Comparison of Time Domain and Statistical IBIS-AMI Analyses

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Asian IBIS Summit 2017
Shanghai, PRC
November 13, 2017

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9 Combinations of TX and RX Model Types

- AMI file has:
  - GetWave_Exists = True — Best for bit-by-bit simulation
  - Init_Returns_Impulse = True — Best for statistical analysis
  - 3 types: "Init-only", "GetWave-only", "Dual"
  - 3 TX * 3 RX = 9 combinations

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

Simulation limitations

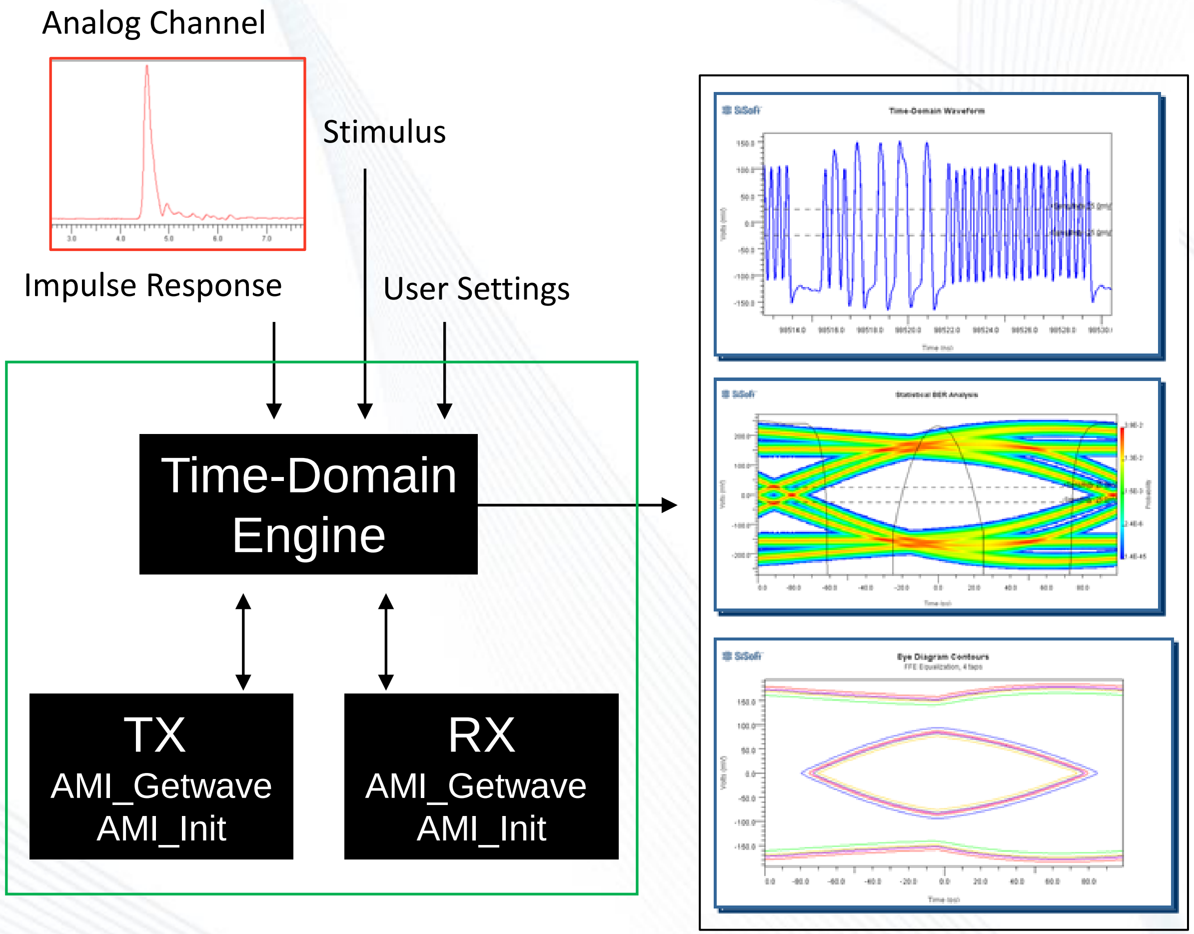
(dark green)	Correct equalization of TX and RX modeled
(light green)	Correct equalization of TX and RX modeled: Assumes no adaptation in TX
(light yellow)	Assumes Static RX Equalization is a good representation of the RX: No adaptation
(yellow)	Assumes Static RX EQ is a good representation of the RX: No Adaptation, Requires advanced math capabilities in Simulator
(pink)	Equalization data is missing

Case #	TX	RX	Statistical	Time Domain
1	Init Model Only	Init Model Only	OK	Static TX EQ, Static RX EQ
2	Init Model Only	Getwave Model Only	No RX EQ	Static TX EQ, Dynamic RX EQ
3	Init Model Only	Dual Model	OK	Static TX EQ, Dynamic RX EQ
4	Getwave Model Only	Init Model Only	No TX EQ	Dynamic TX EQ, Static RX EQ
5	Getwave Model Only	Getwave Model Only	No TX or RX EQ	Dynamic TX EQ, Dynamic RX EQ
6	Getwave Model Only	Dual Model	No TX EQ	Dynamic TX EQ, Dynamic RX EQ
7	Dual Model	Init Model Only	OK	Dynamic TX EQ, Static RX EQ
8	Dual Model	Getwave Model Only	No RX EQ	Dynamic TX EQ, Dynamic RX EQ
9	Dual Model	Dual Model	OK	Dynamic TX EQ, Dynamic RX EQ

Best Option

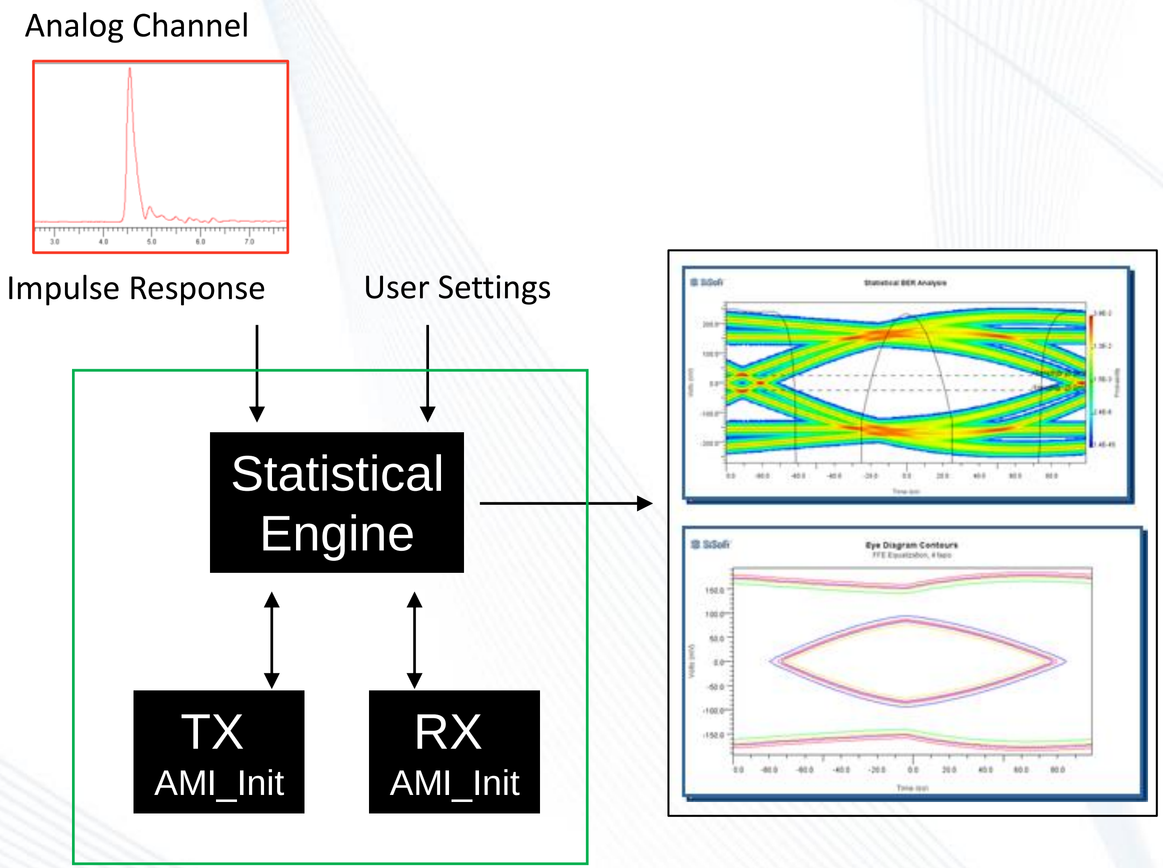
Time-Domain Simulation

- **Inputs:**
  - Channel and buffer Impulse responses
  - User-defined input stimulus
  - Algorithmic models (AMI_GetWave)
- **Analysis Method:**
  - Waveform processing & convolution
- **Outputs:**
  - Bit pattern waveforms
  - 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:**
  - Statistical eye diagrams
  - Eye height / width measurements
  - Eye contours @ probabilities
  - Equalized / unequalized responses



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Which IBIS-AMI Model Type is Best?

- Need to evaluate suitability for modeling:
  - Impairments: The factors that harm the signal
    - Mostly in the channel
    - Statistical analysis has advantages
  - Corrective measures: Signal improvements
    - Mostly inside the SerDes
    - Time domain has advantages

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

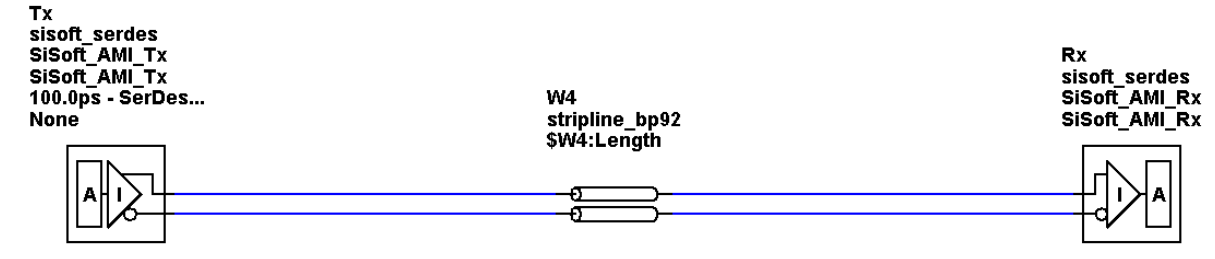
Clock Impairment	Physical Cause
Random Jitter (RJ)	a. Shot noise in oscillator gain element b. Power supply noise modulating gate delays
Duty Cycle Distortion (clock) (DCD)	For half rate clock, duration difference between positive and negative half cycles
Duty Cycle Distortion (data)	Difference between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

