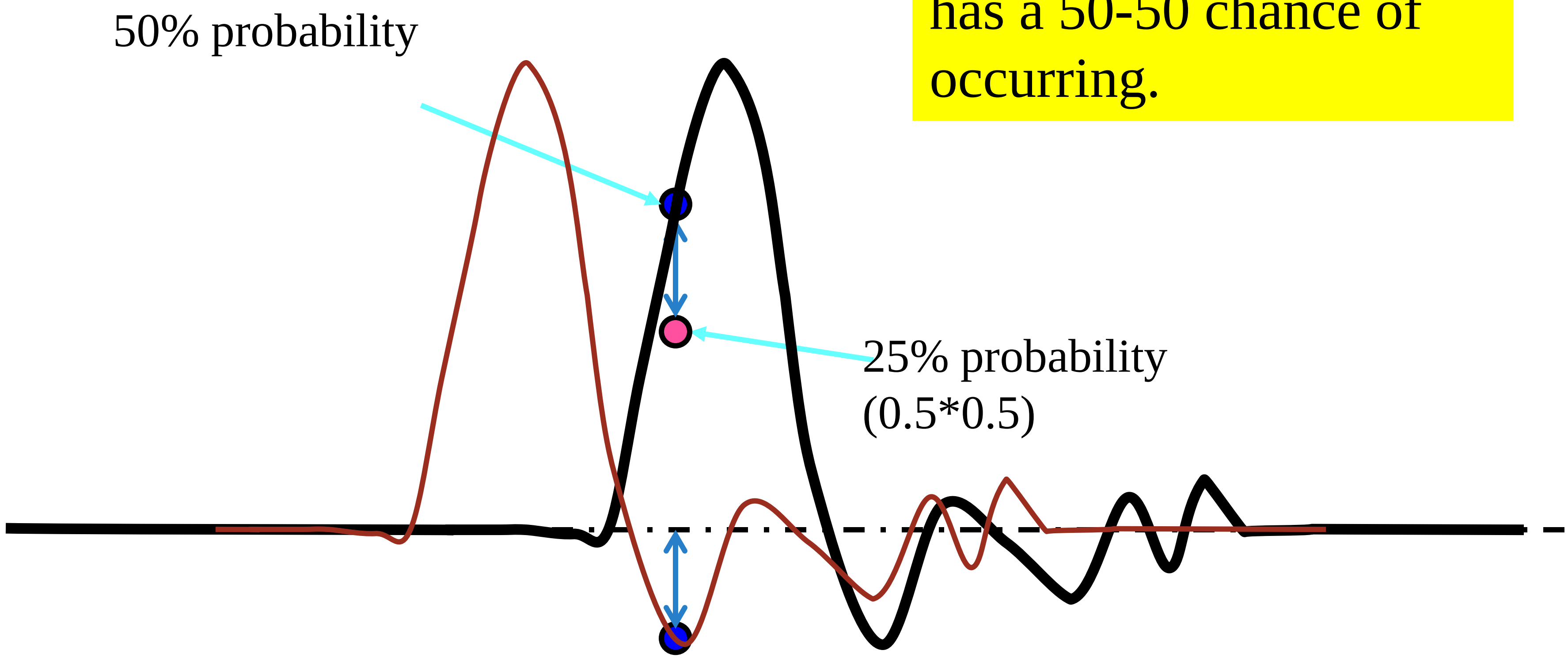
Superposition of pulse responses (bits) are the basis for statistical simulation: “Simple” example:



