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SANTA CLARA CONVENTION CENTER

Channel Operating Margin (COM): Evolution of Channel Specifications for 25 Gbps and Beyond

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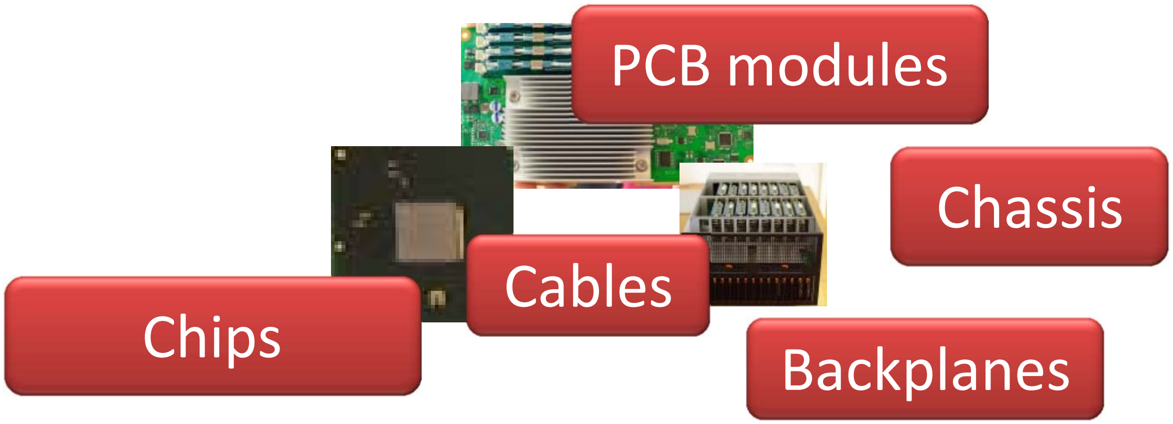
COM

- What is COM?
- What is a Channel?
- Channel Models
- Prior Channel Compliance
- Compliance Gaps
- Single Bit Response (SBR) Statistics
- Deriving COM values
- Experiment/Correlation
- Summary

Channel Operating Margin (COM)

- COM is a <u>figure of merit</u> (FOM) for channels determined from
  - A minimum reference PHY architecture
  - Channel s-parameters
- COM levels the playing field for physical design choices
  - COM budgets between loss, reflection Inter-Symbol Interference (ISI) , dispersion ISI, crosstalk, and device specifications
- COM is the ratio of available signal amplitude, *As*, to <u>statistical</u> noise amplitude, *An*, expressed in dB:
  - $\boldsymbol{COM = 20 * log_{10}\left(\frac{As}{An}\right)}$
  - Similar to signal to noise ratio (SNR)
  - Not a traditional Gaussian (SNR)

A Platform is:



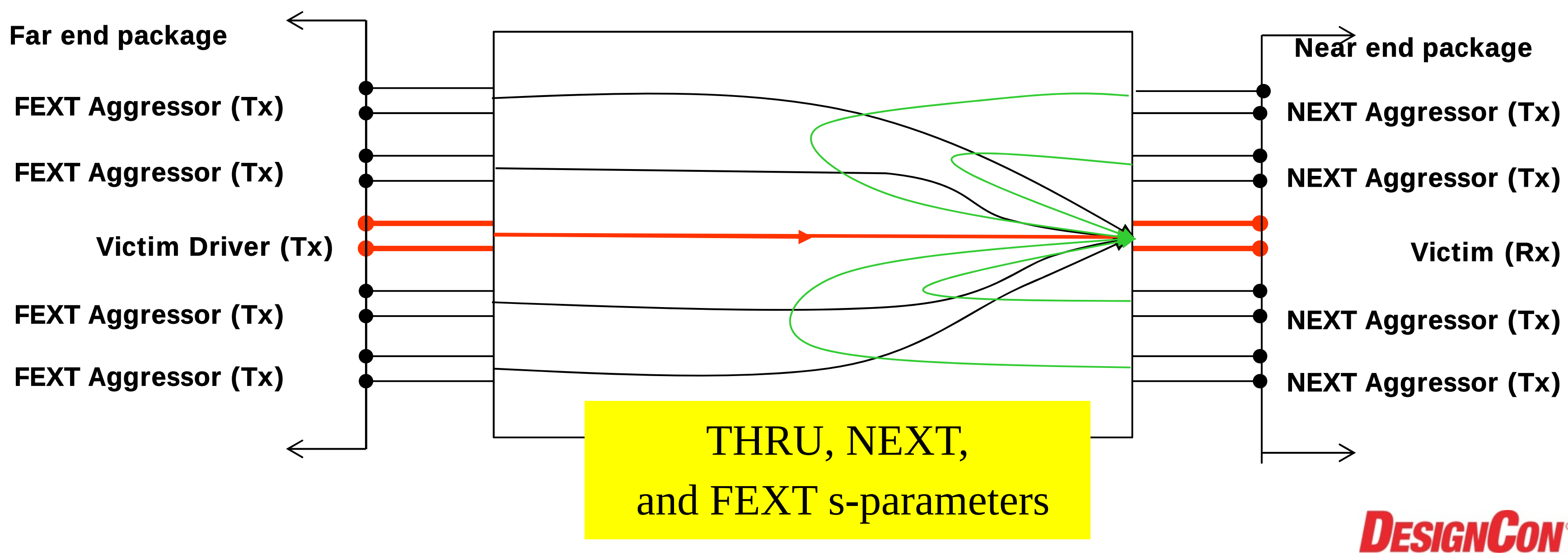
- A collection of printed circuit boards (PCB)
- Maybe some cables
- Maybe some backplanes
- Maybe a chassis
- Maybe a boxed product

What is a Channel?

- A channel is the physical electrical connection between a transmitter and receiver block:
  - for the purpose of transporting data
  - which are devices with their own specifications,
  - The transmitter and receiver blocks embodied in silicon circuits and respective packaging.
- The channel is defined as <u>all the aggregated electrical lanes</u> connecting between devices
- In some cases this may be consider from BGA solder ball to BGA solder ball

Channel Model – Differential Example

- A collection of 4 port s-parameters of sufficient bandwidth and resolution which are converted into 2 port differential mode
- A channel set contains a
  - A victim channel response called **THRU**
  - Some number of far end crosstalk aggressor responses (**FEXT**)
    - Same Tx as victim
  - Some number of near end aggressor responses (**NEXT**)
    - Not same Tx as victim

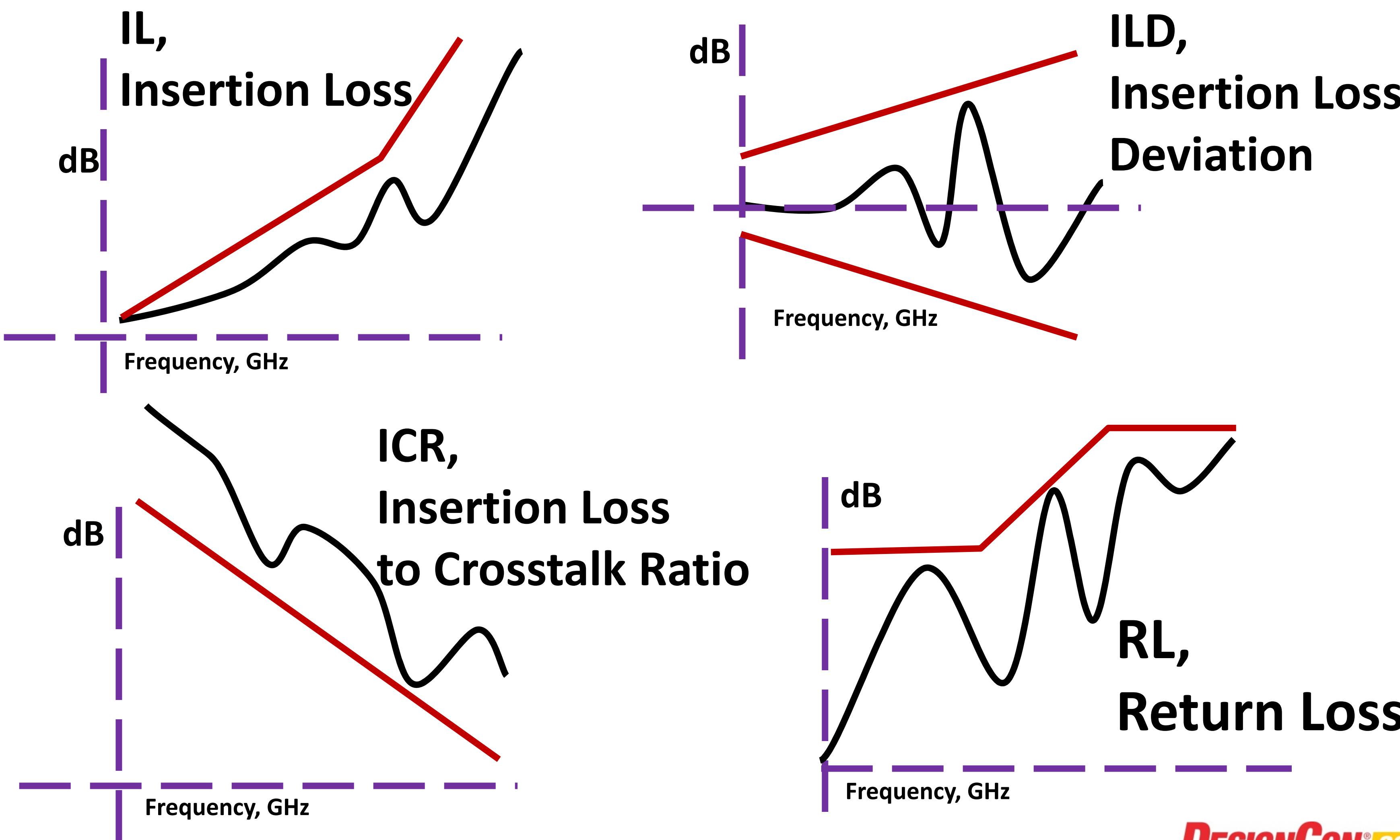


Channel Compliance

- Motherhood statement
  - A compliant transmitter and receiver will operate successfully with a compliant channel.
- Use of guard band may help achieve guaranteed operation
  - At expense of false negatives.
- In the past, the link between device and channel specs were either loose, indirect, or had specific physical implementations in mind.
- COM explicitly links the electrical specifications together and is physically design agnostic.

Frequency Mask Example -10 Gbps Ethernet Copper Backplane (KR)*

*IEEE Std 802.3ap™-2007 Clause 69b



Frequency Domain (FD) Mask

- IL, ILD, ICR, and RL masks are collectively exhaustive
  - Trade off between these are not easily determined or guaranteed to work
- ICR is a budget between crosstalk and insertion loss
  - It does not allow higher ILD with lower ICR even though that may operate with compliant devices.
- The clause 69b is informative
  - It serves as a strong guide
- Other standards may more normative regarding masks
- Mask relationship to device design is not clear

Integrated Method Powers

- Then figure of merit take the basic from of a signal to noise ratio $SNR = \frac{Sx}{\sqrt{{\sigma_{icn}}^2 + {\sigma_{iiln}}^2}}$
  - Where Sx is the available signal derived from a time domain transformation of the insertion loss.
  - σ_{icn} and σ_{iiln} are FD integrated noise terms*
    - Respectively power in crosstalk and ISI plus relfections
    - Assumes noise is Gaussian
- Many channel can have crosstalk and self channel noise that is <u>not Gaussian</u>. Guard band may address this.

* IEEE Std 802.3ap™-2007 Clause 85
"Fast, Accurate, 'Simulation Lite' Approach for Multi-GHz Board Design", Mellitz, Brownell, Ragavassamy, DesginCon2011

What is missing?

