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IBIS-AMI Modeling and Simulation of 56G PAM4 Link Systems

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KEYSIGHT TECHNOLOGIES

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- IBIS-AMI Modeling for PAM4 Signaling
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- Conclusions

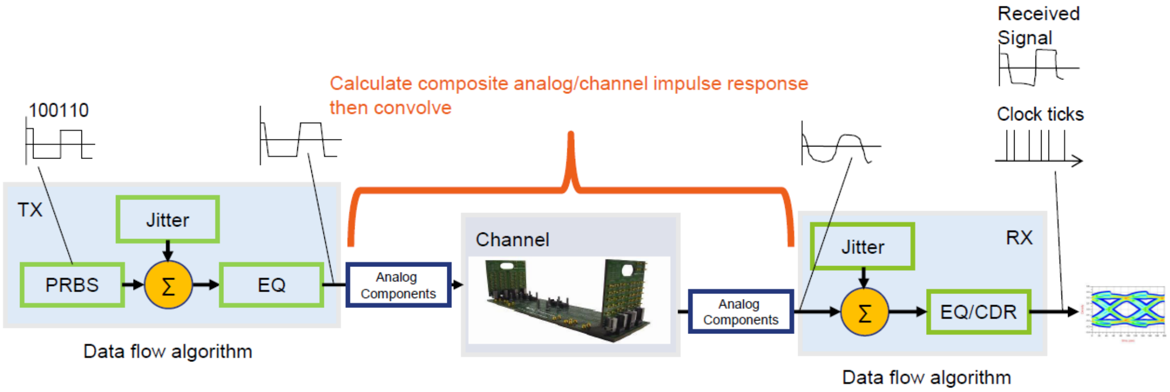
Introduction

- PAM4 signaling becomes competitive for 40G+
- Current IBIS-AMI standard only supports NRZ
- IBIS-AMI modeling of PAM4 signaling possible with two extensions
  - Four TX input levels from simulators
  - RX slicer levels sent to simulators
- PAM4 eye diagrams and bathtub curves
- Proposal for merged NRZ-equivalent eye and bathtub curves

IBIS-AMI Modeling for NRZ Signaling

- **TX DLL input is switching between 0.5V and -0.5V**
- **TX output is convolved with channel impulse response**
- **The resultant waveform is input to the RX DLL**
- **RX equalized signal is sampled at each clock time and compared with 0V for BER calculation**
- **RX data segments are processed sequentially with each *AMI_GetWave()* call.**

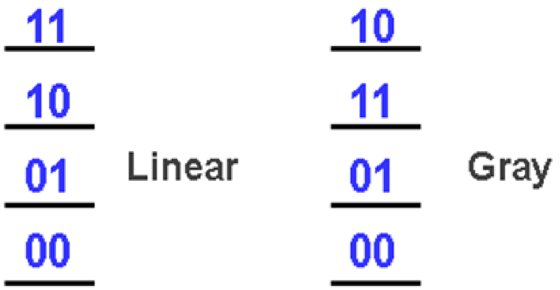
IBIS-AMI Modeling for NRZ Signaling

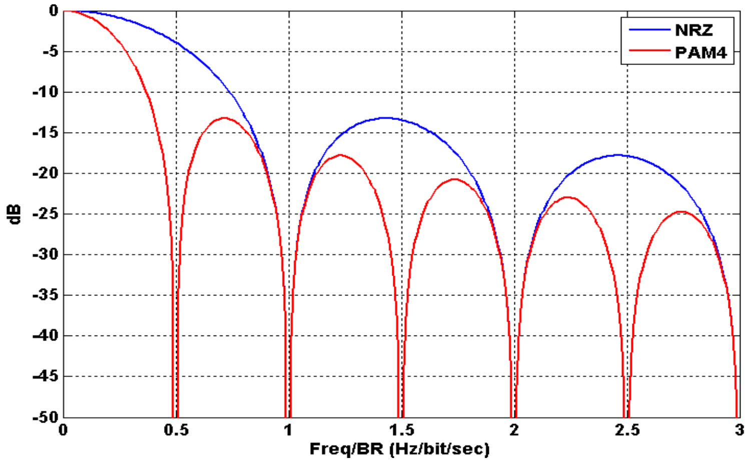


- **The simulator sends square waves to TX IBIS-AMI model**
- **TX output is convolved with channel impulse response**
- **RX sends processed waveform and clock ticks to the simulator**

