



Empirical BER Characterization of Intra-Pair Skew for PCIe® at 64 GT/s

Signal Quality Analyzer-R Series
MP1900A



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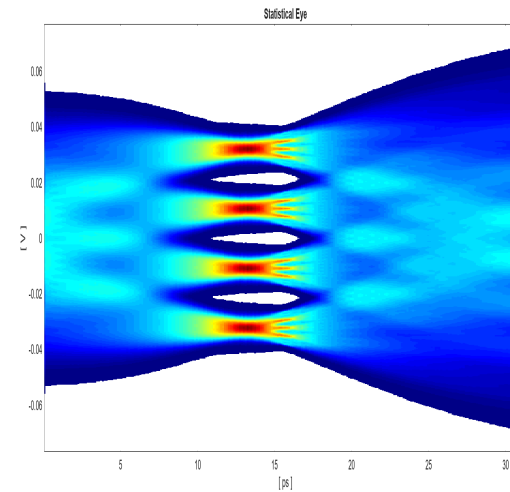
Granular Intra-Pair Skew Characterization with Anritsu MP1900A BERT

- Motivation
- Effect of Intra-Pair Skew on PAM4 Eye
- Skew on a Differential Channel & Eye
- Methodology
- Calibration
- Test Setup
- Results
- Summary
- Call to Action

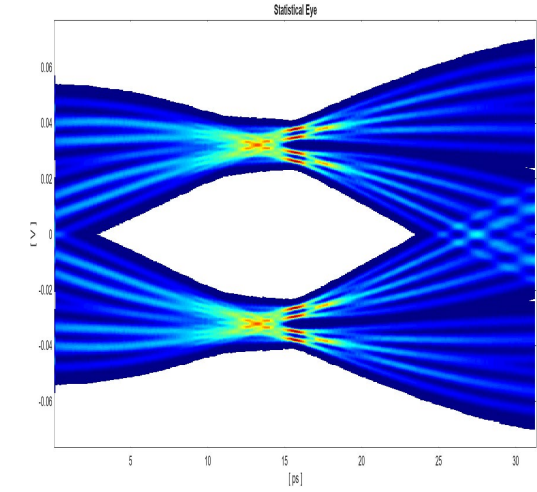
Motivation For Enabling Intra-Pair Skew

- What
 - Want the ability to empirically test intra-pair skew to quantify risk, correlate to sims, and drive skew tolerance guidelines
- Why
 - Transition to PAM4 signaling reduces eye by >3x, thereby increasing sensitivity to margin.
 - Differential to common conversion observed as distorted pos and neg eye within differential pair, needs to be further understood and correlated to BER.
 - Frequency sensitivity observed where pos and neg may have different frequency dips, need to know BER impact.
- How
 - Most BERTs do not natively support intra-pair skew.
 - Previous methods had limited capability, not granular enough.

PAM4 PCIe6



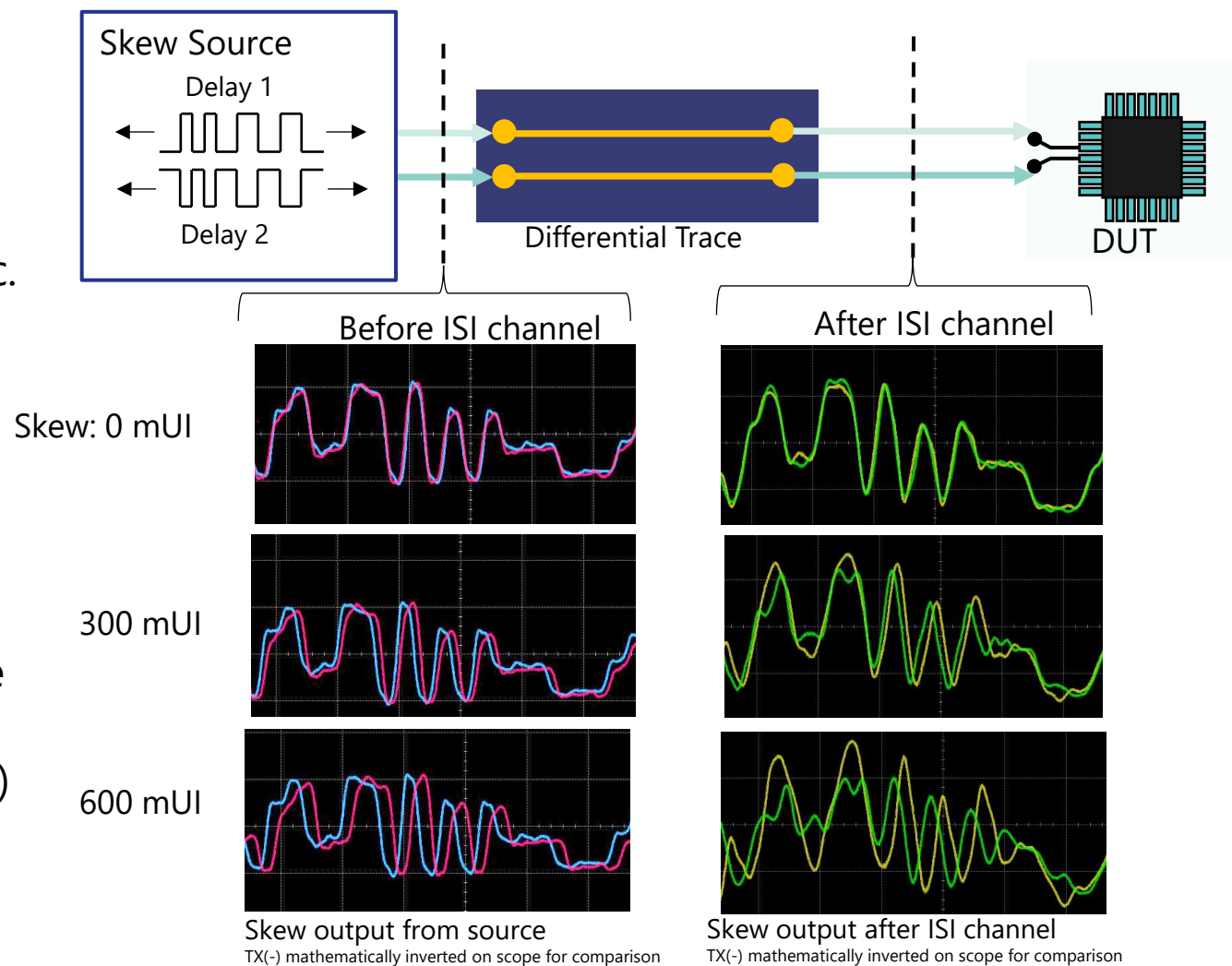
NRZ PCIe5



>3x eye size reduction drives need to reduce signal impairments.

