IBIS-AMI Modeling Formulation for Bi-directional MultiGBase-T1 Automotive Ethernet Links

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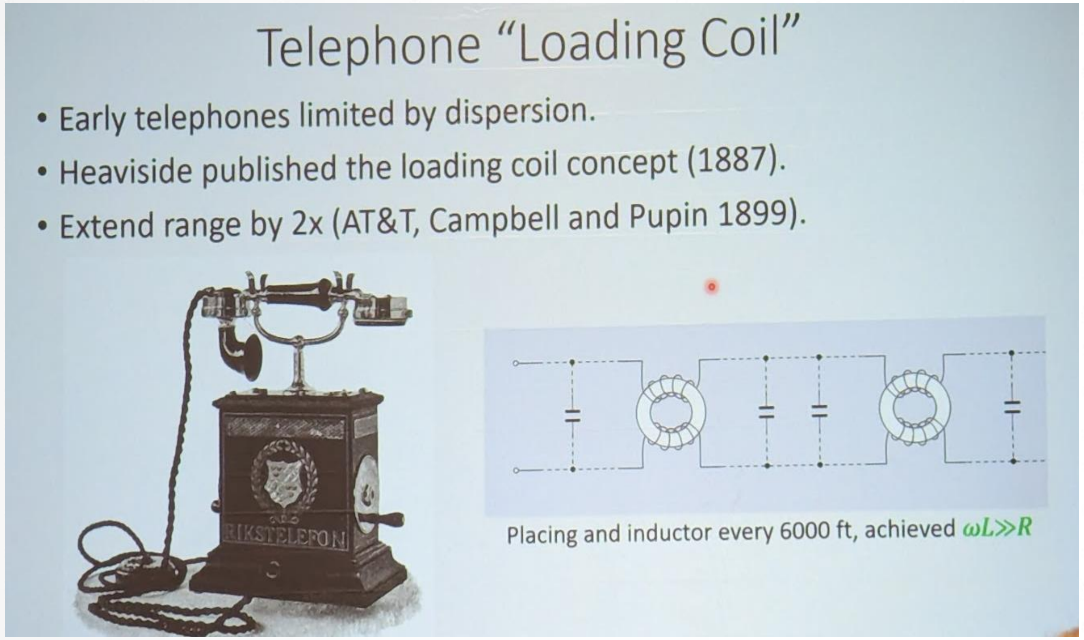
KEYSIGHT TECHNOLOGIES

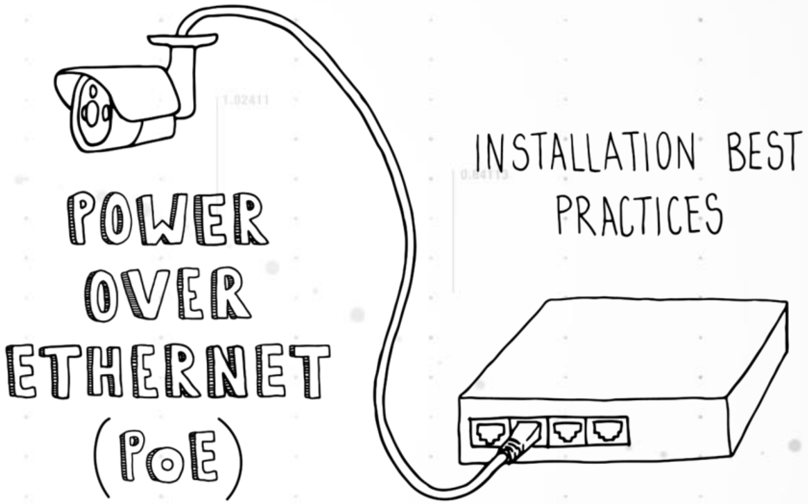
Outline

- Introduction
  - MultiGBase-T1 automotive ethernet
  - Bi-directional link and echo cancellation
- AMI Modeling and Simulation Approach for Bi-directional Links
- Simulation Examples
  - Cable model
  - Hybrid model
  - TX and RX models
  - Simulation results

History of Simultaneous Bi-Directional Communication & Power Delivery over a Signal Cable



*The pic on the left is from the 2024 IEEE EMC & SIPI Conference Keynote Presentation: The Story of the Transatlantic Telegraph and the World's First Internet Presented by: Ed Godshalk, Ph.D., IEEE Fellow



Power over Ethernet (PoE) was invented in 1997 by PowerDsine. The IEEE standardized PoE in 2003 as the IEEE 802.3af standard.

Over 1B PoE ports have been shipped globally.

https://www.truecable.com/blogs/cable-academy/power-over-ethernet-poe-installation-best-practices

