Bridging the Measurement and Simulation Gap

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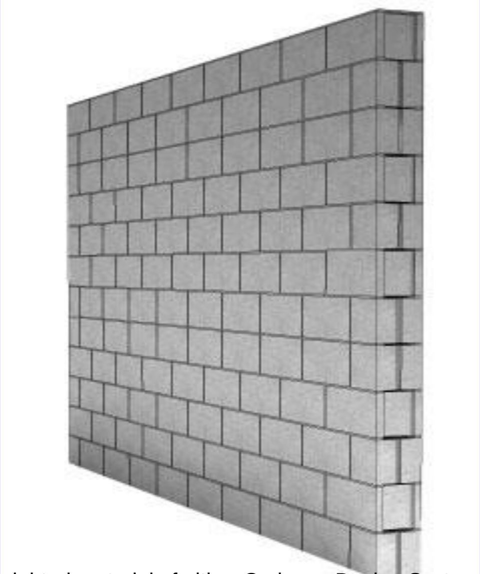
Agenda

- Synergy between simulation and lab based measurements
- IBIS-AMI overview
- Simulation and measurement correlation results
- Impact of channel on jitter and noise measurements
- Summary

Simulation vs. Measurement

- Traditionally two separate worlds
  - ✓ Simulate from the office and measure in the lab
- Today measurement “probe points” are not accessible
  - ✓ Equalization takes place inside the chip for multi-gigabit devices
  - ✓ ***Measurement equipment must simulate*** the equalization to show if the data can be recovered
- Does it make sense to be simulating using different techniques?
  - ✓ NO!

Office



Lab

Considerations for Correlation

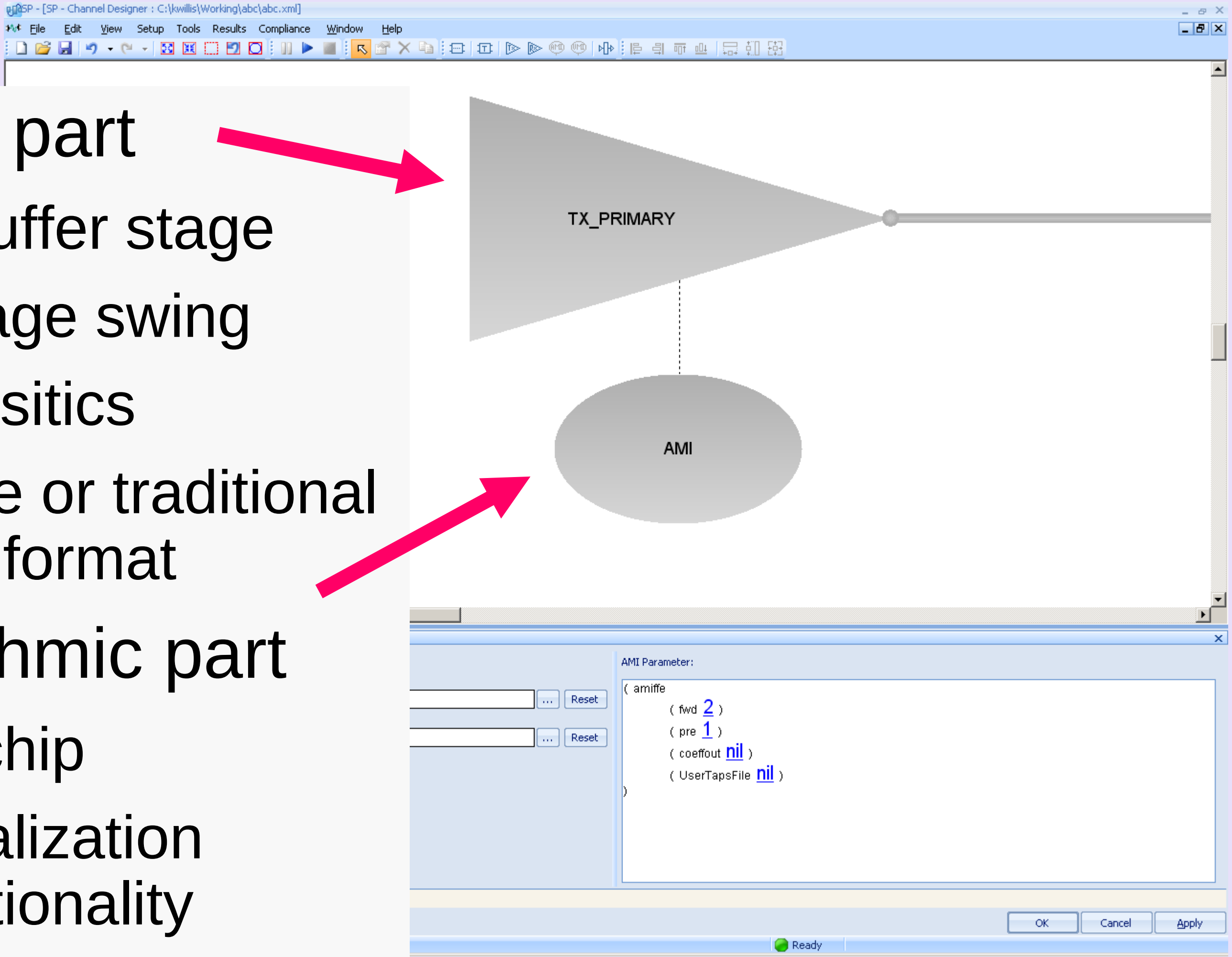
- Lab measurements have artifacts not typically present in simulation
  - ✓ Cables and connectors
  - ✓ Test equipment – scopes, probes
- Simulation must model these or they must be removed from measurements
  - ✓ Models for simulation available from test vendor or can be measured directly
- Receiver models can impact results
  - ✓ IBIS-AMI provides a standard method for RX Equalization

AMI > Algorithmic Modeling Interface

- Extension made to IBIS in 2007
- Enables software-based, algorithmic models to work together with traditional IBIS circuit models
- Enables SerDes equalization algorithms to be modeled and used during channel simulation
- IBIS-AMI enables plug-and-play simulation compatibility between SerDes models from different suppliers, in a standard commercial EDA format

IBIS-AMI Model Sub-Components

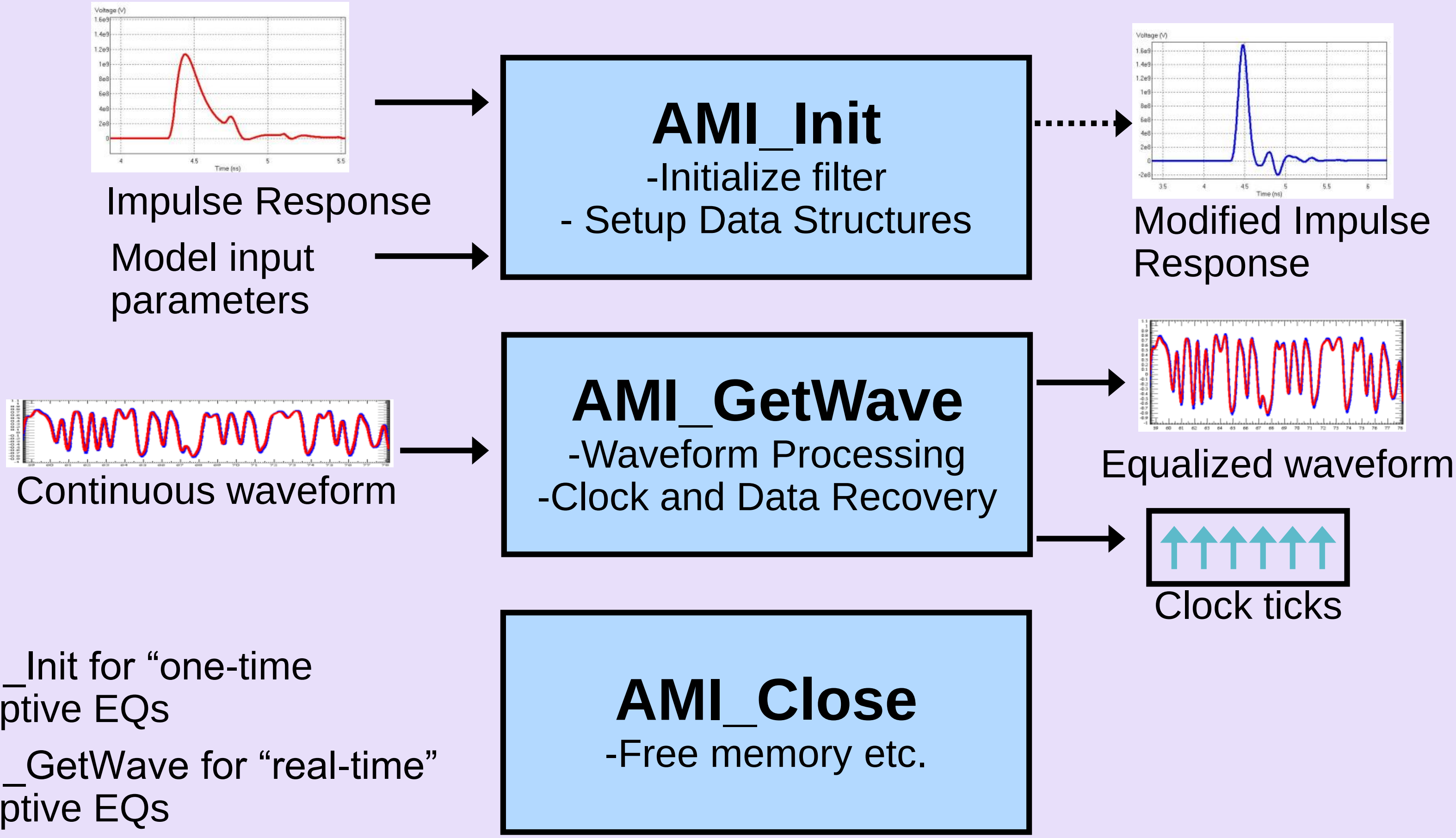
- Circuit part
  - ✓ IO buffer stage
  - ✓ Voltage swing
  - ✓ Parasitics
  - ✓ Spice or traditional IBIS format
- Algorithmic part
  - ✓ On-chip
  - ✓ Equalization functionality
  - ✓ DLL + AMI file



