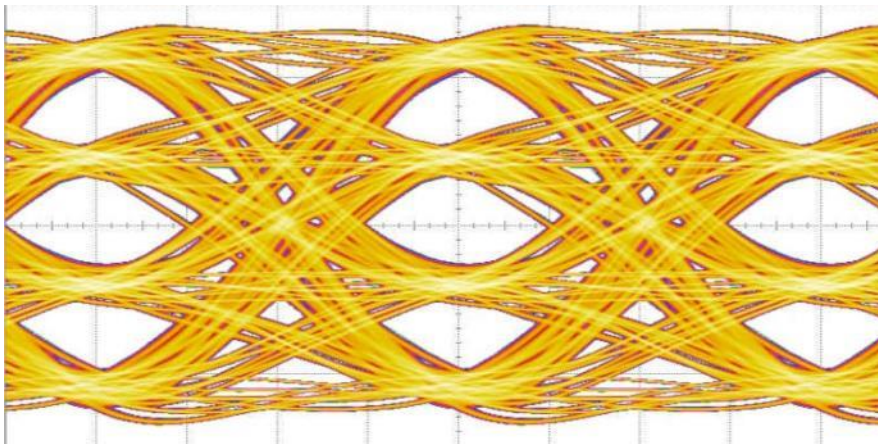


100/400G Ethernet Design – Advanced Characterization and Debug Solution – Part II

서동현

30/08/2016

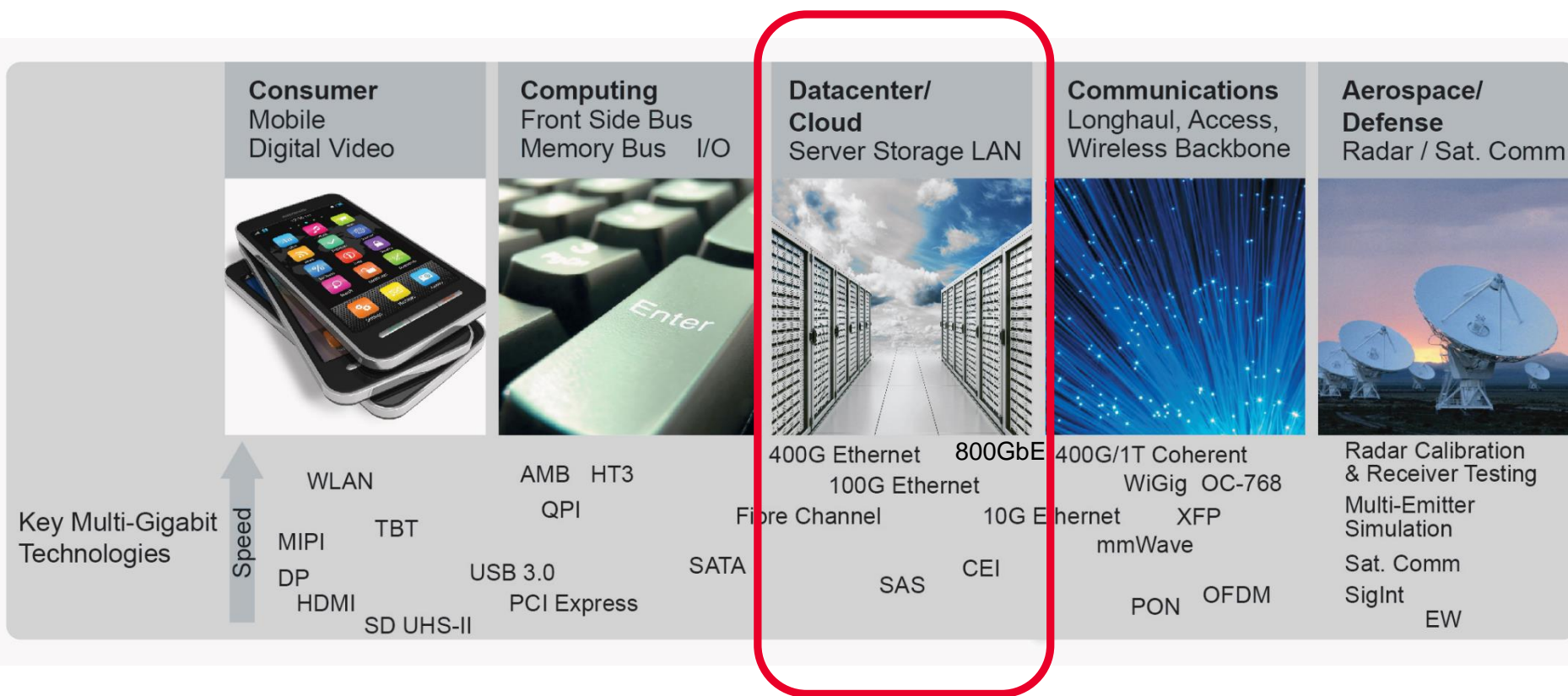
Pulse Amplitude Modulation-4



Agenda

- Overview
- PAM4 use in developing Standards
- Receiver Input Linearity Testing
- PAM-4 Measurements using a Oscilloscope
- Summary

Target High-Speed Digital Applications

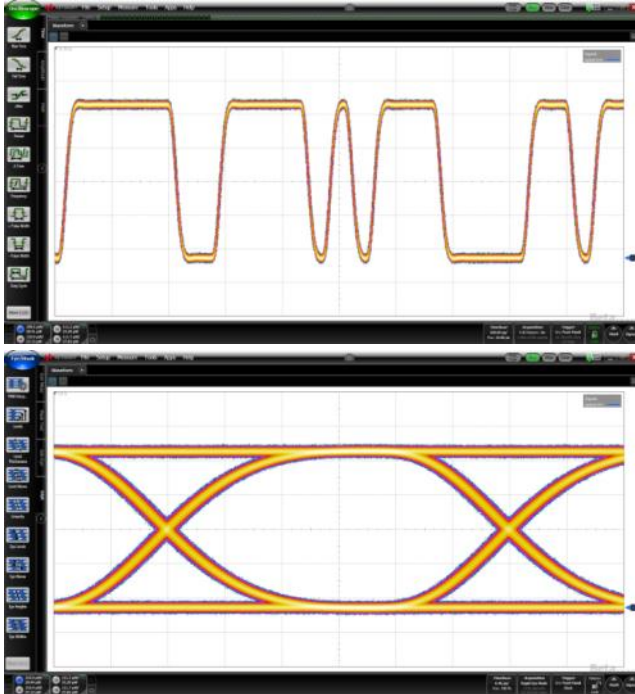


Data center build-out towards 400GbE drives new designs & test demand:

- PAM-4 and NRZ coexist
- 28/56 Gbit/s NRZ, 28/56 GBaud PAM-4
- Electrical and optical interconnects
- 4-16 lanes, new working groups for less lanes (25GbE, 50GbE, 200GbE)

NRZ (Non-Return-to-Zero) vs. PAM (Pulse Amplitude Modulation)

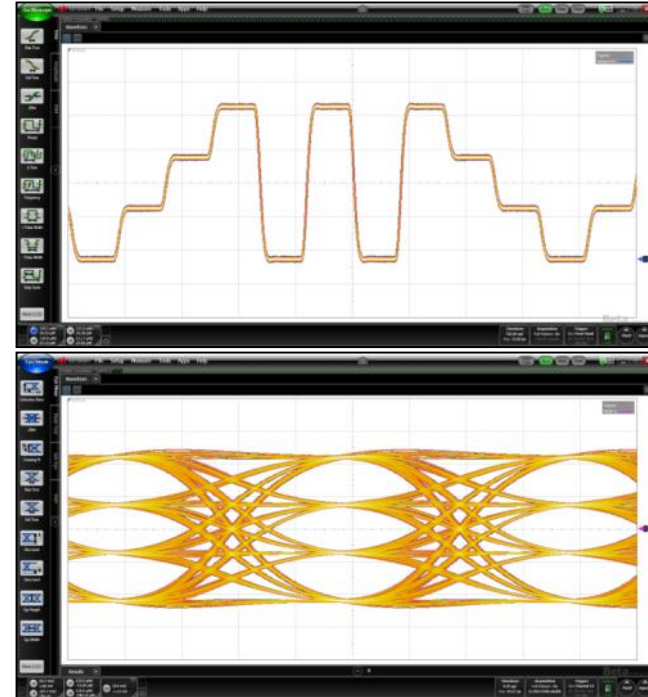
NRZ (PAM-2)



- 2 amplitude levels
- 1 bit of information in every symbol
- 28 Gbaud NRZ = 28 Gb/s

PAM-4 provides ~ 2x the throughput as NRZ, using the same (or similar) channel.

PAM-4



- 4 amplitude levels
- 2 bits of information in every symbol
 - ✓ 2x throughput for the same Baud rate
 - ✓ 28 Gbaud PAM-4 = 56 Gb/s
- Lower SNR, more susceptible to noise
- More complex TX/RX design, higher cost

Why does the industry need PAM-4?

- Its about options...
- NRZ > 28 GB/s means shorter traces or costlier channels
- PAM-4 Slows the “baud” rate, for a given “symbol” rate
 - 2 bits/symbol (PAM4) versus 1 bit/symbol (NRZ)
- Allows vendor to design products to fit cost structure of their ecosystem.