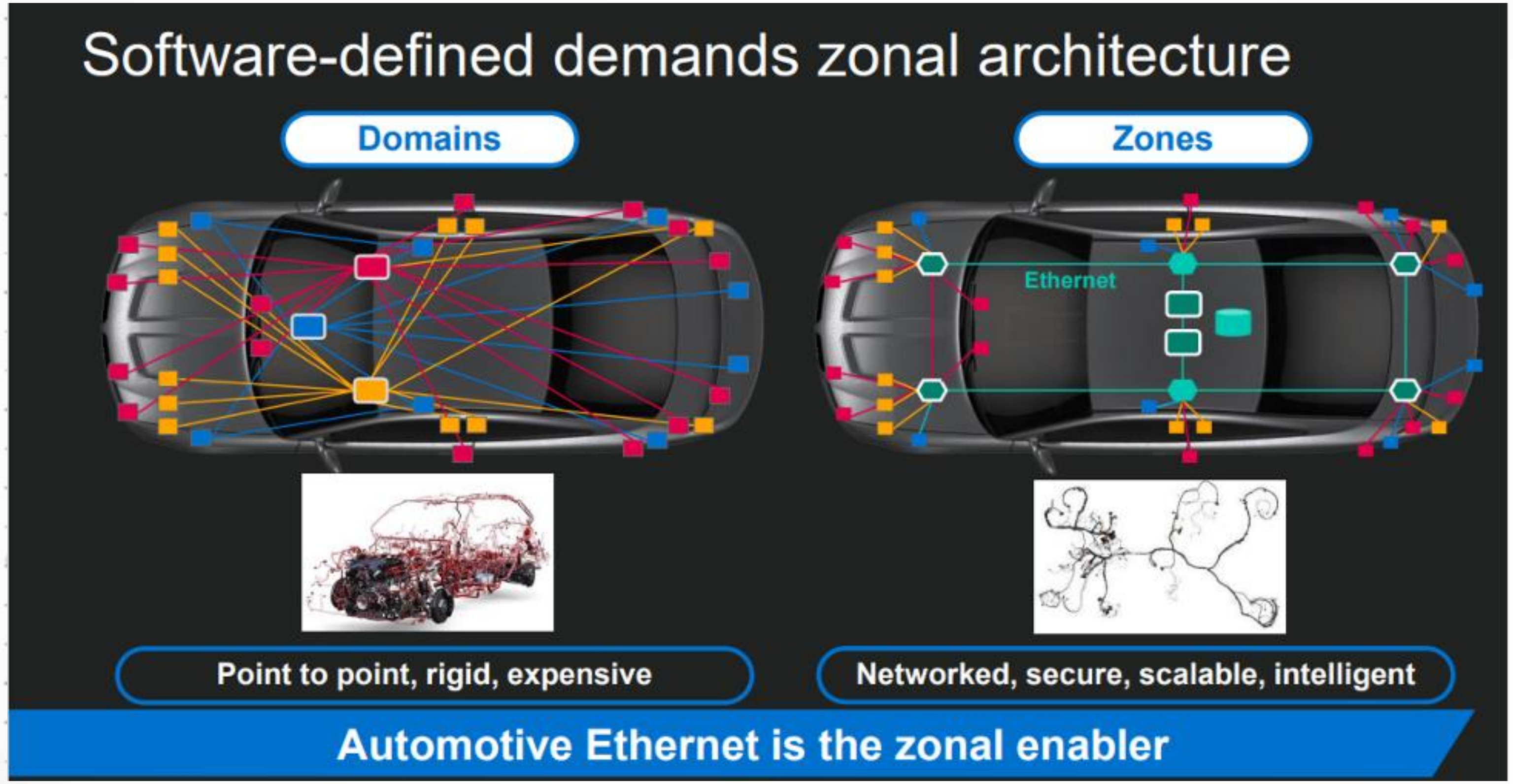
Automotive Adoptions

Cables are critical for the automotive **weight, cost, safety, and efficiency**.

Interfaces	Organization	Levels	Max Speed (Down)	Max Speed (UP)	Cable Type	Max length	PoC	Note
GMSL1	ADI	NRZ	3Gbps	187.5Mbps	Coax or STP	15m	Yes	Properitarty
GMSL2	ADI	NRZ	6Gbps	1.5Gbps	Coax or STP	15m	Yes	Properitarty
GMSL3	ADI	PAM4	12Gbps	187.5Mbps	Coax or STP	15m (Coax)/10m(STP)	Yes	Properitarty
FPD-Link I	TI	NRZ	1.05Gbps	N/A	UTP	2m	N/A	Properitarty
FPD-Link II	TI	NRZ	3.125Gbps	N/A	Coax or STP	10m	Yes	Properitarty
FPD-Link III	TI	NRZ	4Gbps	50 Mbps	Coax or STP	15m (Coax)/10m(STP)	Yes	Properitarty
FPD-Link IV	TI	PAM4	16Gbps	187 Mbps	Coax or STP	15m (Coax)/10m(STP)	Yes	Properitarty
ASA -G1	ASA	NRZ	2Gbps	50 Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes	MSA
ASA -G2	ASA	NRZ	4Gbps	100Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes	MSA
ASA -G3	ASA	NRZ	8Gbps	100Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes	MSA
ASA -G4	ASA	PAM4	12Gbps	100Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes	MSA
ASA -G5	ASA	PAM4	16Gbps	100Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes	MSA
MIPI-A G1	MIPI Alliance	NRZ	2Gbps	100Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes (6W max)	Standard
MIPI-A G2	MIPI Alliance	NRZ	4Gbps	200Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes (6W max)	Standard
MIPI-A G3	MIPI Alliance	PAM4	8Gbps	200Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes (6W max)	Standard
MIPI-A G4	MIPI Alliance	PAM8	12Gbps	200Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes (6W max)	Standard
MIPI-A G5	MIPI Alliance	PAM16	16Gbps	200Mbps	Coax or SDP	15m (Coax)/10m(SDP)	Yes (6W max)	Standard
10BASE-T1S (802.3cg)	IEEE	NRZ	10Mbps	10Mbps	UTP or STP	25m(p2p)/15(md up to 8 nodes)	Yes (PoDL 50W)	Standard
100BASE-T1 (802.3bw)	IEEE	PAM3	100Mbps	100Mbps	UTP or STP	15m	Yes (PoDL 50W)	Standard
1000BASE-T1 (802.3bp)	IEEE	PAM3	1Gbps	1Gbps	UTP or STP	15m	Yes (PoDL 50W)	Standard
2.5G/5G/10GBASE-T1 (802.3ch)	IEEE	PAM4	2.5/5/10Gbps	2.5/5/10Gbps	STP	15m	Yes (PoDL 50W)	Standard
25GBASE-T1 (802.3cy)	IEEE	PAM4	25Gbps	25Gbps	STP	11m	Yes (PoDL 50W)	Standard

PoDL: Power over Data Lines
PoC: Power over Coaxial

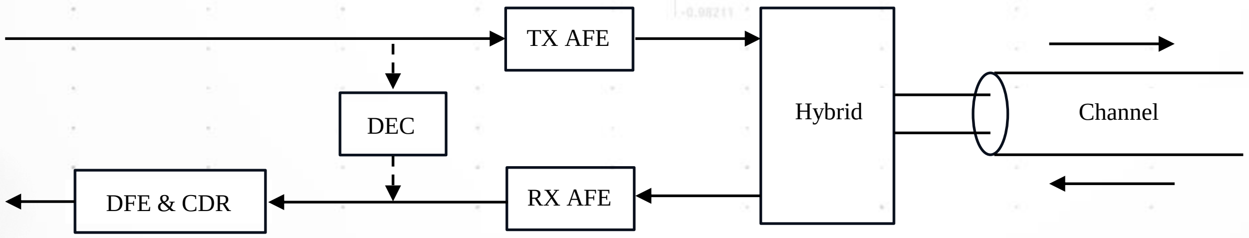
Automotive Applications



Source: https://semiengineering.com/auto-network-speeds-rise-as-carmakers-prep-for-autonomy/

Bi-directional Link and Echo Cancellation

- Bi-directional data is transferred simultaneously over a single cable
- Reduce cable complexity (both cable counts and lengths), weight, and manufacturing and operational costs
- Transceiver implements hybrid and digital echo cancellation (DEC) techniques to remove TX echo in received signal
- Bi-directional link simulation needs to accurately model echo cancellation as well as equalization and CDR