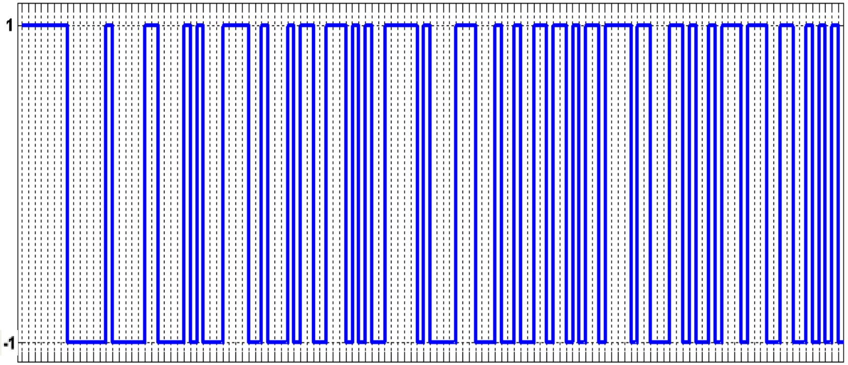
Brief Introduction to PAM4 Signaling

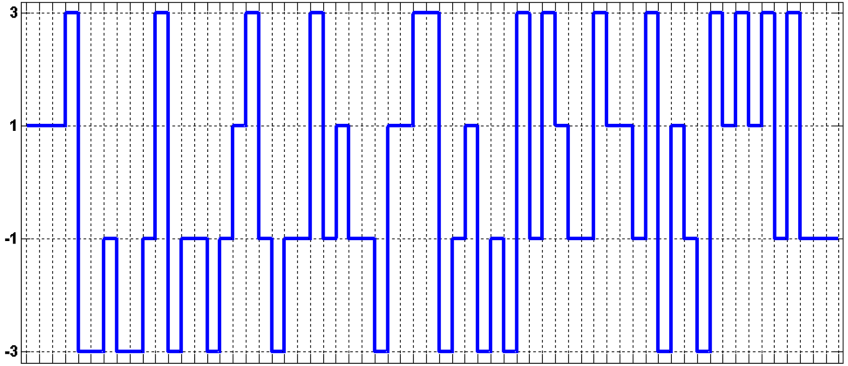
- **PAM4 – 4-level Pulse Amplitude Modulation**
- **Every 2 bits are mapped to one level (one symbol)**
- **Requires half of the bandwidth**
- **SNR penalty: ~9.5dB**
- **Linear mapping vs gray mapping**

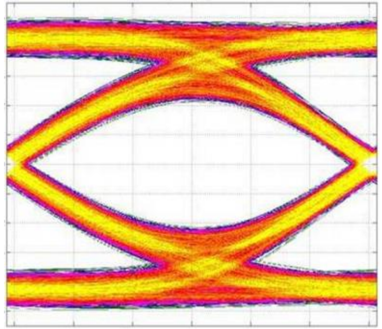




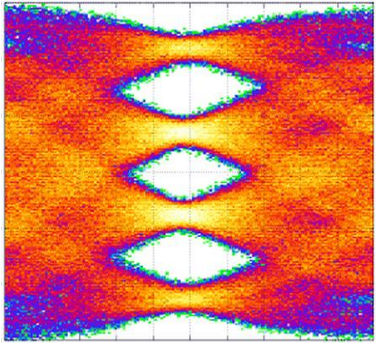
PAM4 Waveform and Eye Diagram







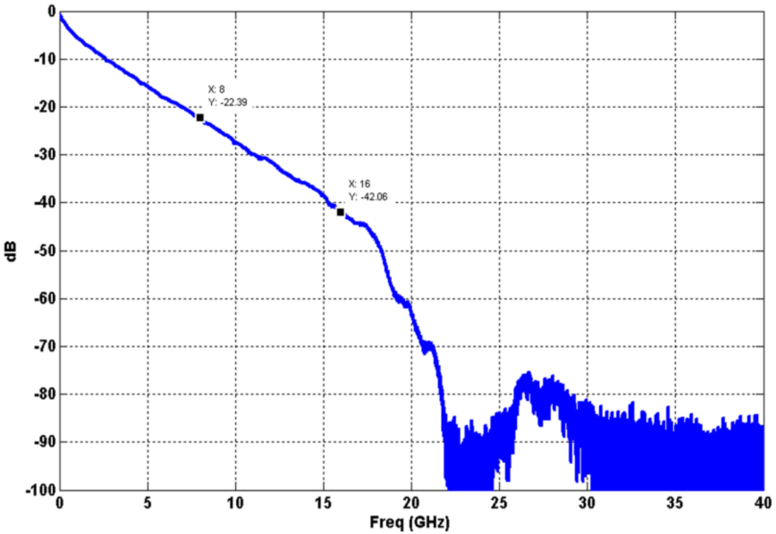
- NRZ has 2 levels (normalized to 1 and -1)
- Two levels form one data eye



- PAM4 has 4 levels (normalized to 3, 1, -1, and -3)
- Four levels form three data eyes