AMI Parameter:

```
( amiffe
        ( fwd 2 )
        ( pre 1 )
        ( coeffout nil )
        ( UserTapsFile nil )
)
```

APIs in IBIS-AMI Modeling



Impulse Response

Model input parameters

AMI_Init

-Initialize filter

- Setup Data Structures

Modified Impulse Response

Continuous waveform

AMI_GetWave

-Waveform Processing

-Clock and Data Recovery

Equalized waveform

Clock ticks

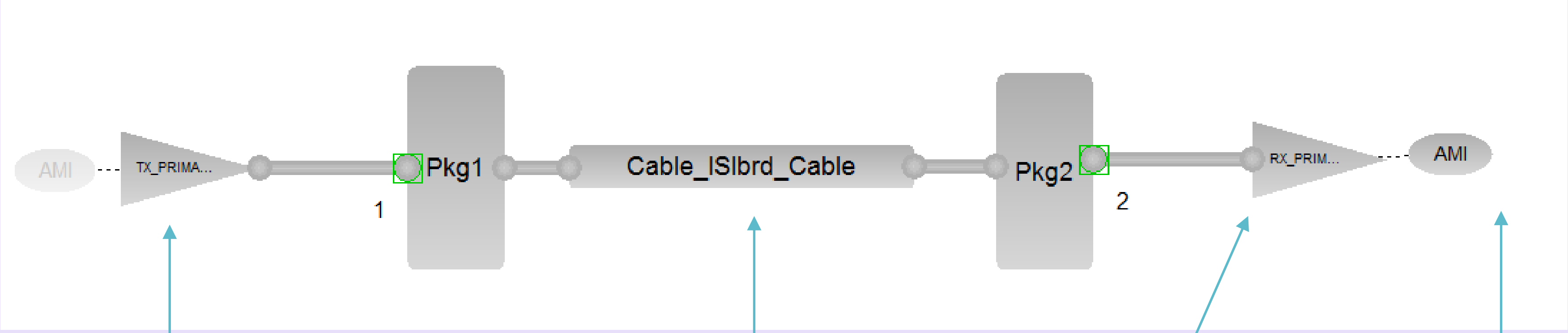
AMI_Close

-Free memory etc.

- AMI_Init for “one-time adaptive EQs
- AMI_GetWave for “real-time” adaptive EQs

System Topology

Simulation



BERT

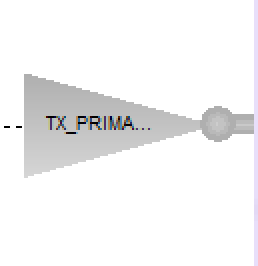
Channel

Scope

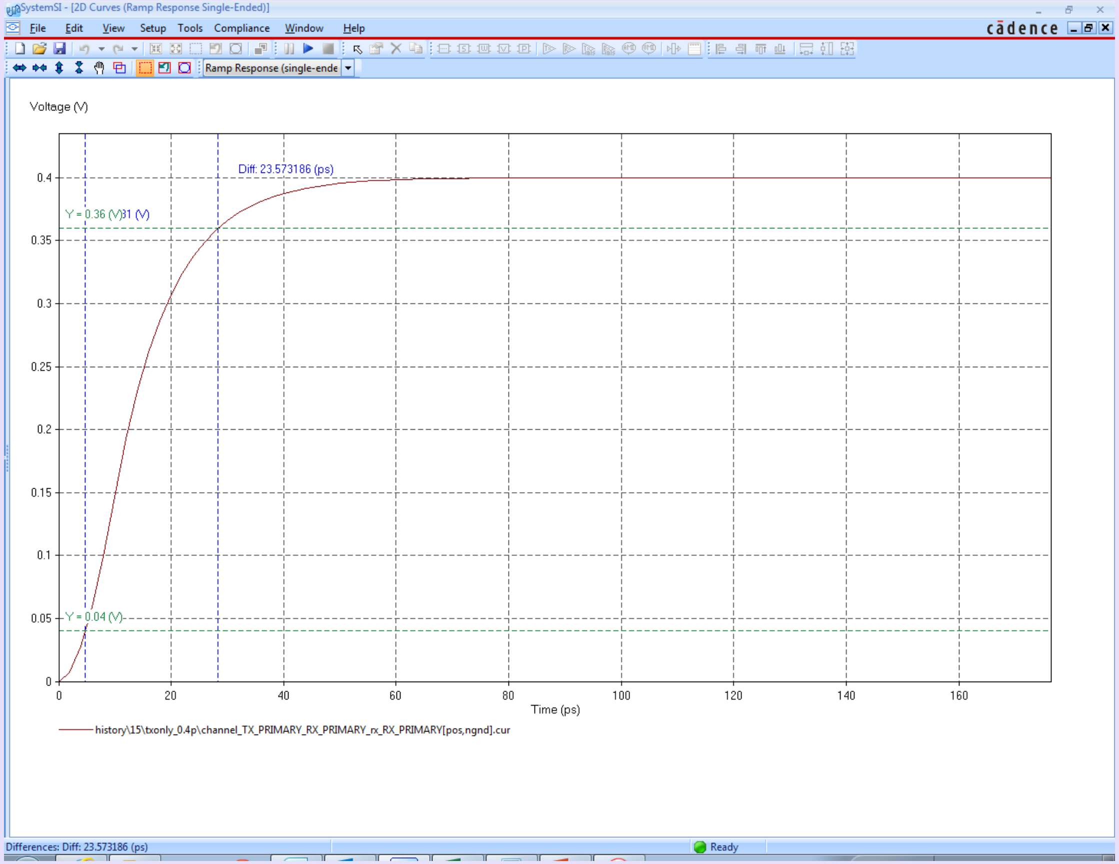
AMI Model

Measurement

Transmitter-BERT Output



- Simulation TX modeled to match measurement TX
- 50 ohm output impedance
- Tune output capacitance to match 23ps rise time of BERT, 10% - 90%
- 800mV diff peak-to-peak
- 16Gbps data rate
- No TX EQ
- Common PCIE compliance pattern for BERT and sim

