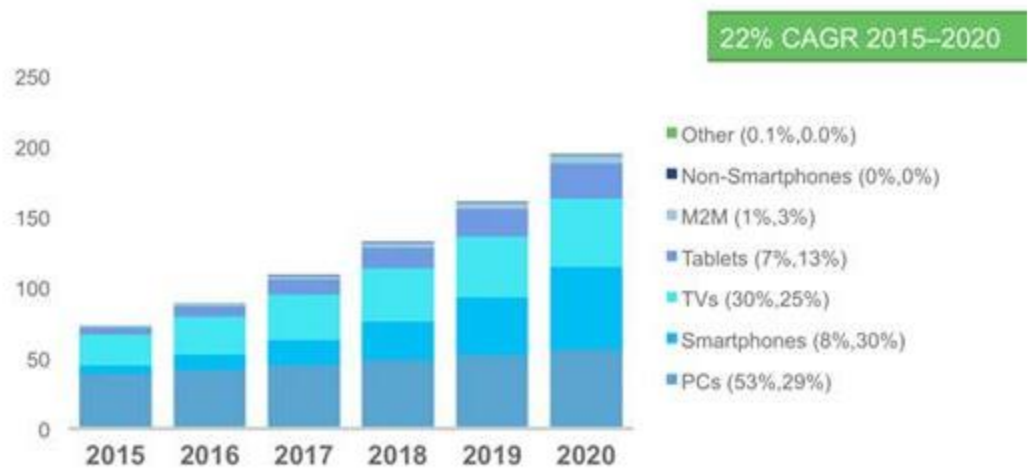
Tektronix

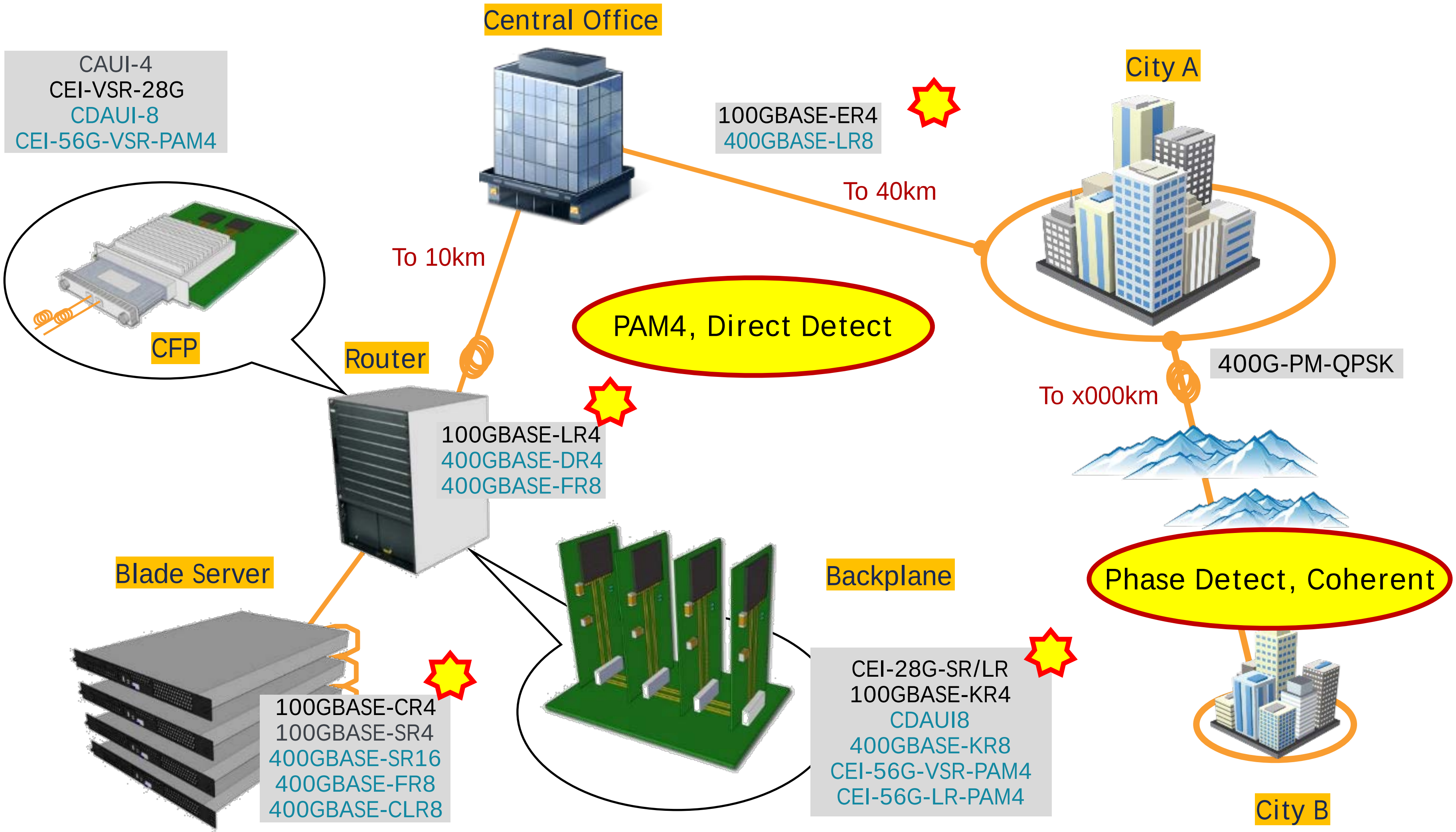
PAM4 Transmitter Test Challenges

Datacom and Networking Trends

- Global IP traffic to triple over next 5 years
- Smart phone traffic to exceed PC traffic by 2020
- Traffic from wireless devices will account for two thirds of the traffic
- Number of devices on IP networks will be more than 3x global population
- Broadband speeds to double by 2020
- PAM-4 signaling is being considered to double throughput to meet expected growth in IP traffic



400G Datacenter Networking Ecosystem



PAM4 Standards

Optical Standard	Modulation	Distance	Data Rate	Multiplex	Signaling Rate
200GBASE-SR4 (802.3cd) similar: 100GBASE-SR2, 50GBASE-SR	PAM4	70m, 100m	N lane x 50Gbps	<n> parallel MMF	26.56 GBd
200GBASE-DR4 (802.3bs)	PAM4	500m	4 lane x 50Gbps	4 parallel SMF	26.56 GBd
400GBASE-DR4 (802.3bs) similar: 100GBASE-DR	PAM4	500m	<n> lane x 100Gbps	4 parallel SMF	53.125 GBd
400GBASE-FR8 (802.3bs) similar: 200GBASE-FR4, 50GBASE-FR	PAM4	2km	<n> lane x 50Gbps	1 SMF 8λ WDM	26.56 GBd
400GBASE-LR8 (802.3bs) similar: 200GBASE-LR4, 50GBASE-LR	PAM4	10km	<n> lane x 50Gbps	1 SMF 8λ WDM	26.56 GBd

Electrical Standard	Modulation	Distance	Data Rate	Multiplex	Signaling Rate
CEI-56G-VSR-PAM4	PAM4	100mm	n lane x 56Gbps	1-n lanes	18-29 GBd
CEI-56G-MR-PAM4	PAM4	500mm	n lane x 56Gbps	1-n lanes	18-29 GBd
CEI-56G-LR-PAM4	PAM4	1m	n lane x 56Gbps	1-n lanes	18-29 GBd
50GAUI-1/100GAUI-2/ 200GAUI-4/400GAUI-8	PAM4	250mm	50Gbps	1,2,4,8 lanes	26.56 GBd
50GBASE-KR/100GBASE-KR2/ 200GBASE-KR4	PAM4	<1m	50Gbps	1,2,4 lanes	26.56 GBd
50GBASE-CR/100GBASE-CR2/ 200GBASE-CR4	PAM4	<3m	50Gbps	1,2,4 lanes	26.56 GBd

Test Requirements

IEEE802.3bs/D3.1 - OPTICAL SYSTEM ARCHITECTURE

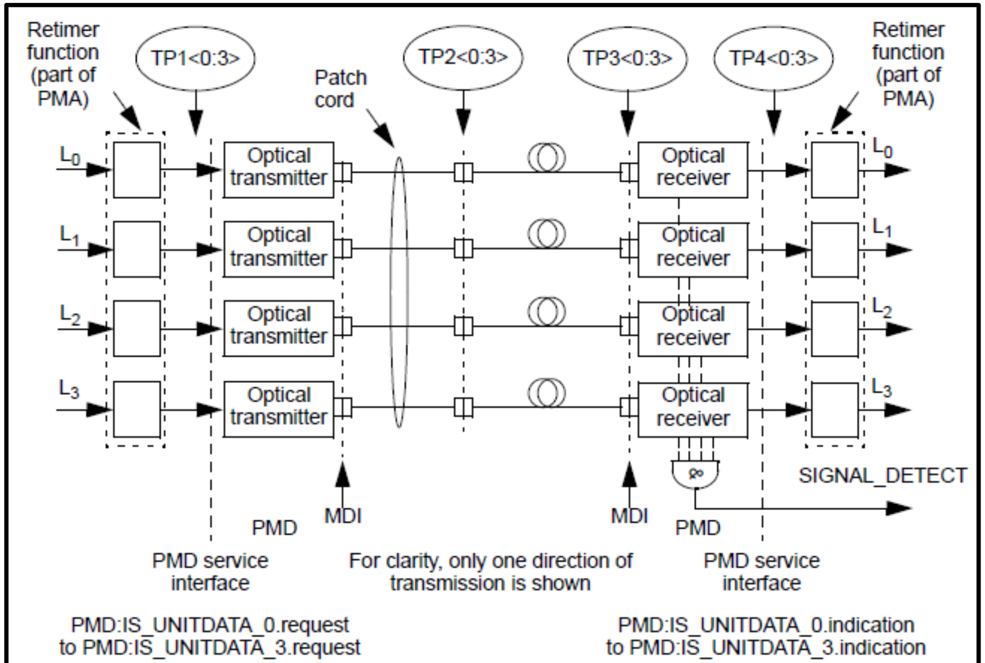
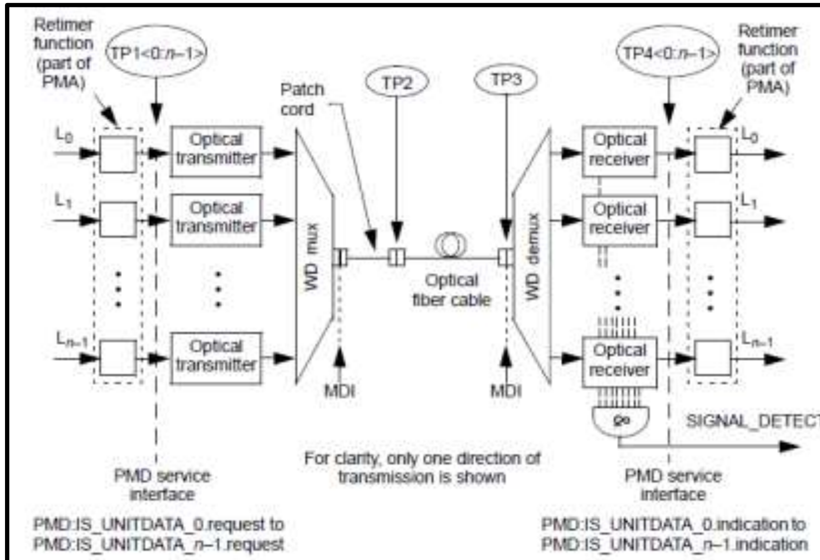


