IBIS-AMI Dual Models: Why the Jitters?

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EDICON IBIS Summit 2017

Boston, Massachusetts

September 13, 2017

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What is a Dual IBIS-AMI Model?

- AMI file has:
  - GetWave_Exists = True
  - Init_Returns_Impulse = True
- Best option for running both time domain and statistical analysis

Case #	TX			RX			Convolution Input	Statistical	Time Domain
	Getwave Exists	**Init_Returns_Impulse**	**Meaning**	**Getwave Exists**	**Init_Returns_Impulse**	**Meaning**			
1	FALSE	TRUE	Init-Only	FALSE	TRUE	Init-Only	3	OK	Static TX EQ, Static RX Eq
2	FALSE	TRUE	Init-Only	TRUE	FALSE	Getwave-Only	1 or 2	No RX EQ	Static TX EQ, Dynamic RX Eq
3	FALSE	TRUE	Init-Only	TRUE	TRUE	Dual	2	OK	Static TX EQ, Dynamic RX Eq
4	TRUE	FALSE	Getwave-Only	FALSE	TRUE	Init-Only	3	No TX EQ	Dynamic TX EQ, Static RX EQ
5	TRUE	FALSE	Getwave-Only	TRUE	FALSE	Getwave-Only	1,2,or 3	No TX or RX EQ	Dynamic TX EQ, Dynamic RX EQ
6	TRUE	FALSE	Getwave-Only	TRUE	TRUE	Dual	1	No TX EQ	Dynamic TX EQ, Dynamic RX EQ
7	TRUE	TRUE	Dual	FALSE	TRUE	Init-Only	iFFT(FFT(3)/FFT(2))	OK	Dynamic TX EQ, Static RX EQ
8	TRUE	TRUE	Dual	TRUE	FALSE	Getwave-Only	1	No RX EQ	Dynamic TX EQ, Dynamic RX EQ
9	TRUE	TRUE	Dual	TRUE	TRUE	Dual	1	OK	Dynamic TX EQ, Dynamic RX EQ

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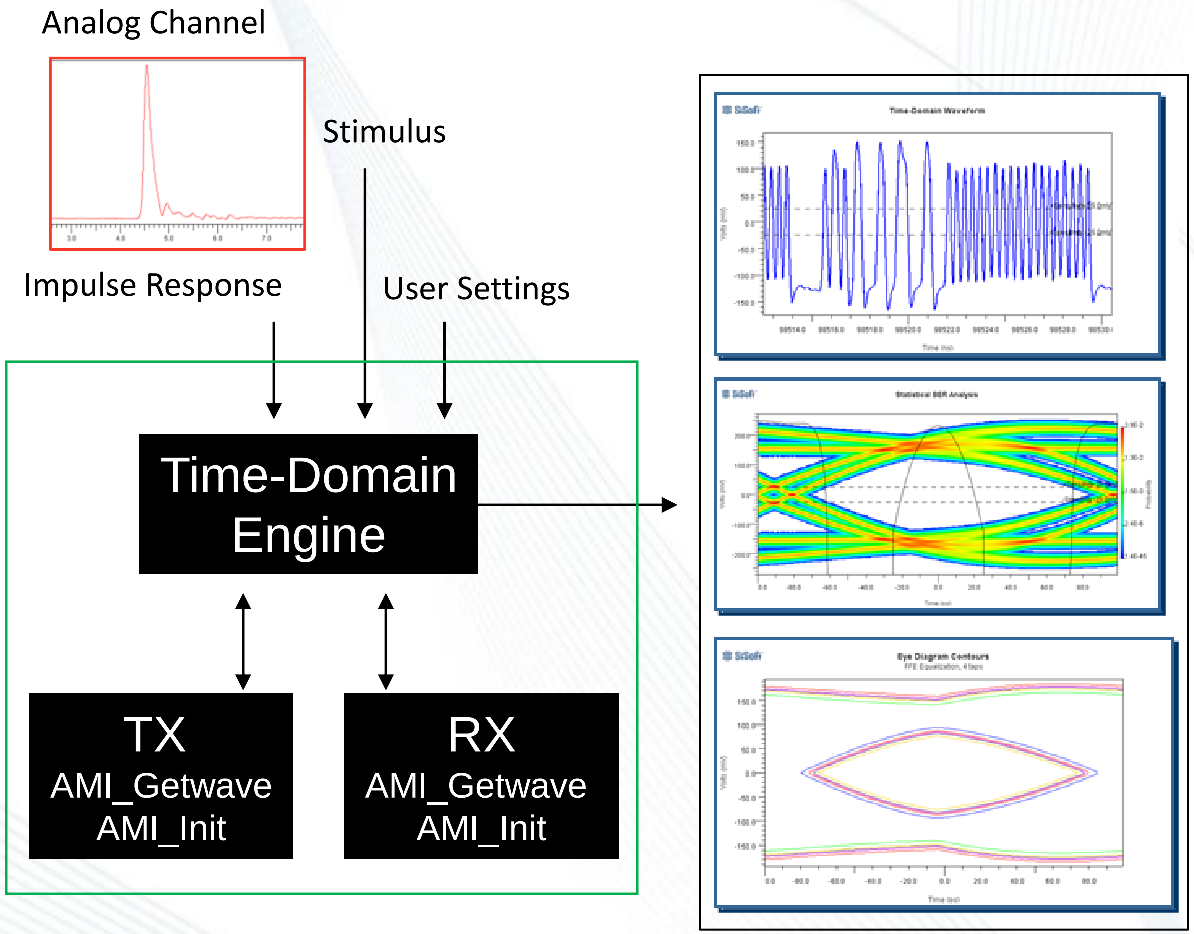
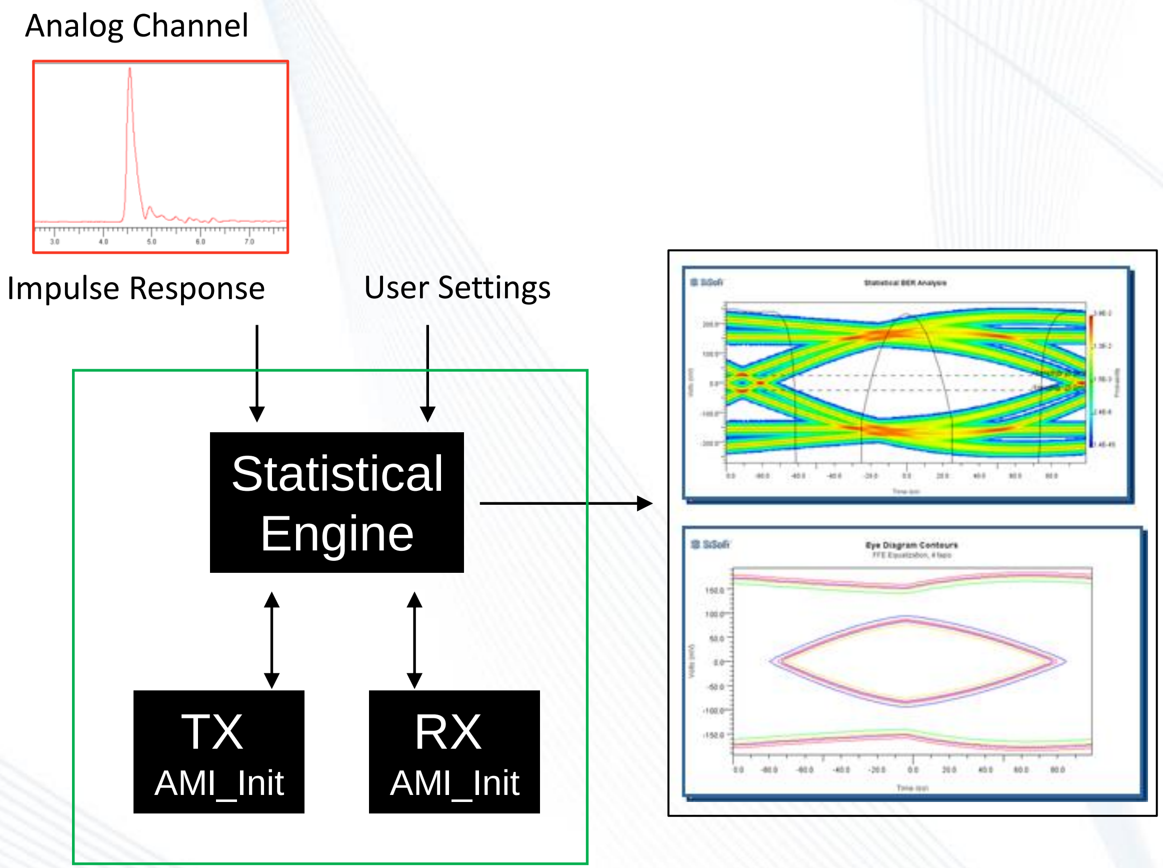
Time-Domain Simulation

- **Inputs:**
  - Channel and buffer Impulse responses
  - User-defined input stimulus
  - Algorithmic models (AMI_GetWave)
- **Analysis Method:**
  - Waveform processing & convolution
- **Outputs:**
  - Not specified by IBIS
  - Persistent eye diagrams
  - Eye height / width measurements
  - Eye contours @ probabilities
  - Equalized / unequalized responses



Statistical Simulation

- **Inputs:**
  - Analog channel impulse response
  - User selections for model parameters
  - Algorithmic models
    (AMI_Init / impulse response processing)
- **Analysis Method:**
  - Convolution engine (pulse response)
- **Outputs:**
  - Not specified by IBIS
  - Statistical eye diagrams
  - Eye height / width measurements
  - Eye contours @ probabilities
  - Equalized / unequalized responses



Impairments To Be Modeled

Amplitude Impairment	Physical Cause
Inter-symbol interference (ISI)	Signal distortion (linear and nonlinear)
Crosstalk	Electromagnetic coupling in passive interconnect
Receiver sensitivity	Low signal amplitude causes decision latch to fail clock-data timing
Additive White Gaussian Noise (AWGN)	Shot noise in receiver amplifiers

Clock Impairment	Physical Cause
Random Jitter (RJ)	a. Shot noise in oscillator gain element b. Power supply noise modulating gate delays
Duty Cycle Distortion (clock) (DCD)	For half rate clock, duration difference between positive and negative half cycles
Duty Cycle Distortion (data)	Difference between data rise and fall times
Sinusoidal Jitter (SJ)	Clock noise on power supply modulating gate delays

Inter-Symbol Interference (ISI) Impairments

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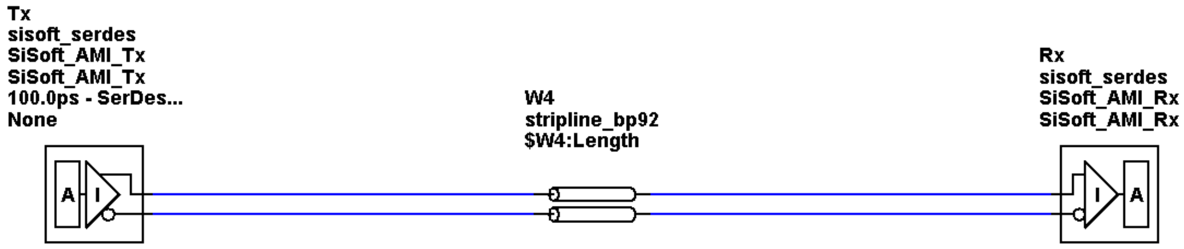
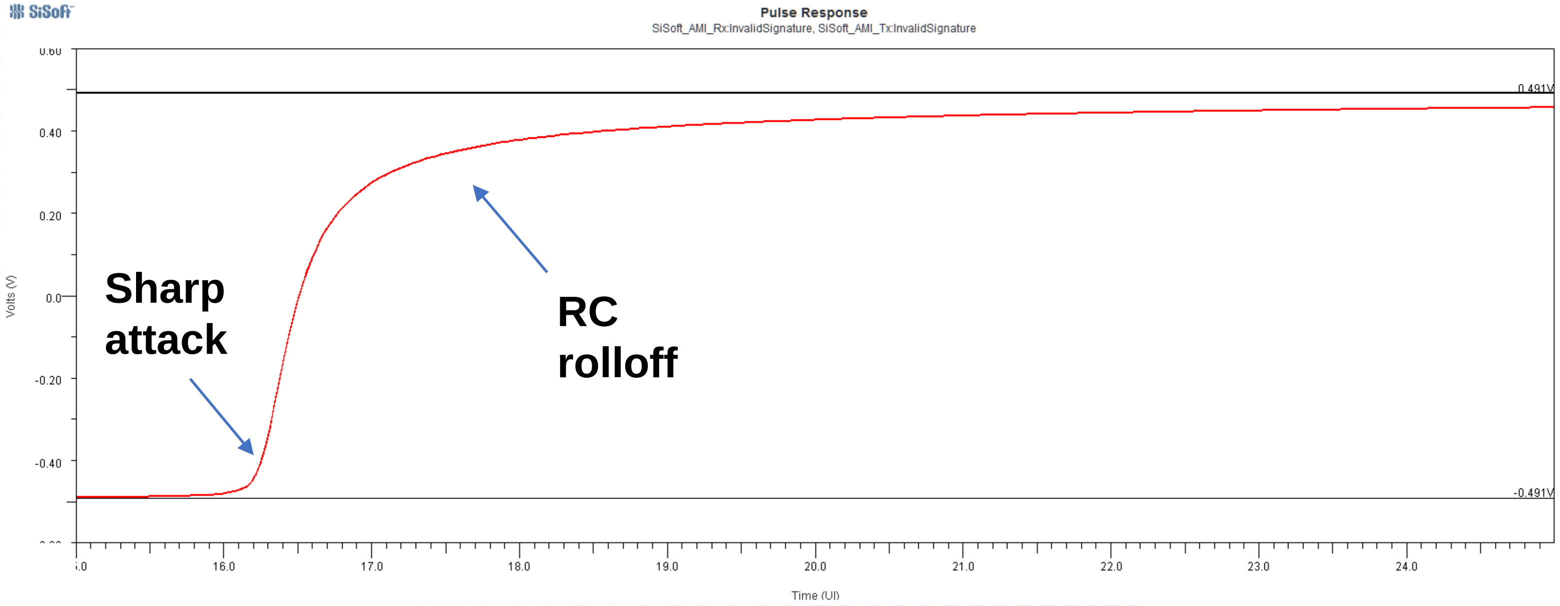
Step Response Analysis



