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Signal Power & Noise and SI | Richard Mellitz, Distinguished Engineer

INTRODUCTION

Purpose: Tie it all together:

- Signals, noise power, performance

Context:

- Differential Signaling > 25 Gb/s
  - Example is 100 Gb/s
- NRZ Baseband
  - Theory applies to PAM too

Assumptions

- LTI interconnect
- Noise power adds
- Example does not include a variety of impairment such jitter

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Bits in, Bits Out, and The Signaling Diagram

Stream of Digital Bits/Symbols, **X**

↓

Transmitter → **Tx signal of bit/symbol steam** → Interconnect Channel → Response of Digital Bits/Symbols, **Y** → Receiver

P — Pulse response observed here

↓

Stream of Digital Bits/Symbols

For signal processing/integrity we have

- **X bits or symbols in**
- **Y bits or symbol response waveform**
- **And the receiver interprets back to bits or symbols back again**

Building a Bit/Symbol Response

Single bit response samples							
1	2	3	5	6	7	8	9
0	-0.1	0.75	-0.05	-0.1			
	0	-0.1	0.75	-0.05	-0.1		
		0	-0.1	0.75	-0.05	-0.1	
			0	-0.1	0.75	-0.05	-0.1

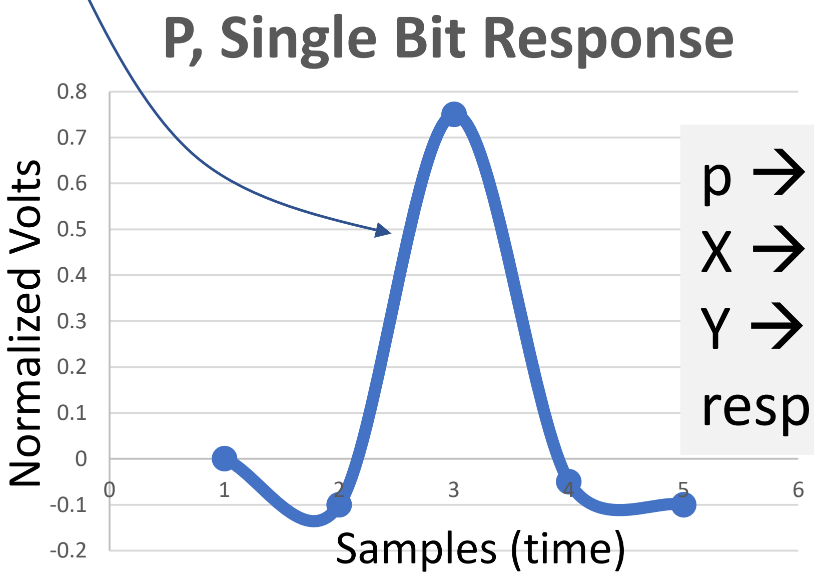
	Bit stream
$x1$	1
$x2$	-1
$x3$	1
$x4$	1

X = [x1, x2, x3, x4], Σ

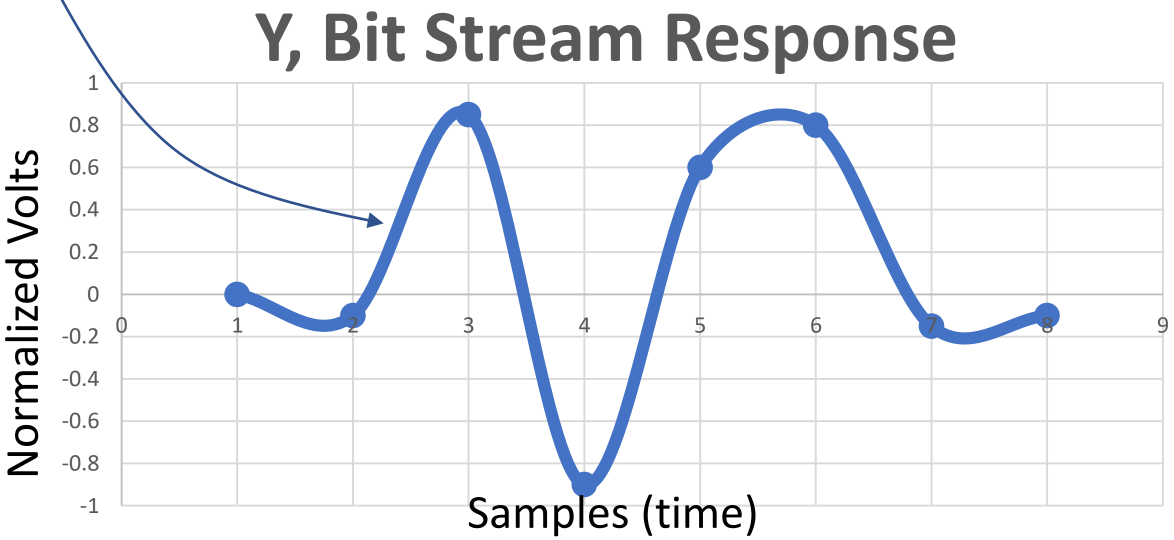
```
P = [ 0, p1, p2, p3, p4, p5,  0,  0,  0]
    [ 0,  0, p1, p2, p3, p4, p5,  0,  0]
    [ 0,  0,  0, p1, p2, p3, p4, p5,  0]
    [ 0,  0,  0,  0, p1, p2, p3, p4, p5]
```

$$Y = [P^T \otimes X]^T$$

Interim bit response samples							
1	2	3	5	6	7	8	9
0	-0.1	0.75	-0.05	-0.1	0	0	0
0	0	0.1	-0.75	0.05	0.1	0	0
0	0	0	-0.1	0.75	-0.05	-0.1	0
0	0	0	0	-0.1	0.75	-0.05	-0.1
0	-0.1	0.85	-0.9	0.6	0.8	-0.15	-0.1



p → pulse response
X → the bits
Y → measured response



Getting a Feel for Convolution (sum and indices)

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- In the prior example, Y is determined from P and X with a series of shifting (delaying) and adding operations.
- That is convolution
- The expression for convolution is given by

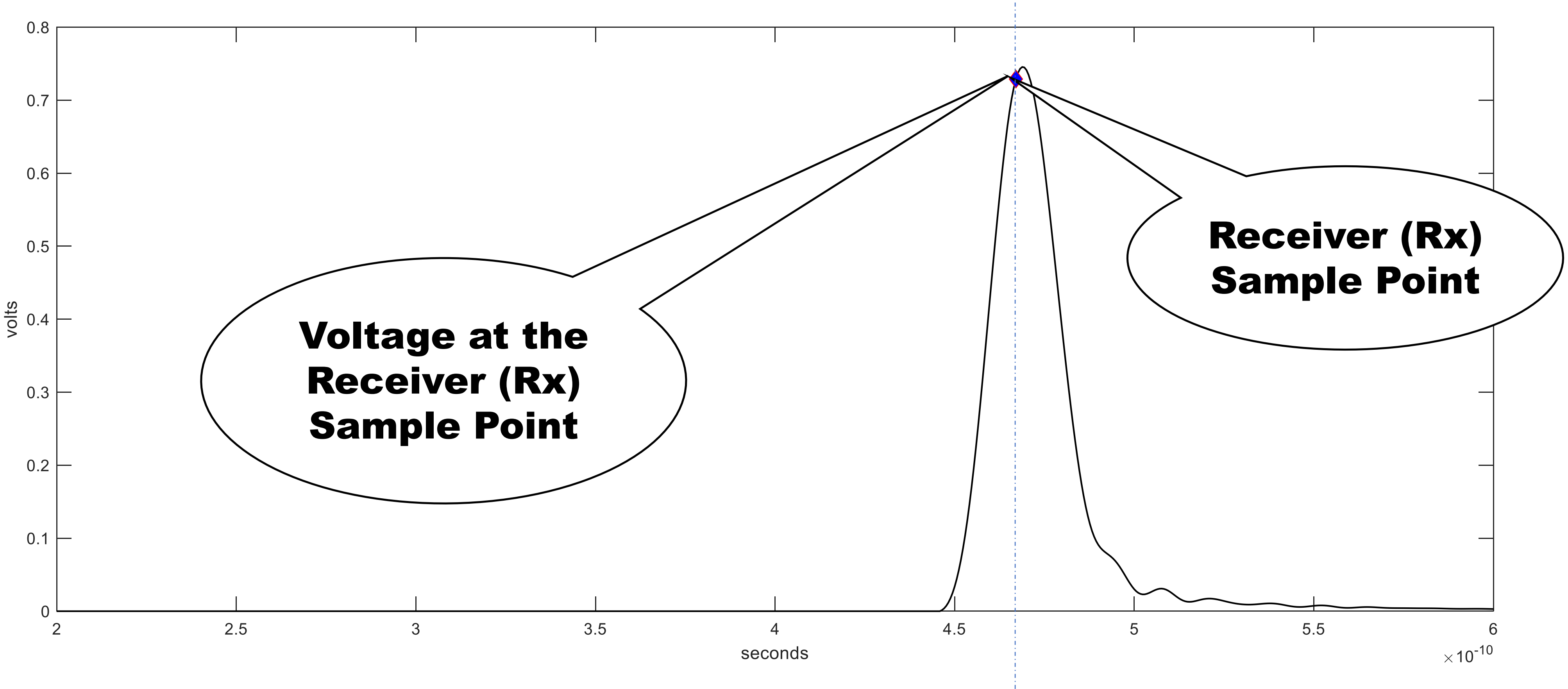
$$y(t) = \int_{-\infty}^{\infty} x(t) * p(t-\tau)\, d\tau$$