Figure 124–2—Block diagram for 400GBASE-DR4 transmit/receive paths



WD = Wavelength division

NOTE—Specification of the retimer function and the electrical implementation of the PMD service interface is beyond the scope of this standard.

Figure 122–2—Block diagram for 200GBASE-FR4, 200GBASE-LR4, 400GBASE-FR8, and 400GBASE-LR8 transmit/receive paths

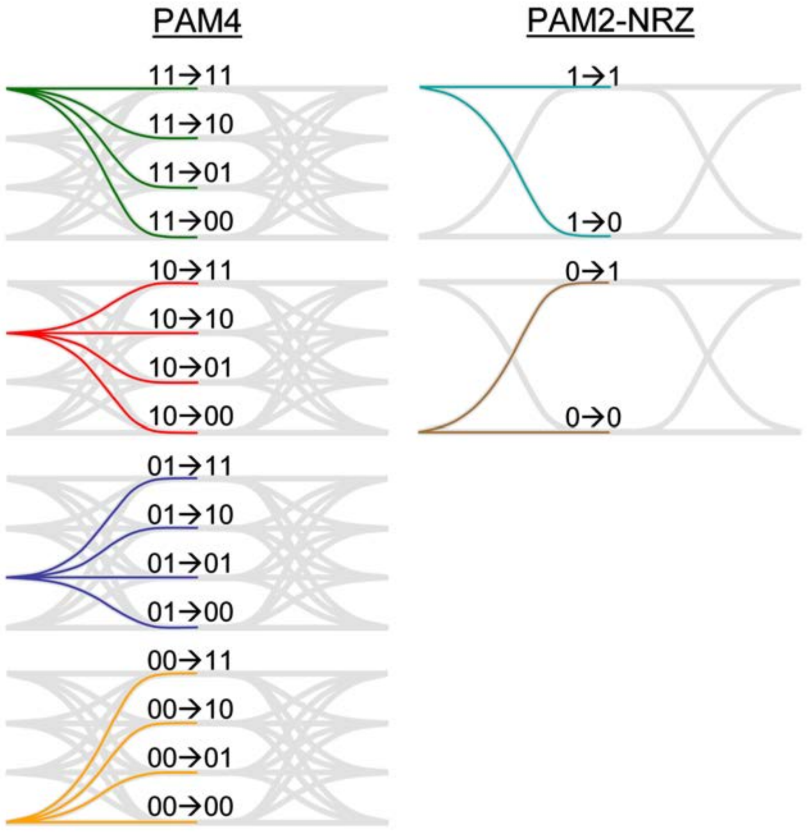
Common Transmitters: VCSEL (850nm, 100m, mm), FP (1310nm, 1km, sm), DFB (1310nm, 10km, sm), EML (1550nm, 40km, sm), Tunable Laser (C-Band, 40km, sm)

Common Receivers: PIN (short distance, low sensitivity), APD (higher sensitivity, long distance)

NRZ vs PAM4

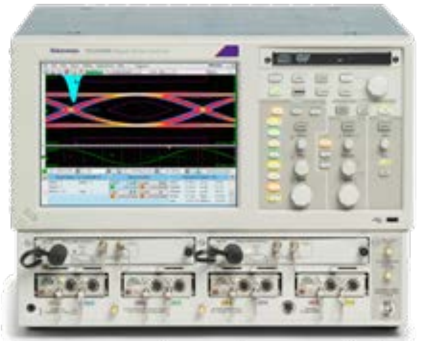
- 2-level vs 4-level signaling
- Transmit 1bit vs 2 bits per UI
- PAM4 requires half of the BW of NRZ for the same data throughput
- 4 possible transitions vs 2 possible transitions from a given level
- Typically use grey coding

	PAM-4	NRZ
Bits per UI	2	1
Levels	4	2
Rising/Falling Edges	6	2
Transitions	12	2
Eye Diagrams per UI	3	1



Test Requirements

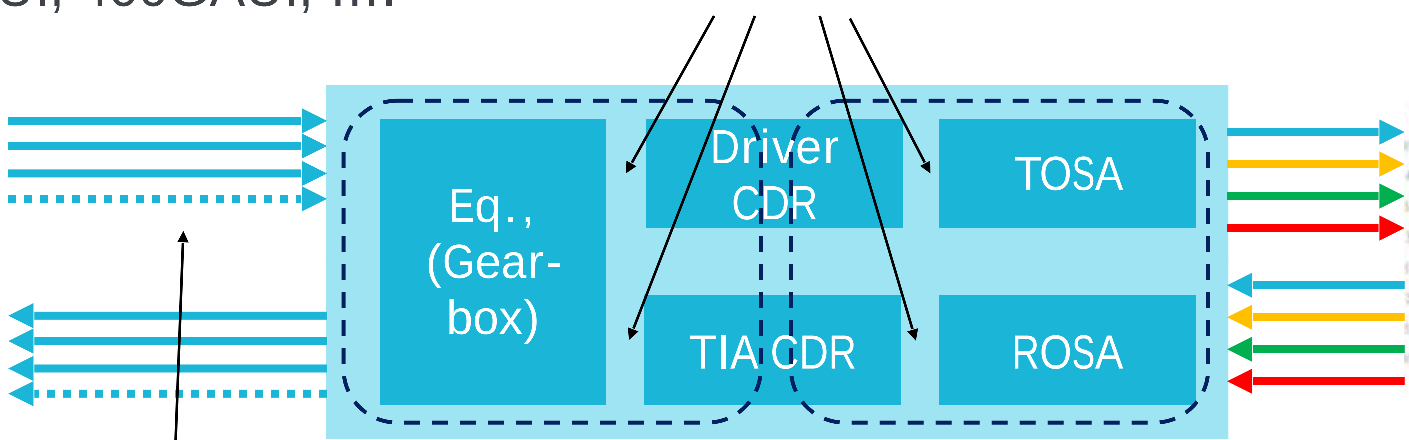
OPTICAL TRANSCEIVERS

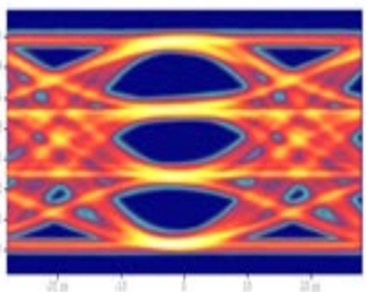


Intermediate test points
Characterization on evaluation boards

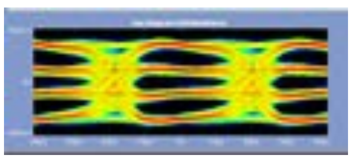
Electrical interface
CDAUI, 400GAUI, ….

Optical
LR8/DR4/…
IEEE 802.3





and debug everywhere!!!