10”, 10 Gb/s



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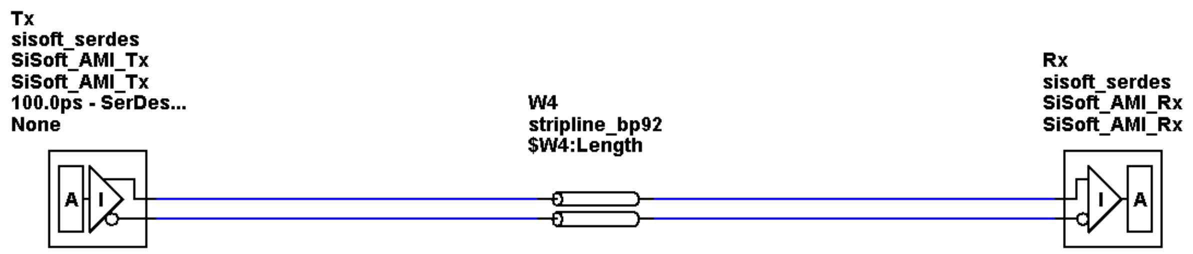
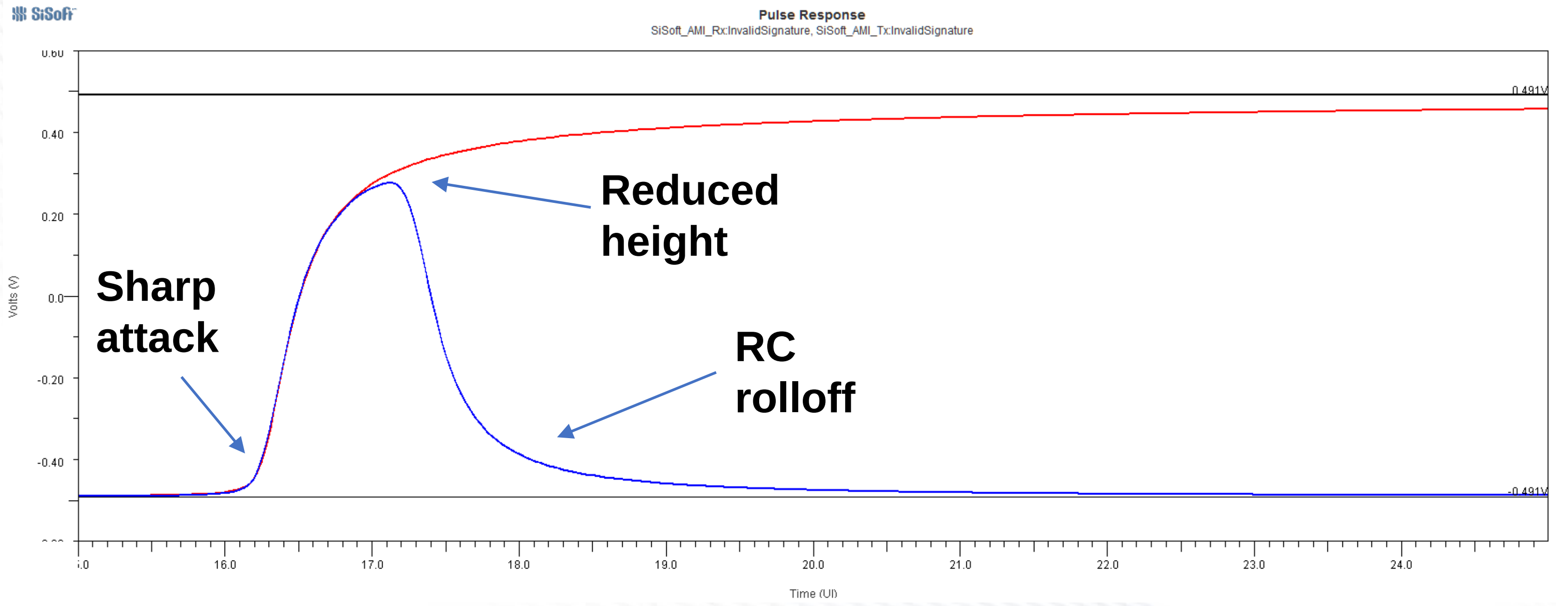
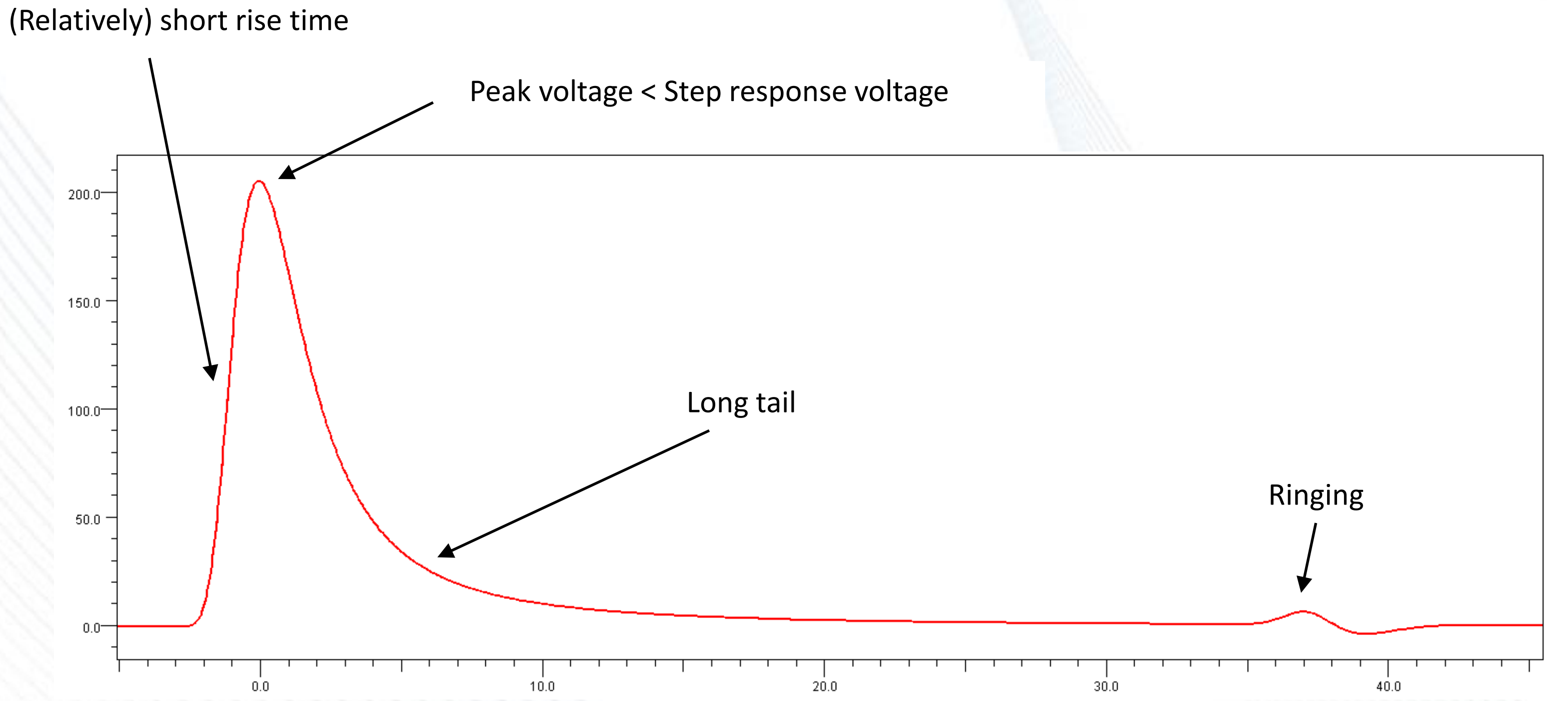
Pulse vs. Step Responses



10", 10 Gb/s



Channel Pulse Response

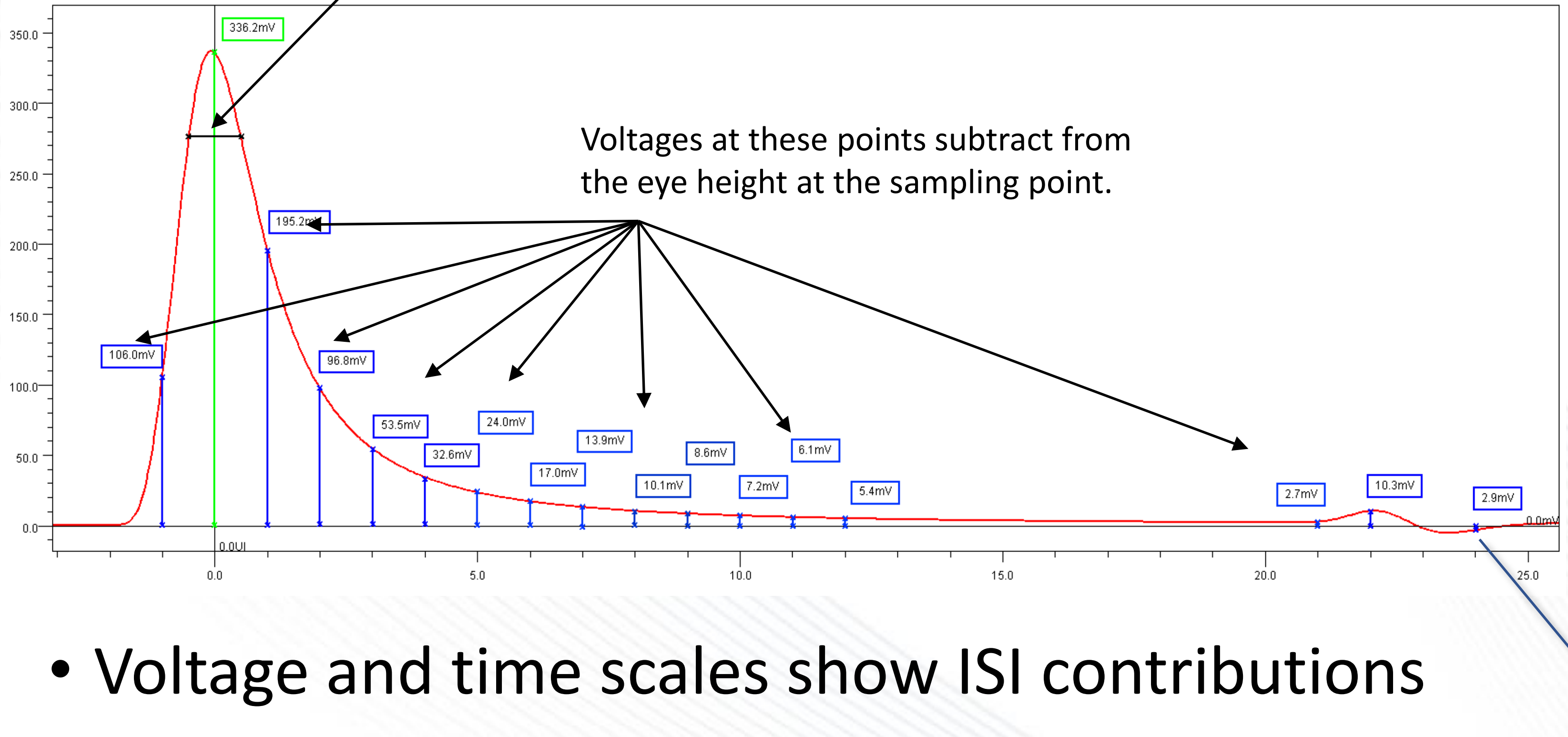


- Requires accurate Tx/Rx analog models to correctly predict ringing due to reflections

Aligned Pulse Response and ISI

Hula hoop algorithm determines clock sampling time and main cursor height.
This is the maximum possible inner eye height.