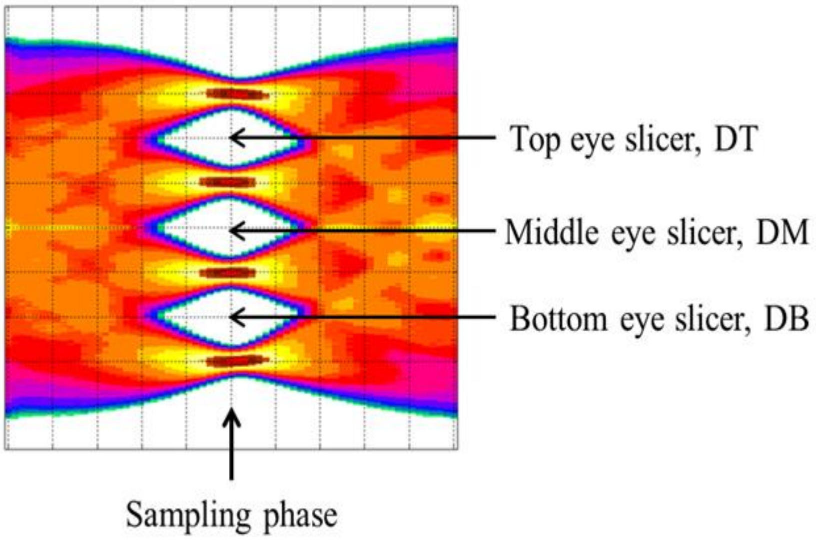
PAM4 Advantage Over NRZ – An Example

- Assume we need 32Gbps throughput.
- For NRZ, the Nyquist frequency is 16GHz. The loss is 42.1dB.
- For PAM4, the Nyquist frequency is half, 8GHz. The loss is 22.4dB.
- The net difference is nearly 20dB, much larger than 9.5dB penalty.
- 42dB is by itself very difficult to equalize, making NRZ extremely challenging.
- In this case PAM4 might be a viable candidate for this link system.



How PAM4 Signal is Detected?

- **PAM4 signaling detection**



$$if\ x_k \geq DT, then\ \widehat{x_k} = 3$$

$$else\ if\ x_k < DT\ \&\ x_k \geq DM, then\ \widehat{x_k} = 1$$

$$else\ if\ x_k < DM\ \&\ x_k \geq DB, then\ \widehat{x_k} = -1$$

$$else\ \widehat{x_k} = -3$$

- **Three data slicers are needed for detecting four signal levels**
- **Data slicer levels are usually adapted to achieve best system SNR**
- **Typically, DB = -DT, and DM=0**

IBIS-AMI Modeling for PAM4 Signaling – TX

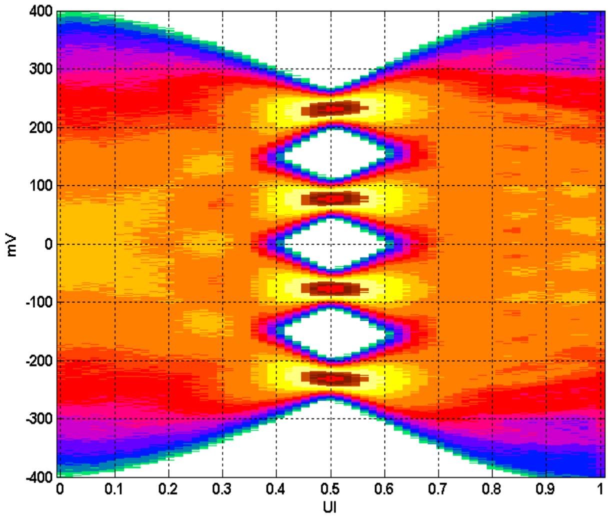
- TX DLL input needs to switch between 0.5V, 0.5/3V, -0.5/3V and -0.5V, represent the 4 normalized levels, 3, 1, -1, and -3
- There is no need to make changes to the TX DLL interface for PAM4, from NRZ
- The simulator is responsible for mapping a given NRZ bit stream into a PAM4 data stream for a given coding scheme
- Impairments, such as jitter and noise, are handled the same as that for NRZ

IBIS-AMI Modeling for PAM4 Signaling – RX

- RX DLL passes slicing levels to the simulator through *AMI_parameters_out* in AMI_GetWave()
- EDA tools use these slicer levels for deriving 3 sets of bathtub curves, and for SER/BER calculations
- An NRZ equivalent merged bathtub curve and eye diagram can be formulated in the post processing
- FEC is not currently included in the AMI modeling, but could be another topic to study next

PAM4 Signal Eye Diagram

- There are three vertically stacked eyes
- Each eye is treated with respect to its own data slicer
- For ADC based architecture, there is only one sample per symbol, thus no conventional eye diagram exists
- From simulation point of a virtual eye can be constructed



PAM4 Signal Bathtub Curves

- Three sets of independent bathtub curves are formulated
- Each set contains a vertical bathtub for voltage and a horizontal bathtub for timing
- Each slicer samples every symbol regardless of the expected signal level
- An error may be counted in multiple bathtub curves (e.g. a level -3 signal appears above DM)