- In a discrete version of this we replace the integration with a **sum** and $(t-\tau)\, d\tau$ with just a collection unit delays
- Unit delays may be discretely represented by **indices**
  - This is well suited for computer operations

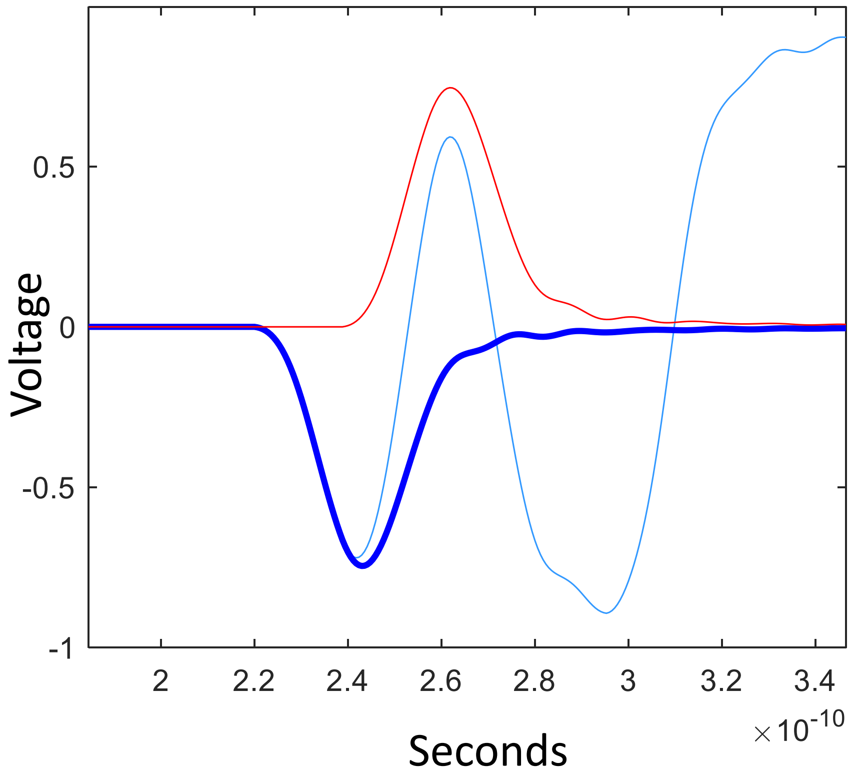
Start with a Single Pulse Response

The response to a 1 unit interval (UI) pulse

Normally the UI is $\frac{1}{f_{nq}}$, where f_{nq} is the Nyquist sampling frequency

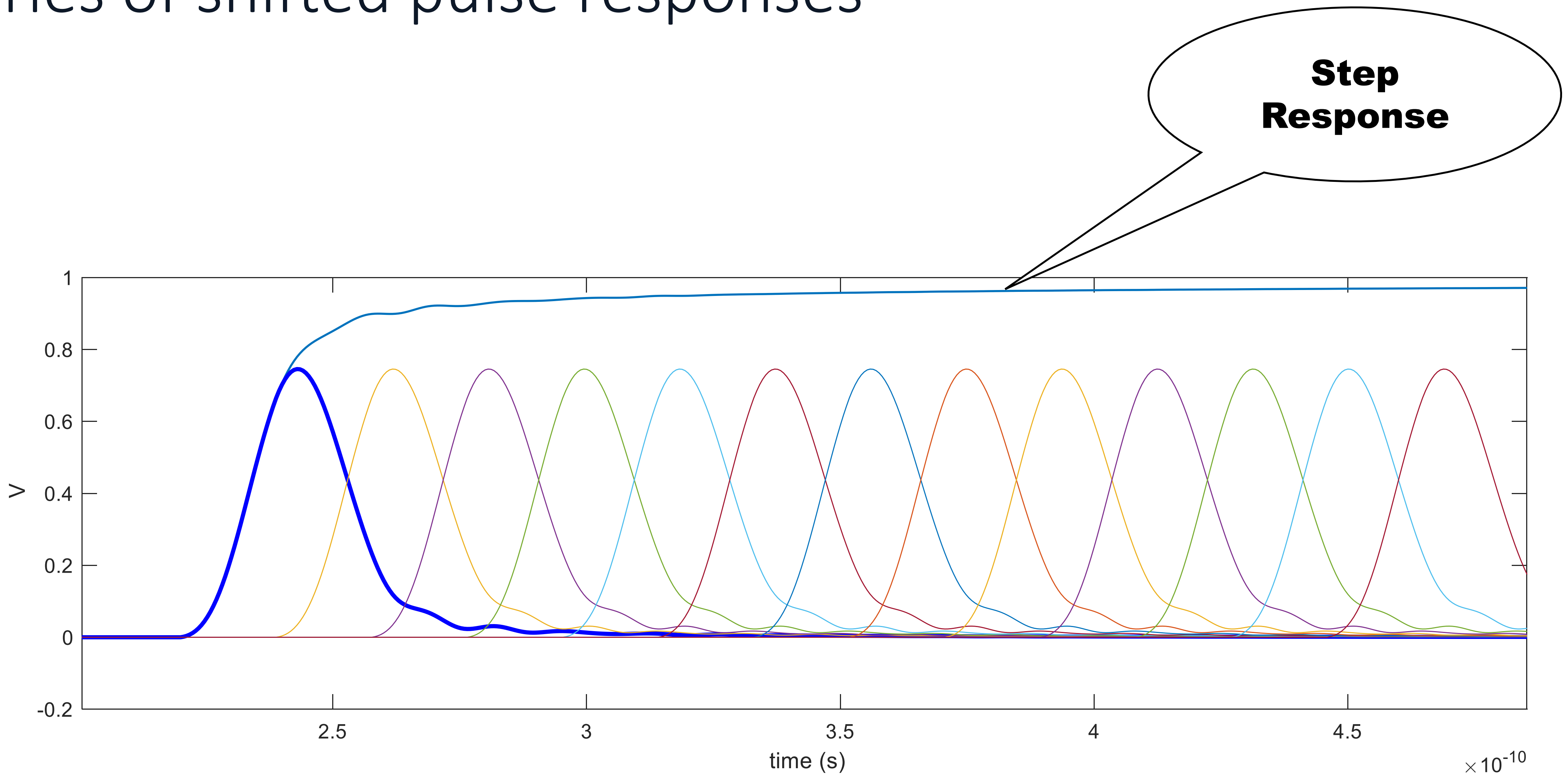


Pulse Response Waves Exceeding 1 UI Add Into Surrounding Cycles



Another example of this is building the step response

A step response is just the response of long sum of a series of shifted pulse responses



The Sample Point: Food for Thought

- How many samples are used to capture a waveform
  - Answer many
- How many samples are in most simulations
  - Answer many
- How many samples do SERDES normally use.
  - Answer 1 !

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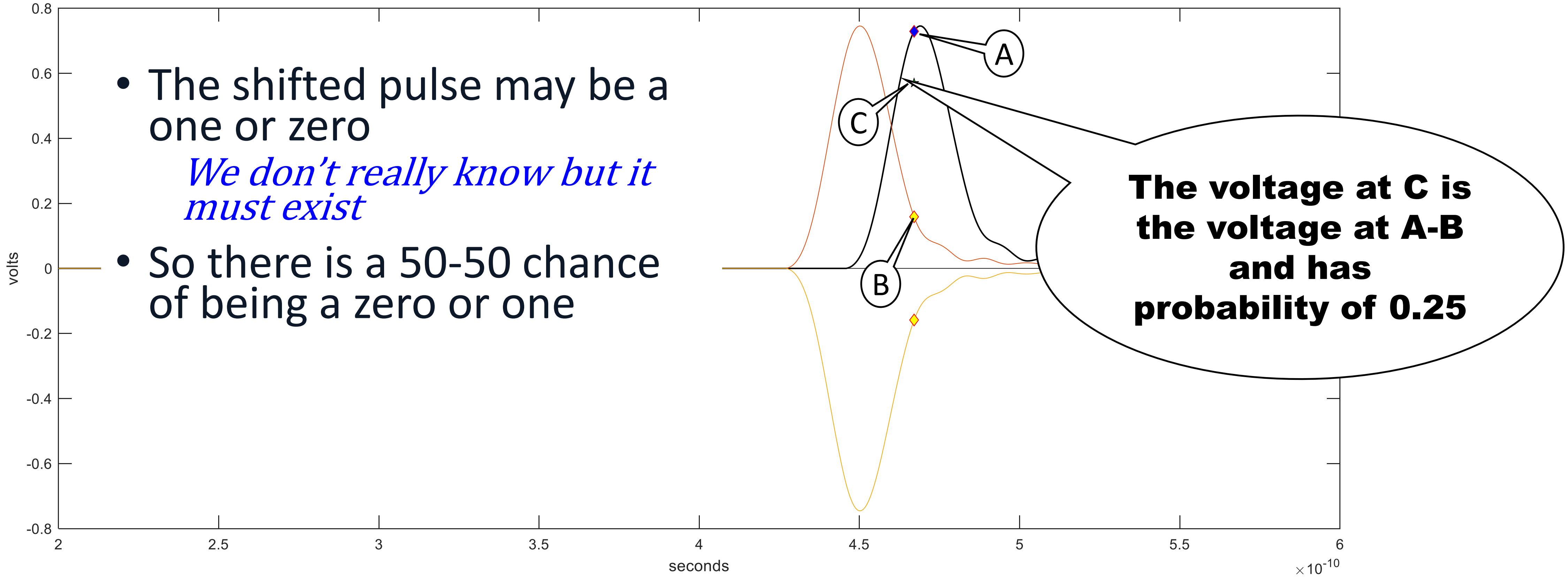
Building a Response: The Basics