Voltages at these points subtract from
the eye height at the sampling point.



$$\textit{Inner Eye Height} =$$

main_cursor – Σ |ISI_voltages|

- Voltage and time scales show ISI contributions
- Useful in evaluating EQ & predicting eye opening

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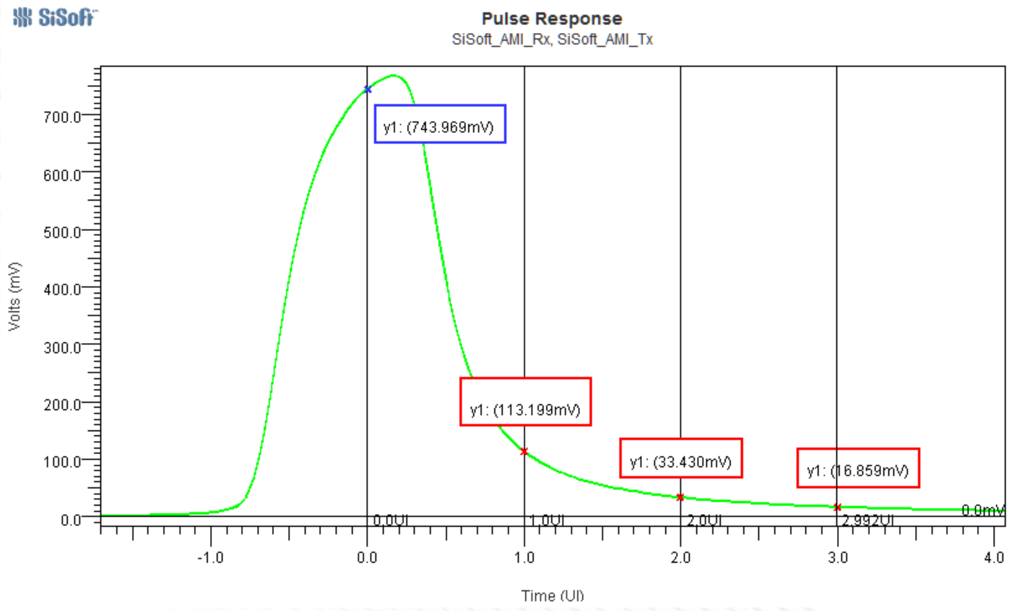
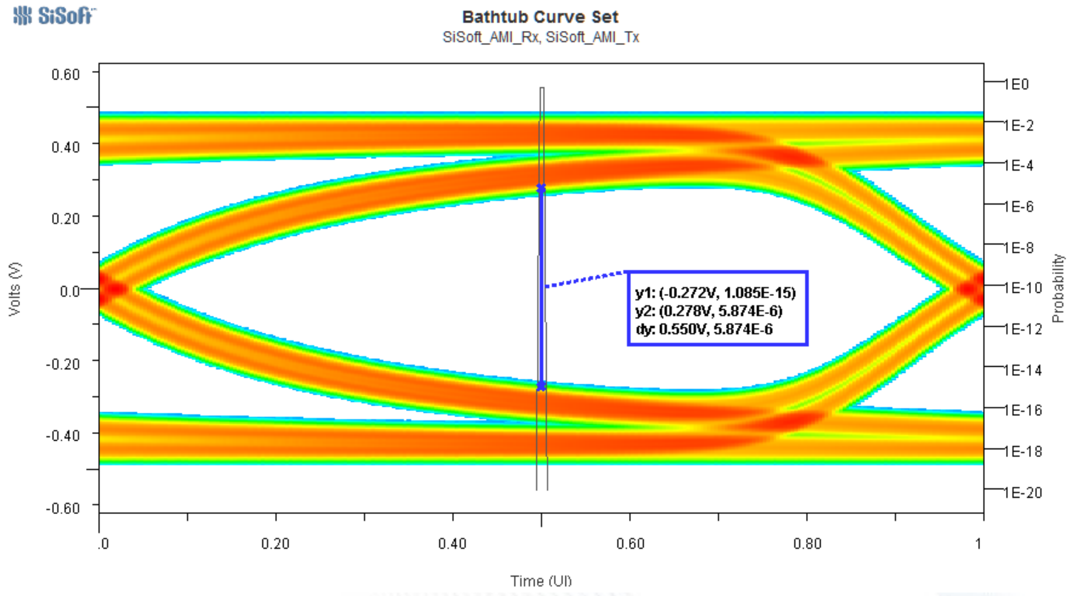
ISI Inner Eye Calculation Example





Prediction: 580mV

Simulated Actual: 550mV

$$\textit{Inner Eye Height} = \text{main\_cursor} - \Sigma\ |\text{ISI\_voltages}|$$

A quick calculation gets us close, but small amounts of energy in the tail add up

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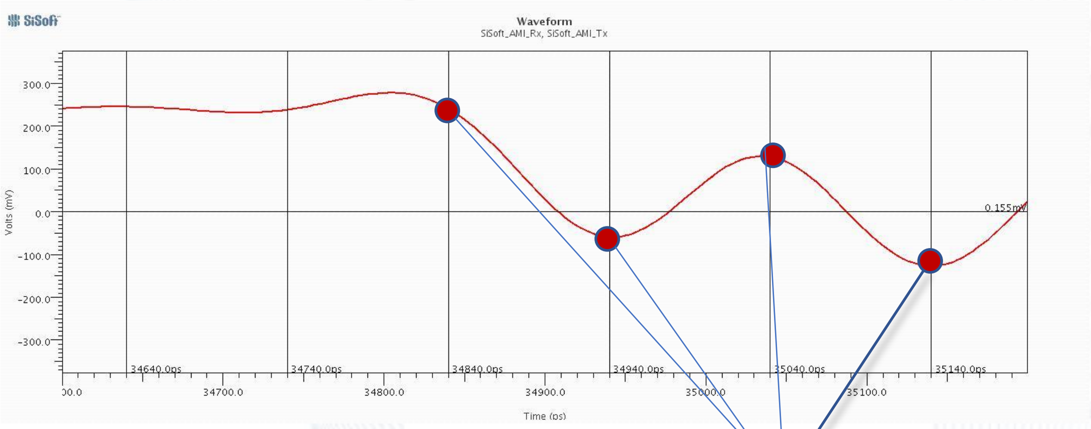
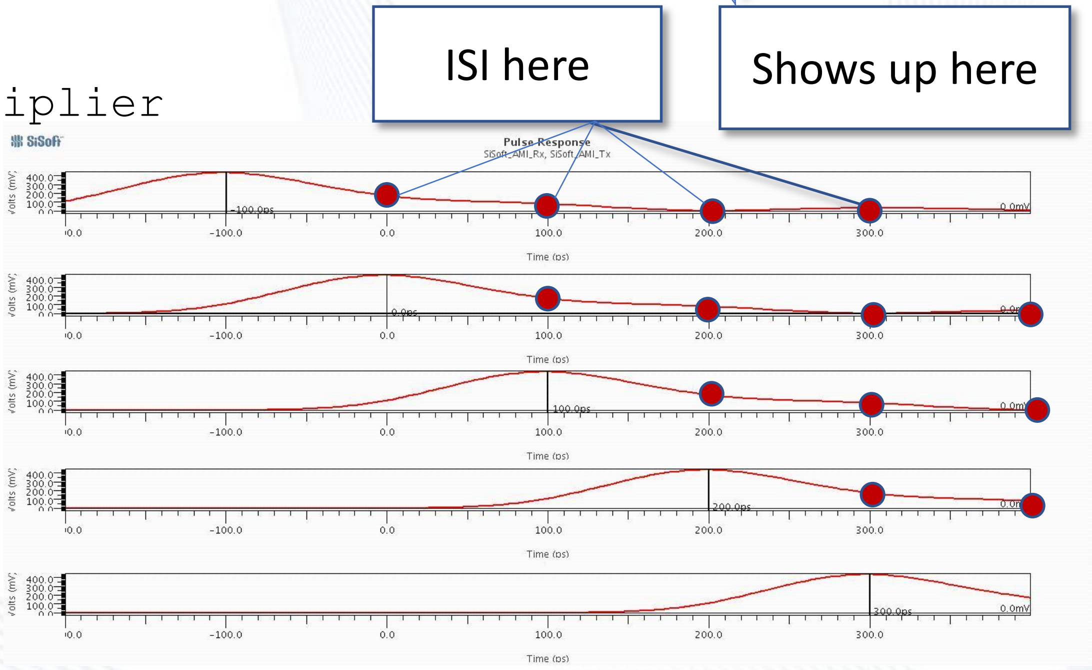
Time Domain ISI

- Time domain waveform from impulse response
- Bit pattern modulated
- Linear superposition
- LTI assumed



Data		Multiplier
1	x	0.5
1	x	0.5
0	x	-0.5
1	x	0.5
0	x	-0.5



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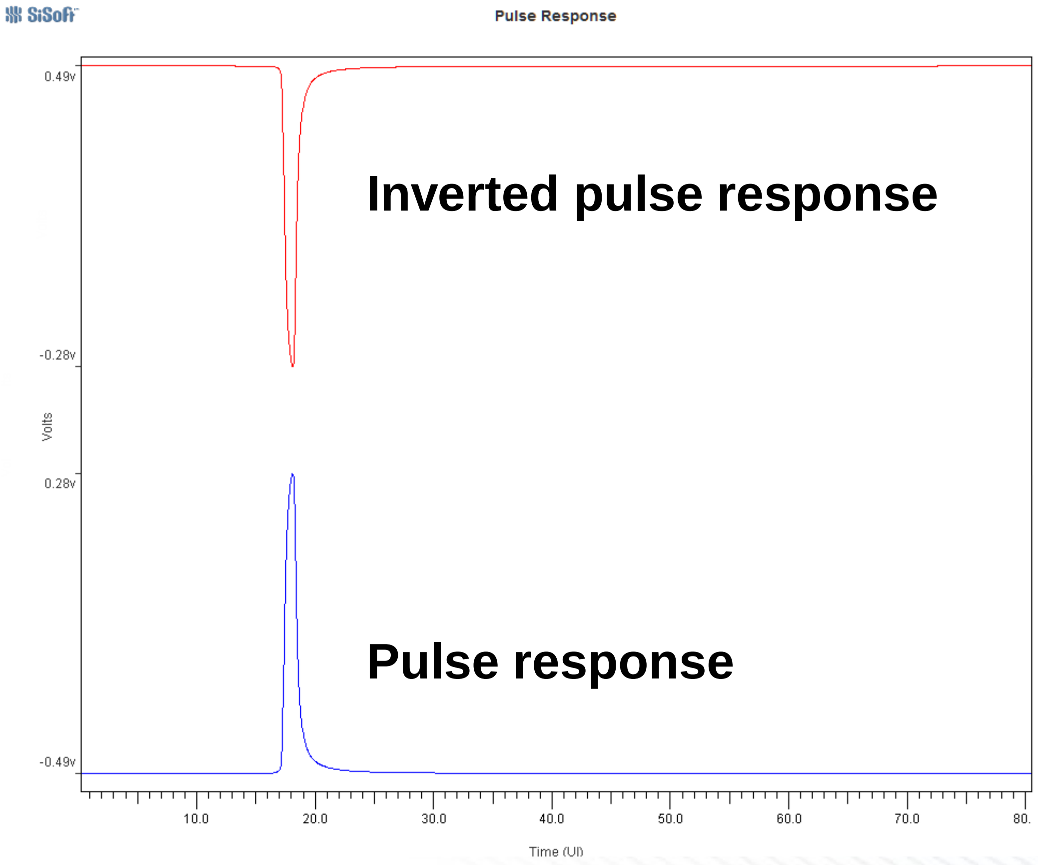
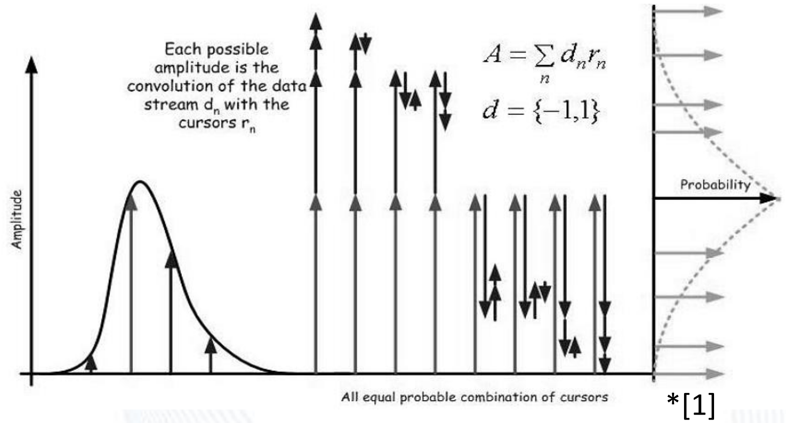
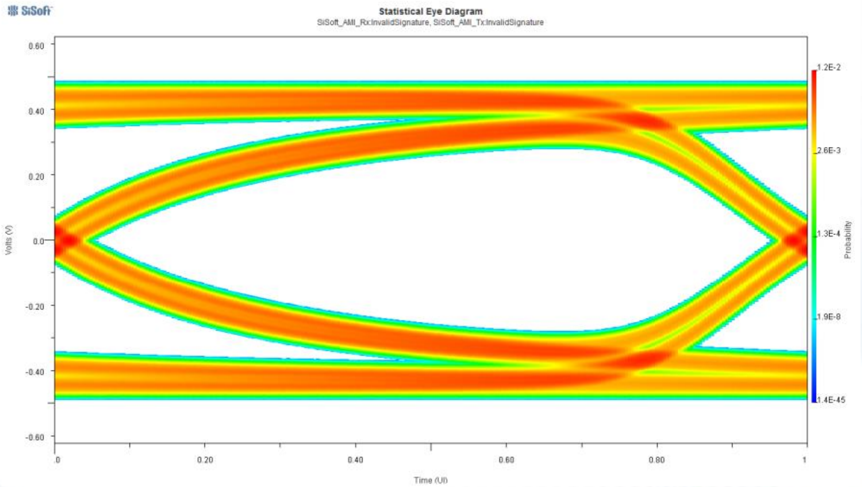
Statistical ISI