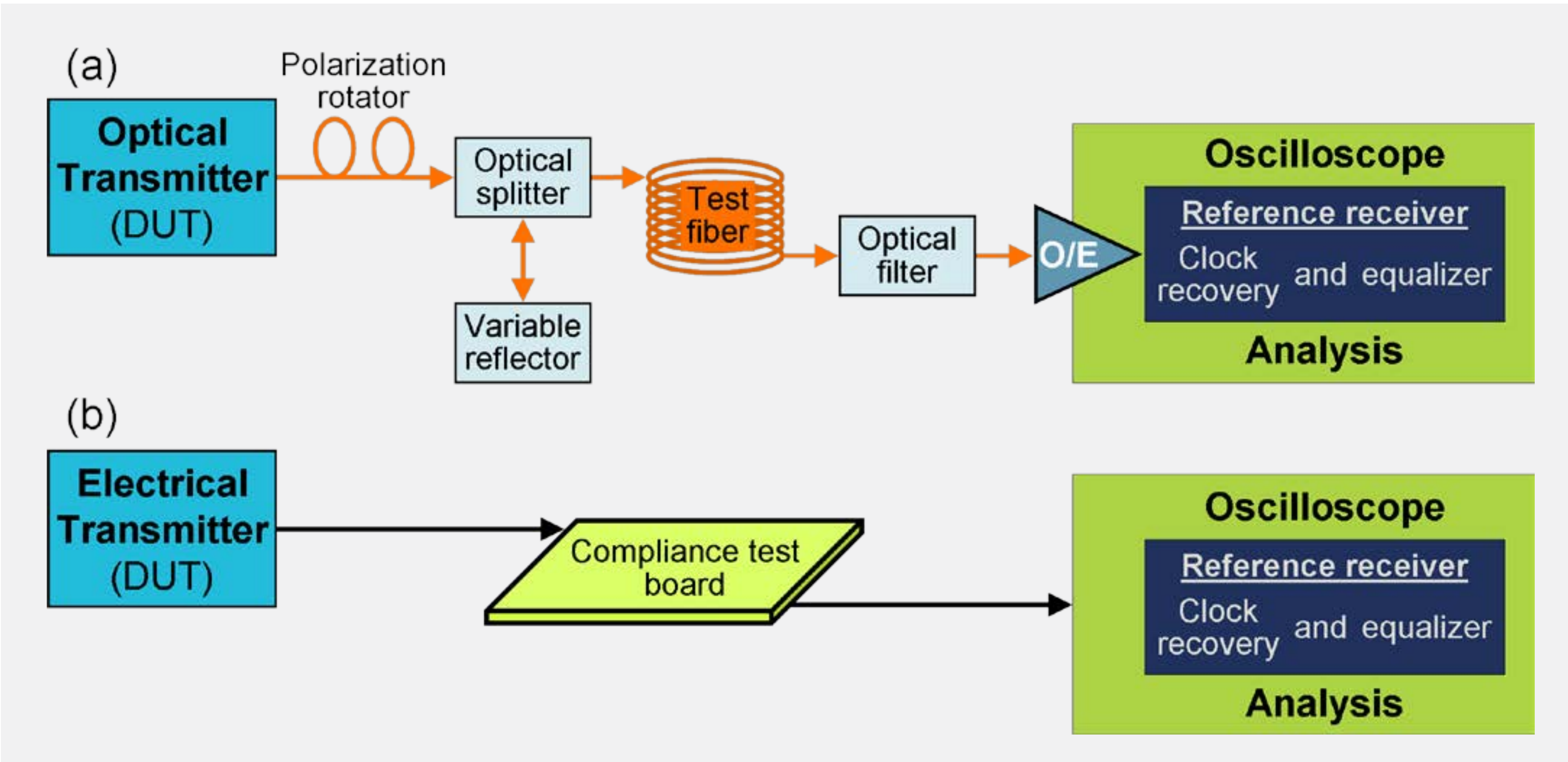


Clock recovery
Channel modelling
Equalization
Error Detection post-equalization
Error rate and location
DSP simulation

PAM4 Testing

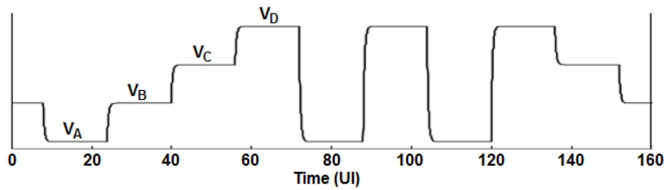
Test Requirements

TYPICAL TX TEST SETUP



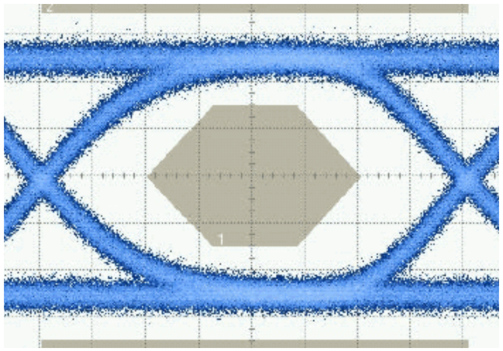
PAM4 Test Patterns

- **Linearity** (160 symbols)
  - 10 sections, each composed of 16 repeats of a symbol

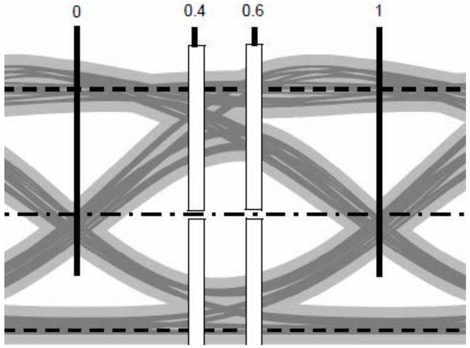


- **Square Wave** (16 symbols)
  - 8 threes, 8 zeros
- **SSPRQ** (32768 symbols)
  - 3 sections, each extracted from a stressful portion of the PRBS31Q pattern
- **PRBS13Q**: (8191 symbols)
- **PRBS31Q**: (> 2 billion symbols)
  - Commonly used as a crosstalk aggressor

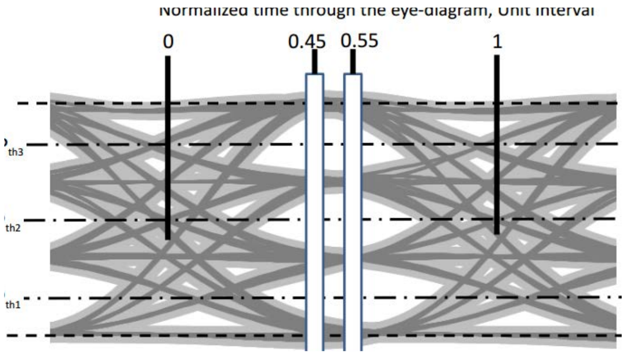
Evolution of Optical Measurements



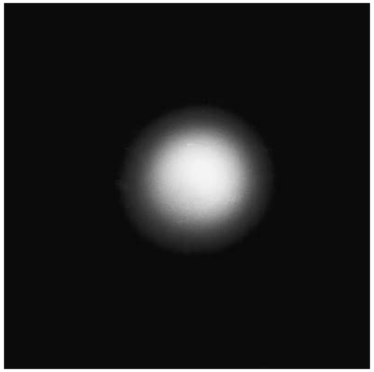
NRZ – Eye Histogram
(provides BER + SNR)

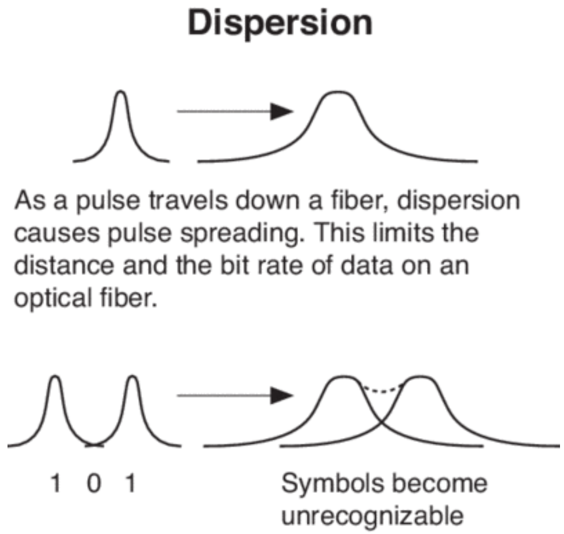


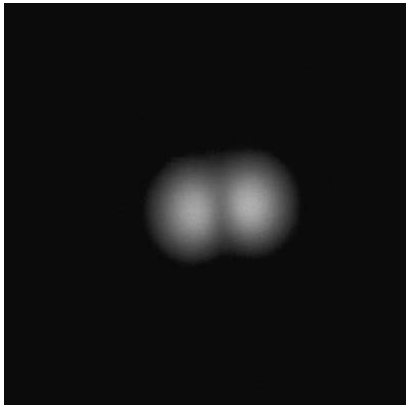
PAM4 – Eye Histogram
(provides BER + SNR)