- The Context
- Simulation offers this but …

Expertise

Time

Cost

IP

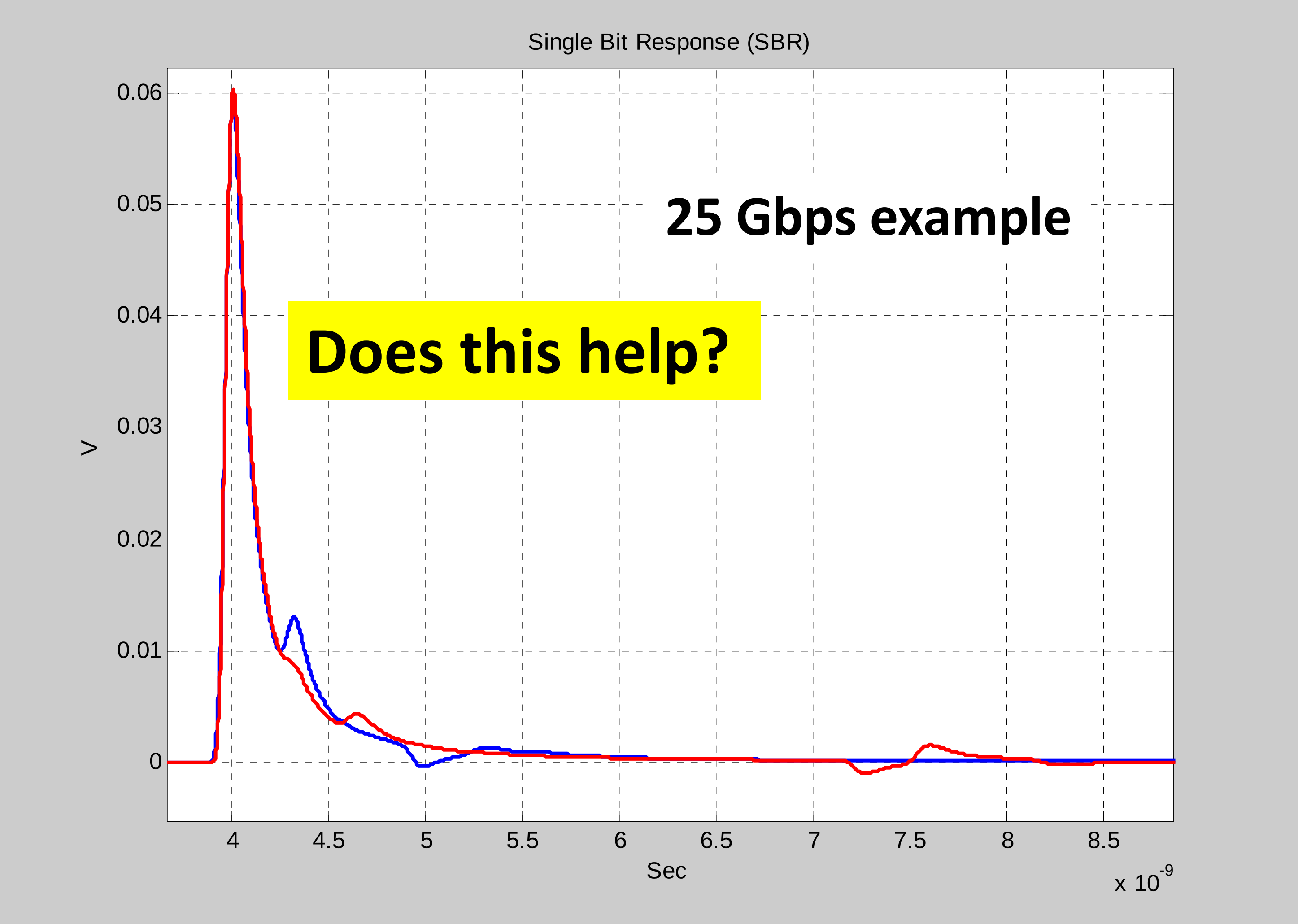
- COM provides context and …
  - Can be implemented with lower expertise
  - With reduced analysis
  - With lower cost
  - With IP protection

Context is important!

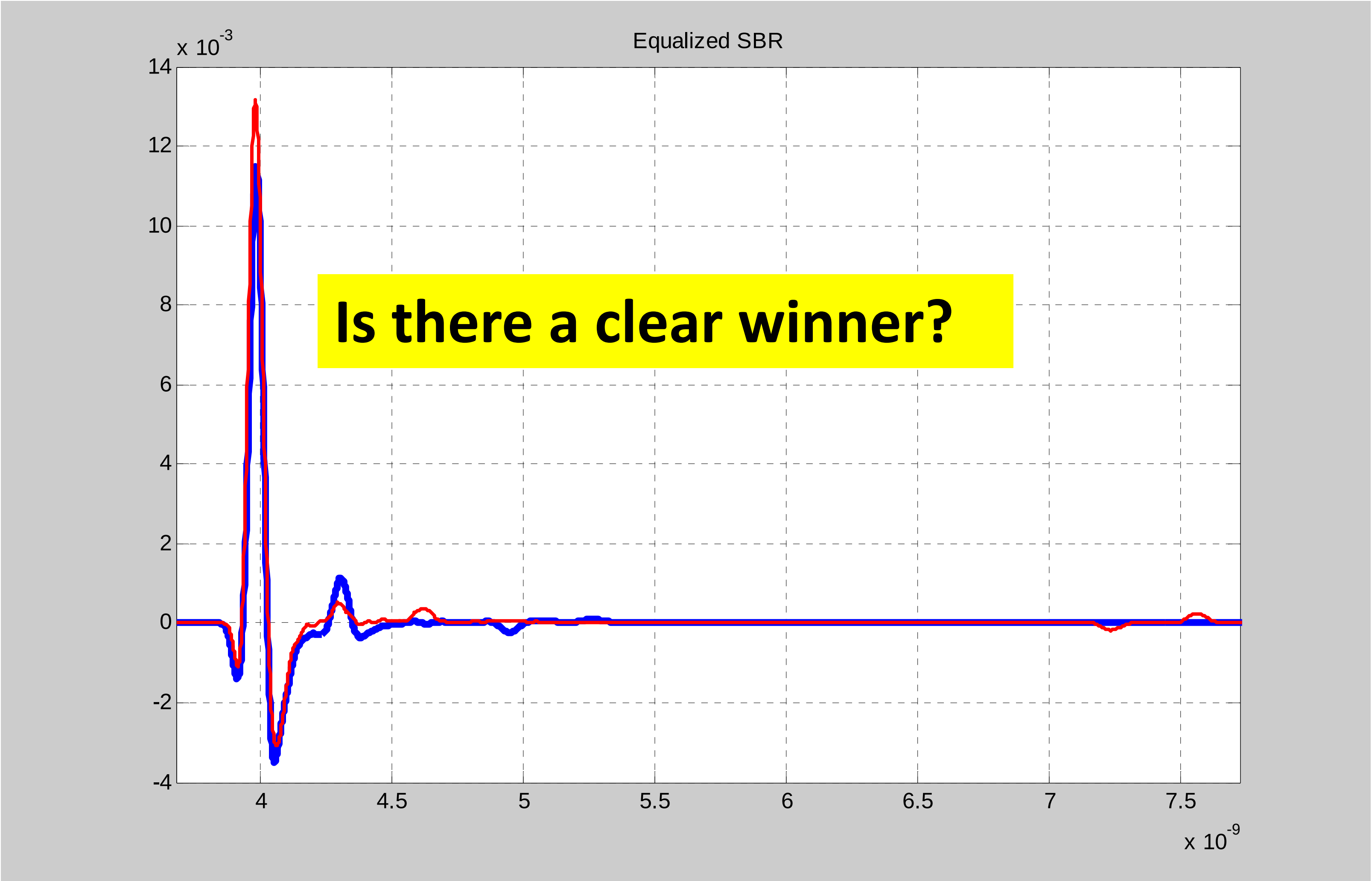
Blue Topology	1" FR4	1" Meg6	2" FR4	10" Meg6	10" Meg6
	60Ω	110 Ω	60 Ω	90 Ω	90 Ω

Red Topology	1" FR4	10" Meg6	1" Meg6	10" Meg6	2" FR4
	60Ω	90 Ω	110 Ω	90 Ω	60 Ω

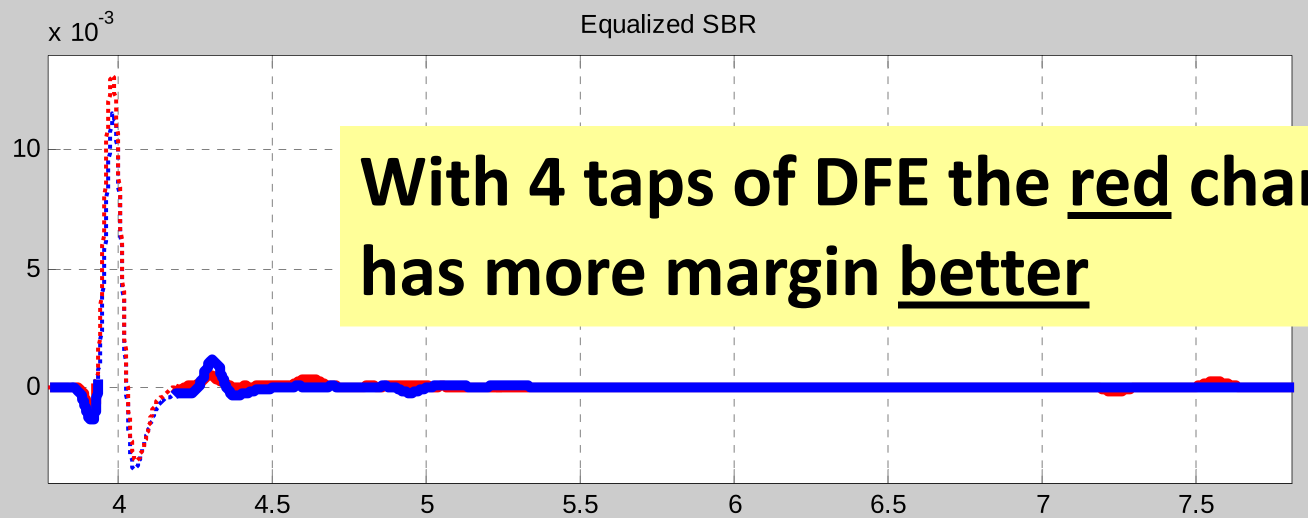
Single Bit Response (SBR) "AKA Pulse Response"



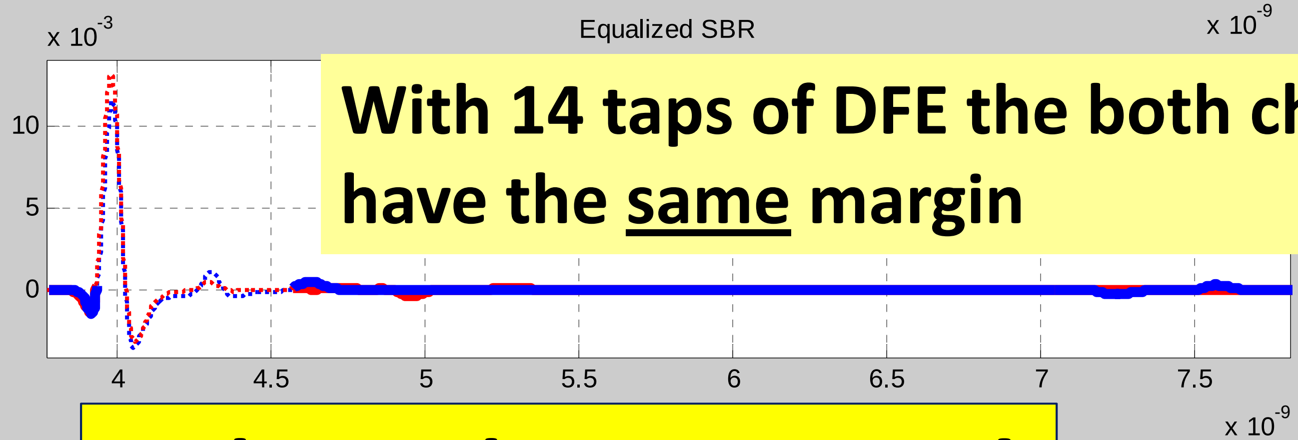
Apply FFE3 and CTLE From Grid Search



With 14 taps of DFE, the Channels Have the Same Margin!



