Using measured waveform data in AMI simulation for system design

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Problem Statement

- In high-speed link systems, the pivotal elements ensuring design success are transceiver equalization and Clock Data Recovery (CDR)

- To evaluate the overall link performance, designers should be able to analyze Rx post-processing signal

- *However, in the lab measurements, measuring signal inside the Rx chip is very limited*

- *Additionally, Tx AMI models are not always available*

- In this presentation, we propose an innovative approach that leverages the Rx AMI model to simulate the Rx post-processing signal based on the measured input waveform.

KEYSIGHT

Measurement and Simulation Approach

Highlights

- Transceiver equalization and CDR are essential in high-speed link systems

- Designers need to analyze Rx post-processing signal to assess the overall link performance

- On the measurement side, access to the signal inside the Rx chip is limited

- On the simulation side, Tx models are not always available

- Solution: combine measurement and AMI modeling
  - measure signal waveform at Rx input
  - process measured waveform with Rx AMI model to simulate Rx post-processing signal
  - No Tx model is required

- Generalization:
  - measure signal waveform at any location of the channel, e.g. at Tx output
  - in simulation, apply the measured waveform as input to any channel whose impedance matches the measurement condition

Measurement To Simulation Workflow

- **Step 1**: measure the waveform at Rx input. No specific data pattern is required.

- **Step 2**: extract the impulse response of the upstream channel (Tx EQ + Tx analog + passive channel) from the measured waveform. Call Rx AMI_Init with the extracted impulse response as input.

- **Step 3a**: in bit-by-bit simulation with Rx model that has AMI_GetWave, call Rx AMI_GetWave with the measured waveform as input

- **Step 3b**: in bit-by-bit simulation with Rx model that doesn't have AMI_GetWave (Init-only model), convolve the Rx AMI_Init output impulse response with the bit/symbol pattern

- **Step 3c**: in statistical simulation, use the Rx AMI_Init output impulse response to compute the Rx output eye

Rx input waveform

Processed by Rx AMI model

Rx output signal and eye

Tx

Rx
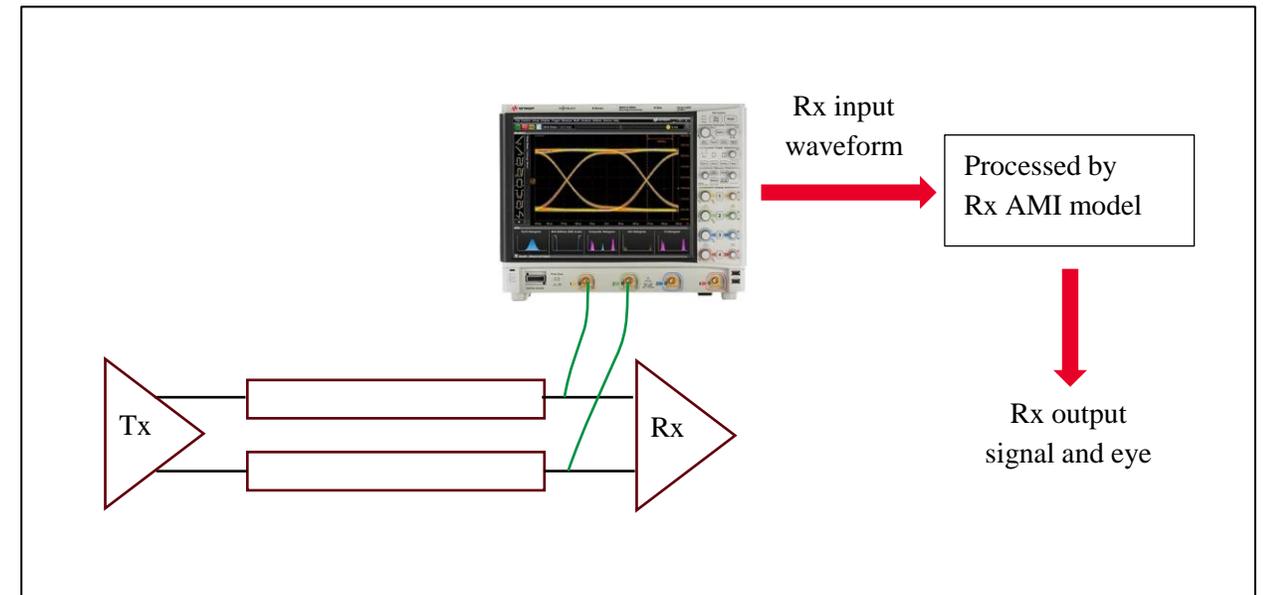
Verification

- Compare with end-to-end AMI simulation

- Use simulated Rx input waveform as measured waveform

- Test NRZ, PAM3 & PAM4

- Baud rate: 25 Gbaud

- Tx model
  - 4-tap FFE

- Rx model
 - 3-pole-2-zero CTLE
  - 10-tap DFE
  - 2nd order CDR

Processed by Rx AMI model → Rx output signal

differential input waveform

End-to-end AMI simulation
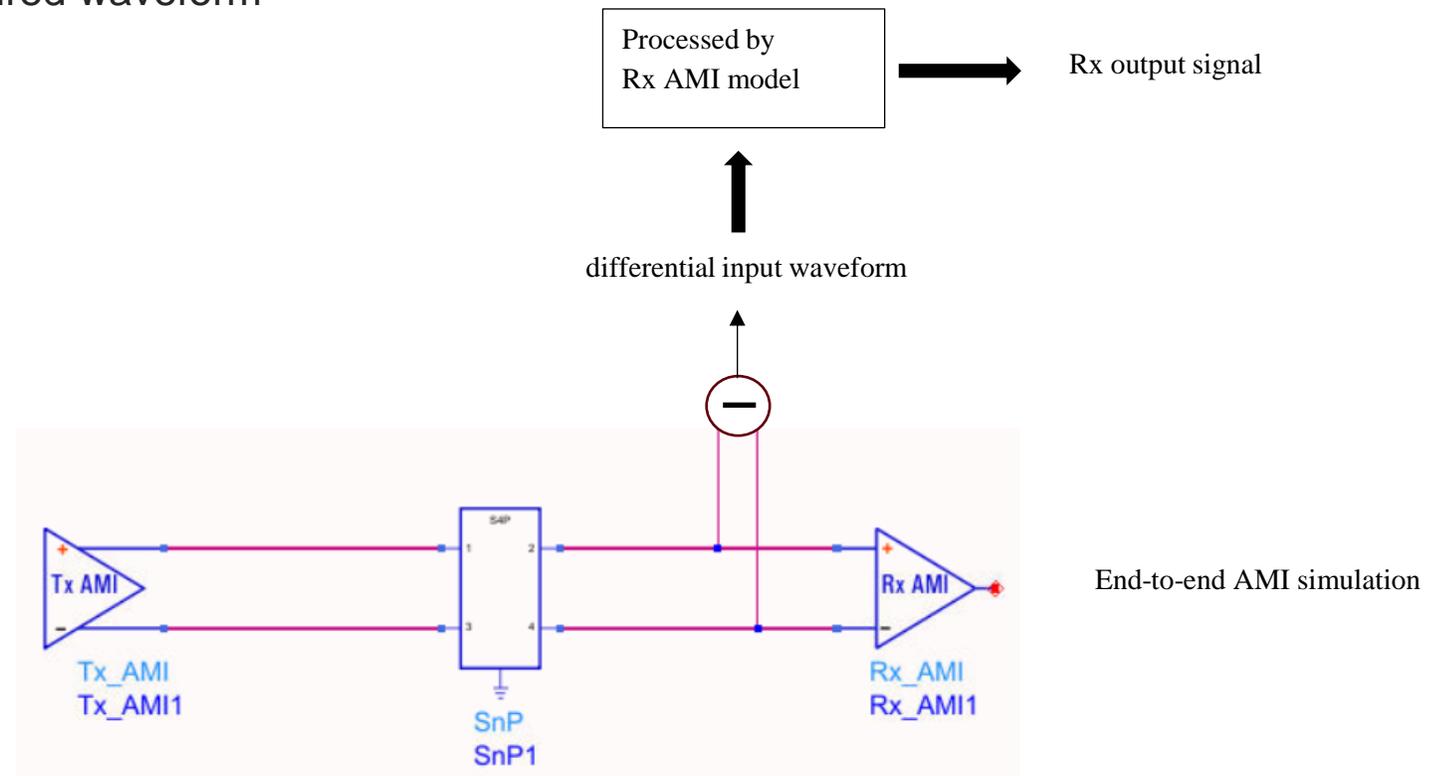
Verification (cont'd)