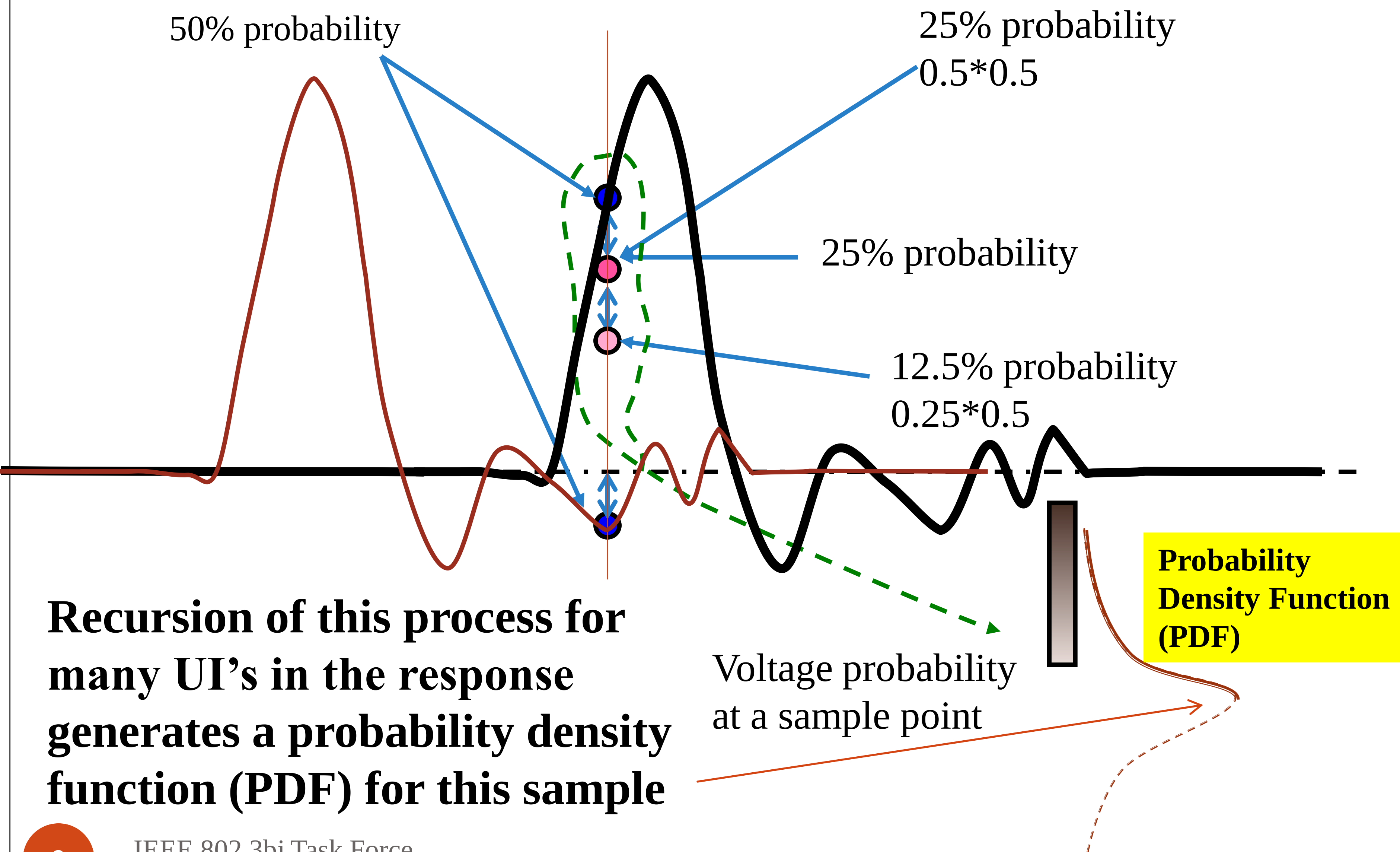
Sample point (time) for target bit pulse response

Look at a 1 UI shift back: i.e. previous bit

Any single random bit has a 50-50 chance of occurring.