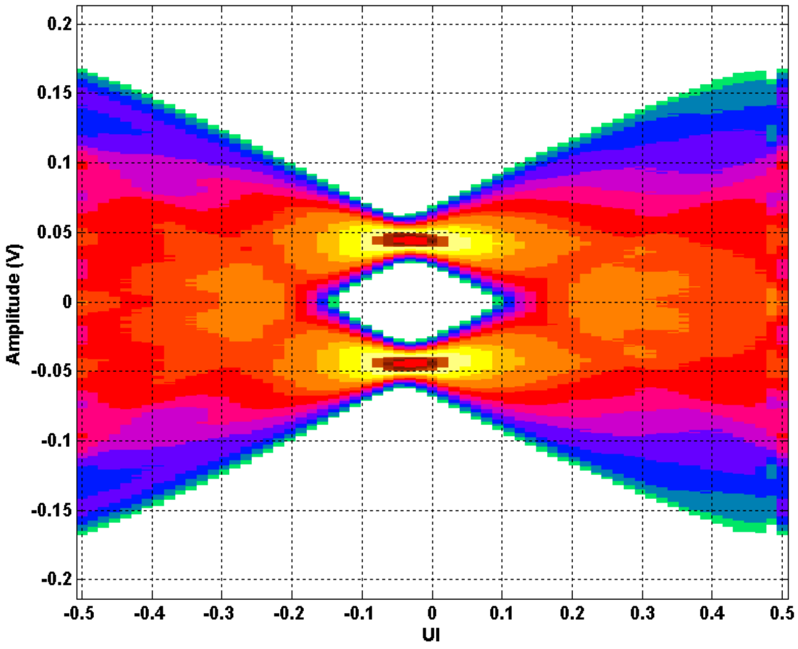
Slicer level	Logic high traces	Logic low traces
DT	$v_3(t) - DT(t)$	$v_1(t) - DT(t)$ $v_{-1}(t) - DT(t)$ $v_{-3}(t) - DT(t)$
DM	$v_3(t) - DM(t)$ $v_1(t) - DM(t)$	$v_{-1}(t) - DM(t)$ $v_{-3}(t) - DM(t)$
DB	$v_3(t) - DB(t)$ $v_1(t) - DB(t)$ $v_{-1}(t) - DB(t)$	$v_{-3}(t) - DB(t)$

PAM4 Merged Eye and Bathtub Curves Construction

- Bathtub based on the following equivalent eye construction

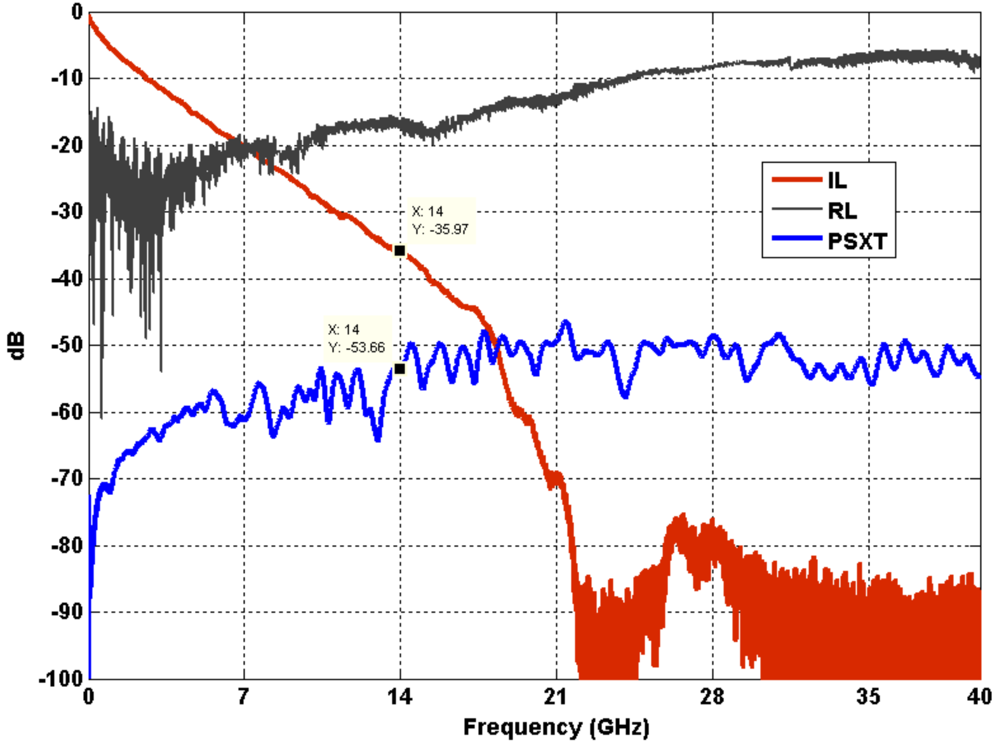
$v_3(t) - DT(t)$	$v_1(t) - DM(t)$	$v_{-1}(t) - DB(t)$	Logic 1
--			0V
$v_1(t) - DT(t)$	$v_{-1}(t) - DM(t)$	$v_{-3}(t) - DB(t)$	Logic 0