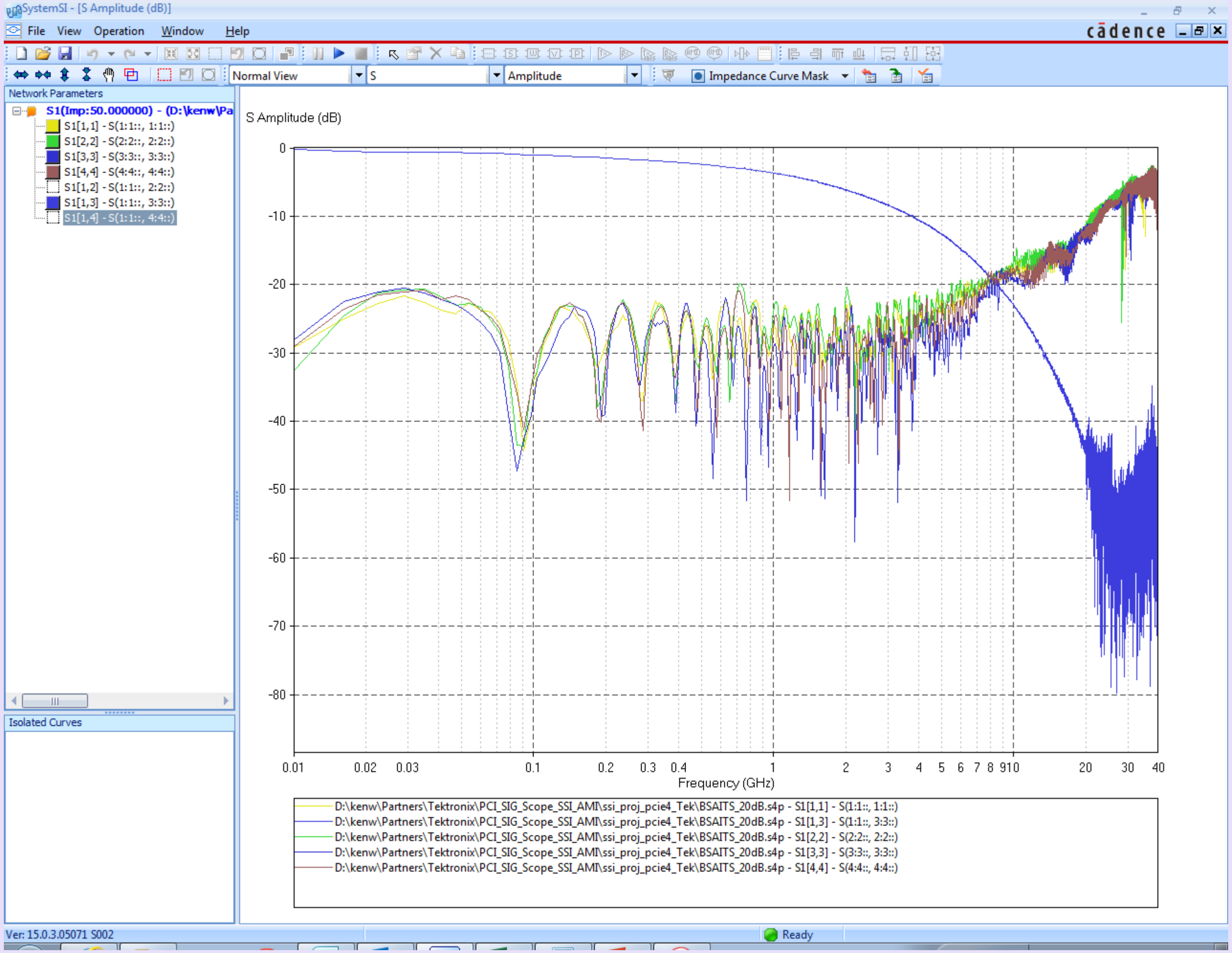


history\15\txonly_0.4p\channel_TX_PRIMARY_RX_PRIMARY_rx_RX_PRIMARY[pos,ngnd].cur

Differences: Diff: 23.573186 (ps)

Channel – Measured S-Parameter

- Cable + ISI board + cable
- 20dB insertion loss at about 8GHz



S1(Imp:50.000000) - (D:\kenw\Pa
- 🟨 S1[1,1] - S(1:1::, 1:1::)
- 🟩 S1[2,2] - S(2:2::, 2:2::)
- 🟦 S1[3,3] - S(3:3::, 3:3::)
- 🟫 S1[4,4] - S(4:4::, 4:4::)
- ☐ S1[1,2] - S(1:1::, 2:2::)
- 🟦 S1[1,3] - S(1:1::, 3:3::)
- ☐ S1[1,4] - S(1:1::, 4:4::)

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D:\kenw\Partners\Tektronix\PCI_SIG_Scope_SSI_AMI\ssi_proj_pcie4_Tek\BSAITS_20dB.s4p - S1[1,3] - S(1:1::, 3:3::)
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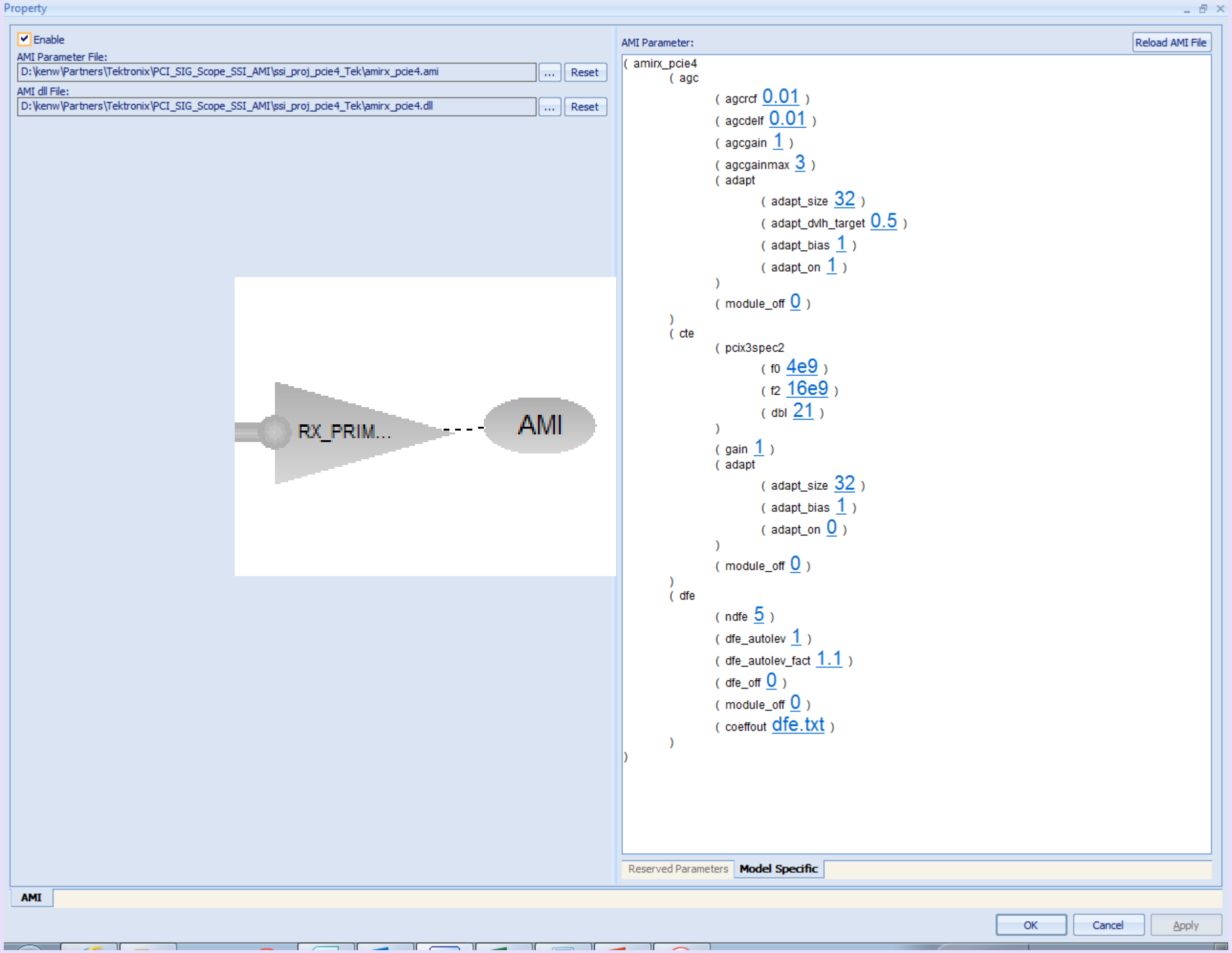
Receiver- Scope Input With Common AMI Model

- 50 ohm input impedance
- Automatic gain control
- CTLE per PCIE spec
- 5 tap DFE



☑ Enable

AMI Parameter File: D:\kenw\Partners\Tektronix\PCI_SIG_Scope_SSI_AMI\ssi_proj_pcie4_Tek\amirx_pcie4.ami

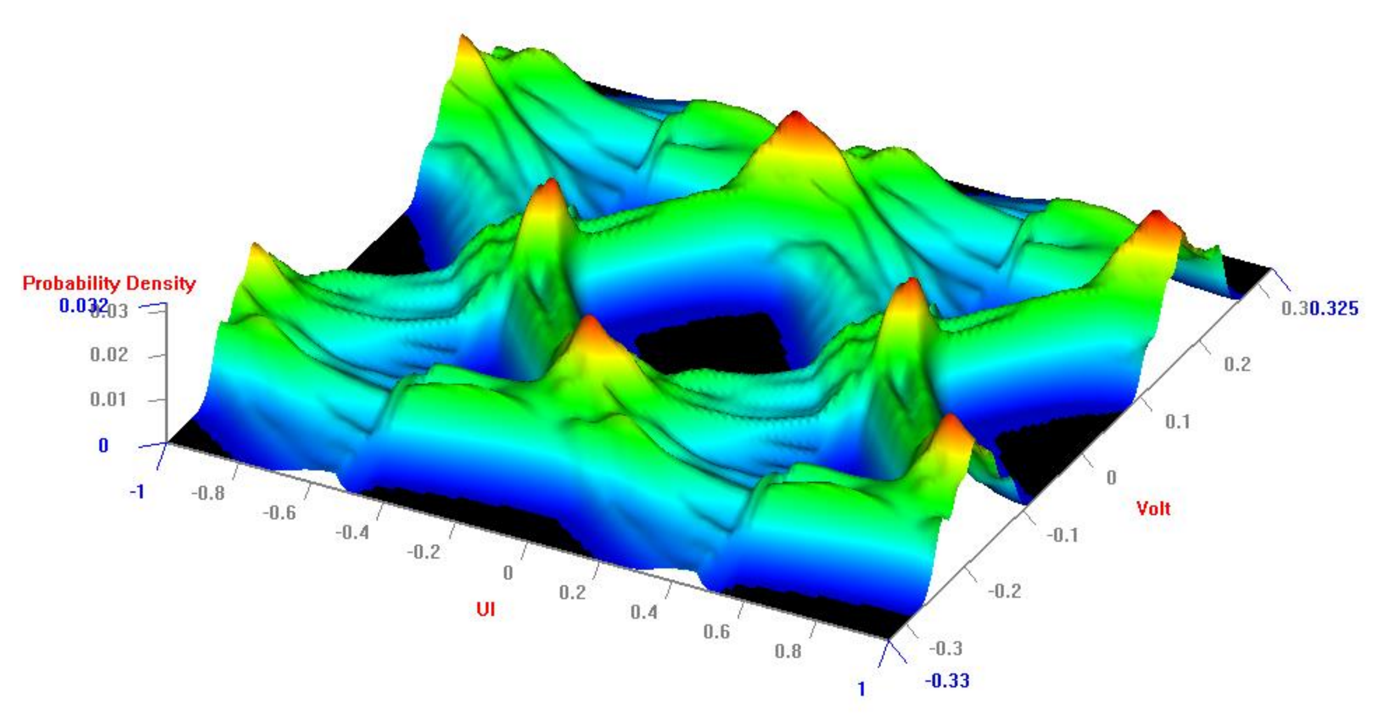
AMI dll File: D:\kenw\Partners\Tektronix\PCI_SIG_Scope_SSI_AMI\ssi_proj_pcie4_Tek\amirx_pcie4.dll