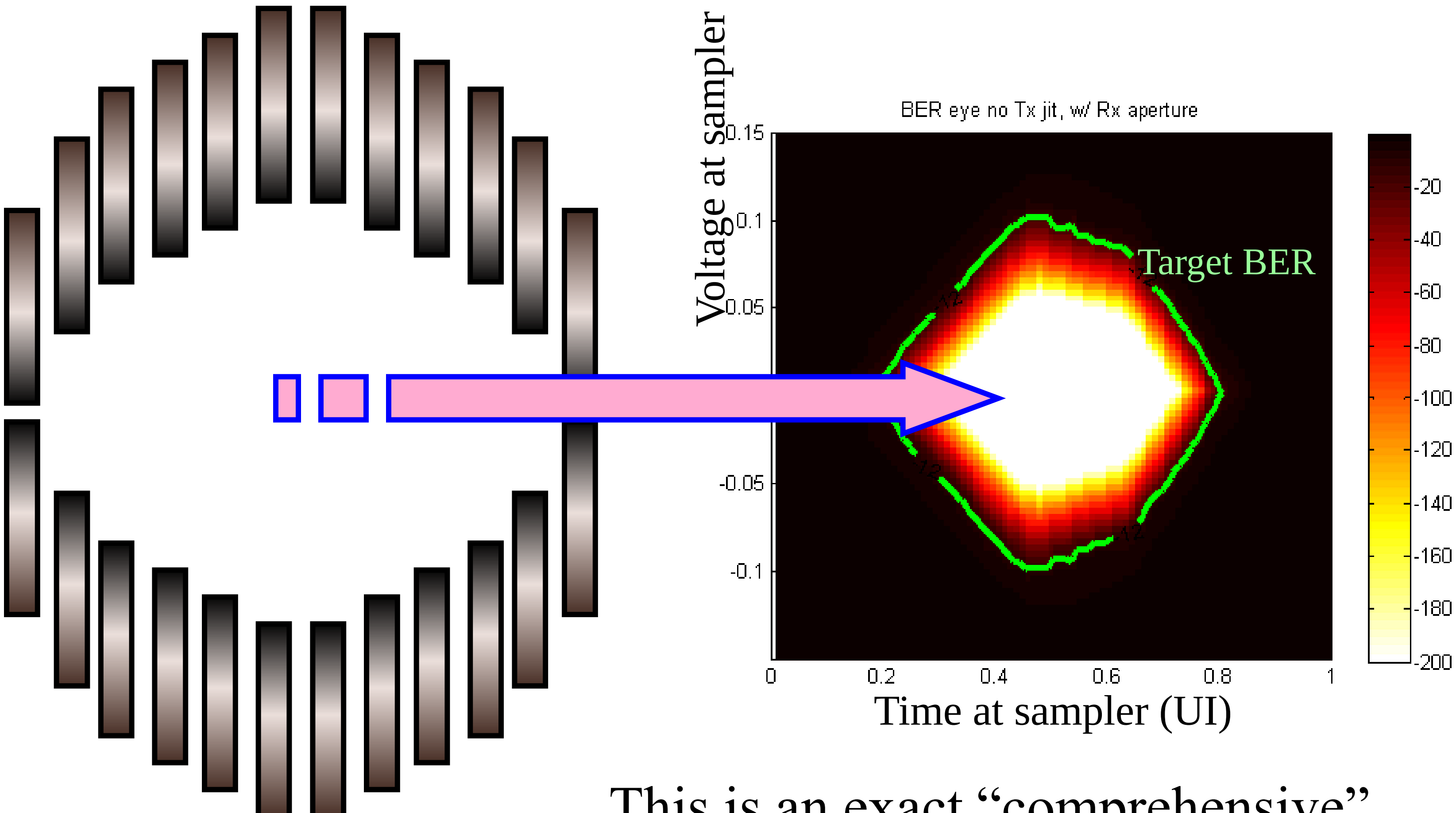


Look at the next UI back



Recursion of this process for many UI's in the response generates a probability density function (PDF) for this sample

Probabilities for all sample are combined and integrated… creating a 2 dimensional cumulative distribution function (CDF) which we call a statistical eye.



