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Noise and Simulation Correlation | Richard Mellitz

INTRODUCTION

- Statistical terms and experiments
- Bit Stream, Measurement, and COM Correlation
- Adjust COM Parameters to System Error for Correlation
- Summary

What is Correlation?

- Takeaway: “Why” is the answer
- More later…
- First let's review some statistics

R square

- In statistics, “the **coefficient of determination**, denoted R^2 or r^2 and pronounced ‘R square’, is the proportion of the variance in the dependent variable that is predictable from the independent variable(s)[1]”
- R^2 ranges between 0 and 1
- If the R^2 of a model is 0.50, then half of the observances can be attributed to model's inputs
- If the R^2 of a model is 1.0, then all of the observances can be attributed to model's inputs
- Now for the rest of the story

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Simple Experiment

- ***X** are the independent parameters variables*
- ***Y** are the dependent parameters or in our case simulated results*

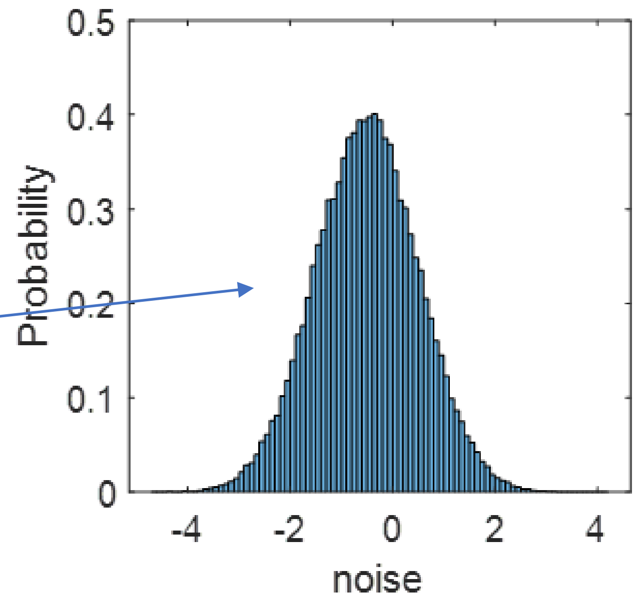
For this experiment, let's take a quadratic

$$y(x) = 0.05x^2 - 0.5x - 2.2 \quad \lfloor x \;\{-10\; to\; 10, step\; 0.05\}$$

- Now add some Gaussian noise to that equation and call it the signal

$$\text{signal}(x) = y(x) + noise$$

2 cases:
1 mV RMS noise
0.1 mV RMS noise



Plotting and Fitting *signal(x) w/ 1mV RMS noise*

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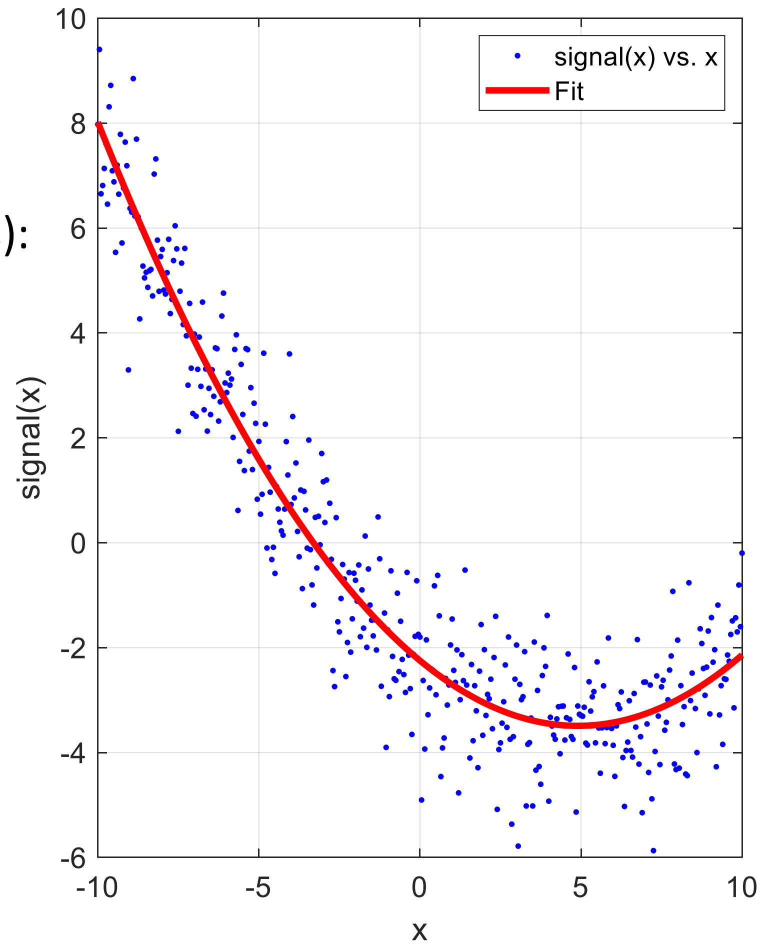
fit_model =
    Linear model Poly2:
    fit_model(x) = p1*x^2 + p2*x + p3
    Coefficients
        (with 95% confidence bounds):
    p1 =   0.05186 (0.04864, 0.05507)
    p2 =   -0.5079 (-0.5246, -0.4913)
    p3 =   -2.246 (-2.391, -2.102)

goodness_of_fit =
    rsquare: 0.9204
    rmse: 0.9818



- R-square (R^2) is like a correlation factor
  - R^2 is 0.9204 i.e. data is ~92% correlated to the fit
- RMSE is the Root Mean Square Error
  - One way to interpret is:
  - The equation is on average +/- 0.9818 accurate
- The goal is to find the original equation,
  $y(x) = 0.05x^2 - 0.5x - 2.2$
  from the dots (samples) in the curve on the left
- The fit is an equation called f(x) at the left
  - With p1, p2, and p3 coefficients

Plotting and Fitting *signal(x)* *w/ 0.1mV RMS noise*

fit_model =

Linear model Poly2:

fit_model(x) = p1*x^2 + p2*x + p3

Coefficients

(with 95% confidence bounds):

p1 = 0.04992 (0.04957, 0.05026)

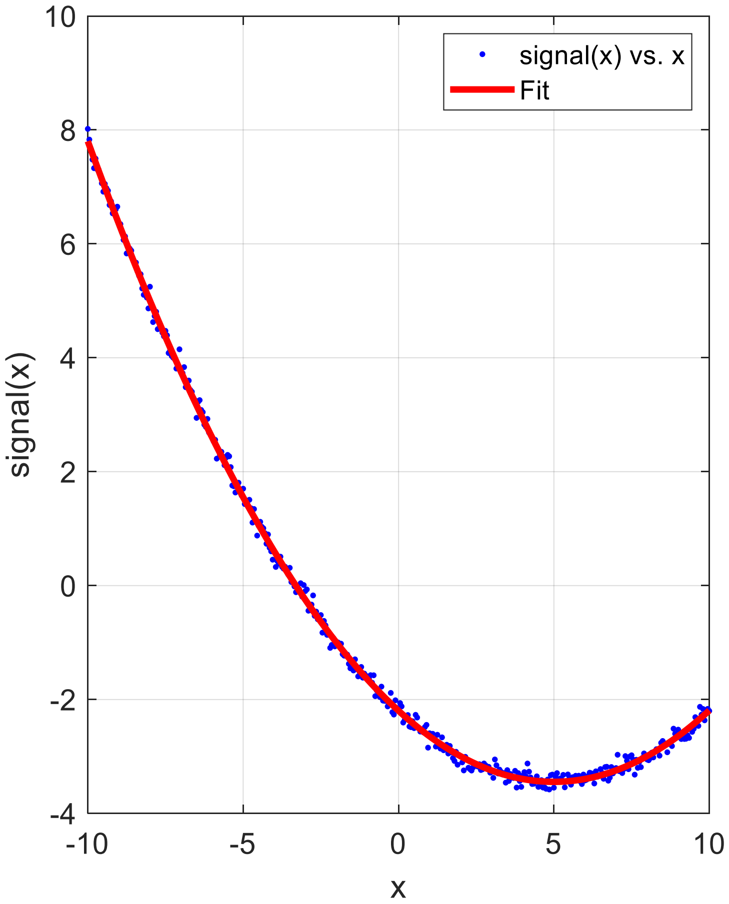
p2 = -0.4999 (-0.5017, -0.4981)

p3 = -2.204 (-2.22, -2.188)