Let's start by looking at the pulse shifted back 1 unit interval (UI)

- The shifted pulse may be a one or zero

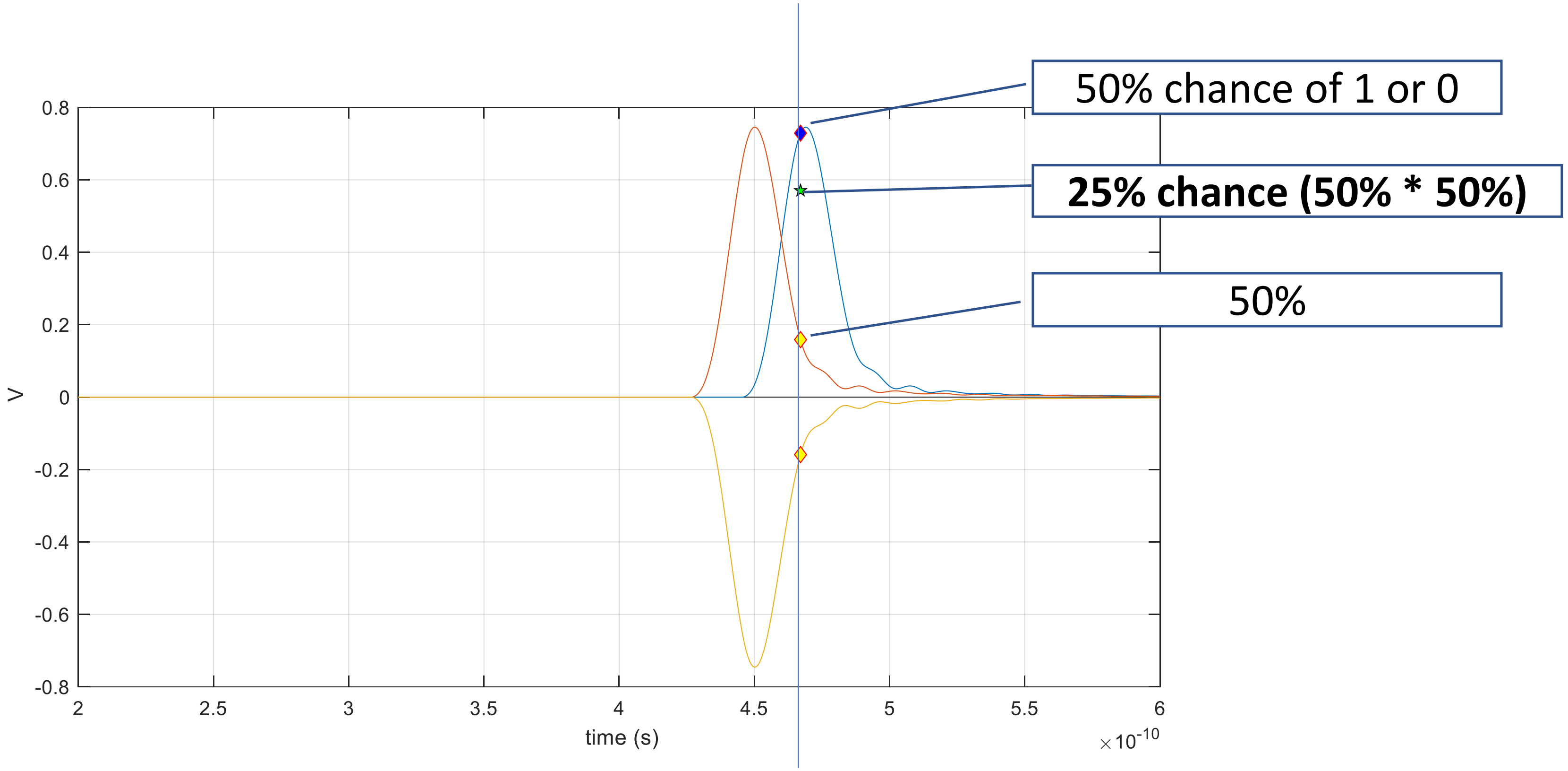
  We don't really know but it must exist