*[1]



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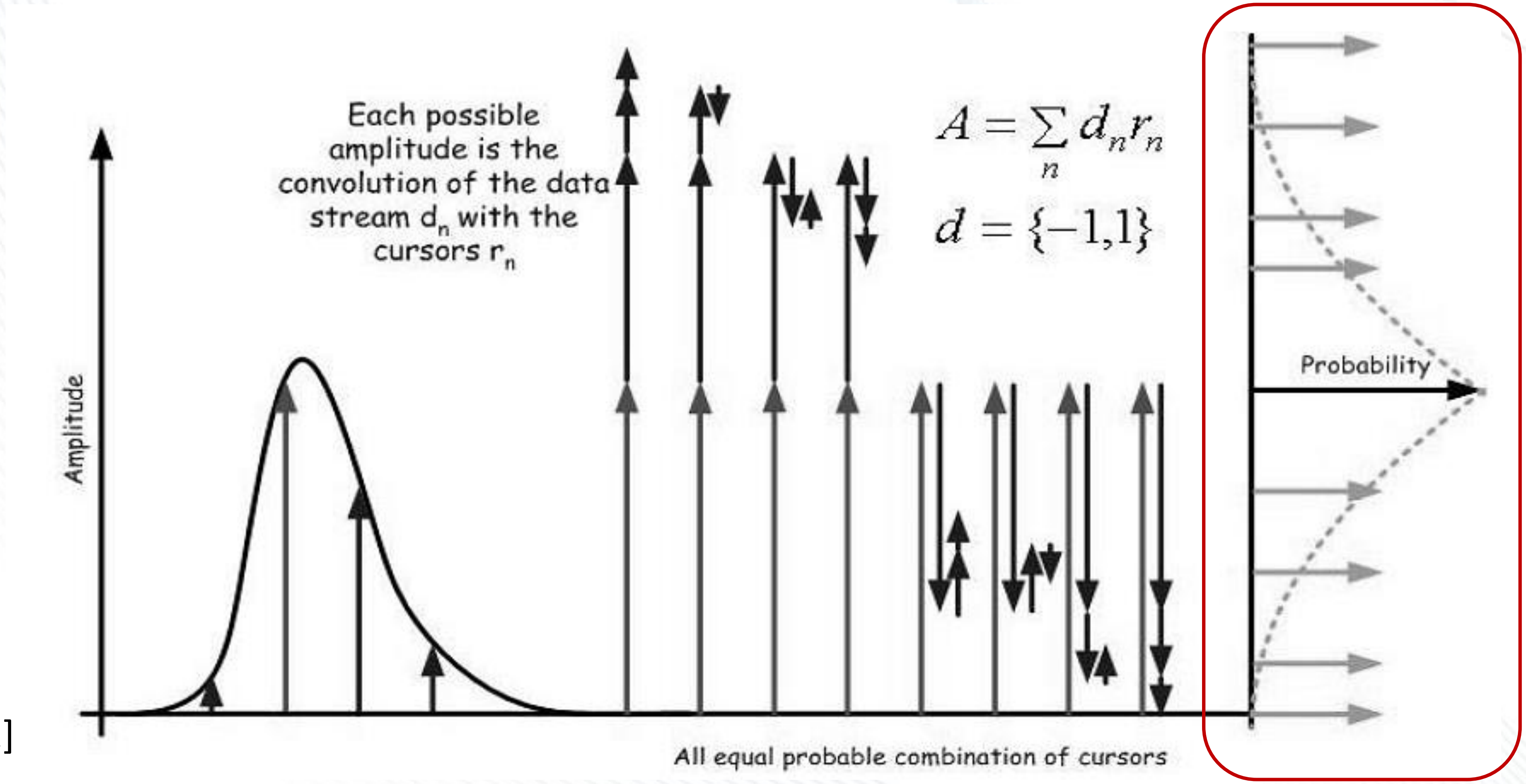
All Possible LTI Combinations Evaluated



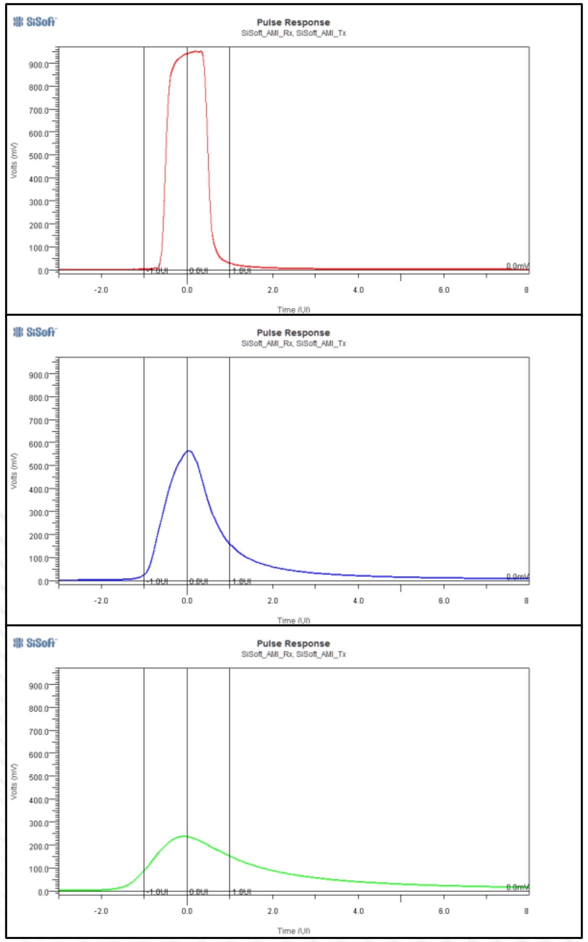
*[1]

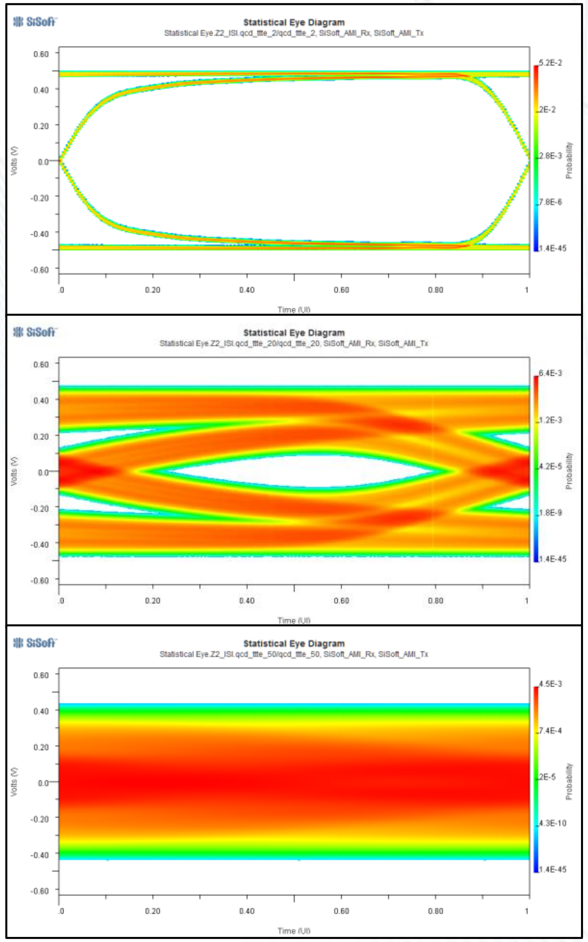
Channels, Pulses and Statistical Eyes

Short channel, Minimal ISI

Medium channel, Moderate ISI

Long channel, Extreme ISI





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Accounting for All ISI Scenarios

- A 28Gbps link may have a bit every 0.2 inches
- Many bits can be on the channel at once
- With reflections that number is multiplied
- Required impulse response may be many UI in length
- <u>The bit pattern affects how these interact</u>

To completely model all possible ISI scenarios we must try every possible bit pattern for the number of UI needed to capture all significant ISI

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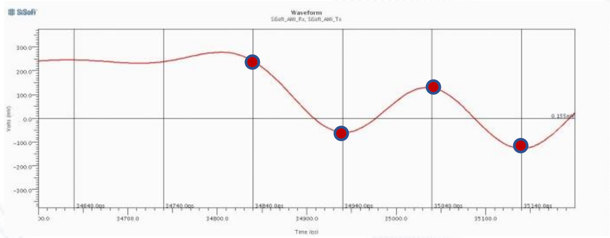
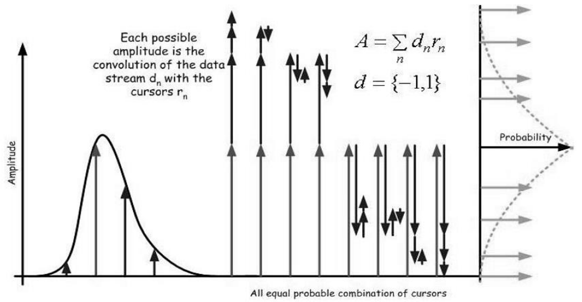
Can We Account for All ISI Scenarios?

- Theoretically need to try 2^N patterns, where N is the number of UI before ISI becomes insignificant
  - Example: 24 UI impulse response must simulate 2^{24} = 16,777,216 patterns, each 24 UI in length, total of 402,653,184 bit computations
- Time domain simulation
  - N-length patterns strung out sequentially
  - PRBS helps reduce redundancies
  - Often able to simulate only a fraction of cursor combinatior
- Statistical analysis
  - Directly calculates all 2^N cursor combinations
  - Efficient computation of channel response, not a circuit
  - May still have a practical upper limit for N





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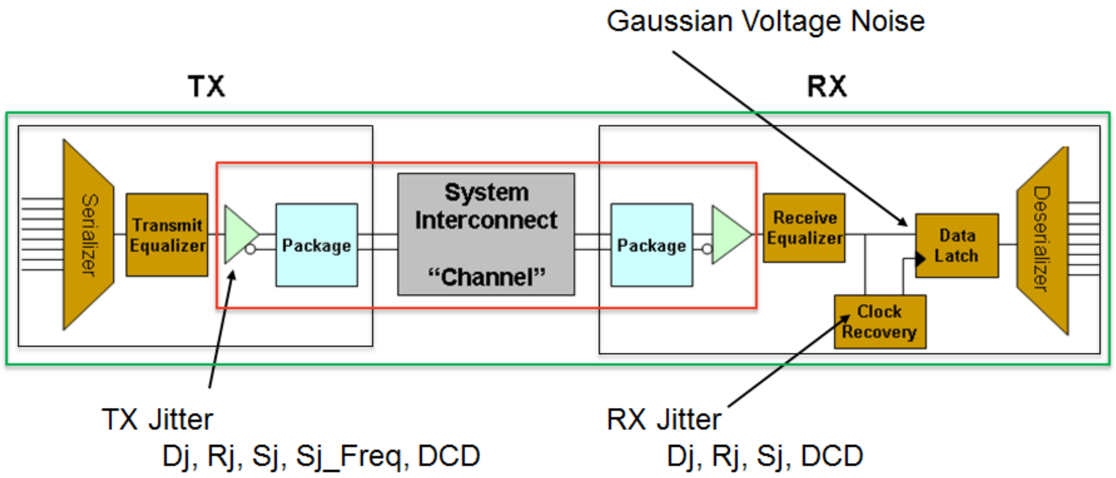
Jitter and Noise Impairments