AMI Parameter:

```
( amirx_pcie4
    ( agc
        ( agcrcf 0.01 )
        ( agcdelf 0.01 )
        ( agcgain 1 )
        ( agcgainmax 3 )
        ( adapt
            ( adapt_size 32 )
            ( adapt_dvlh_target 0.5 )
            ( adapt_bias 1 )
            ( adapt_on 1 )
        )
        ( module_off 0 )
    )
    ( cte
        ( pcix3spec2
            ( f0 4e9 )
            ( f2 16e9 )
            ( dbl 21 )
        )
        ( gain 1 )
        ( adapt
            ( adapt_size 32 )
            ( adapt_bias 1 )
            ( adapt_on 0 )
        )
        ( module_off 0 )
    )
    ( dfe
        ( ndfe 5 )
        ( dfe_autolev 1 )
        ( dfe_autolev_fact 1.1 )
        ( dfe_off 0 )
        ( module_off 0 )
        ( coeffout dfe.txt )
    )
)
```

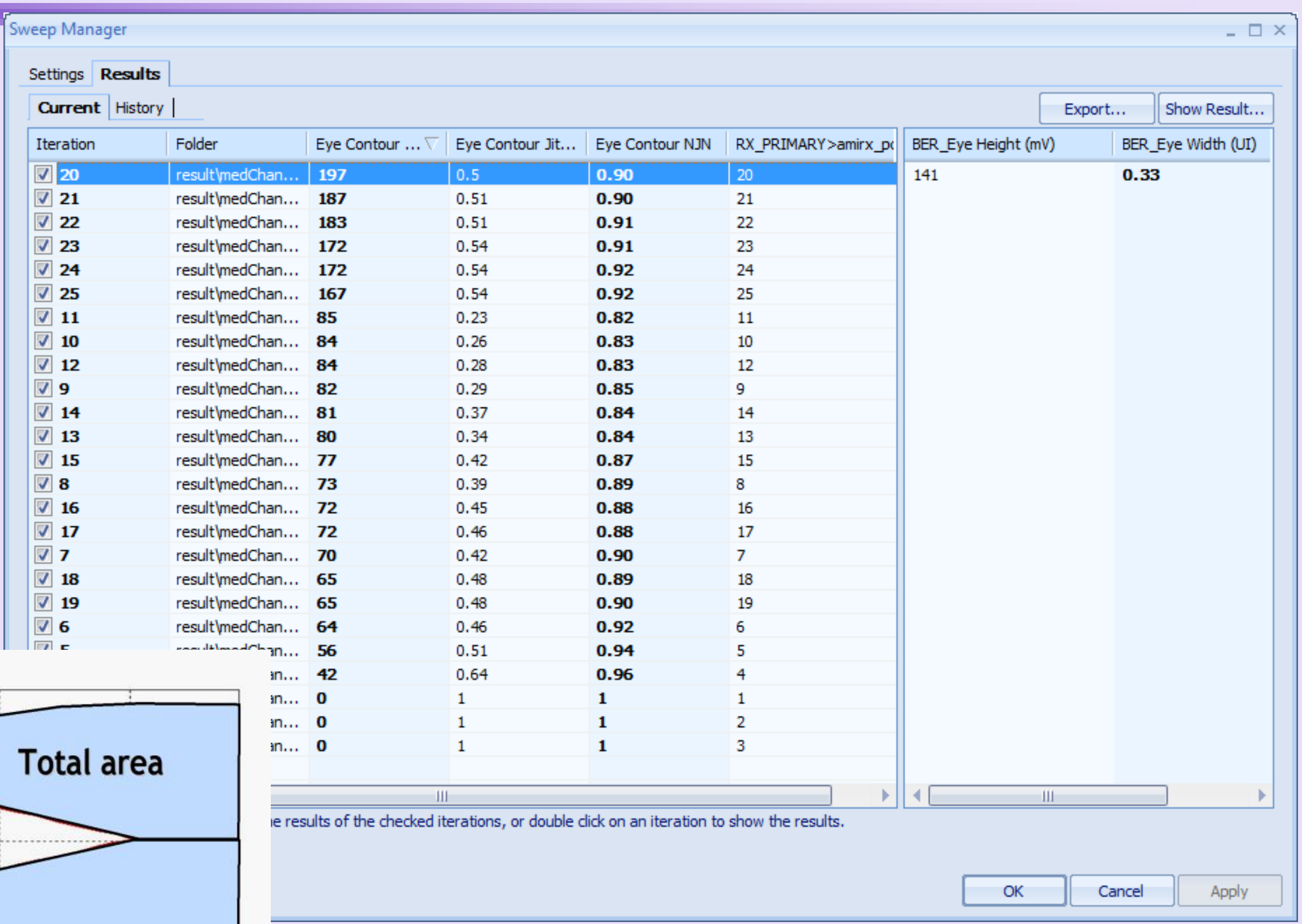
Simulate 800k Bits

- Scope recorded 5M samples at 100G samples/sec with UI of 62.5ps



Swept CTLE Setting to Determine Best One

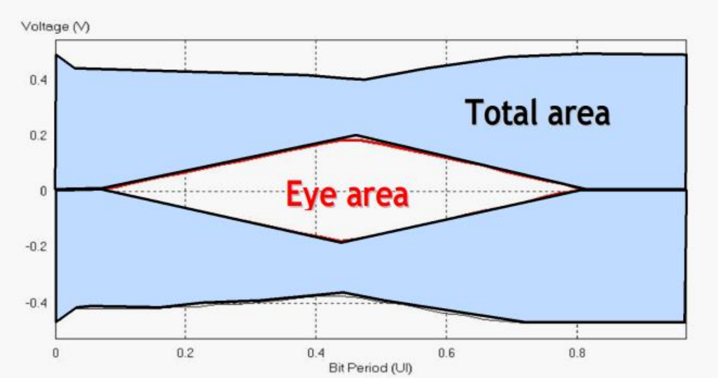
- Sorted by “NJN”
- Selected result with minimum jitter
- Set dbl=21 for sim and measurement



Iteration	Folder	Eye Contour ...	Eye Contour Jit...	Eye Contour NJN	RX_PRIMARY>amirx_pc
☑ 20	result\medChan...	197	0.5	0.90	20
☑ 21	result\medChan...	187	0.51	0.90	21
☑ 22	result\medChan...	183	0.51	0.91	22
☑ 23	result\medChan...	172	0.54	0.91	23
☑ 24	result\medChan...	172	0.54	0.92	24
☑ 25	result\medChan...	167	0.54	0.92	25
☑ 11	result\medChan...	85	0.23	0.82	11
☑ 10	result\medChan...	84	0.26	0.83	10
☑ 12	result\medChan...	84	0.28	0.83	12
☑ 9	result\medChan...	82	0.29	0.85	9
☑ 14	result\medChan...	81	0.37	0.84	14
☑ 13	result\medChan...	80	0.34	0.84	13
☑ 15	result\medChan...	77	0.42	0.87	15
☑ 8	result\medChan...	73	0.39	0.89	8
☑ 16	result\medChan...	72	0.45	0.88	16
☑ 17	result\medChan...	72	0.46	0.88	17
☑ 7	result\medChan...	70	0.42	0.90	7
☑ 18	result\medChan...	65	0.48	0.89	18
☑ 19	result\medChan...	65	0.48	0.90	19
☑ 6	result\medChan...	64	0.46	0.92	6
☑ 5	result\medChan...	56	0.51	0.94	5
	an...	42	0.64	0.96	4
	an...	0	1	1	1
	an...	0	1	1	2
	an...	0	1	1	3