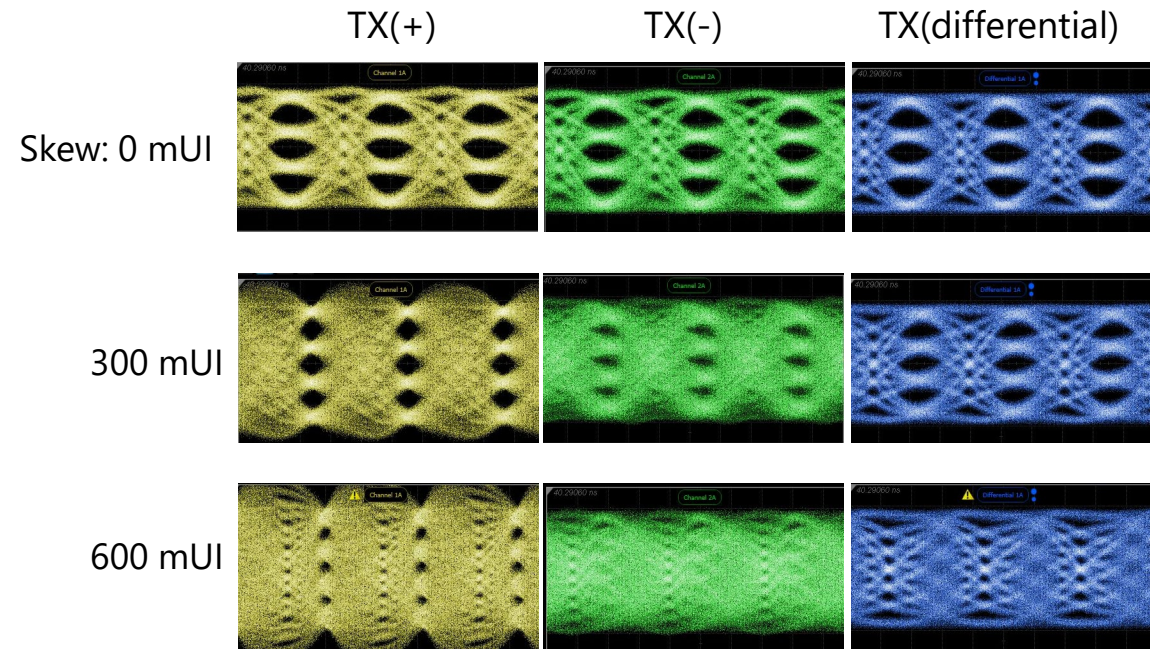
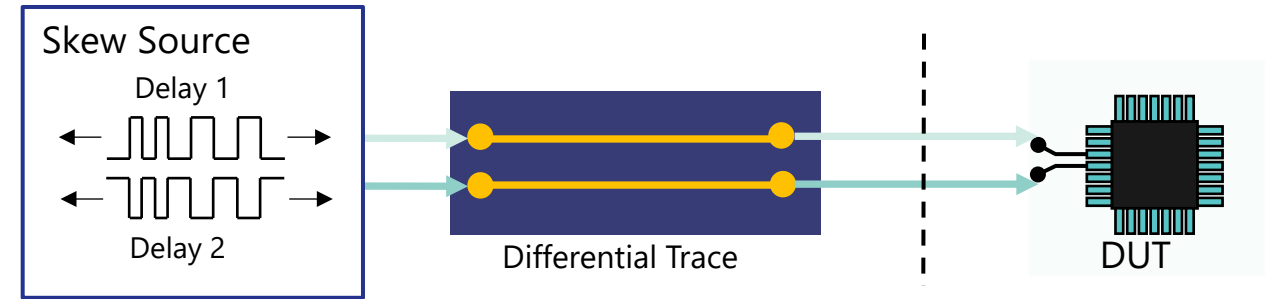
Skew on a Differential Channel at 64 GT/s

- At the source:
 - The skew source generates a differential waveform, where both TX(+) and TX(-) are symmetrical: same amplitude, edge rate, etc.
 - Scope captures on the right show a TX(+) and TX(-) superimposed on each other for comparison
- After the ISI channel:
 - Differential to common mode conversion occurs
 - As a result, distortion is observed within the differential pair
 - Distortion is not symmetrical between TX(+) and TX(-)



Intra-Pair Skew on PAM4 Eye at 64 GT/s

- Before channel
 - Eye diagrams for both TX(+) and TX(-) look comparable
 - Differential eye also looks similarly shaped
- After channel
 - Common mode conversion is apparent in the eye shapes
 - TX(+) and TX(-) are no longer symmetrical
 - Differential eye is distorted and degraded



Eye diagrams after skew on a differential ISI channel

Previous Method: Arbitrary Intra-Pair Skew

- Previous Method:
 - Use of various coaxial adapters from multiple vendors to introduce artificial skew
 - Adapters can vary in length by up to $\sim 0.2''$. This length is what introduces the skew

These 2-sets of adapters shown above can be mixed & matched to produce various levels of skew. By combining Male-Female adapters with Female-Male, they essentially become a low-loss coax extension for a given channel.

2.4 mm
Male end



2.4 mm
Female end

2.92 mm connection

Adapters used in the lab for introducing skew



Achievable Intra-Pair Skews & Tradeoffs

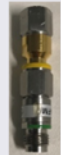
- Pros:

- Skew can be stepped in discrete amounts based on combination used
- Skew can be introduced anywhere in the channel that has coaxial connections

- Cons:

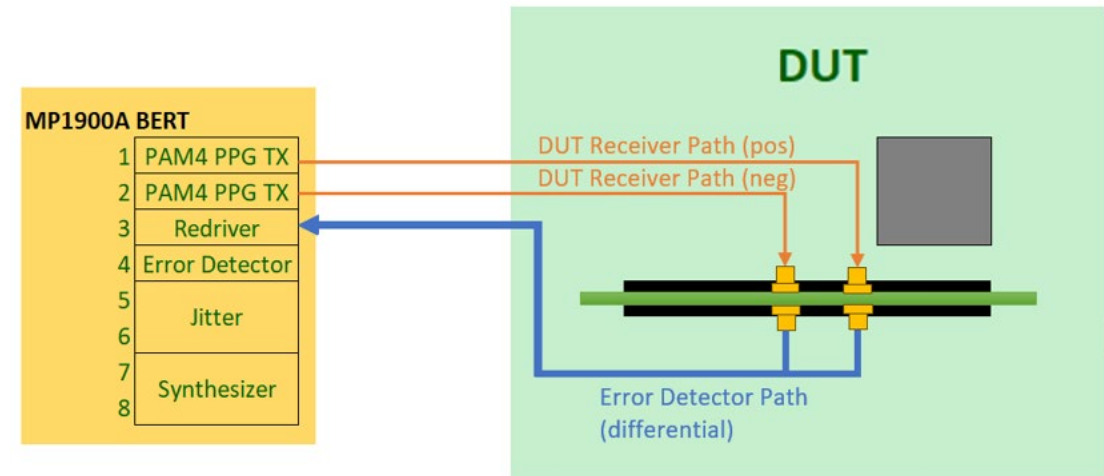
- Not very granular skew steps
- Introduces additional connections which add reflections and reduce overall BW of the setup.
- Not very suitable for higher data rates
- Skew combinations are arbitrary, which yield irregular step sizes for a skew sweep.
- Each new skew delay setting requires setup to be torn apart and reconnected which yields some variability in results
- Is reliant on consistent torquing, and cable positioning to minimize variability
- Calibrations can depend on number of insertions

Combination		Parts	Measured PN Skew
Pos 	Neg 	Pos channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM	0 ps
Pos 	Neg 	Pos channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: 40286 2.4-2.92FM: SM3185	-7.1 ps
Pos 	Neg 	Pos channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: SM3065 2.4-2.92FM: CC-A-24292-FM	-7.8 ps

Combination		Parts	Measured PN Skew
Pos 	Neg 	Pos channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: INMET 5153 2.4-2.92FM: CC-A-24292-FM	2.7 ps
Pos 	Neg 	Pos channel 2.4-2.92MF: 40286 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: SM3065 2.4-2.92FM: SM3185	-15 ps
Pos 	Neg 	Pos channel 2.4-2.92MF: INMET 5153 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: SM3065 2.4-2.92FM: SM3185	-17.7 ps
Pos 	Neg 	Pos channel 2.4-2.92MF: INMET 5153 2.4-2.92FM: CC-A-24292-FM Neg Channel 2.4-2.92MF: 40286 2.4-2.92FM: SM3185	-10.3 ps