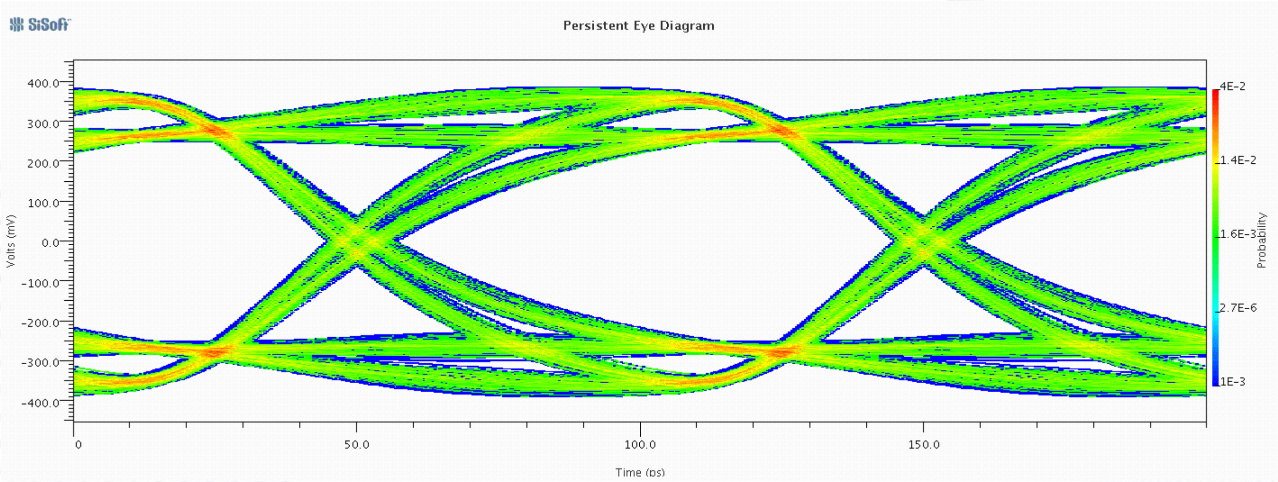
Jitter and Noise in IBIS

- IBIS 6.1 provides multiple TX & RX impairments
- TX jitter directly modulates the TX output
  - Simulators jitter the pattern sent to the TX in time domain simulations
  - Statistical analysis convolves jitter with eye diagram
- RX jitter affects recovered clock behavior
  - Simulators combine jitter data with clock information returned by the RX
  - Statistical analysis convolves jitter with eye diagram
- RX noise affects sampling latch data input
- **Jitter and noise are handled by the simulator, not by the models**



Time Domain Eyes With and Without Tx Jitter

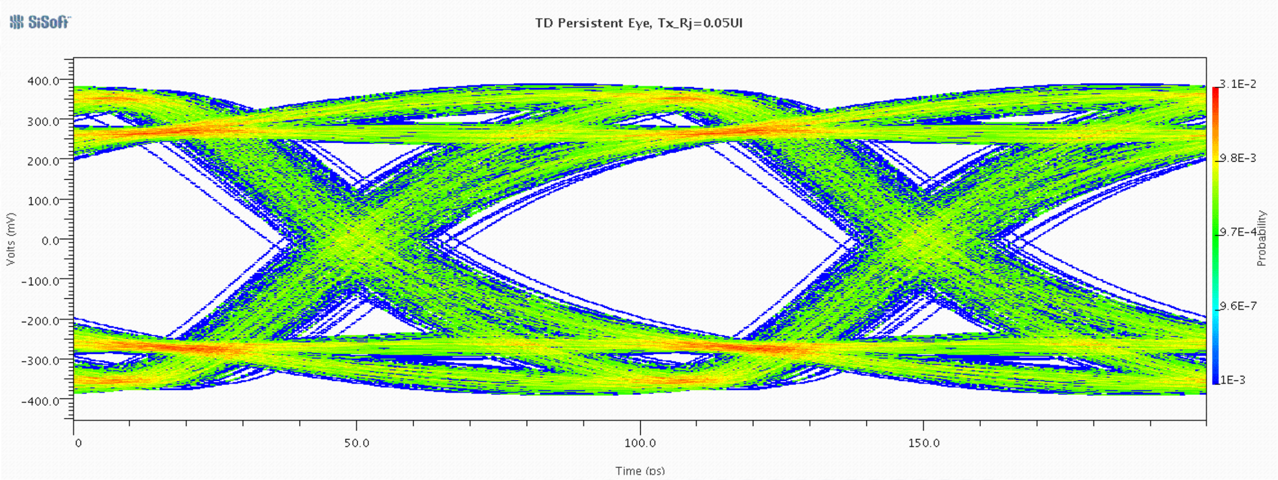
Random Jitter (Tx_Rj) = 0



1e-3

Only Impairment is Inter-Symbol Interference (ISI)

Tx_Rj = 0.05UI



1e-3

ISI + Jitter

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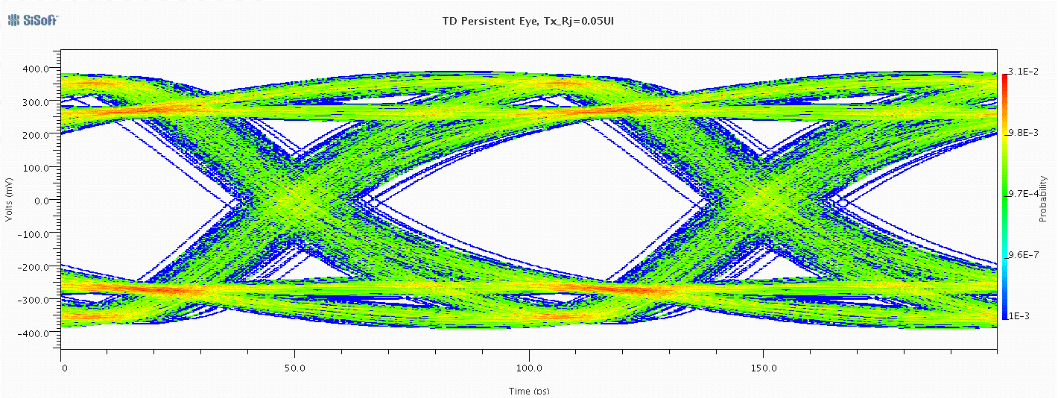
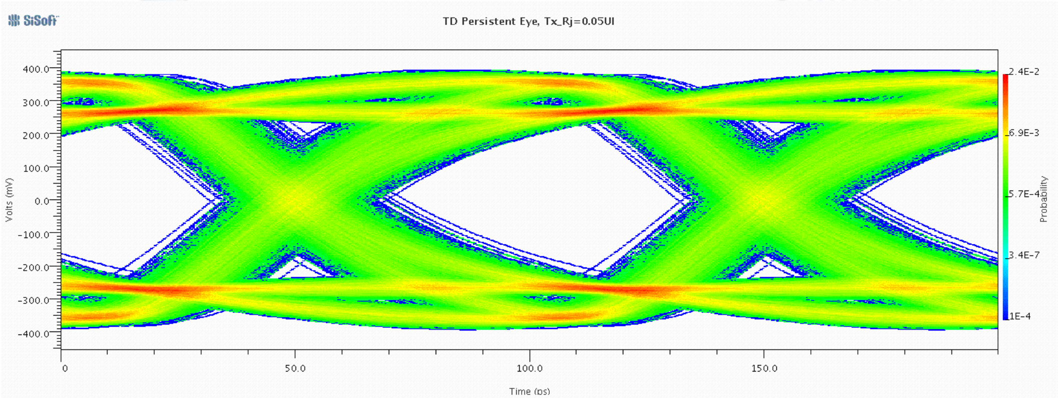
Time Domain: How Many Bits to Simulate?

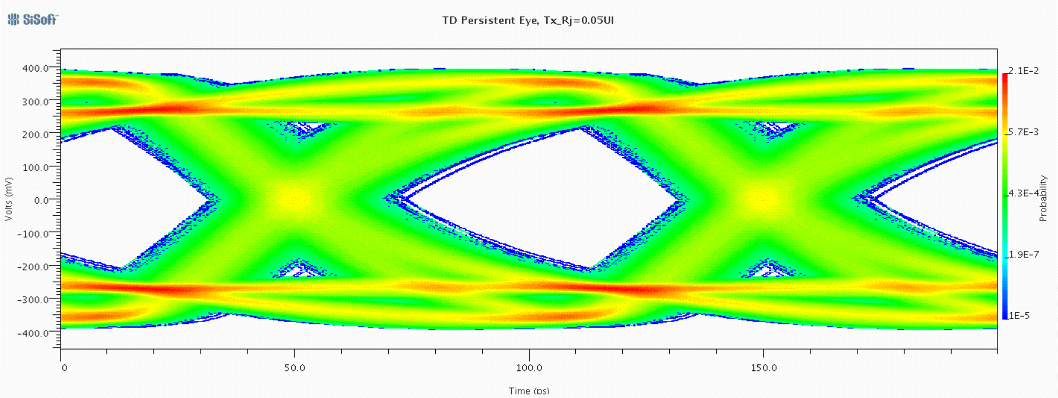
1,000 UI



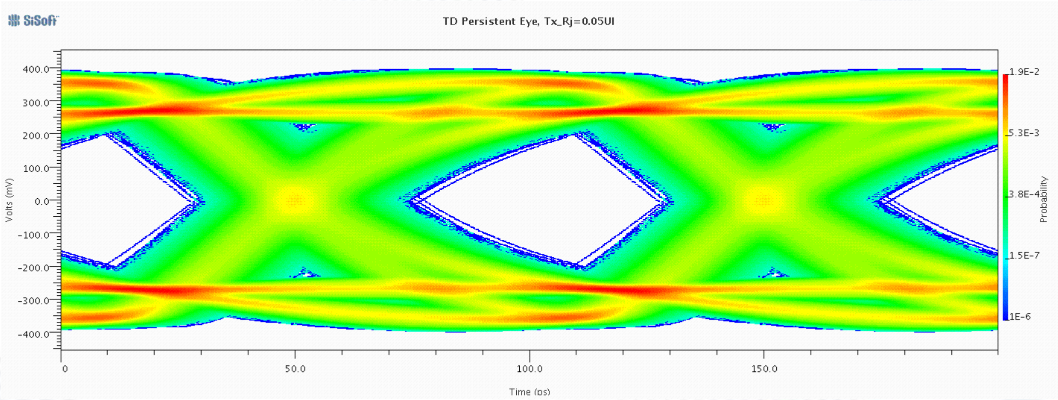
10,000 UI



100,000 UI



1,000,000 UI



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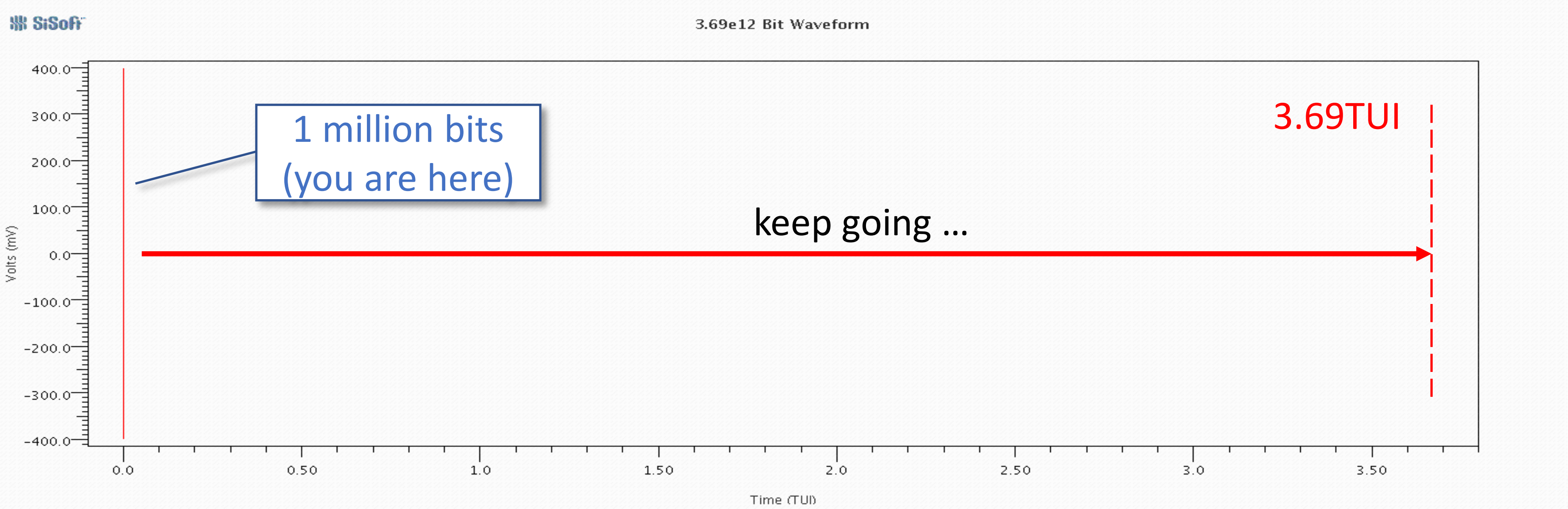
What Maximum BER Can We Tolerate?

• IEEE-802.3bj-KR4 FEC on	1e-5	
• IEEE-802.3bj-KR4 FEC off	**1e-12**	if low latency required
• OIF-CEI-56G FEC on	1e-4	
• OIF-CEI-56G FEC off	**1e-20**	
• PCIe-G3	**1e-12**	
• PCIe-G4	**1e-12**	
• DDR4	**1e-12**	eye mask rules
• DDR5	TBD	

How Many Error-Free Bits for 1e-12 BER?