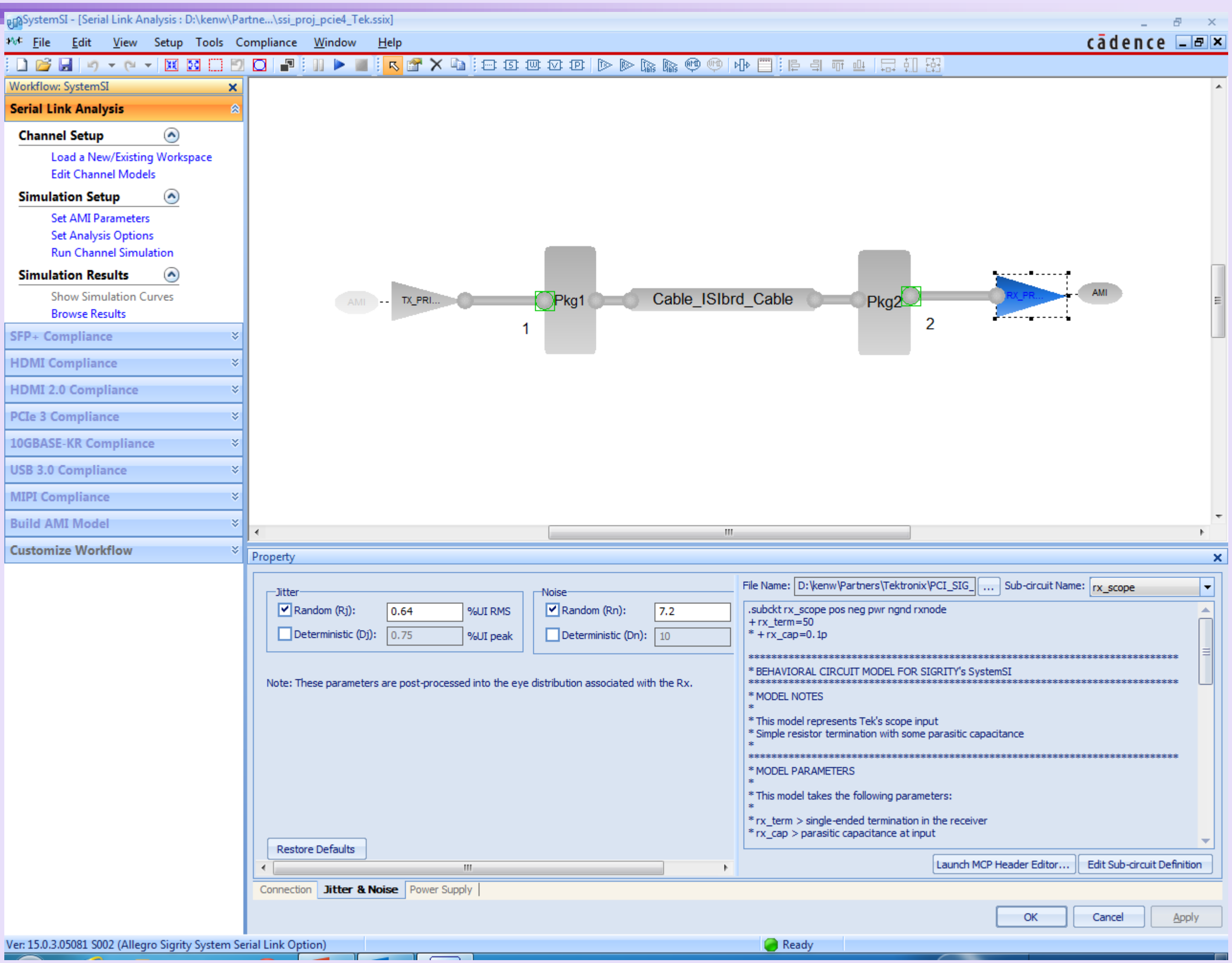
BER_Eye Height (mV)	BER_Eye Width (UI)
141	0.33

e results of the checked iterations, or double click on an iteration to show the results.



Obtain Measured Rj and Rn Values

- Run BERT directly into scope
- Measure Rj and Rn at 0.64%UI and 7.2mV RMS, respectively
- Inject these values into channel simulation



Jitter
- ☑ Random (Rj): 0.64 %UI RMS
- ☐ Deterministic (Dj): 0.75 %UI peak

Noise
- ☑ Random (Rn): 7.2
- ☐ Deterministic (Dn): 10

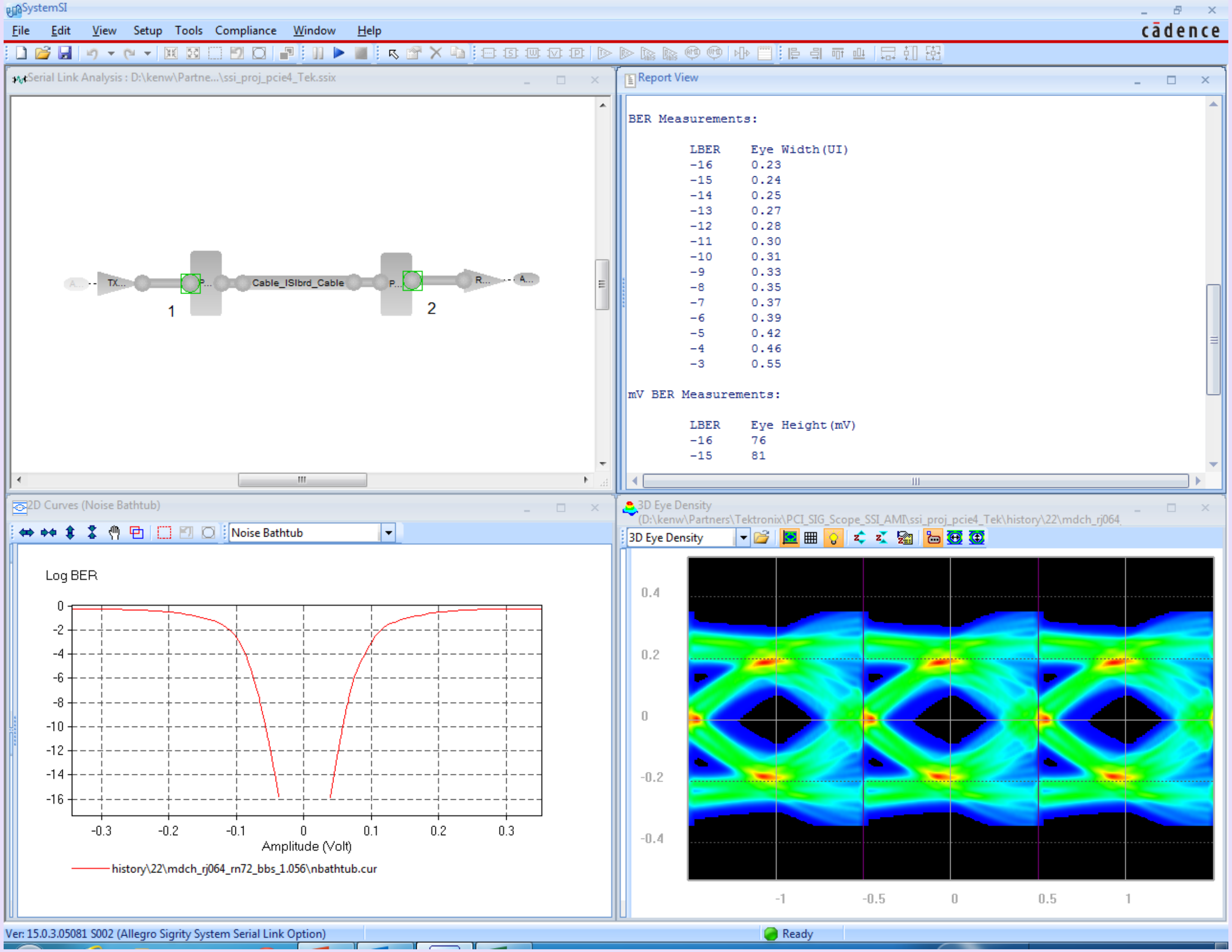
Note: These parameters are post-processed into the eye distribution associated with the Rx.