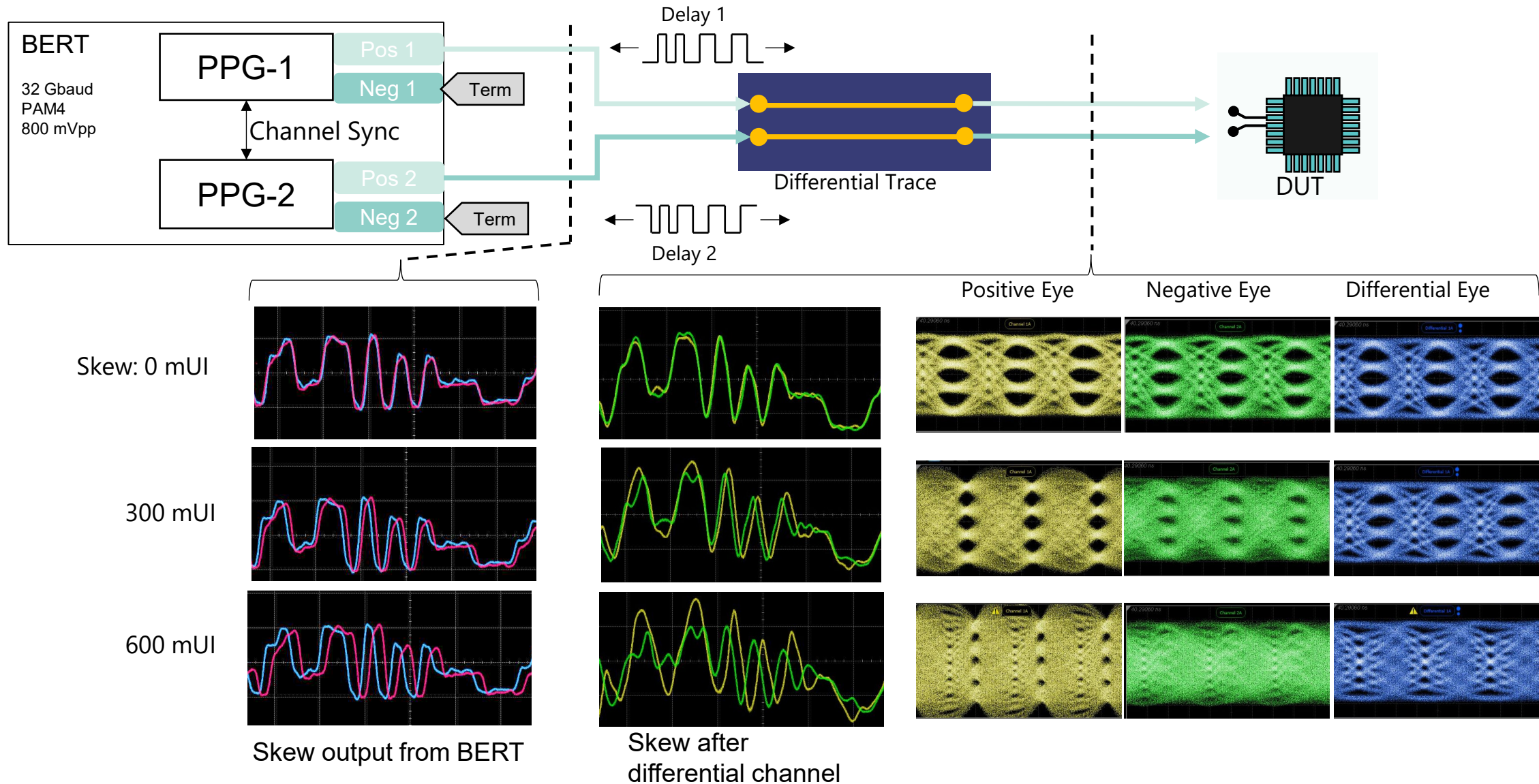
New Methodology Using BERT

- Intra-pair skew test requires single-ended control of the differential pair signal
 - Enabling this capability requires the use of dual transmitters on the MP1900A
 - Transmitters need to be clock and jitter synchronized but independently controlled by phase
 - 2nd PPG module not in standard CEM Compliance Test configuration but is added for skew test
 - PCIe specs do not currently cover this type of test
- Benefits:
 - Fine granularity intra-pair skew: 2 mUI (unit interval) resolution which is 0.0625 ps for PCIe6
 - Can be dialed across the entire UI range



Intra-pair skew solution

Effect of Skew on PAM4 Eye at 64 GT/s

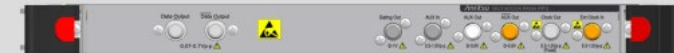


MP1900A BERT Config for Skew

- 8 slot chassis populated with 6 Modules
- Dual PAM4 Transmitters (placed next to each other)
- PAM4 Redriver
- PAM4 Error Detector
- Jitter Modulation Source
- Synthesizer

PAM4 TX(+)

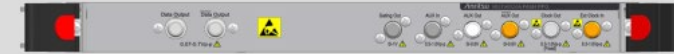
Slot 1



MU196020A

PAM4 TX(-)