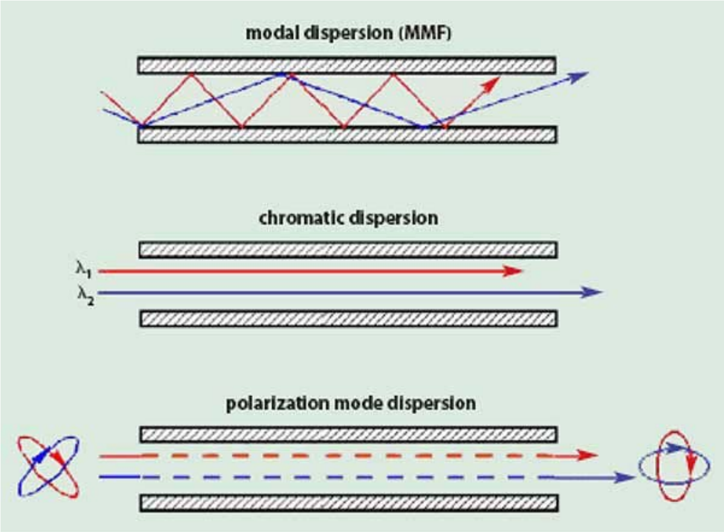


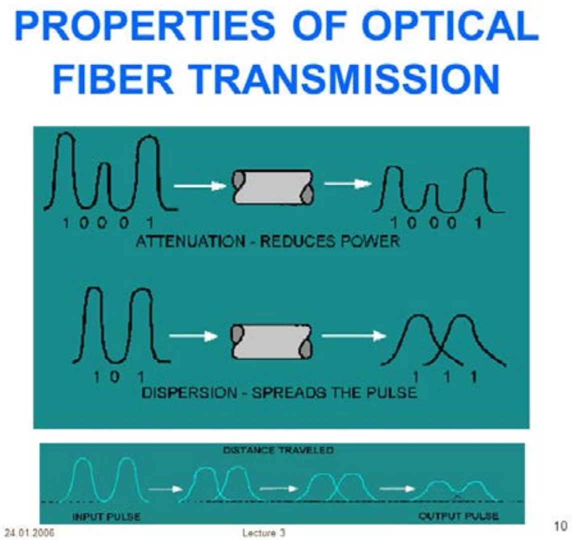
Optical Fiber Basics









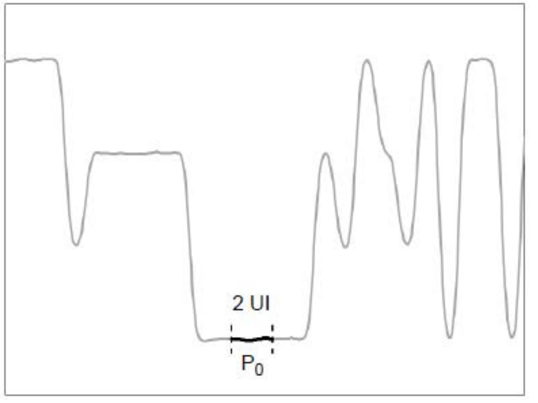


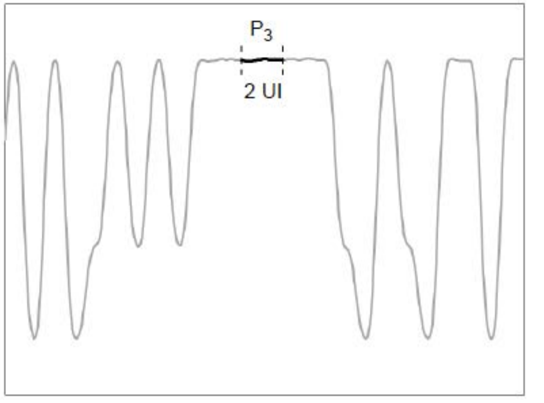
Key Measurements - Optical

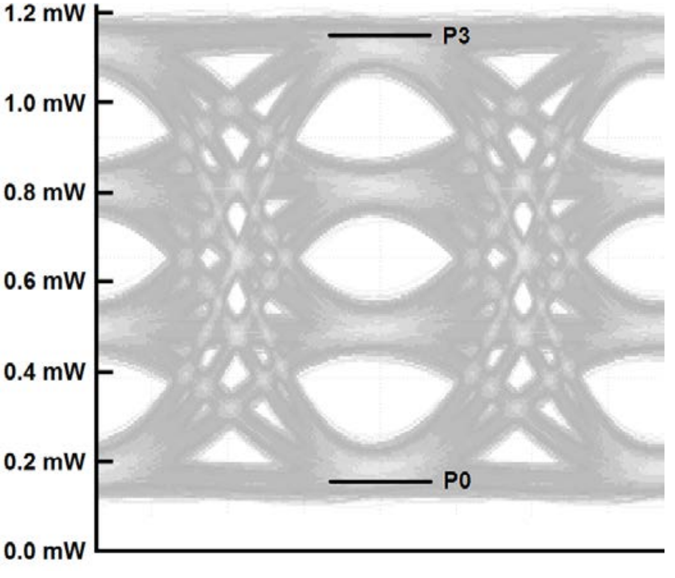
- **Extinction Ratio (ER)** : Ratio of the 2 optical launch power levels
- **Optical Modulation Amplitude (OMA)** : Difference between the 2 optical launch power levels
- **Average Optical Power (AOP)** : Average power level for the entire waveform (not based launch power levels)
- **Optical Launch Power Levels**
  - NRZ Signals – Light “ON” Light “OFF”
  - PAM4 Signals – P0 (Lowest Level) and P3 (Highest Level) middle levels P1 and P2 are not considered.

Key Measurements – ER and OMA

P0 and P3 are measured on strings of consecutive symbols







ER and OMA are calculated from P0, P3

ER = P3 / P0

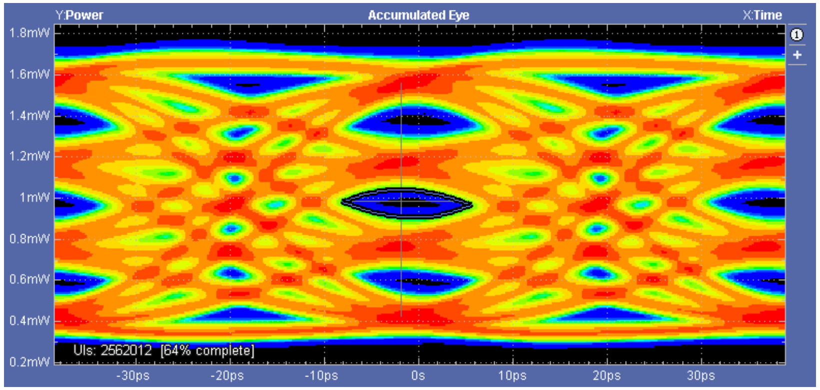
- usually expressed in dB
- sensitive to proper dark-level calibration

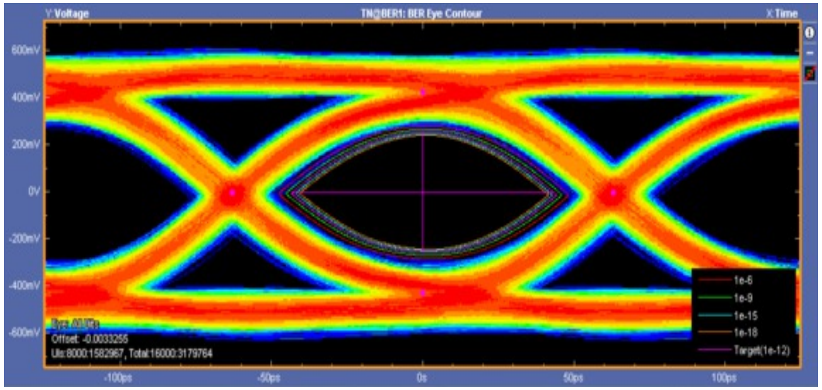
OMA = P3 – P0

- may be in dBm or Watts

Test Challenges

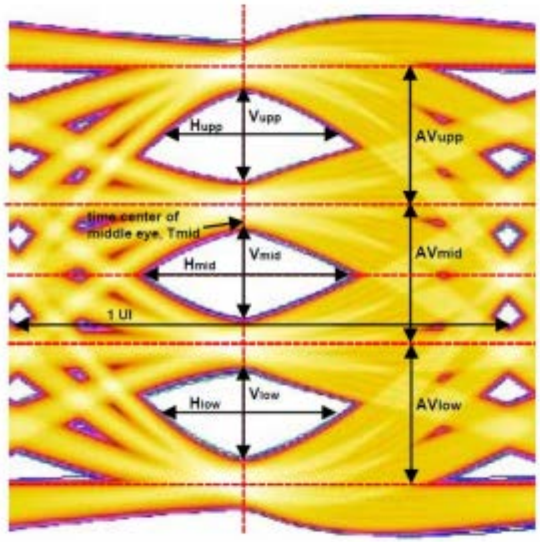
- Two bits are grouped and mapped to one symbol resulting in four signal levels, which form 3 eyes
- Vertical eye opening (eye height) @ BER
  - PAM-4 individual eye height 33% of NRZ at same supply voltage
- Horizontal eye opening (eye width) @ BER
  - PAM-4 eye width is reduced by transitions between non-adjacent levels

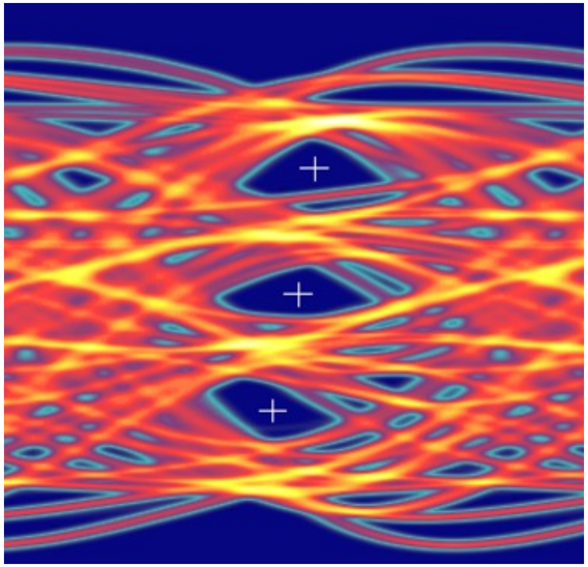




Test Challenges

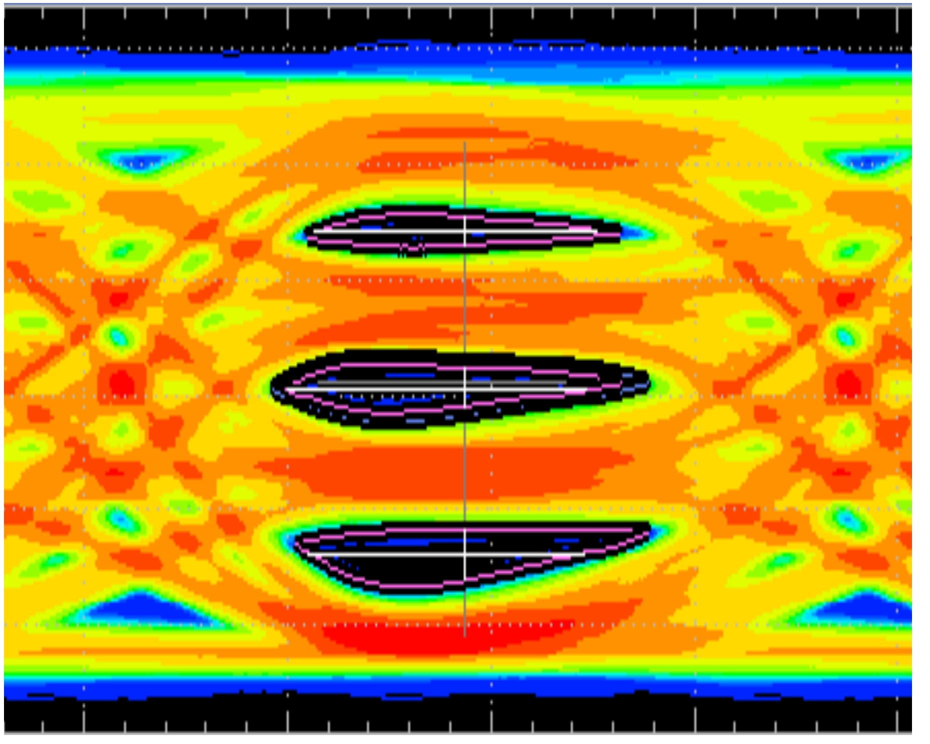
- PAM4 is more susceptible to noise due to reduced eye height
- Three different eye's require additional care in making sure that all of them are symmetric
- Multi Level Signaling introduces additional complexity in clock recovery, Pattern detection and Jitter measurements
- As PAM4 evolves newer more complex measurements are being defined into the standards