goodness_of_fit =

rsquare: 0.9989

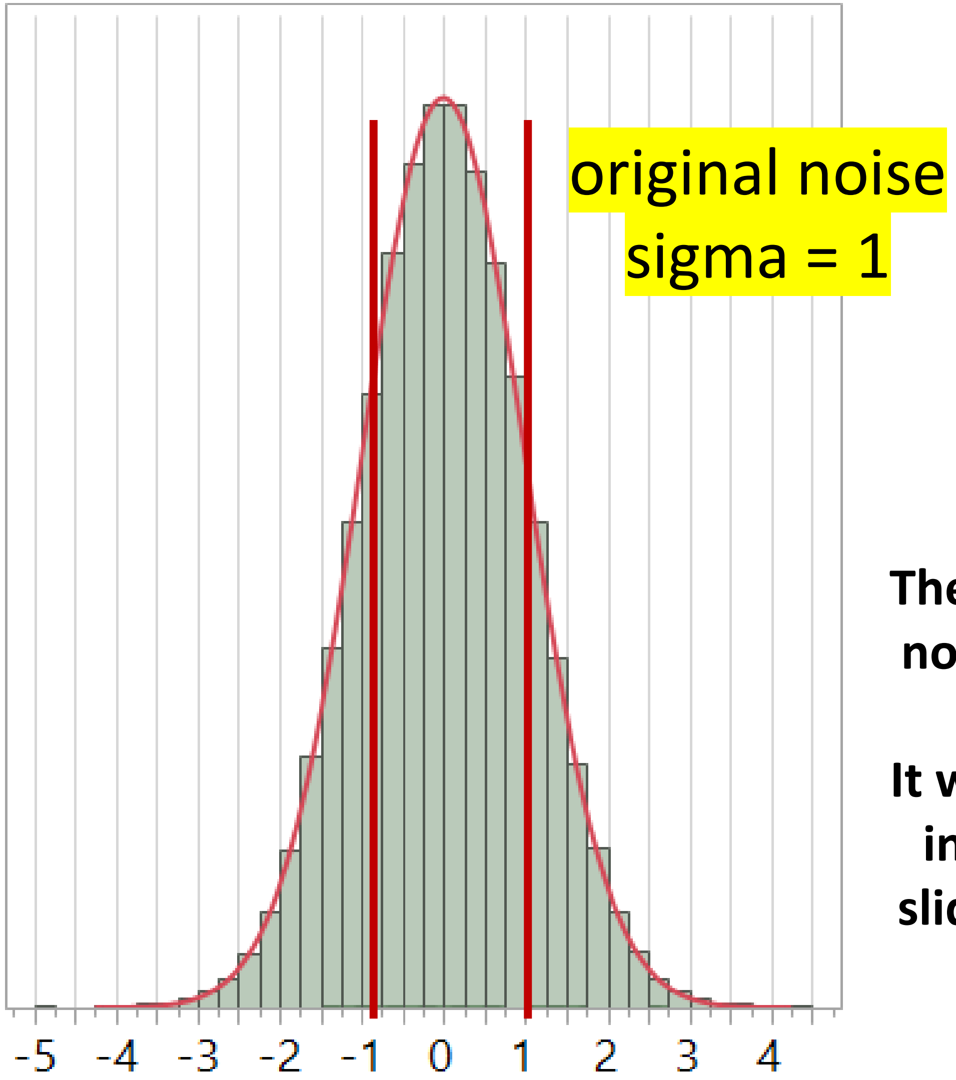
rmse: 0.1061



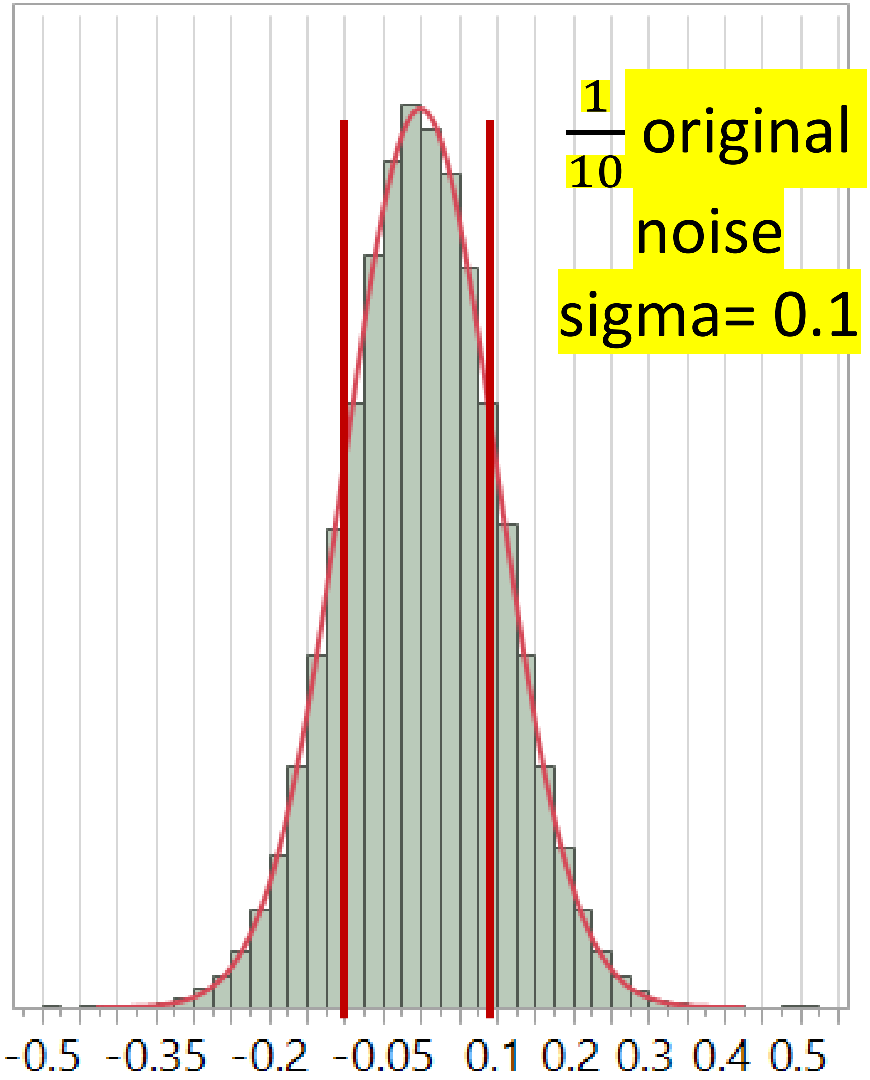
- This time R^2 is 99.89%
- We can reproduce the equation well but there still is an uncertainty
- This time RMSE is 0.1061 accurate
- Often RMSE is more important than the correlation (R^2)

An almost perfect fit does not have zero uncertainty

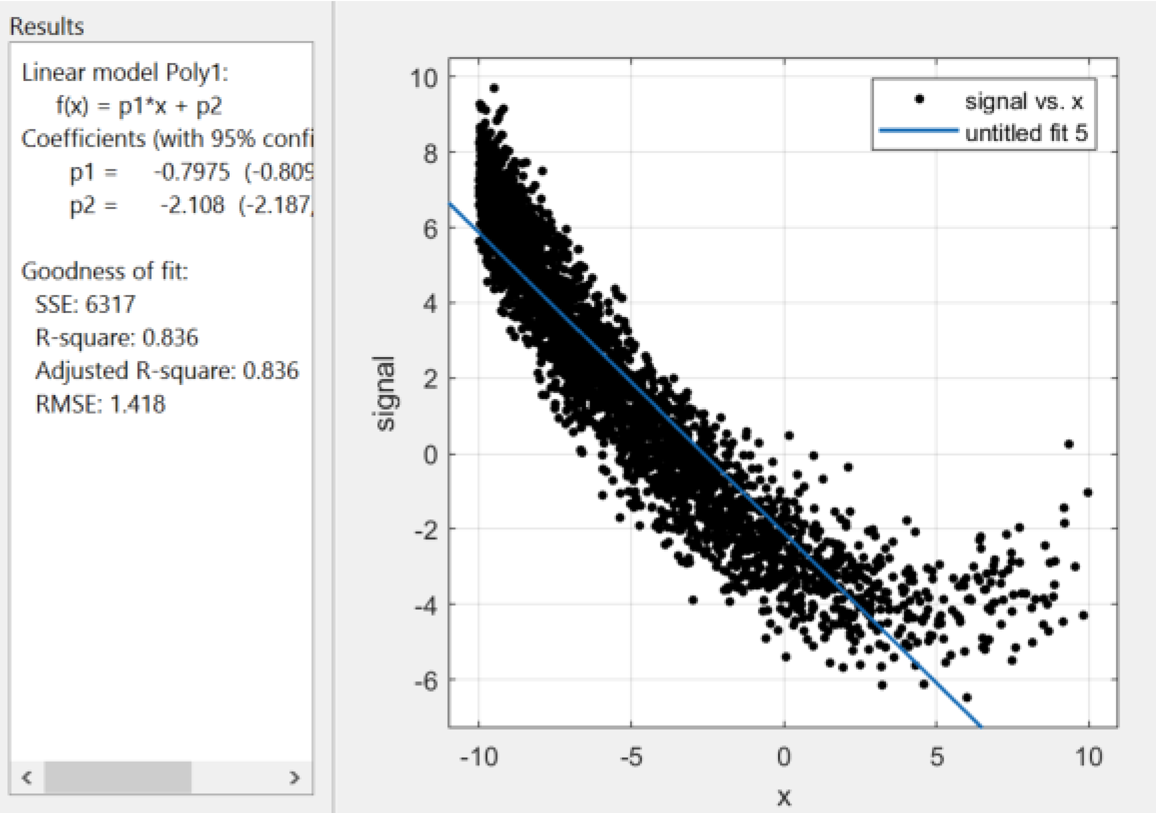
Let's Reduce the Noise by a Factor of 10