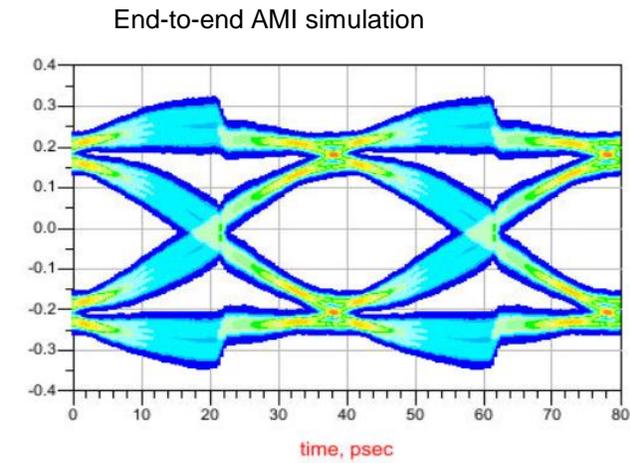- Channel model: 29 dB loss at the Nyquist frequency of 12.5 GHz
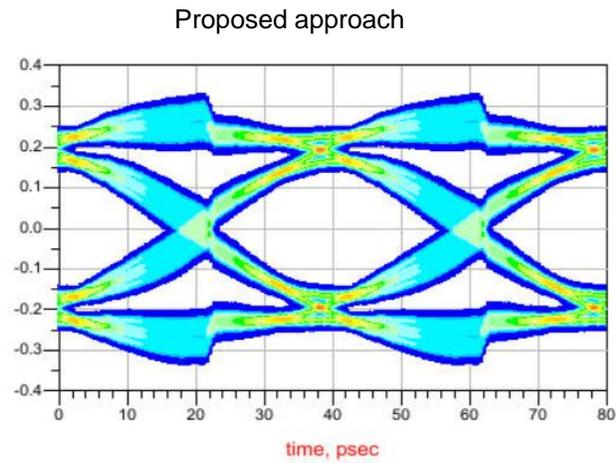
- Package is lossless/bypass in initial studies
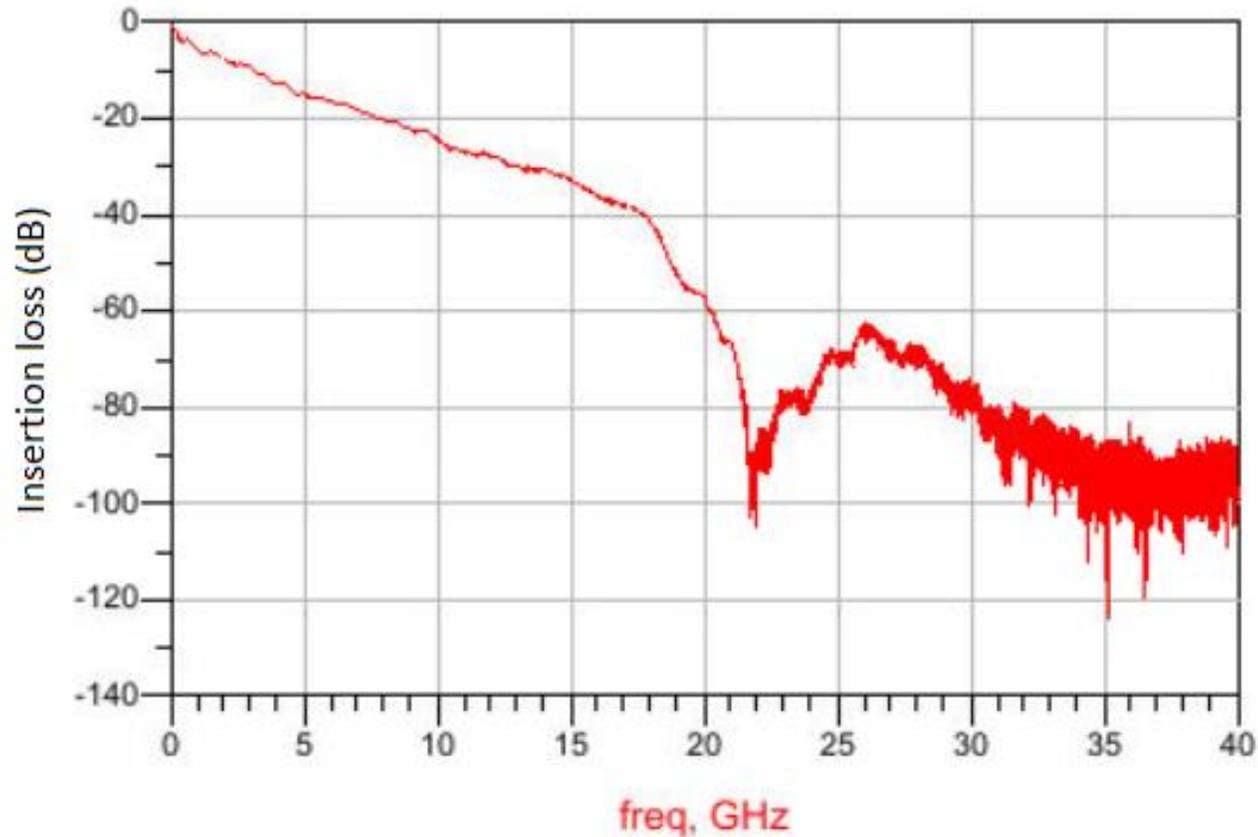
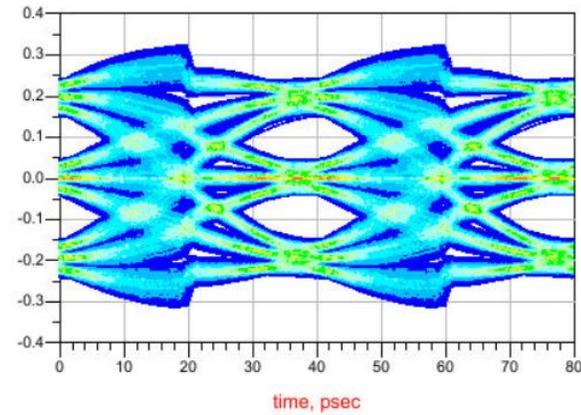# Verification: NRZ