Corrective Measures To Be Modeled

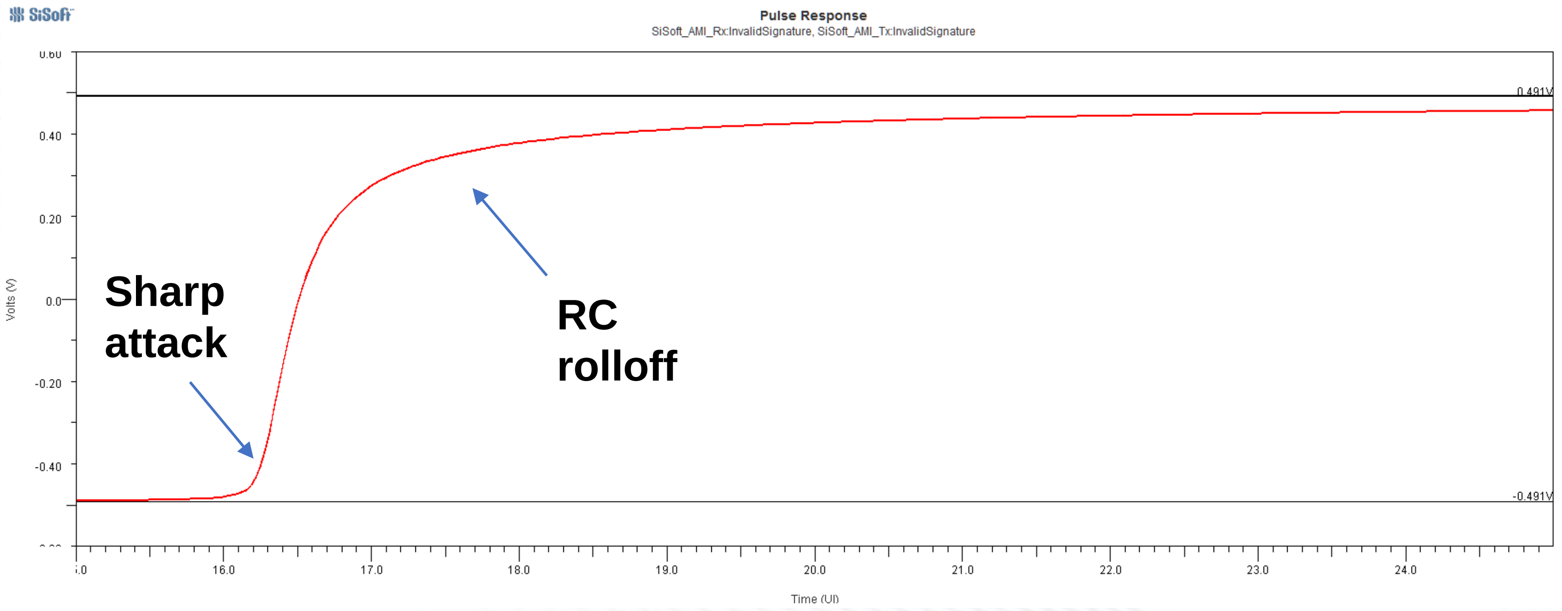
Corrective Measure	Time Domain Behavior
TX FFE	May adapt in time domain, but this is rare
RX CTLE	Linear, time-invariant (LTI)
RX AGC	Adapts in time domain
RX Saturation	Not adaptive, but not time-invariant either
RX DFE	Adapts in time domain
Others…	

Inter-Symbol Interference (ISI) Impairments

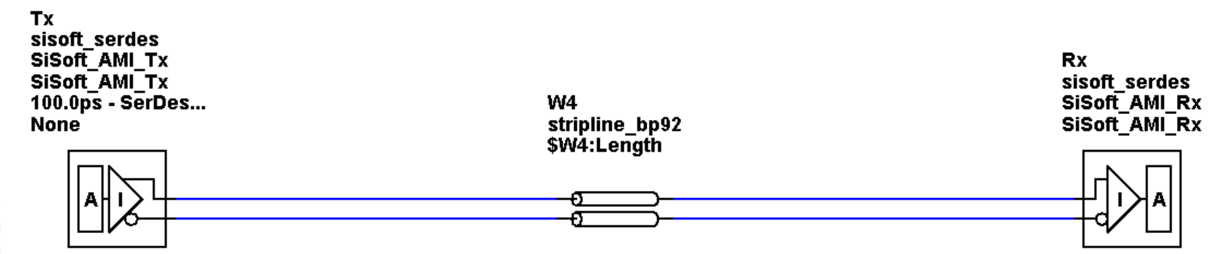
Step Response Analysis



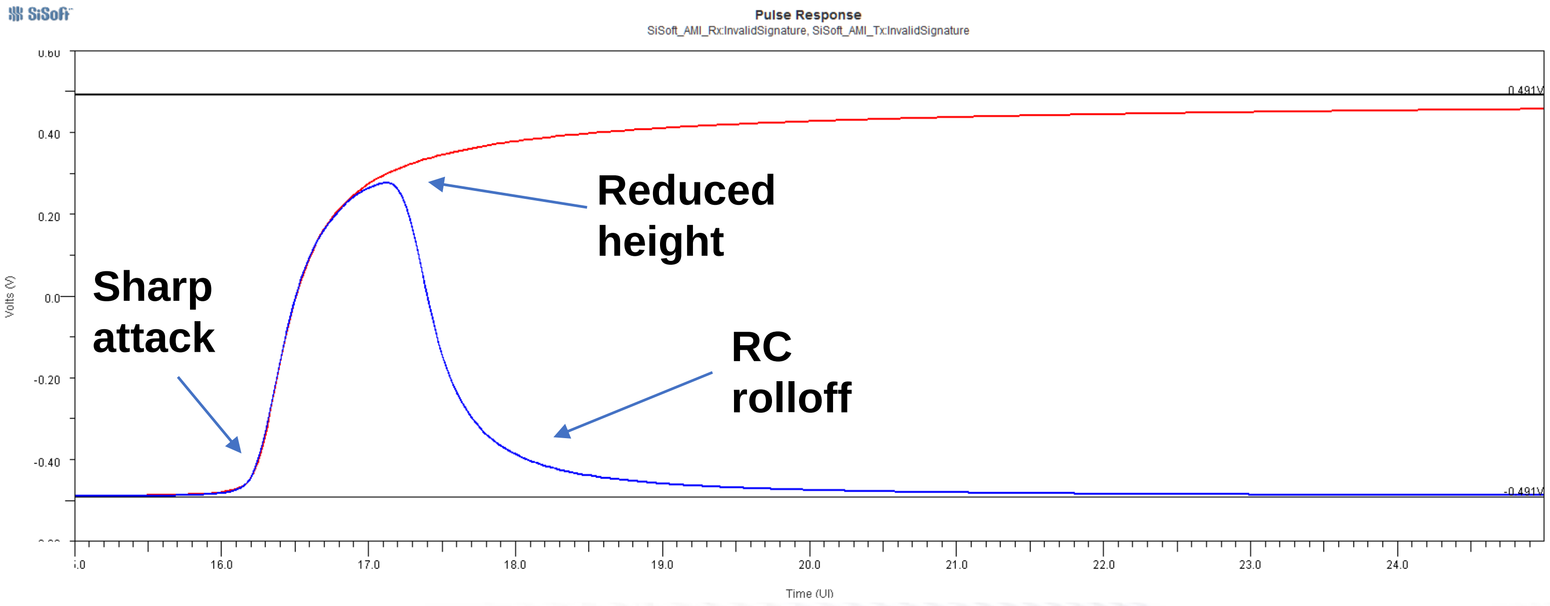
10", 10 Gb/s



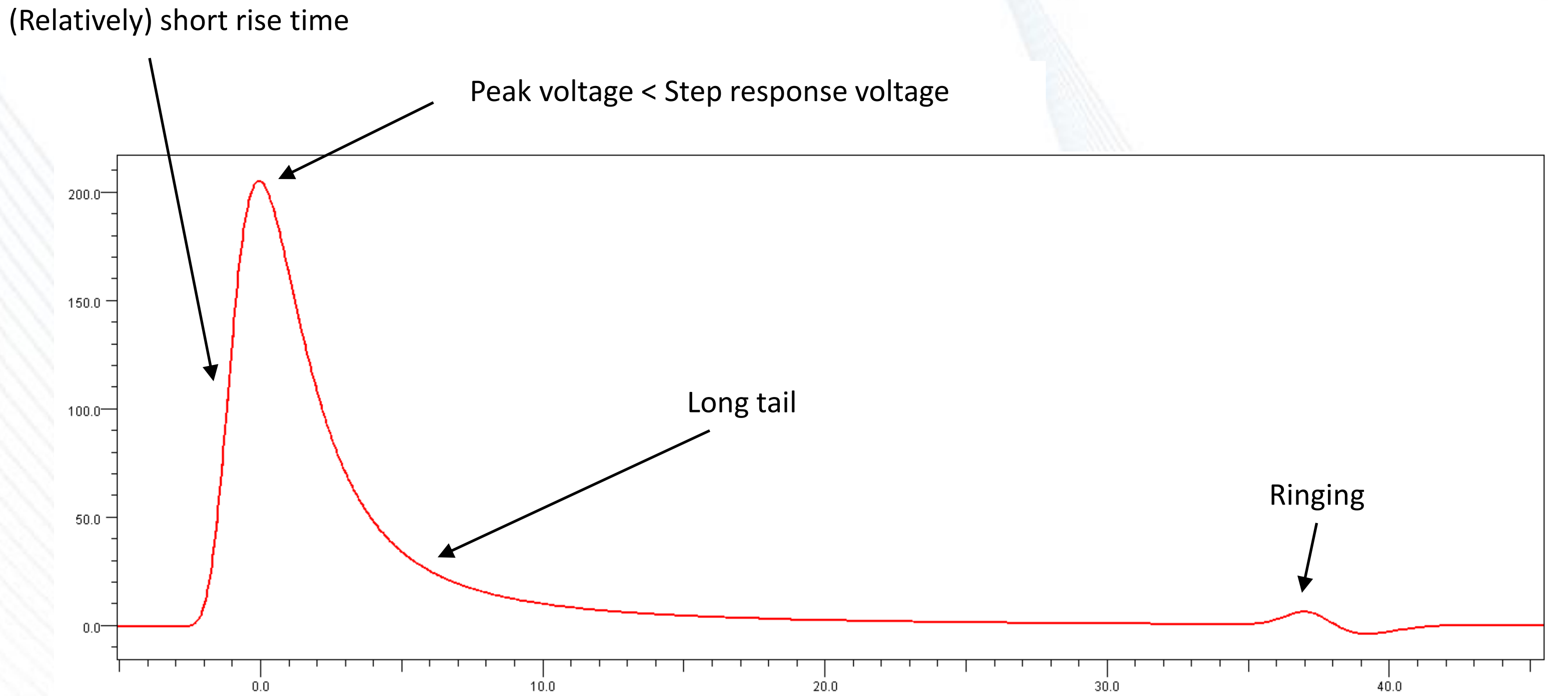
Pulse vs. Step Responses



10”, 10 Gb/s



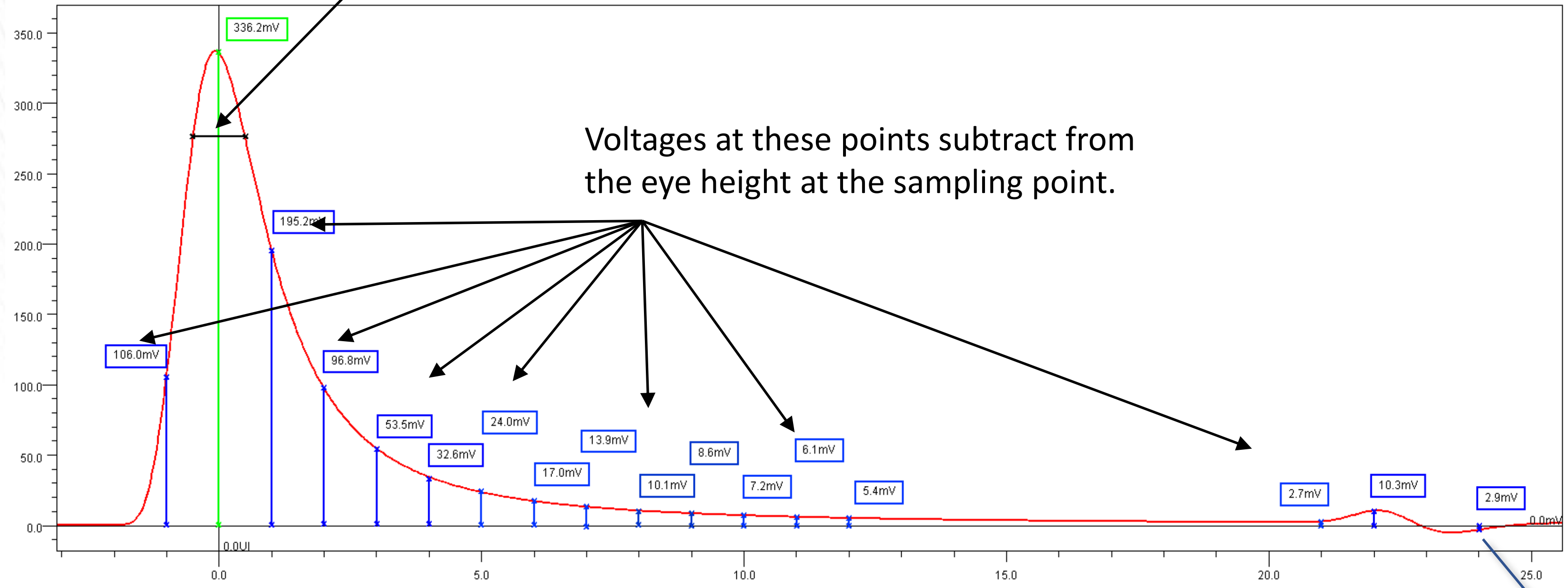
Channel Pulse Response



- Requires accurate Tx/Rx analog models to correctly predict ringing impairment 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.