The RMS of the noise added is sigma.
It was reported in the fitting slides as RMSE



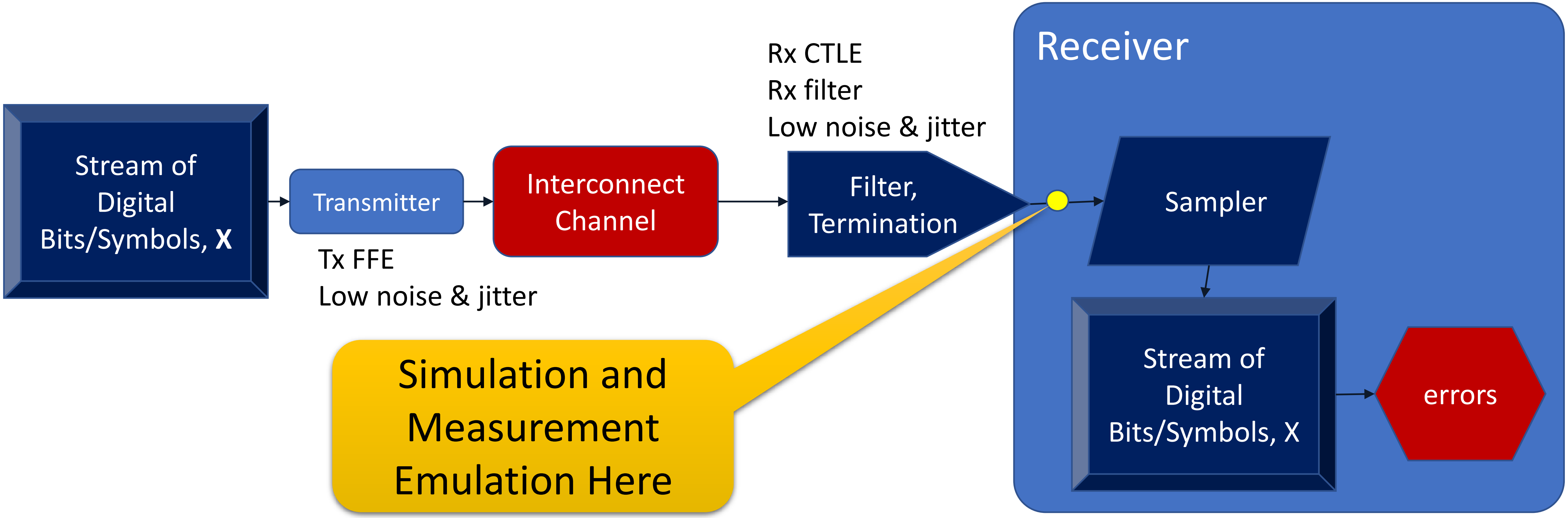
A Word of Caution: Choose Your Data Wisely



- This time our x samples are a normal distribution shifted by -2.
- If you didn't know better, you might think a linear fit is OK
  - R-square is 83.6% (previously ~92%)
  - RMSE is 1.418 (previously ~0.98)
- Correlation depends on what the end goal is
- Determining the end goal is often the most difficult task.

Speaking of End Goals … The End Goal Here is to Predict Error Ratios

- Example: Compare simulation, measurements, and BER (bit error ratio)
- Then use noise to achieve correlation

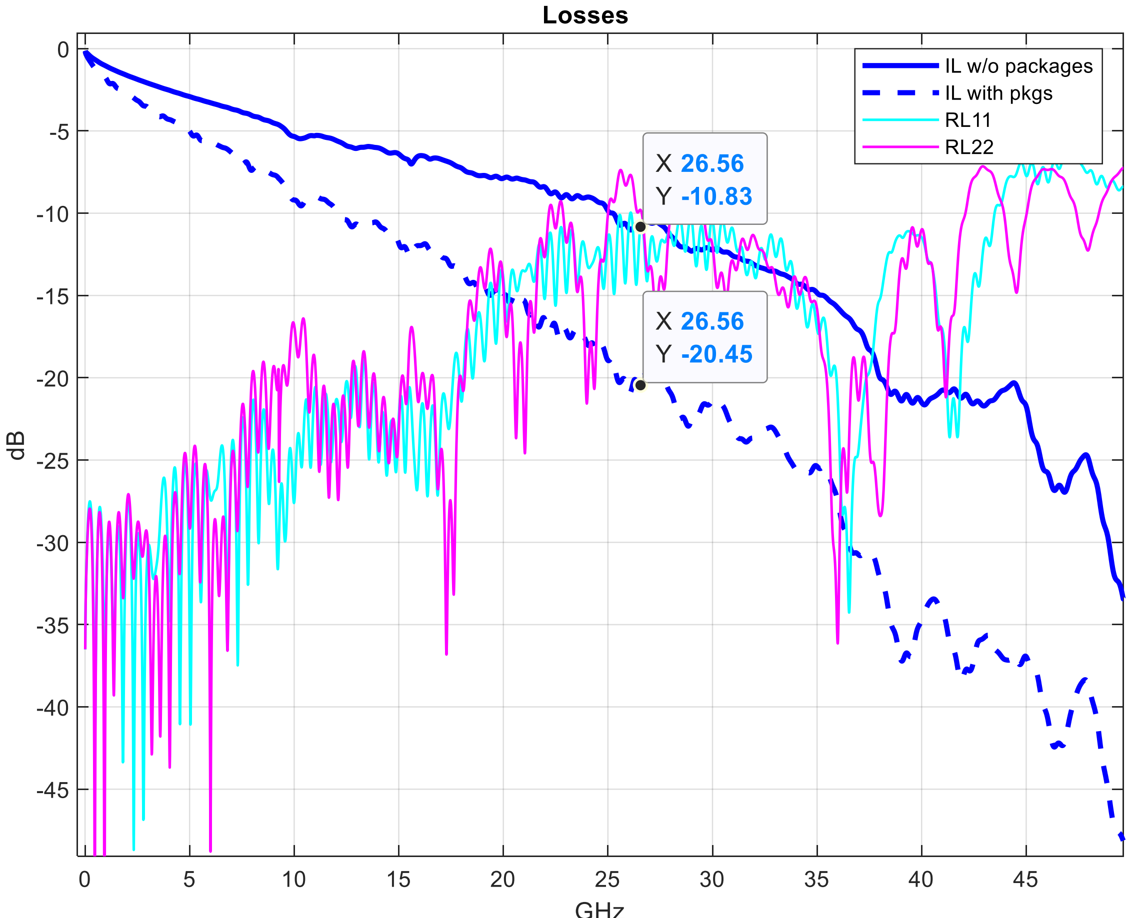


For Reference background:

112 Gbps PAM-4 channel
example at 53.126 Gbaud(Gb)

~ Channel IL plus packages

IL ~= 20.45 dB loss at 26.6 GHz



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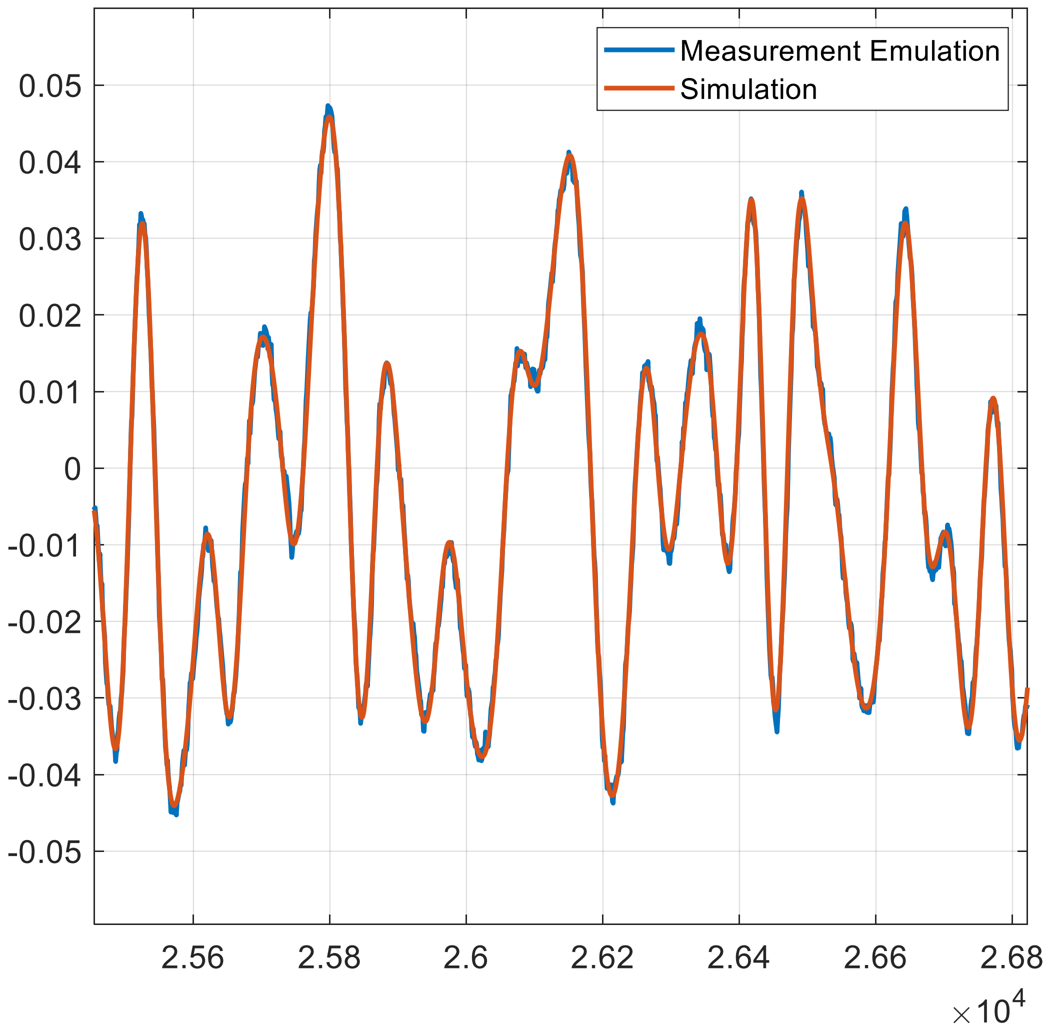
Measurements Emulation and Simulation Signals at a Sampler



- The simulation was using a bit stream (not COM)
  - PRBS19Q was used
  - ~10^5 symbols