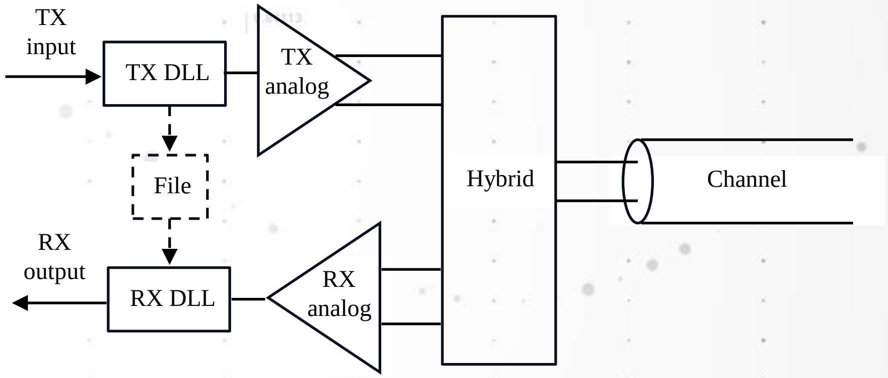


IBIS-AMI Extension for Bi-directional Links

- IBIS-AMI modeling and simulation methodology is widely adopted in SerDes and parallel channel designs
- AMI offers modeling versality and flexibility, model interoperability and portability, silicon IP protection, and superior simulation speed, allowing accurate yet efficient end-to-end link analyses at low BER
- IBIS 7.2 only defines simulation flows for unidirectional channels
- The standard needs to be extended to support simultaneous bi-directional buffer (SBD), especially for the modeling of echo cancellation

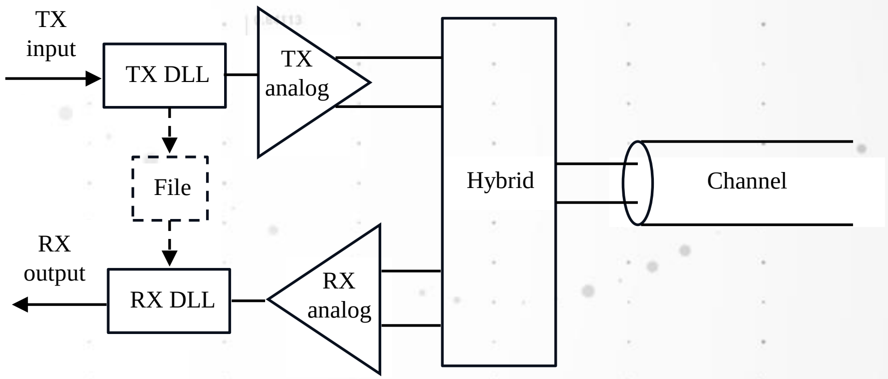
AMI Modeling and Simulation Approach for Bi-directional Links (1)

- Transceiver is modeled by a pair of TX and RX AMI models
- Hybrid block is treated as part of the analog channel and represented by analog components such as S-parameters
- DEC is included in RX DLL
- TX AMI_GetWave writes TX waveform (input or output or both) to a file
- RX AMI_GetWave reads the data from the same file and uses it in DEC
- File name is specified by a Model Specific parameter of Type “String” and Usage “In” in both TX and RX models
- Model user or EDA tool is responsible for assigning a unique file name for each TX-RX pair



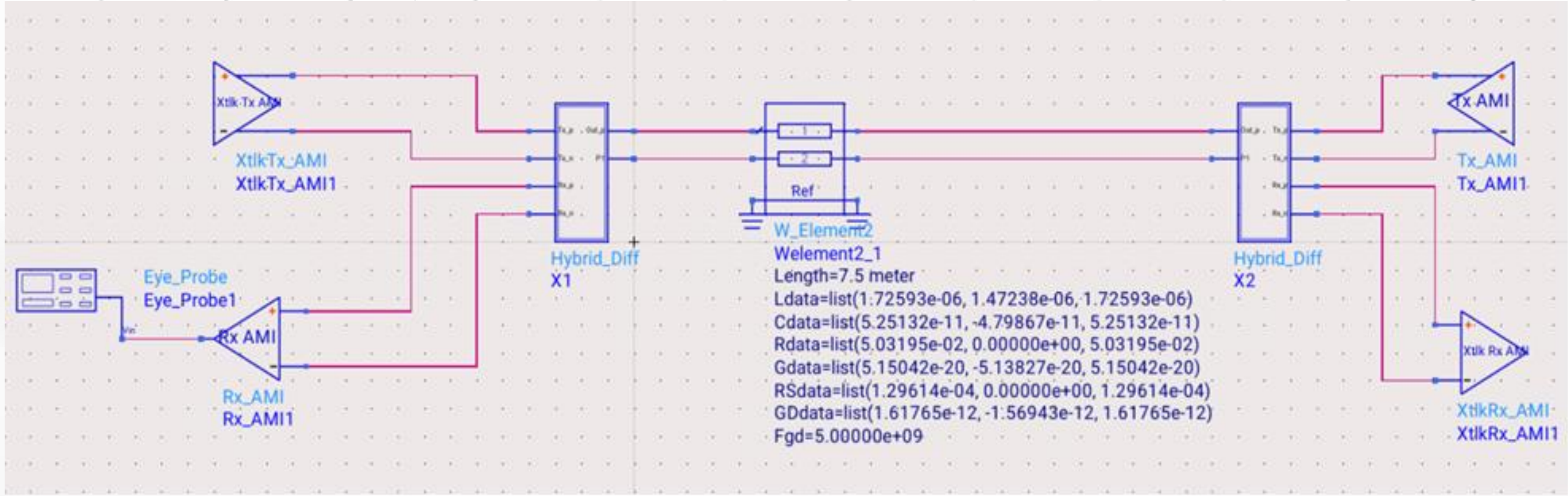
AMI Modeling and Simulation Approach for Bi-directional Links (2)

- Reserve the first aggressor column in the AMI_Init impulse matrix for the echo signal
- RX AMI_Init can optimize DEC based on the echo impulse response
- RX AMI_Init can also add the DEC filter to this impulse matrix column to support statistical domain simulation
- Introduce a new IBIS keyword to associate TX and RX pins (models) in the similar way to the [Repeater Pin] keyword in Repeater model



Simulation Example

- 10GBase-T1 link with two identical bi-directional transceivers connected by a shielded twisted pair (STP) cable
- Data rate at 10 Gbps
- PAM4 modulation
- Each time-domain simulation runs 1 million PAM4 symbols
- Signals in the left RX are studied