It's Not 1e12

Confidence Level	90%	95%	99%
Maximum BER	1e-12	1e-12	1e-12
Error-free Bits Simulated *[2]	3.00e12	3.69e12	5.30e12



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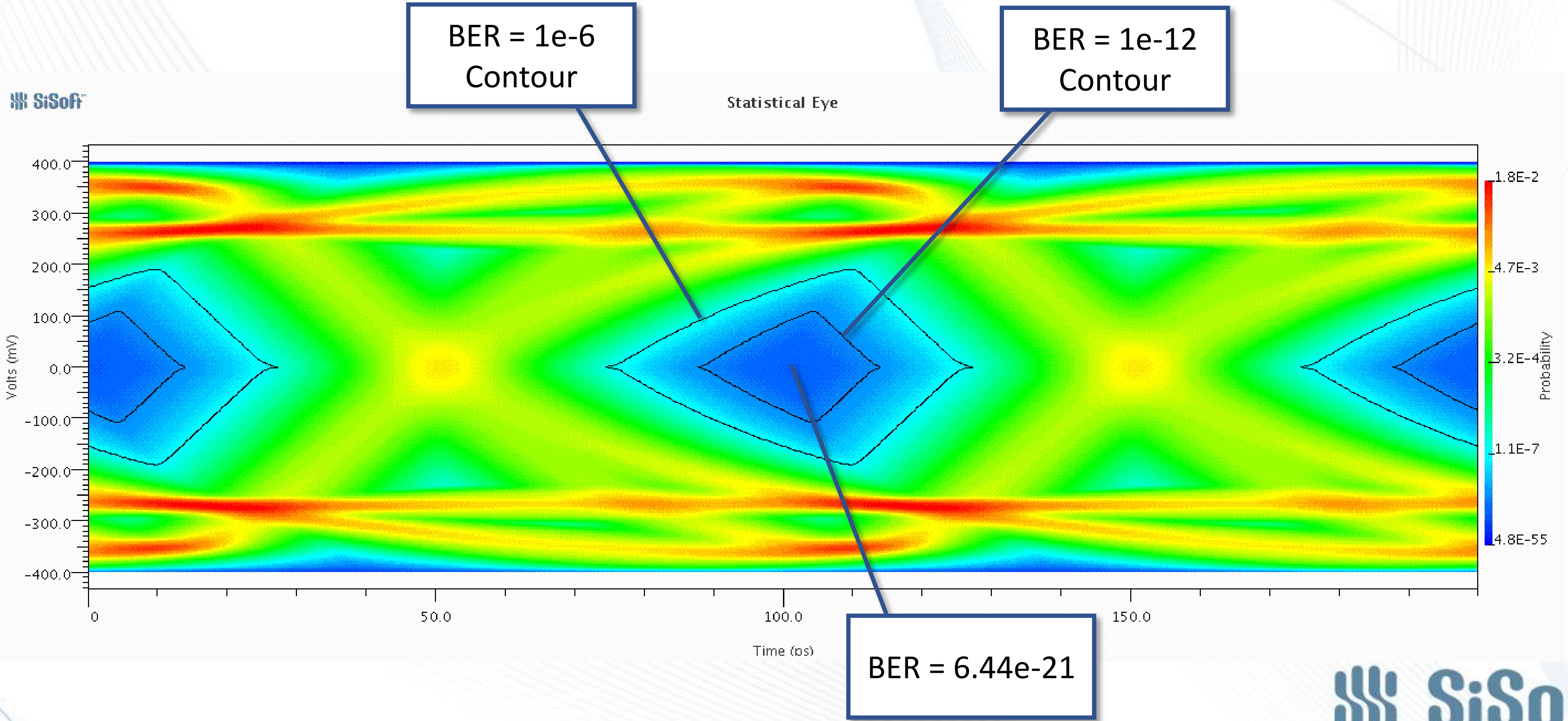
Statistical Eye With ISI and Jitter



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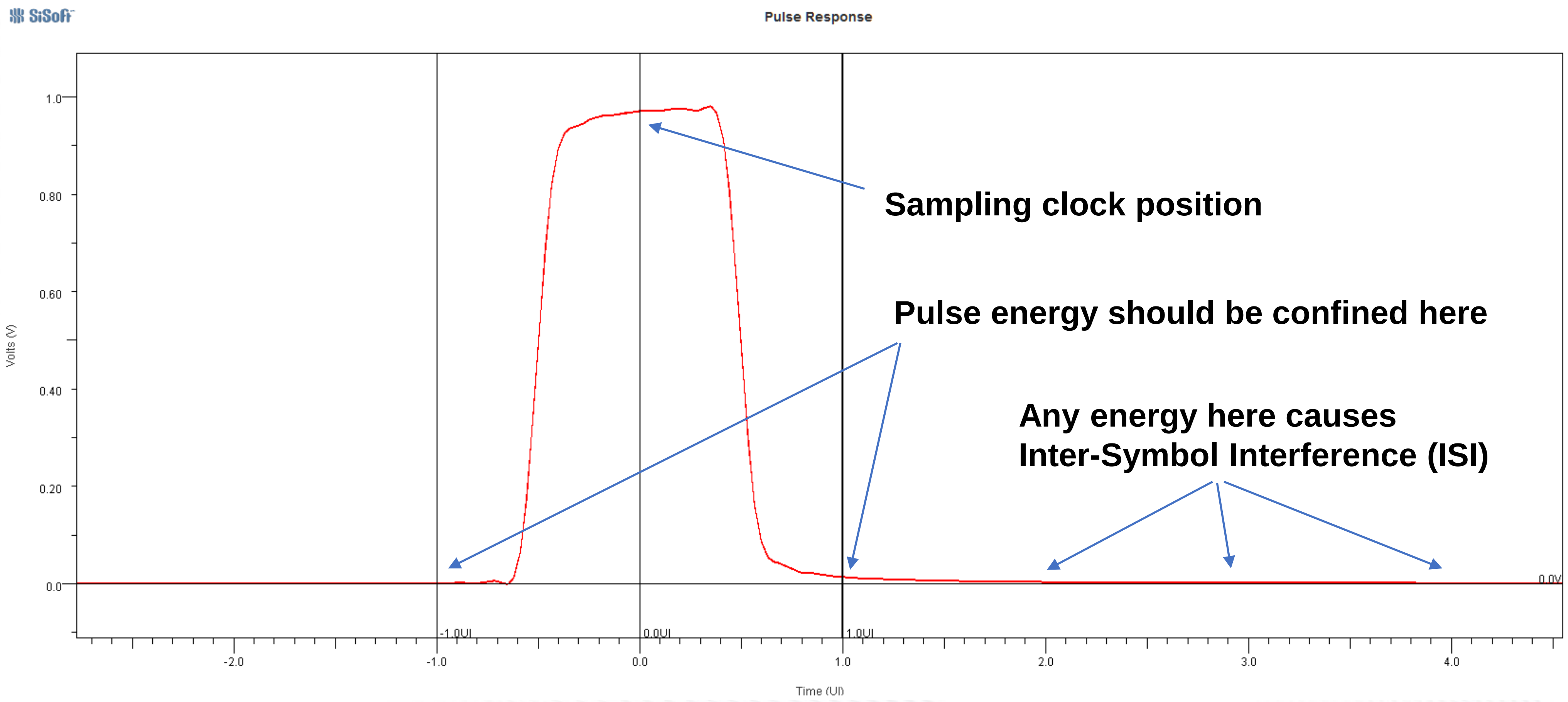
Corrective Measures

Desired Pulse Response for Low ISI



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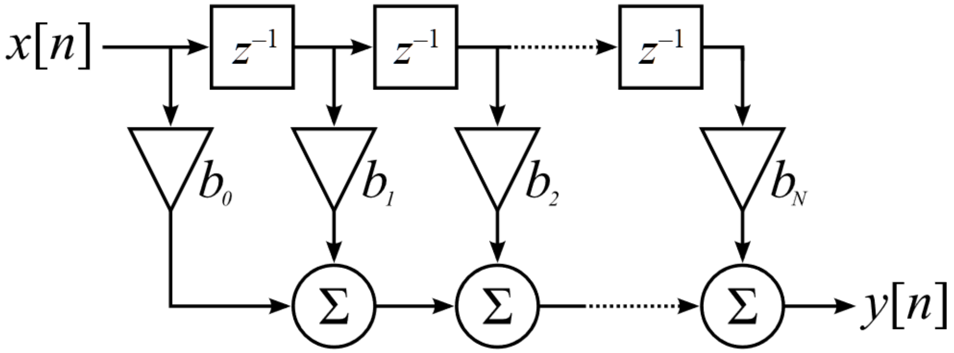
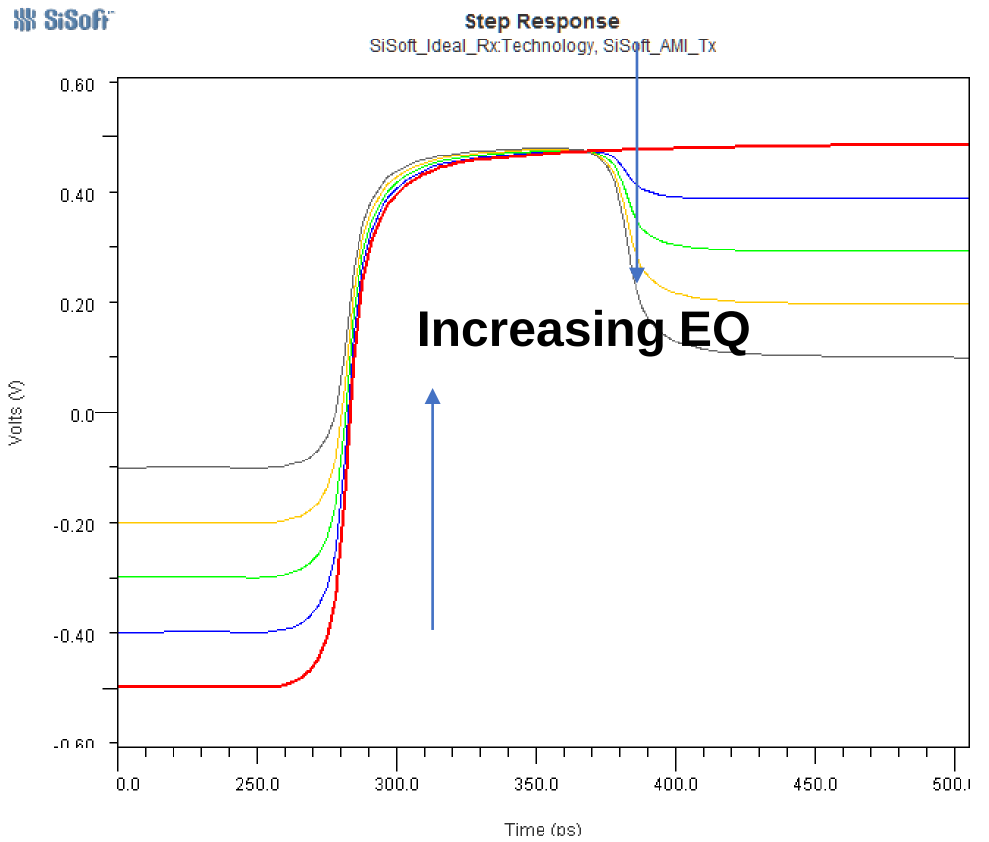
Tx Equalization