- The measurement emulates quantized noise from digital signal processing at a sampler
- Is this a good correlation?
- Subject for a good discussion… ?

Coefficient of Determination (R^2) Seems Good

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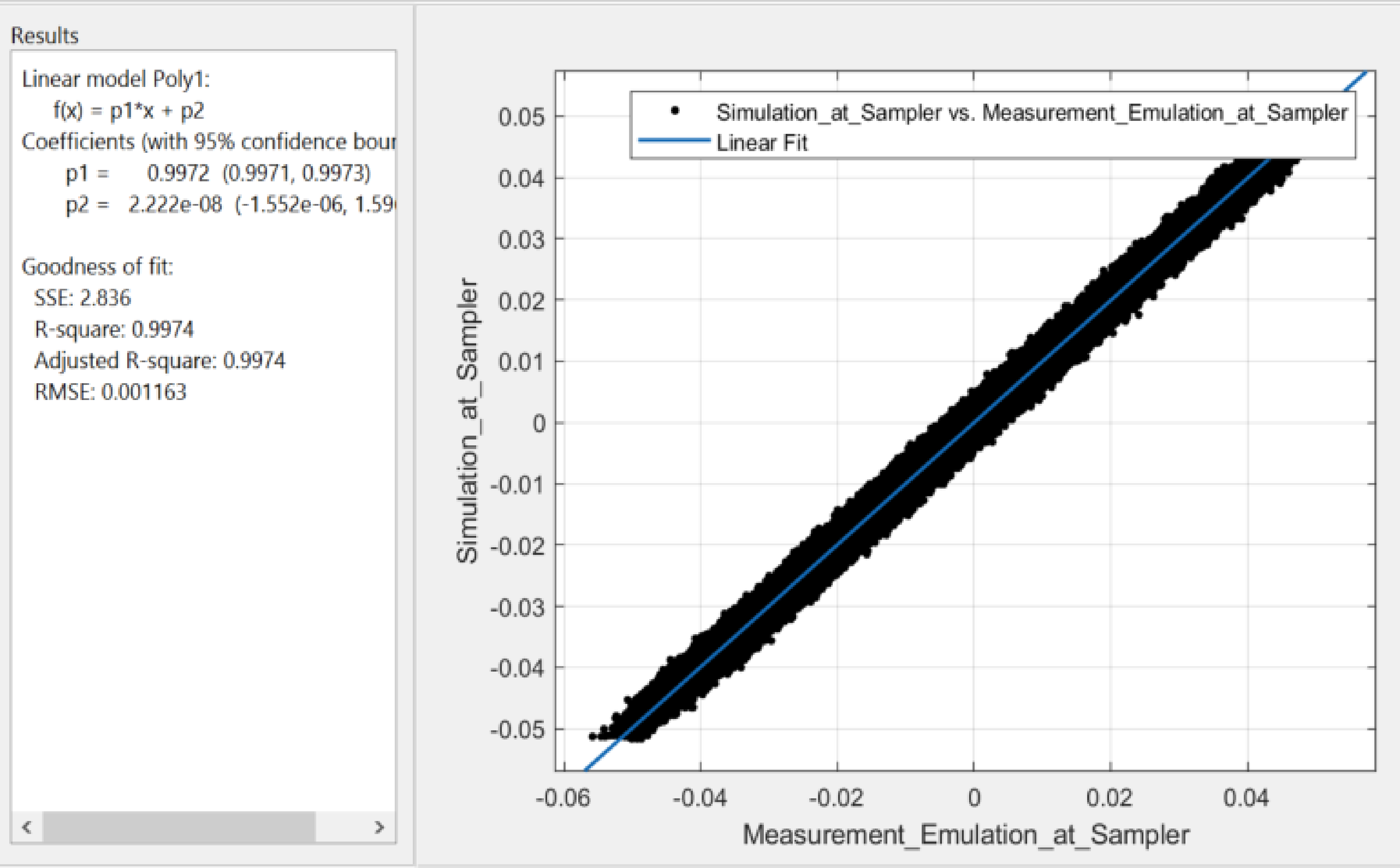
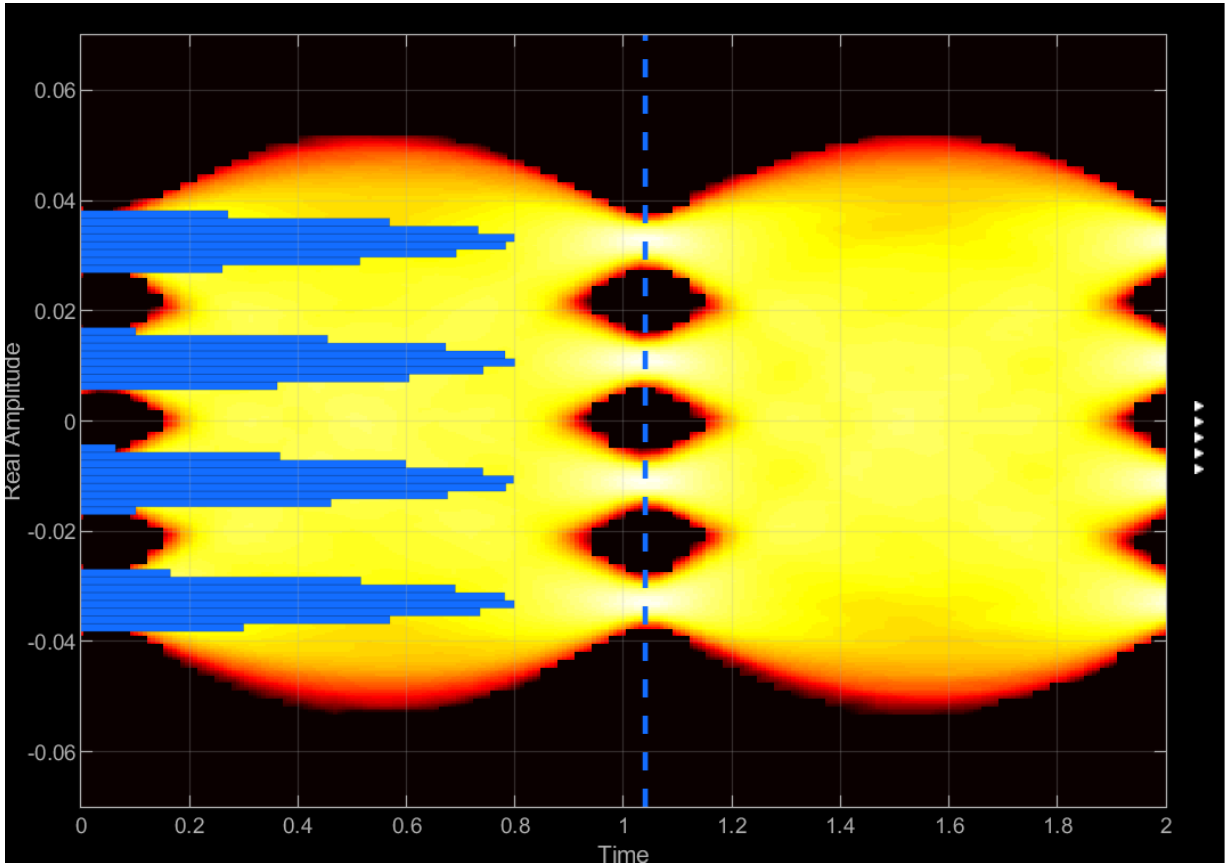
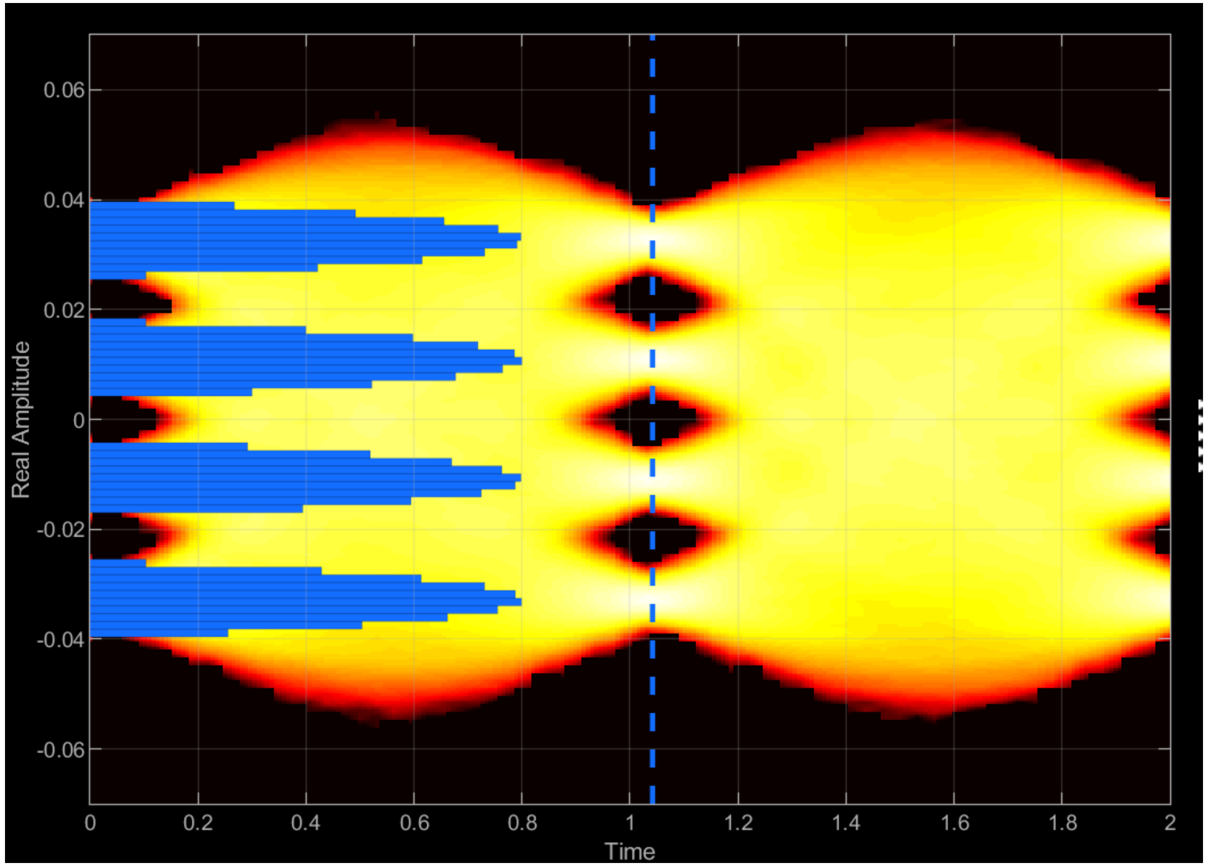