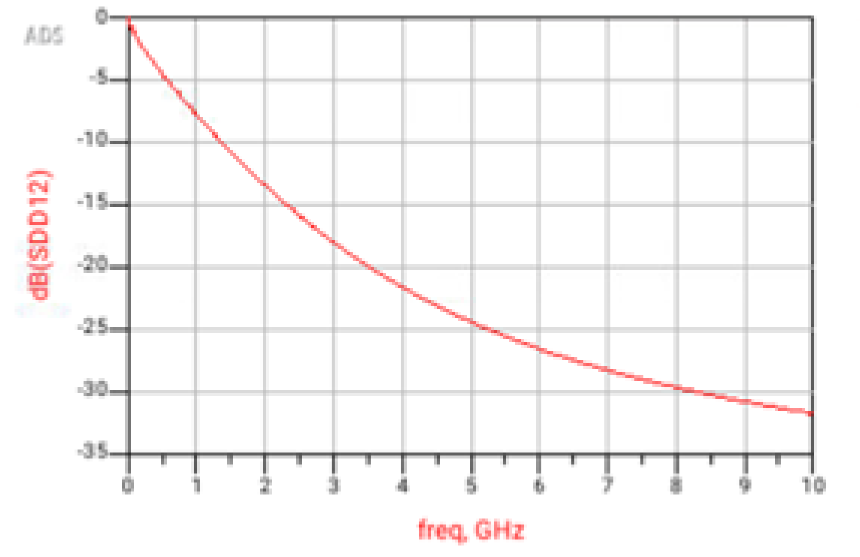
KEYSIGHT TECHNOLOGIES

Cable Model (1)

- 7.5 meters STP cable

Conductor diameter (mm)	Insulator thickness (mm)	Center-to-center wire pitch (mm)	Twist pitch (mm)	Cable diameter (mm)	Sheath thickness (mm)
0.68	0.223	1.2	10	3.06	0.123

- Represented by W-element model with extracted RLGC matrices (values shown on schematic)
- 100 Ohm differential impedance
- 16dB differential insertion loss



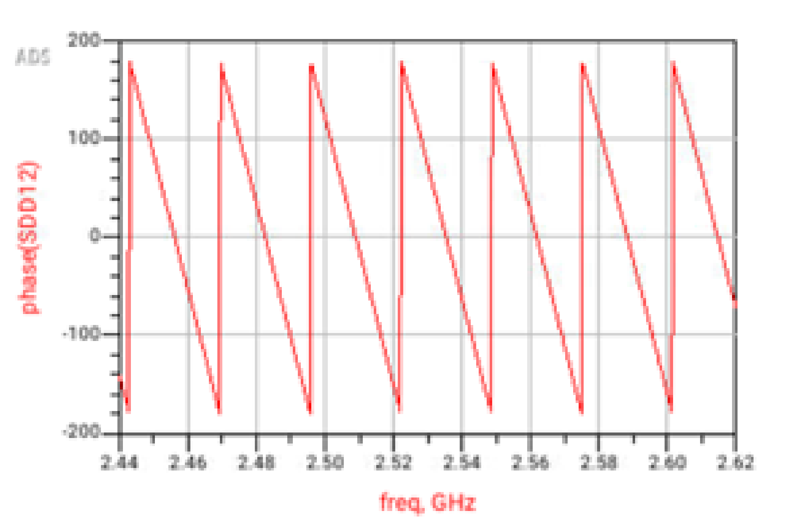
Cable Model (2)

- LC matrix

$$L_d C_d \begin{bmatrix} 0.22 & -0.06 \\ -0.06 & 0.22 \end{bmatrix}$$

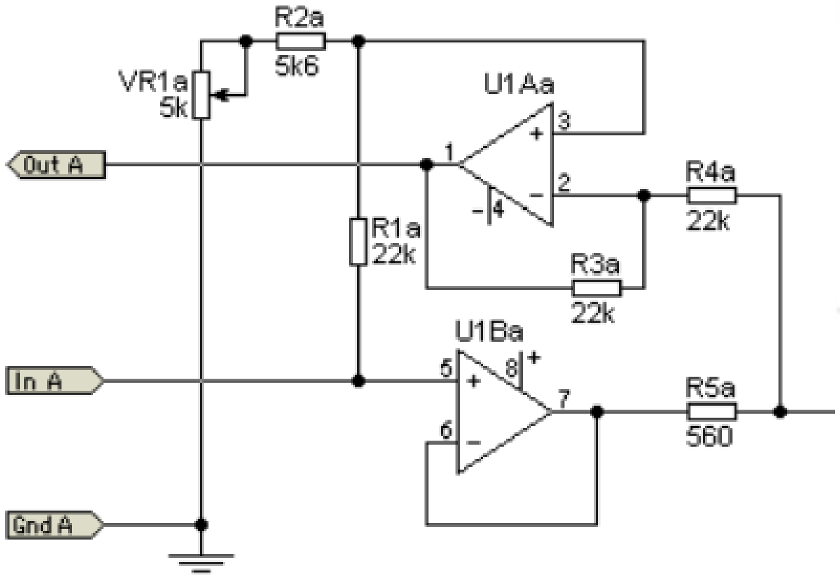
(L_d, C_d: diagonal elements of L, C)

- Two eigenmodes, [1,-1] (differential mode) and [1,1] (common mode), with corresponding eigenvalues $0.28 L_d C_d$ and $0.16 L_d C_d$, respectively
- Two modes are orthogonal and perfectly symmetric or anti-symmetric
- No CM-to-DM or DM-to-CM conversion
- Differential propagation velocity is $1/\sqrt{0.28 L_d C_d} = 2 \times 10^8$ m/s (ignoring R and G terms, which are small)
- Differential delay of length of 7.5 meters is 37.5 ns, matching the phase slope of SDD12



Hybrid Model

- Basic architecture

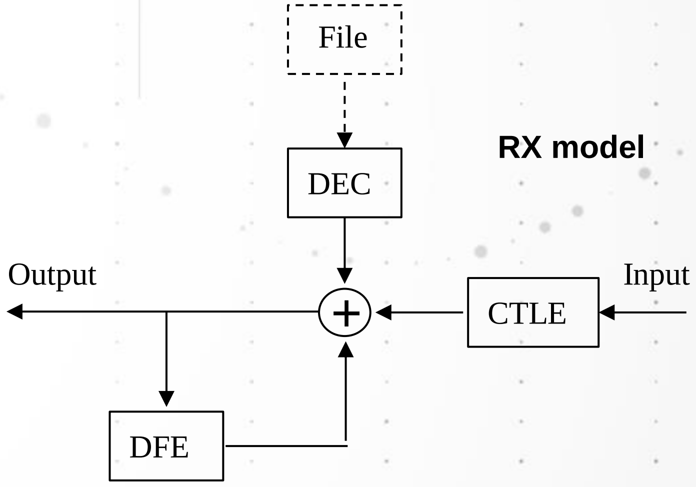


- Transmitted signal is applied to both inputs of the opamp U1A and canceled at the output
- In this study, the Hybrid is differential with 31dB echo rejection