Rx output eye of 10K bits

Proposed approach

End-to-end AMI simulation

Rx output eye of statistical simulation
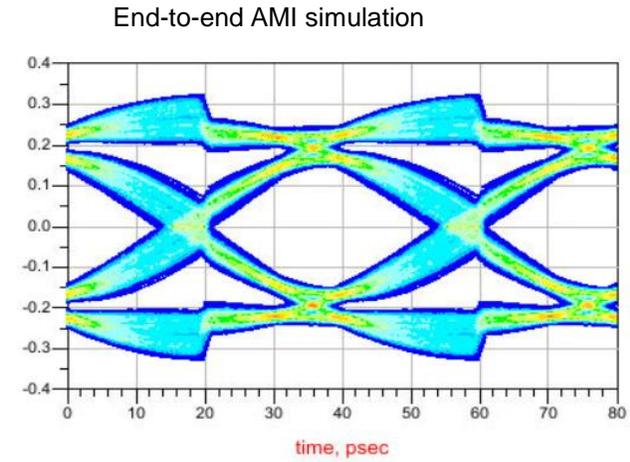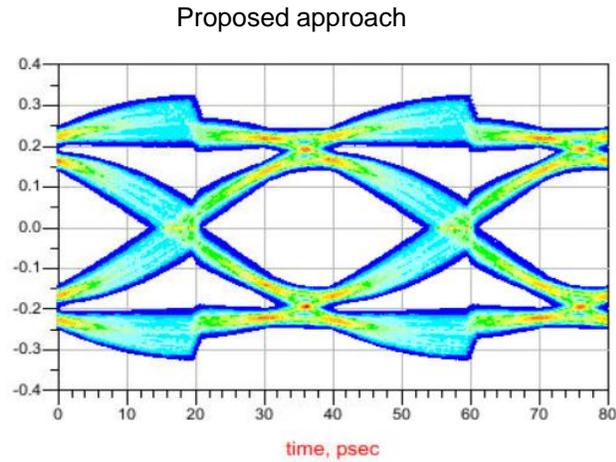
Proposed approach
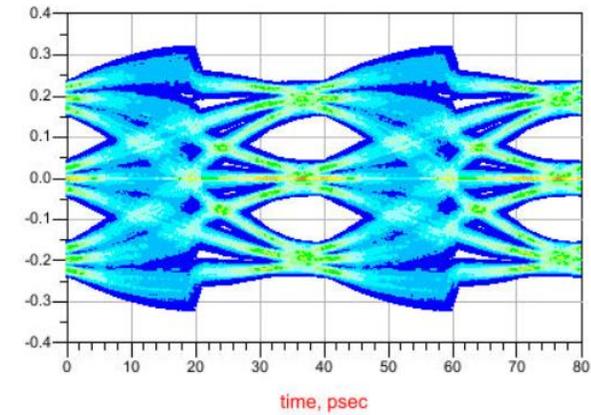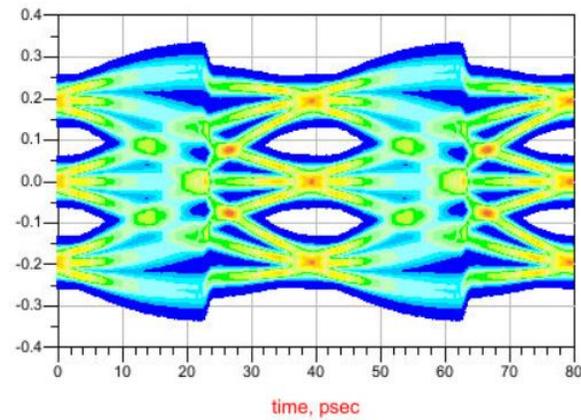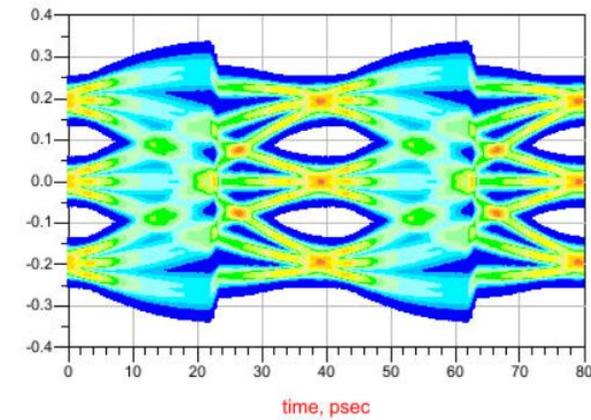
End-to-end AMI simulation

Verification: PAM3

Rx output eye of 10K symbols

Proposed approach

End-to-end AMI simulation

Rx output eye of statistical simulation

Proposed approach

End-to-end AMI simulation

Verification: PAM4

Rx output eye of 10K symbols

Proposed approach

End-to-end AMI simulation

Rx output eye of statistical simulation
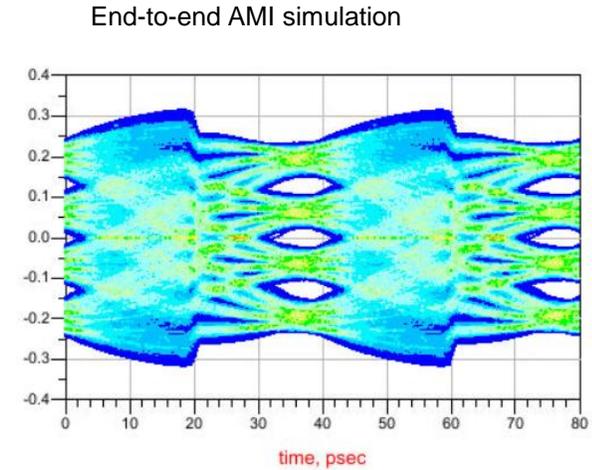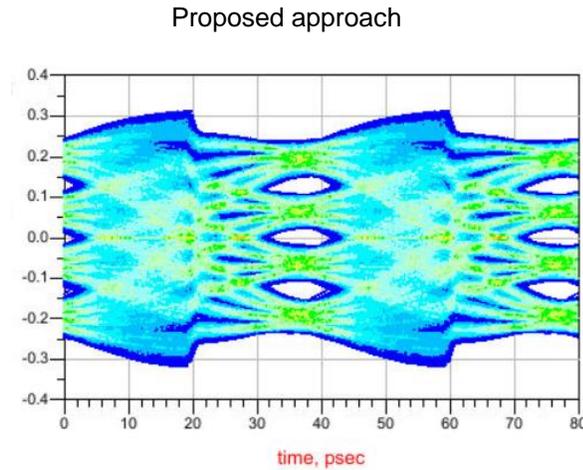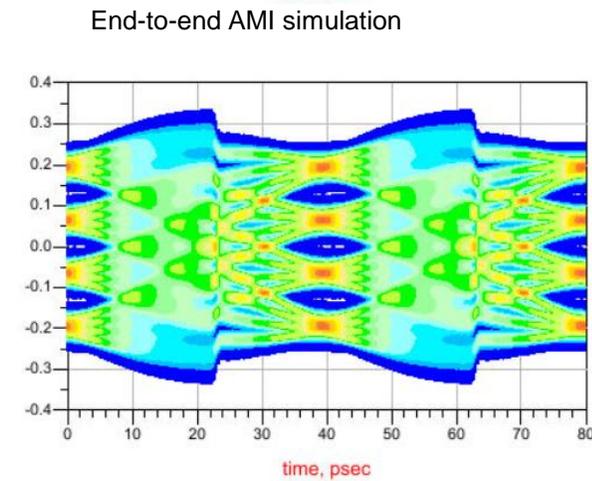
Proposed approach