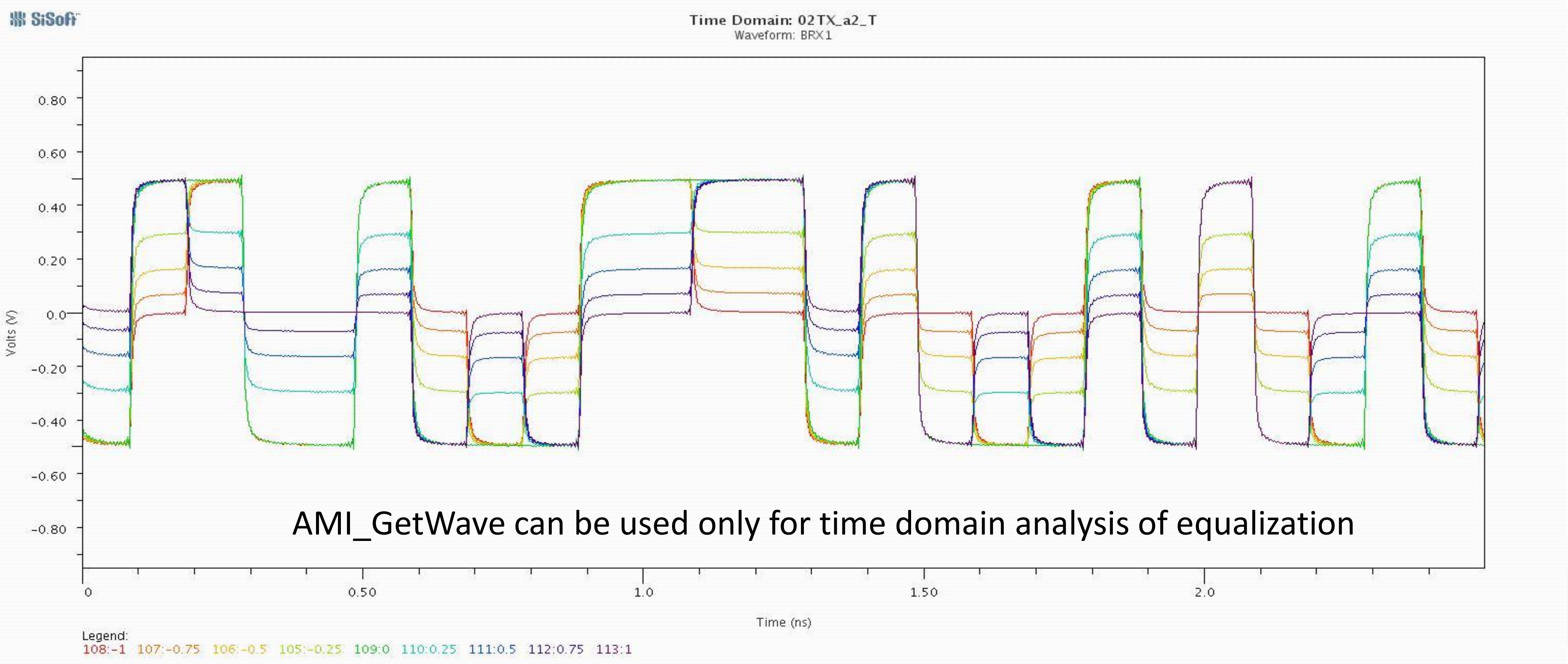
- Usually implemented as taps spaced at the signal data rate
- Can precede the signal (pre-cursor), follow the signal (post-cursor), or both
- Typical configuration is 1 pre-cursor, 2 post-cursor taps

TX Equalization (1st post-cursor)

- Goal: boost high frequency content
- Transition occurs at full strength, then driver “pulls back” for subsequent bits
- TX EQ is often referred to as de-emphasis
- TX EQ always reduces the energy sent into the channel



AMI_GetWave Models Can Process Equalization Directly in Time Domain



AMI_GetWave can be used only for time domain analysis of equalization

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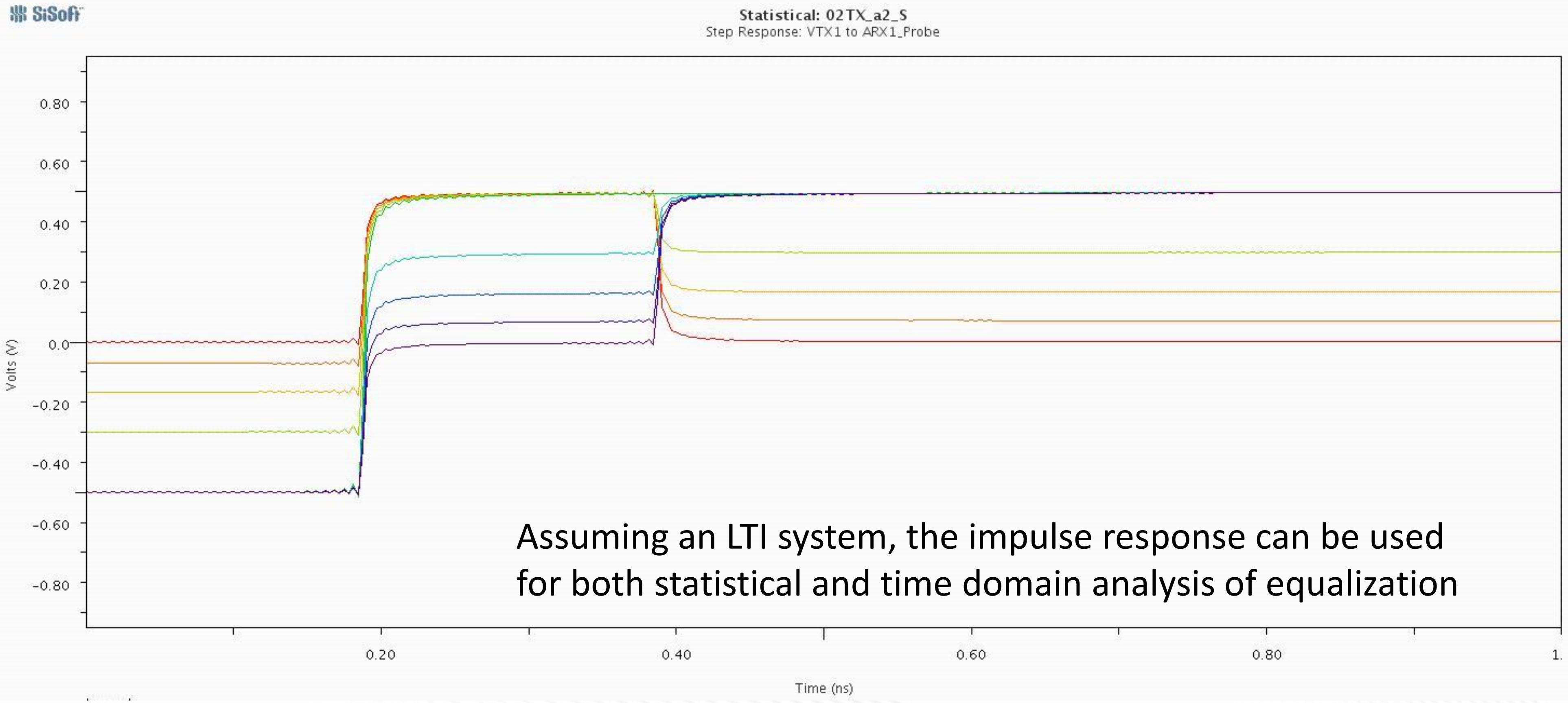
AMI_Init Can Return Impulse Response for Equalization



Assuming an LTI system, the impulse response can be used for both statistical and time domain analysis of equalization

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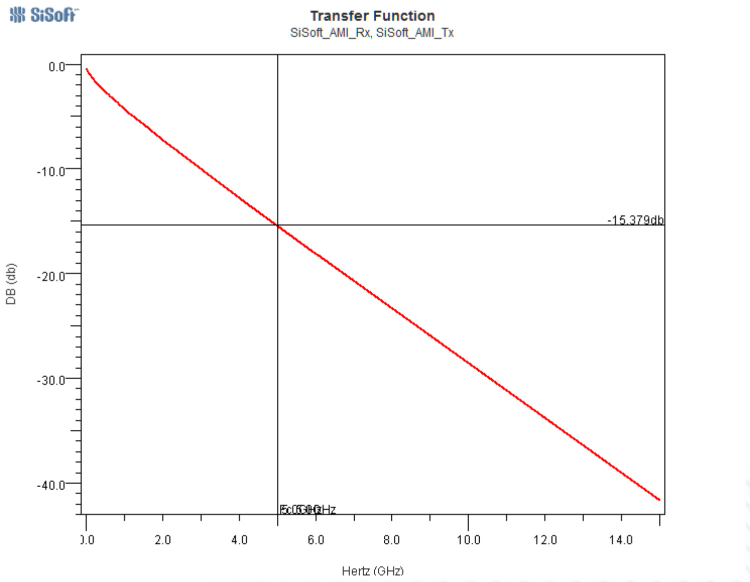
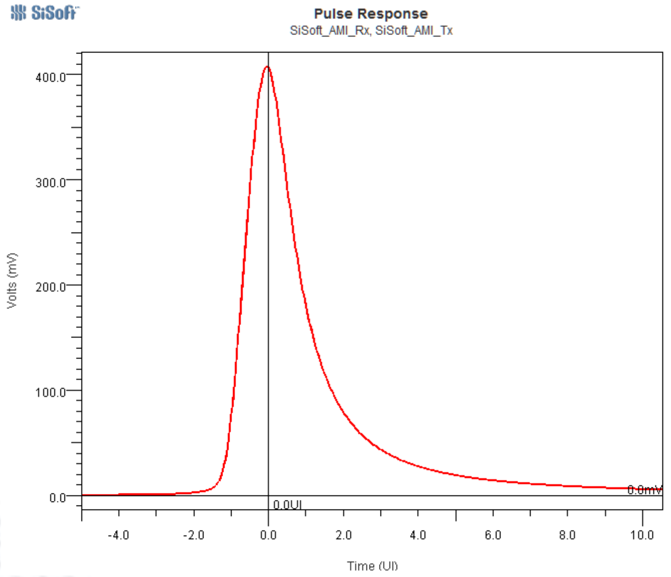
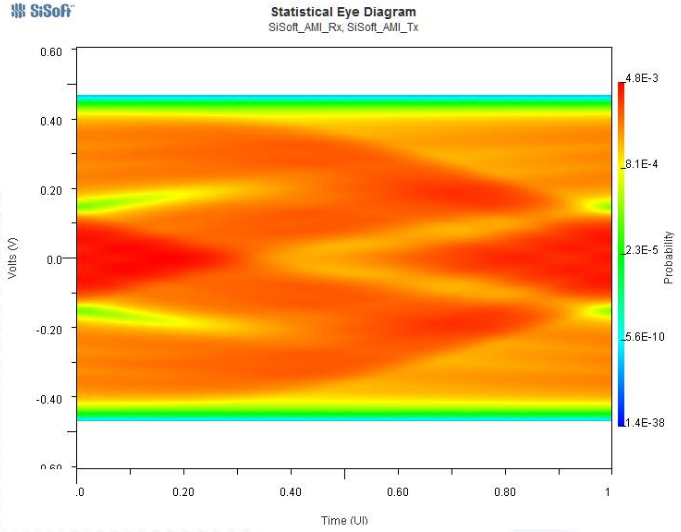
EQ Example: 20 inch channel, 10 Gb/s







15.3 dB loss

12+ bits of ISI

No EQ = No eye

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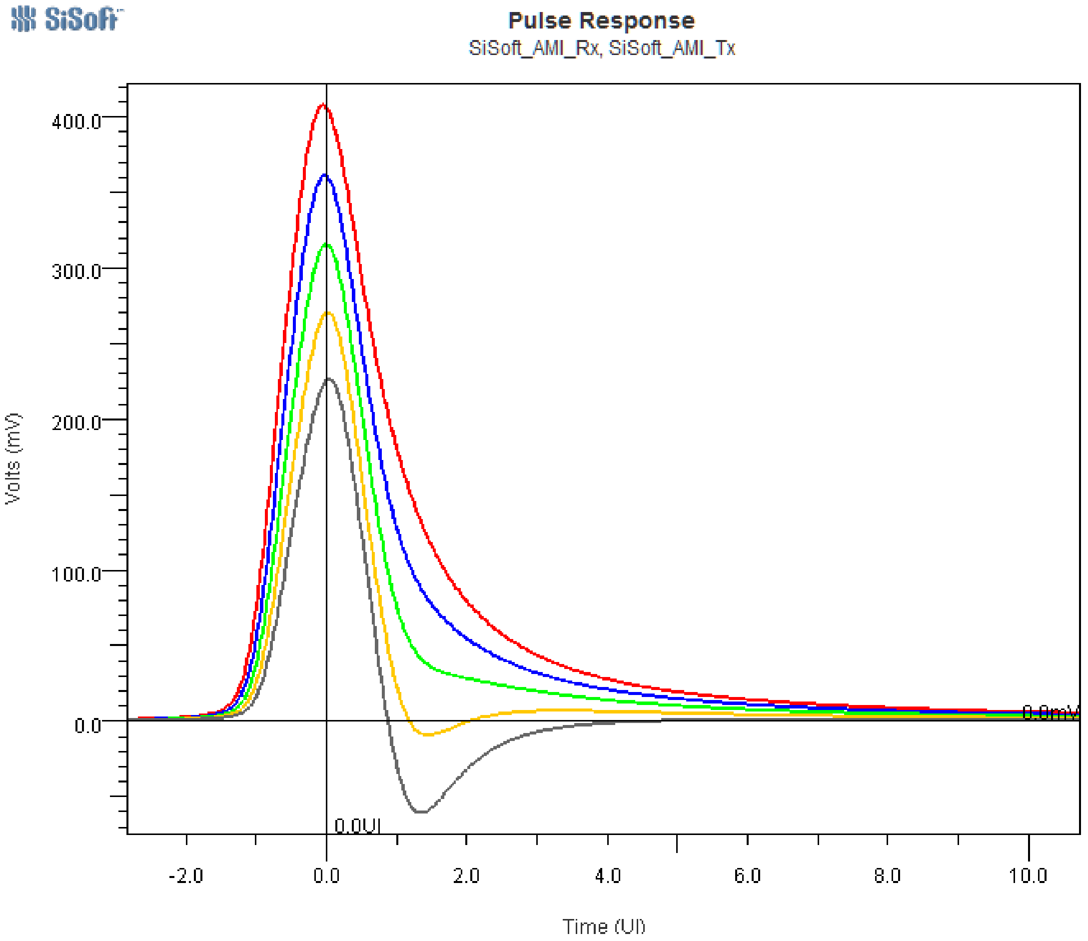
Sweeping the 1st Post-cursor Pulse Response

Case	Cursor	1st Post
1	1.0	0.0
2	0.9	-0.1
3	0.8	-0.2
4	0.7	-0.3
5	0.6	-0.4

- Which case will give us the best eye?