24 UI

$$Inner\ Eye\ Height =$$

main_cursor – Σ |ISI_voltages|

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

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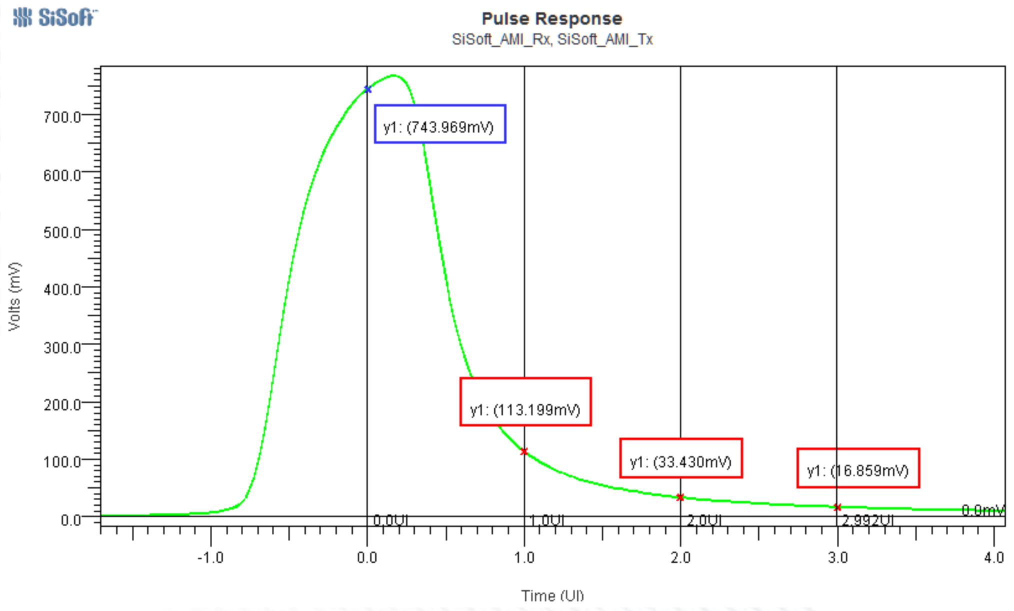
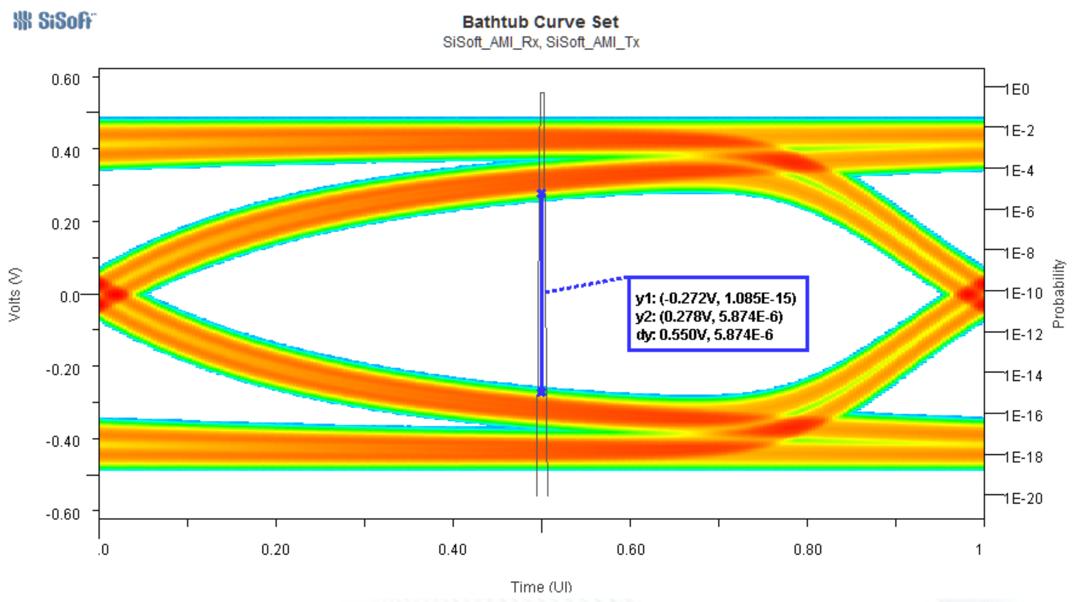
Statistical ISI Inner Eye Quick Calculation





Prediction: 580mV **Simulated Actual: 550mV**

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

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

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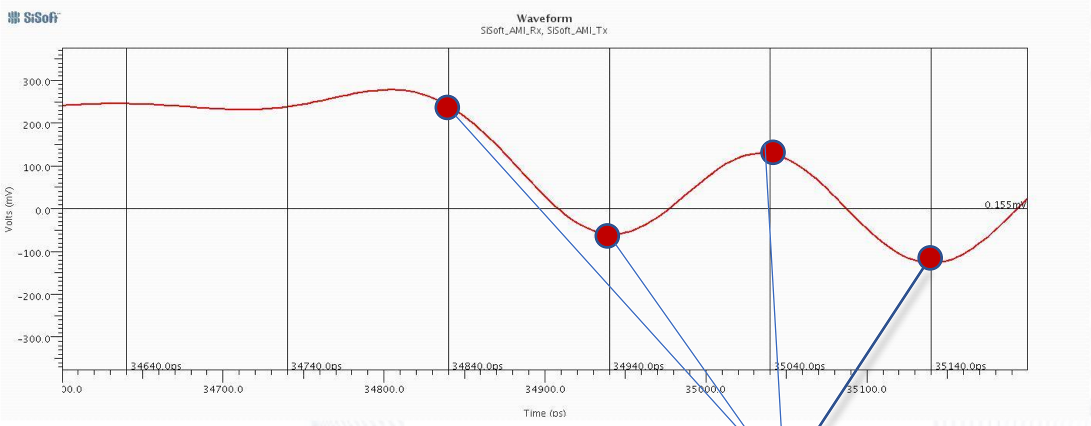
Time Domain ISI

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

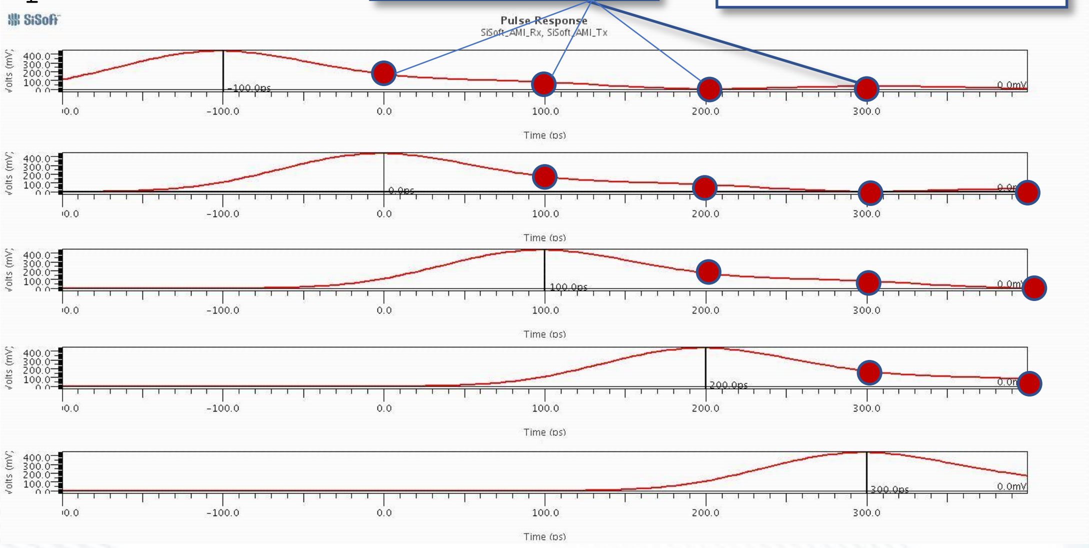
Example bit pattern: 11010



ISI here

Shows up here

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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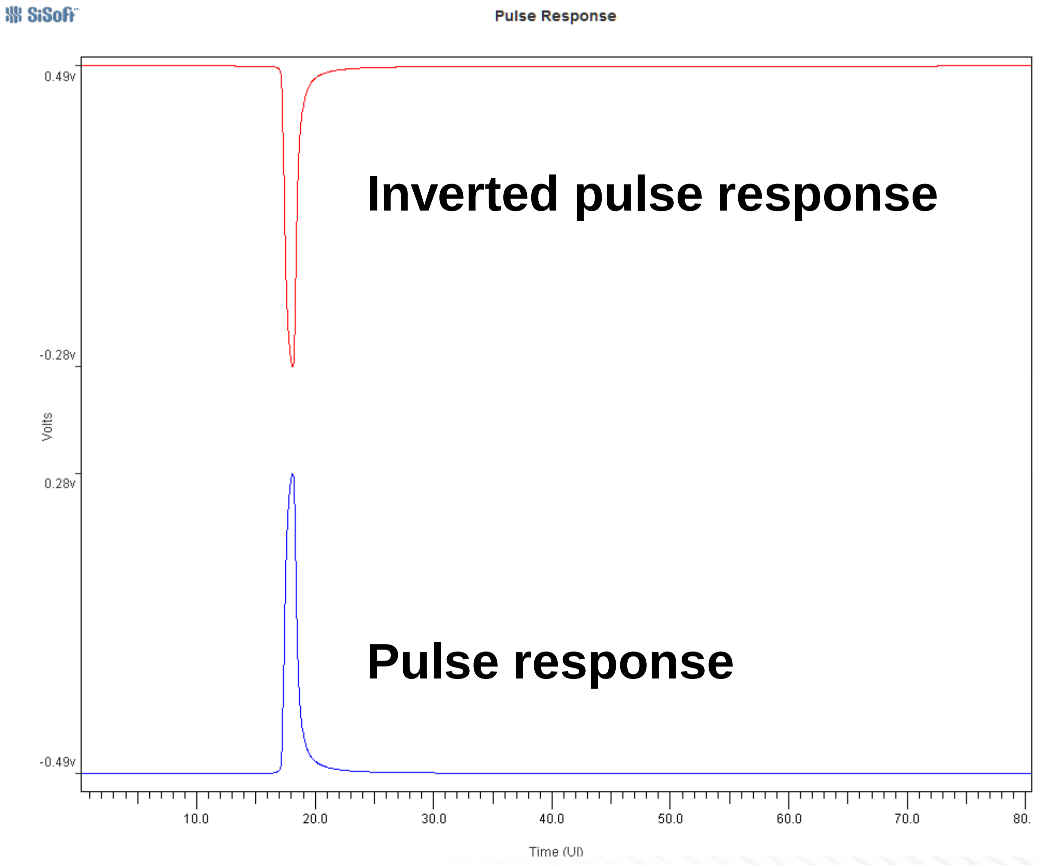
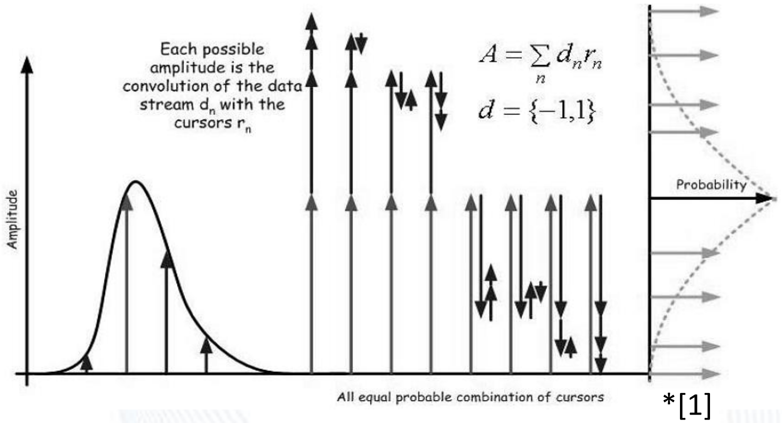
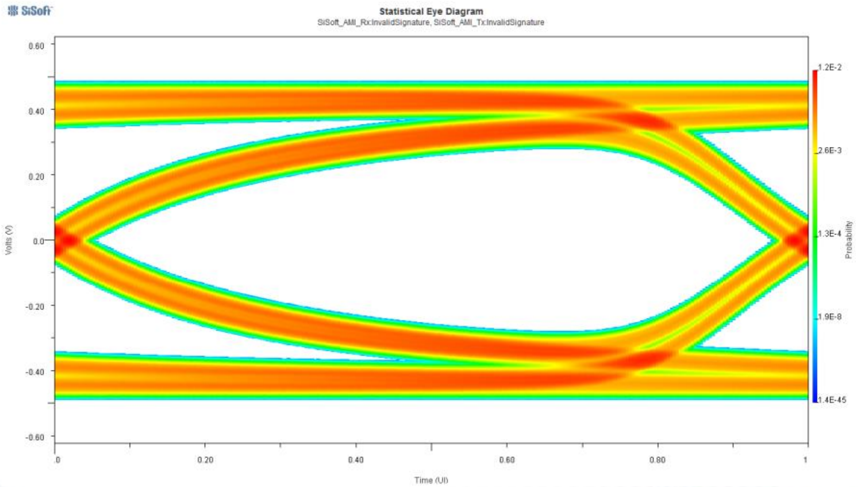
Statistical ISI