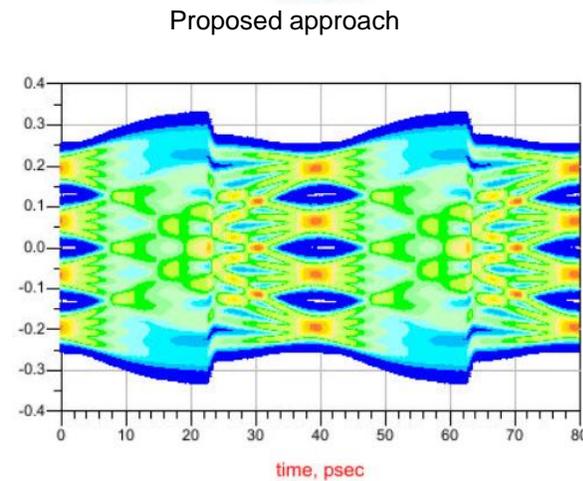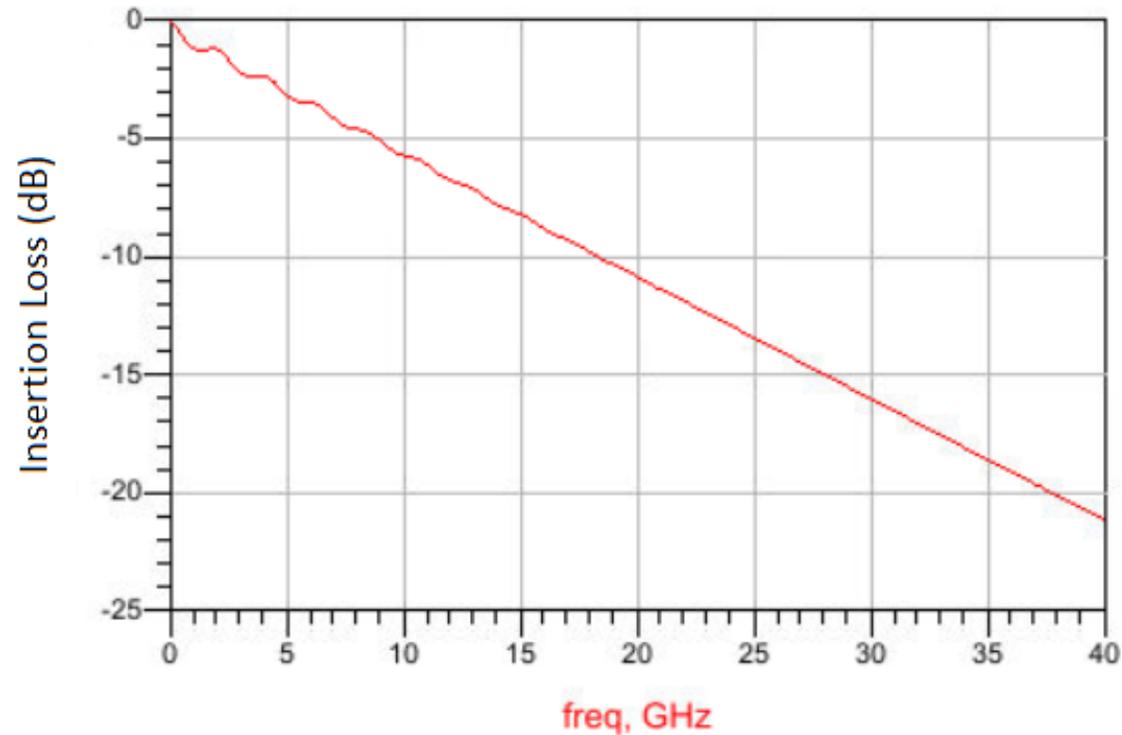End-to-end AMI simulation

Package Effect

- Waveform is usually measured at Rx package pins

- Rx AMI DLL's input is assumed to be at the die node

- Need to include Rx package effect

- Solution: Rx package impulse response is characterized and applied to measured waveform and extracted channel impulse response

- Note: Rx package model must match the physical Rx package used in measurement
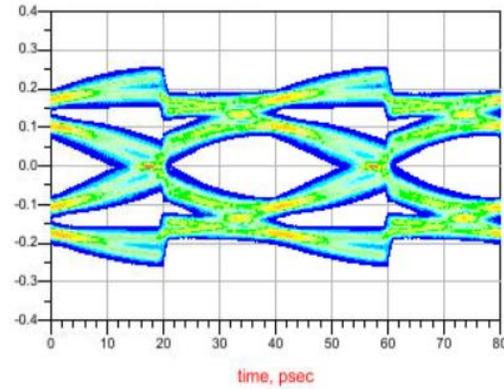
Package Effect Verification

- Replace the lossless/bypass package model in previous studies with lossy package model

- Package loss is 6.9 dB at the Nyquist frequency of 12.5 GHz
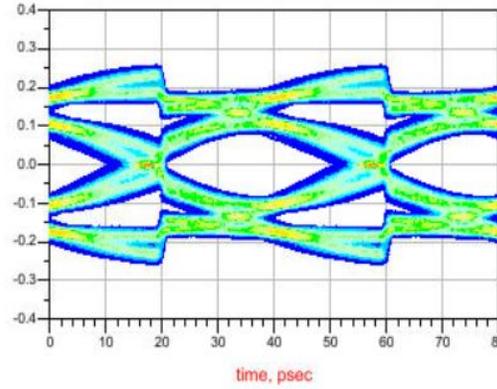
Package Effect Verification (cont'd)
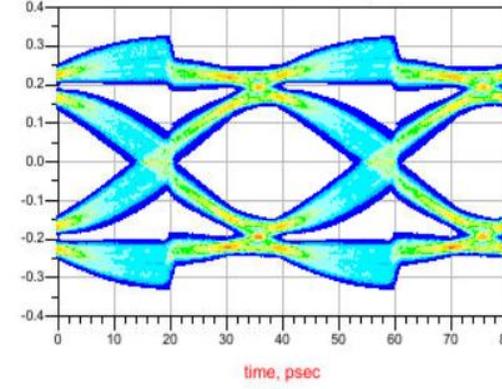
Rx output eye of 10K bits