Slot 2



MU196020A

Redriver

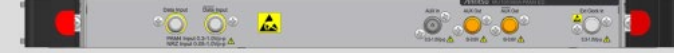
Slot 3



MU196060A

PAM4 ED

Slot 4



MU196040B

Jitter

Slot 5



MU181500B

Slot 6



Synthesizer

Slot 7



MU181000B

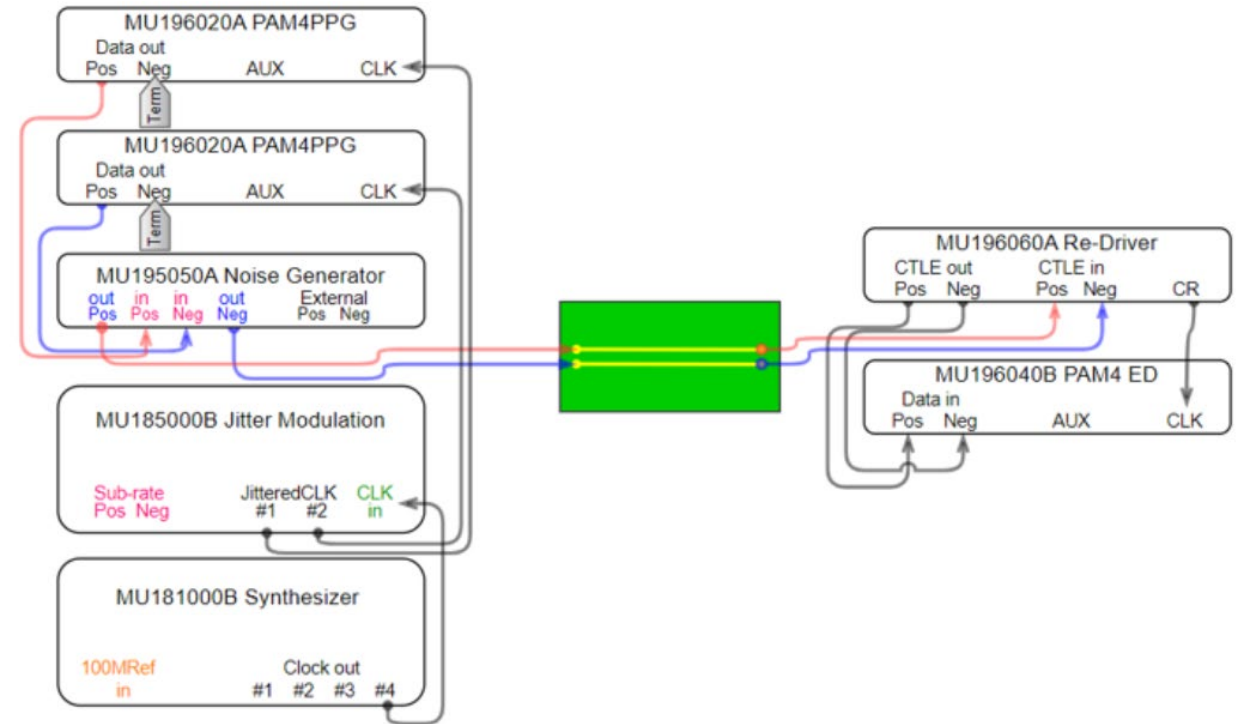
Slot 8



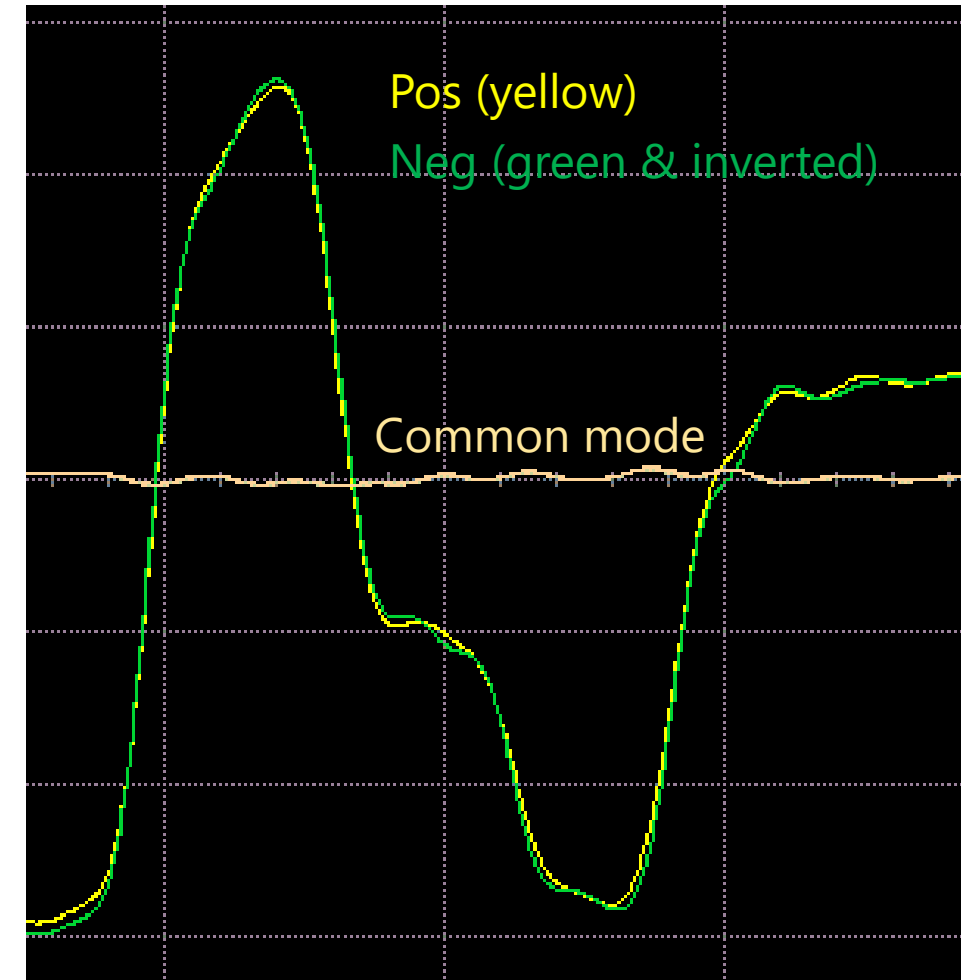
MU181000B

- Source clock generation:
 - Forwarded clock, where synthesizer can be the clock source.
 - Optionally, clock can be fed into synthesizer from 100 MHz source
- Multiple clock output generation:
 - Jitter module is used to produce multiple synchronized clocks to feed each of the PPGs and add jitter
- Skew delay generation:
 - Skew itself is introduced by a delay block inside each PPG
 - Delay can be advanced/retarded by providing option to dial skew in either positive or negative direction as needed
- Differential signal generation:
 - Differential signal is derived from the "Data Pos" outputs of each PPG to provide best symmetry
 - Both PPGs drive the same pattern but PPG2 is a logic inversion
 - Data Neg on both PPGs are terminated 50 Ohms at source (or fed to a scope)
 - Optionally, skewed signal can be passed through noise generator, if desired, as shown (may require dual-mainframe setup for connectivity)

MP1900A BERT connectivity diagram for Intra-pair skew



- Calibration
 - Ensuring best match between Pos and Neg is critical
 - Parameters to match between the two PPGs include:
 - Amplitude, edge rate, duty cycle, jitter, equalization, among others
 - Example shown inverts neg signal on scope to superimpose it on top of pos to ensure best match
- Important Considerations:
 - Use of reasonably well-matched BERT transmitter modules to generate Data(pos) and Data(neg)
 - Skew matching of all cable pairs used



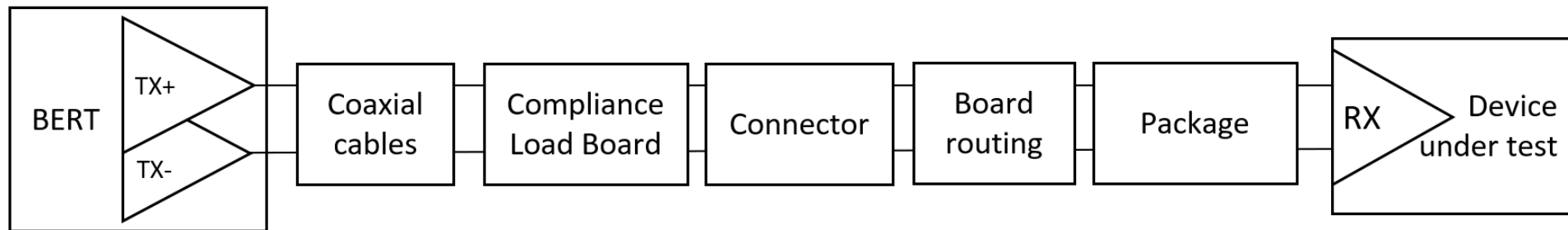
Skew calibration

Skew Calibration & Matching of Pos & Neg PPG Outputs

- Calibrated overlaid waveform
- Everything is very well matched

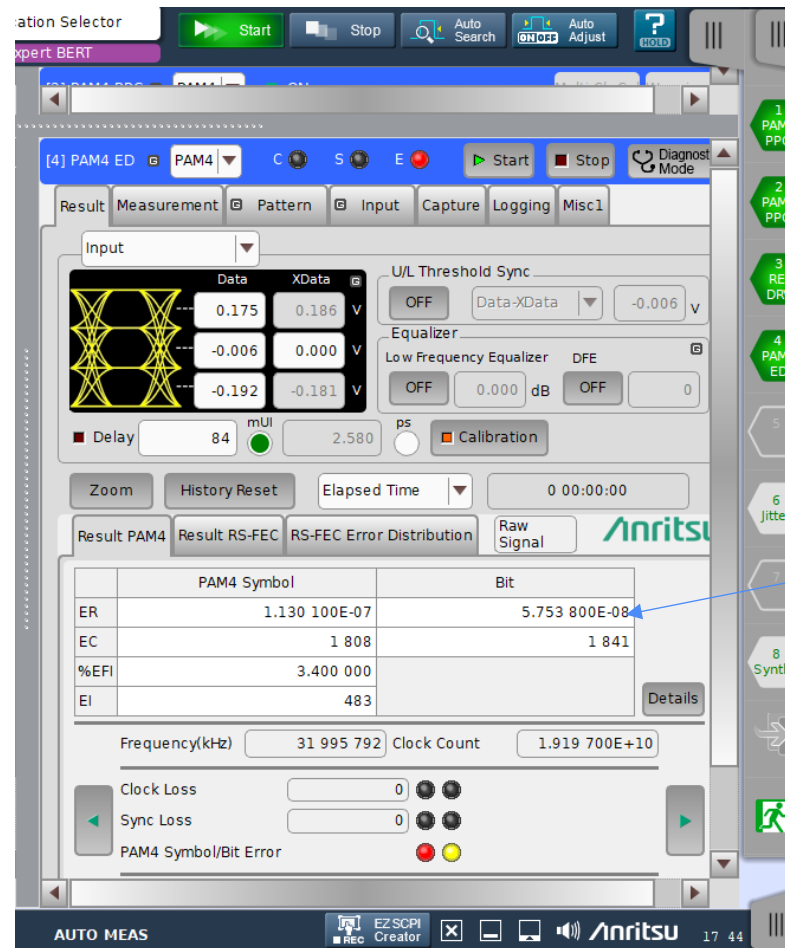


- Various tests were conducted using a 30 dB end-to-end interconnect channel
- Channel components:
 - BERT with dual transmitters
 - PCIe Compliance Load Board (CLB)
 - System under test



Interconnect topology used for enabling intra-pair skew BER measurement (~30 dB).
Device under test is a PCIe6 root complex platform.