- So there is a 50-50 chance of being a zero or one



First Step in Building the Sample Point Voltage Histogram

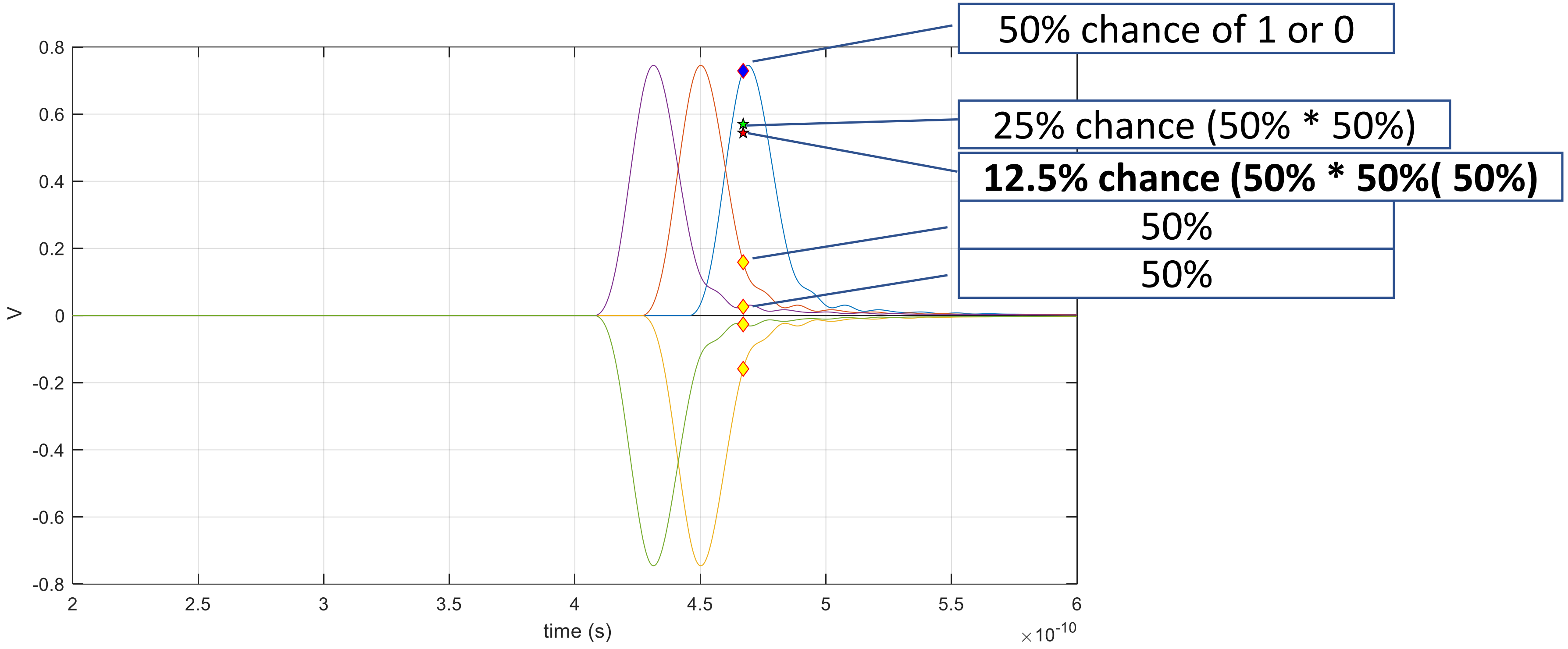
1st bit history



Target Sample Point

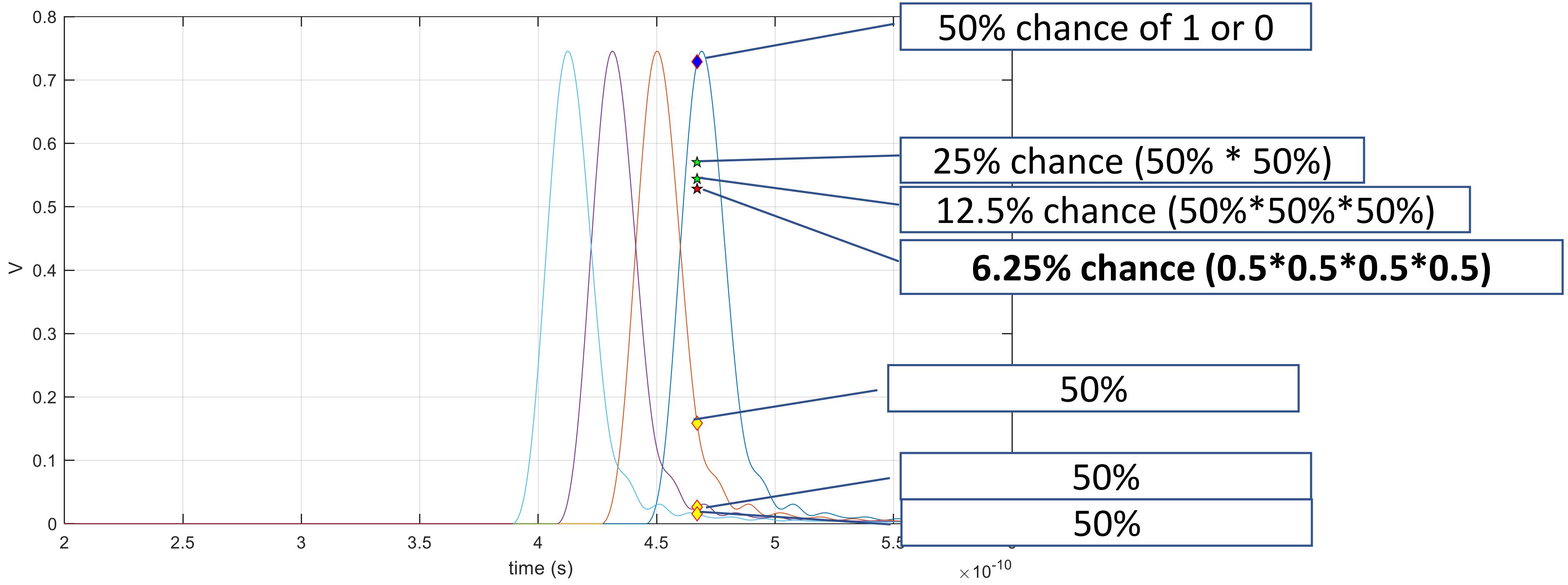
Building a Histogram: 2nd Bit

2 bit history



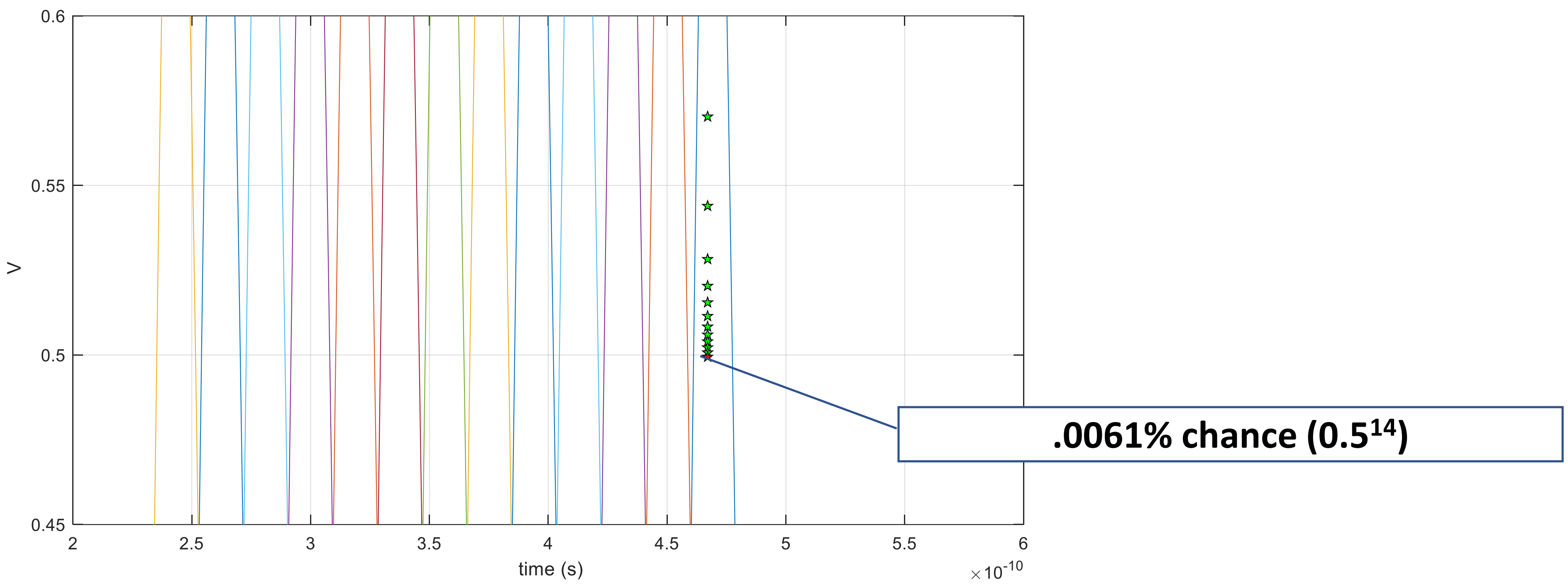
Building a histogram: 3rd Bit

3 bit history



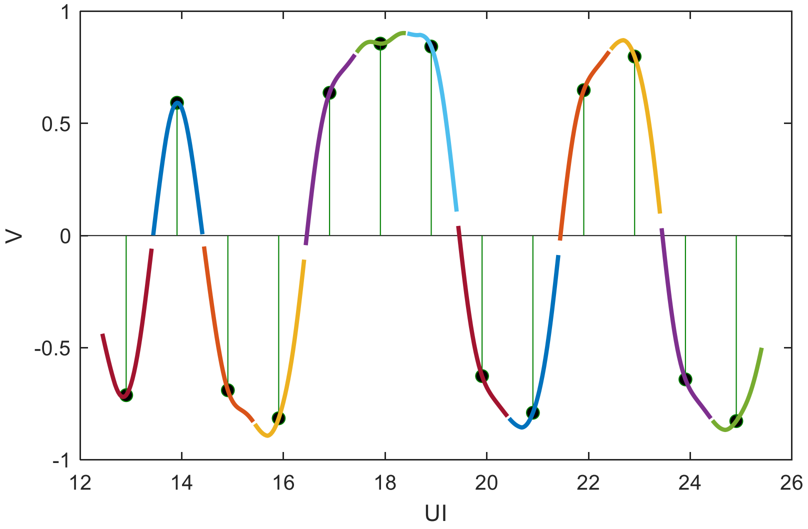
Building a Histogram: 13^{th} Bit

13 bit history



We create a voltage histogram i.e. probability density, at that sample point

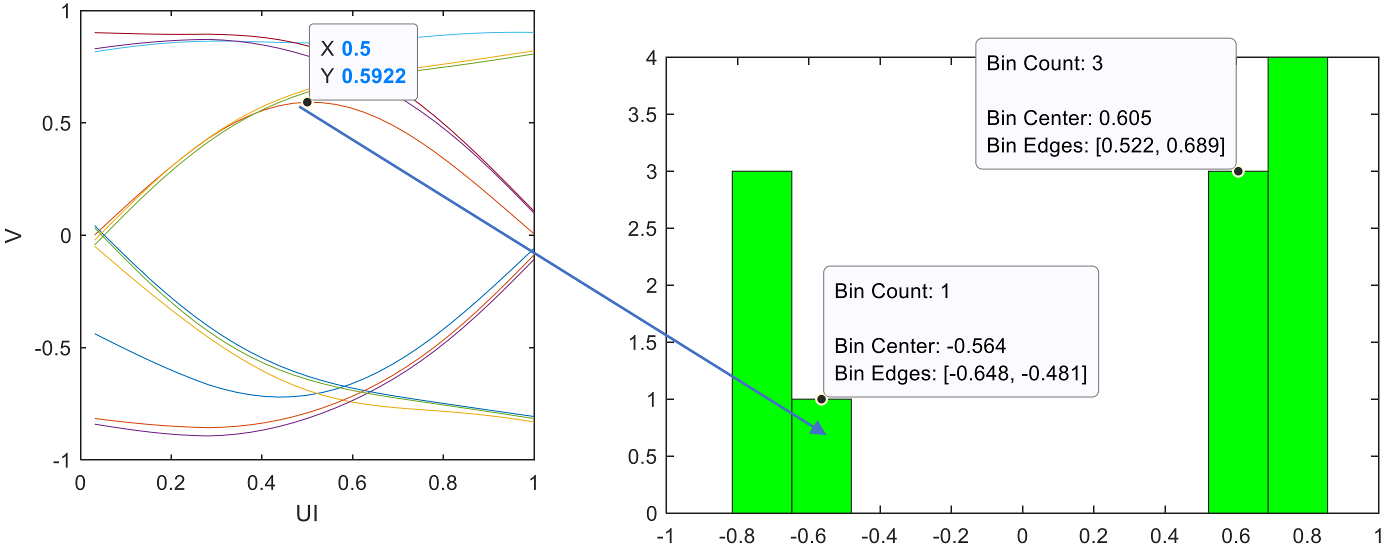
“Signal”