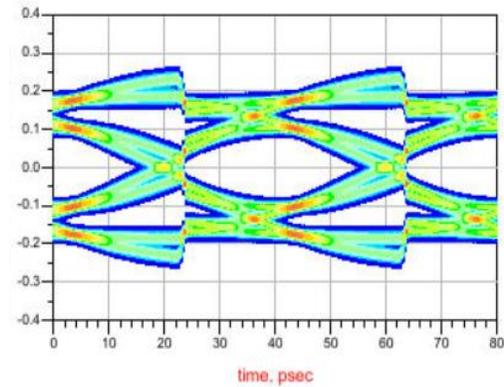| Proposed approach w pkg | End-to-end AMI sim w pkg | End-to-end AMI sim w/o pkg |

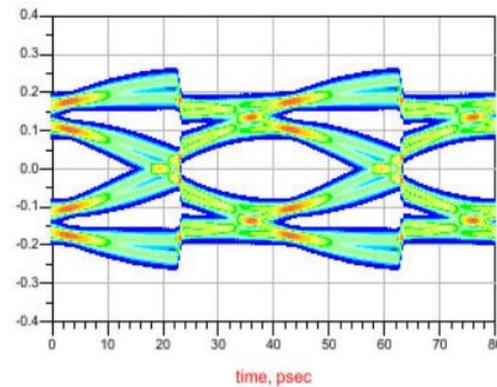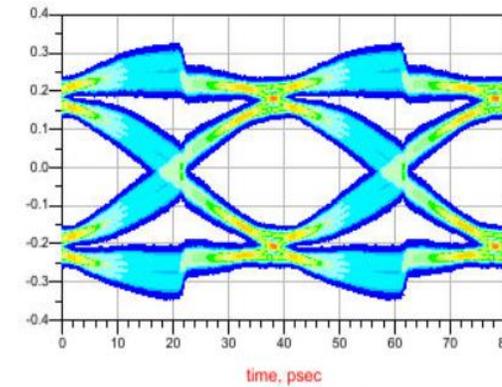Rx output eye of statistical simulation

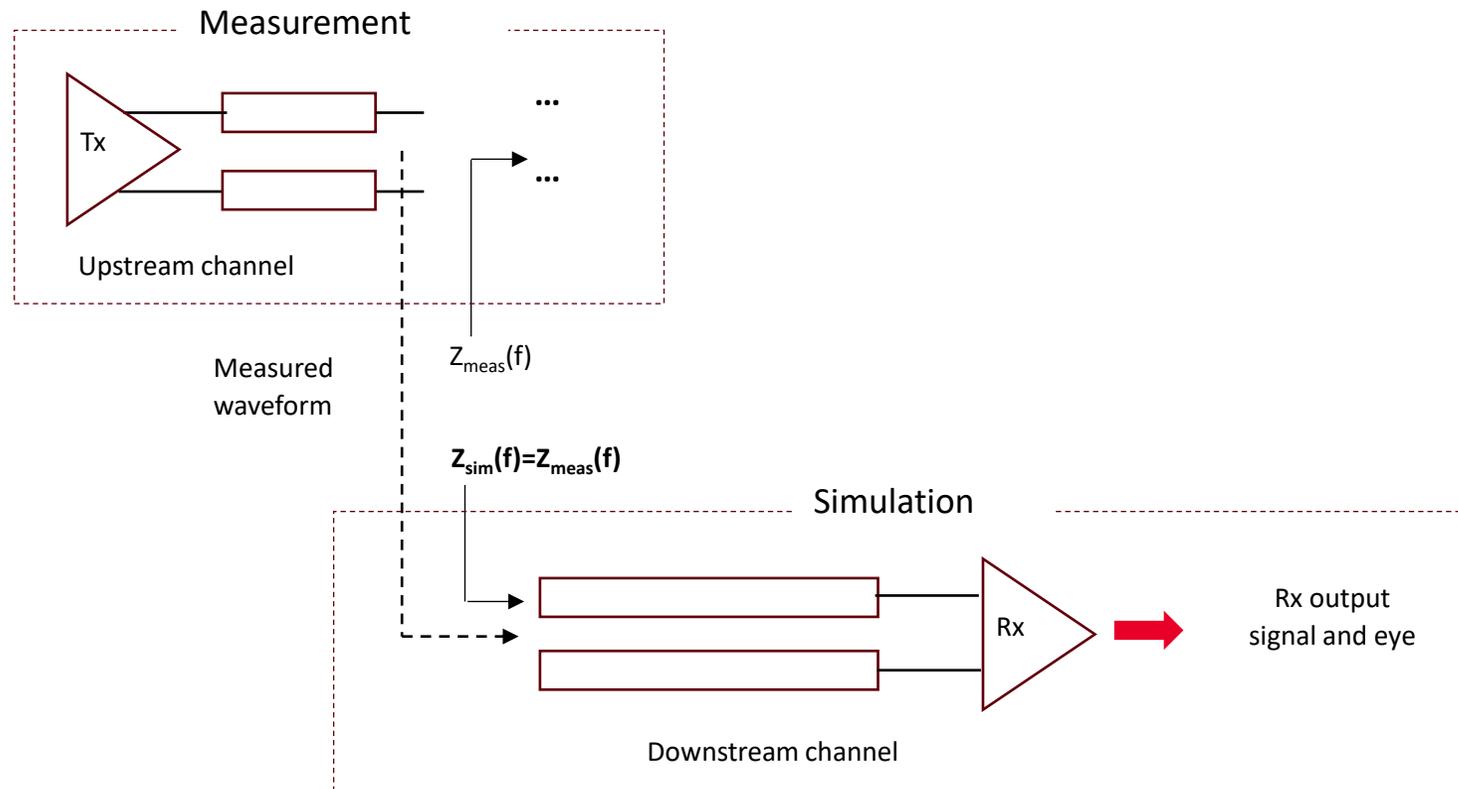| Proposed approach w pkg | End-to-end AMI sim w pkg | End-to-end AMI sim w/o pkg |

Generalized Flow

- Extend the approach for Rx package effect to process data measured at locations other than Rx input

Generalized Flow (cont'd)

- Measure waveform at any location of the channel, e.g. at Tx output. No specific data pattern is required.

- Extract the upstream channel impulse response (Tx EQ + Tx analog + upstream passive channel) from the measured waveform

- In simulation, characterize downstream analog channel impulse response (downstream passive channel + Rx analog).