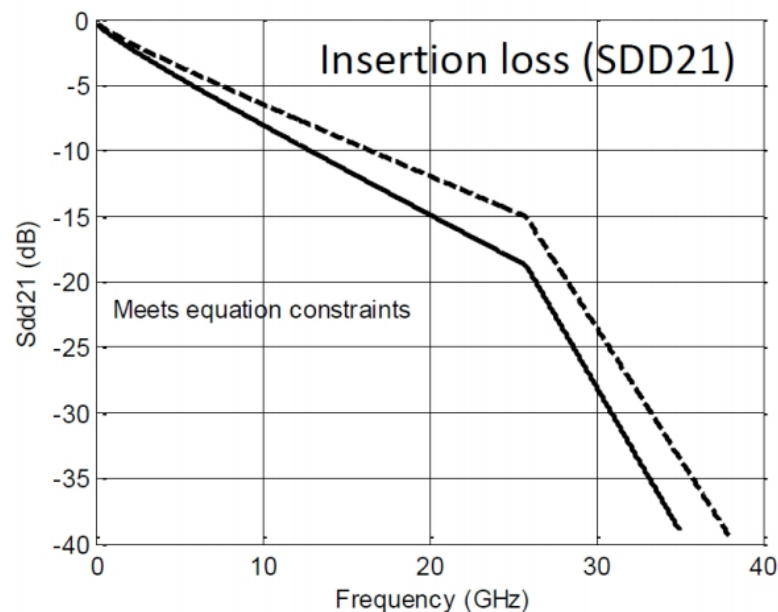
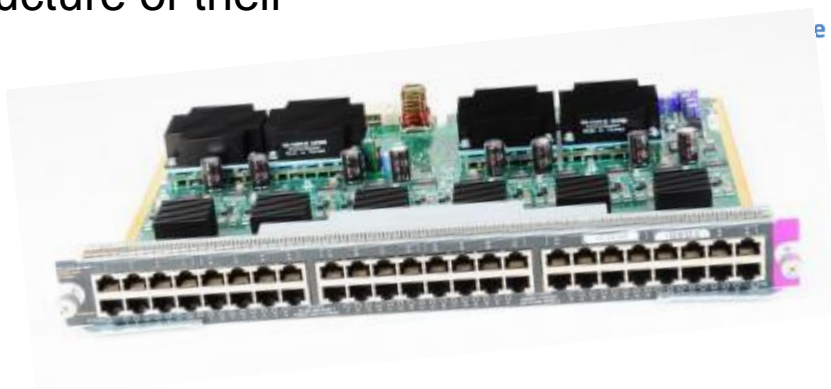


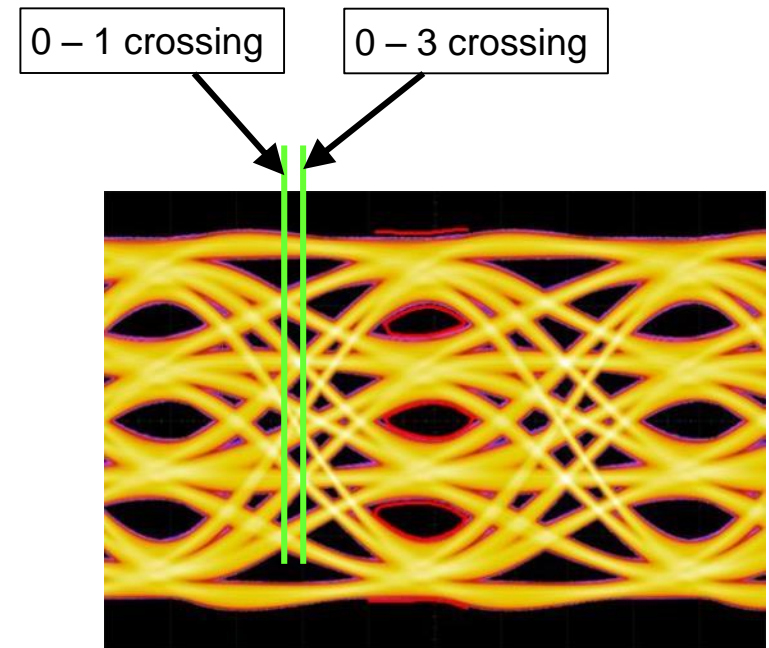
Figure 5: CEI-56G VSR NRZ channel



Challenges moving from NRZ to PAM-4

Design and Measurement

- Packing 4 levels into amplitude swing of 2 – lose 9.6 dB SNR
 - It is not just about timing jitter budgets anymore!
 - Better management of noise and return loss
- Finite rise time creates inherent DDJ
- How to implement clock recovery?
- Closed eyes with lower SNR
 - FEC often required
-
-



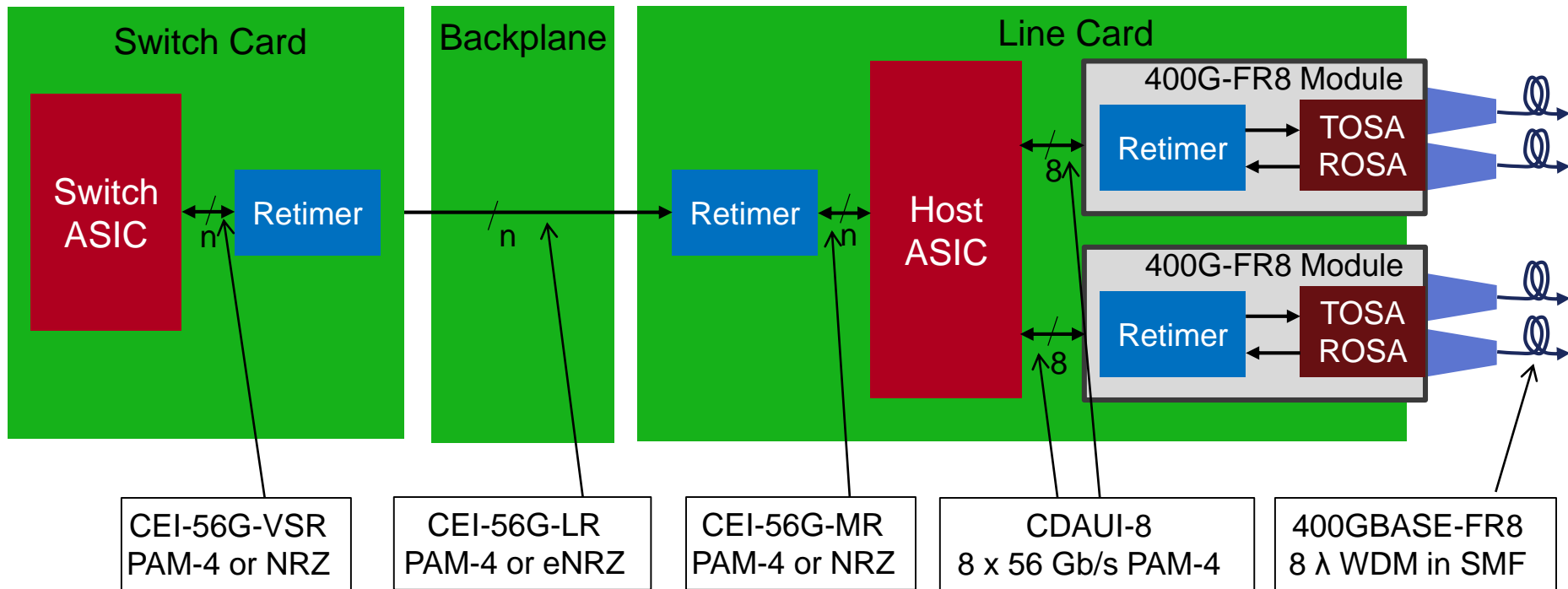
Where is PAM-4 being used

Standards and Implementation Agreements under development:

- 400G Ethernet: IEEE 802.3bs
 - 400GBASE-SR16 - 16 lanes of 25Gb/s NRZ in MMF
 - 400GBASE-FR8/LR8 - 8 lanes of 56Gb/s PAM-4 in SMF
 - 400GBASE-DR4 - 4 lanes of 112 Gb/s PAM-4 in SMF
 - CDAUI-8 – 8 lane 50 Gb/s electrical Chip to Chip (C2C) and Chip to Module (C2M) Attachment Unit Interface
- OIF CEI-56G
 - CEI-56G-XSR-PAM4 (Extremely Short Reach) C2 nearby C
 - CEI-56G-VSR-PAM4 (Very Short Reach) C2M
 - CEI-56G-MR-PAM4 (Medium Reach) C2 distant C, cables
 - CEI-56G-LR-PAM4 (Long Reach) backplanes and cables
- Fibre Channel 64GFC / 256GFC
 - PI-7 and MSQS-3 – several fibre reaches (MMF & SMF) and C2M
- Infiniband – 600G HDR using 50G lane rate

Understanding the application space

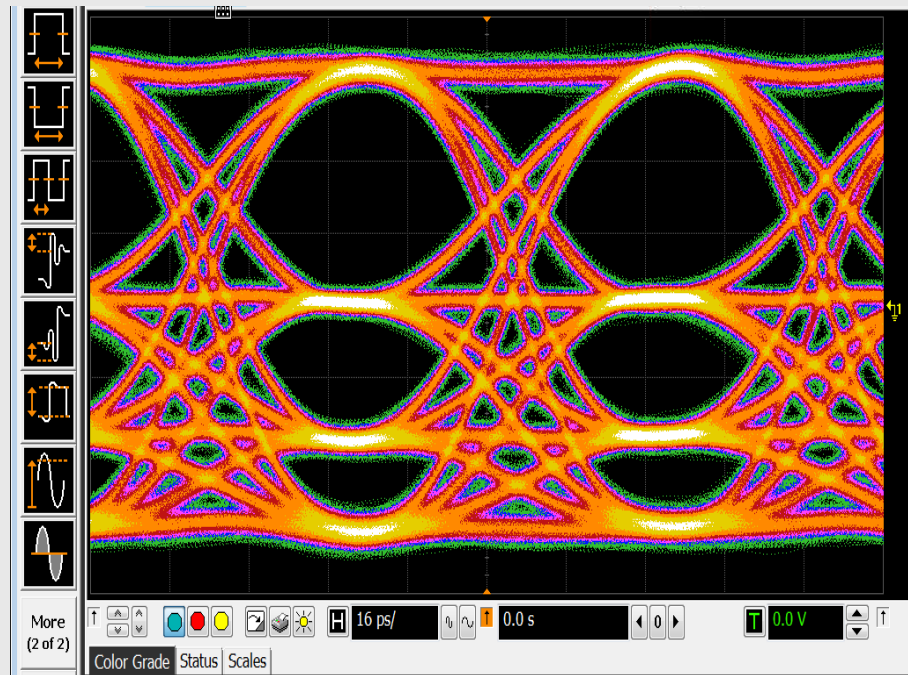
Typical implementation: 400GBASE-FR8 Optical Link
Both IEEE and OIF-CEI are used