*[1]



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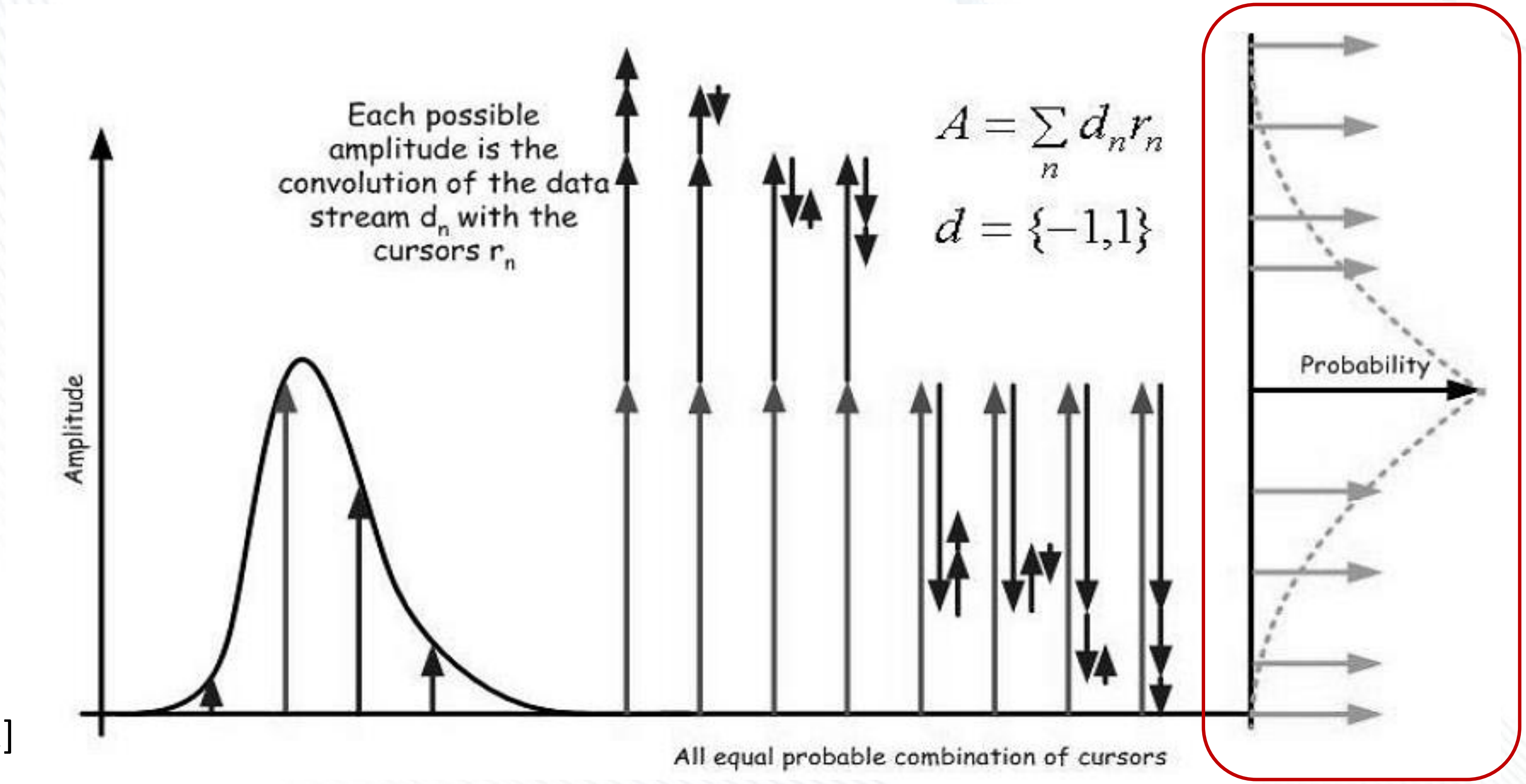
All Possible LTI Combinations Evaluated



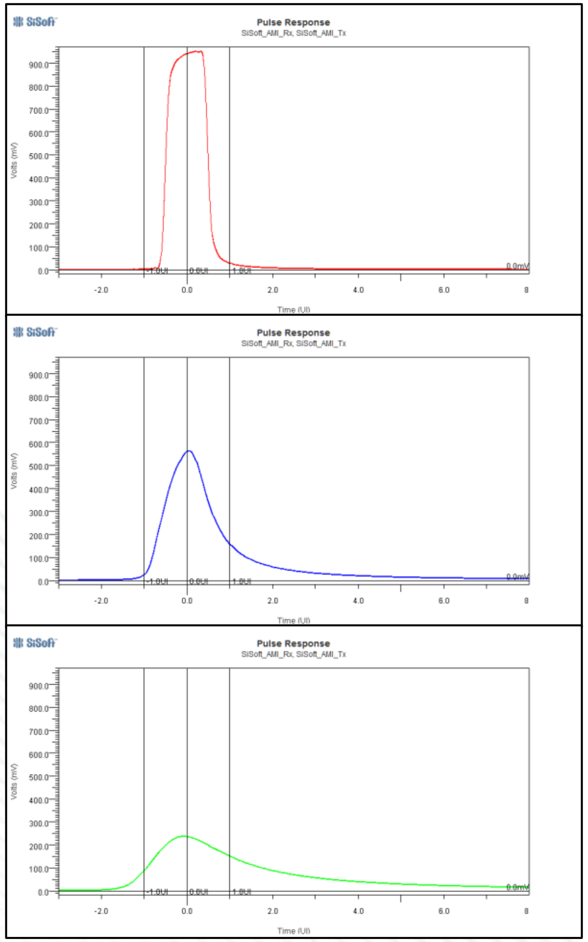
*[1]

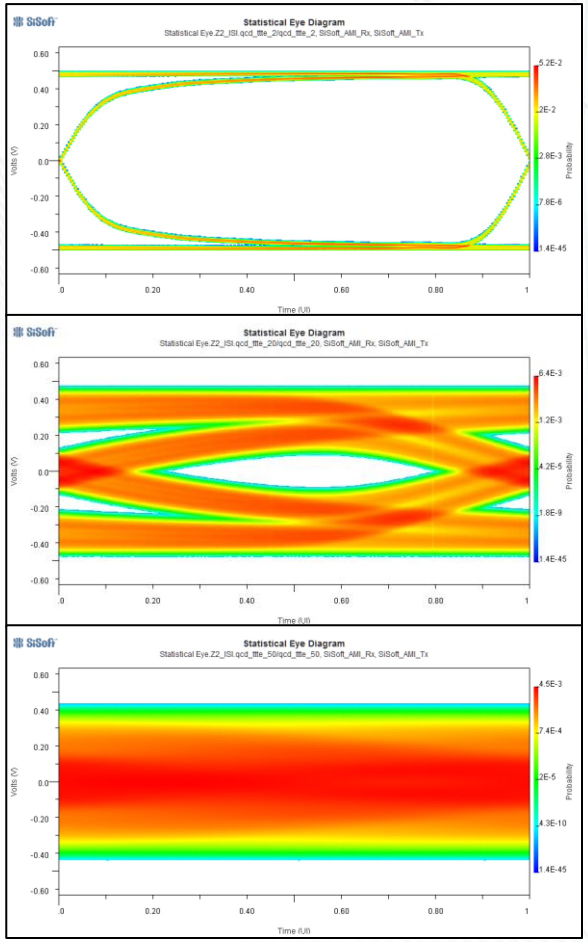
Channels, Pulses and Statistical Eyes

Short channel, Minimal ISI

Medium channel, Moderate ISI

Long channel, Extreme ISI





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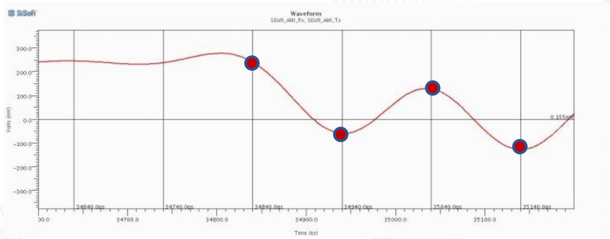
Accounting for All ISI Scenarios

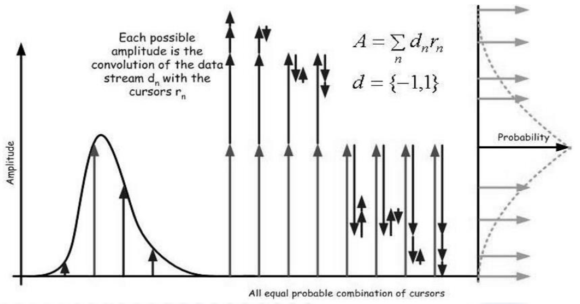
- A 28Gbps link may have a bit every 0.2 inches
- Many bits can be on the channel at once
- With reflections that number is multiplied
- Required impulse response may be many UI in length
- The bit pattern affects how these interact

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

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 NRZ 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 tested sequentially
  - PRBS helps reduce redundancies
  - Often able to simulate only a fraction of cursor combinations
- Statistical analysis
  - Able to directly calculate 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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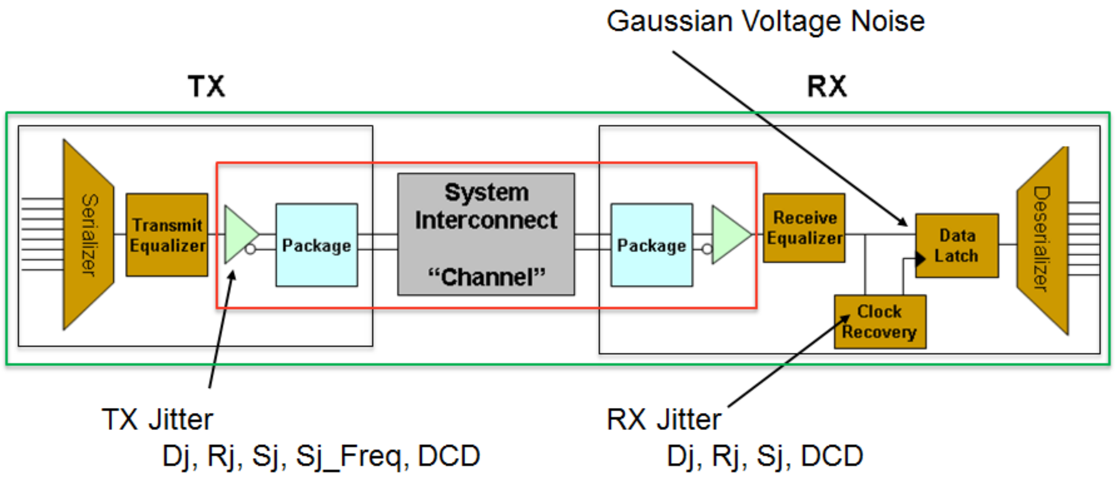
Jitter and Noise Impairments

Jitter and Noise in IBIS-AMI

- IBIS 6.1 provides multiple TX & RX impairments
- TX jitter directly modulates the TX output
  - Simulators jitter the stimulus 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**