BER Measurement on a 30 dB Channel

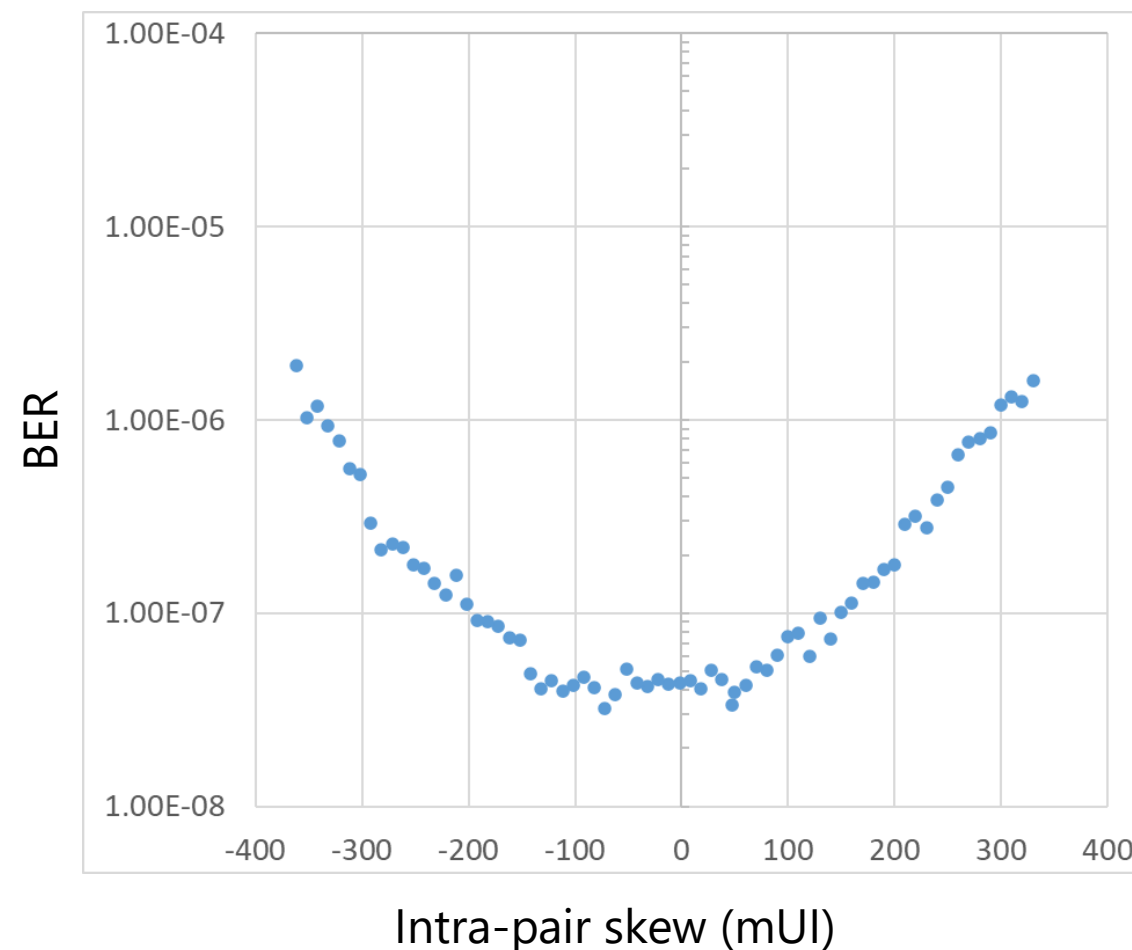


BER: 5.753 800E-08

Example of Measurement Results Displayed on the MP1900A

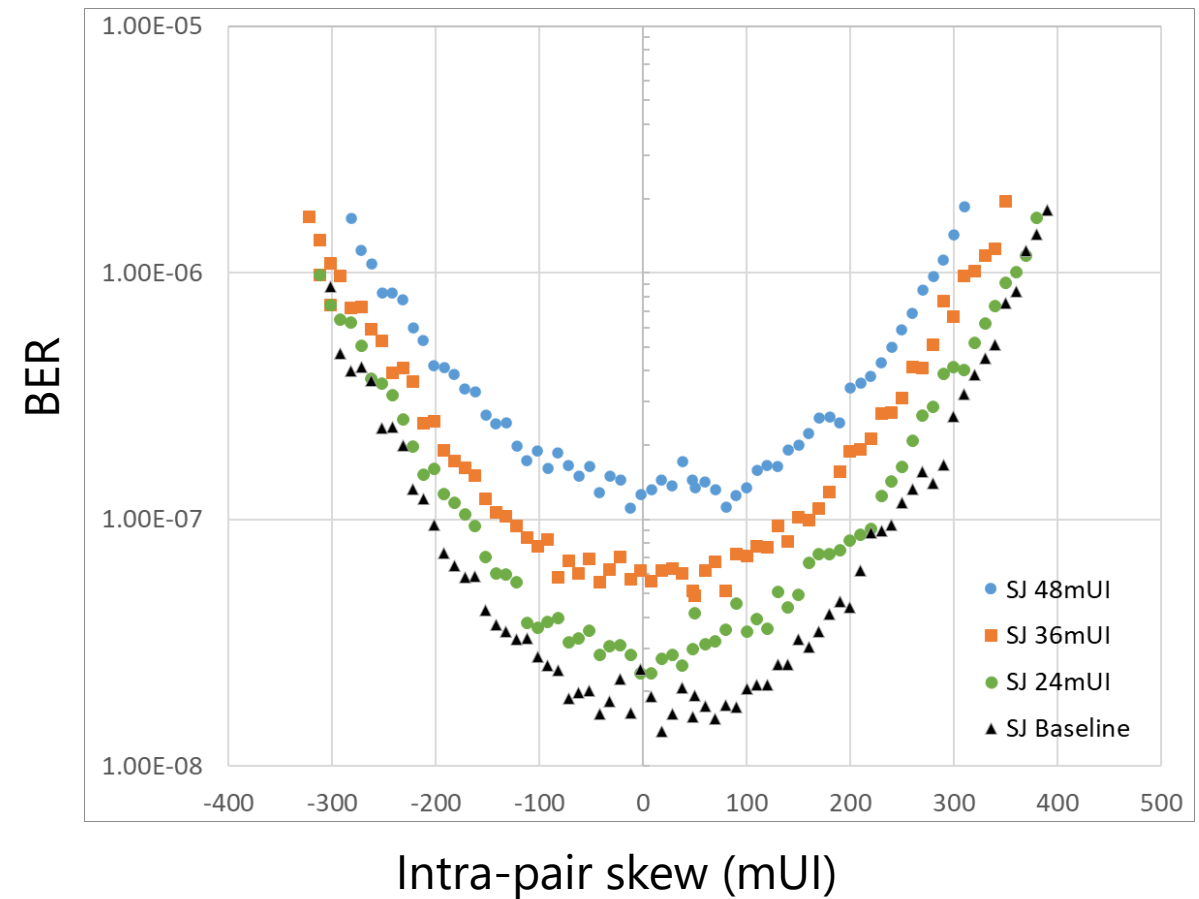
Intra-Pair Skew Results without Impairments