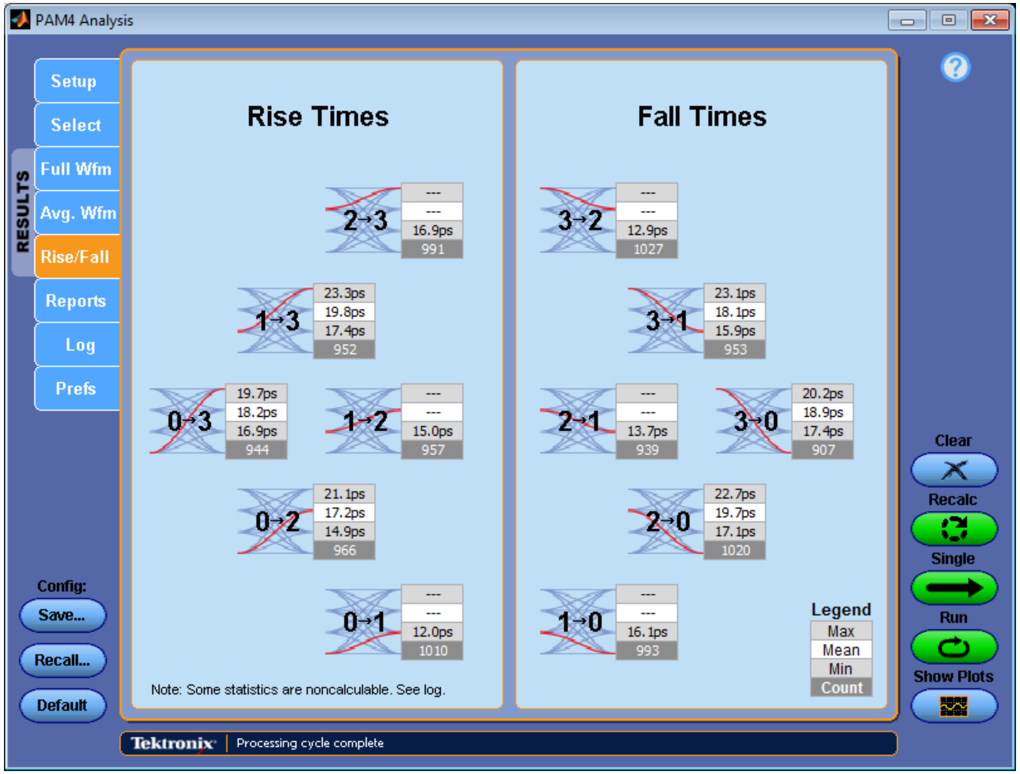
Key Measurements

- **Eye Height / Width** : The eye height / width of the PAM4 signal provides a measure of the eye opening.
  - Actual Eye Height and Widths at corresponding reference voltage
  - EW6 and EH6 per OIF-CEI Spec
  - EW5 and EH5 per IEEE specifications
- **Jitter**: Total Jitter at selected BER, Deterministic Jitter and Random Jitter using the Dual Dirac model on the PAM4 signals.



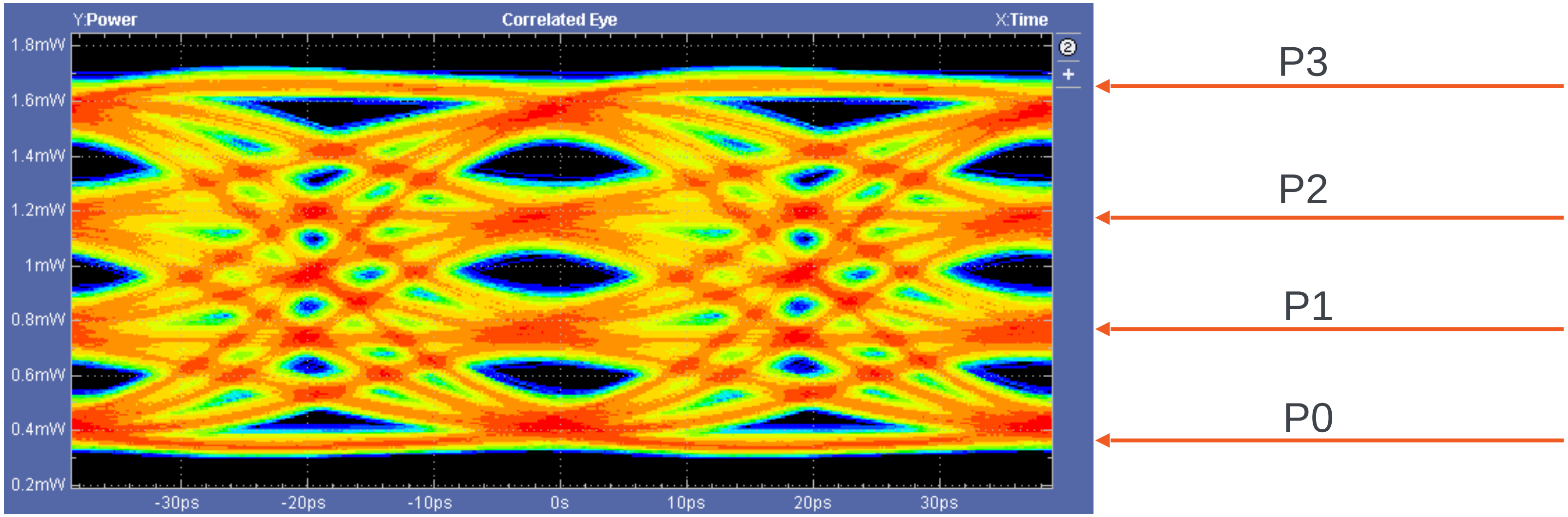
Key Measurements

- **Rise / Fall time**: Time for signal transition from the 20% to 80% of nominal symbol level
- Statistics for all 12 transitions
  - Rise time min, max, mean values
  - Fall time min, max, mean values

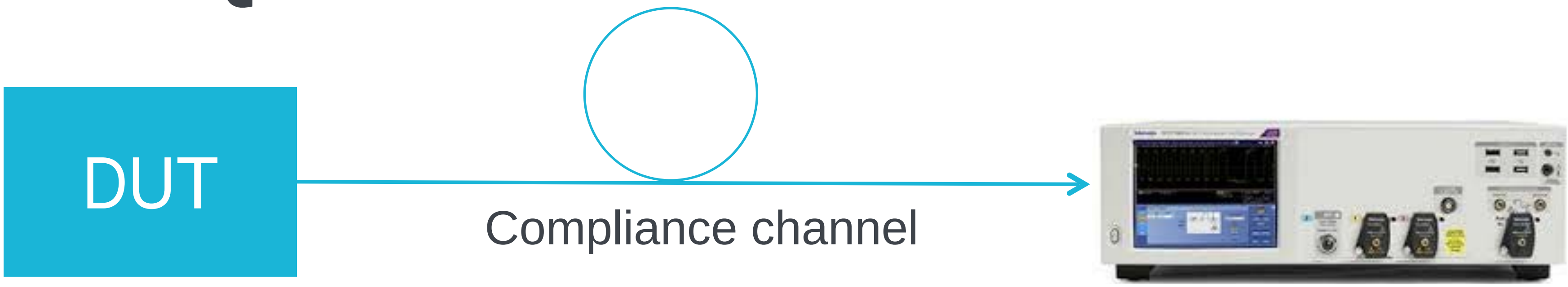


Key Measurements

- **Linearity**: it is a measure of how the 4 symbol levels are spaced in vertical dimension.
- **Level Deviation** : A measure of the deviation of the vertical intervals between levels from perfectly equal spacing where 0% represents perfect spacing.
- **Level Thickness:** An overall measure of the vertical thickness of the symbol levels in the correlated waveform, where an ideal signal with maximally open eyes would have a thickness of 0%.



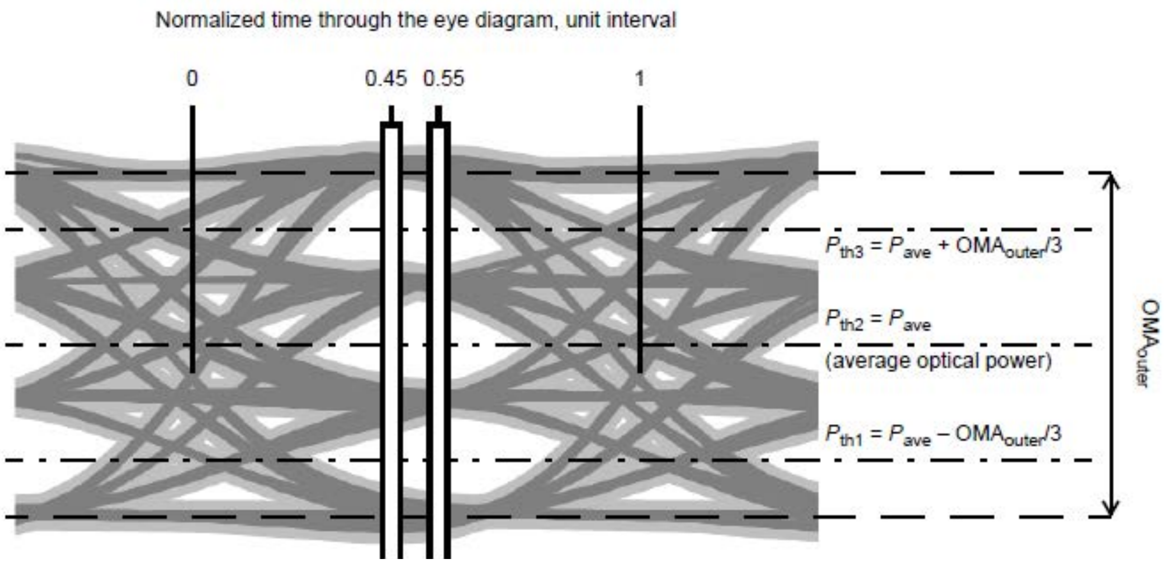
TDECQ Measurement



Test pattern

- TDECQ is a measure of each optical transmitter’s vertical eye closure as measured through an optical to electrical converter (O/E).
- Bandwidth requirement: follow 4^{th}-order BT filter from DC to 0.5 x Baud rate. Equivalent to a combined reference receiver.
- Test pattern to be used for measurement of TDECQ: SSPRQ or PRBS patterns.
- Measured after 5tap, T spaced FFE reference equalizer. The sum of the tap coefficients is equal to 1.