- Combine upstream and downstream channel impulse responses to obtain the input impulse response to Rx AMI_Init

- If Rx model has AMI_GetWave, apply downstream analog channel impulse responses to the measured waveform to obtain the input waveform to Rx AMI_GetWave

- Note: the measured waveform is valid only if the downstream channel's impedance matches the measurement condition

KEYSIGHT

Simulation vs. Measurement Validation

- Channel output signal is measured by scope and processed by scope's built-in CTLE

- Jitter is tracked by scope's CDR

- Scope acts effectively as a Rx

- A Rx model is built to replicate scope's CTLE

- The Rx model is Init-only

- No GetWave, hence no CDR

- Compare post-CTLE eye between simulation and scope
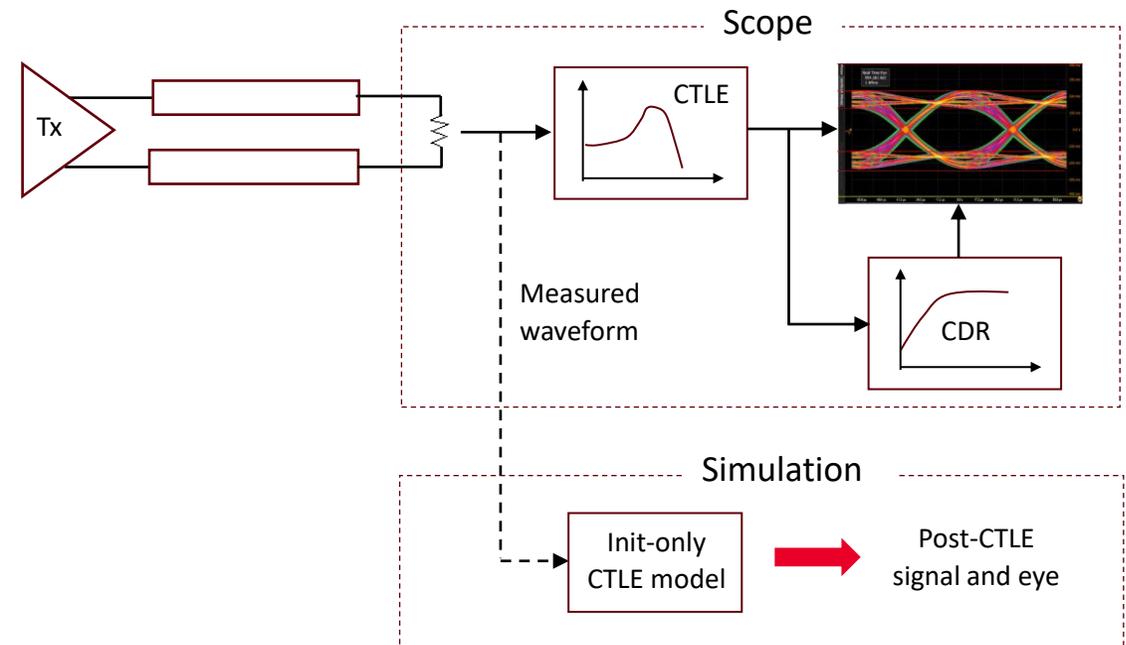
Simulation vs. Measurement Validation (cont'd)

- Measured and simulated eyes have the same amplitude and shape

- Simulated eye has large jitter due to the fact that the Rx model is Init-only and does not model CDR

Simulated post-CTLE eye (w/o CDR)　　　　　Measured post-CTLE eye (with CDR)
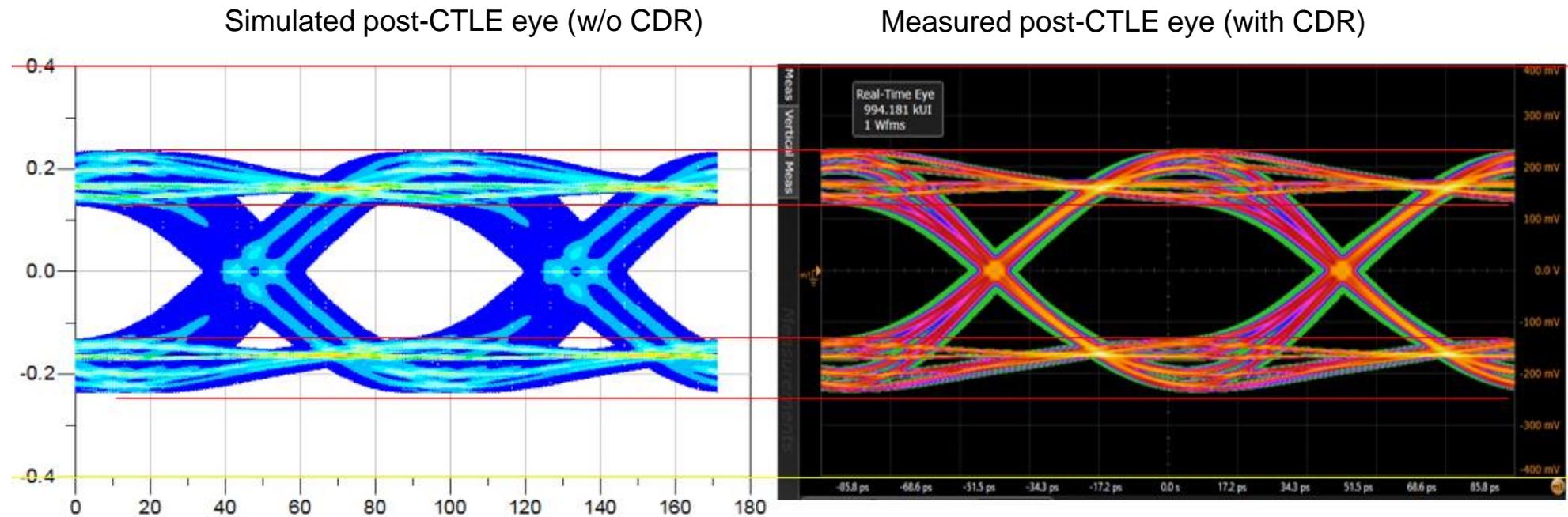
Application Cases

Case1: Pre-compliance testing using measured lab-sourced signal and Rx AMI model

- Using the calibrated BERT test signal, the SI simulation using Rx AMI can be done with channel/package models and Rx AMI model.

- The major benefit of this use case is that the user can estimate how much margin it has before silicon or package tape-out against the IO standard criteria.
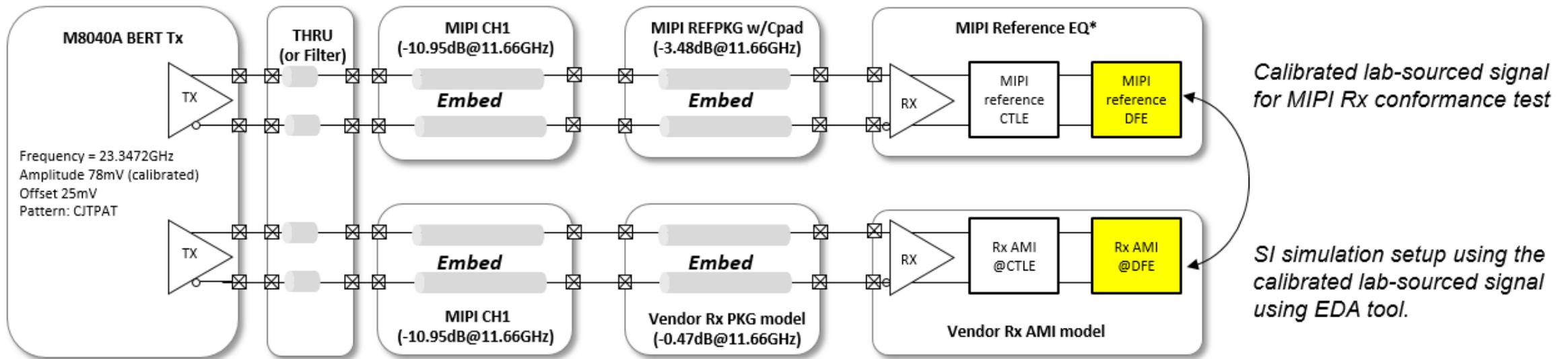
Case1: Pre-compliance testing using measured lab-sourced signal and Rx AMI model (cont'd)

- This is an example of lab-sourced signal calibration to use it for SI simulation using Rx AMI model.