- R^2 is great … 99.74%
- RMSE is 1.163 mV
- Keep this RMSE in mind
  - In essence this is the noise(RMS) seen at the sampler

Two Eye Diagrams: Simulation and Measurement Emulation

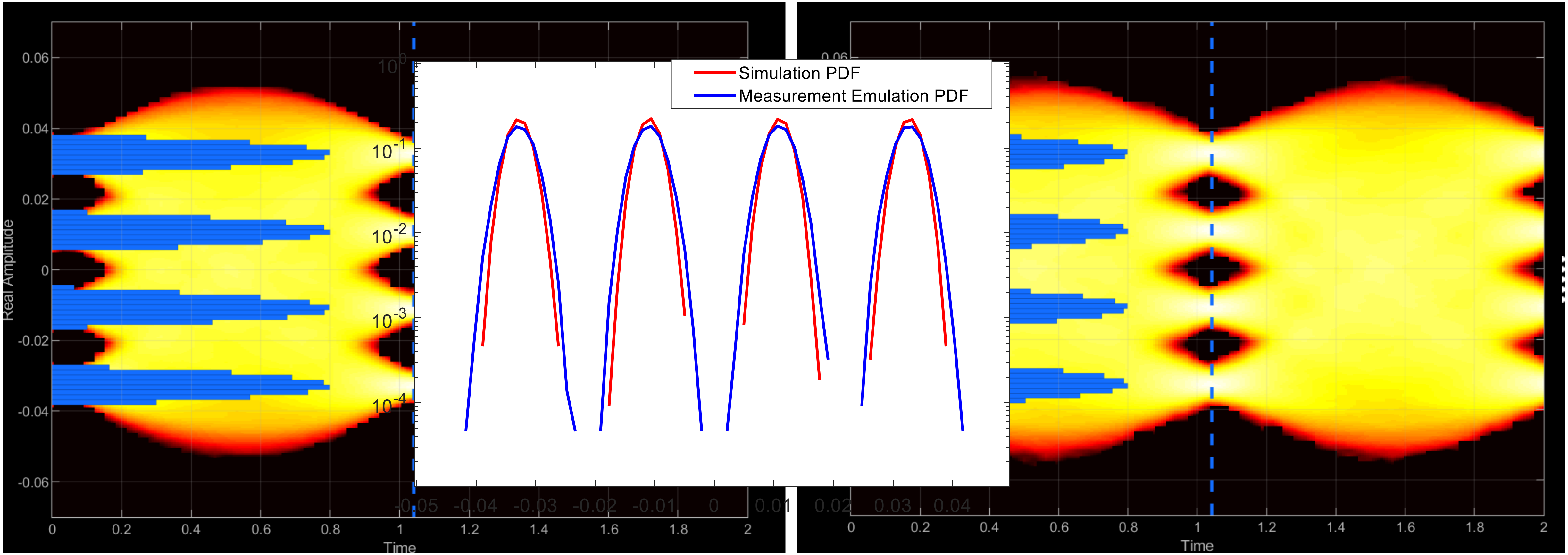


Simulation Signal at Sampler
Larger eye opening



Measurement EMULATION Signal at Sampler
BER higher than Simulation

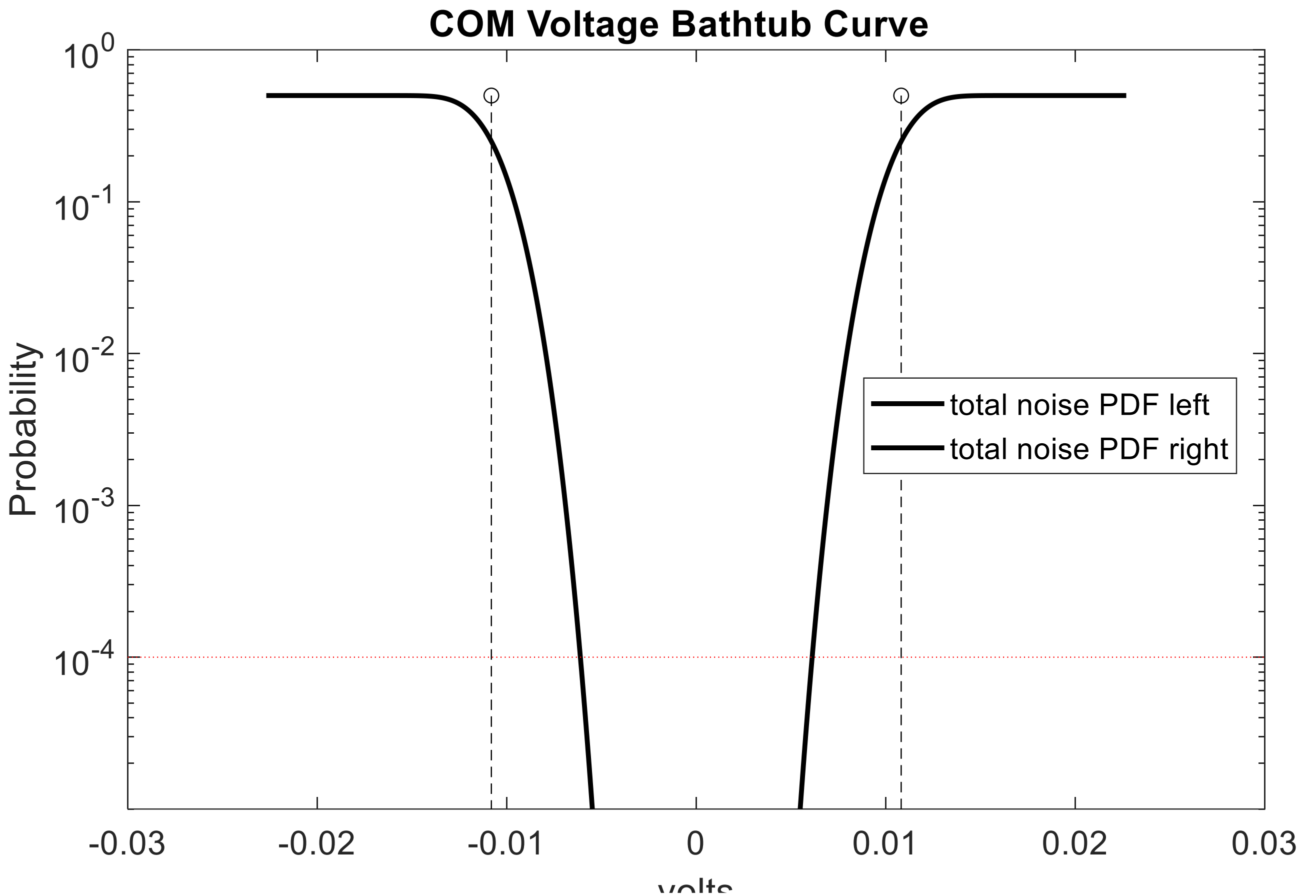
First step: Look at the histograms i.e. probability distributions functions (PDF)



Simulation Signal at Sampler

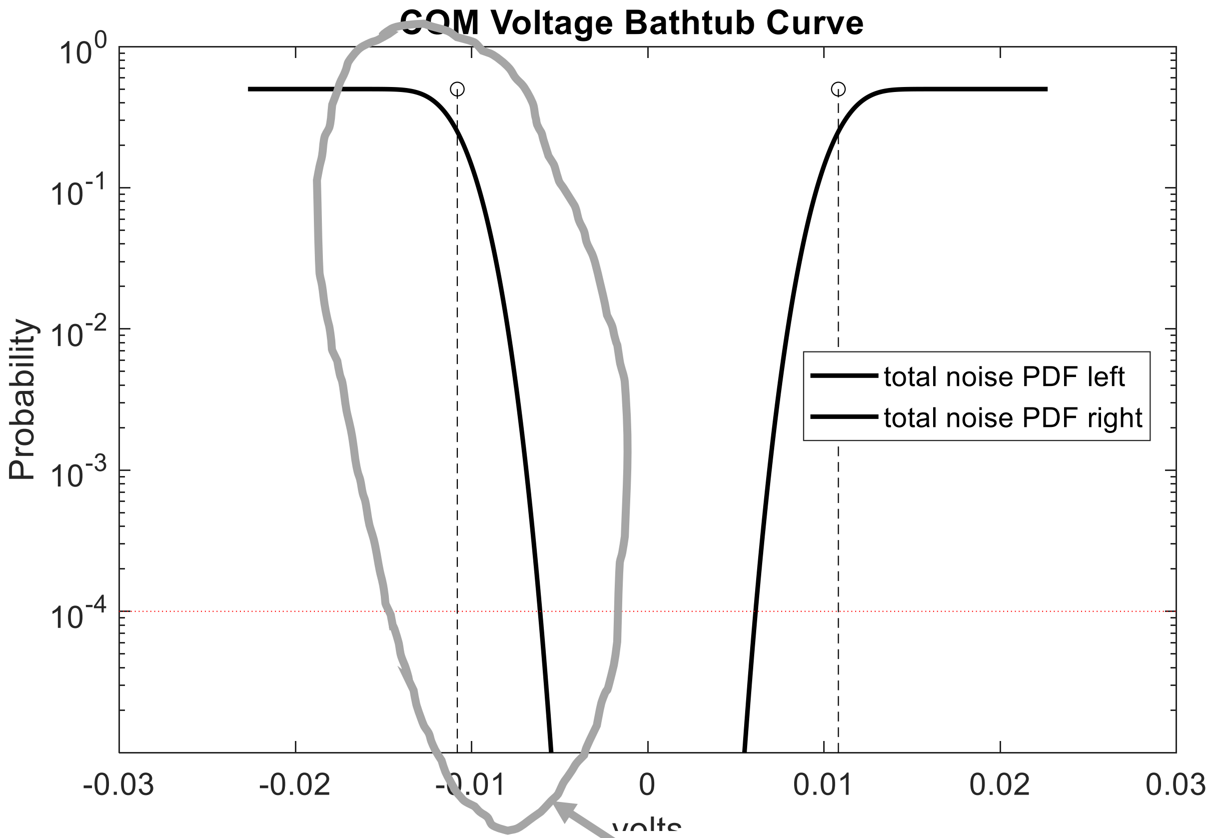
Measurement EMULATION Signal at Sampler

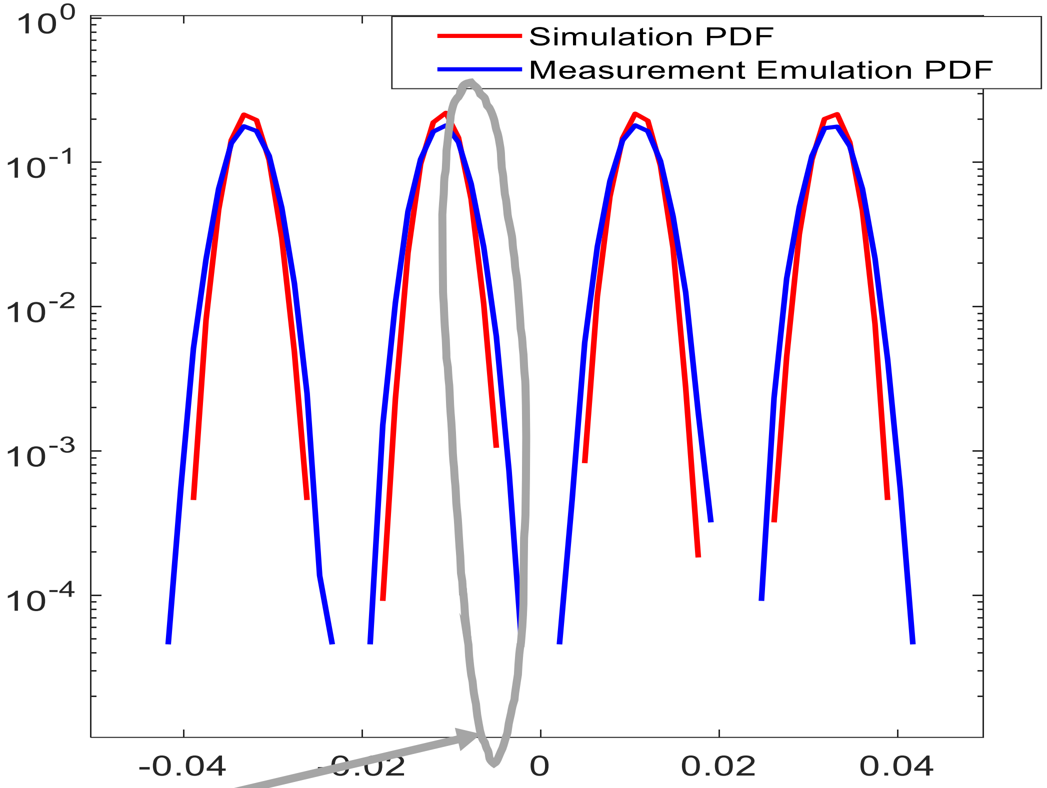
Now Let's Do the Simulation Using COM



- COM Voltage Bathtub Curves and simulation bathtub curves should be approximately the same
- This is a cumulative distribution function (CDF) curve
  - For worst symbol eye
- Not a probability density function (PDF)
- We need to covert the prior histogram to a CDF to do comparisons