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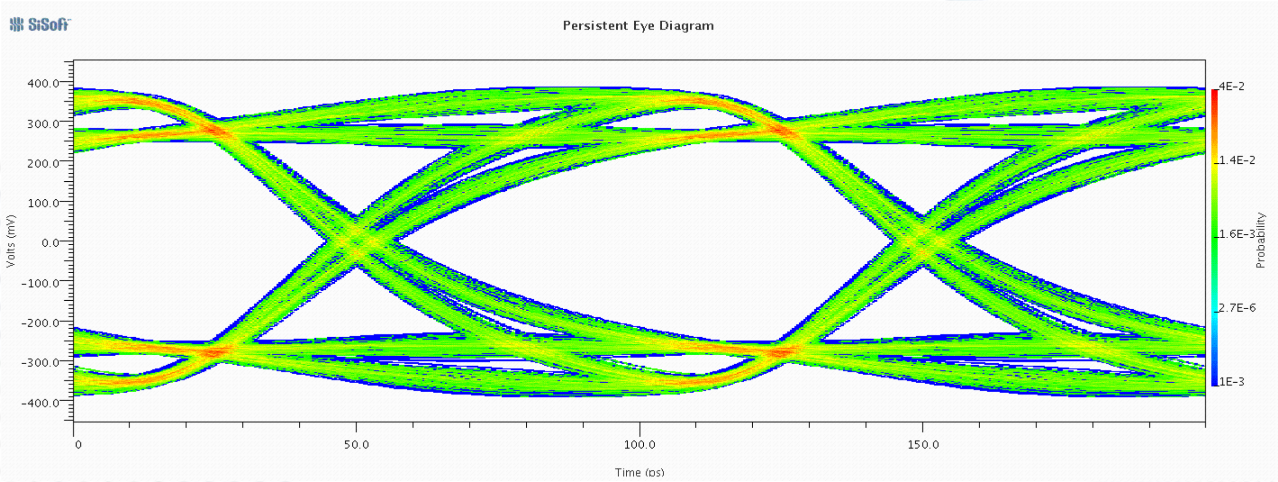
Time Domain Eyes With and Without Tx Jitter

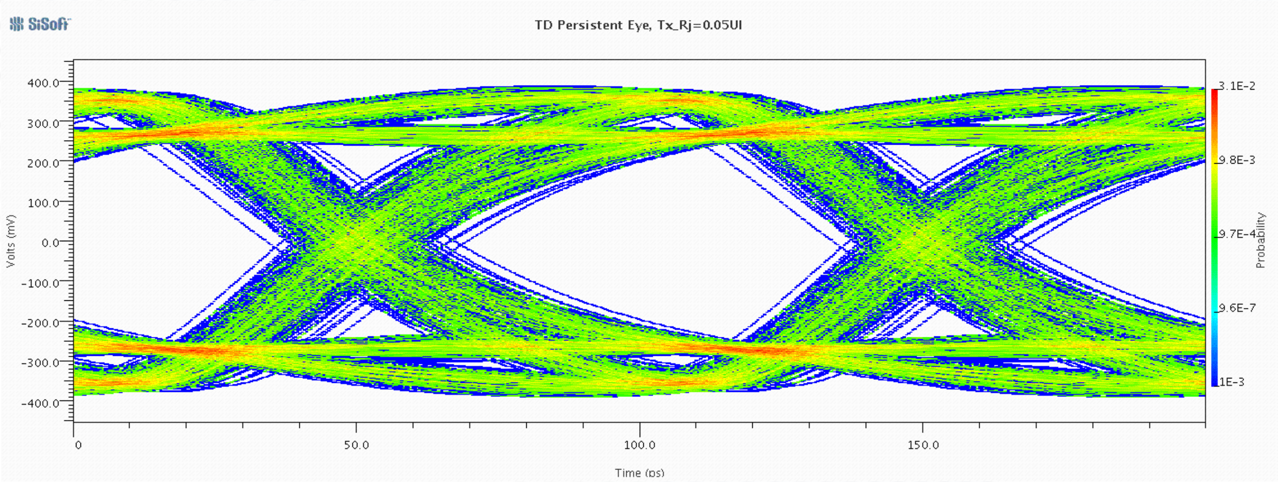
Random Jitter (Tx_Rj) = 0



1e-3

Only Impairment is Inter-Symbol Interference (ISI)

Tx_Rj = 0.05UI



1e-3

ISI + Jitter

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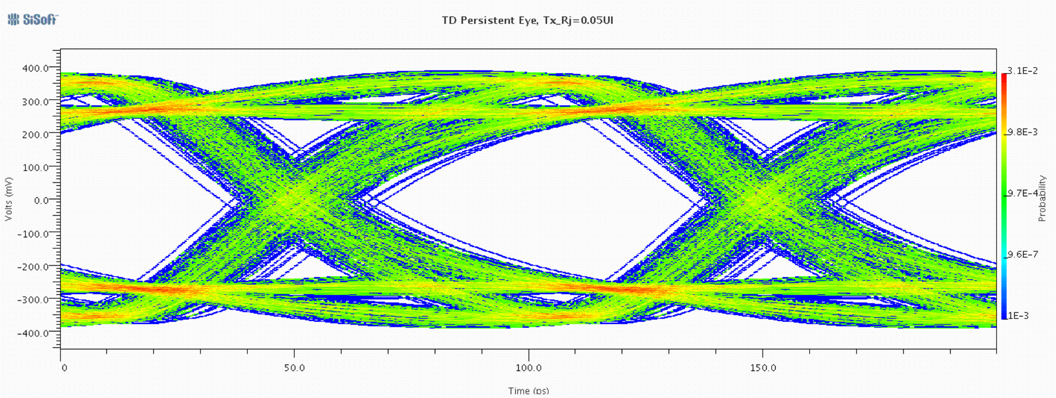
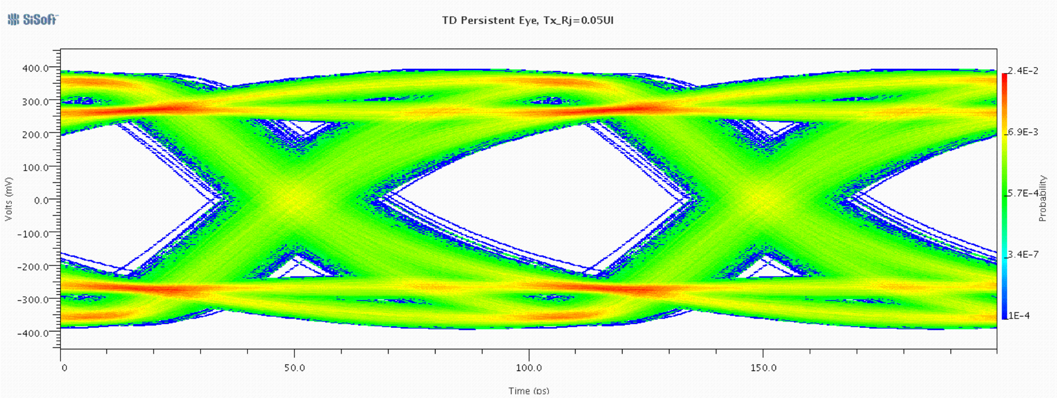
Time Domain: How Many Bits to Simulate?

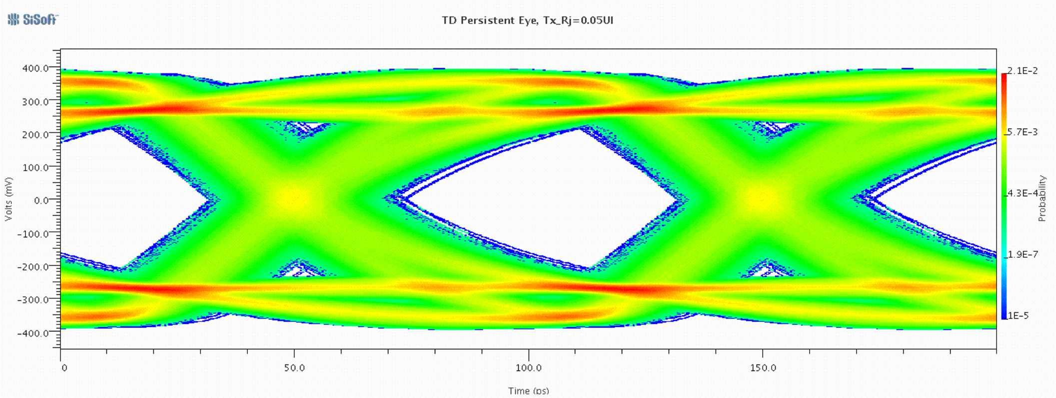
1,000 UI



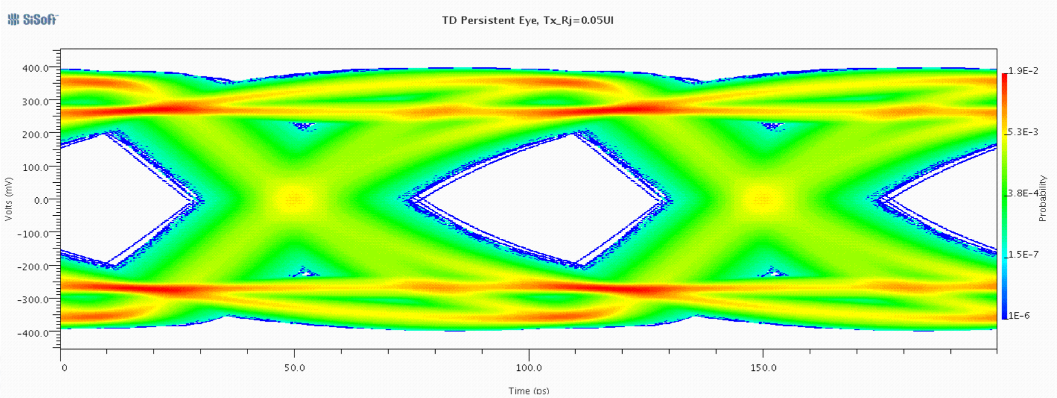
10,000 UI



100,000 UI



1,000,000 UI



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

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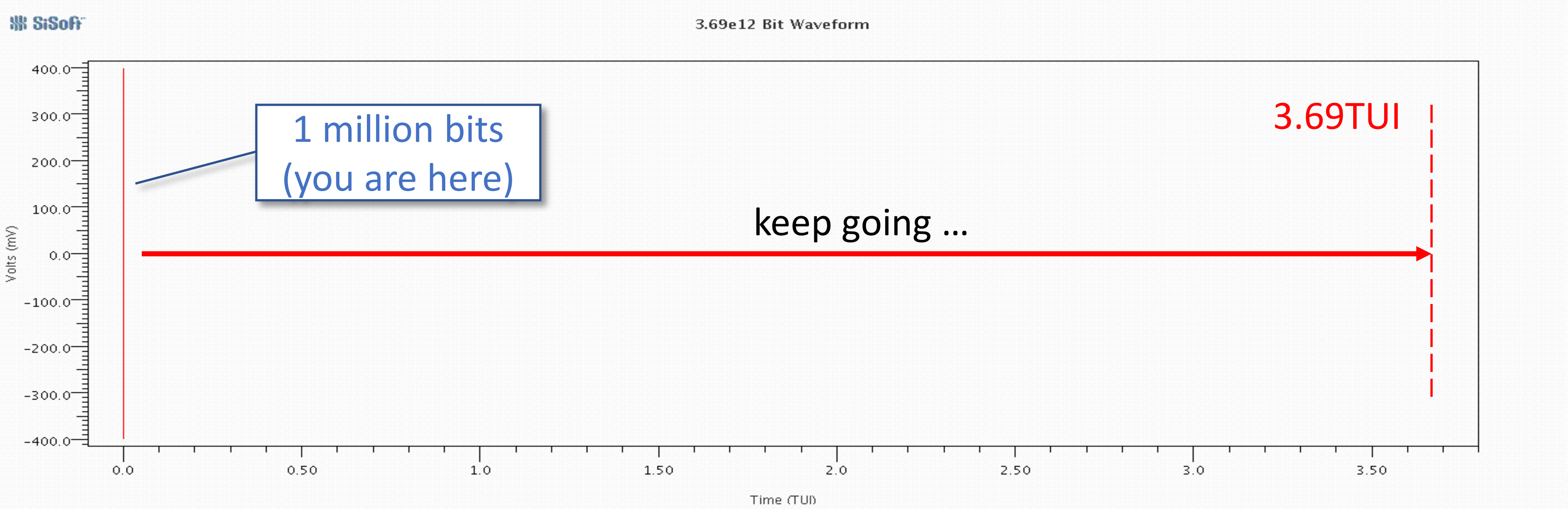
How Many Error-Free Bits for 1e-12 BER?