Case1: Pre-compliance testing using measured lab-sourced signal and Rx AMI model (cont'd)

- After embedding the target channel and package, Rx SI simulation is done with the lab-sourced calibrated test signal.
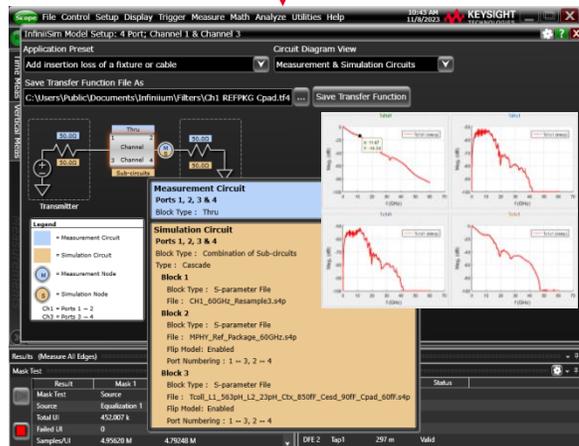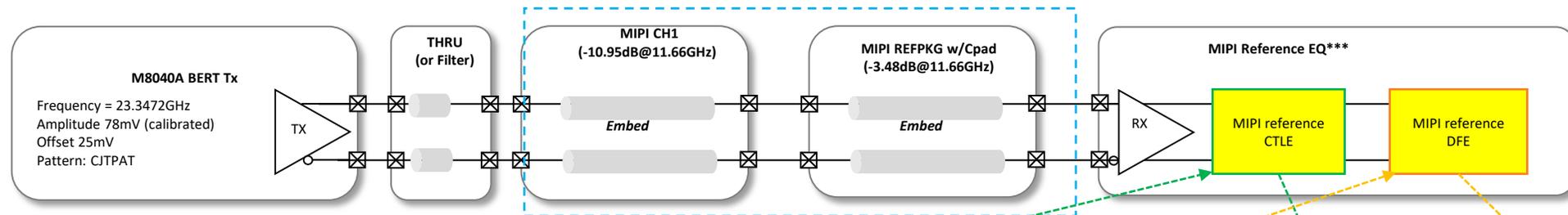
Case2: Channel simulation using measured Tx signal and Rx AMI model

- This example is to use the measured Tx signal ① from the test board for Rx SI simulation.

- Unlike the BERT use case, the Tx signal ② at the Tx bump (or BGA ball) should be acquired after de-embedding the test board channel.

- After embedding the target channel and package models, run Rx simulation and get the Rx equalized eyes at CTLE ③ and DFE ④.
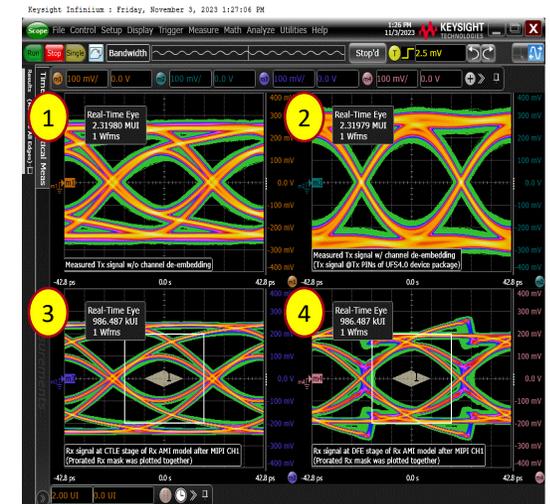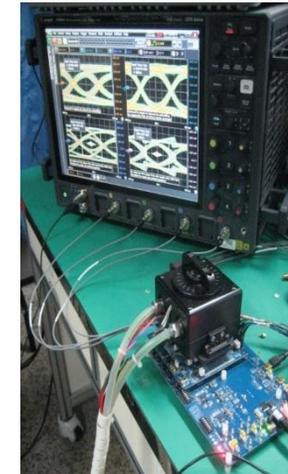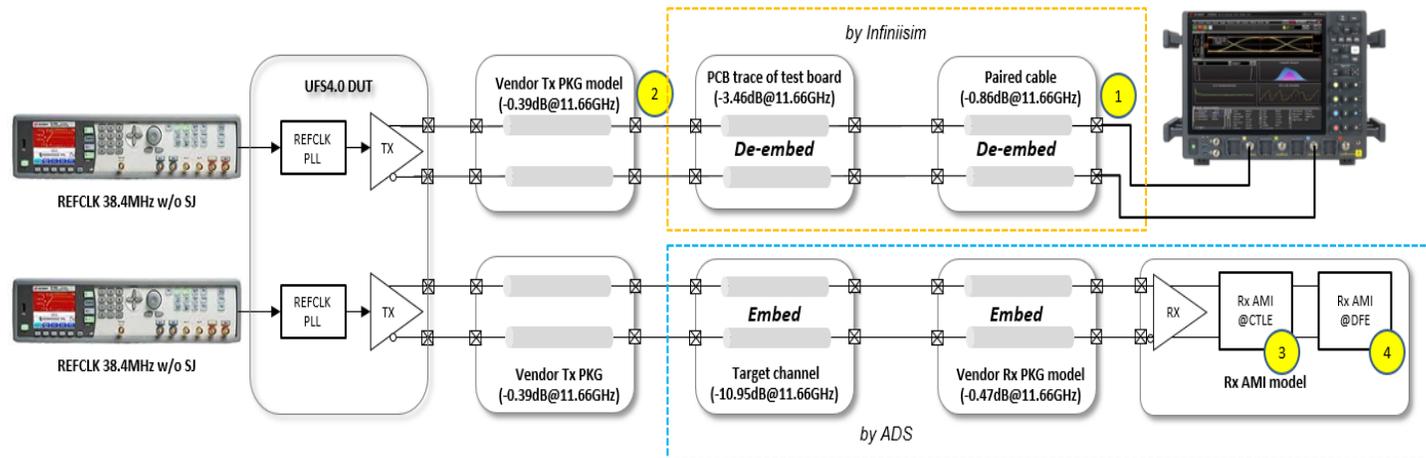
Case3.1: Rx SI simulation with the measured SJ injected Tx signal from DUT

- Tx output from the test board will have coupled Tx jitter since the intentional SJ was injected.