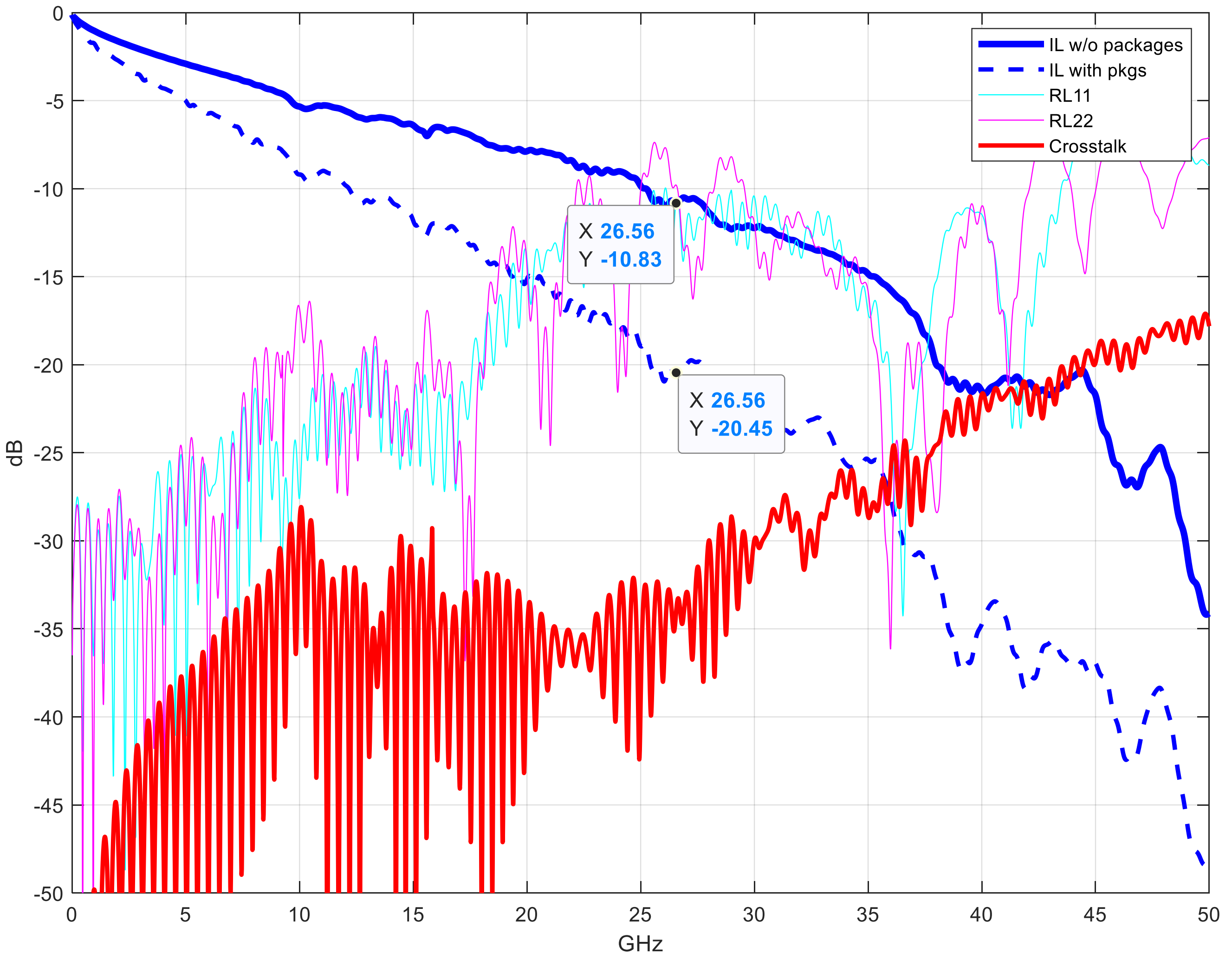
Dots (stems) are sample points

“eye diagram”

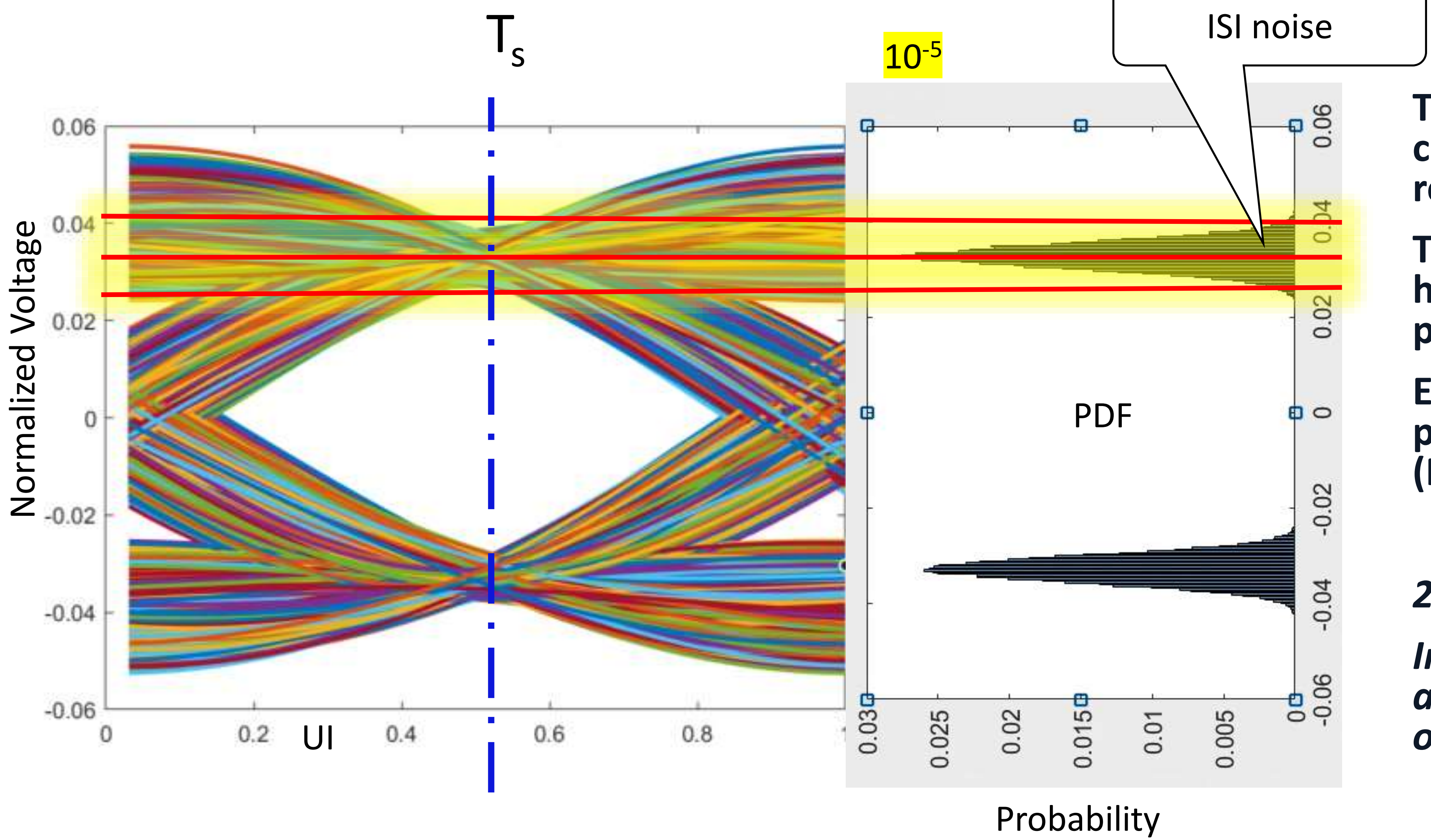
Histogram of voltage at sample points



NRZ channel example at 53.126 Gb ~ Channel IL plus package IL ~ 20.45 dB loss at 26.6 GHz



NRZ Example Put Together as in a Simulator



The right plot is a NRZ eye composed from a pulse response

To the left is a voltage histogram at the sample point T_s

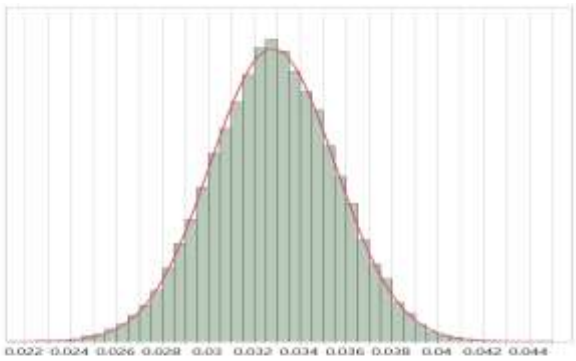
Each histogram is a ISI noise probability density function (PDF)

2^{15} bits simulated

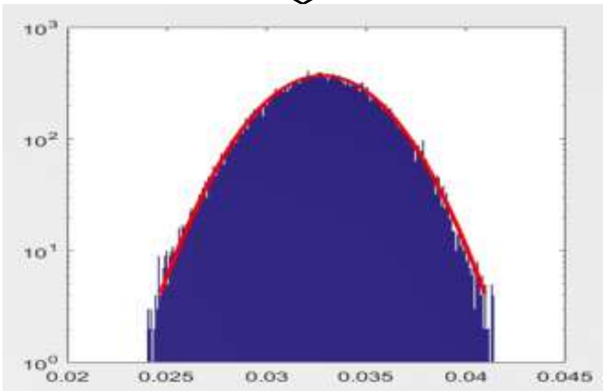
In this example we are using a CTLE, Tx FFE, no jitter or other noise sources

Consider the Progression

V → V² → σ → V² → V



Log Scale:
look for the parabola



- Gaussian function
- $\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-m}{\sigma}\right)^2}$
- On a semi-log y plot it looks like a parabola
- The RMS is a σ.