- Consolidated to only one set of bathtub curves
- No double counting of errors



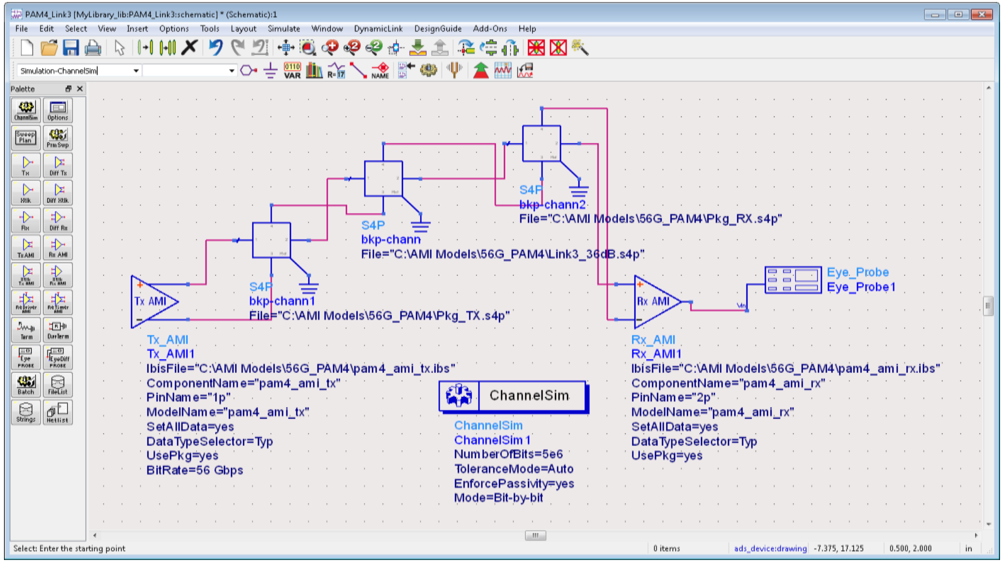
An Examples of AMI Model Simulation of PAM4

- An AMI model for 56G PAM4 is constructed
- Simulation conditions:
  - 56G PAM4 with Gray coding
  - IL = 36dB at 14 GHz
  - RL = 17dB at 14 GHz
  - PSXT = -54dB at 14 GHz



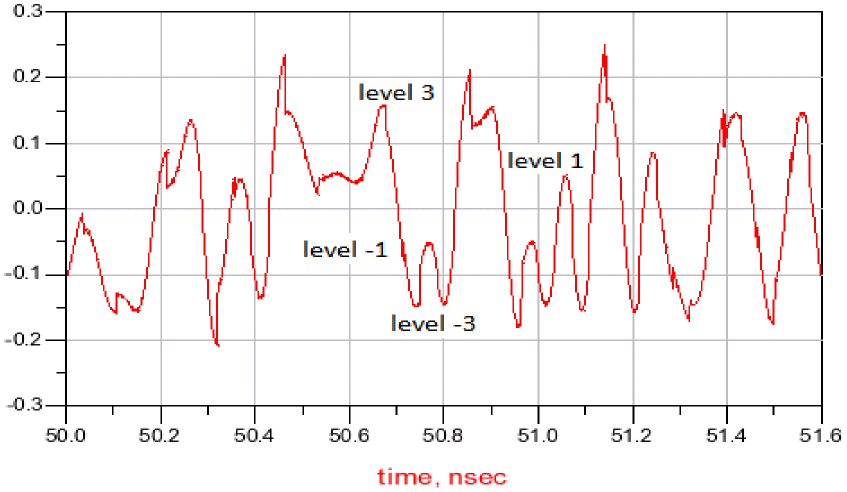
AMI Model for PAM4 Simulator Setup

- Test bench setup is in ADS (modified version)
- ICN is computed from the crosstalk aggressors
- ICN is then treated as noise, to simply the setup



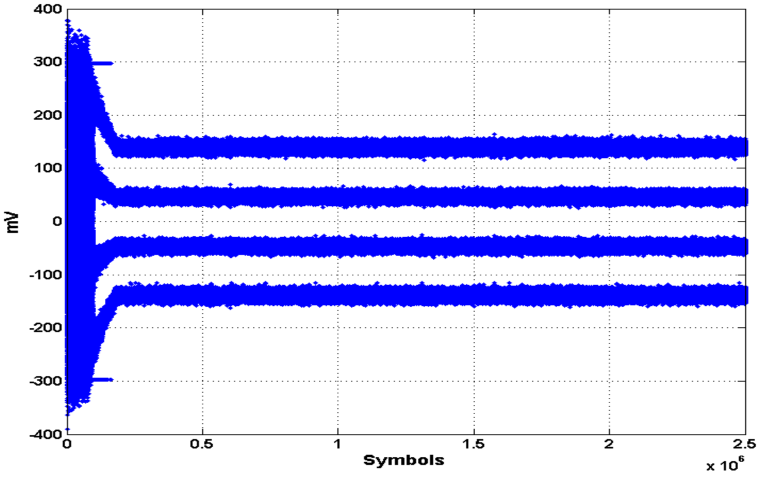
Simulated RX Output – Waveform

- A section of waveforms at data slicers are shown to the right
- The waveform and data slicer levels are used for post processing
- The three data slicer levels are changing with time
- The data slicer levels are output from the RX DLL