- Settings:
 - PRBS31 Pattern (no Gray coding)
 - 30 dB Channel (Package, socket, board trace, CLB, 1.85 to MMPX coaxial cables)
 - Baseline BER $\sim 4\text{e-}8$
- Observations:
 - ~ 1 order of magnitude BER impact at 0.2 UI
 - BER degradation slope gets steeper as more skew is introduced
- Assumptions:
 - No crosstalk
 - No differential mode noise (DMI)/ common mode noise (CMI) impairments
 - No jitter, no Spread Spectrum Clock (SSC)



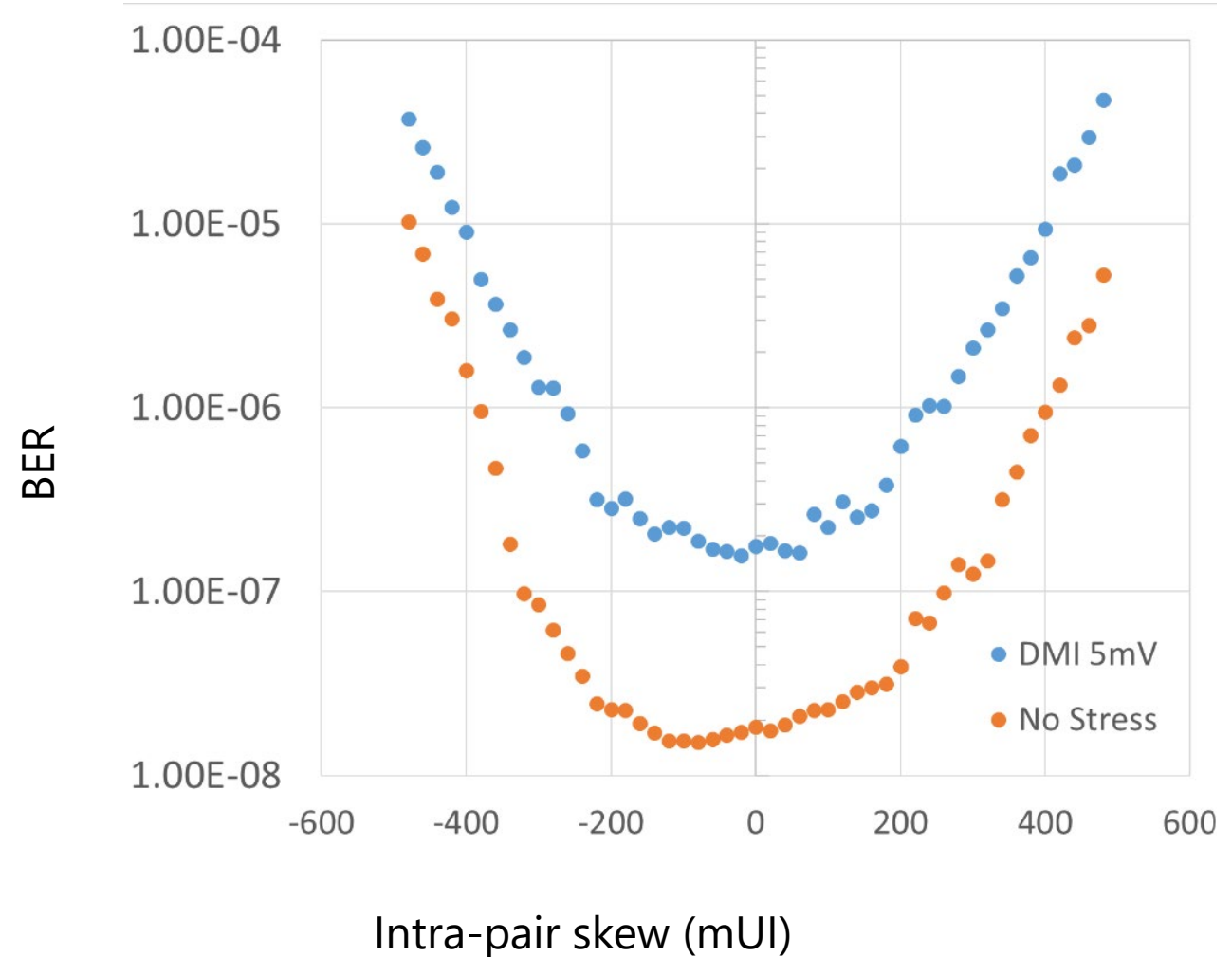
Intra-Pair Skew Results with SJ

- Settings:
 - ~30 dB Channel (Package, socket, board trace, CLB, MMPX cables)
 - MCP pattern
- Observations:
 - At baseline (0 SJ) the BER degrades ~1 order of magnitude at 0.2 UI
 - Sinusoidal Jitter (SJ) brings the baseline BER higher
 - The tails of the bathtub remain steep in slope