With 4 taps of DFE the red channel has more margin better



With 14 taps of DFE the both channels have the same margin

It depends on context!

Takeaway on Channel Quality Metrics

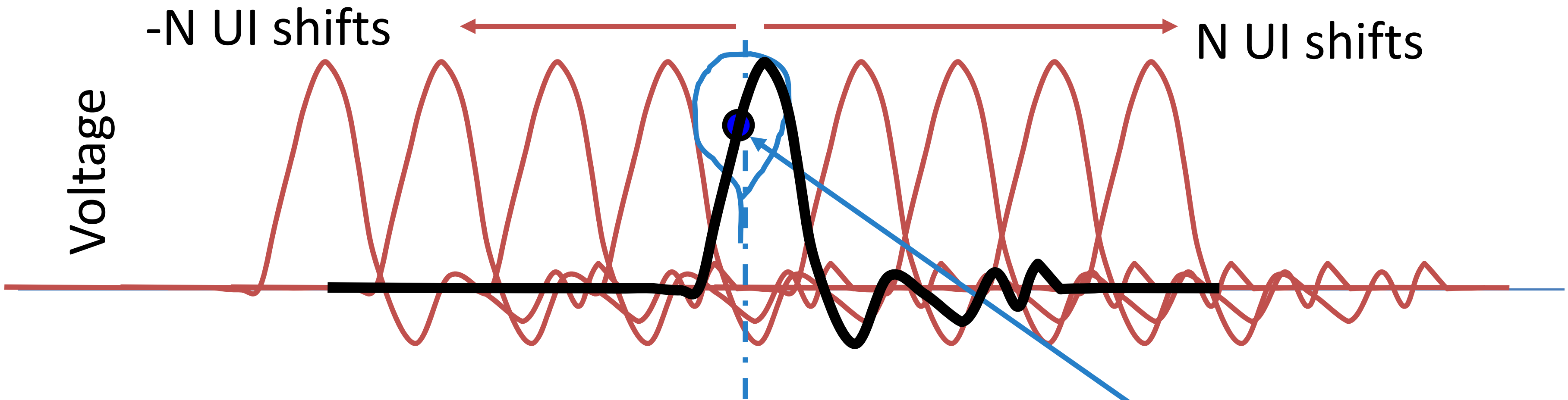
- Frequency domain mask and integrated power parameters may be useful but don't seem to have enough precision
- SBR contains enough information but requires the knowledge of expected equalization capability

Using SBR

- A receiver (Rx) signal data stream is the superposition of Rx SBRs.
  - Assumes linear time invariance (LTI)
  - SBR may used by some link simulators
- An efficient method to determine link quality is view a the problem statistically
  - Utilizing an SBR

Overview of Statistical Simulation

Superposition of SBR (bits) is the basis for statistical simulation: "Simple" example:

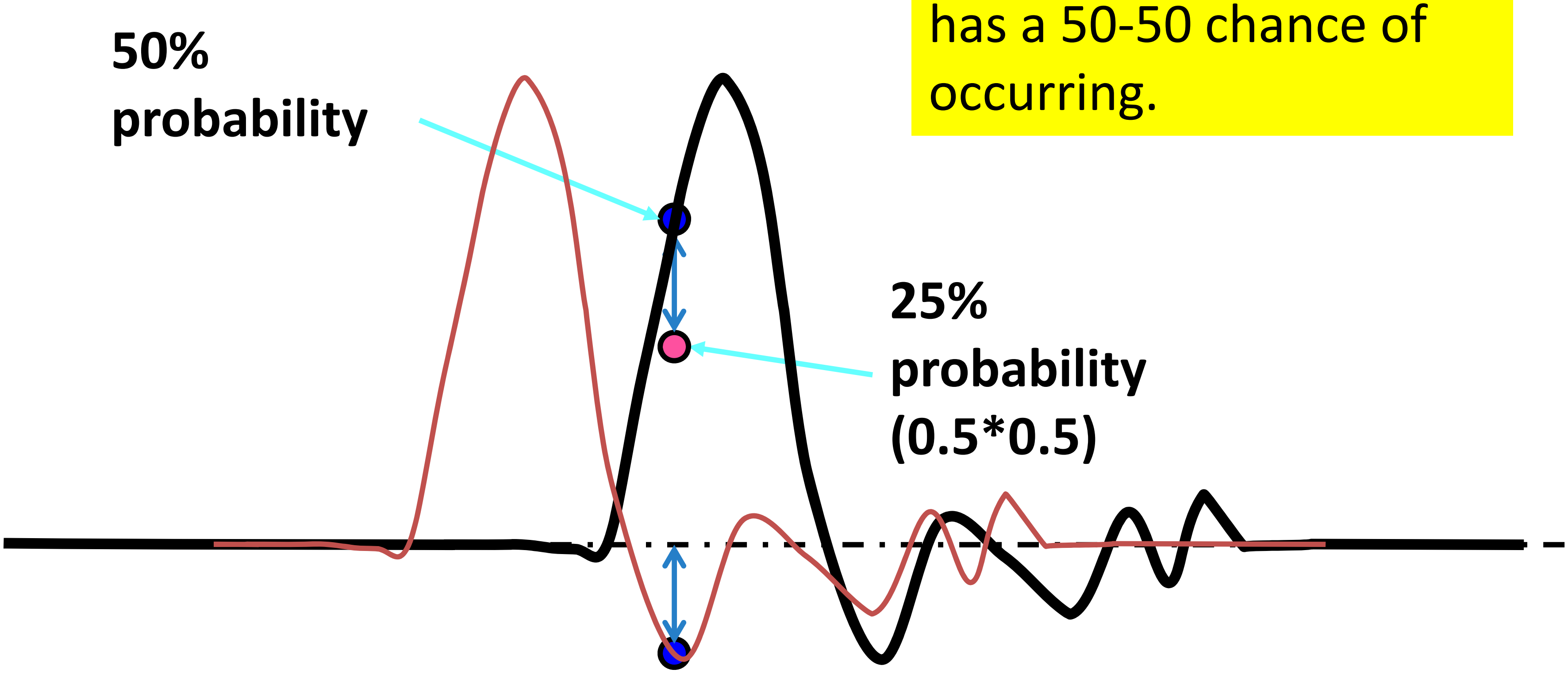


Sample point (time) for target bit pulse response

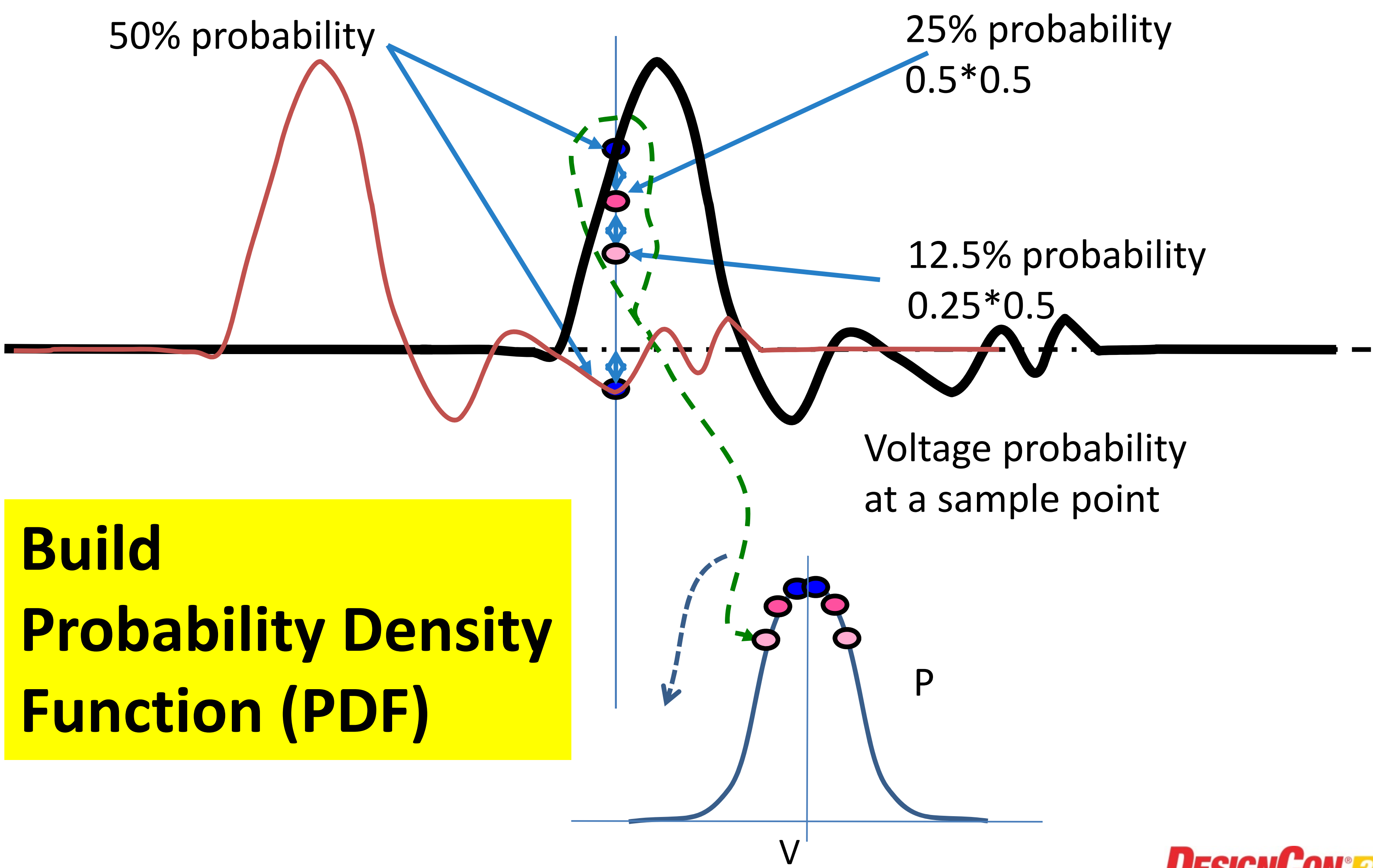
Look closer on next slide

Look at a 1 UI Shift Back: i.e. previous bit

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



Look at 1 UI More UI Back

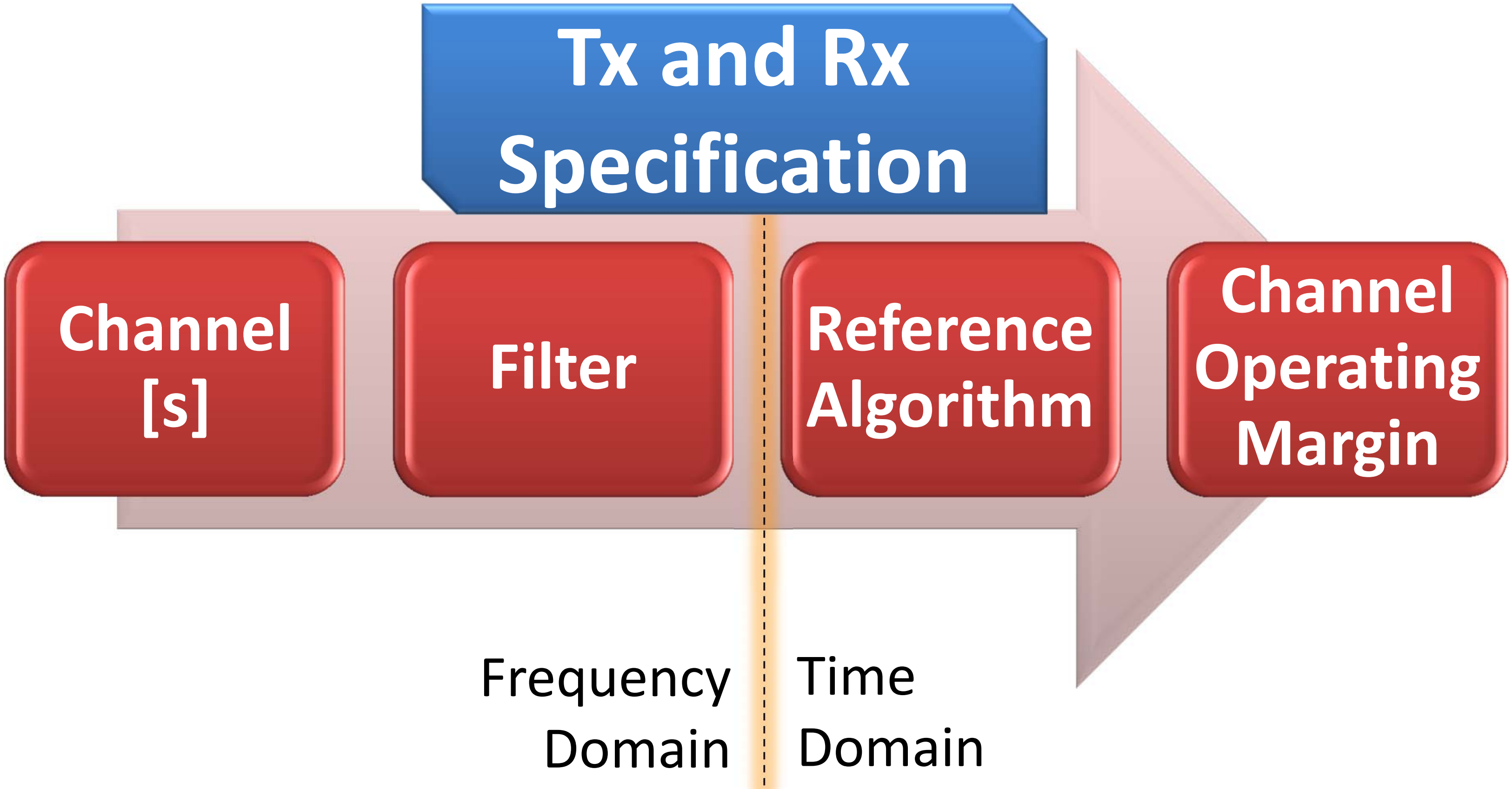


Build Probability Density Function (PDF)

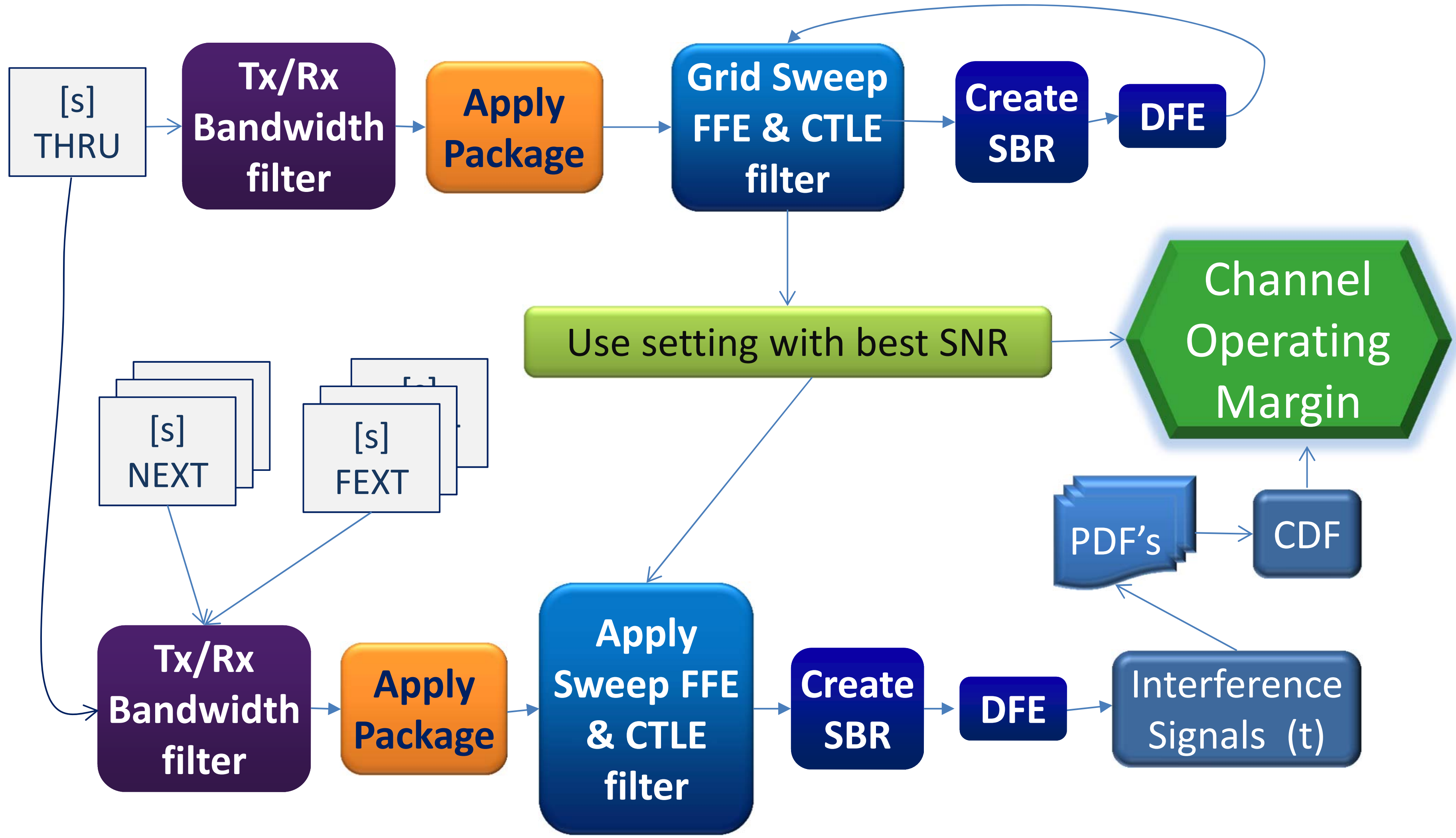
The COM Simplification

- COM is a simplified and fast simulation
  - Same statistical basis as “Channel Compliance Testing Utilizing Novel Statistical Eye Methodology”, DesignCon 2004, Resso, Sanders, D'Ambrosia.
  - It is relatively fast to compute using convolution
- Crosstalk noise, uncompensated ISI, and jitter and are converted into PDFs.
  - They are combined statistically
  - Using convolution
- ISI and crosstalk are bounded noise
  - No a priori assumptions of a noise profile
- The figure of merit it defined by available signal and the total peak noise at the specified bit error ratio (BER) probability