Source: https://sound-au.com/appnotes/an010.htm

TX and RX AMI Models

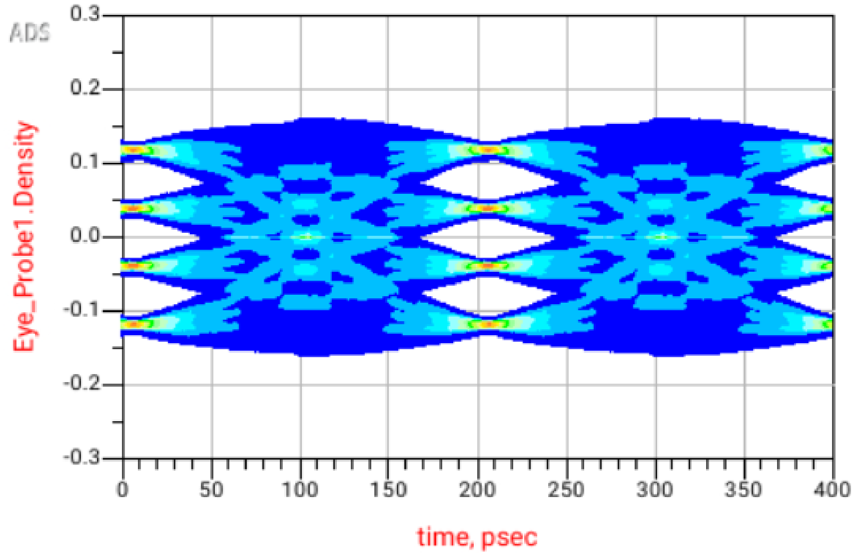
- TX model
  - 7-tap FFE (3 pre-cursors and 3 post-cursors)
  - AMI_GetWave writes input PAM4 stimulus waveform to a file
- RX model
  - 2-pole 1-zero CTLE
  - 5-tap DFE
  - CDR
  - DEC is a FIR with configurable number of taps
  - DEC input is the TX input waveform retrieved from the file
  - DEC output is added to post-CTLE signal before DFE and CDR



KEYSIGHT TECHNOLOGIES

Unidirectional Channel Results

- In the initial study, RX's neighbor TX is kept silent, and the channel is unidirectional
- RX DEC is turned off
- TX FFE, RX CTLE and DFE are optimized
- After FFE and CTLE, optimal DFE taps are in the order of mV, suggesting that DFE is not critical as the 16dB channel loss is relatively mild
- 4-tap TX FFE (1 pre-cursor and 2 post-cursors) is found to yield practically the same eye opens as 7-tap TX FFE does

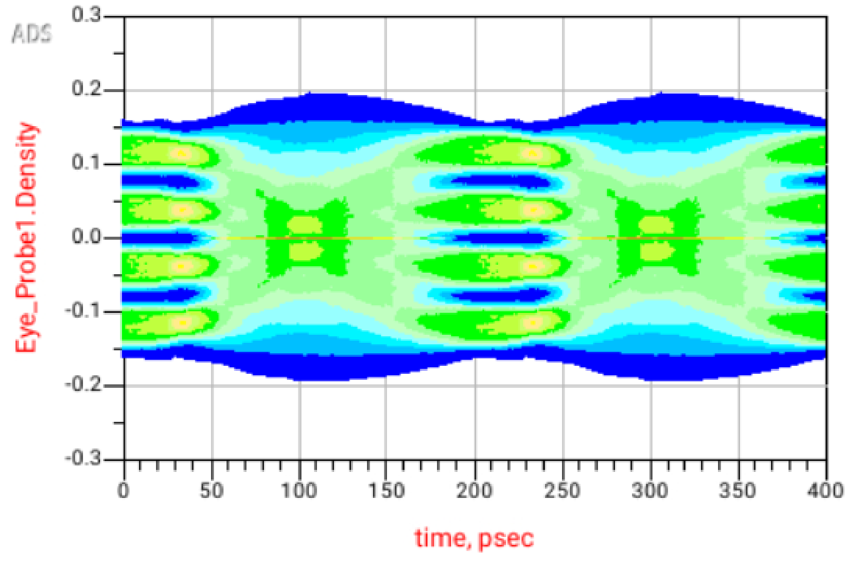


RX output eye

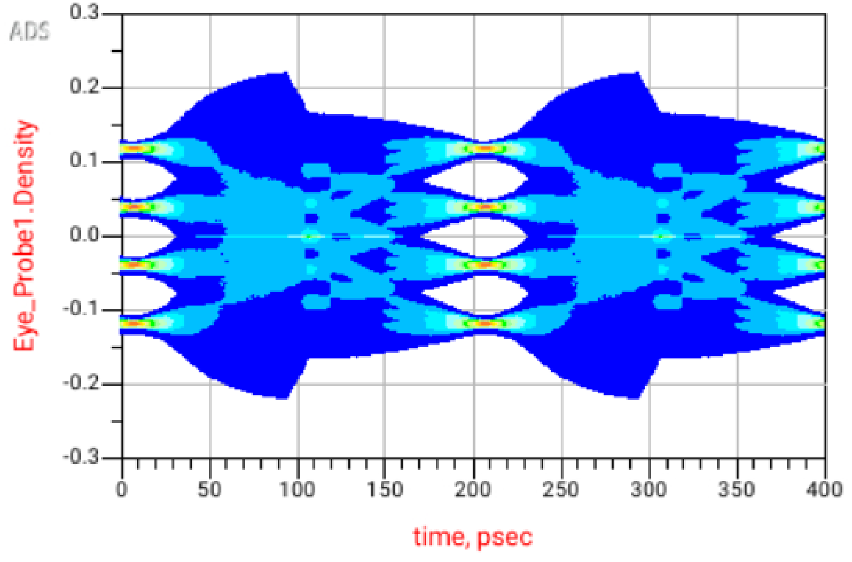
Bi-directional Channel Results (1)

- RX's neighbor TX is activated, and the channel is bi-directional
- Optimal TX and RX EQ settings found in unidirectional simulations are used in bi-directional simulations
- Without DEC, RX output eyes are closed by the residual echo that leaks through the Hybrid
- With DEC, RX output eyes are opened