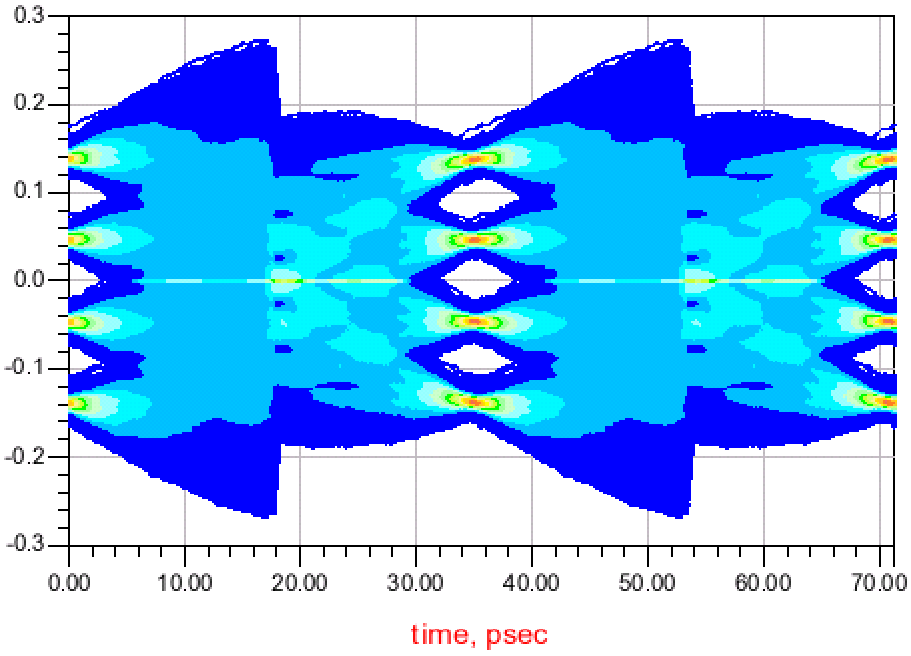
Simulated RX Output – Sampled Eye

- RX output at sampling point, the “sampled eye”, which is a function of time (symbols)
- For post processing it is important to ignore enough symbols to make sure the adaptation converged
- System SER/BER can be computed either through true comparison or statistical computation



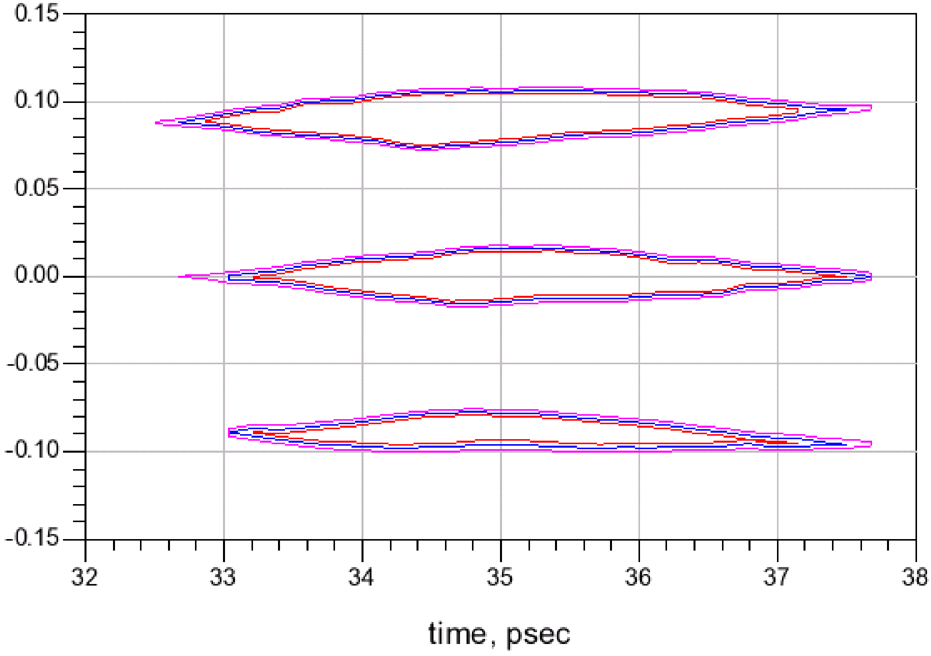
Simulated RX Output – Eye Diagrams

- **Eye diagram constructed from ADS for the case study**
- **Clock ticks are used same as in NRZ AMI modeling**
- **Note that ADS always shows two UI of the data**



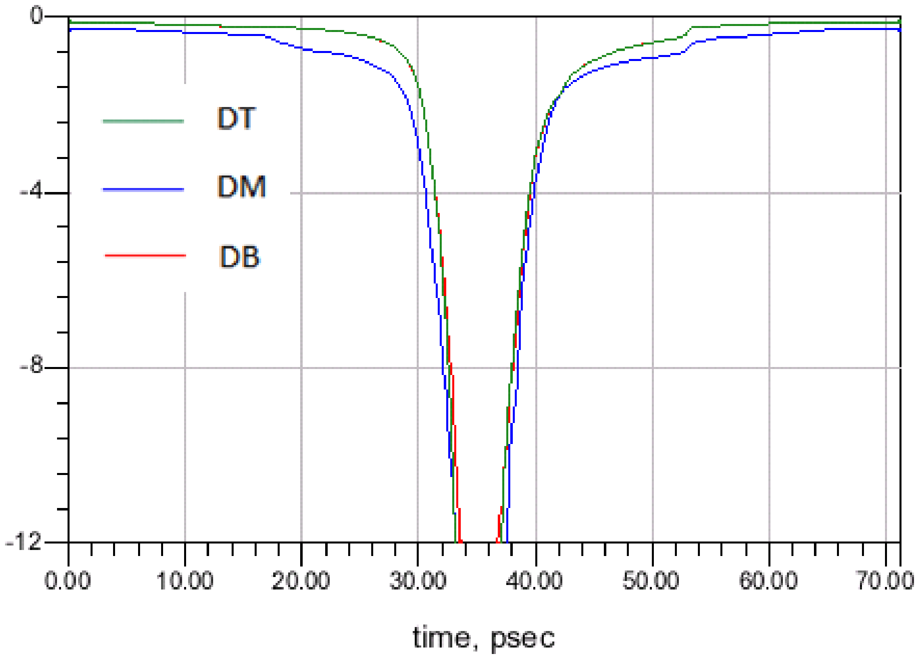
Simulated RX Output – SER Contours

- **Three sets of PAM4 SER contours are constructed by ADS (at 1E-10, 1E-11, and 1E-12)**
- **Each set is centered around its own data slicer**
- **System SER is determined by the worst of the set**