Top Level Flow:
Starting with channel s-parameters

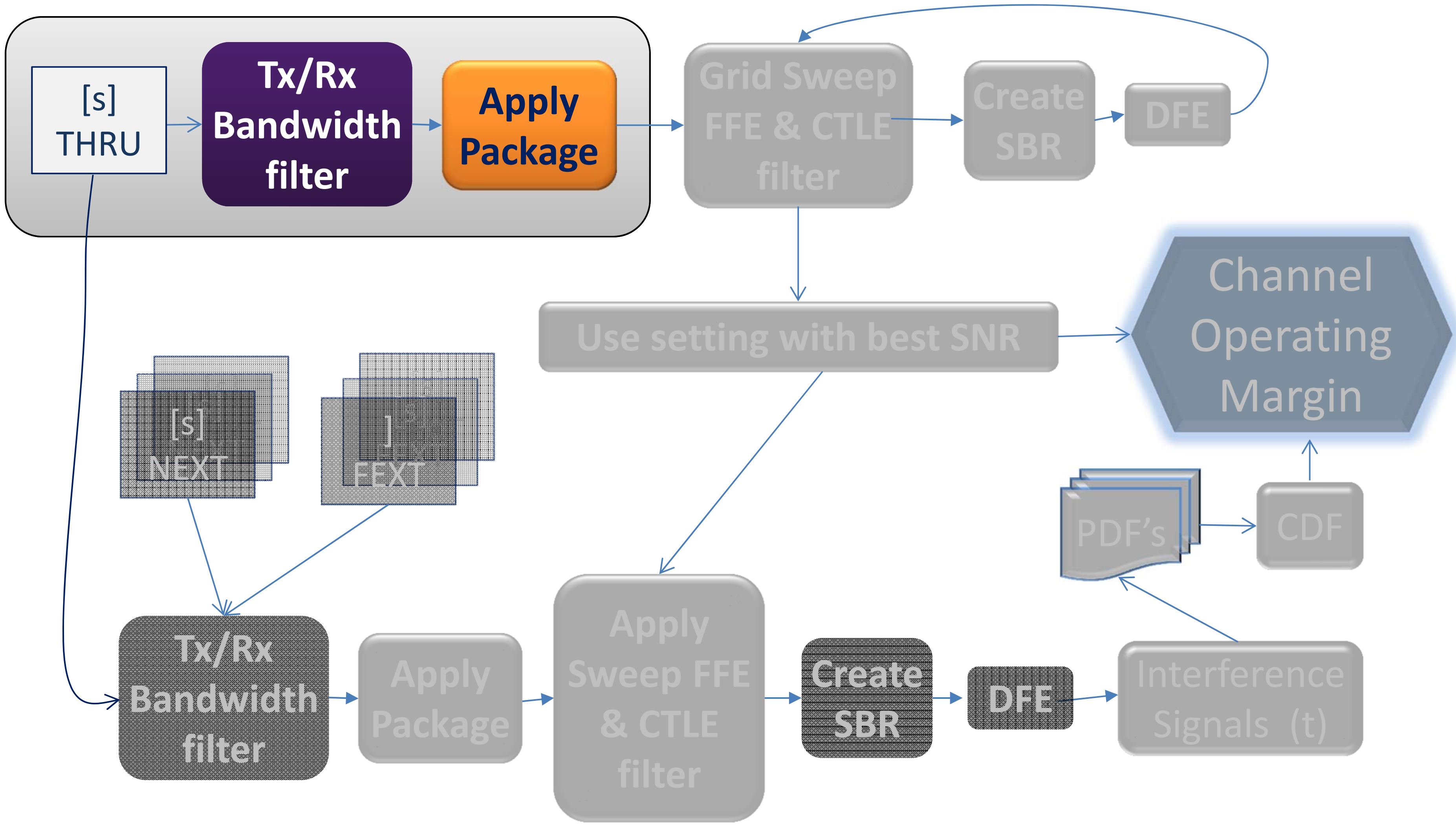


Flow Example



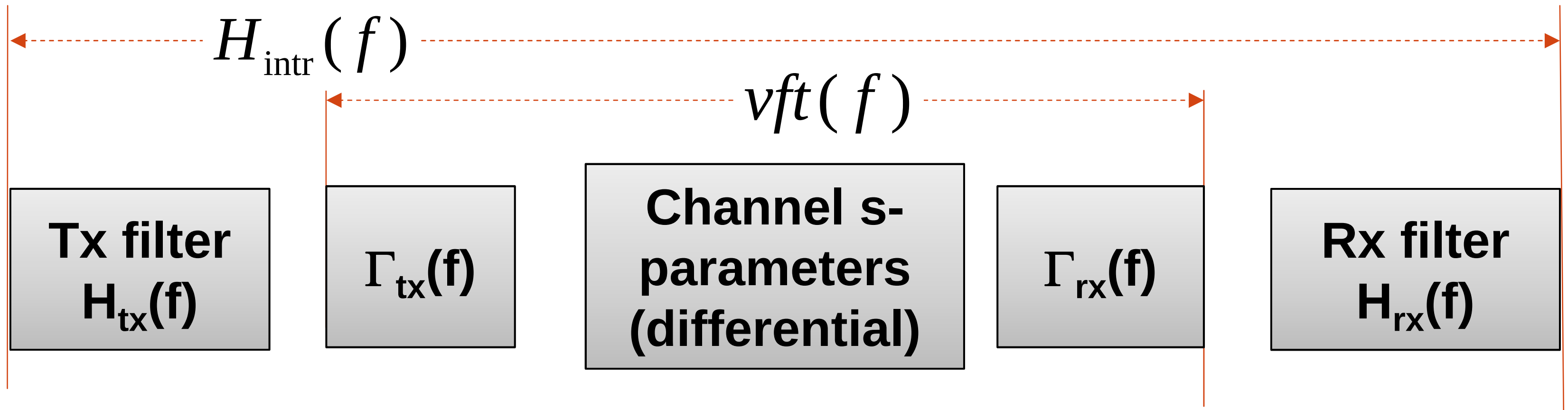
Tx FFE is not applied to NEXT

Intrinsic Filtering



Tx FFE is not applied
to NEXT

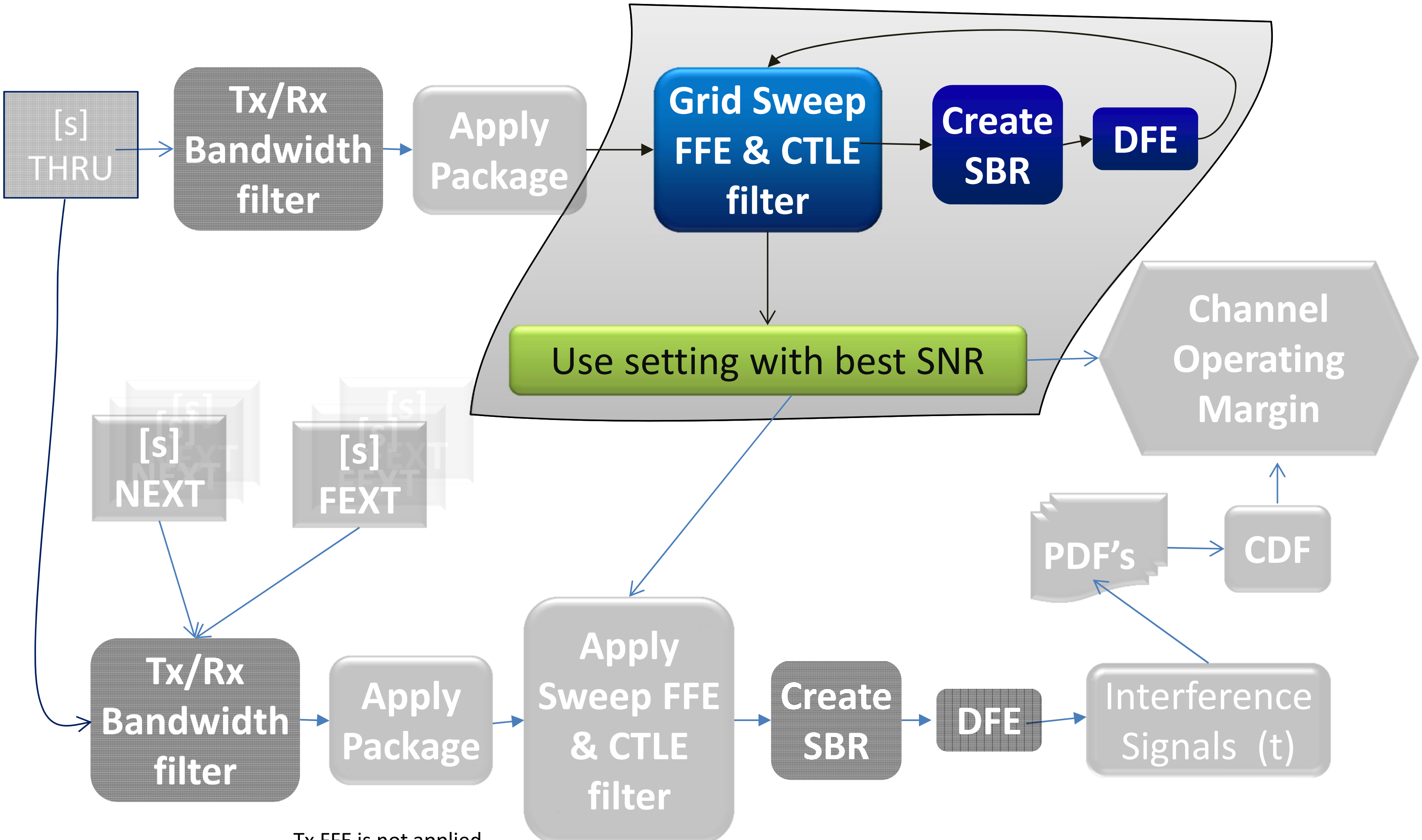
Step 1: Thru Filtering



$$H_{intr}(f) = H_{tx}(f) * vtf(f) * H_{rx\_pkg\_loss}(f) * H_{rx}(f)$$

- Compute of total intrinsic gain, $\boldsymbol{H_{intr}}(\boldsymbol{f})$, from linear filters and channels differential s-parameters
  - Package loss is comprehended in device block specification, voltage swing, transition time, etc.
  - Package return loss, Γ, is observable per device specification
  - Device reflections are comprehended in a voltage transfer function $\mathbf{vtf}(\boldsymbol{f})$ which is computed from channel s- parameters and Γ.

Full Grid Search Finds Best Equalization Settings

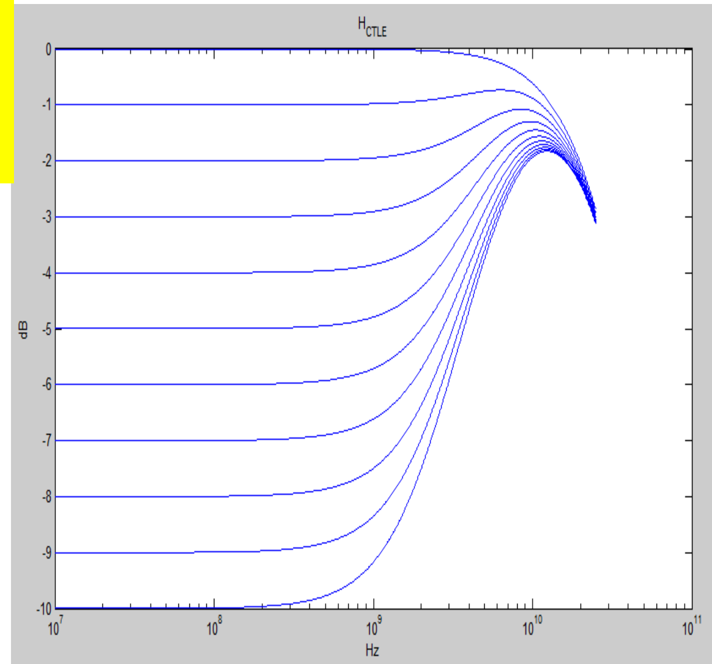


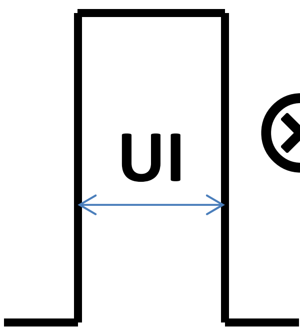
Tx FFE is not applied to NEXT

Determine Equalization Settings

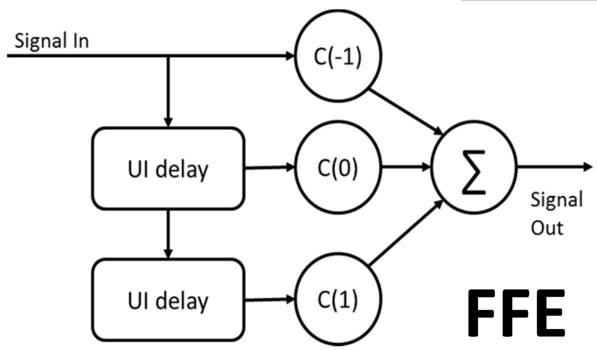
An exhaustive search finds the settings with the best SNR

$$H_{intr}(f) * H_{CTLE}(f) \rightarrow \boldsymbol{h(t)}$$

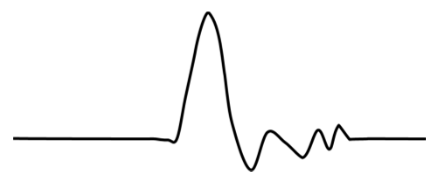




$$\otimes\ \boldsymbol{h(t)}$$



FFE



$$\boldsymbol{SBR(t)}$$

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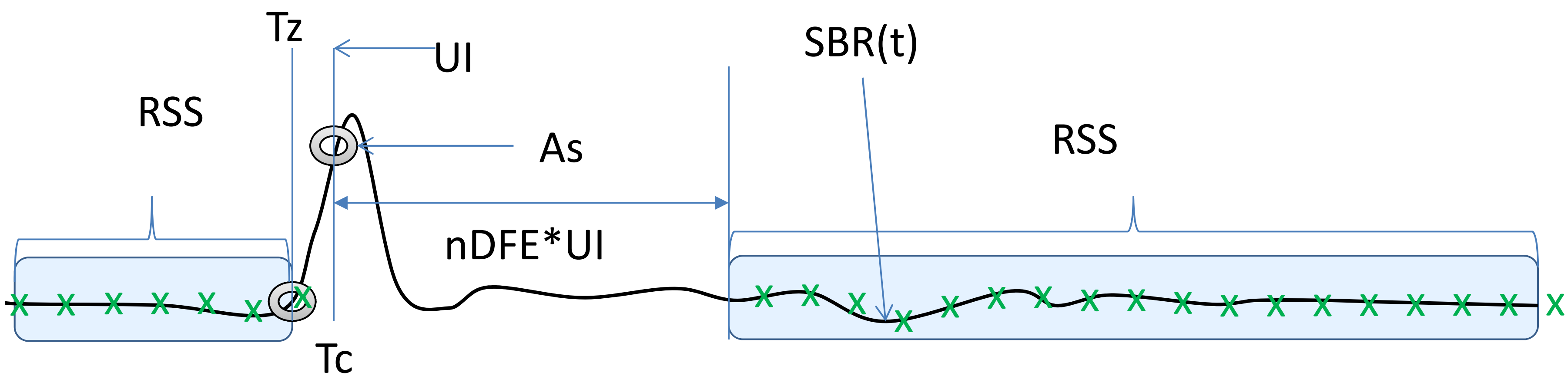
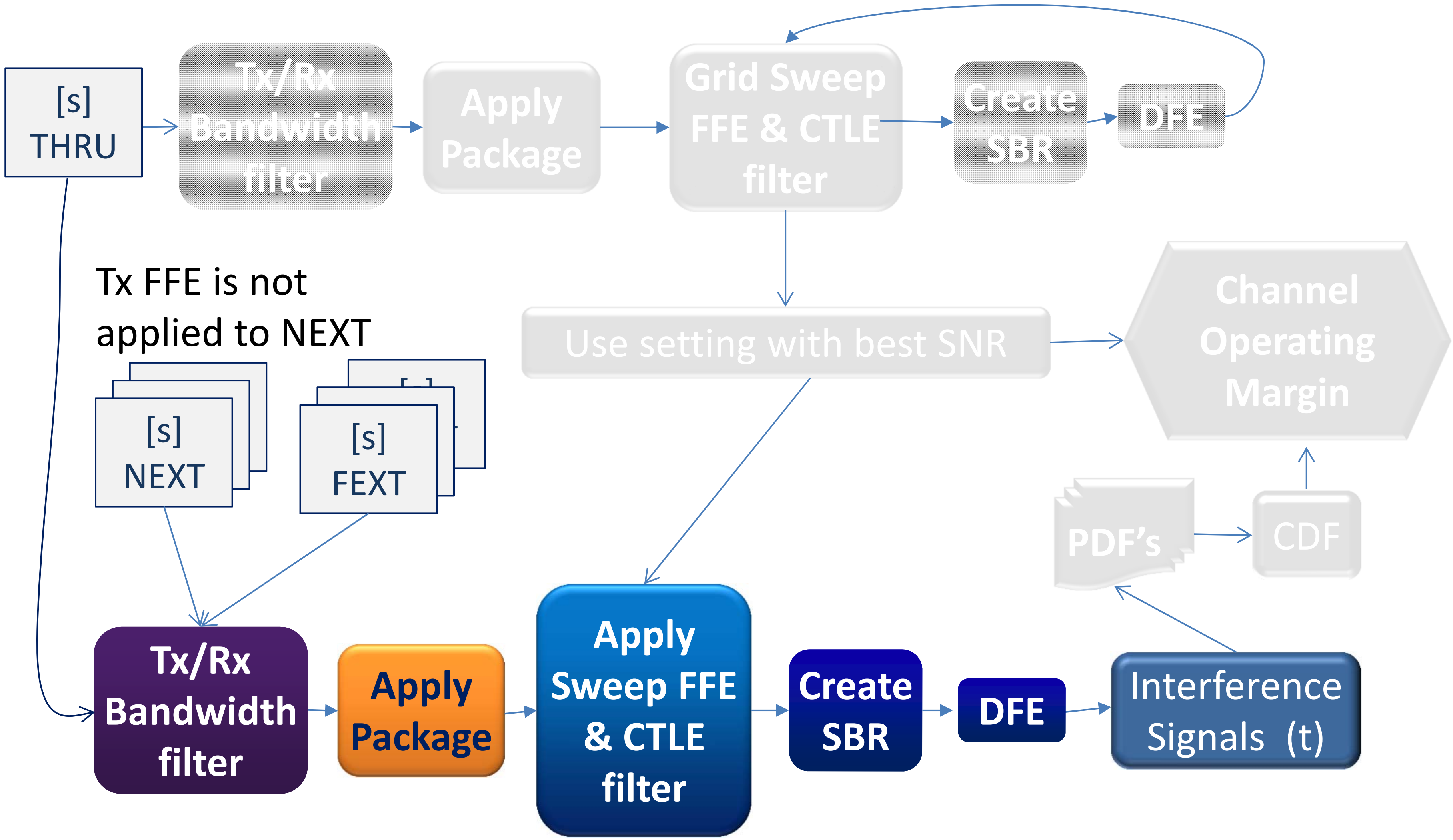
SBR SNR for Exhaustive Search