RX output eye w/o DEC



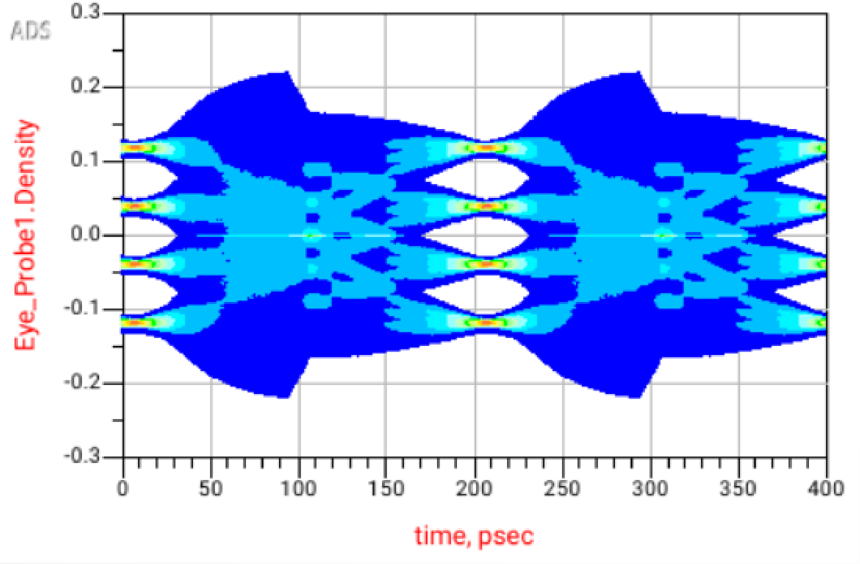
RX output eye with DEC



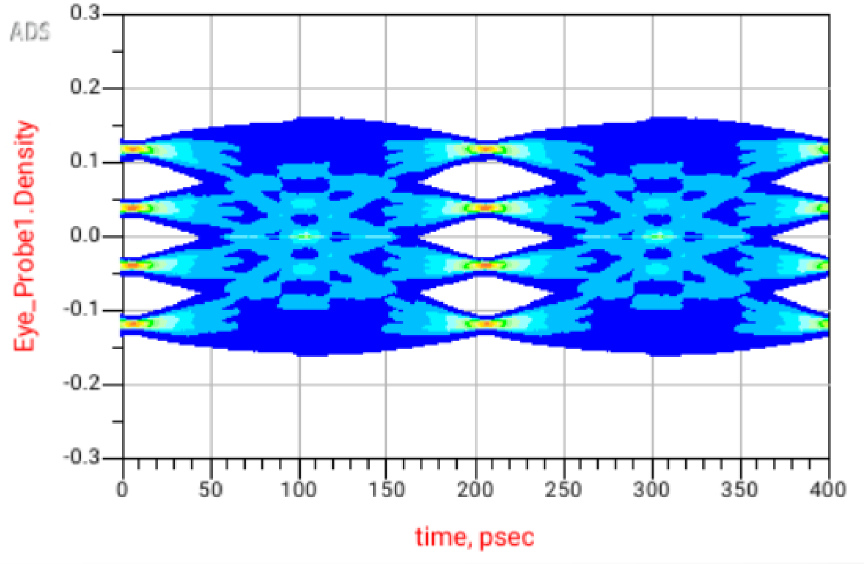
Bi-directional Channel Results (2)

- At RX output eye center, eye heights and voltage noise in the bi-directional channel with DEC are the same as those in the unidirectional channel, demonstrating the effectiveness of the DEC
- Eye widths in the bi-directional case are marginally smaller than those in the unidirectional case
- The right side of bi-directional eyes shrinks horizontally more than the left side does
- No substantial eye improvement is gained after the DEC tap number reaches 5

Bi-directional RX output eye with DEC



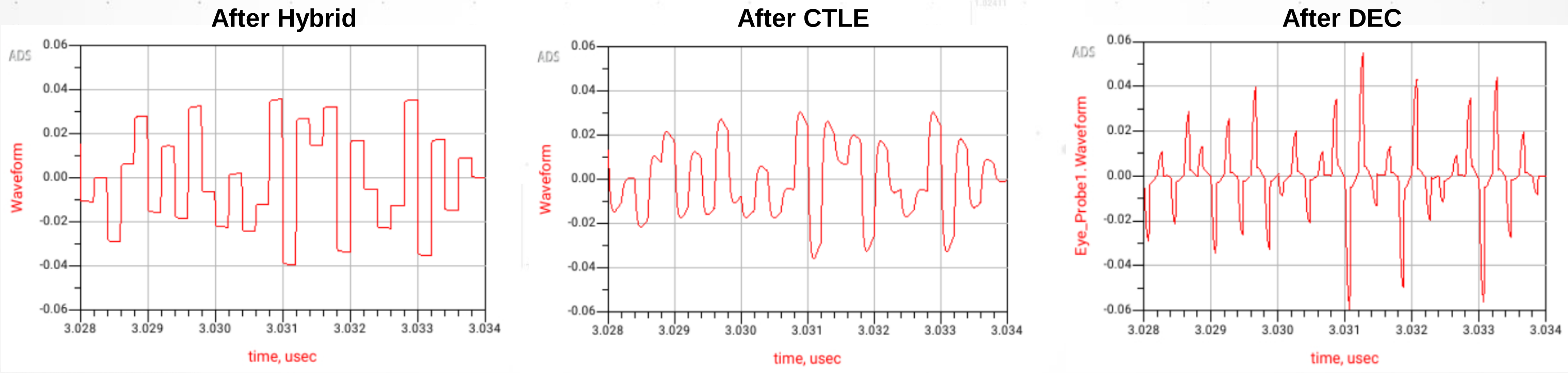
Unidirectional RX output eye



KEYSIGHT TECHNOLOGIES

Bi-directional Channel Results (3)