Standards using PAM-4 are evolving

- Standards working group members are contributing simulations and measurement results for test chips
- Many changes beyond early work from 802.3bj clause 94:
 - New test patterns give “appropriate” levels of stress
 - Many new specifications for eye measurements
 - Longer reach CEI-56G are adding second pre-cursor on Tx
 - Linearity added to stress mix in CEI-56G
 - *CEI linearity stress defined – center eye is largest*
- Standards and IAs are continue to evolve - weekly!
 - Check the latest draft versions from the working groups
 - Keysight actively participates in these working groups

Receiver & Receiver Input Linearity Testing



M8000 Series of BER Test Solutions

*Highly integrated
and scalable for simplified,
time efficient testing*

High-performance BERT

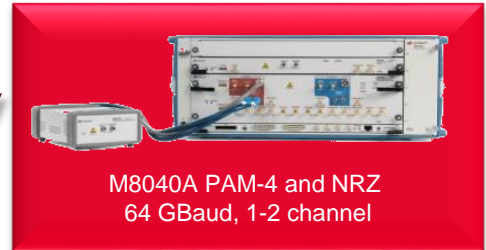
16 / 32 Gb/s, 1 - 4 channels

Highly integrated

Interactive link-training

Automated in-situ calibration

*Now: Extension to 400GbE:
PAM-4 & NRZ, 64 GBaud*



M8000 Series of BER Test Solutions



16 Gb/s J-BERT M8020A
1 - 4 channel



M8195A AWG,
4 channel



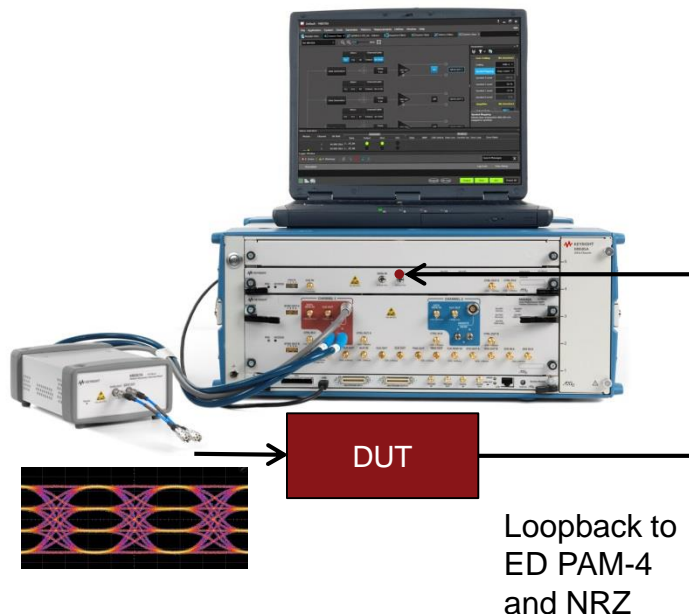
32 Gb/s J-BERT M8020A
and M8062A



M8030A
10 channel

Master your next design

M8040A 64 GBaud High-performance BERT



Where used:

- 400GbE, 200GbE, CEI-56G
- Input (RX) characterization and compliance test
- For PAM-4 and NRZ signals up to 64 GBaud

Key capabilities:

- Highly integrated BERT, AXIe based
- Accurate physical layer characterization and compliance test of next generation digital high-speed I/Os with NRZ and PAM-4 data formats
- Control via M8070A system software for M8000

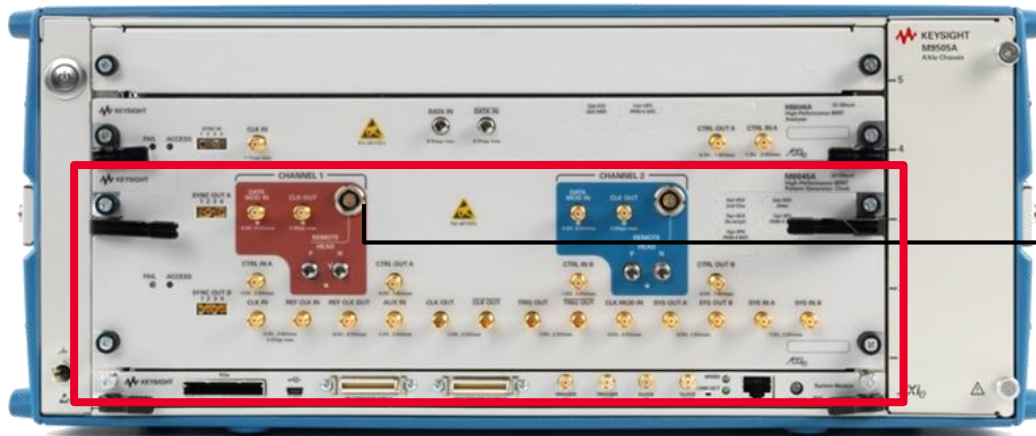
Pattern Generator (M8045A)

- Single or dual 32/64 GBaud NRZ/PAM-4
- Built-in de-emphasis
- Clean and jittered data patterns and clocks
- Remote head for close connection to DUT
- NRZ and PAM-4 is switchable by software

Error Detector (M8046A)

- 32/64* GBaud error detector for PAM-4 and NRZ
- Equalizer* and clock recovery* (* = second release)

M8045A 64 GBaud NRZ/PAM-4 Pattern Generator Module



PAM-4 or NRZ



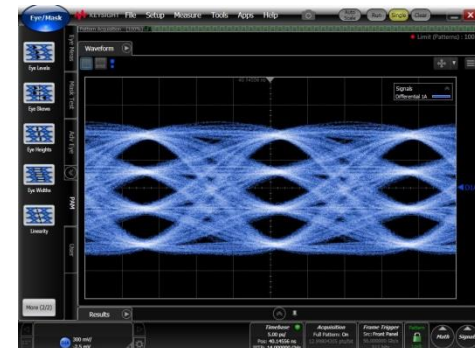
Remote head

Input (RX)
under test

Key features pattern generator:

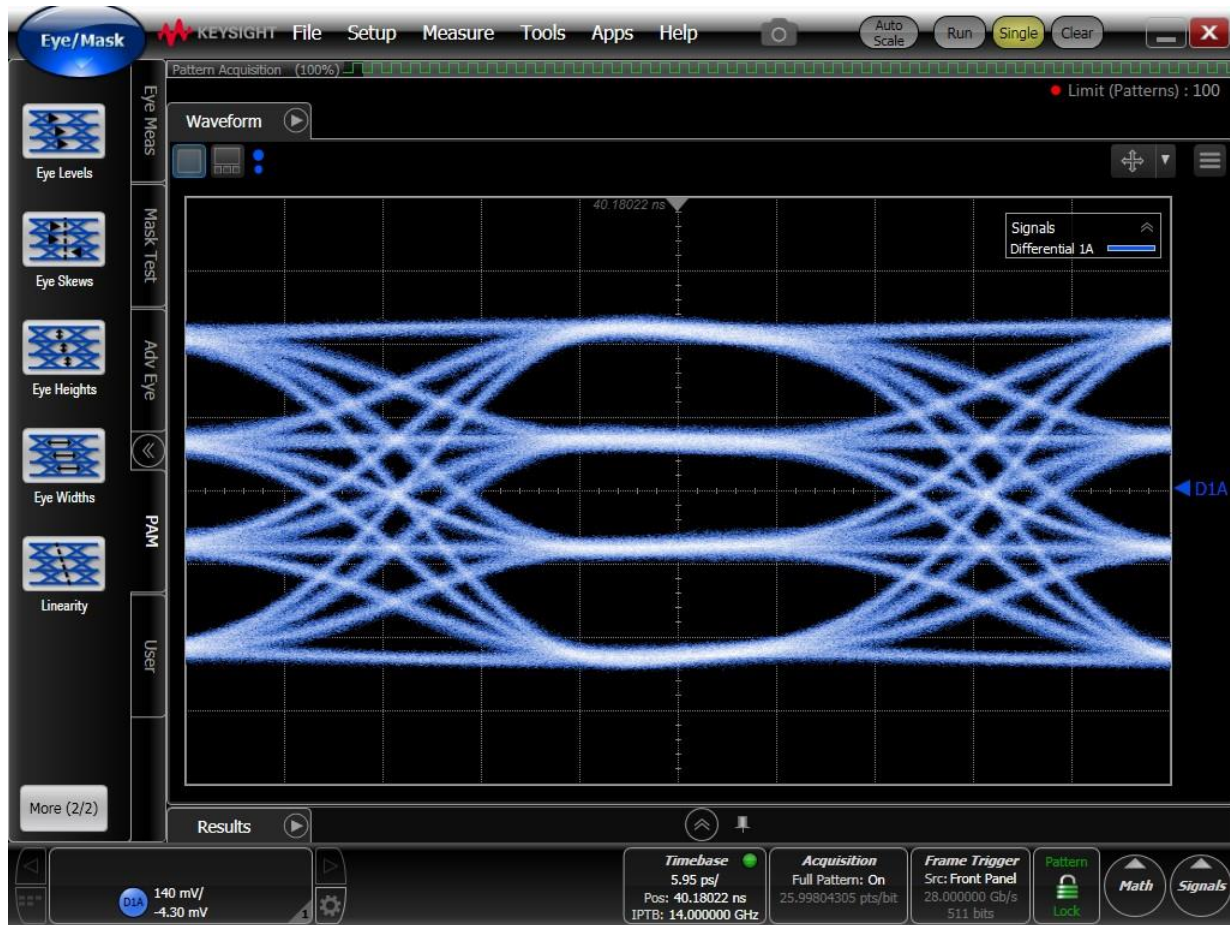
- 1 or 2 channels per module with synthesizer (M8045A, 3U)
- Up to 32/64 Gbaud data rate for each channel
- PAM-4/NRZ format selection by user interface
- **Built-in de-emphasis 4 taps**
- Built-in calibrated jitter injection: RJ, SJ (multi-tone), clk/2, BUJ, SSC
- **Level non-linearity** for PAM-4
- Remote head to get close to the DUT (M8057A)
- Output amplitude 1.8/1.2 Vpp differential @ <32/<56GBd
- Fast transition times 9 ps (20/80%)
- Low intrinsic RJ <150 fs rms (@ 64 Gb/s NRZ)