Power ∝ Voltage squared

- RMS, σ, is a measure of power

Given a sequence of semi-random voltages

- We can make statistical voltage predications

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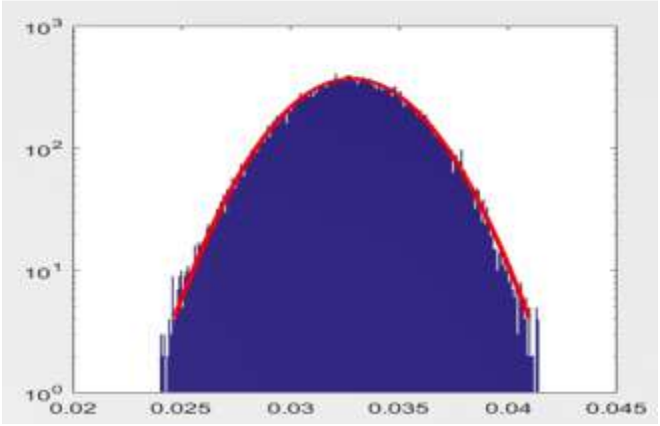
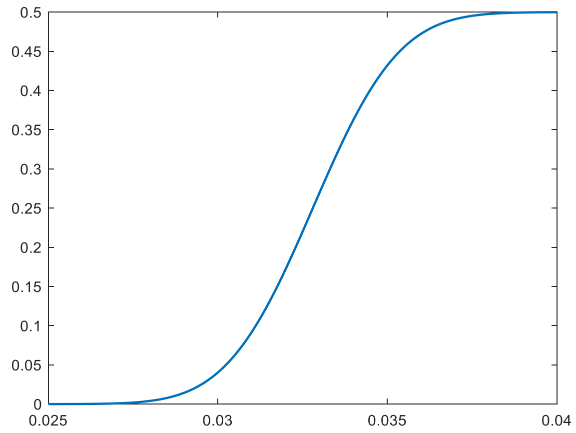
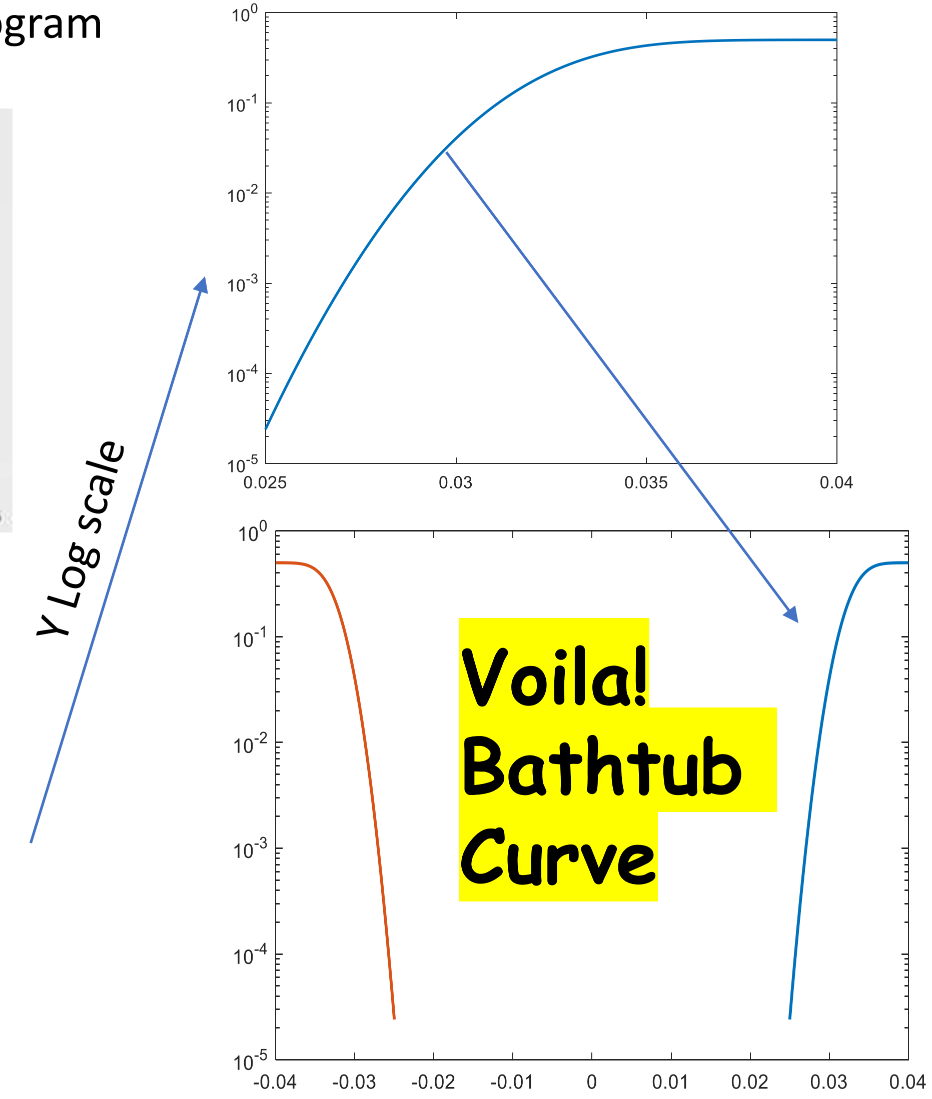
Getting to a bath tub curve

Start with half the prior log histogram



Cumulative Distribution Function





Predictions

- 68.27% of a normal population reside between +/- 1 σ
  - Variance of Gaussian process is defined as σ^2
- We can use this to predict probability of a voltage
- Say we are looking for the voltage a probability of 1e-12
  - The corresponds to approximately +/- 7 σ.
- If sigma, σ, is 1 mV,
  then 7 mV has a single sided probability of 10^{-12}

There are interesting and useful properties of a Gaussian process.

- The variance of an aggregate of gaussian processes is the sum of the variance of the components
  - $\sigma^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \cdots$

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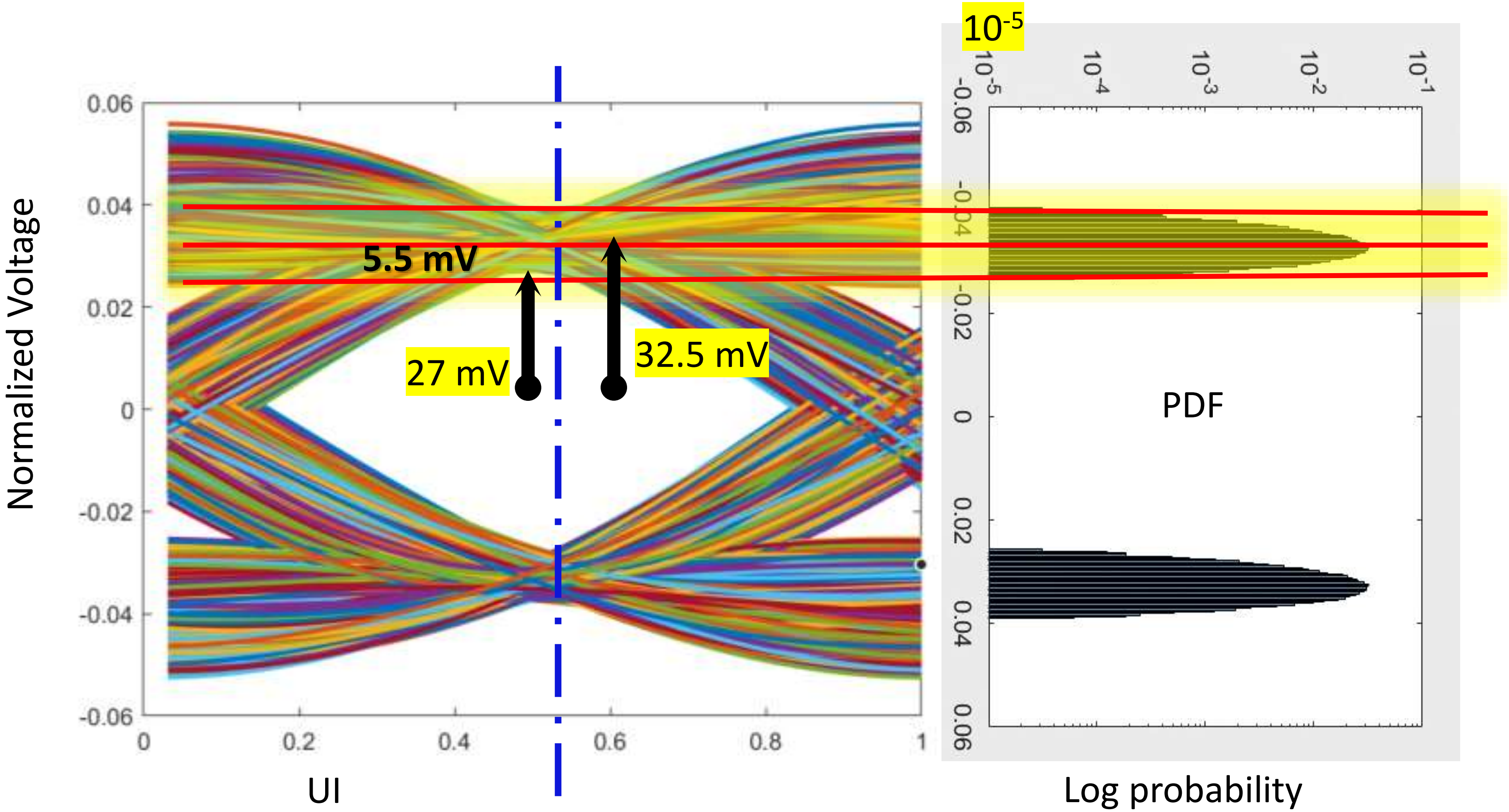
ISI Noise from Prior Example