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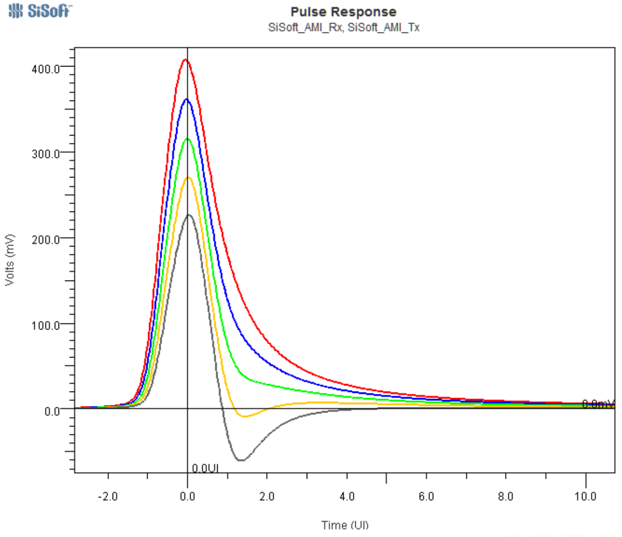
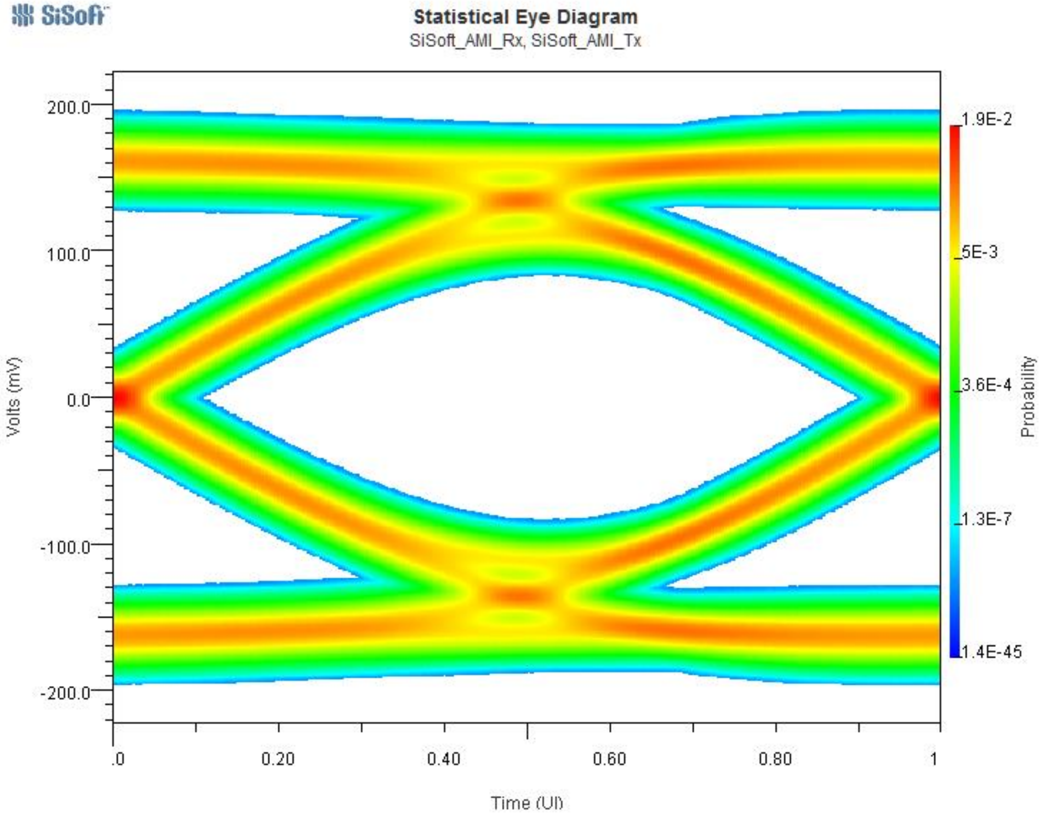
Using Pulse Responses to Find TX Equalization

Row	Tx:tap_filter.0	Tx:tap_filter.1	Stat Eye Height (V)
1	1	0	0
2	.9	-.1	0
3	.8	-.2	0.0706985
4	.7	-.3	0.166147
5	.6	-.4	0.126204





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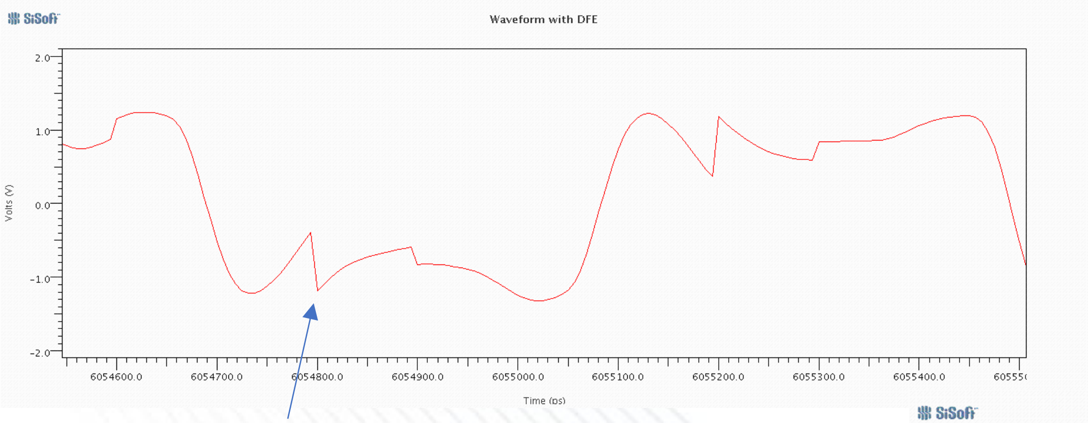
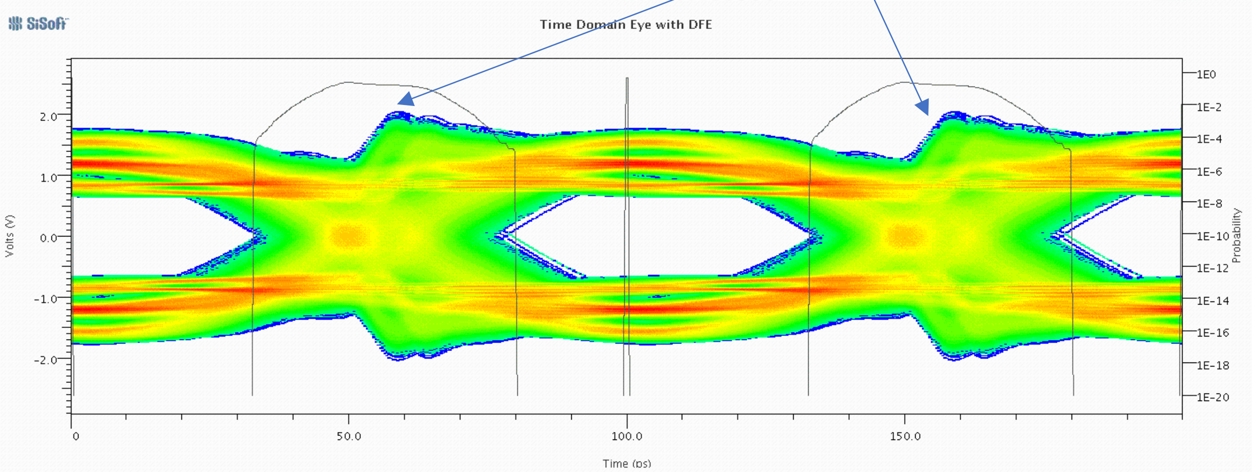
AMI_GetWave Can Also Model Time-Variant Effects



RX DFE taps

DFE action visible in eye diagram



- Adaptive corrections
  - DFE
  - CTLE
  - AGC
- Non-Linear Impairments
  - Saturation

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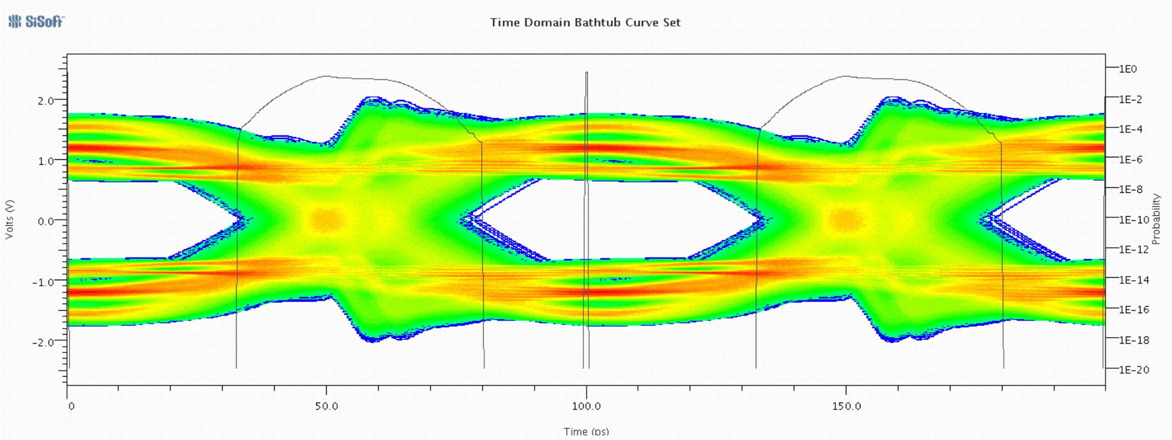
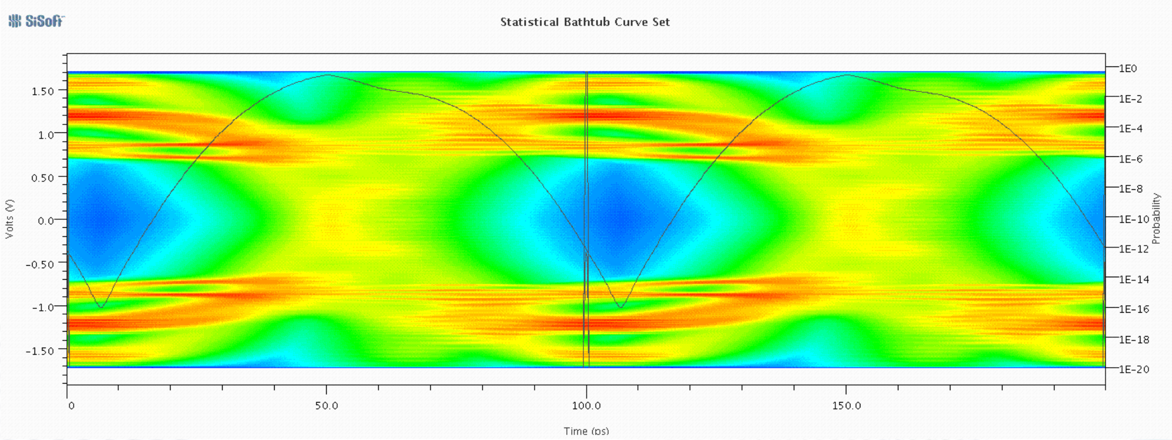
Using Both Time Domain and Statistical Analysis

- No single analysis method models all impairments and all corrective measures well enough
- Many helpful techniques, eg.: get adapted settings from time domain and apply to statistical
- Dual IBIS-AMI models are required





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Conclusions

- IBIS-AMI time domain simulation with AMI_GetWave can model non-linear effects such as DFE and saturation.
  - But it can be impossible to simulate enough bits in time domain to prove the low BER requirements of some technologies.
- IBIS-AMI statistical analysis can quickly evaluate very low BER.
  - But can not see time-variant effects such as DFE and saturation.
- Well constructed dual IBIS-AMI models are required.

Thank You

- Much content copied from:
  - *Pragmatic Signal Integrity Boot Camp*
    - Donald Telian, SiGuys
    - Michael Steinberger, SiSoft
    - Tripp Worrell, SiSoft
    - Todd Westerhoff, SiSoft
    - Graham Kus, SiSoft
    - Eric Brock, SiSoft
  - DesignCon 2017, Santa Clara, CA
- References

[1] Anthony Sanders, Mike Resso, John D'Ambrosia, *Channel Compliance Testing Utilizing Novel Statistical Eye Methodology*, DesignCon 2004

[2] Jeruchim, Michel C., Philip Balaban, and K. Sam Shanmugan, *Simulation of Communication Systems*, Second Edition, New York, Kluwer Academic/Plenum, 2000.

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