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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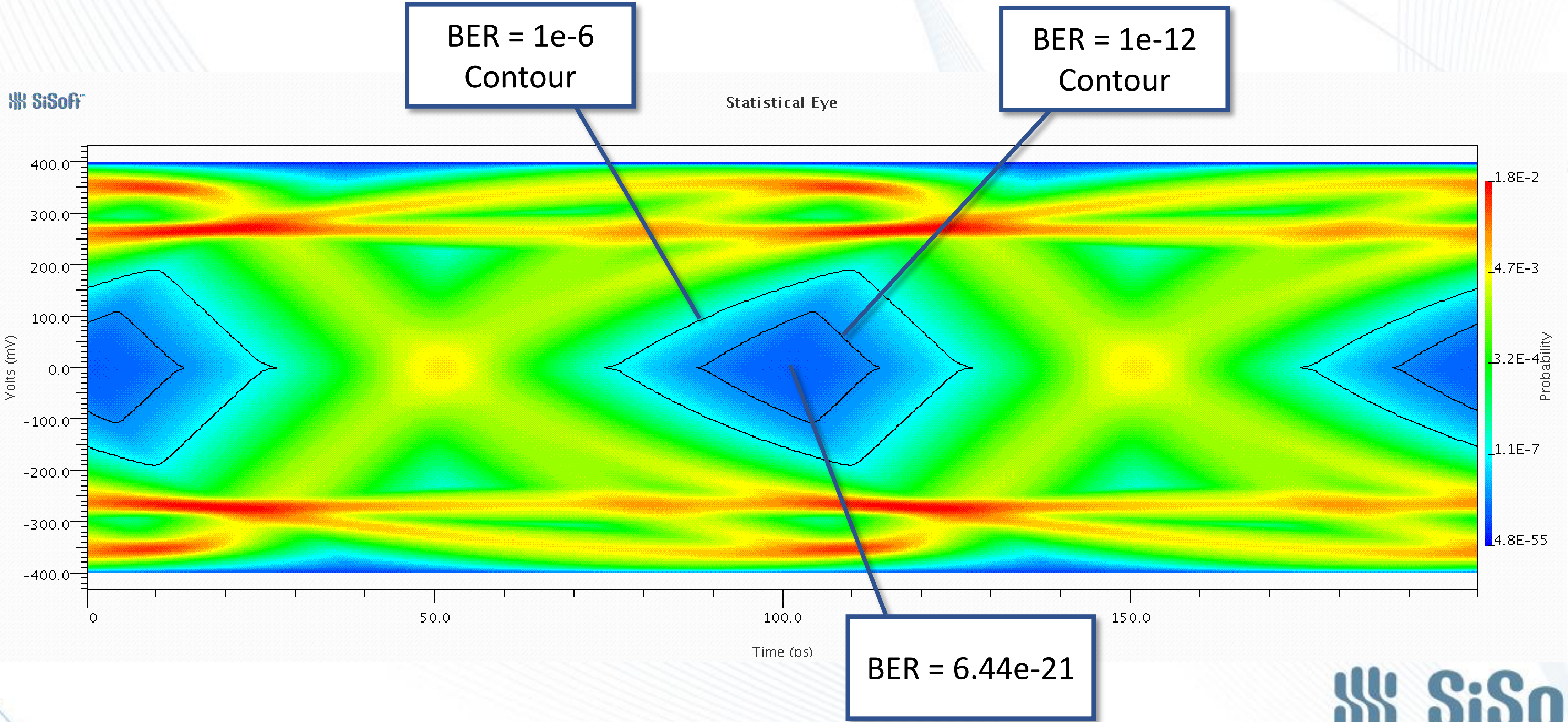
Statistical Eye With ISI and Jitter



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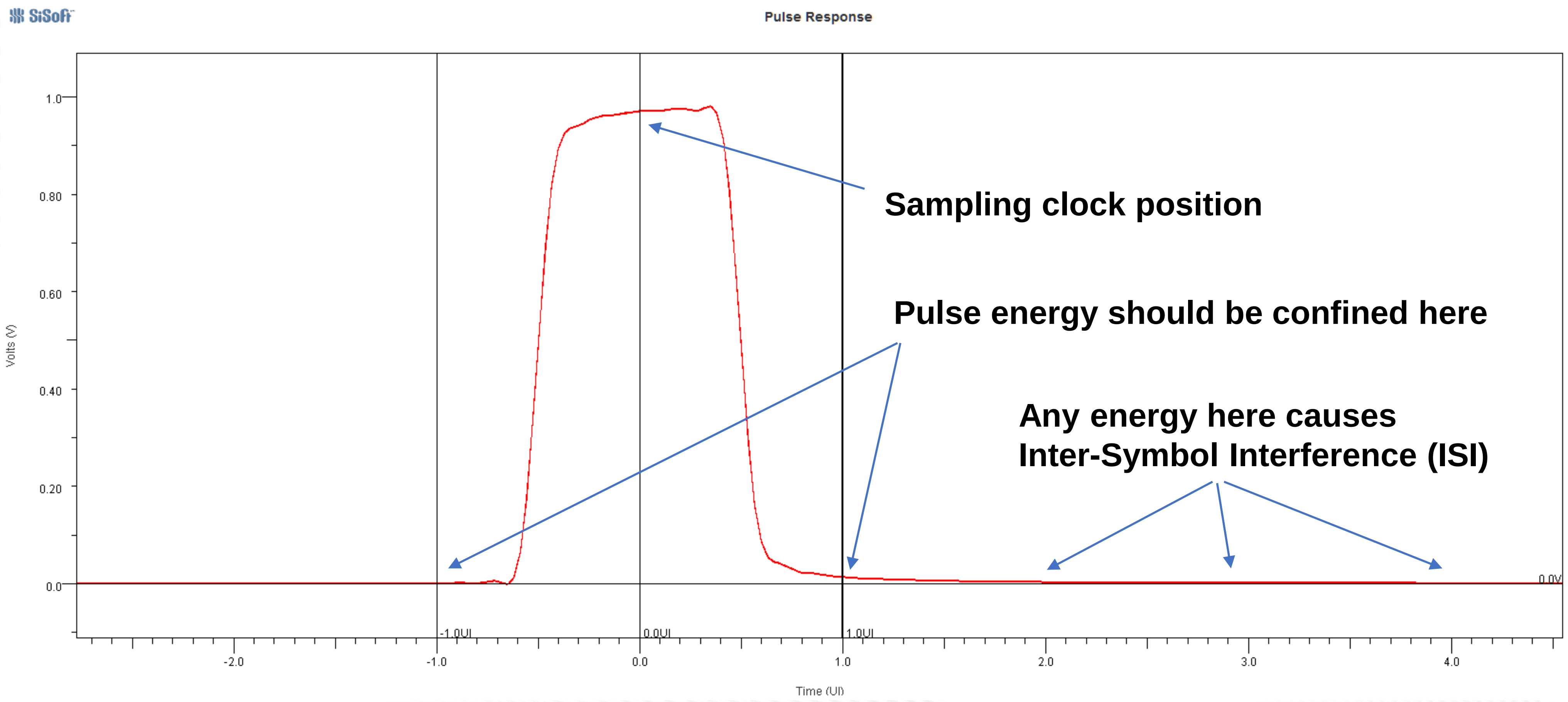
Tx Corrective Measures

Desired Pulse Response for Low ISI



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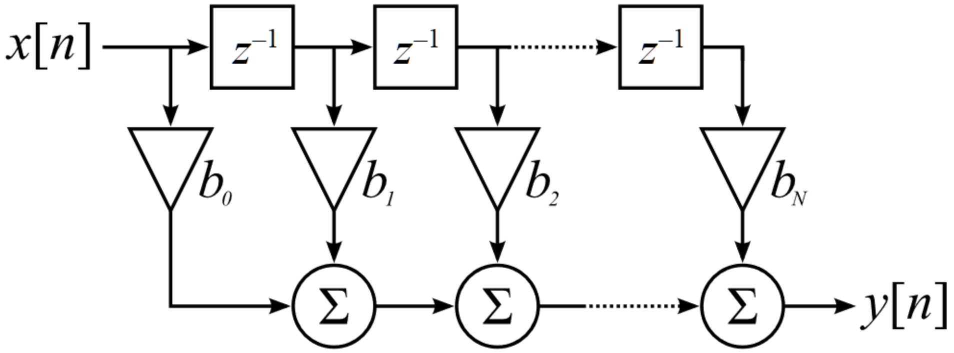
Tx Feed-Forward Equalization (FFE)



- 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

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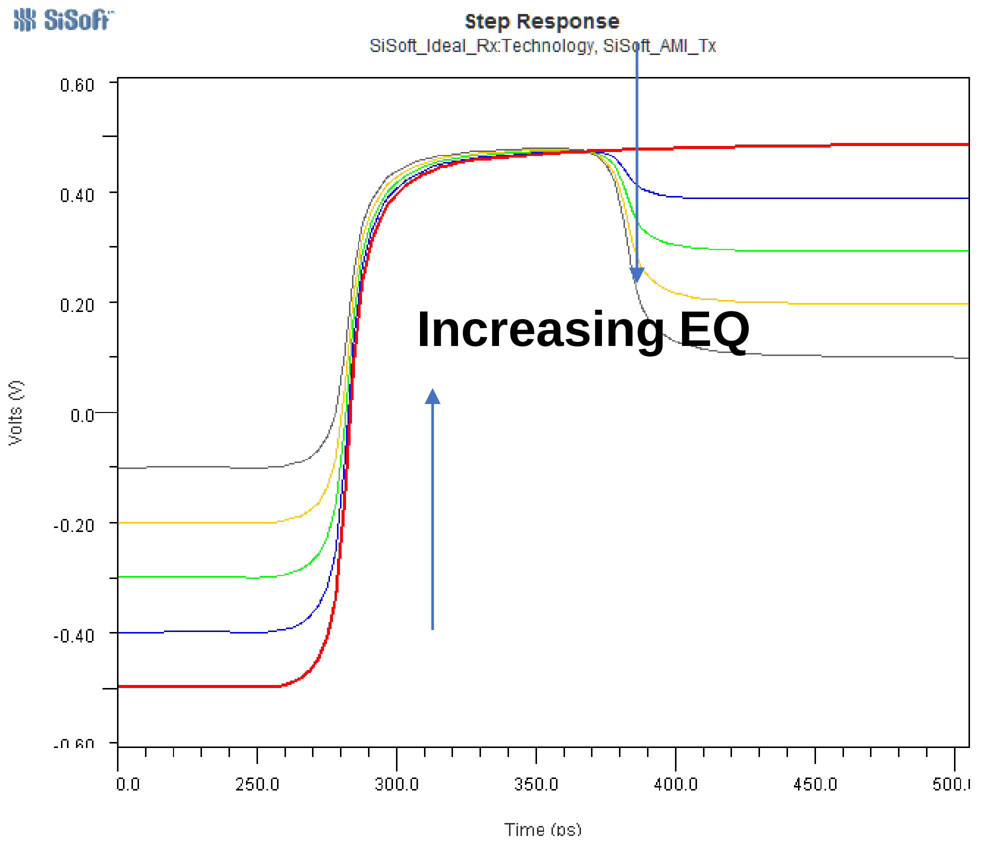
TX FFE Equalization (1st post-cursor)