56 GBd PAM-4



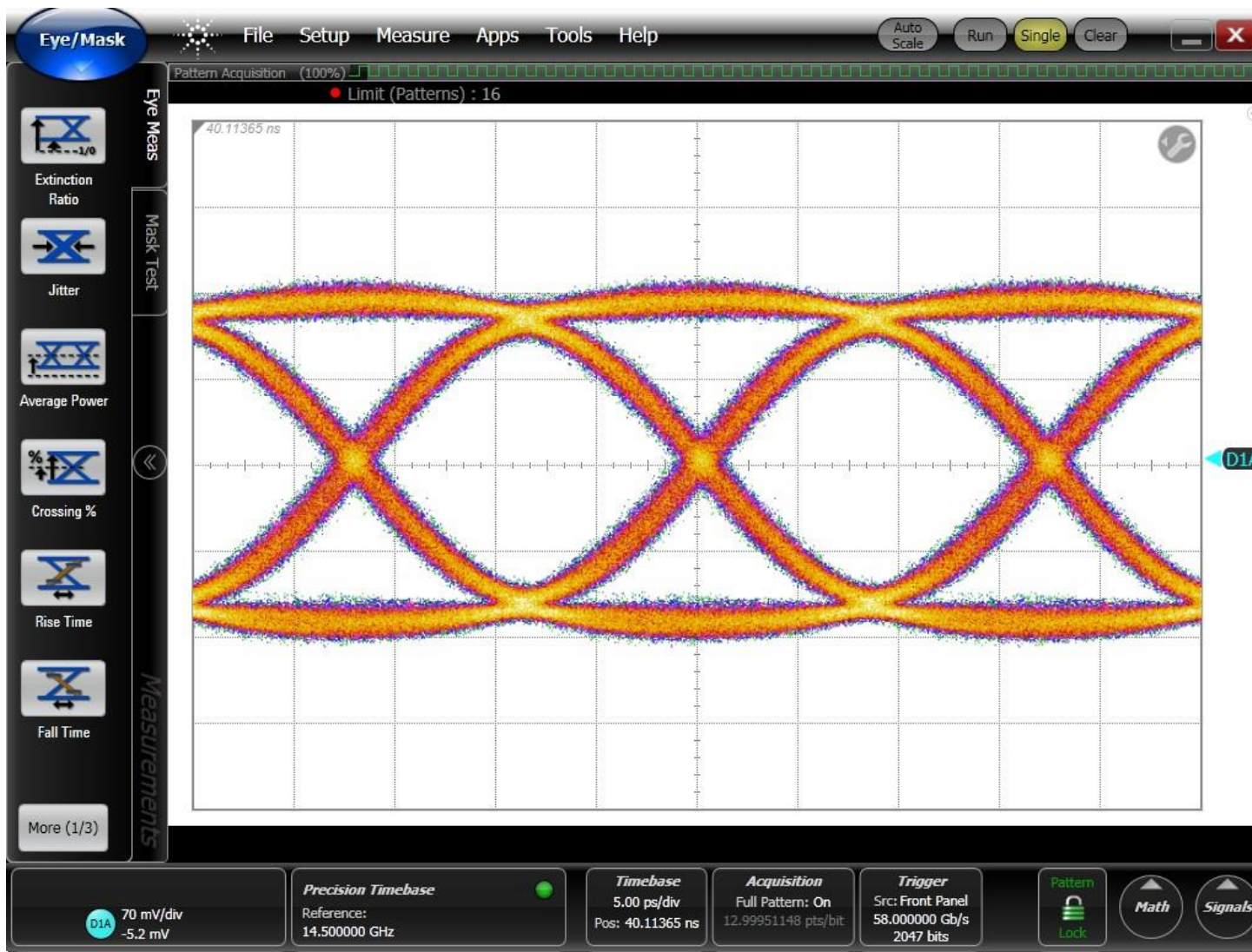
Preliminary

Performance at 28 GBaud PAM-4



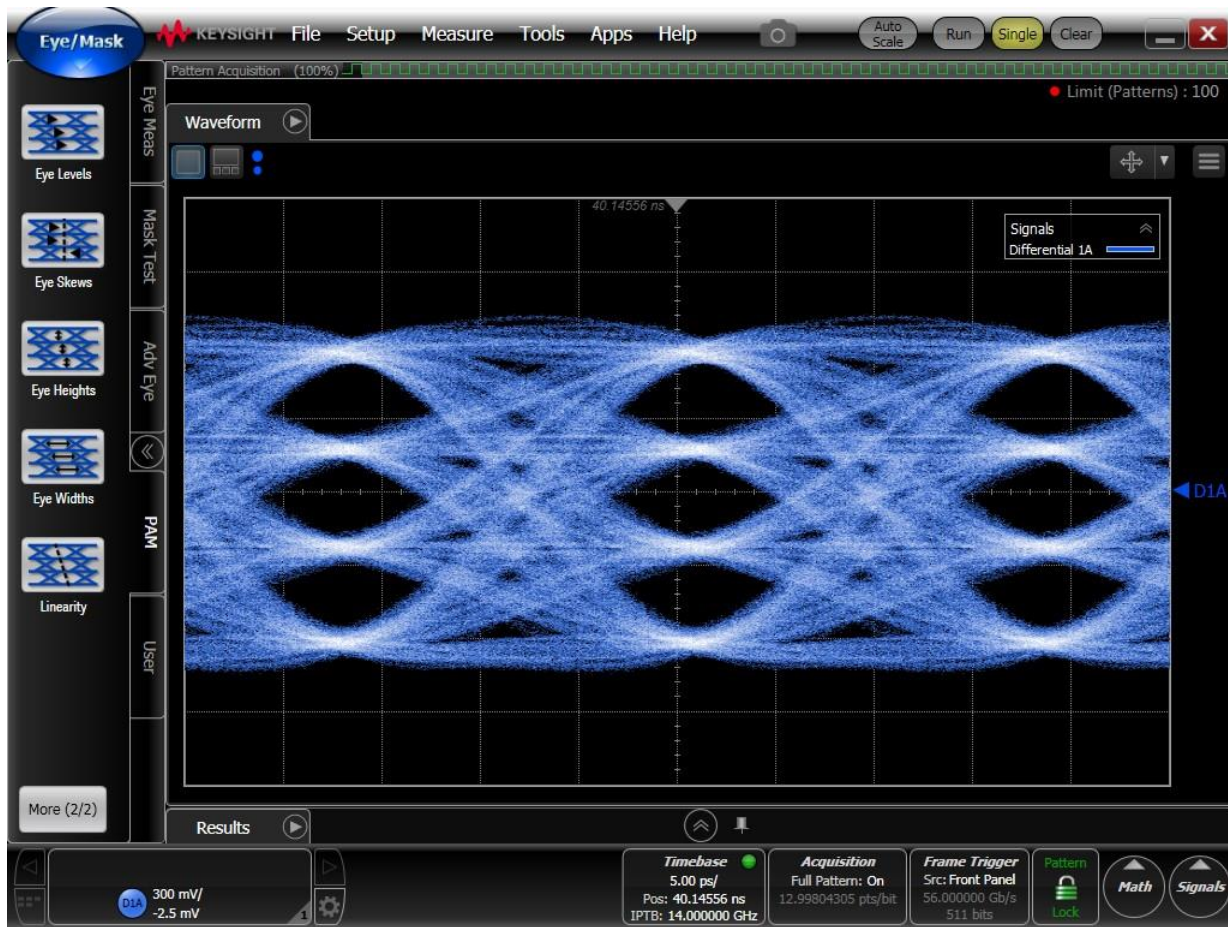
Preliminary June 2016. M8045A with internal clock and remote head M8057A. 600 mVpp. DCA 86118A.