- FOM → $SNR = \frac{As}{\sqrt{RSS^2 + other\_noise^2}}$



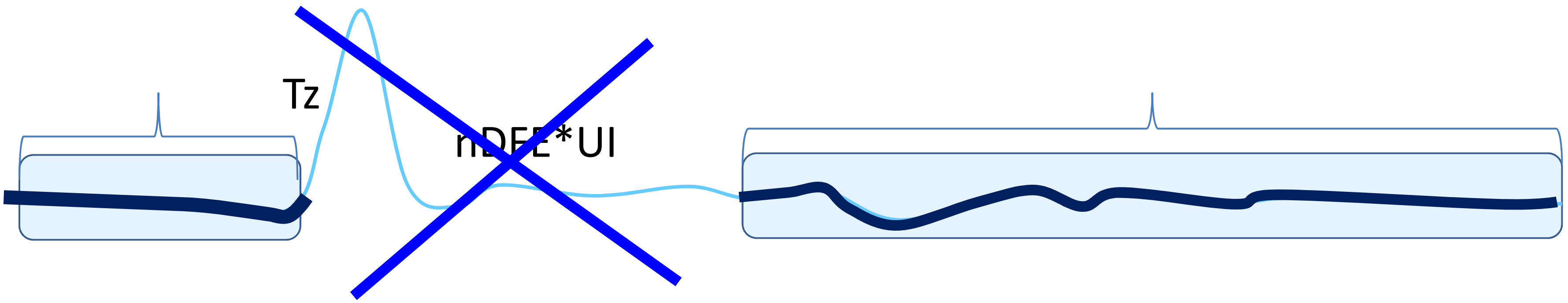
For best SNR, use settings and available signal, As in the next steps

Determine Interference Signals

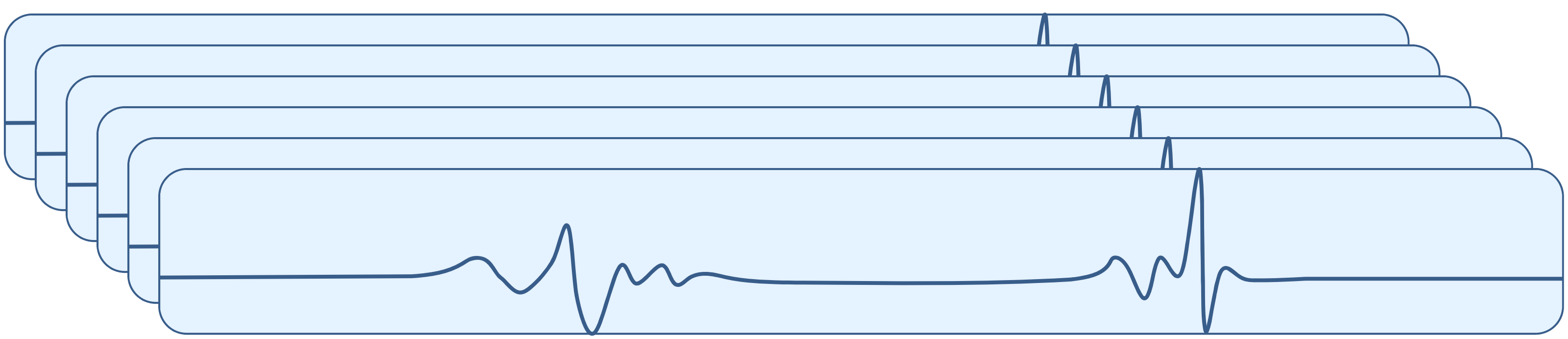


Interference Signals

Victim Interference Signal



Crosstalk Interference Signals



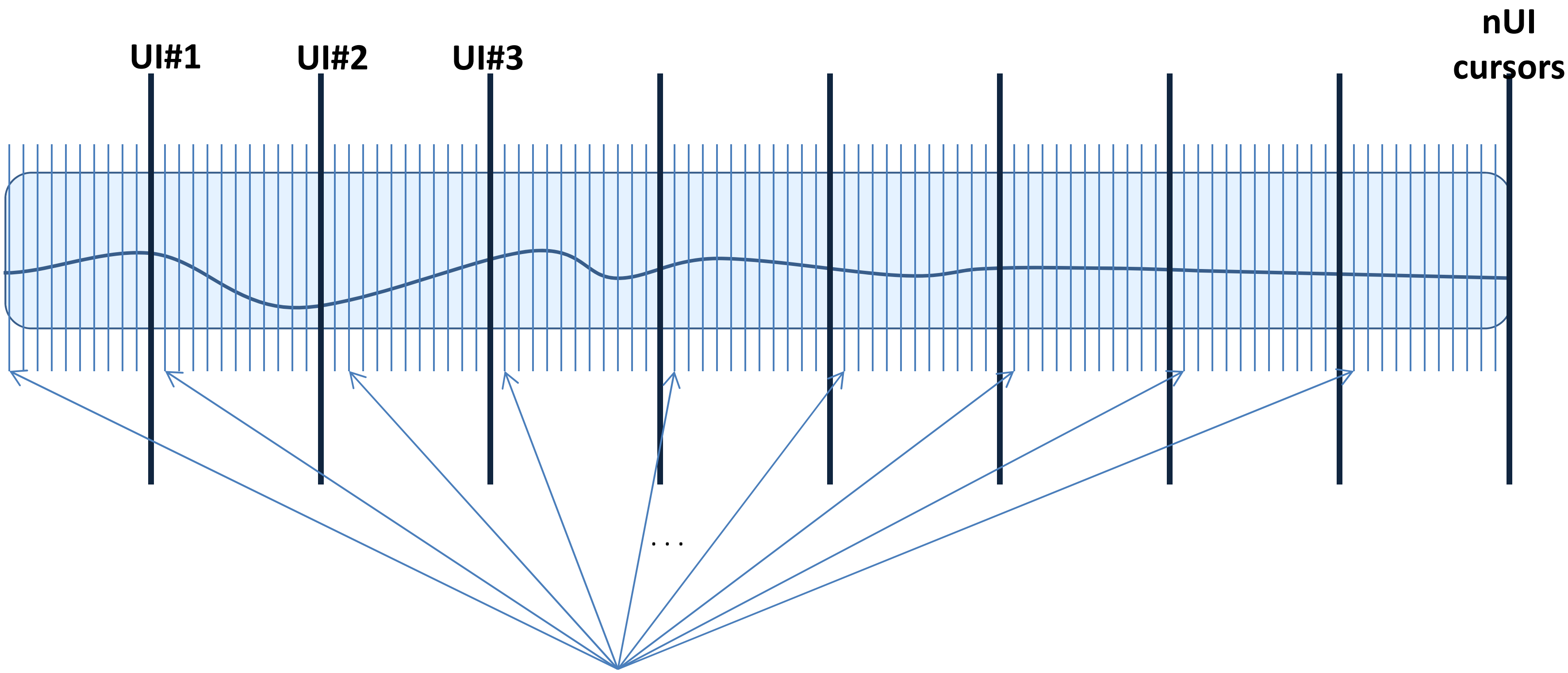
Process cont'd: Steps 5 and 6

Interference signals, and symbol PDF	PDF ISI, MDNEXT, MDFEXT Other Effects	Convolve all PDF's → CDF	Channel Operating Margin (COM)

Using the Interference signals:

- Compute interference PDFs for some number of sampling phases and select the PDF with the worst variance and then compute a CDF.
- Computation of channel operating margin (COM) is dB ratio of the available signal amplitude (Sx) to the CDF voltage at the specified raw BER probability.

Oversample the Interference Signal



$ts_i(nui)$, $vs_i(nui)$ for each sample i

Create voltage vectors for each sample which are nUI cursors long

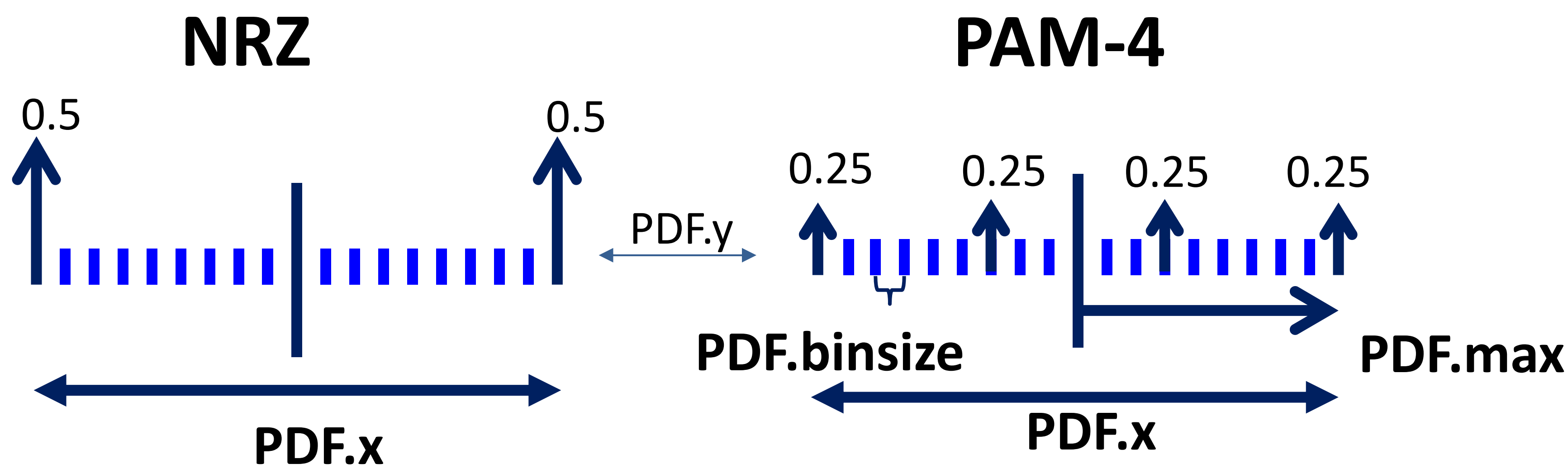
Start with PDF for a single sample

- For an example in NRZ,
  the voltage at a given cursor has probability of 50 - 50 of that value or negative of that value

  pdf.y= [0.5 0.5]

  pdf.x= [$-vs_i(nui)$ $vs_i(nui)$]