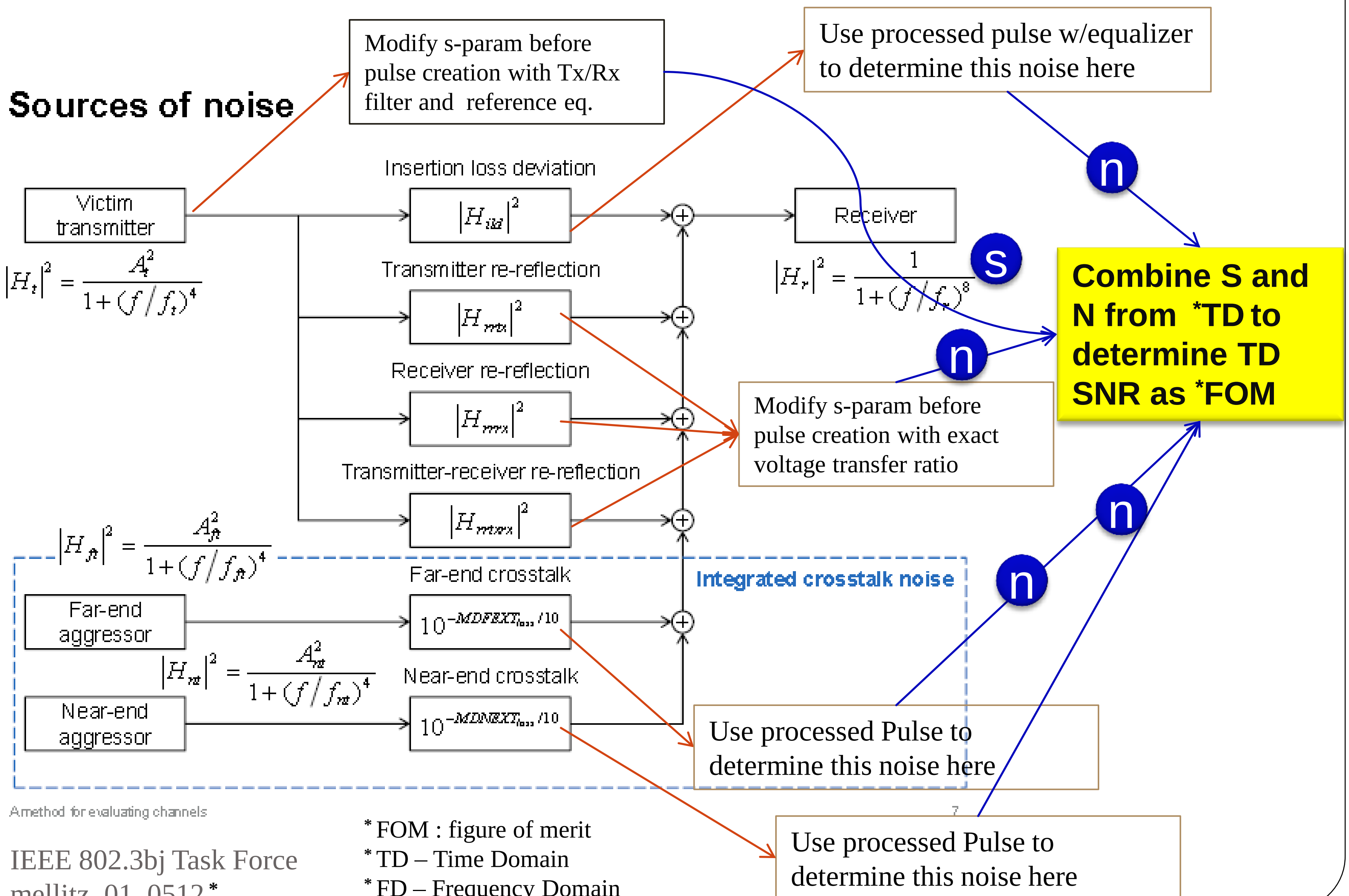
This is an exact “comprehensive” statistical representation

"Quick PDF" is a fast and simple way to estimate these exact "comprehensive" statistics from a single pulse response

1. Post-process waveform with Tx/Rx filters
2. Determine a time domain interval of interest
3. Determine the progressive sums of the 40 largest samples in each UI
4. Add in an RMS term
   - to account for average switching of all bits not in sums
5. Produce a probability density function (PDF) of these noise voltages for probabilities of 0.25 to 1e-12

Use the PDF's to determine the "n"s here:

*Similar to *FD SNR, moore_01_0311.pdf*

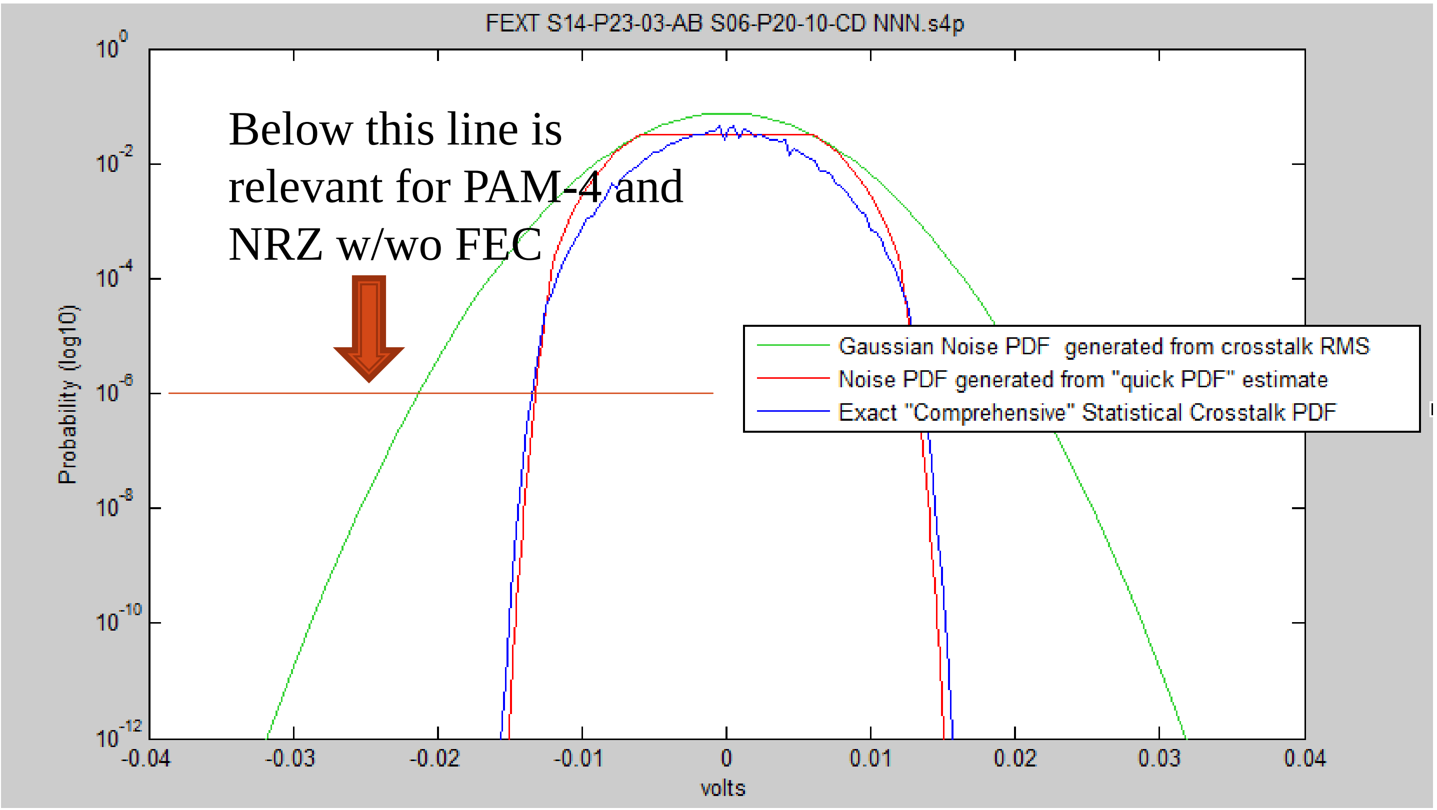


* FOM : figure of merit
* TD – Time Domain
* FD – Frequency Domain

PDFs of Noise is Not Represented by a Gaussian Distribution When:

- Highly reflective interference is short lived
- Equalization alters the impact of noise
- Noise is composed of Dirac like strong cursor spikes cause by
  - NEXT generated from tight BGA via patterns
  - Anisotropic FEXT (μ-strip)
- Aggregate distributions for a few channels are dominant and bounded

Comparison Between Probability Density Functions (PDF) Suggests Gaussian Estimation is Conservative