Performance at 58 Gbps NRZ



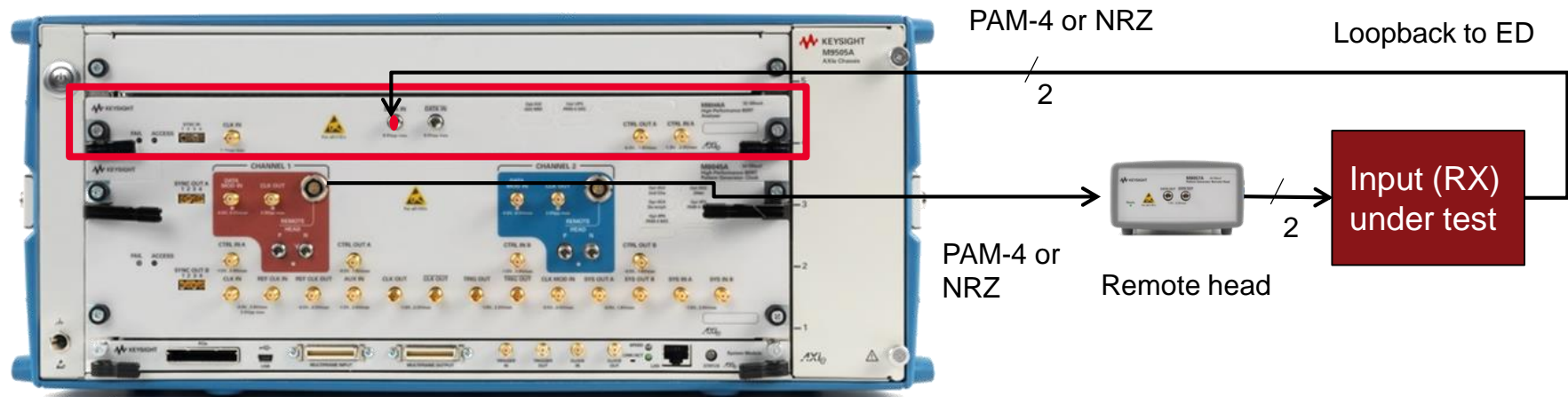
Preliminary
w/o PG
remote
head.
DCA.

Performance at 56 GBaud PAM-4



Preliminary (June 2016). M8045A with internal clock and remote head M8057A. 1.2 Vpp. DCA 86118A.

M8046A 64 GBaud NRZ/PAM-4 Analyzer Module



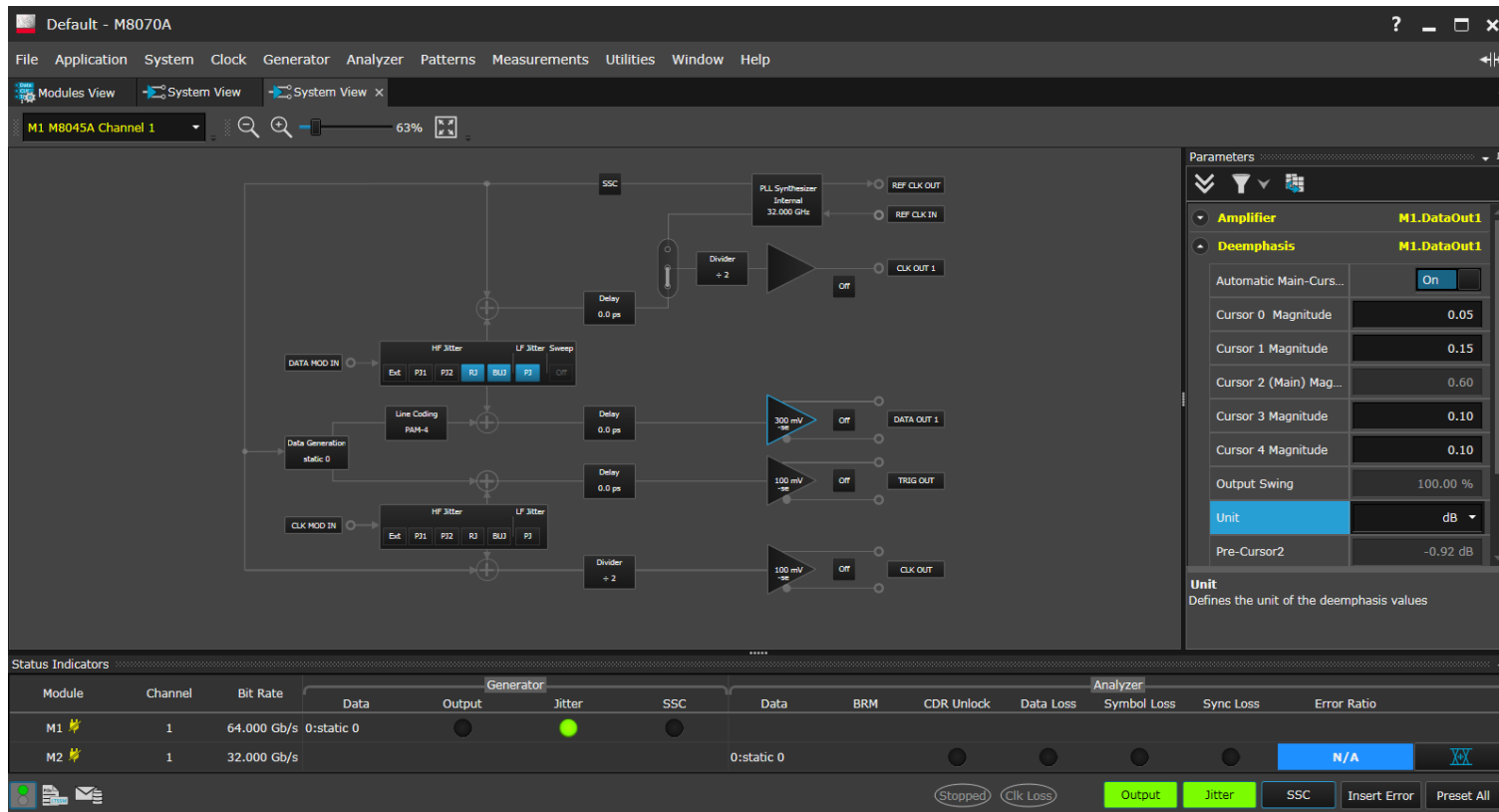
Key features analyzer:

- 1 analyzer channel per module (M8046A, 1U)
- Symbol rates:
 - 2 to 32 Gb/s NRZ and 32 GBaud PAM-4
 - 2 to 64 Gb/s NRZ and 64 GBaud PAM-4*
- Detects NRZ and PAM-4 signals without power splitters
- True real-time symbol error rate for PAM-4 without post-processing
- Full sampling even for long PRBS and low BERs, e.g. 10^{-15}
- Jitter tolerance measurements

*64 Gbaud version come in a second release

M8040A User Interface

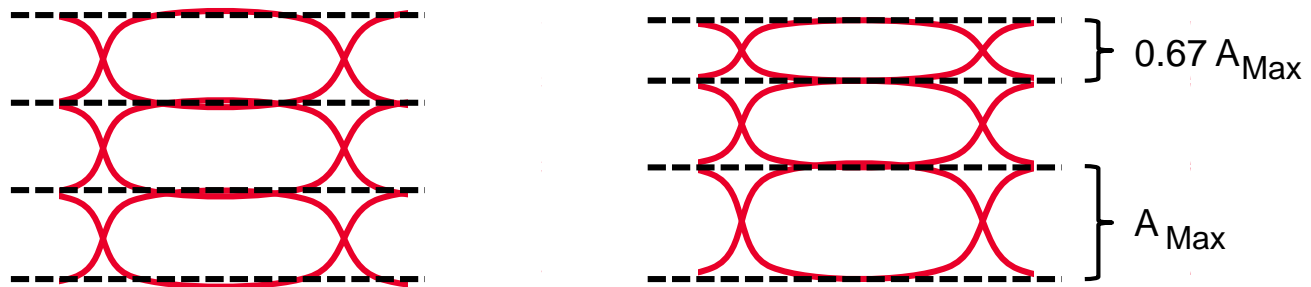
Based on M8070A System Software for M8000 Series



All M8040A parameters can be controlled via the M8070A GUI and remote interface, similar to J-BERT M8020A. DUT control interface, Python scripting interface, also M819xA AWG control via M8070A. This GUI (June 2016) shows a system view with block diagram of pattern generator with jitter sources.

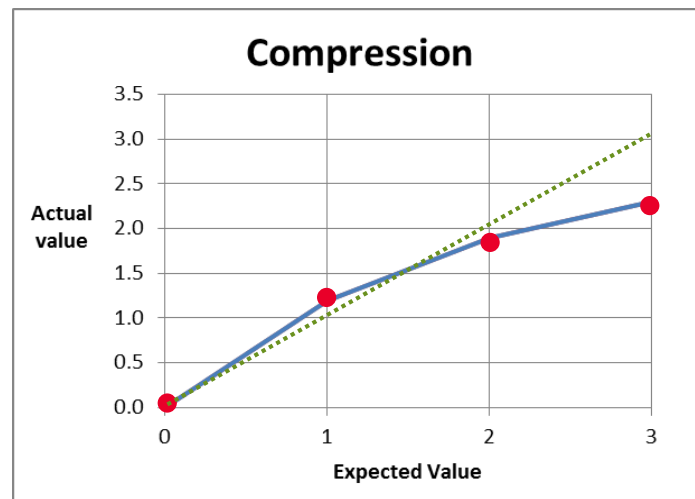
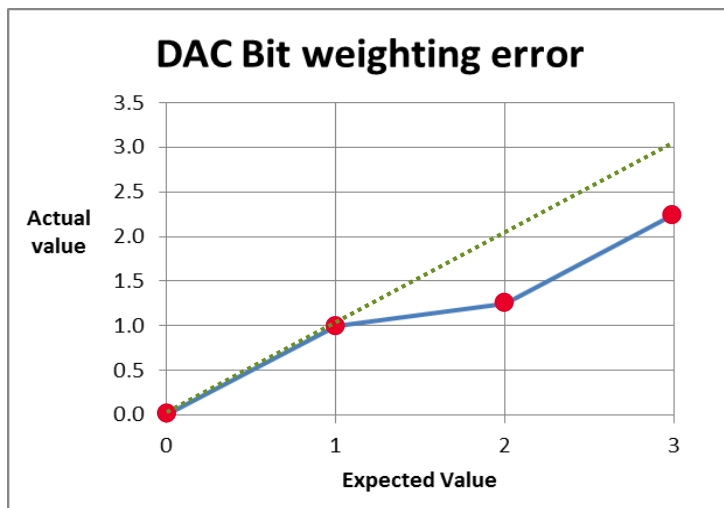
Linearity included in input stress tests