Mean "1" signal – 32.5 mv

At probability density of 10^{-5} the Eye Amplitude = 27 mV

ISI Amplitude =

32.5 mV –27 mV (ISI) =

5.5 mV

NRZ Example with crosstalk

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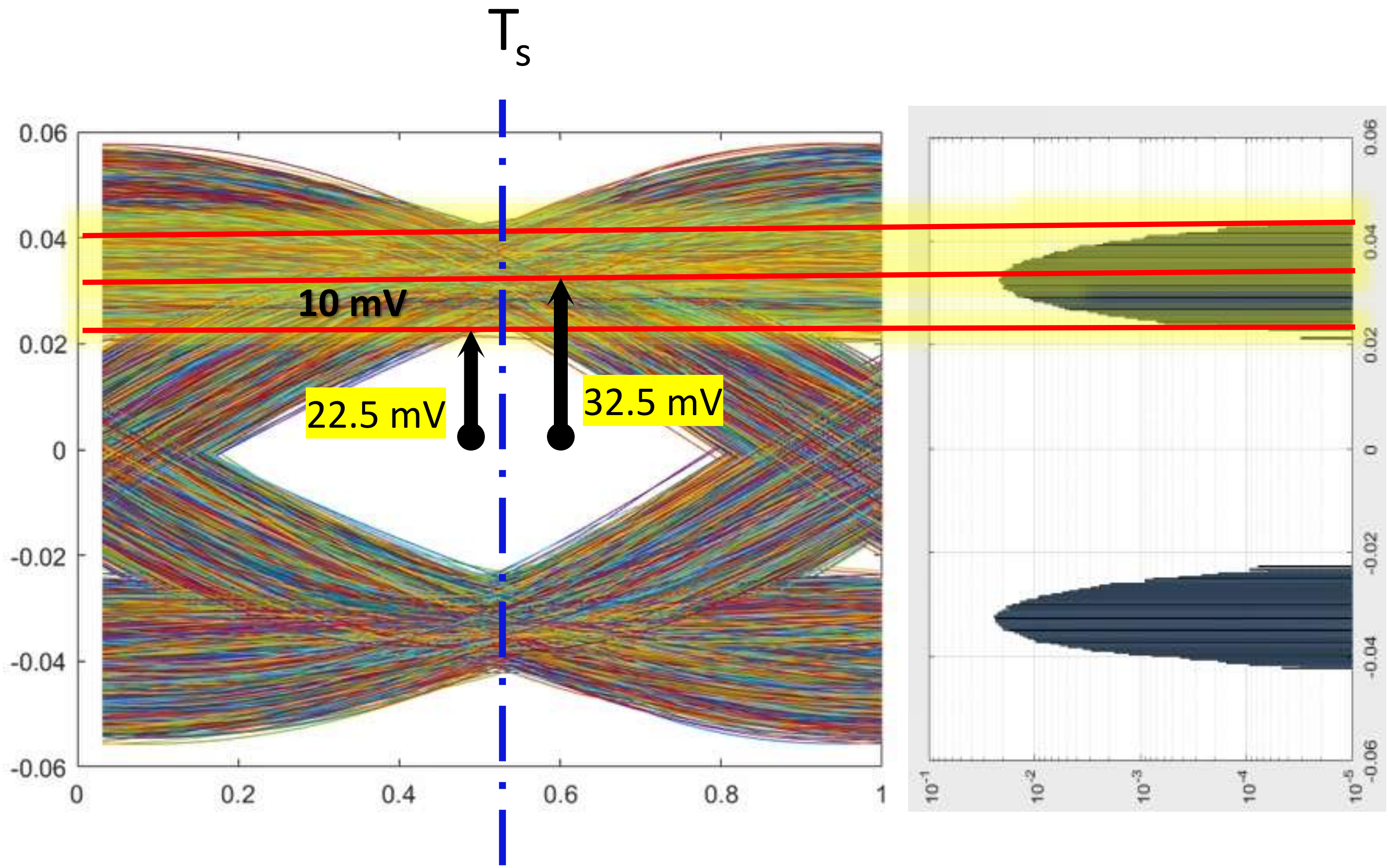


At a probability density of 10^{-5} :

Total Nosie Amplitude =

32.5 mv –22.5 mv(ISI) =

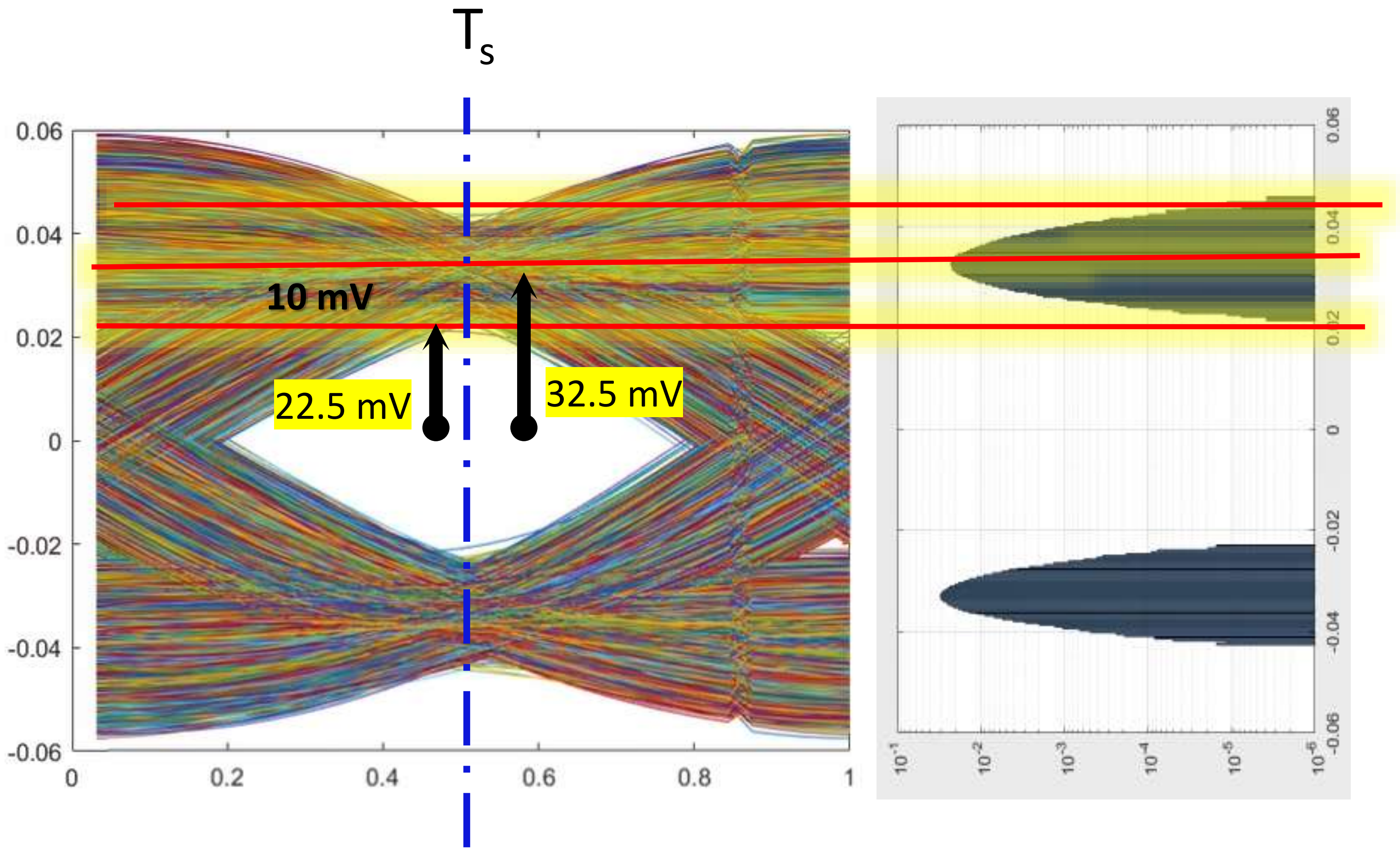
10 mV

10^{-5} = 4.2649 σ (sigma)

4.2649 σ → $\sqrt{10^2 - 5.5^2}$ = 8.3516 mV

Solving: $\sigma = 1.95$ mV

NRZ Example with 1.95 mV RMS noise NO Crosstalk!