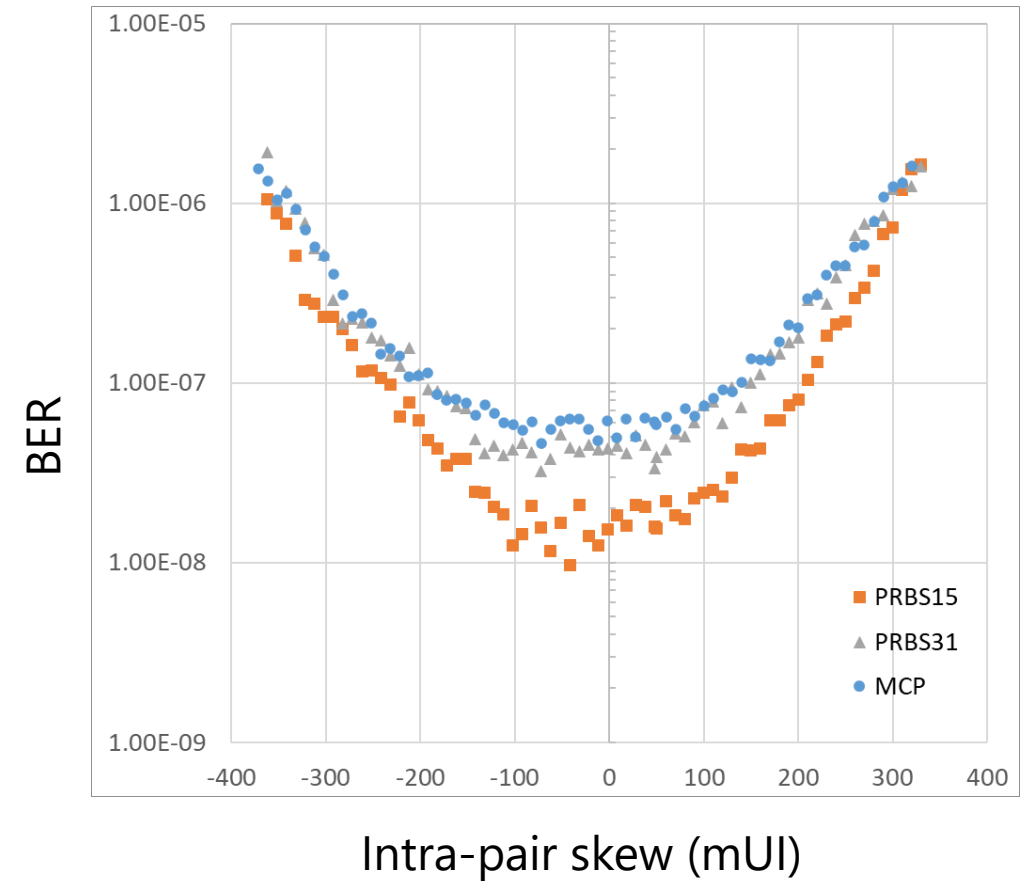
Intra-Pair Skew Results with DMI

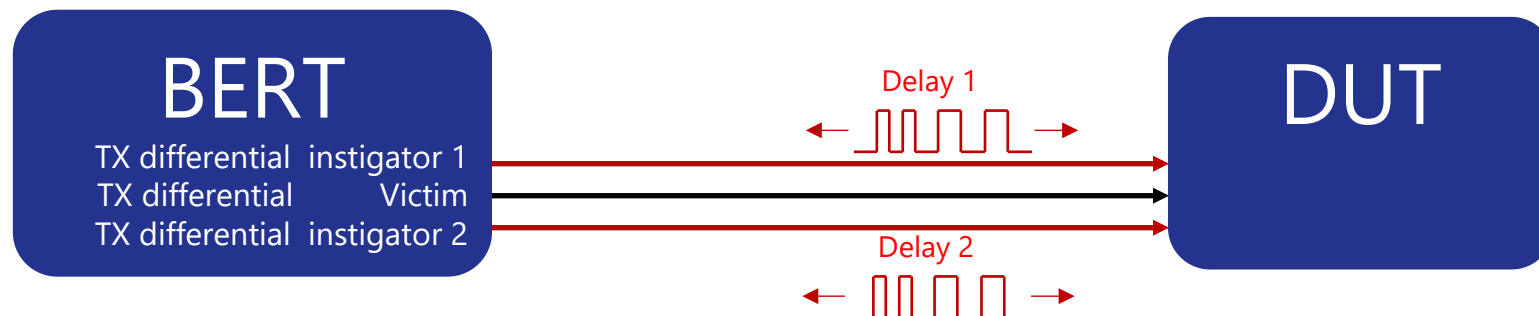
- Settings:
 - ~30 dB Channel (Package, socket, board trace, CLB, MMPX cables)
 - MCP pattern
- Observations:
 - At baseline (0 DMI) the BER degrades ~1 order of magnitude at 0.2 UI
 - 5 mV DMI raises the baseline BER ~ 1 order of magnitude at zero skew
 - The tails of the bathtub remain steep in slope
 - BER from DMI is additive to skew generated BER.



Intra-Pair Skew: Pattern Sensitivity

- Bit pattern sensitivity can have some impact to BER. Once skew is added, further BER degradation occurs.
- Generally, the higher order PRBS (Pseudo-Random Bit Sequence) the higher the BER.
- Accounting for pattern sensitivity, the impact to BER from intra-pair skew can range from between 0.5 to 1 order of magnitude at 0.2 UI, so it can be a significant contributor to overall system margins.



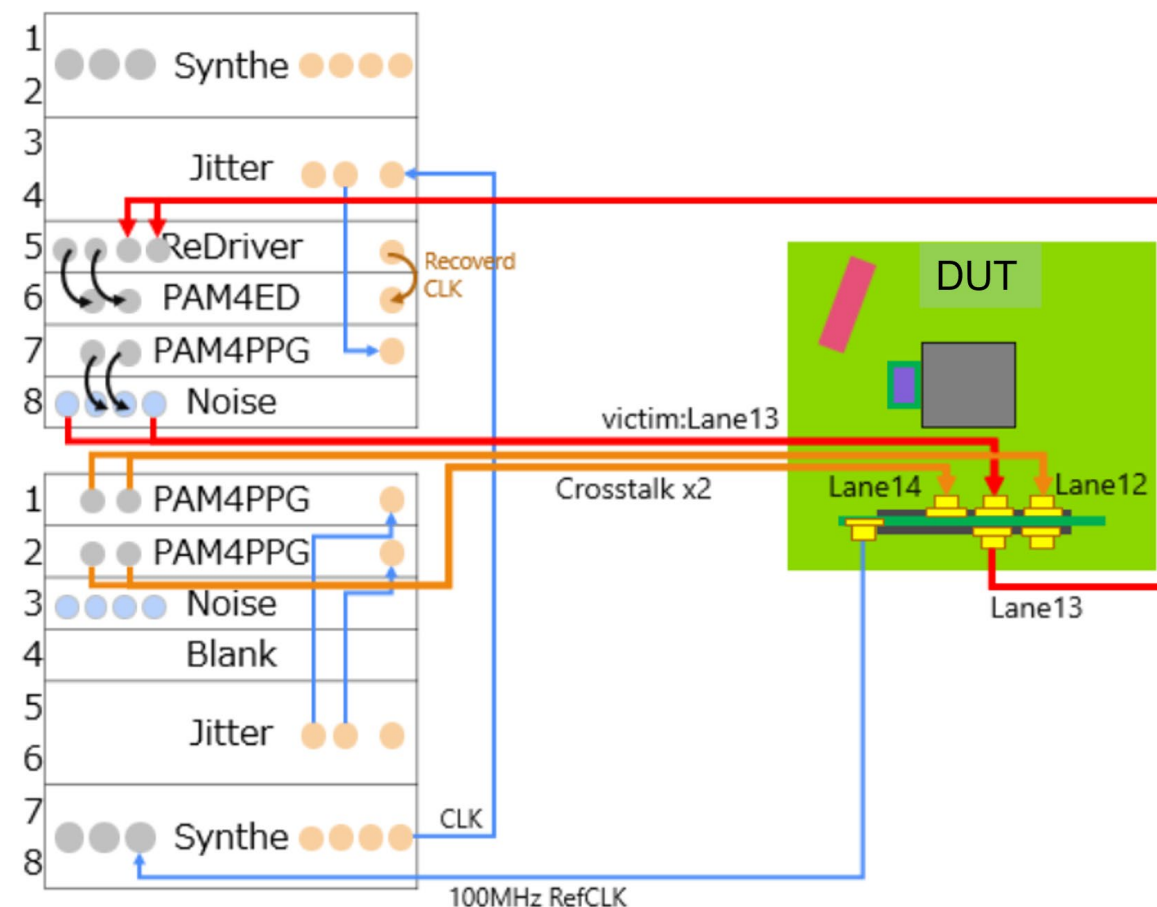


- Benefits:
 - **Instigator Synchronization**: Ability to synchronize instigator phase (w/respect to victim)
 - **Custom Phase Delay**: Instigator delay can be swept -500 to +500 mUI to identify worst phase.
 - **Custom Pattern**: Worst case instigator pattern
 - **Instigator can be NRZ or PAM4**: L0-L3 level transitions have fastest edge rate & largest amplitude (CLK pattern)