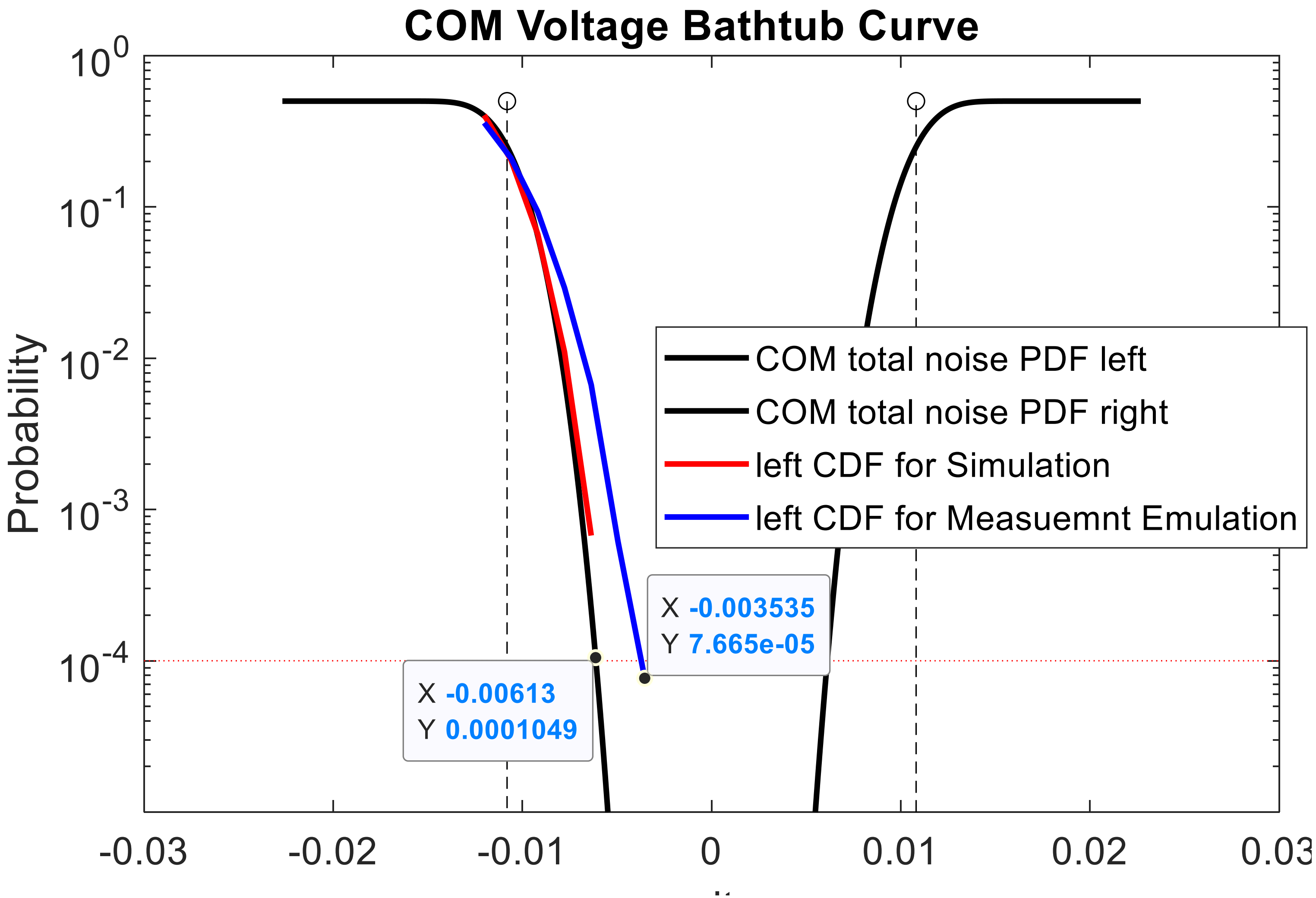
Voltage Bathtub Curves in COM and Bitstream Simulation





Let's focus in the left pdf for the middle eye

COM Agrees with Bit Stream Simulation



- The red and blue curves were created with a “cumsum” function of the PDF’s on the prior slide
- The Measurement Emulation (blue) has about 7 mv less eye opening.
  - 3.5 mv mean to peak
- Goal: Adjust COM to agree with the measurement emulation?

COM noise and related parameters definition

Config keyword	Units	Comments
sigma_RJ	UI	Random Jitter (RMS)
A_DD	UI	Normalized peak dual-Dirac noise, this is half of the total bound uncorrelated jitter (BUJ) in UI
eta_0	v^2/GHz	One-sided noise spectral density
SNR_TX	dB	transmitter SNR noise (RMS)
R_LM	Unitless	Ratio of level separation mismatch. Relevant for PAM-4 only.
DER_0	errors per symbol detection	Target detector error ratio

COM parameter used for this experiment

Config keyword	Value	Units	Comments
sigma_RJ	0.0001	UI	No jitter
A_DD	0.0002	UI	
eta_0	8.2E-011	v^2/GHz	No Rx noise
SNR_TX	100	dB	No Tx noise
R_LM	1	Unitless	No level mismatch
DER_0	0.0001	errors per symbol detection	Target detector error ratio

Eta 0 (η_0) One-sided noise spectral density

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- In the correlation experiment we showed an RMSE of ~ 1.163 mV
  In essence this is the noise (RMS) seen the sampler
  - which is **not** in the simulation
  - **but is** in the measurement emulation
- In the COM computation there is a similar term, s_n, used as input referred noise

$$\sigma_n^2 = \eta_0 \int_0^\infty \left| H_r(f) H_{ctf}(f) \right|^2 df$$

Where $H_r(f)$ is the receiver bandwidth and $H_{ctf}(f)$ is the voltage transfer response of the continuous time filter (aka CTLE).

- $H_r(f)$ is specified by COM and $H_{ctf}(f)$ is determined during COM optimization

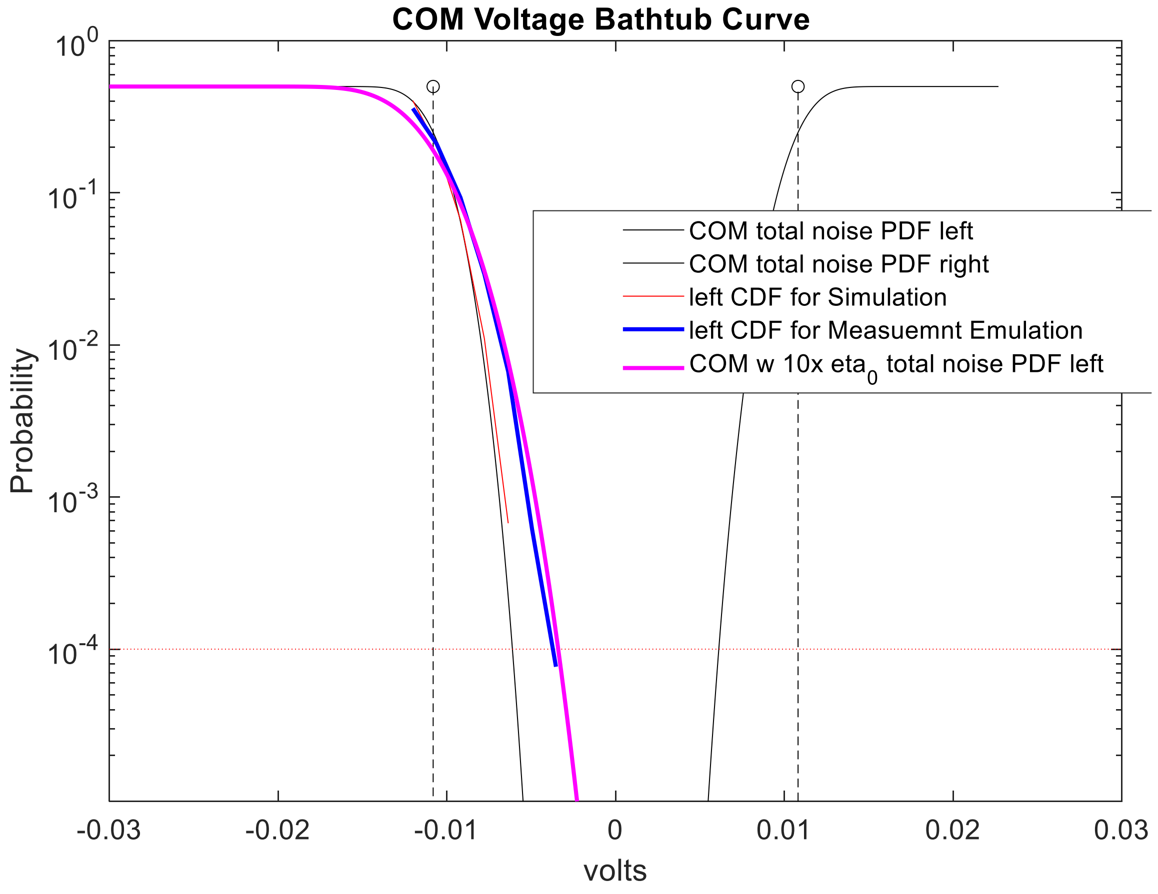
If we assume the RMSE is, σ_n, we can determine η_0 (eta_0)