File Name: D:\kenw\Partners\Tektronix\PCI_SIG_

Sub-circuit Name: rx_scope

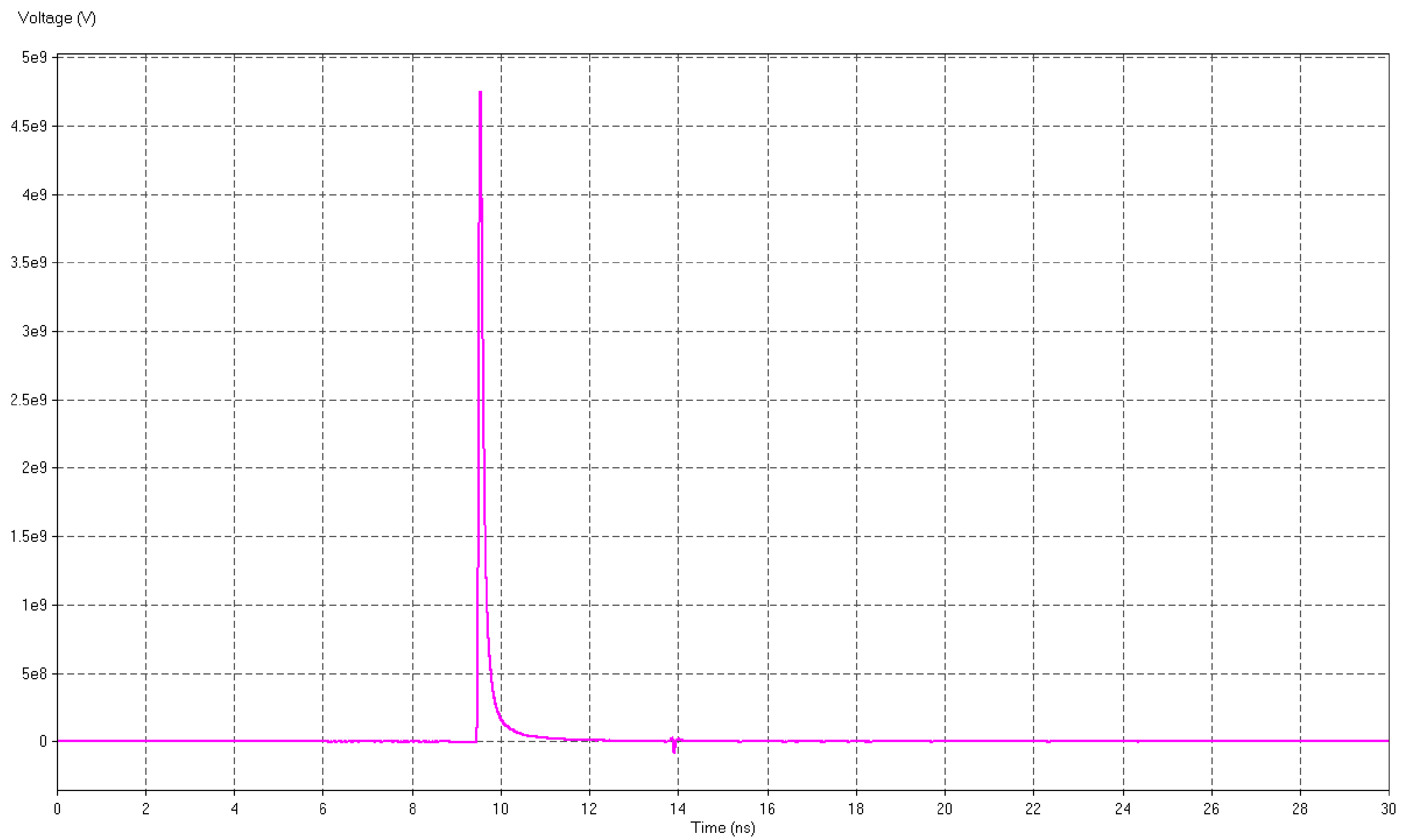
```
.subckt rx_scope pos neg pwr ngnd rxnode
+ rx_term=50
* + rx_cap=0.1p

********************************************************************************
* BEHAVIORAL CIRCUIT MODEL FOR SIGRITY's SystemSI
********************************************************************************
* MODEL NOTES
*
* This model represents Tek's scope input
* Simple resistor termination with some parasitic capacitance
*
********************************************************************************
* MODEL PARAMETERS
*
* This model takes the following parameters:
*
* rx_term > single-ended termination in the receiver
* rx_cap > parasitic capacitance at input
```

Set CTLE Value (dbl=21) and Run



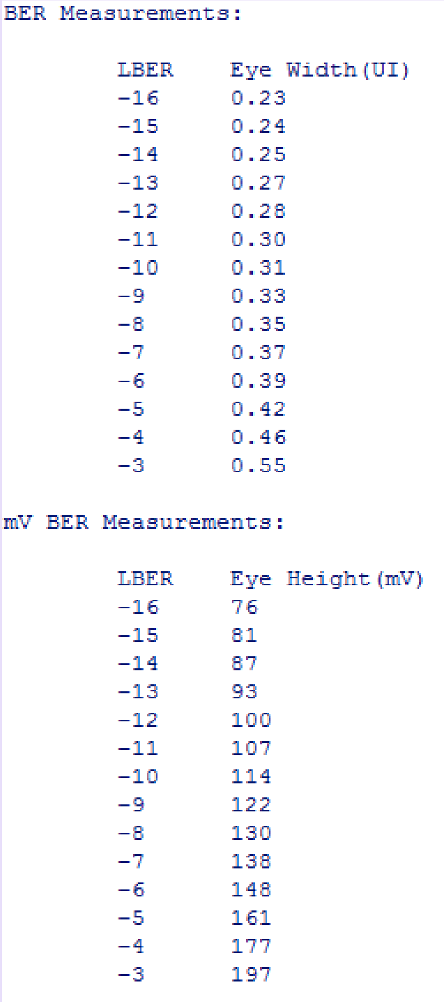
```
BER Measurements:

        LBER     Eye Width(UI)
        -16      0.23
        -15      0.24
        -14      0.25
        -13      0.27
        -12      0.28
        -11      0.30
        -10      0.31
        -9       0.33
        -8       0.35
        -7       0.37
        -6       0.39
        -5       0.42
        -4       0.46
        -3       0.55

mV BER Measurements:

        LBER     Eye Height(mV)
        -16      76
        -15      81
```

Impulse Response



Simulation Bathtub Report

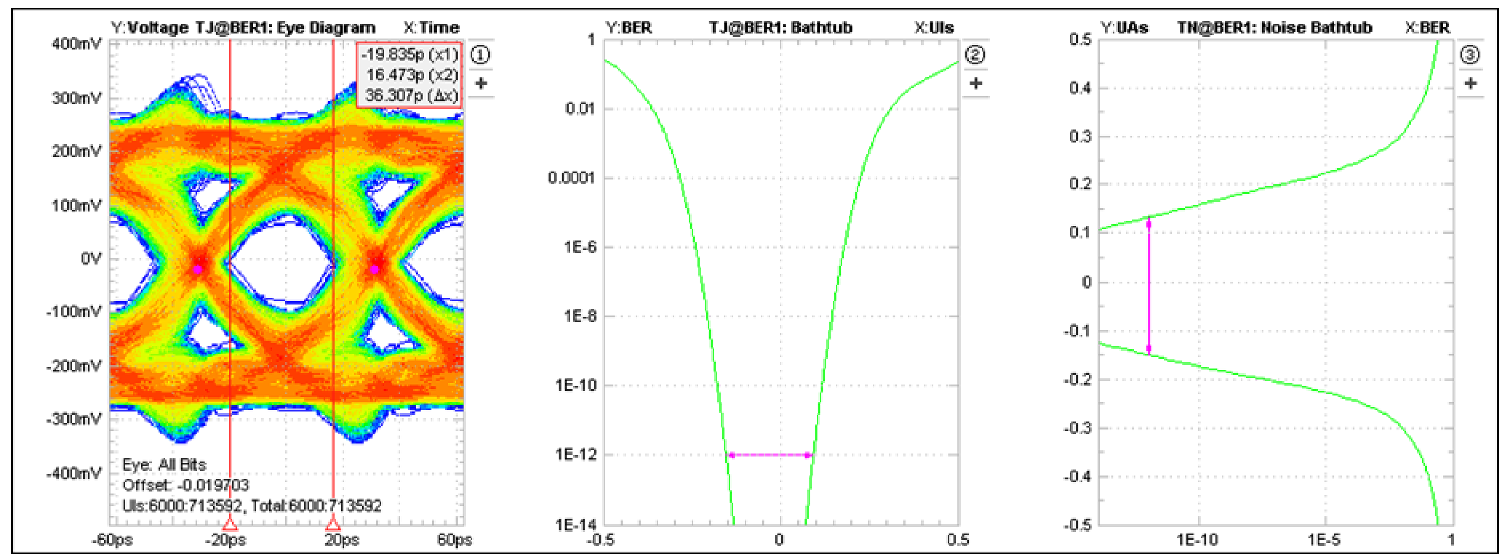
- LBER-8
  - ✓ 0.35UI and 130mV
- LBER-10
  - ✓ 0.31UI and 114mV
- LBER-12
  - ✓ 0.28UI and 100mV