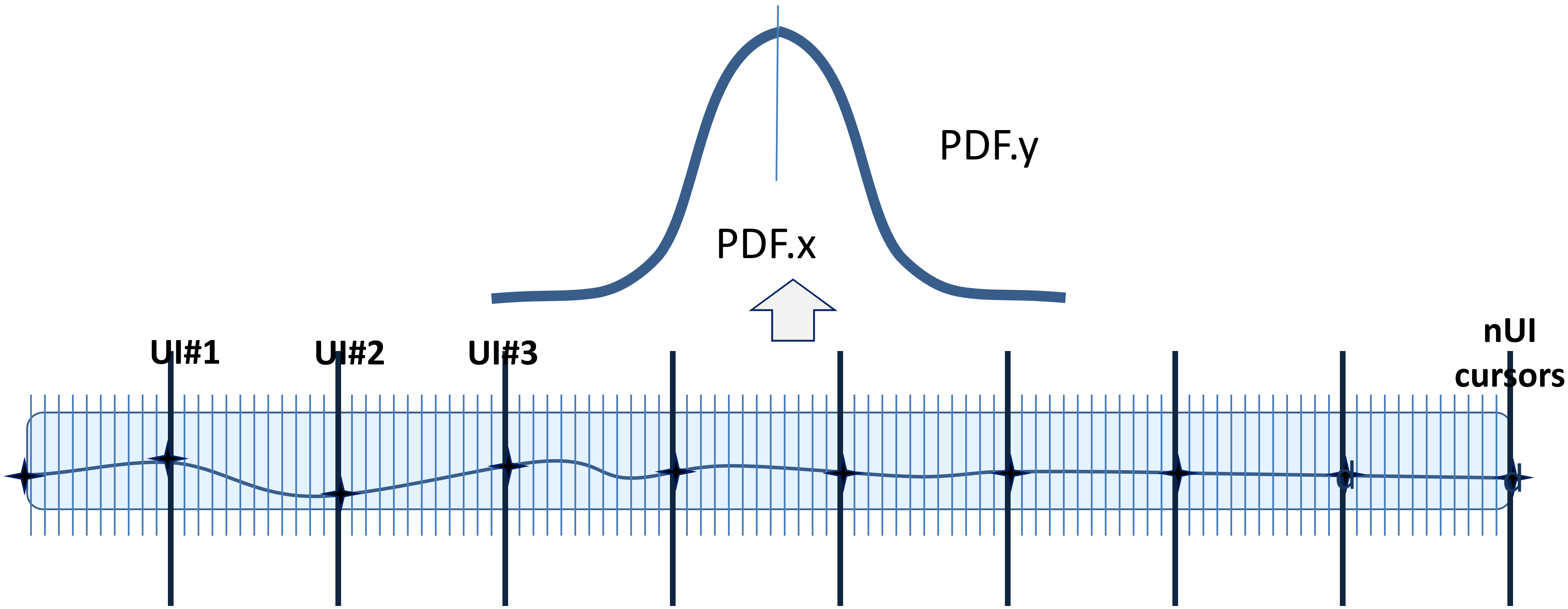
Graphic Example



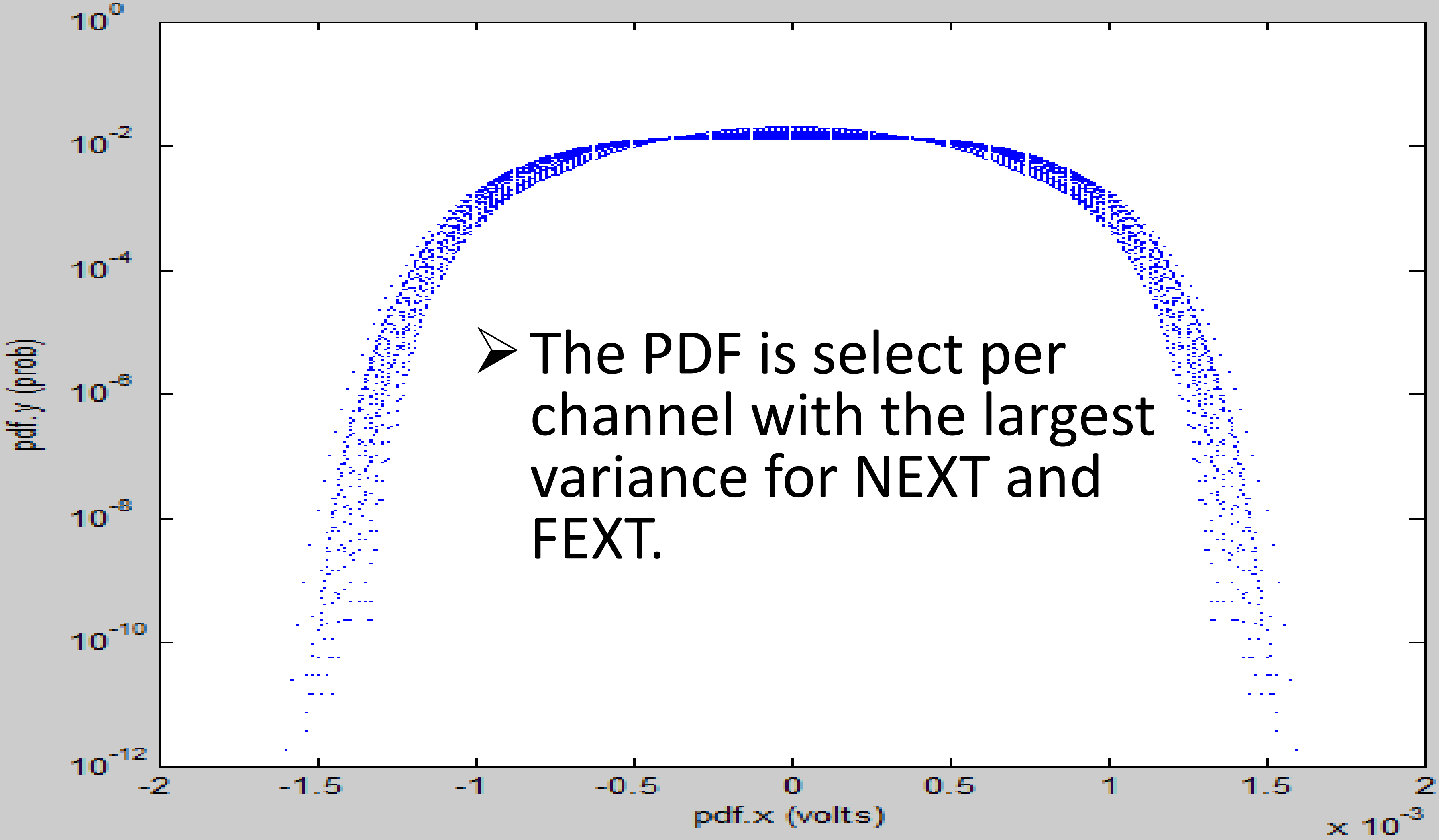
- Simplifying assumptions
  - PDF x values are distributed into pre-specified "binsize" buckets
  - Interim values of x do not need to be store
    - Computed from PDF.binsize and PDF.max

Determine the PDF for Each Interference Signal

- Choose a starting UI and a sample point
- Add one point at a time to the running aggregate PDF tally for all the UIs
- This is convolving (⊗) the running PDF with the sample point PDF from previous slide
  - **PDF_running = PDF_running ⊗ PDF_sample_point**



At this point there is one PDF for each sample of NEXT, FEXT, at Thru channels



- The PDF is select per channel with the largest variance for NEXT and FEXT.

Multi Aggressor NEXT and FEXT PDFs

- **Same PDF convolution in pervious process**
- **Create MDFEXT_PDF (Multi aggressor FEXT)**
  - MDFEXT_PDF = PDF_FEXT(1)
  - For i=1,n_fext
    - MDFEXT_PDF = MDFEXT_PDF⊗PDF_FEXT(i)
- **Create MDNEXT_PDF (Multi aggressor NEXT)**
  - MDNEXT_PDF = PDF_NEXT(1)
  - For i=1,n_next
    - MDNEXT_PDF = MDNEXT_PDF ⊗ PDF_NEXT(i)

Channel Noise PDF

- Convolve all the NEXT, FEXT and THRU PDF's together
- Channel_Noise_PDF =

  MDFEXT_PDF ⊗

  MD_NEXT_PDF⊗

  THRU_PDF

Include Tx Specification Parameters and Find Total Noise PDF

- RMS Jitter →
  RMS voltage noise PDF (**PDF_RMS_JIT**)
- Determinist Jitter →
  Dual Dirac voltage noise PDF (**PDF_DD**)
- Tx and Rx voltage noise RMS →
  RMS voltage noise PDF (**PDF_RMS_TXRX**)
- **PDF_SPEC_NOISE** =
  PDF_RMS_JIT ⊗ PDF_DD⊗ PDF_RMS_TXRX
- **TOTAL_NOISE_PD**F =
  PDF_SPEC_NOISE ⊗ Channel_Noise_PDF

Determine interference noise at the “specified BER”

- $CDF(i) = \sum_{k=1}^{i} \text{TOTAL\_NOISE\_PDF}.y(k)$

- The peak interference,

  An= TOTAL_NOISE_PDF.x(spec_i),

  is where the

  CDF(spec_i) = “the specified BER”

Channel Operating Margin

$$COM = 20 * log_{10}\left(\frac{As}{An}\right)$$

PCI Express® 3.0 8Gbps

Experiment to Demonstrate

Correlation

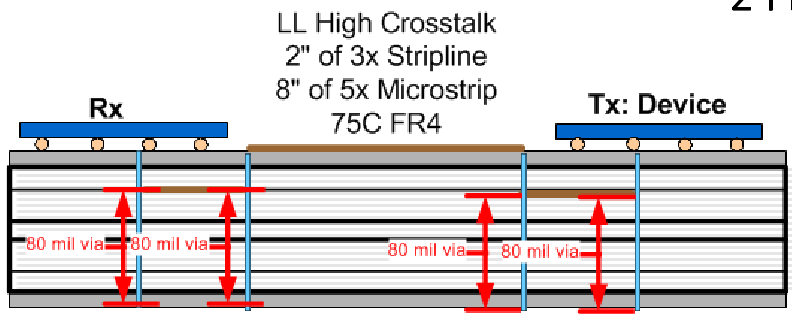
Next:

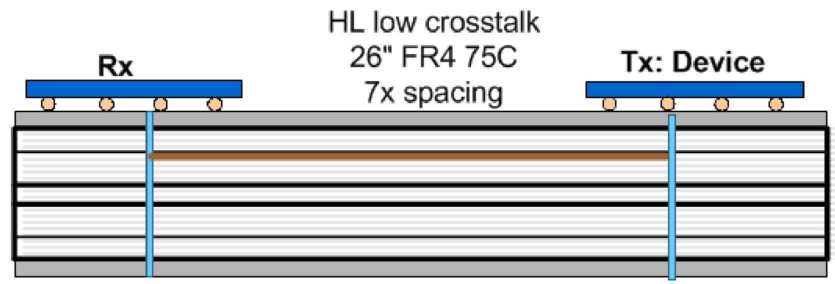
COM Correlation to Proprietary Full Link Simulation

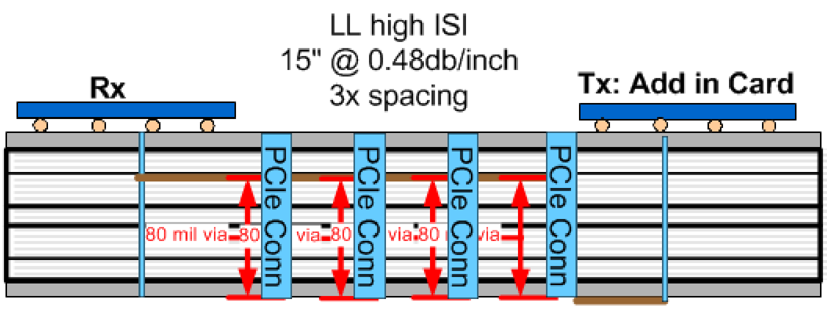
- Correlate eye height population with equivalent line in COM population
- Simulation time - many, many hours
- COM calculation time < 1 hour
- 320 cases examined