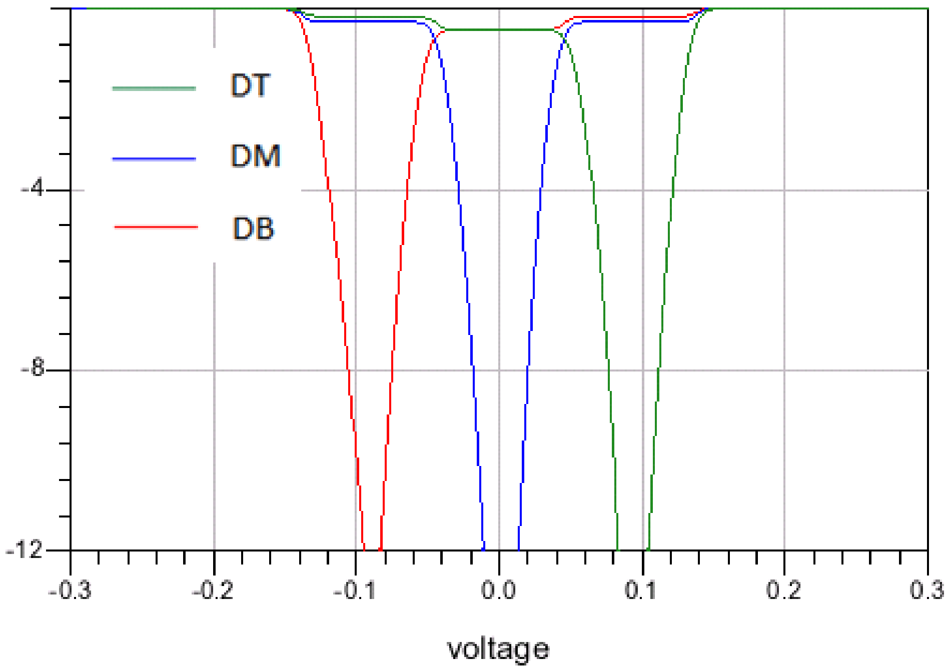
Simulated RX Output – Timing Bathtub Curves

- **Timing bathtub curves at the top, middle and bottom eye are formulated by ADS**
- **The overall performance is limited by the worst one**



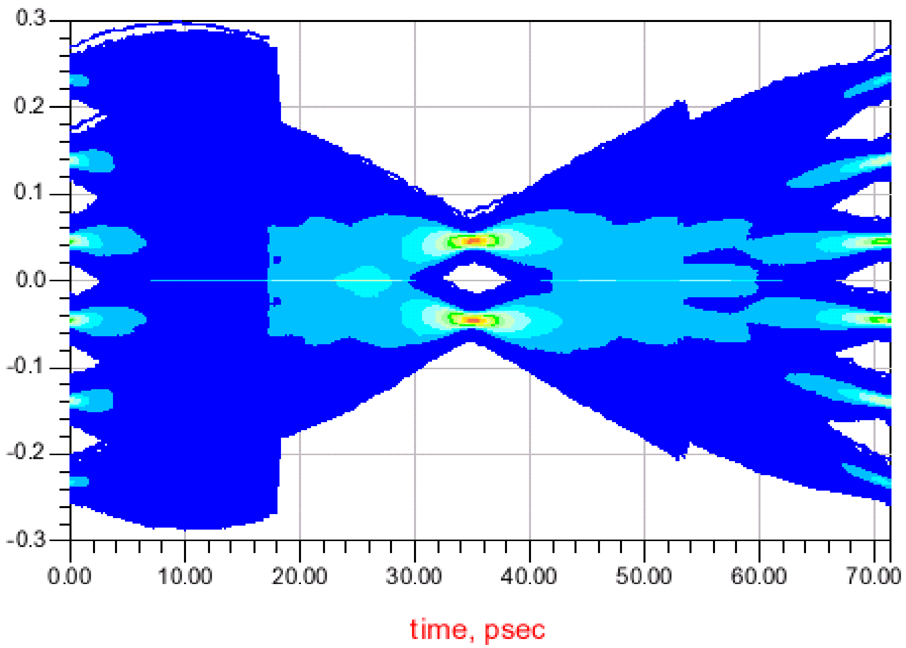
Simulated RX Output – Voltage Bathtub Curves

- **Voltage bathtubs at the top, middle and bottom eye are formulated in ADS**
- **The overall performance is limited by the worst one**