- Included in some data center networking Standard drafts
- Compliance is static pass/fail test, combined with jitter or interference stress.
- Test with stressed PAM-4 eye, with inner levels offset to spec limit
- Linearity expressed as either:
 - Eye Linearity (spec limit 0.67) (OIF-CEI-VSR/XSR far end)
 - Level Separation Mismatch Ratio (spec limit 0.95) (802.3 & OIF-CEI near end)
 - Set rail voltages with PAM-4 BERT / AWG, or individual output amplitudes with 2 channel NRZ BERT



Linearity margin test

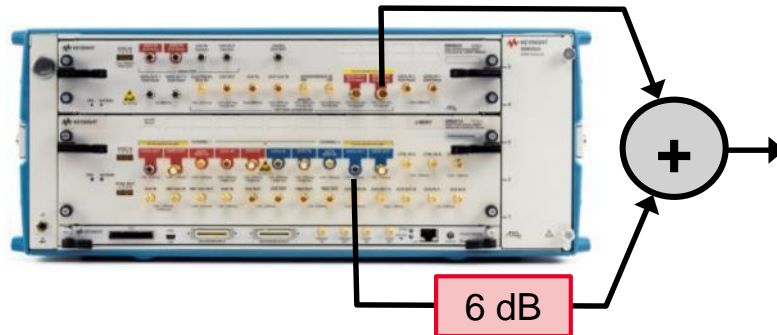
- Margin test steps through increasing degrees of stress until link failure
 - (BER worse than target for FEC, - not error free)
- Design the stress to emulate the impairment
- Two general linearity impairment classes in PAM-4
 1. DAC bit weighting error
 2. Compression/Expansion in linear stage



Generating linearity stressed PAM-4 pattern



- Three choices for generating stressed PAM-4 patterns



2 Channel BERT with analog combiner



Integrated PAM-4 BERT

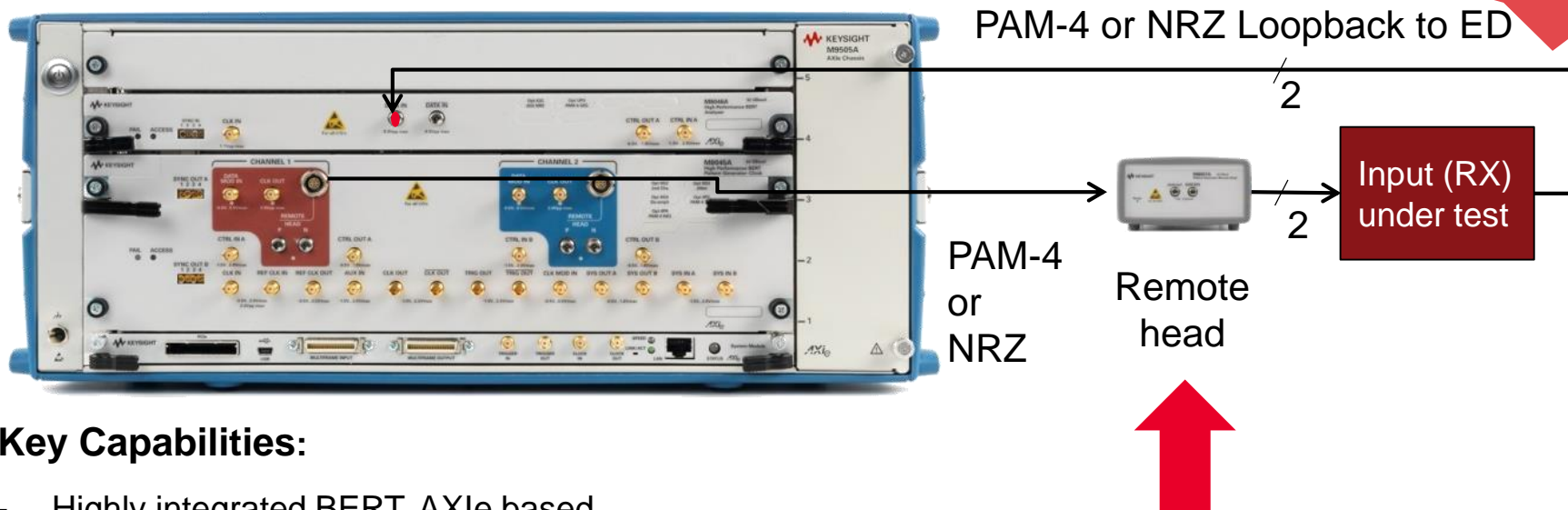


Arbitrary Waveform Generator

- 2 channel NRZ BERT can easily emulate DAC weight error stress, but compression is more difficult
- Integrated PAM-4 BERT or AWG can do both easily

M8040A 64 GBaud High-performance BERT

NEW!

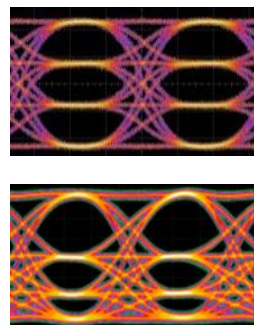


Key Capabilities:

- Highly integrated BERT, AXIe based
- Accurate physical layer characterization and compliance test of next generation digital high speed I/Os with NRZ and PAM-4 data formats

Pattern Generator (M8045A)

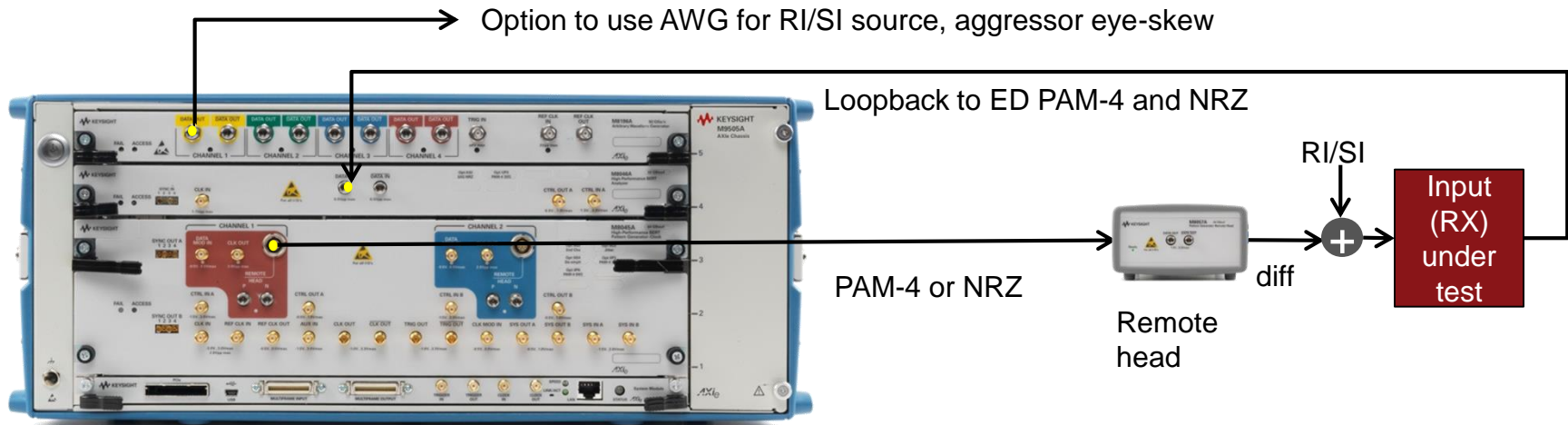
- Single or dual 32/64 GBaud NRZ/PAM-4
- Built in adjustable linearity
- Built-in de-emphasis
- Remote head for close connection to DUT
- NRZ and PAM-4 is switchable by software



Error Detector (M8046A)

- 32 GBaud error detector for PAM-4 and NRZ

PAM-4 Input Testing using M8040A with M8196A



M8040A 64 Gbaud BERT provides:

- Highly integrated for simplified test setup
 - Built-in 4 tap de-emphasis
 - Emulate jitter, calibrated and built-in
 - Emulate aggressor w/ fast tr on 2nd cha
 - Level non-linearity test
- True PAM-4 error detector
 - Low bit/symbol ratios, long PRBS/sequences
 - Automated jitter tolerance tests
- PAM-4 and NRZ switchable
- Scalable/upgradeable via options: 32/64 Gbaud

M8196A complements input test setup when used as:

- Random/ sinusoidal interference source with directional couplers
- Aggressor channel
- PAM-4 generator to emulate horizontally skewed eyes
- Economic PAM-4 generator (see AWG slide for some restrictions)

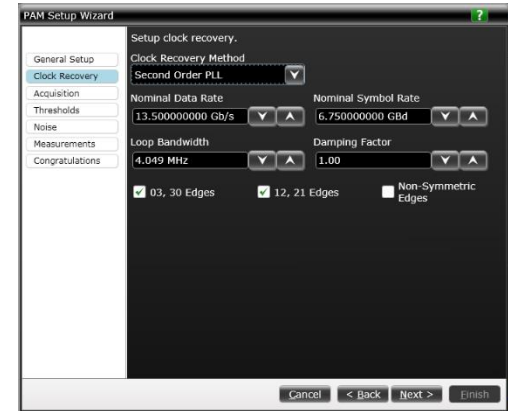
PAM-4 Measurements using Oscilloscope



PAM-4 Measurement Challenges

■ Clock Recovery (CR) – used to track out low-frequency jitter, trigger the scope