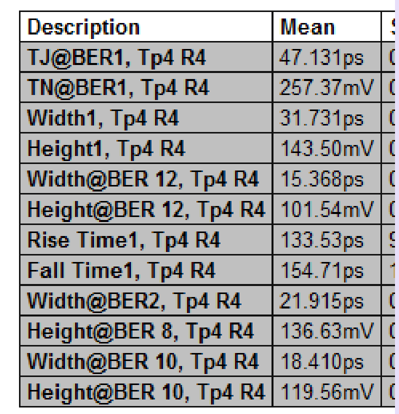


```
BER Measurements:

        LBER     Eye Width(UI)
        -16      0.23
        -15      0.24
        -14      0.25
        -13      0.27
        -12      0.28
        -11      0.30
        -10      0.31
        -9       0.33
        -8       0.35
        -7       0.37
        -6       0.39
        -5       0.42
        -4       0.46
        -3       0.55

mV BER Measurements:

        LBER     Eye Height(mV)
        -16      76
        -15      81
        -14      87
        -13      93
        -12      100
        -11      107
        -10      114
        -9       122
        -8       130
        -7       138
        -6       148
        -5       161
        -4       177
        -3       197
```

Measurement Results

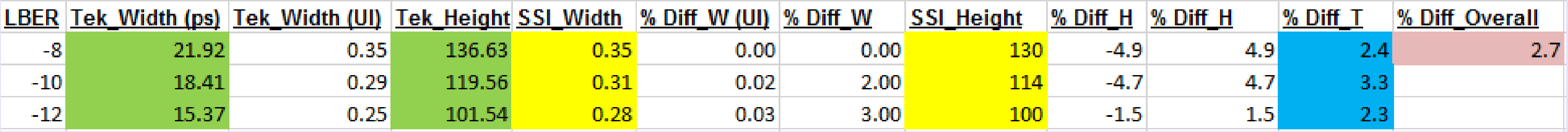
- RX after EQ





Description	Mean
TJ@BER1, Tp4 R4	47.131ps
TN@BER1, Tp4 R4	257.37mV
Width1, Tp4 R4	31.731ps
Height1, Tp4 R4	143.50mV
Width@BER 12, Tp4 R4	15.368ps
Height@BER 12, Tp4 R4	101.54mV
Rise Time1, Tp4 R4	133.53ps
Fall Time1, Tp4 R4	154.71ps
Width@BER2, Tp4 R4	21.915ps
Height@BER 8, Tp4 R4	136.63mV
Width@BER 10, Tp4 R4	18.410ps
Height@BER 10, Tp4 R4	119.56mV

Compare Simulation Results vs. Measurement

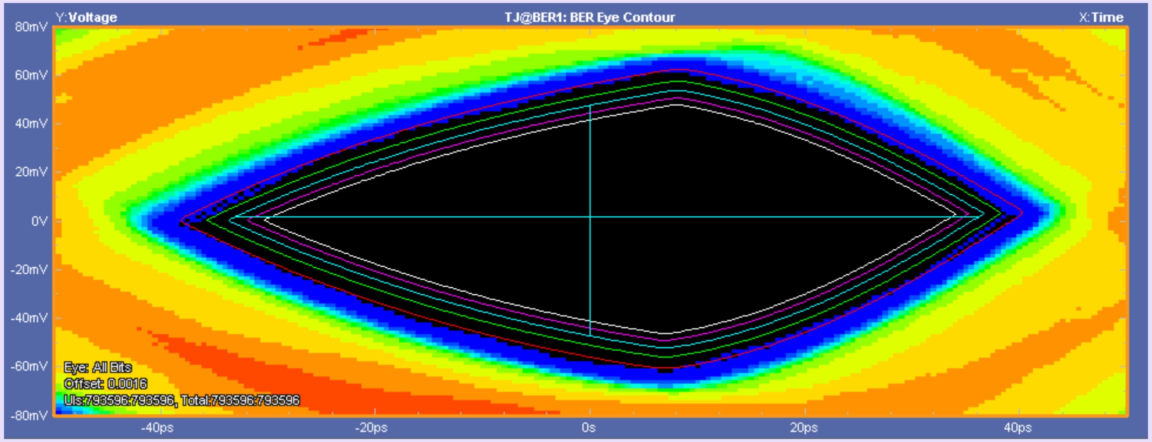


LBER	Tek_Width (ps)	Tek_Width (UI)	Tek_Height	SSI_Width	% Diff_W (UI)	% Diff_W	SSI_Height	% Diff_H	% Diff_H	% Diff_T	% Diff_Overall
-8	21.92	0.35	136.63	0.35	0.00	0.00	130	-4.9	4.9	2.4	2.7
-10	18.41	0.29	119.56	0.31	0.02	2.00	114	-4.7	4.7	3.3	
-12	15.37	0.25	101.54	0.28	0.03	3.00	100	-1.5	1.5	2.3	

- Width correlated from perfect match at LBER -8 to 3%UI difference at LBER -12
- Height ran from 4.9% difference at LBER -8 to 1.5% difference at LBER -12
- Overall composite match at target LBER -12 within 2.3%
- Overall composite match across all 6 metrics within 2.7%

Further Measurement Considerations

- Measurements were done at the far end of the channel
- Channel effects on signal slew rate can result in AM-to-PM and PM-to-AM conversion
- These effects can be measured

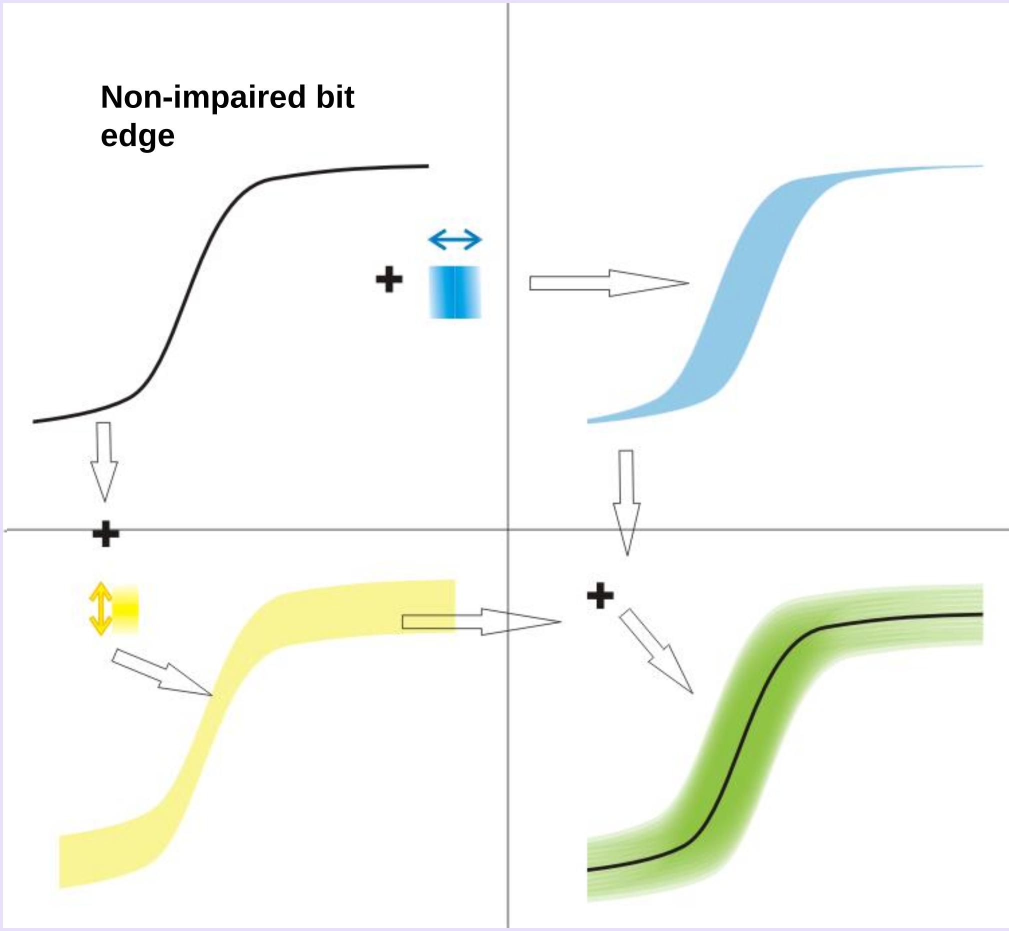


Channel Impact on RN/RJ

We can separate the noise contribution of jitter for diagnostic purposes by breaking RJ into RJ(v) and RJ(h)

Consider: an “ideal” edge in a pattern actually has two impairments:

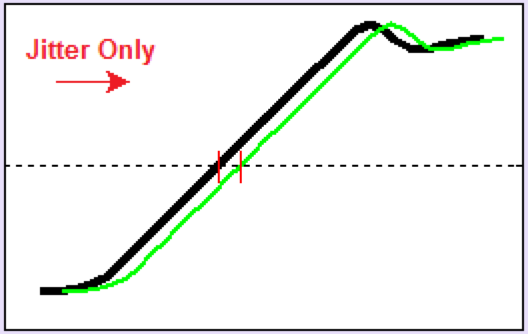
- ✓ Jitter(h) (see the blue trace)
- ✓ and Noise
  (note that both of Jitter *and Noise* result in jitter on edge)



The Combined response (bottom right) includes the jitter caused by noise

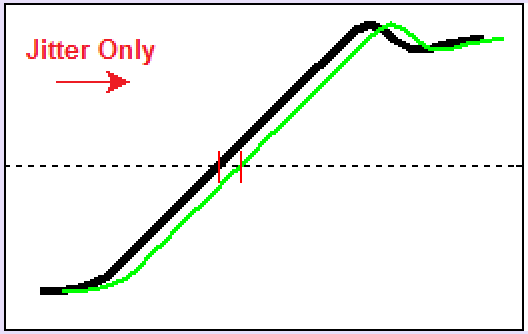
Timing-Induced Jitter

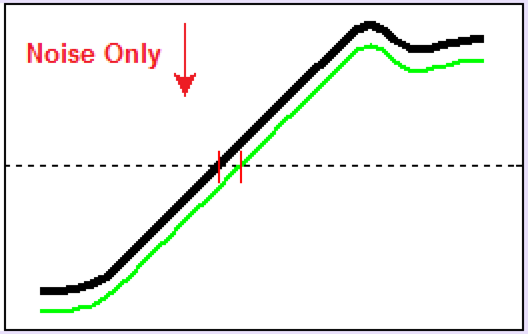
- Since jitter is defined as a shift in an edge's time relative to its expected position, it is easy to think of jitter as being <u>caused</u> by horizontal (chronological) displacement.
- Note that the displaced edge (green) has not moved vertically in this example.