TDECQ Measurement



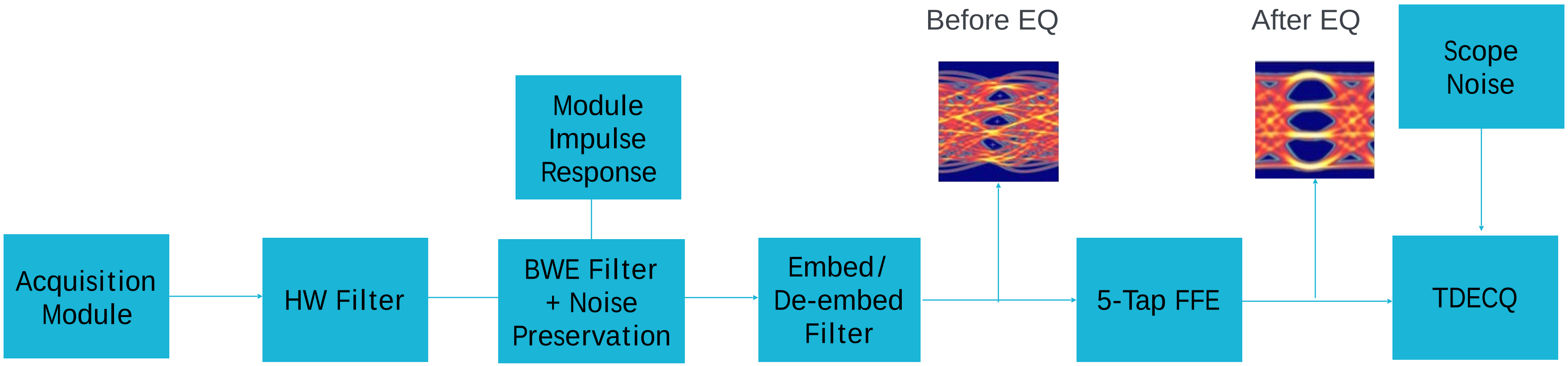
$$TDECQ = 10\log_{10}\left(\frac{OMA_{outer}}{6} \times \frac{1}{Q_t R}\right)$$

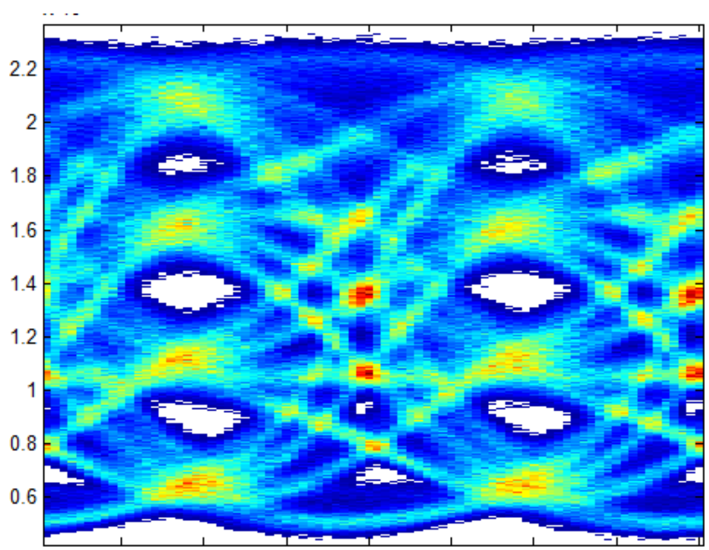
OMA,outer = amplitude of PAM4 signal
R = standard deviation of acceptable receiver noise @ SER of 4.8 E-4
- compensated for scope and E to O noise

Q,t = 3.414
Smaller TDECQ is better (penalty). More acceptable receiver noise is better.

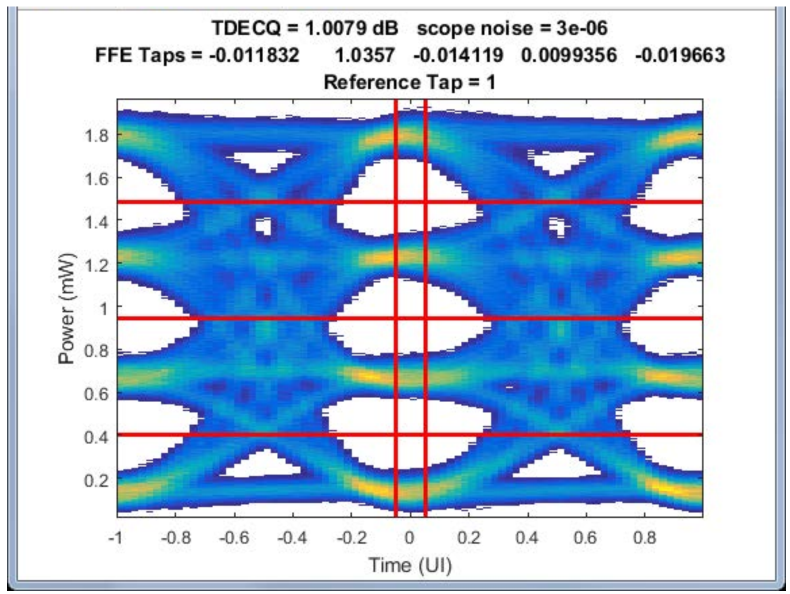
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	2.5	dB