Phased Crosstalk Test

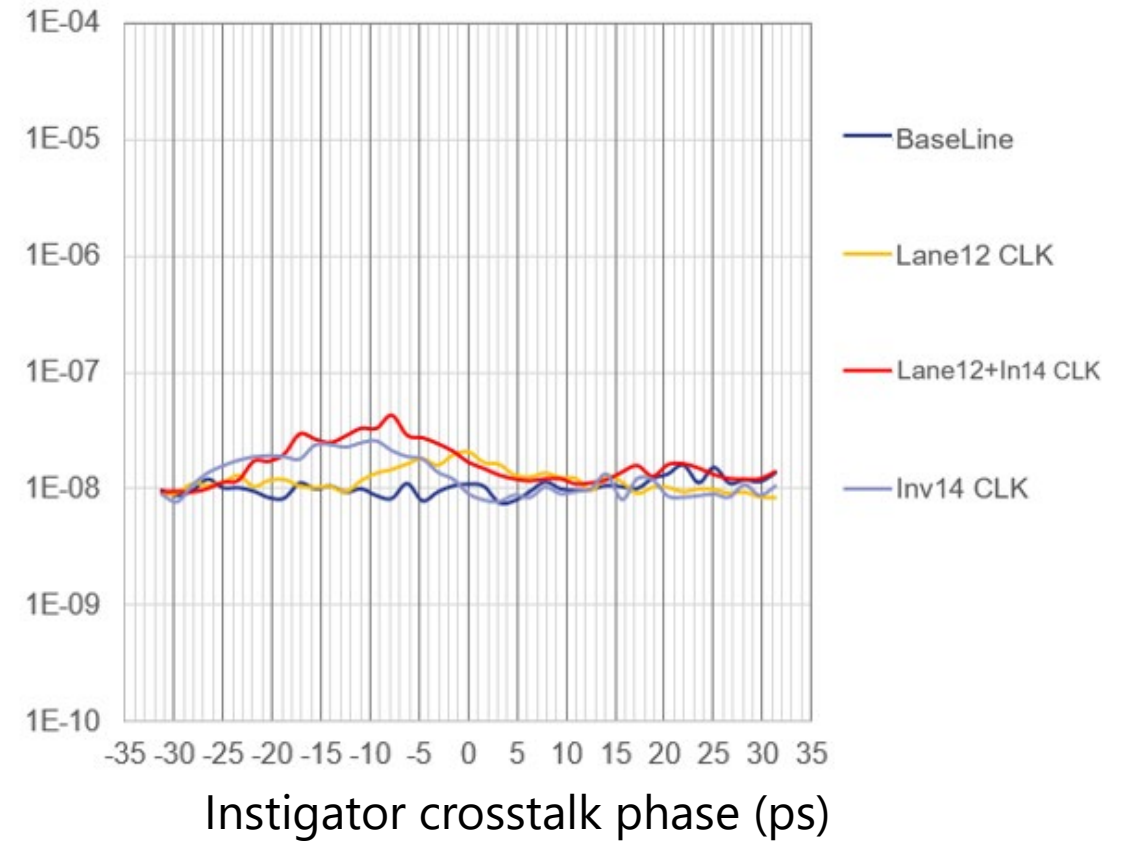
- Goal:
 - Measure the impact of Dual instigator Crosstalk on PCIe 64 GT/s.
- PCIe 64 GT/s DUT CEM topology (~27 dB)
- Setup
 - DUT Loopback with three-PPGs, dual-mainframe BERT.
 - MCP Pattern (Victim)
 - CLK and/or PRBS pattern (instigator)
 - BERT is calibrated to have zero phase between instigators
 - Phase of instigator is then swept across the victim eye to determine impact of crosstalk for the entire eye.
- Test
 - Crosstalk phase sweep in 10 mUI increments ranging from -500 mUI to +500 mUI. This translates into PN skew on the differential signal incoming to DUT.

MP1900A BERT connectivity diagram for
Phased crosstalk



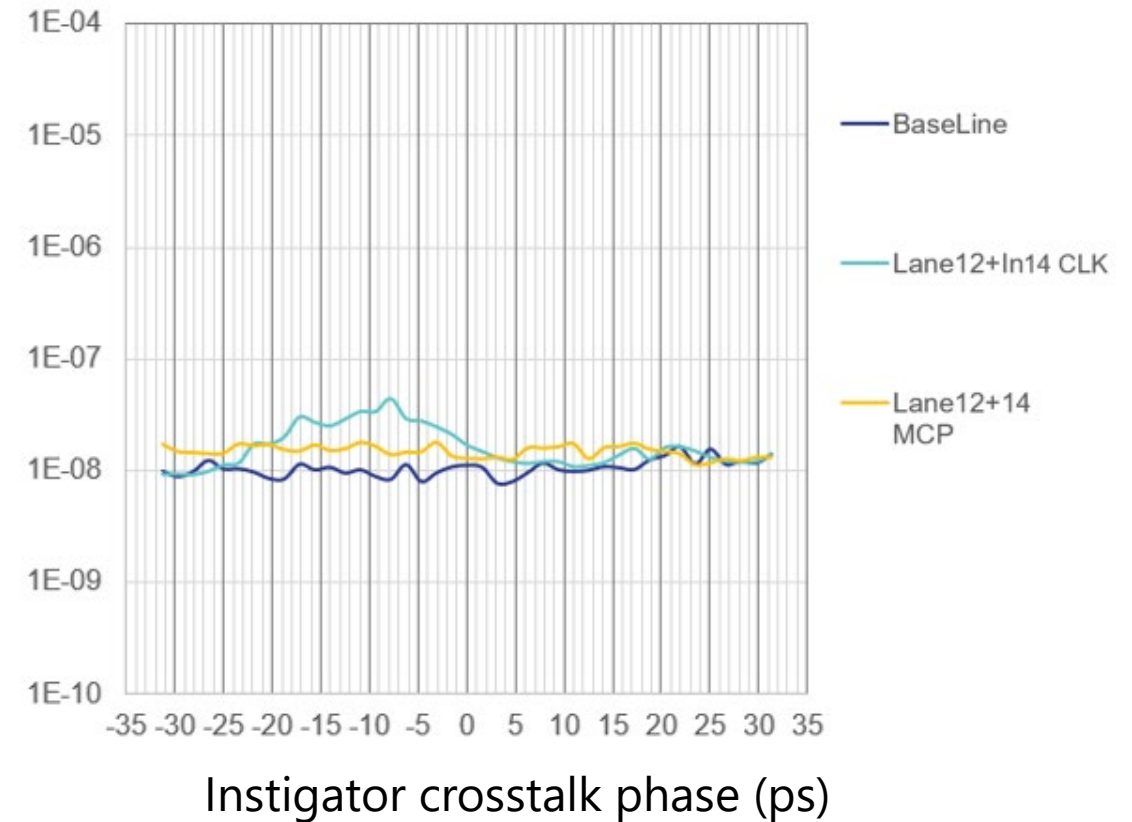
Phased Crosstalk – Dual Instigator

- Impact of crosstalk is readily seen causing peaks above the nominal BER.
- Baseline (no crosstalk is $\sim 1\text{e-}8$)
- Worst-case crosstalk coupling magnitude and phase from each instigator is dependent on DUT layout
- Results:
 - Instigator 1 only BER: $2.10\text{e-}8$
 - Instigator 2 only BER: $2.61\text{e-}8$
 - Dual Instigator BER: $4.34\text{e-}8$



Phased Crosstalk: Pattern Sensitivity

- Different patterns can have different worst-case crosstalk profiles.
- Graph on the right shows comparison between CLK instigator (PAM4 0-3 level transition) vs. MCP (Compliance patterns which include pseudo-random like bit sequences)
- Baseline (no crosstalk is $\sim 1e-8$)
- Worst-case crosstalk coupling magnitude and phase from each instigator is dependent on DUT layout
- Results (Lane13 Victim):
 - MCP BER: $1.58e-8$
 - PAM4 CLK BER: $4.34e-8$



- A novel method for measuring granular intra-pair skew was presented
- Dual transmitters on the BERT are used for single-ended control of the phase of the signals within the differential pair
- PAM4 is more sensitive to intra-pair skew compared to NRZ signaling. Distortion due to skew can be readily observed on scope captures
- Results show that intra-pair skew can have quantifiable impact to BER margins on PCIe at 64GT/s, even without any additional impairments
- Skew BER is additive to SJ and DMI stress
- Multi-PPG config can also be used for phased crosstalk analysis. Results show the amount of crosstalk seen can be dependent on phase and pattern.

- Skew test all cables before a compliance run
 - In addition, cable phase stability may degrade with usage
 - Mixing old and new cables can add severe skew
 - Proper torquing and mechanical relief is recommended to minimize skew impact
- Further study needed on intra-pair skew impact to BER to map impact against various topologies
- Further study needed on PAM4 differential to common mode conversion and frequency domain resonances generated as a result
- Further study needed on the impact of crosstalk phase and pattern.