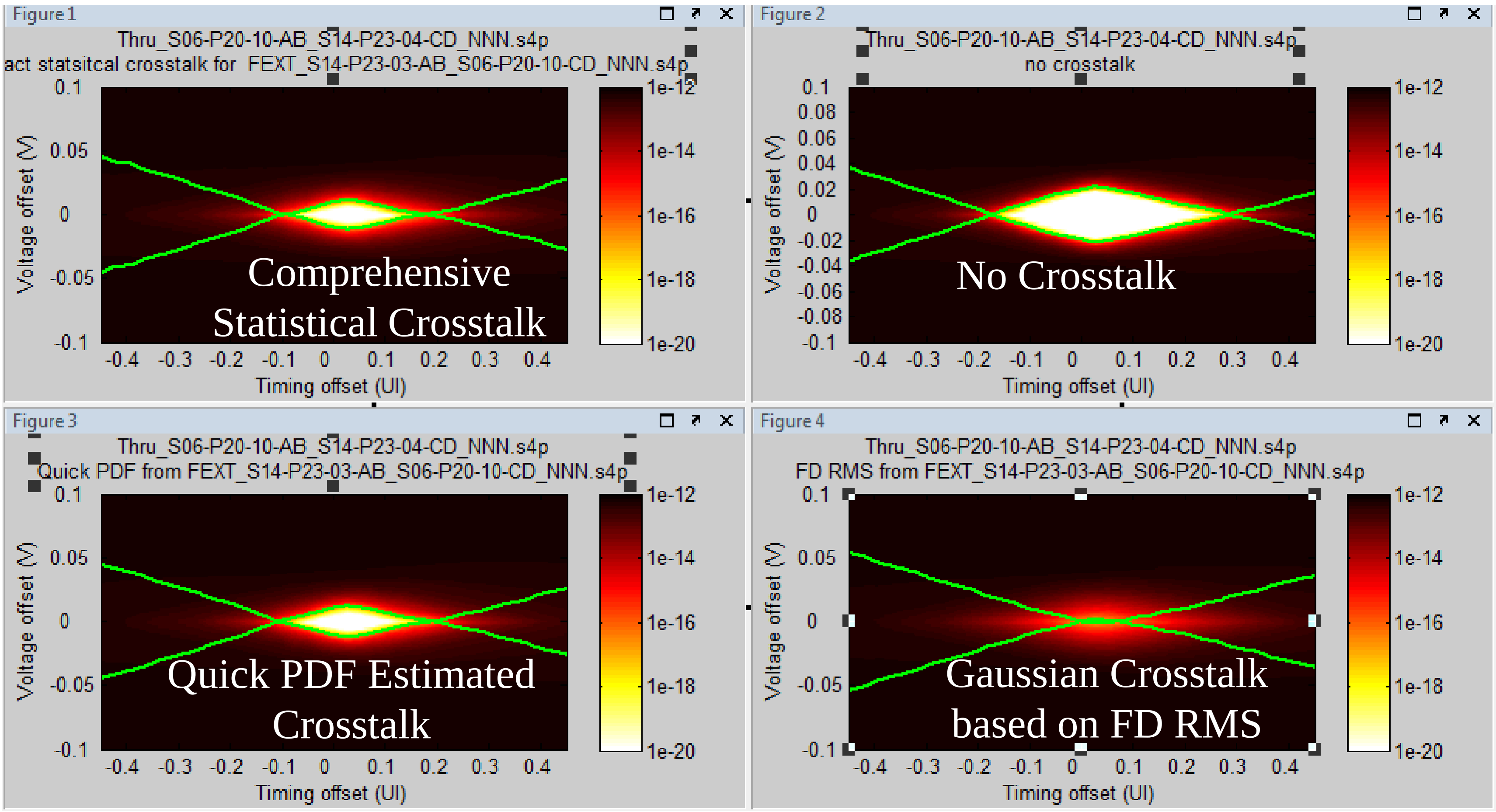


Results from combining all noise source in some cases may reduce conservatism.