TDECQ Measurement Process - ET





Before EQ

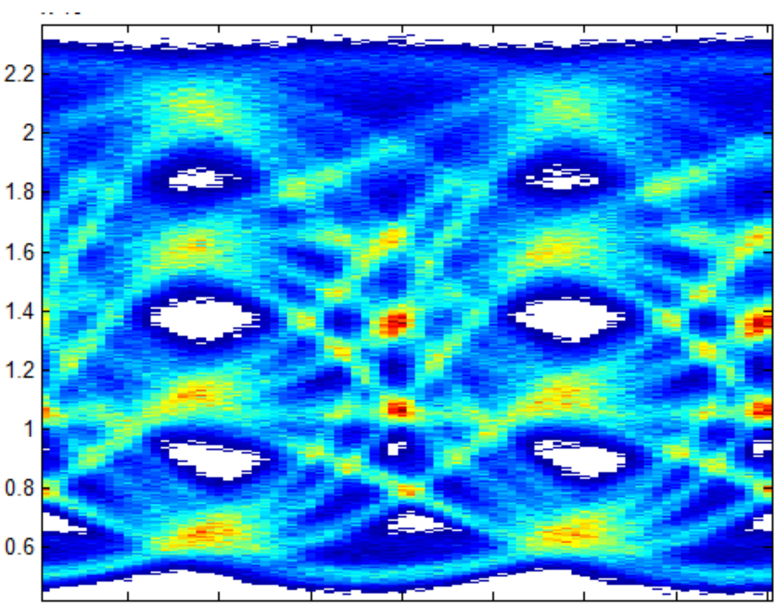


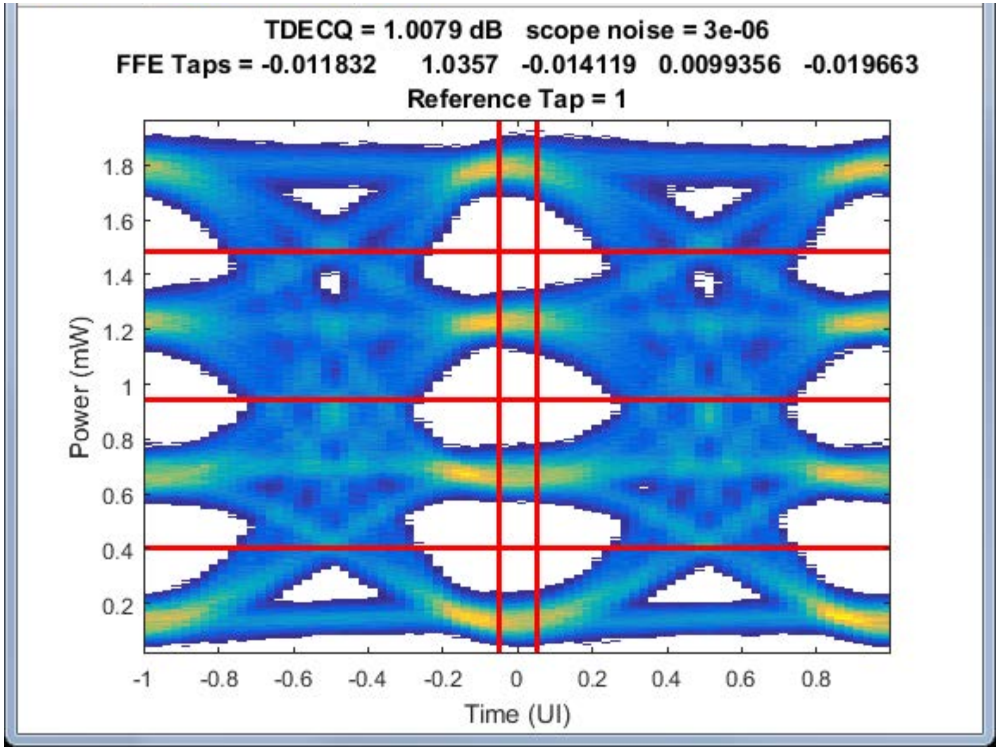
After EQ

Reference Equalizer Optimizes TDECQ

Before EQ

After EQ





Oscilloscope BW Requirements

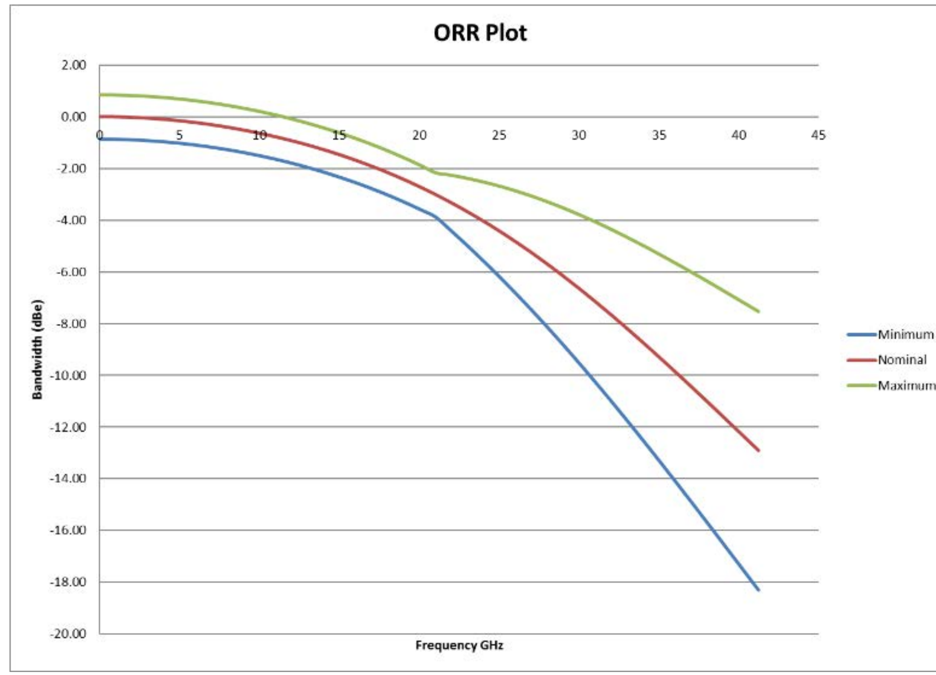
- In optical communications an optical reference receiver (ORR) with a fourth-order Bessel-Thomson (BT4) frequency response generally used

Optical Bandwidth Requirements for NRZ and PAM4 Signaling

WHITEPAPER

There is confusion about Optical Bandwidth and Electrical Bandwidth of optical channels and how these terms relate to Optical Reference Receivers (ORRs). PAM4 signaling has further complicated minimum bandwidth requirements in order for receivers to be spec compliant.

Up until recently, both optical and electrical bandwidth produced similar results when using 0.75 x baud rate; however, with the recent IEEE spec change to 0.5 x baud rate, electrical and optical bandwidths are no longer the same, thus causing confusion about the relationship between the two. This paper clarifies these terms by starting with the proper definitions, mathematically showing how they are related, and provides the basis to understand and confidently calculate optical and electrical bandwidth for an optical channel.v



Optical BW Requirements

(Double-click to open)

Tektronix 400G Acquisition Solutions

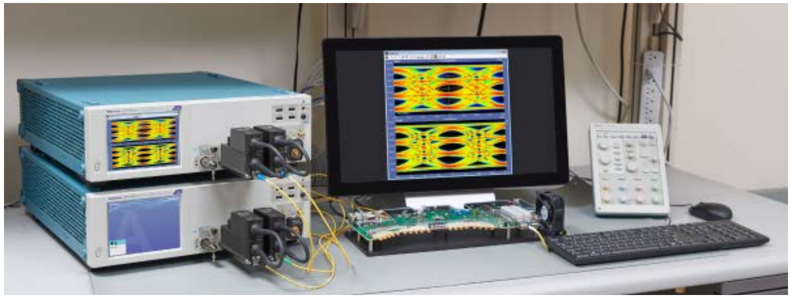
Equivalent Time Scope

80GHz Optical Bandwidth
70GHz Electrical Bandwidth
<100fs jitter noise floor
20nW to .6uW Optical Resolution
Automated test of 80+ Industrial Standards
Best overall Optical solution
Trigger Signal Needed (CDR-HW)
Higher Dynamic Range
Optical module better sensitivity for lower optical power signals (-10dBm on 80C20/21)

ET

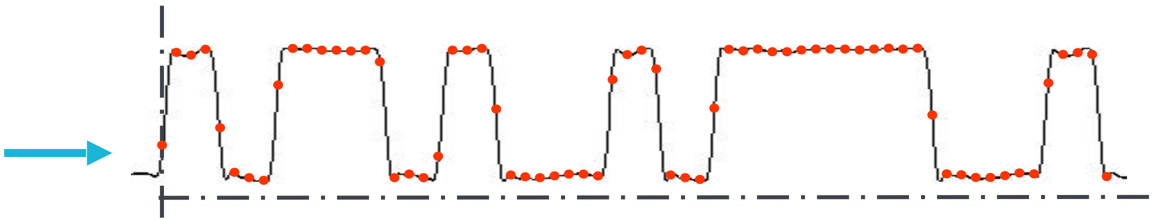
Real Time Scope

70GHz Analog Bandwidth
4.3ps rise time (20%-80%)
200GS/s Sample Rate
<125fs jitter noise floor
≥25GHz Edge trigger bandwidth
Compact 5 ¼” Oscilloscope package
SW clock recovery required (key to 400G)
Comprehensive CTLE, DFE, FFE signal processing
Lowest noise real time acquisition system
No Trigger signal needed
Requires higher Optical Power Input (-3dBm), 7OE2 Conv Gain 110V/1W

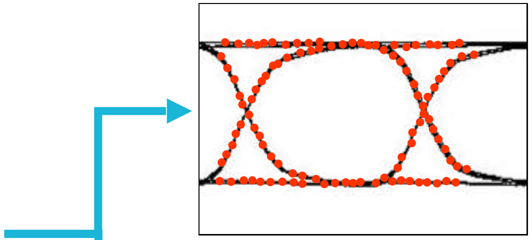


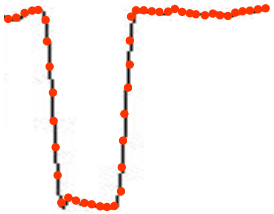
RT

Real-Time Solution



RT





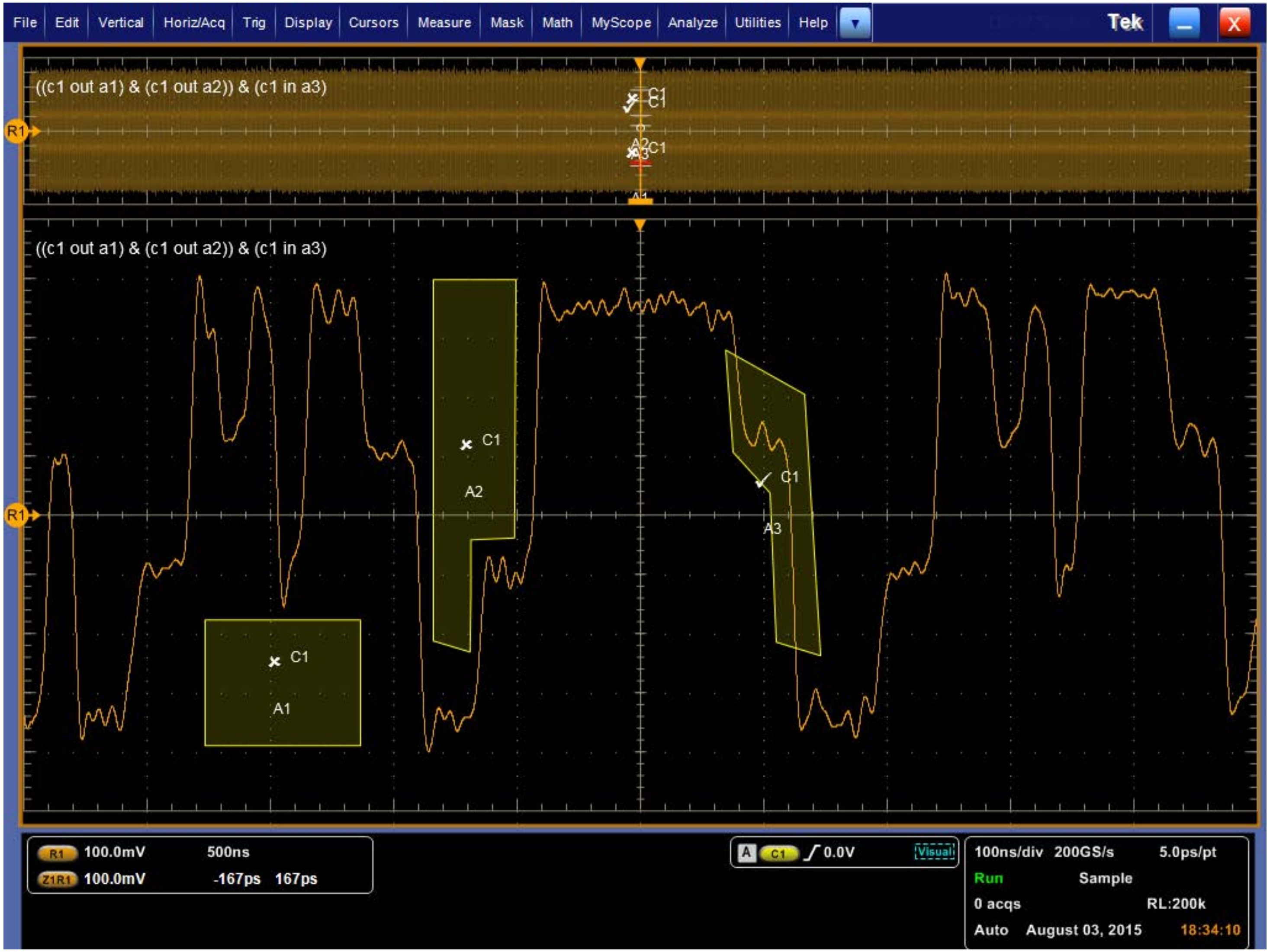
ET

Real-Time Solution

- What can you do with a continuous waveform ?
  - Clock Recovery
  - Pattern detection
  - Pattern comparison
  - Measurements per unit interval or symbol interval
  - Statistics per unit interval or symbol interval
  - Triggering on pattern sequences