Noise-Induced Jitter

- Consider a burst of voltage noise (right) that displaces a waveform vertically.
  - ✓ In this case, the displaced edge (green) has not moved horizontally.
- The jitter as measured at the chosen reference voltage is identical in these cases!
  - ✓ So, why should we care?

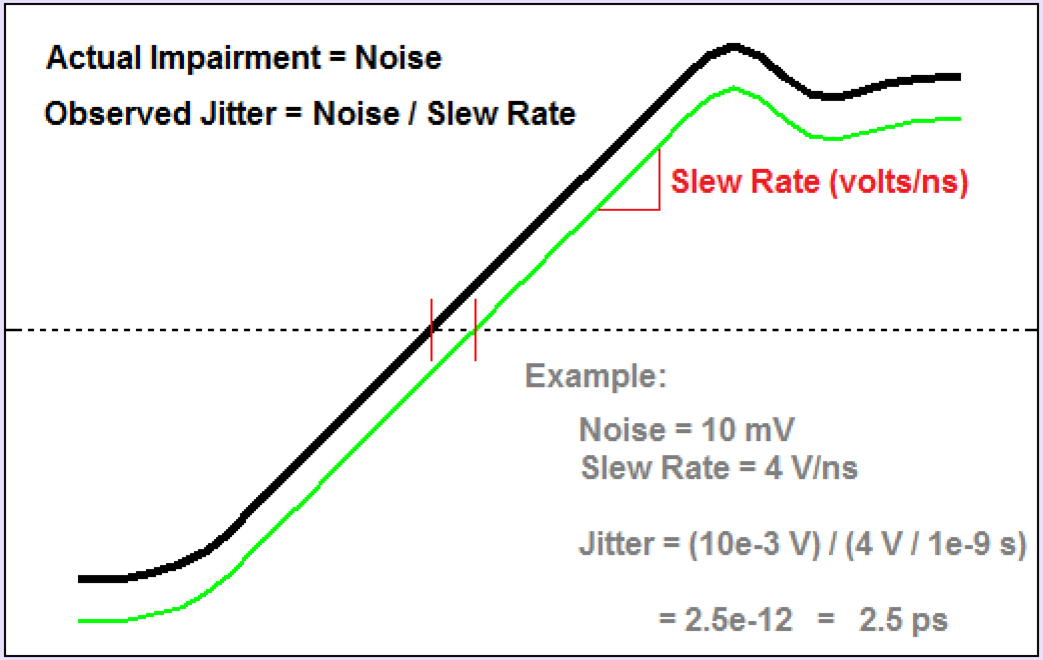




- Two fundamentally different effects have caused the same amount of jitter, and either one will close the eye by the same amount <u>at this reference voltage</u>, but:
  - ✓ They will have different effects at other voltages where the slew rate is different.
  - ✓ Their differences give insight to root cause

Noise-to-Jitter (AM-to-PM) Conversion

- Since waveform transitions are never instantaneous, the slope (slew rate) of the edge acts as a gain constant that controls how effectively noise is converted to “observed jitter”.



Actual Impairment = Noise

Observed Jitter = Noise / Slew Rate

Example:

Noise = 10 mV
Slew Rate = 4 V/ns

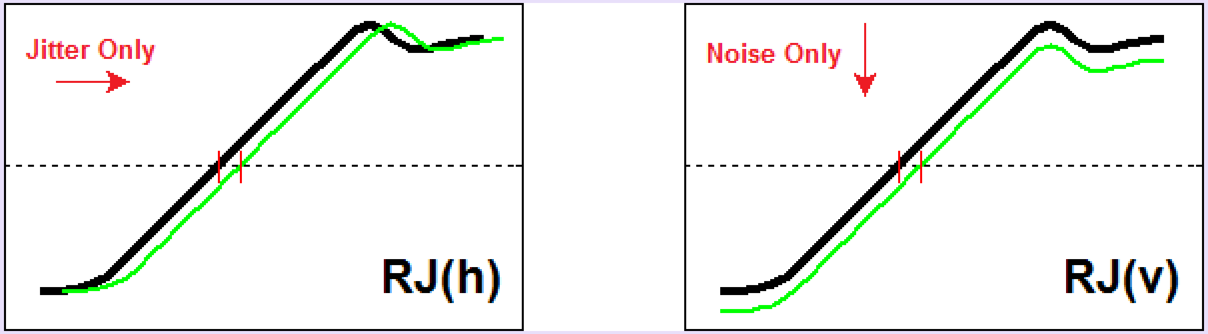
Jitter = (10e-3 V) / (4 V / 1e-9 s)

= 2.5e-12 = 2.5 ps

- An analogous effect occurs when voltage is measured at the center of the bit interval: If the slew rate is not zero, then jitter will cause PM-to-AM conversion and appear as noise!

Horizontal and Vertical Components of Random Jitter

- We can think of RJ as being composed of two components.
  - ✓ Horizontally induced: RJ(h)
  - ✓ Vertically induced: RJ(v)



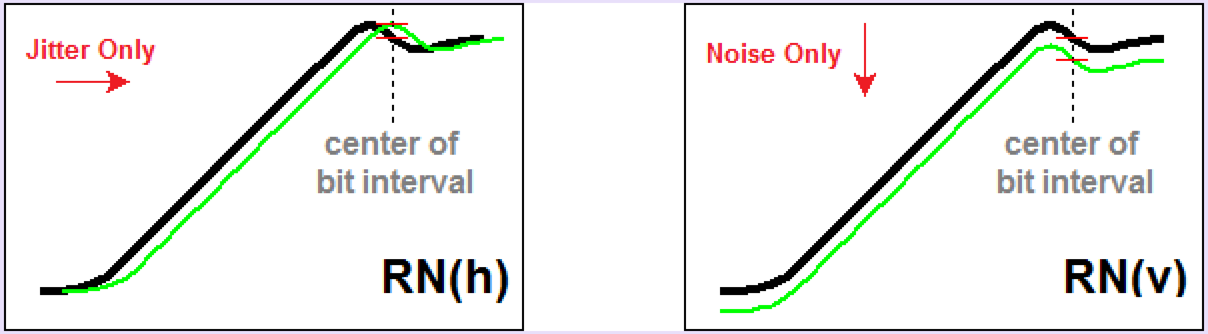
- Since these two components are uncorrelated with each other, they add in the RSS sense:

$$\mathrm{RJ} = \sqrt{\mathrm{RJ(h)}^2 + \mathrm{RJ(v)}^2}$$

- Similarly, PJ can be decomposed into PJ(h) and PJ(v) based on root cause

Horizontal and Vertical Components of Random Noise

- We measure noise at a reference point in the bit interval (usually 50%)
- If slew rate isn't zero, jitter (horizontal displacement) causes observed noise



- So as with RJ, RN can be decomposed into components:
  - ✓ Horizontally induced: RN(h)
  - ✓ Vertically induced: RN(v)

- Similarly, PN can be decomposed into PN(h) and PN(v) based on root cause

Summary

- Simulation / Measurement correlation requires accurate modeling of TX/RX/Channel
  - ✓ Amplitude, Rise Time, Jitter and Noise profiles need to be modeled
- IBIS-AMI models enable accurate prediction of signaling inside the device after adaptive EQ
  - ✓ Design space exploration in early design phase (Design Level)
  - ✓ Final design signoff before going to manufacturing (System Level)
  - ✓ Final verification in the lab using measurement equipment
- Understanding and decomposing the effects conversion of jitter to noise and vice versa provides insight into the root cause of eye closure
- Cadence and Tektronix are bridging the gap between simulation and lab measurement
  - ✓ Make Tektronix MSO/DPO70000 Series and Cadence® Sigrity™ SystemSI™ tool your lab measurement and simulation solutions

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Presentation Title

Speaker

Title

Company