All other parameters are known

For our case we found η_0 is approximately 8.20E-08 V^2/GHz

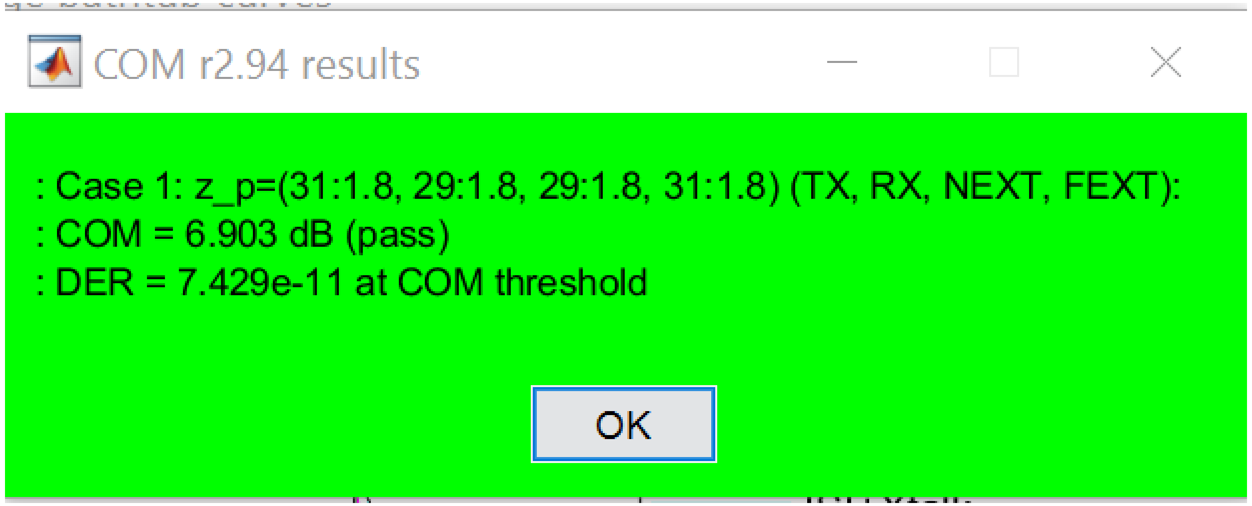
The next step is run COM with this new η_0

- The COM simulation with new η_0 (eta_0) produces approximately the same bathtub curve as the measurement emulation
  – Remember we derived the new η_0 from the RMSE of the correlation at the sampler



Let’s Look at this Another Way

- COM reports and approximate DER at failure
  - Assuming COM exceeding the limit produces an error.



Sample of COM report

--- Testcase 1 results ---

code_revision: '2.94'

redo_cmd_str: 'eval(['My_var_0 = ' getappdata(0,'cmd_str')])'

RL: [1×1 struct]

fitted_IL_dB_at_Fnq: 10.8098

VEO_normalized: 0.5483

VEC_dB: 5.2200

VEO_mV: 13.1813

EW_UI_est: 0.2188

COM_dB: 6.9026

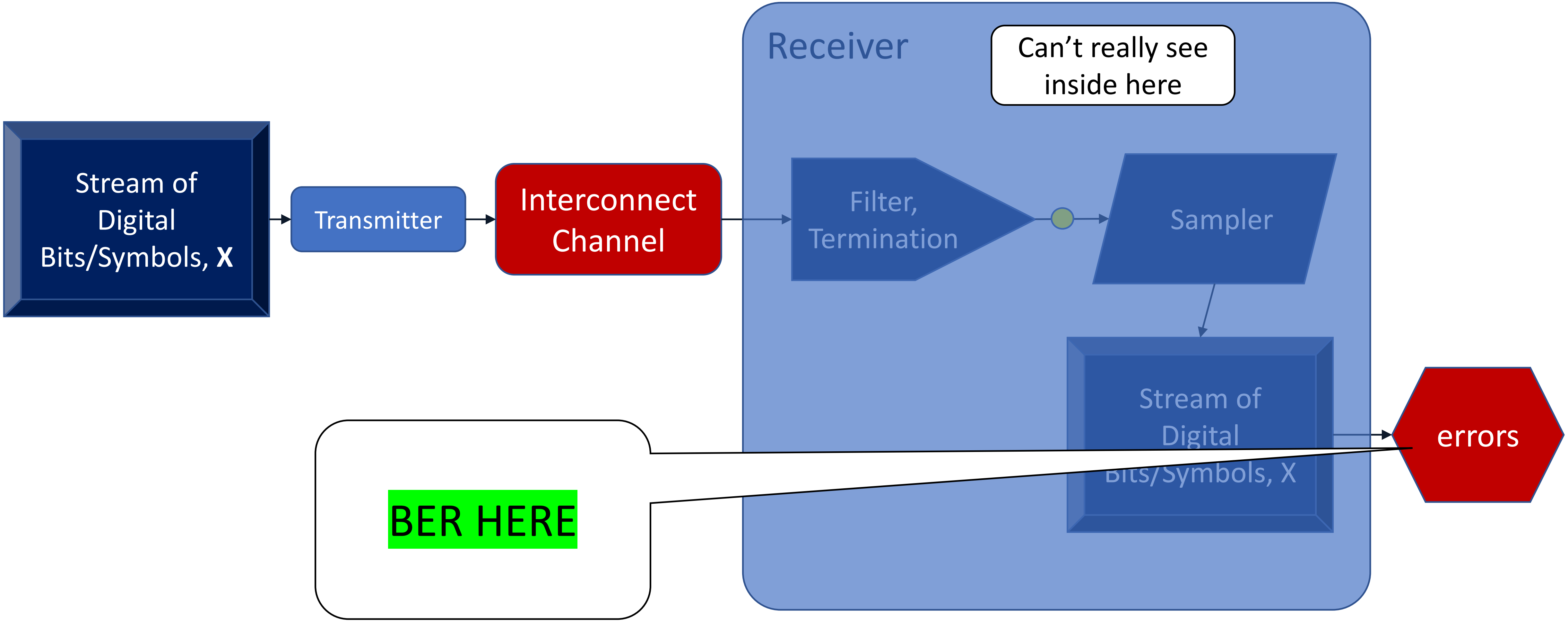
DER_thresh: 7.4295e-11

rtmin: 1.1884

PASS ... COM = 6.903 dB

DER = 7.429e-11 at COM threshold

Let's Say We Can Determine the BER of an Actual Running System



Example of Correlating COM to the Reported System BER

- Determine the detector error ratio from measured BER
- Adjust the COM parameter eta_0 until the measured DER approximates the reported DER at COM threshold
  - Just like we did for the waveform correlation
- Now we have a COM model which is somewhat correlated to measurements

Summary

- Statistics can be misleading
  - Scrutinize data selection
- Waveform correlation is only a first step
- Make sure you know the “end goal”
- Use of noise is a good tool for achieving model correlation to reported system errors

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Footnoted References

1. *See* Wikipedia ,' Coefficient of determination',
   https://en.wikipedia.org/wiki/Coefficient of determination , as of 4 August 2020, at 14:30 (UTC)

COM References

- COM Matlab download

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

- Early paper on COM

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

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