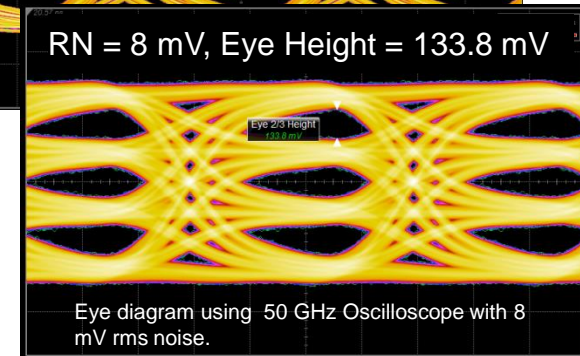
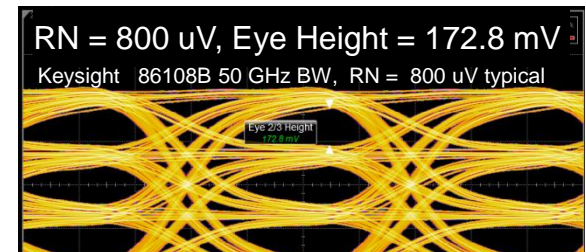
- Real-time oscilloscopes use software CR
 - Transition level qualified SW CDR will include 0-3/3-0 and 1-2/2-1 level transitions.
- Sampling oscilloscopes use hardware CR
 - Existing Keysight HW clock recovery designs work on PAM-4 signals



■ Noise

- Noise will reduce eye opening and degrade system BER
- Random Noise (RN) from DUT TX will Root Sum Square (RSS) add to intrinsic RN from the scope\
- Slower edge speeds (slew rate, S) exacerbate the issue due to AM-to-PM conversion
- Sampling oscilloscopes offer the lowest noise solution for a given bandwidth
(often 5-10x lower than a real-time scope that has equivalent BW)

$$\text{Jitter}_{\text{rms}} = \frac{\text{RN}_{\text{rms}}}{S}$$



The Challenge – most parameters must be analyzed using new methodology/algorithms designed for PAM-4

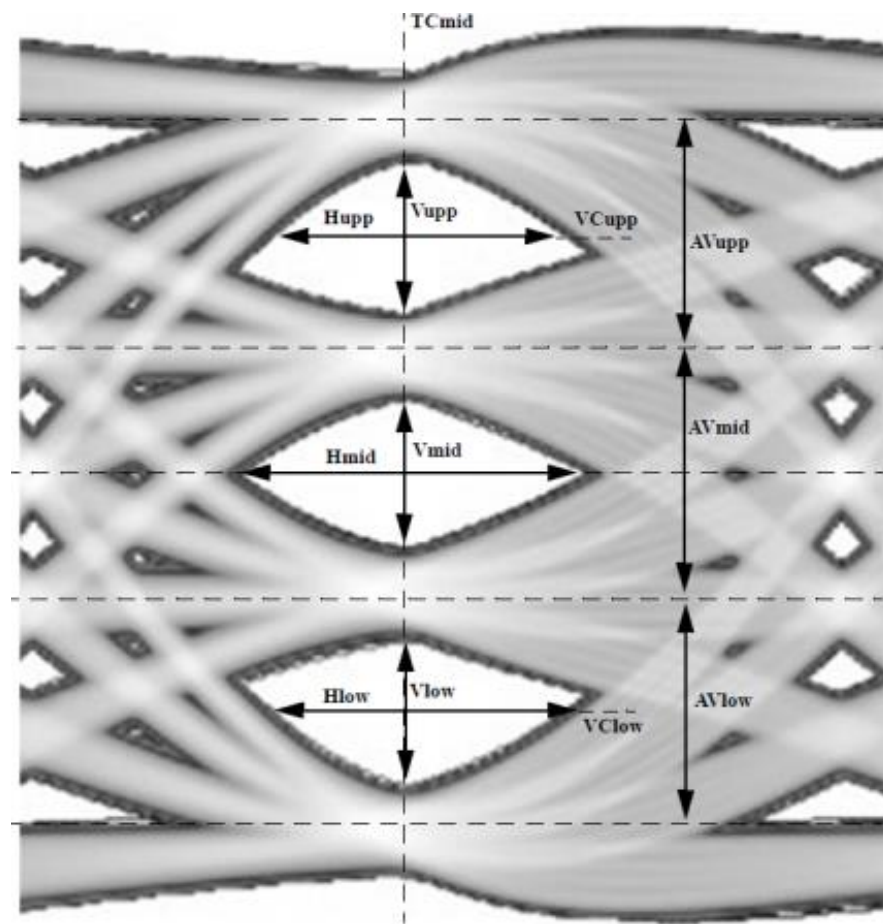
Example: IEEE P802.3bs

CDAUI-8 is a 26.5625 GBd by 8 lane PAM4 physical instantiation of the 400 Gb/s connection.

Annex 120E: CDAUI-8 Chip-to-Module

Table 120E-1—CDAUI-8 host output characteristics (at TP1a)

Parameter	Reference	Value	Units
Signaling rate per lane (range)	120E.3.1.1	26.5625 ± 100 ppm	GBd
DC common-mode output voltage (max)	120E.3.1.2	2.8	V
DC common-mode output voltage (min)	120E.3.1.2	-0.3	V
Single-ended output voltage (max)	120E.3.1.2	3.3	V
Single-ended output voltage (min)	120E.3.1.2	-0.4	V
AC common-mode output voltage (max, RMS)	120E.3.1.2	17.5	mV
Differential peak-to-peak output voltage (max) Transmitter disabled Transmitter enabled	120E.3.1.2	35 900	mV
Eye width ^a (min)	120E.4.2	0.25	UI
Eye height A^b , differential (min)	120E.4.2	50	mV
Differential output return loss (min)	83E.3.1.3	Equation (83E-2)	dB
Common to differential mode conversion return loss (min)	83E.3.1.3	Equation (83E-3)	dB
Differential termination mismatch (max)	120E.3.1.4	10	%
Transition time (min, 20% to 80%)	120E.3.1.5	TBD	ps



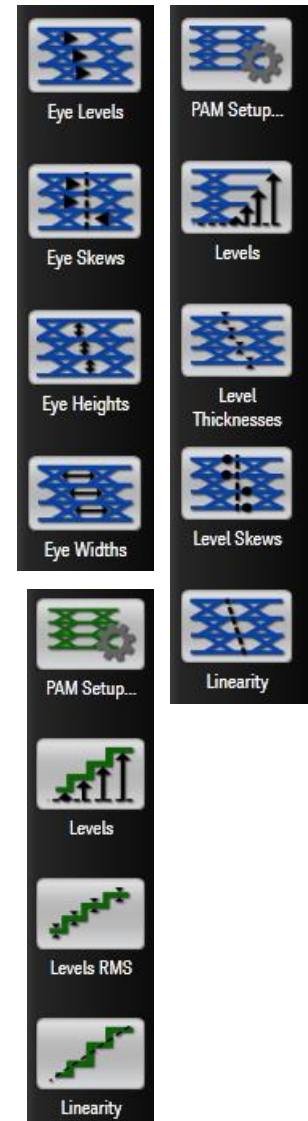
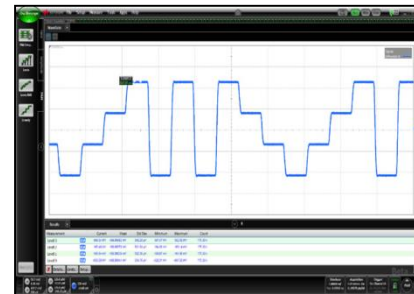
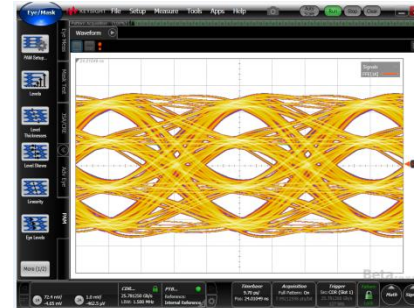
Existing PAM-4 Measurement Capability

Keysight was **FIRST TO MARKET** with PAM-4 SW options for real-time and sampling scope platforms in early 2015:

- 86100D-9FP for the 86100D DCA-X



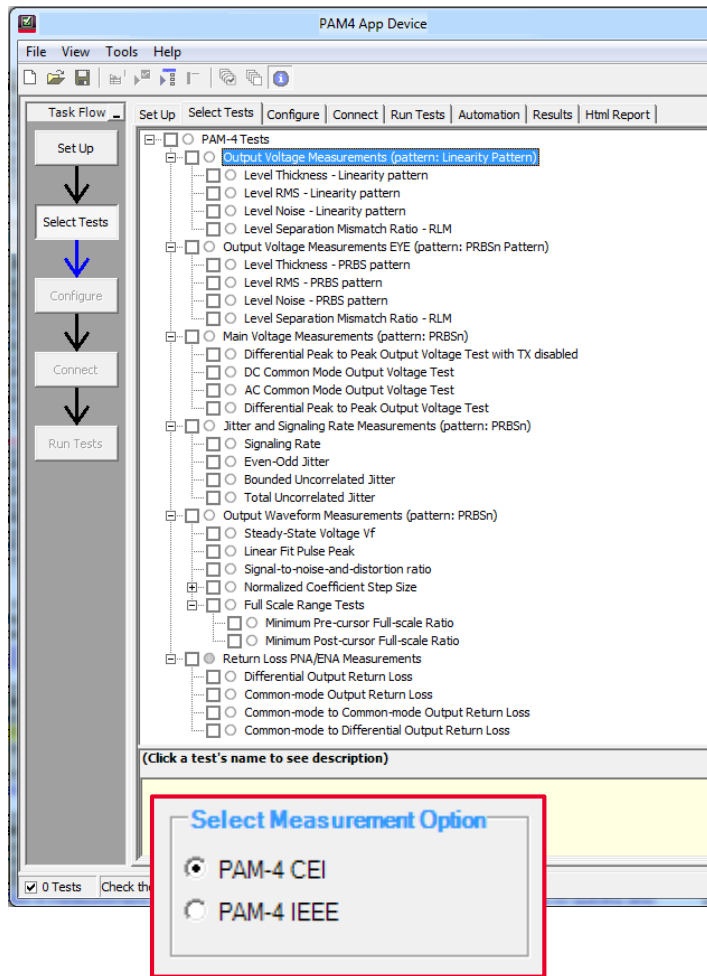
- N8827A/B PAM-4 Analysis Software for RT scopes



These SW options perform the basic PAM-4 measurements required by the Standards, but they do NOT setup and control the instrument, they do NOT compare measurement results to any specs, etc.