- 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



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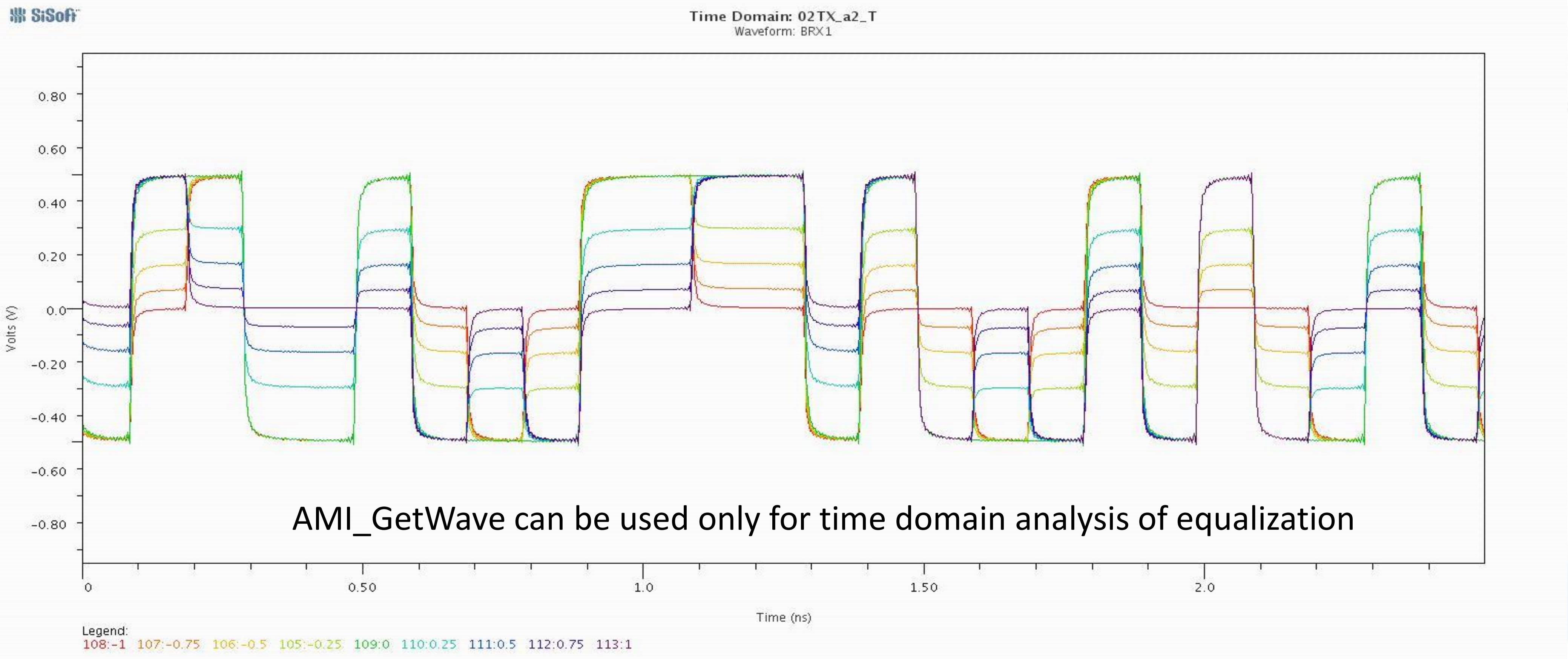
AMI_GetWave Models Can Process Equalization Directly in Time Domain



AMI_GetWave can be used only for time domain analysis of equalization

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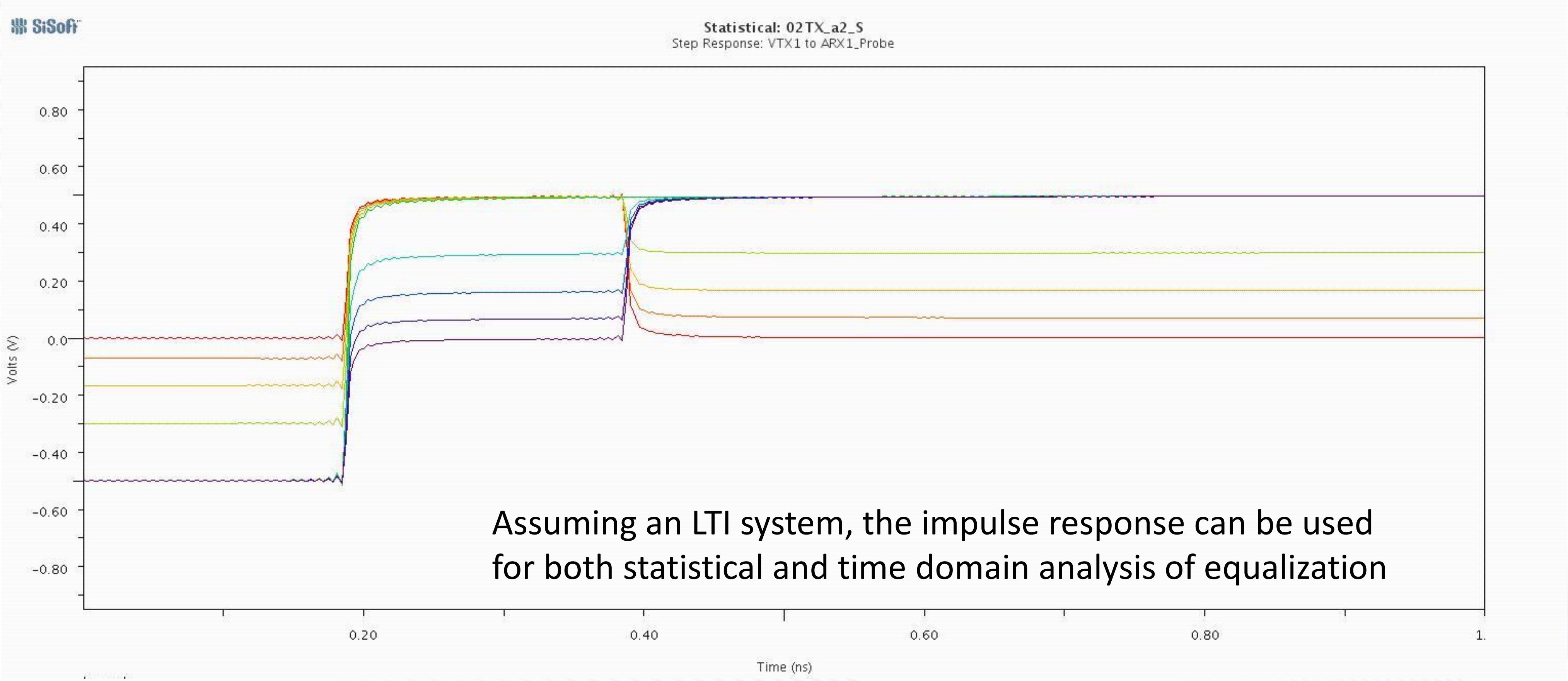
AMI_Init Can Return Impulse Response for Equalization



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

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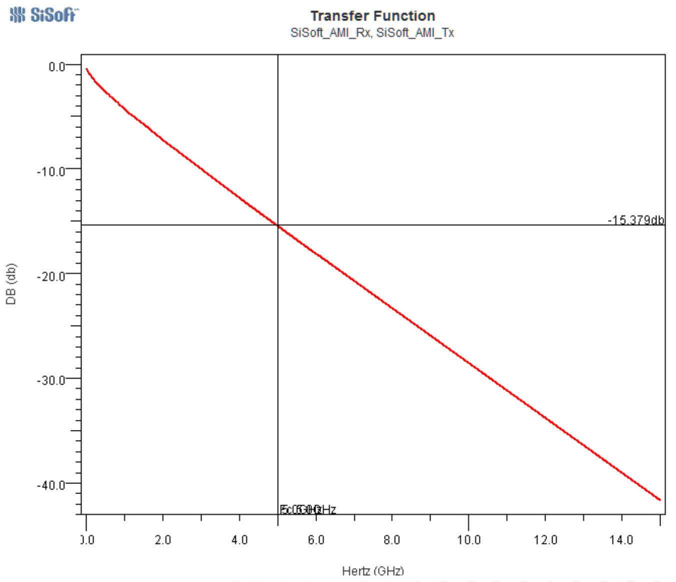
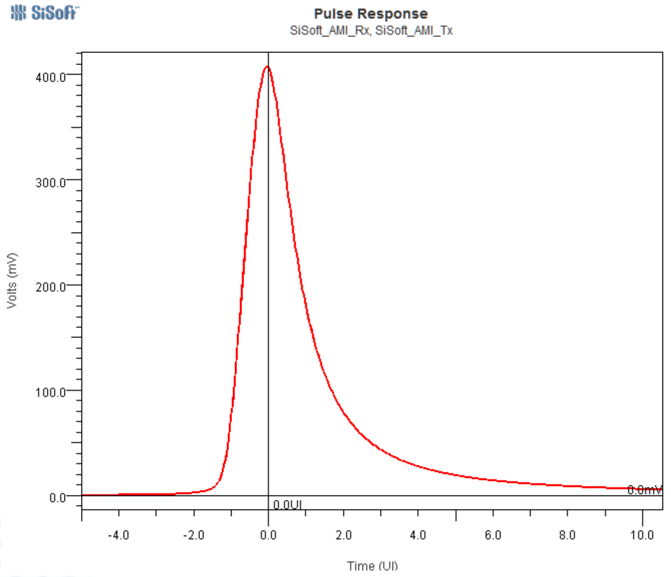
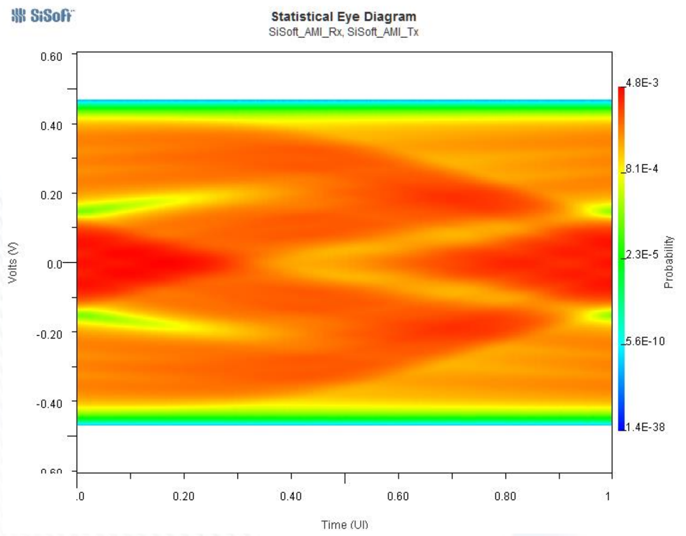
EQ Example: 20 inch channel, 10 Gb/s



15.3 dB loss



12+ bits of ISI



No EQ = No eye

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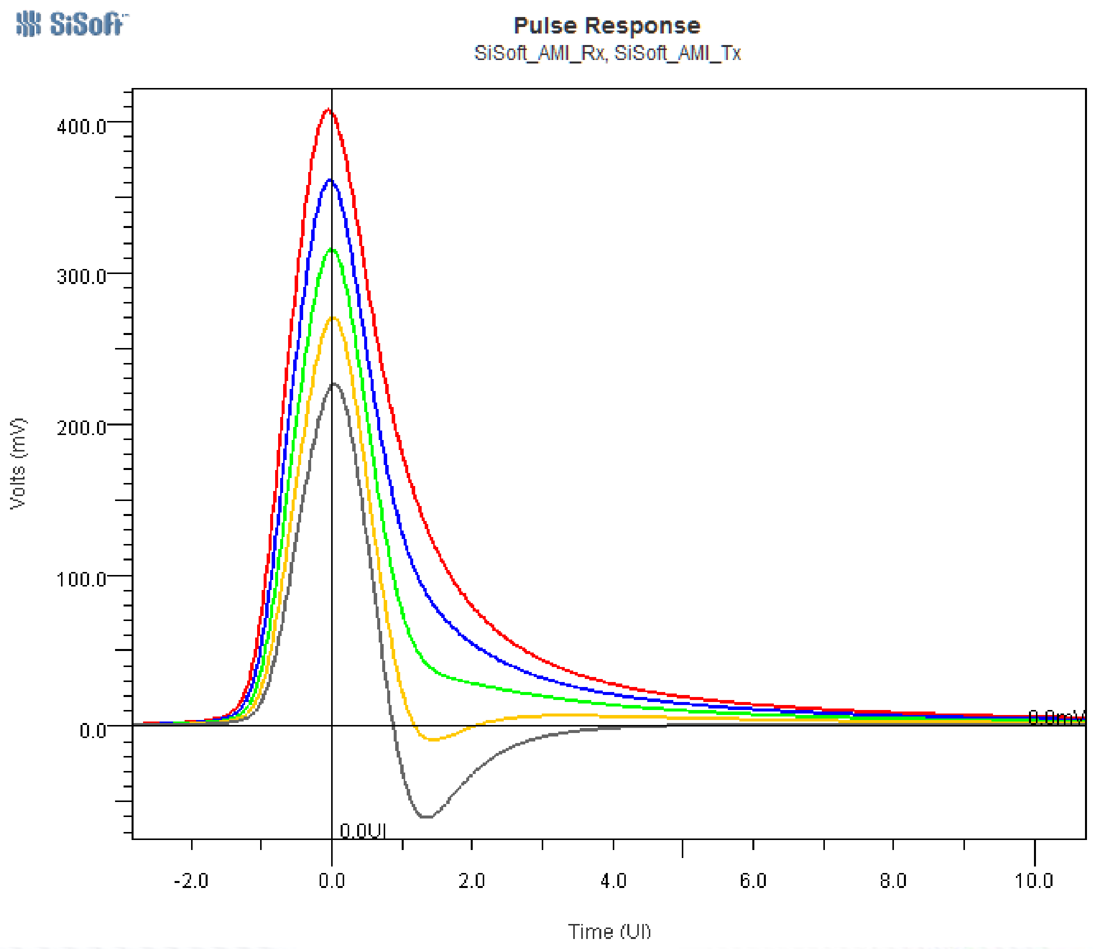
Sweeping the 1st Post-cursor Pulse Response