2^{15} bits simulated

At a probability density of 10^{-5} :

Eye Amplitude =

32.5 mv –10 mv (total noise) =

✓22.5 mV

Signal Power and Signal Integrity

- Power is useful tool for estimating signal performance
- Power can emulate signal impairments
- Noise power generators are readily available
- Integrated Crosstalk Noise (ICN) is common application of noise power

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Conservation of Energy Can Be used

Parceval's theorem relates to the Fourier transform

$$\int_{-\infty}^{\infty} |h(t)|^2 dt = \int_{-\infty}^{\infty} |H(f)|^2 df$$

Where:

t is time and f is frequency and

$H(f) = \mathcal{F}\{h(t)\}$ i.e. H(f) is the Fourier transform of h(t)

Consider,

h(t) maybe a voltage time wave and

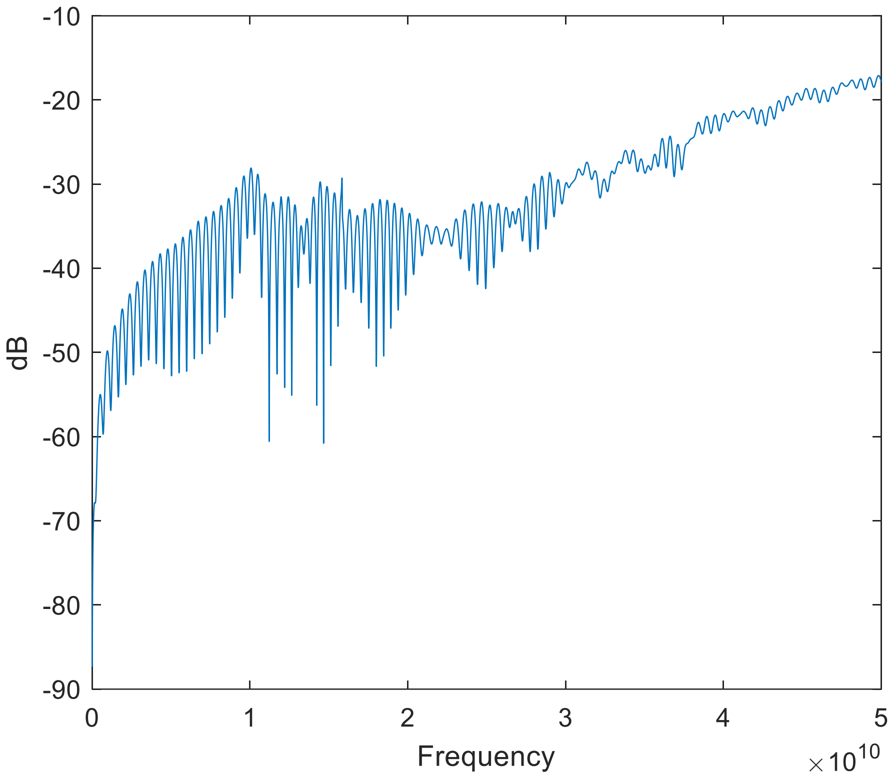
H(f) would be the voltage spectral content,

then the square of voltage divided by resistance is power.

So very simplify,

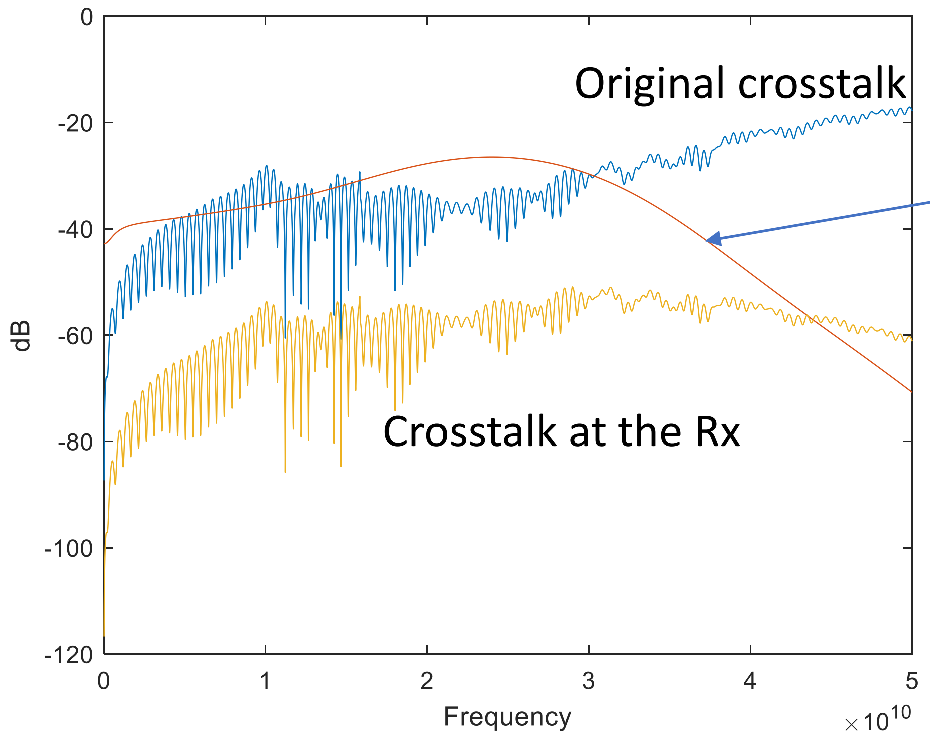
the total sum of all power in the frequency domain must be same as the sum of all power in the time domain.

This is the crosstalk response (dB) vs. Frequency



- We should be able to integrate this and the 2 mV RMS in the prior example.
- But this is this integrates to about 7 mV

All the power does not get to the receiver



- To determine the power which get to the receiver…
  multiply by the Power Spectral Density from
  - data
  - Transmitter FFE
  - Transmitter edge rate filter
  - Receiver noise filter
  - Receiver continuous time filter
- That ends up with about 2 mV
  - Just like in the eye closure experiment.
- Classic ICN (integrated crosstalk noise) only includes the PSD from
  - data
  - Transmitter edge rate filter
  - Receiver noise filter
  - Results is 5 mv of noise
- For a partial channel, i.e. a connector, fully comprehensive ICN may not be possible
  - However the classic ICN is more useful than raw frequency plots.

The Rest of the Story

- If we are lucky, we get to apply the Central Limit theorem
- That is if we have enough non dominate independent Gaussian processes, the result is Gaussian
  - We can play the add up variance games
- We can lose margin if, for example, the noise distributions are bounded.
  - This why we do time domain statistical simulations of channel impairments
- The good news is a the end of the day at the Rx, the aggregated noise form all sources tend to be Gaussian
- What means is we can use a noise source to test
  - Even though we cannot see inside a receiver.

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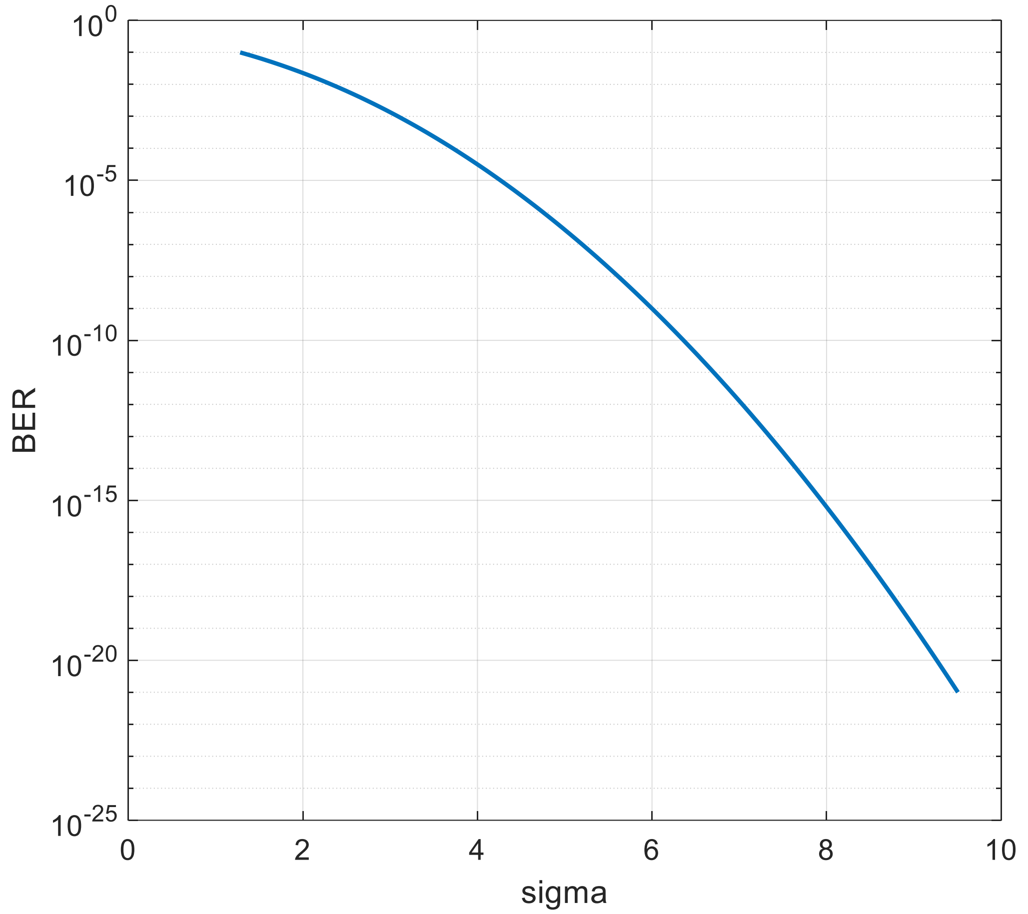
BER vs. single sided Sigma

BER	Sigma		BER	Sigma
0.1	1.282		1.00E-12	7.034
0.01	2.326		1.00E-13	7.349
0.001	3.090		1.00E-14	7.651
0.0001	3.719		1.00E-15	7.941
1.00E-05	4.265		1.00E-16	8.222
1.00E-06	4.753		1.00E-17	8.494
1.00E-07	5.199		1.00E-18	8.757
1.00E-08	5.612		1.00E-19	9.013
1.00E-09	5.998		1.00E-20	9.262
1.00E-10	6.361		1.00E-21	9.505
1.00E-11	6.706			



Matlab Code

sigma = sqrt(2)*erfcinv(BER/2)

- http://www.ieee802.org/3/ck/public/tools/tools/mellitz_3ck_adhoc_01_052020_COM2p93.zip

- https://pdfs.semanticscholar.org/7e9c/b8b162fe93a131d37fa1408fb56d9e5b05f8.pdf

COM References

- COM Matlab download

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- Early paper on COM

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