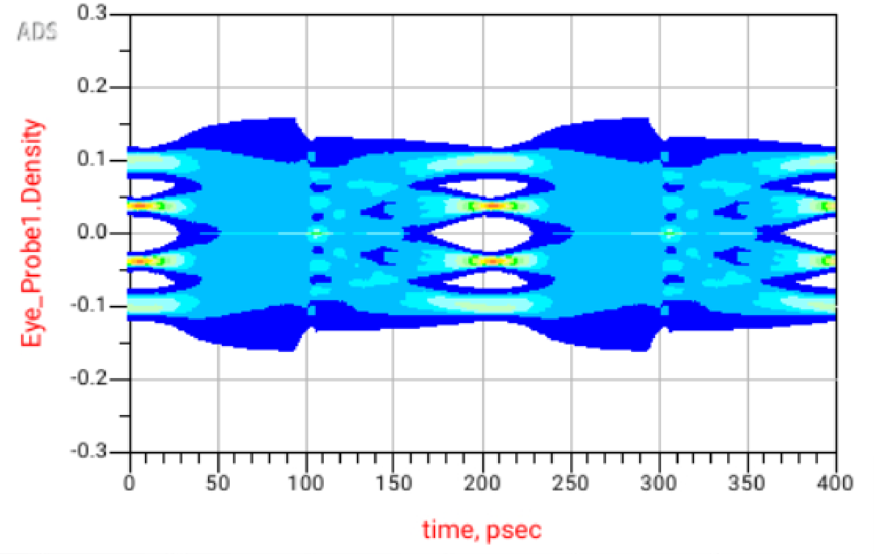
- Echo waveforms in RX



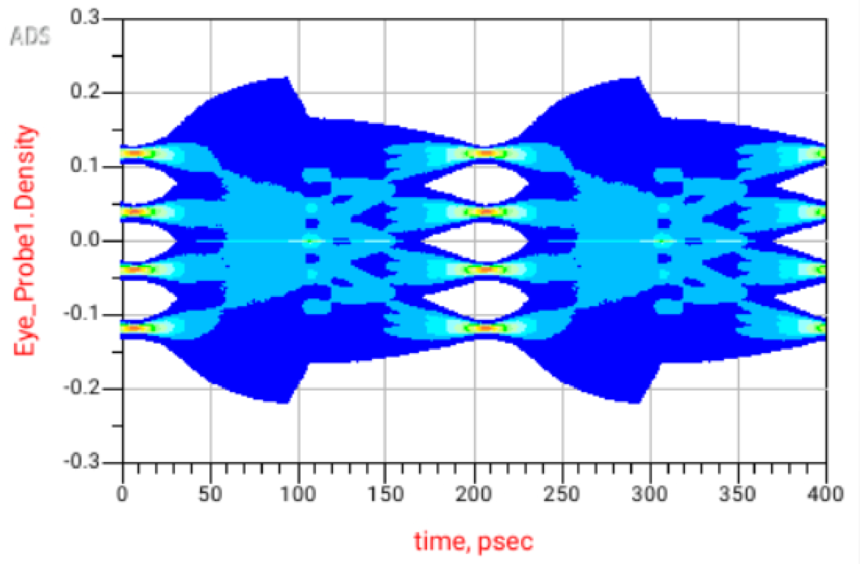
Impact of RX Nonlinearity on DEC

- RX compression is applied after CTLE but before DEC
- Heights of upper and lower eyes are reduced by the compression, whereas height of the center eye remains unchanged
- Voltage noise at top and bottom levels (levels 0 and 3) is found to increase due to the fact that the DEC is a linear filter and its efficiency on high amplitude signals is impaired by compression

RX output eye with compression



RX output eye w/o compression

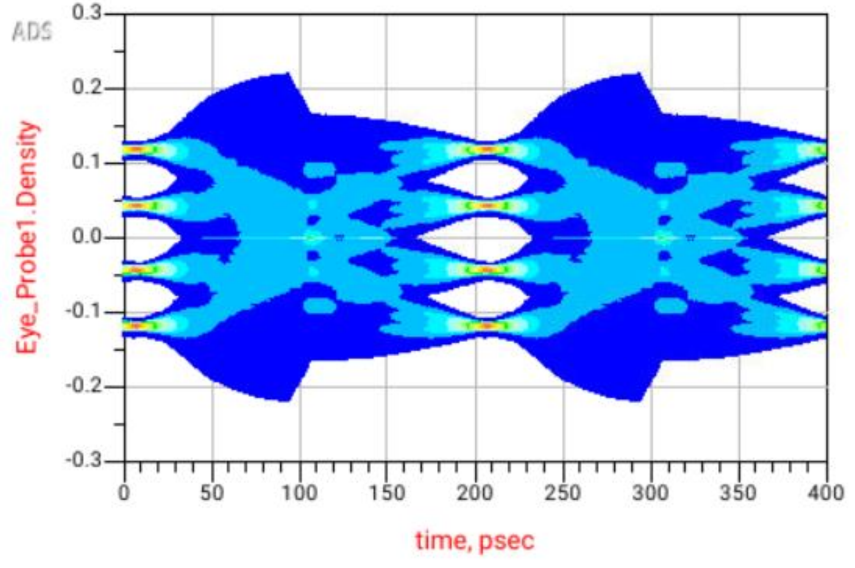


KEYSIGHT TECHNOLOGIES

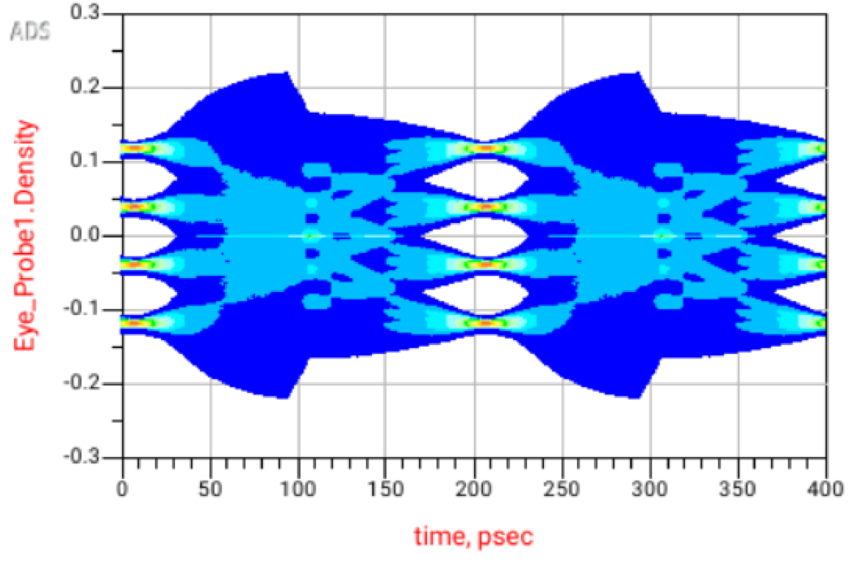
Impact of TX Nonlinearity on DEC

- PAM4 level separation mismatch ratio R_{LM} of 0.9 is applied in TX (RX compression is turned off)
- The center eye is taller than upper and lower eyes
- Voltage noises at all four levels are similar to those w/o TX level separation mismatch
- At 0.9 R_{LM}, impact of TX nonlinearity on DEC is limited