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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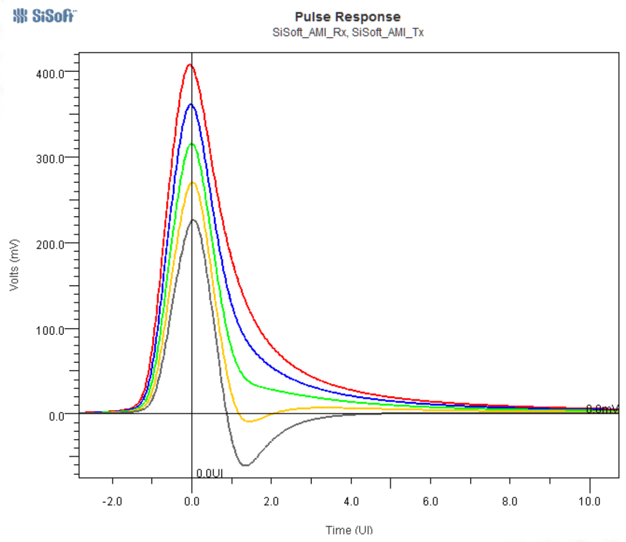
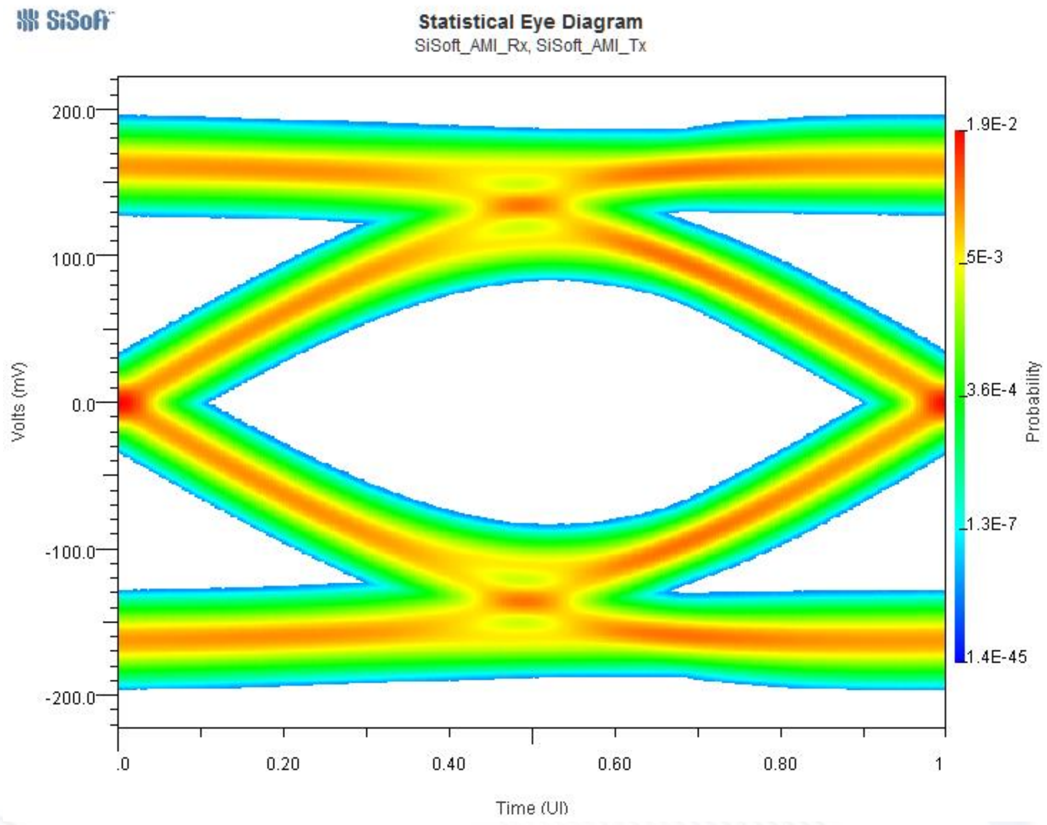
Using Pulse Responses to Find TX Equalization

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





Full Time Domain analysis not required

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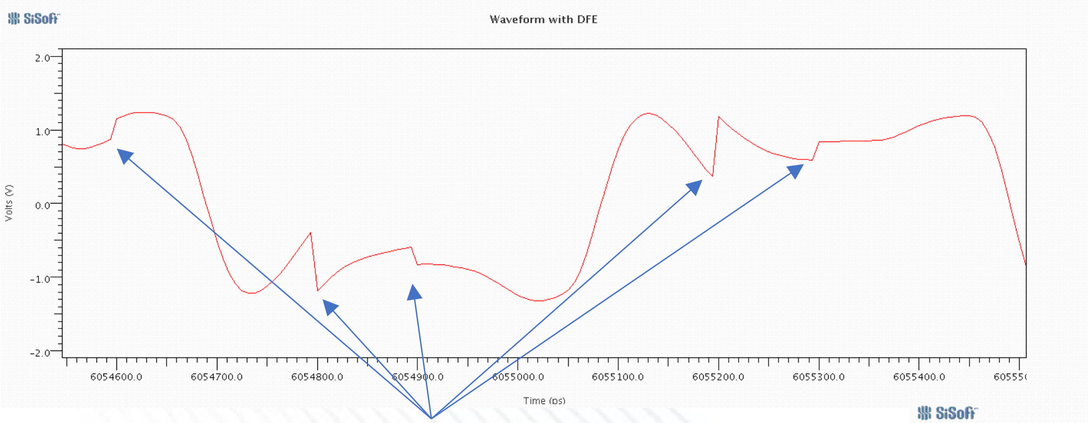
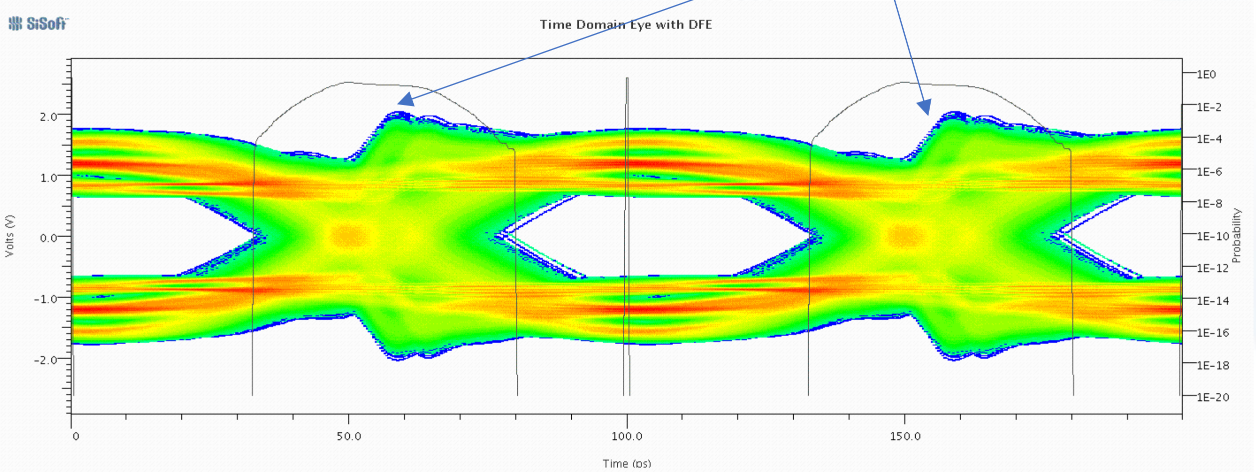
AMI_GetWave Can Also Model Time-Variant Effects



RX Decision Feedback Equalizer (DFE) taps

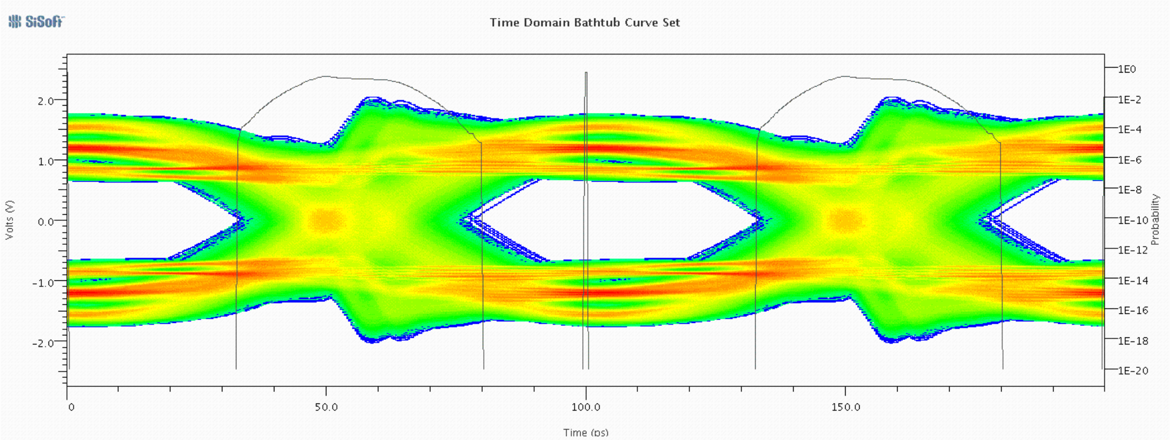
RX DFE action visible in eye diagram

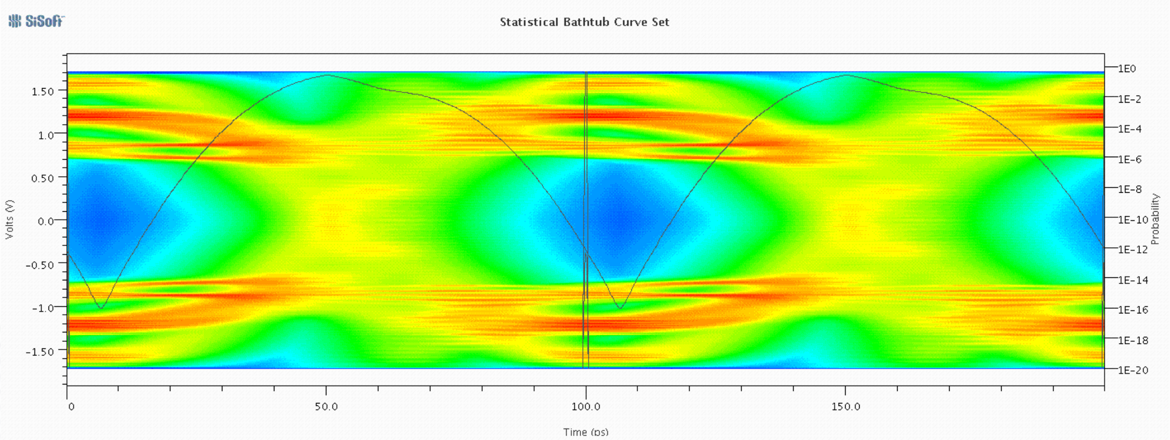


- Adaptive corrections
  - DFE
  - CTLE
  - AGC
- Non-Linear Impairments
  - Saturation

Using Both Time Domain and Statistical Analysis

- No single analysis method models all impairments and all corrective measures well enough
- Many helpful techniques, eg.:
  - Statistical extrapolation of time domain
  - Get adapted settings from time domain and apply to statistical (can reduce Ignore_Bits)
  - Approximate adapted DFE in RX AMI_Init





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Conclusions

- IBIS-AMI time domain simulation with AMI_GetWave can precisely 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 it can not precisely model time-variant effects such as DFE and saturation.
- It is good practice to use both analysis methods.

Thank You

- Much content copied from:
  - *Pragmatic Signal Integrity Boot Camp*
    - Donald Telian, SiGuys
    - Michael Steinberger, SiSoft
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