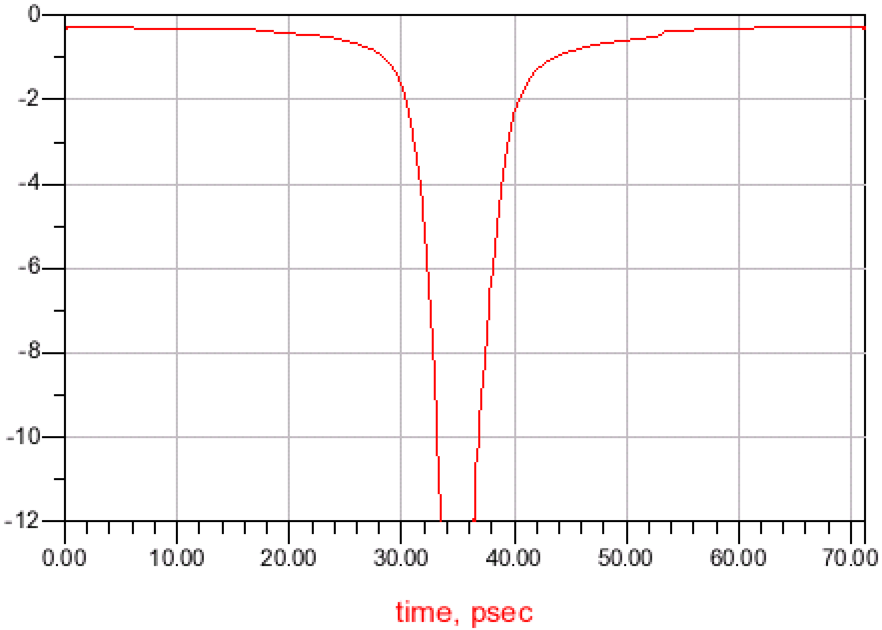
Simulated RX Output – Merged NRZ Eye

- **Merged NRZ-equivalent eye is constructed by ADS**
- **As ADS uses 2-UI to do the construction, only center 1-UI portion reflects an NRZ eye**
- **This makes the post processing similar as in NRZ**



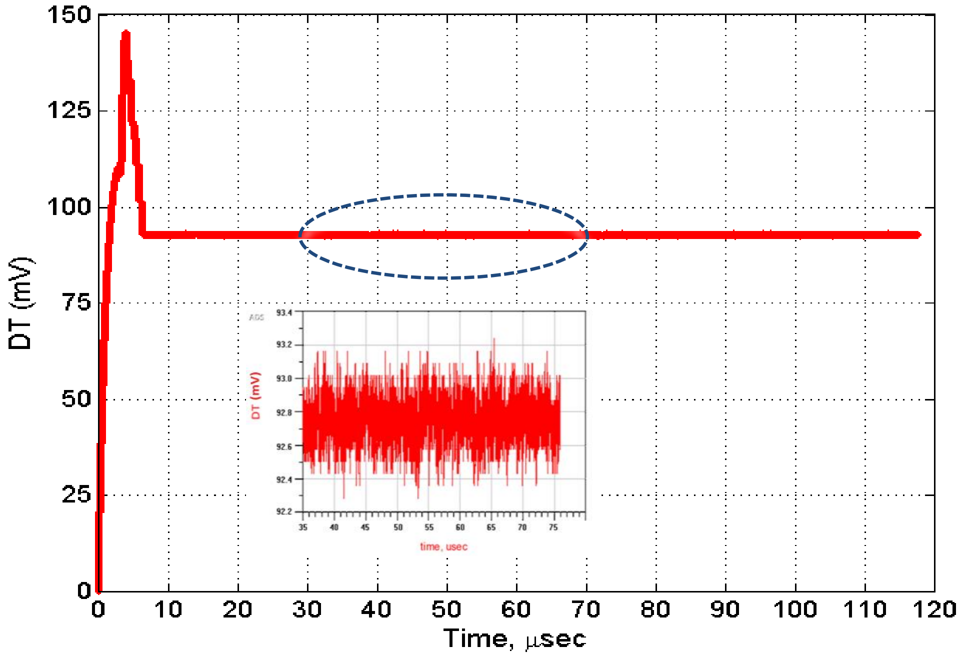
Simulated RX Output – Merged Timing Bathtub

- The merged NRZ-equivalent timing bathtub curve is constructed by ADS
- It alone can be used to determine the link system performance margin



Simulated RX Output – Data Slicer Level

- **Top eye data slicer, DT, from RX DLL output is plotted**
- **Its convergence profile provides useful information**
  - **Even after convergence, the slicer level is still dithering around some mean value**
  - **We need to ignore 10 μsec of the data, or about 280K UI**
  - **In this example DM is set to 0 and DB is tied to –DT for processing convenience**



Conclusions

- AMI modeling for PAM4 systems is illustrated
- TX needs to send 4 different levels at ±0.5V and ±0.5/3V
- RX needs to pass on adapted slicer levels to EDA tools using *AMI_parameters_out* for eye plots and BER bathtubs/contours
- Three sets of bathtub curves can be merged into one set
- NRZ and PAM4 dual mode support is both feasible and desirable
- BER/SER calculation should consider the coding scheme
- FEC is important for PAM4 systems, but not included here