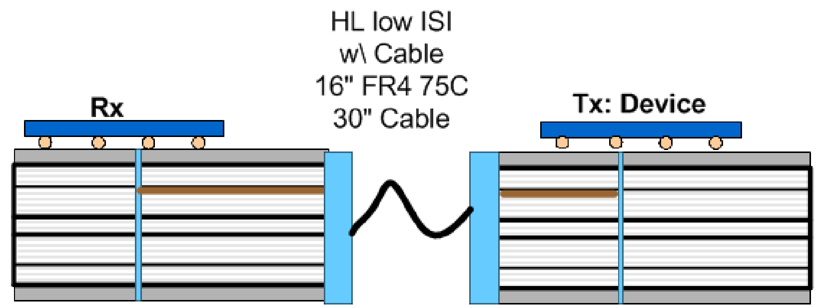
8Gbps Topologies with Some Randomized Parameters

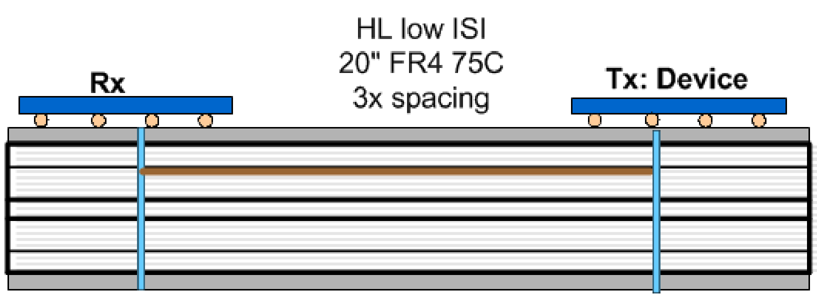
2 FEXT and 1 Victim







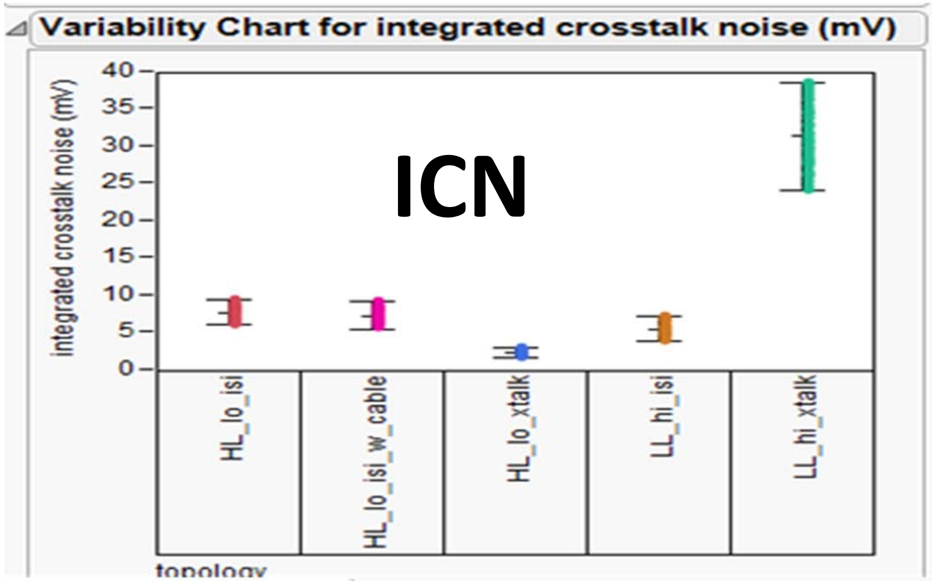


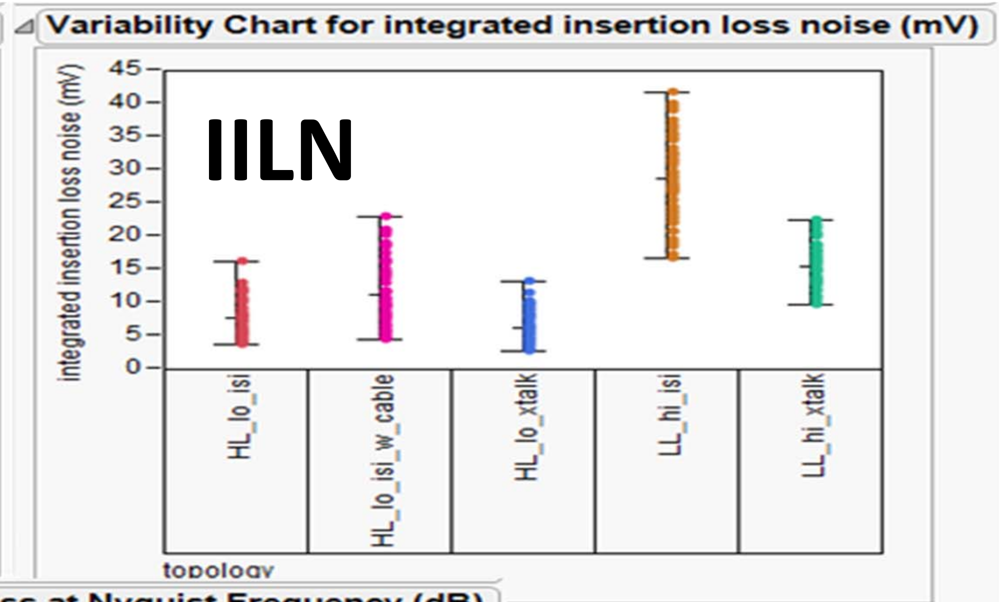


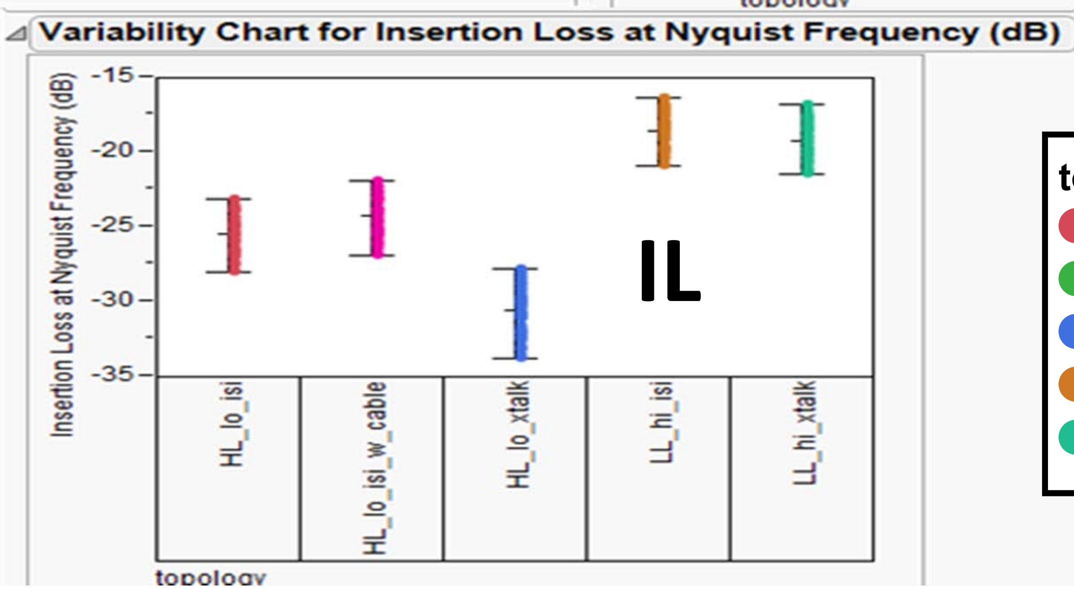
topology

- HL_lo_isi
- HL_lo_isi_w_cable
- HL_lo_xtalk
- LL_hi_isi
- LL_hi_xtalk

ICN, IILN, and IL population variably

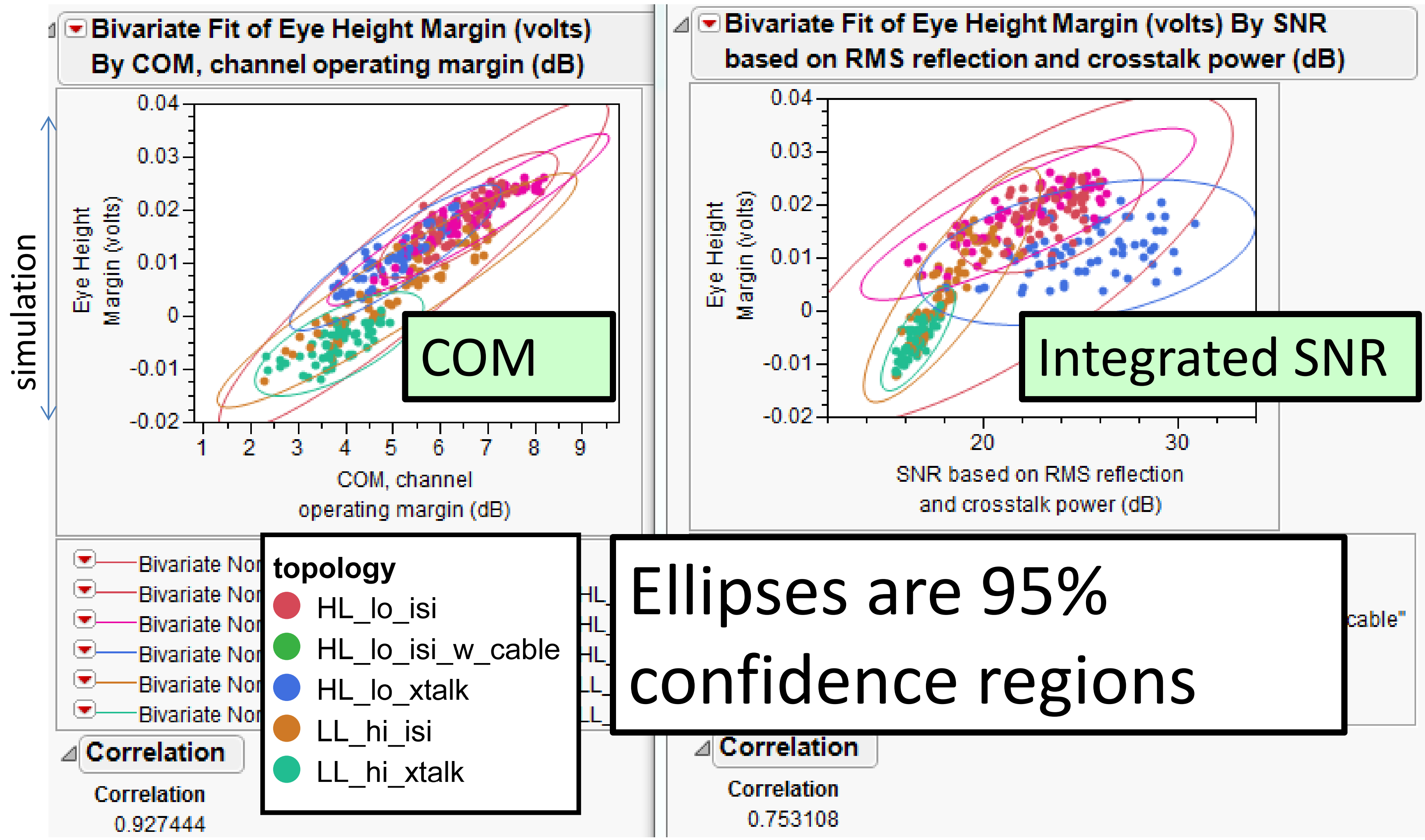






topology
- HL_lo_isi
- HL_lo_isi_w_cable
- HL_lo_xtalk
- LL_hi_isi
- LL_hi_xtalk

Correlation For 320 Randomized Cases



Summary

- COM method is the channel compliance method for IEEE STD 802.3bj™ 100G (4x25 Gbps) backplane and copper cable, assembly specification
- COM can be used to articulate a "contract" or agreement IC's and boards.
- COM input parameters are meaningful to IC designers
- COM is fast compared to simulation
- COM is shown to be sufficiently accurate
- COM can be easily incorporated into EDA tools.
- COM can be easily adapted to other PHYs