These Eye Diagrams illustrate:

- Gaussian PDF estimate is conservative
- Quick PDF estimate is similar

to the comprehensive statistical analysis



Green lines are contours for BER=1e-12

Summary

- A Gaussian noise assumption may be a conservative estimate of performance
  - Particularly when there are one or two dominant XTALK sources.
- Estimation results for insertion loss noise may track this trend for similar reasons
- Results are applicable to NRZ and PAM-4 applications
  - Significant channel guard band is observable even at BER of 1e-6 which may be applicable to FEC applications.
- Results suggest quick PDF estimation tracks low BER performance
  - Follow on: comparisons with more channels

Back Up

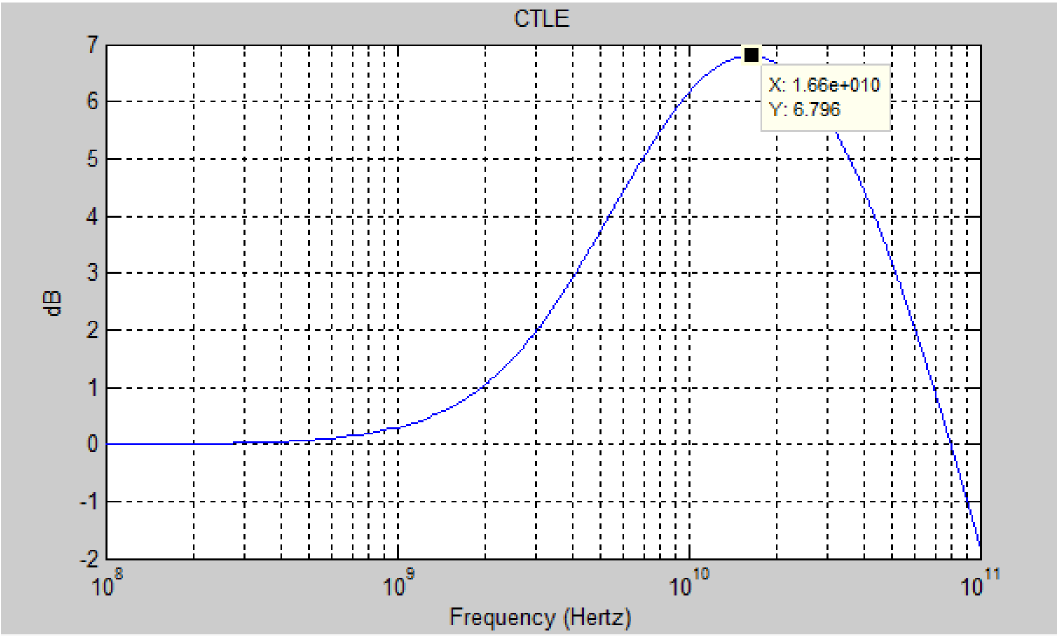
- Simulation Assumptions
- Review of Probabilities

Controlled Experiment Simulation Parameters… "Just an experiment"

- Channel for experiment
  - \meier_02_1011\Longest Link
    - Thru_S06-P20-10-AB_S14-P23-04-CD_NNN
    - FEXT_S14-P23-03-AB_S06-P20-10-CD_NNN
- For this analysis:
  - UI = 38 ps
  - No jitter, package, or die load capacitance
  - Termination is 50 ohm single ended (100 ohm differential)
  - All signals 1 Volt at source (peak to peak, differential)
  - FFE3 in the transmitter (8 bits resolution)
    - Pre cursor tap bound -.1
    - Post cursor tap bound -.4
  - DFE5 in the receiver (9 bits resolution)
    - Target signal amplitude (threshold) = 100 mV
  - CTLE (~ 6.7 dB boost at ~ 16 GHz)
    - Zero: 3.5GHZ
    - Poles: 10GHz, 30Ghz
  - BER: target 1e-12
  - No AGC
  - 80 bins for PDFs
  - Eye height coordinate descent optimization
  - This experiment is for NRZ but impact is similar for PAM4

- The equalization settings are not an indication of any design in particular and are a control in the experiment.
- The only variable in this experiment is the model for crosstalk

CTLE, FFE and DFE solutions



FFE taps (c-1, c0, c1) = -0.0625 0.585938 -0.35156
DFE tap (d1:5)=0.023438 -0.01172 -0.00195 0 0

- Simulation applies CTLE and Tx/Rx filters to crosstalk

Roughing out Probabilities

- Basic rules
  - Voltages add
  - Probabilities multiply
  - Probability densities convolve
- A PDF at each sample point is generated for a complete random bit sequence:
  - By finding voltages all possible sums for each shift of the edge
  - By assigning probability to each sum
  - This is a convolution process
- PDF's are created in the same way for both crosstalk and the thru channel
- PDF convolution is the basis for the statistical simulation.