RX output eye with 0.9 R_{LM}



RX output eye w/o level separation mismatch

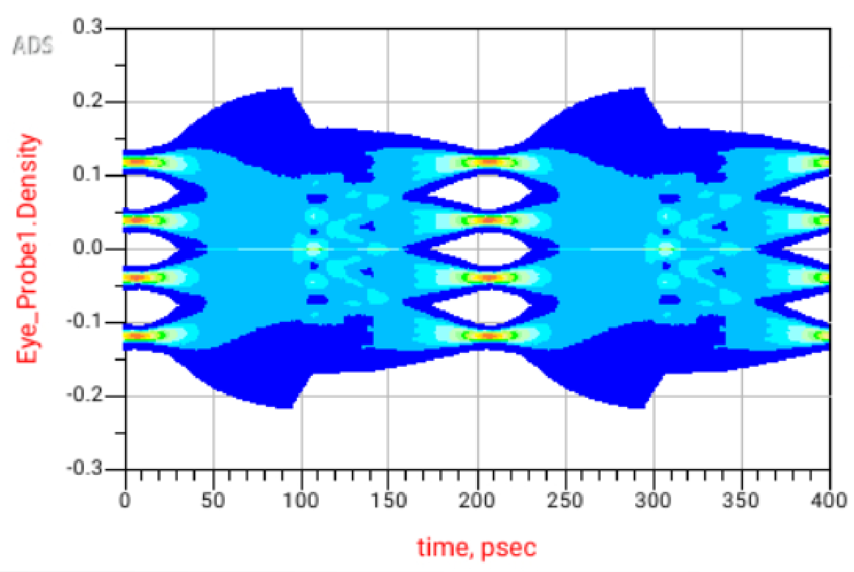


KEYSIGHT TECHNOLOGIES

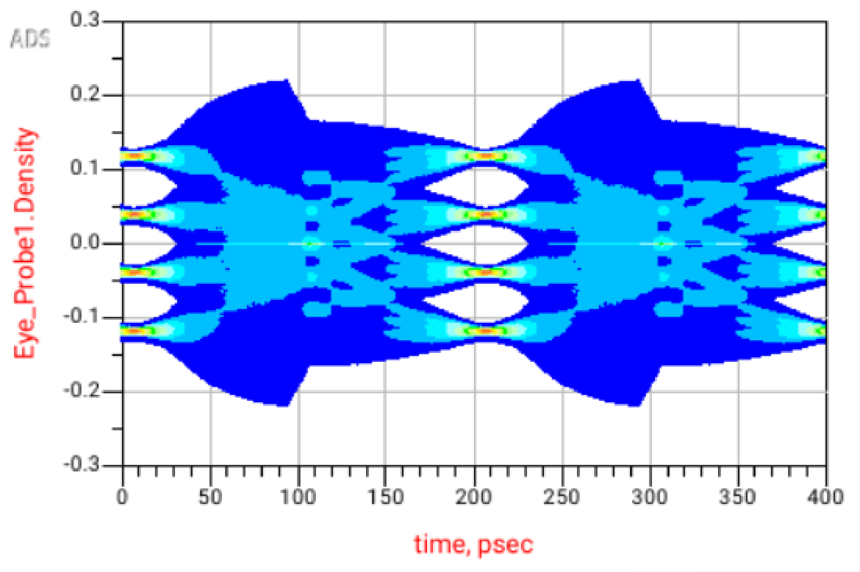
TX Noise Effect

- 20dB signal-to-noise and distortion ratio (SNDR) is applied in TX (TX level separation mismatch and RX compression are both turned off)
- Voltage noises at all four levels are larger than those w/o TX noise

RX output eye 20dB TX SNDR



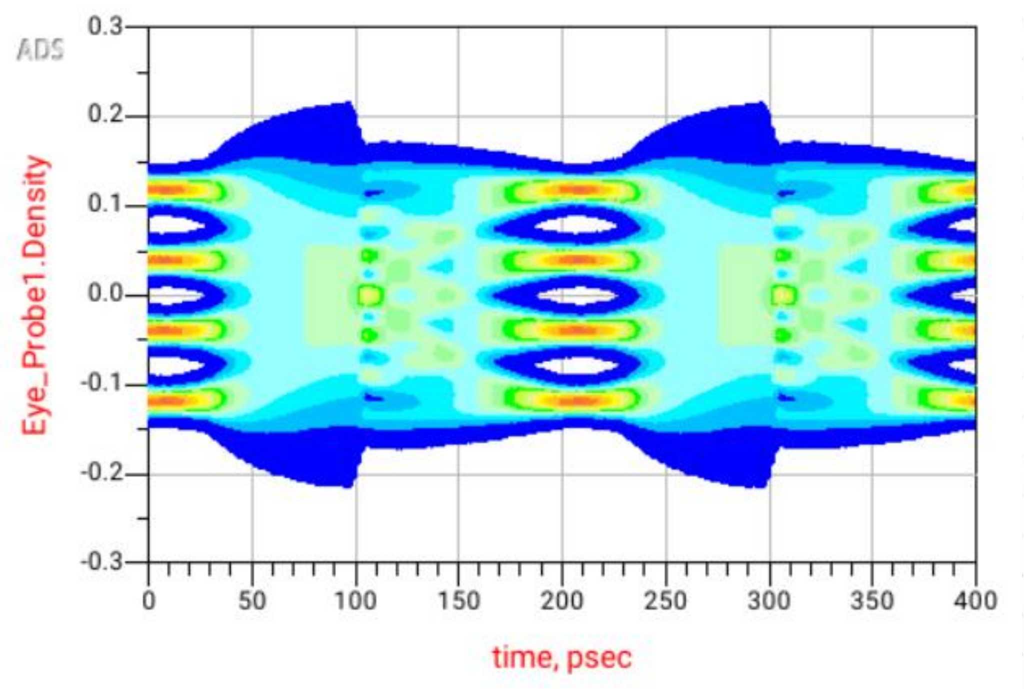
RX output eye w/o TX noise



Statistical Simulation Result

- RX AMI_Init optimizes DEC FIR and adds it to the 1st aggressor column of impulse_matrix
- Result is consistent with time-domain simulation

RX output eye of statistical simulation with DEC



KEYSIGHT TECHNOLOGIES

Summary

- In MultiGBase-T1 links, bi-directional data is transferred simultaneously over a single STP cable
- Hybrid and DEC are implemented in transceivers to cancel TX echo in received signal
- IBIS-AMI extension for bi-directional channels
  - Transceiver is modeled by a pair of TX and RX models
  - Introduce a new IBIS keyword to associate TX and RX pins (models)
  - Hybrid is treated as part of the analog channel and represented by analog components such as S-parameters
  - DEC is modeled in RX DLL
  - TX AMI_GetWave writes TX waveform into a file
  - RX AMI_GetWave reads TX waveform from the file and uses it as the input to DEC
  - Reserve the 1st aggressor column of the impulse_matrix for echo signal. RX AMI_Init can use it to optimize DEC and add DEC filter to it to support statistical simulation
- Time-domain and statistical simulation flows are demonstrated with simulation results of a 10GBase-T1 link example

Thank you!