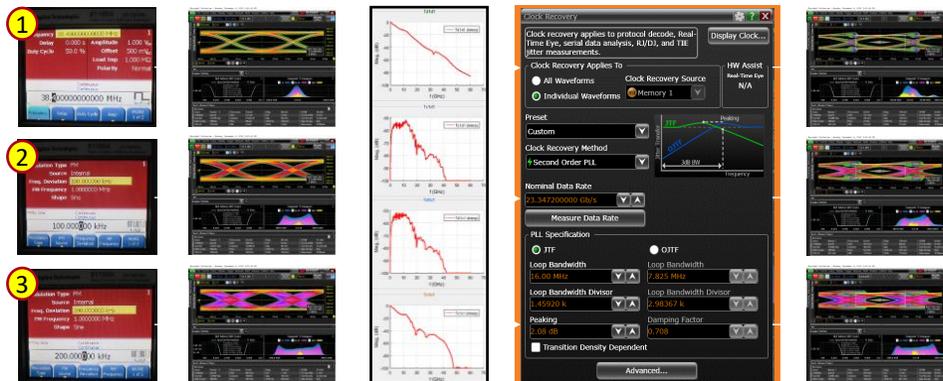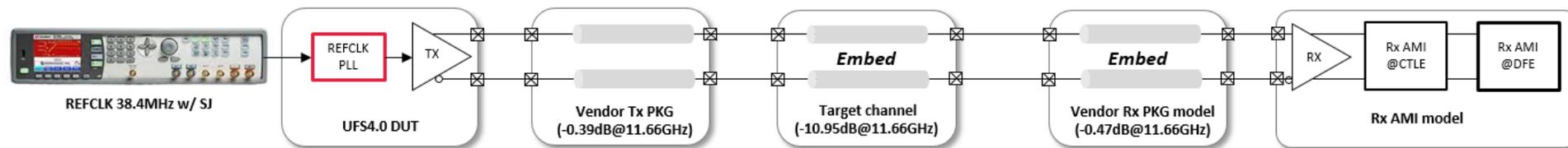- This is a test case when there is a coupled noise at REFCLK from buck regulator or others.

- After acquiring the measured Tx signal with SJ, it is used for SI simulation for the target channel.

- If the reference clock recovery setting can have a margin, the DUT is supposed to have no problem.

In this examples, the SJ was intentionally injected to the REFCLK for the Tx output of to generate a stressed Rx eye, which does not violate the Rx eye mask spec.
① No SJ was coupled to the REFCLK 38.4MHz output of Keysight 81160A pulse function arbitrary generator.
② SJ frequency of 1MHz and its deviation as 100KHz was coupled to the REFCLK 38.4MHz output of Keysight 81160A pulse function arbitrary generator.
③ SJ frequency of 1MHz and its deviation as 200KHz was coupled to the REFCLK 38.4MHz output of Keysight 81160A pulse function arbitrary generator.

Case3.2: Rx SI simulation with the measured SJ injected Tx signal from DUT

- Since this simulation method can have a benefit to use the scope's clock recovery tool when plotting the eye diagram, the user can adjust the CDR parameters and check the margin against the noised Rx signals.

- This will help when deciding the optimal CDR setting of the DUT when it is suffered from the noise.


This SI simulation uses the real Tx waveform from the device under test.

① In this example, the REFCLK input to the DUT was supplied by Keysight 81160A pulse function generator with SJ of 2MHz and its frequency deviation as 100KHz as an example case.
② As like the previous other example, the captured waveform from the DUT will be used for SI simulation also, but there's unwanted phase noise at the DUT's output.
③ The required PLL bandwidth to have Rx jitter margin can be estimated by adjusting the "Loop Bandwidth" option of the clock recovery.
④ DFE waveform when the loop bandwidth is 16MHz.
⑤ DFE waveform when the loop bandwidth is 8MHz.
⑥ DFE waveform when the loop bandwidth is 6MHz.
⑦ DFE waveform when the loop bandwidth is 4MHz.

Case4: Correlation between simulation and M-PHY eye monitor

- The Rx eye-monitor is commonly used Rx margining feature for most high-speed IO standard.

- If the equalized Rx eye does not correlate with the Rx eye monitor result, this may be due to the actual clock recovery setting of the DUT is not same as reference CDR.

- Since this simulation method can have a benefit of various clock recovery methods, user can figure out the current CDR status and optimize the CDR setting of the DUT.
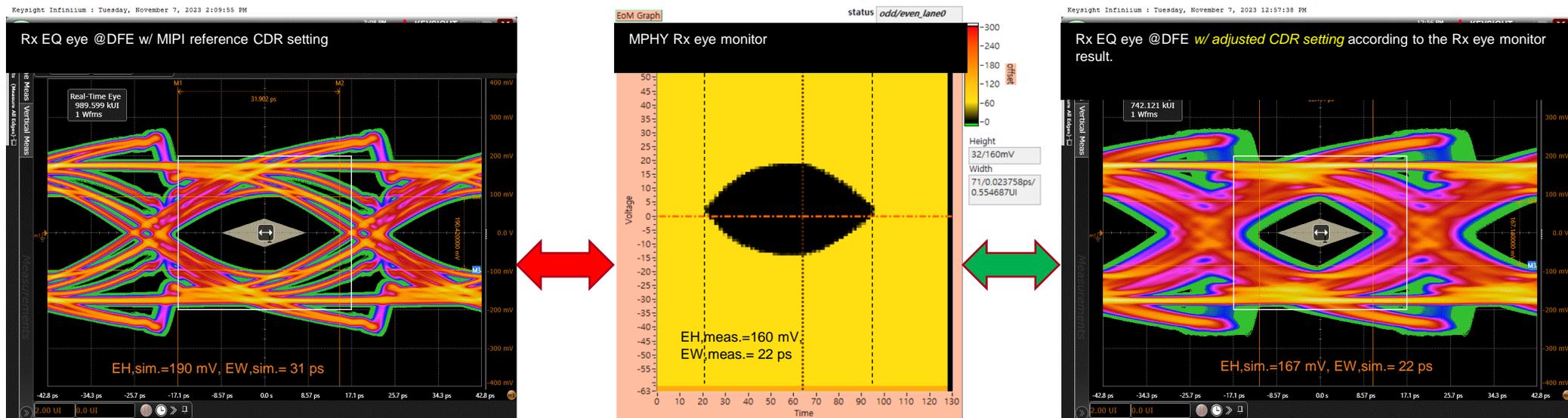
Conclusion

- In addressing the inherent challenges posed by limited access to probe the post-processing signal within the Rx device, we introduced a novel simulation flow that seamlessly integrates measurement and AMI modeling.

- The proposed approach leverages scope-measured Rx input waveforms, subsequently processed through the Rx AMI model to simulate the Rx output signal.

- Throughout this study, diverse application cases have been presented to demonstrate the practicality and efficacy of this approach.

Thank you!