New PAM-4 Measurement Application

“Pre-Compliance” SW Apps for emerging Standards using PAM-4



- **N1085A PAM-4 Measurement App**
for Ethernet and OIF-CEI (for the 86100D DCA-X)



- **N8836A PAM-4 Measurement App**
for Ethernet and OIF-CEI (for Infiniium real-time scopes)



Keysight PAM-4 Measurement Application

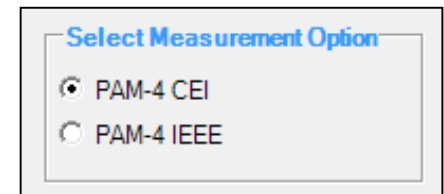
“Pre-Compliance” SW Apps for emerging Standards using PAM-4

Keysight PAM-4 Measurement App covers PAM-4 transmitter measurements outlined in IEEE 400g Ethernet (P802.3bs) and four OIF-CEI-4.0 (56G) clauses.

a. N1085A / N8836A - 1TP

Performs PAM-4 transmitter tests outlined in:

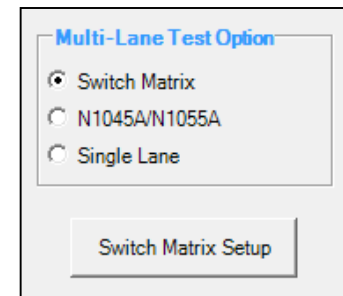
- i. IEEE P802.3bs, Annex 120D, CDAUI-8 chip-to-chip
- ii. IEEE P802.3bs, Annex 120E, CDAUI-8 chip-to-module



b. N1085A / N8836A - 4TP

Performs PAM-4 transmitter tests outlined in:

- i. OIF-CEI-56G-XSR-PAM4 (Extra Short Reach interface)
- ii. OIF-CEI-56G-VSR-PAM4 (Very Short Reach interface)
- iii. OIF-CEI-56G-MR-PAM4 (Medium Reach interface)
- iv. OIF-CEI-56G-LR-PAM4 (Long Reach interface)



c. N1085A / N8836A - 7TP

- a. Provides the ability to control a switch, allowing users to use a single channel to test multiple channels.

Keysight PAM-4 Measurement Application

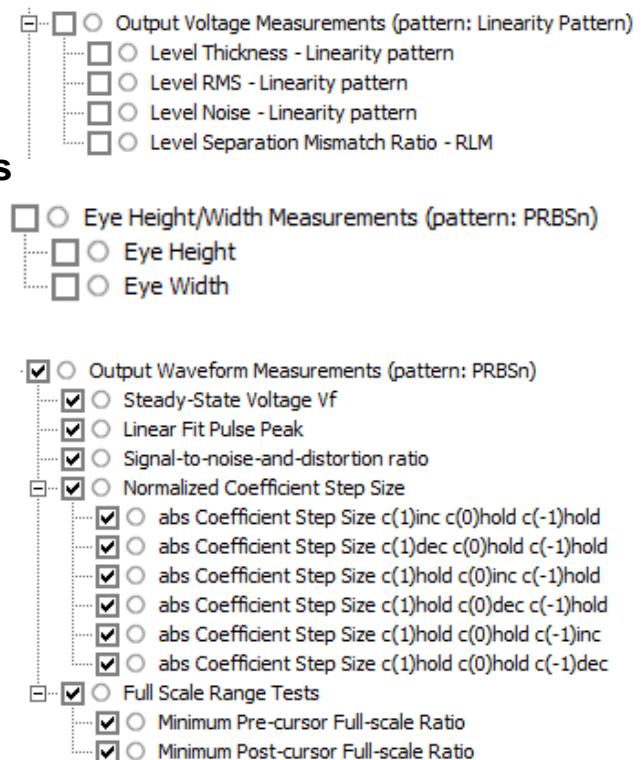
Choose from over 20 tests

Provides comprehensive coverage of all PAM-4 tests that are specific to the Clause you are testing. You may click on all tests, a group of tests or individual tests. The full test name appears in the test list, and is also shown in the test results and reports. A description of the test and reference to the Standard / IA are shown for each test.

- **Linearity (RLM) and Level Measurements**
- **Eye Width (EW), Eye Height(EH) Measurements**
- **Output Waveform Measurements**

Plus

- **Jitter and Signaling Rate Measurements**
(JP03A/JP03B pattern)
- **Return Loss Measurements**
(using ENA/PNA, or N1055A TDR)



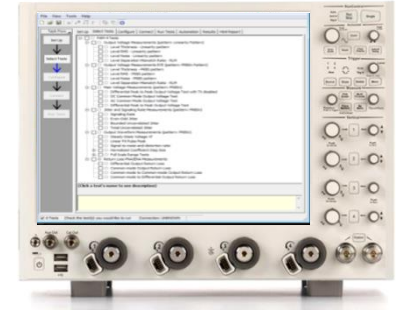
N8836A for Keysight Infiniium Real-time Oscilloscopes

Required Software Options and Bandwidth Requirements

Required Software Options

The N8836A requires that the E2688A Serial Data Analysis package and the N8827A PAM-4 Analysis Software also be licensed on the platform.

If you are using the N8900A Infiniium Offline software with the N8836A, then N8900-006 and N8900-002 must also be licensed in addition to the appropriate N8836A software option indicated in the above table.



Bandwidth Requirements

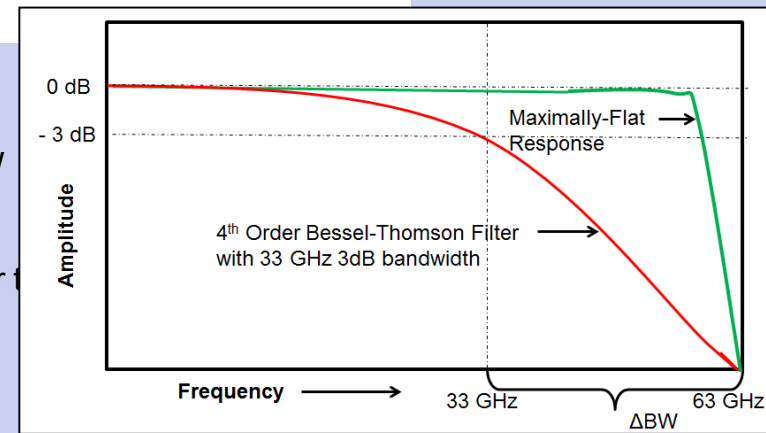
From IEEE 400G Ethernet (P802.3bs):

A test system with a fourth-order Bessel-Thomson low-pass response with 33 GHz 3 dB bandwidth is to be used for all transmitter signal measurements, unless otherwise specified.

What does this mean for my scope requirements?

For a “compliant” reference receiver response, users will need a high BW real-time scope (50 GHz min, 63 GHz preferred).

That is, users must start with a 63 GHz “maximally flat” response in order to achieve a 33 GHz Gaussian/Bessel response specified by Standard. Sampling scope receivers have an inherent Gaussian/Bessel response.



Which scope should I use?

- ✓ **Best for validating / characterizing PAM-4 designs.**
(best signal fidelity due to lower noise).



Electrical – Sampling Scope

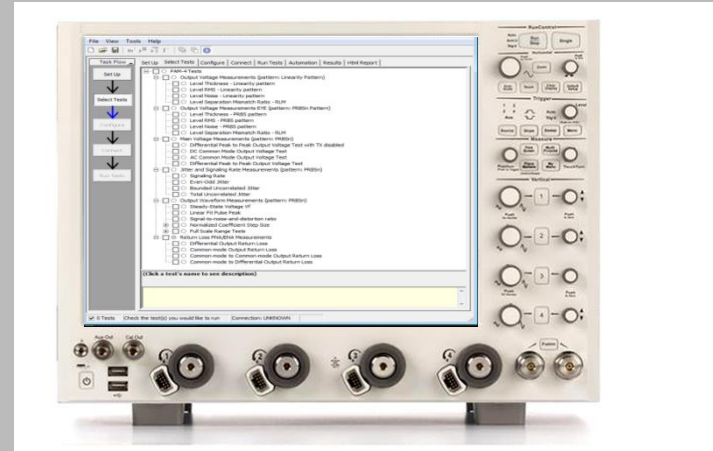
(includes built-in clock recovery and precision timebase)

Keysight 86100D DCA-X with 86108B

- Channels: 2
- Bandwidth: 50 GHz
- Jitter: <45 fs rms typ.
- Electrical Clock Recovery – integrated HW Clock Recovery works with PAM-N signals to 32G Baud
- 86100D-9FP PAM-4 Analysis Software
- N1085A PAM-4 Measurement App for Ethernet and OIF-CEI

NEW

- ✓ **Best for troubleshooting PAM-4 designs.**



Electrical – Real-time Scope

Keysight DSO Z-Series

- Channels 2-4
- Bandwidth: up to 63 GHz
- Sample Rate: Up to 160 GSa/s
- PAM-4 Serial Data Analysis Wizard
- Software Clock Recovery (specify transitions for CR)
- N8827A PAM-4 Analysis Software
- N8836A PAM-4 Measurement App for Ethernet and OIF-CEI

NEW

Summary



- Transition from NRZ to PAM-4 is revolutionary
 - Many new challenges in both electrical and optical links
- Required Output (Tx) measurements and Input (Rx) stress types will change
 - New eye measurements for PAM-4 Output tests
 - Linearity added to stressed Input testing
- New tools are needed for characterizing and troubleshooting links using FEC
- Learn more on the web at: www.keysightcom/find/pam4

Thank you!

Any questions?