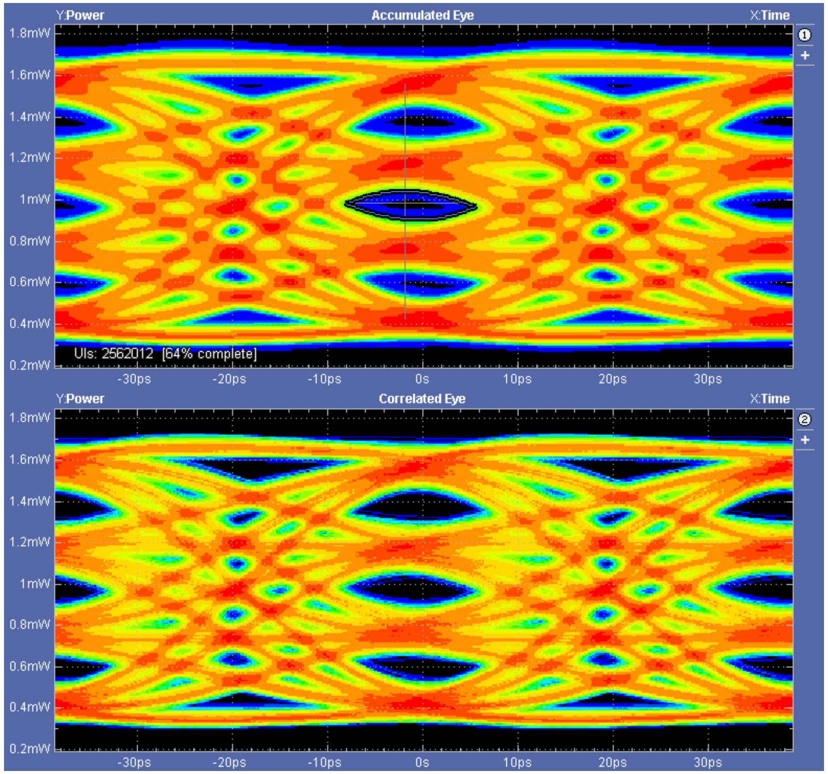
PAM4 Triggering

VISUAL



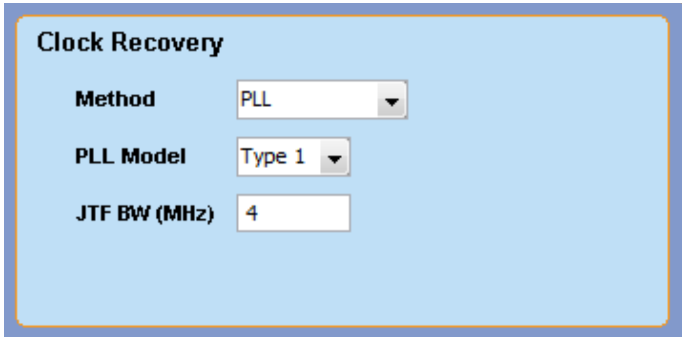
Full vs Correlated Waveform

- Full Waveform
  - Can be defined for waveforms with repeating or non repeating pattern
  - Fold the entire waveform to create eye
- Correlated Waveform
  - Only defined on waveform with repeating patterns
  - Single repeat of the pattern that shows only deterministic effects
  - Fold the single repeat to create eye



PAM4 Analysis

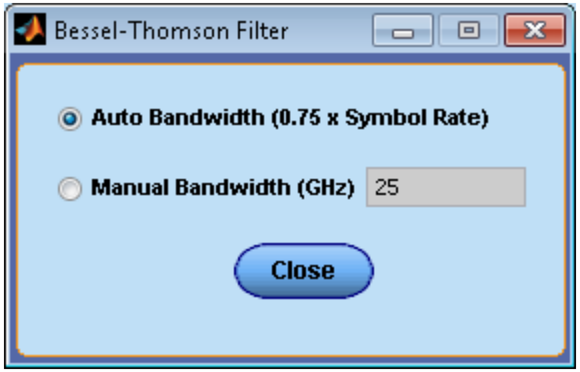
- Clock Recovery
  - Enables recovery of the sample clock from the acquired waveform
  - Uses a noise tolerant software model of PLL with programmable options

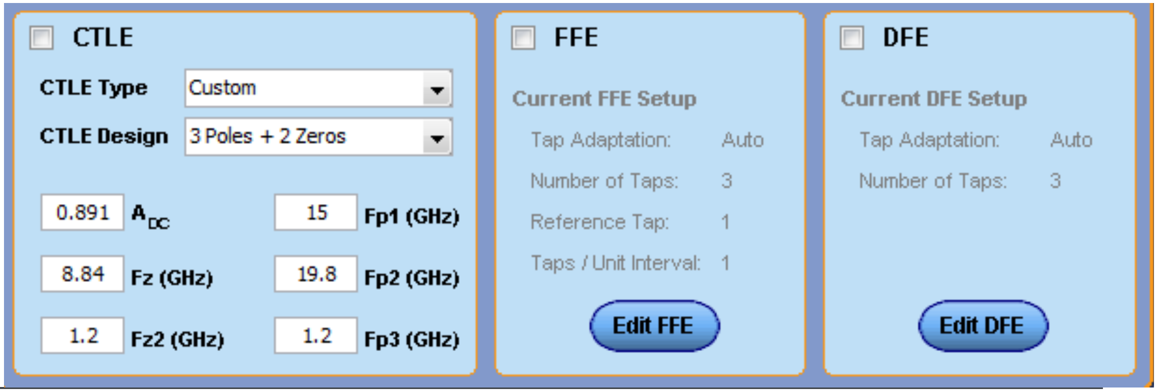


- Waveform Filter
  - Test fixtures used for signal access have effect on the signal
  - De-embed to remove effect of test fixtures
  - Embed to study effect of different channels

PAM4 Analysis

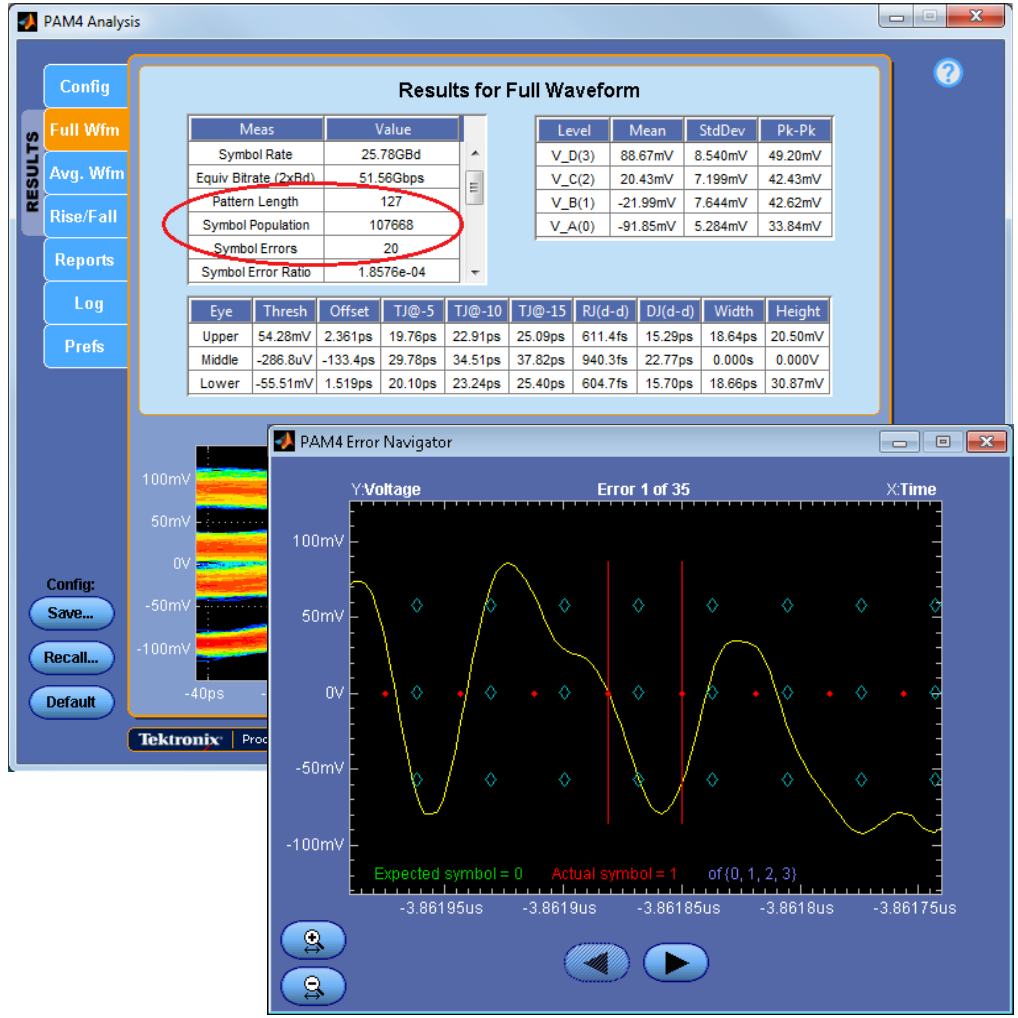
- BT Filter
  - Automatically apply BT filter based on detected bandwidth
- Equalizer
  - Enables the acquired eye to be opened by applying equalizers
  - Generic equalizer with programmable CTLE, FFE DFE offered
  - Load standard specific equalizer settings with single click
  - Auto-optimization of tap values per selected optimization criteria





Error Detector

- Automatically detect symbol errors
- Visualize Symbol errors on error navigator
- Navigate to individual symbol / bit errors
- Clock recovery, eye centers and expected symbols annotated
- Accumulate SER and BER over multiple acquisition cycles



Comprehensive Measurement Suite

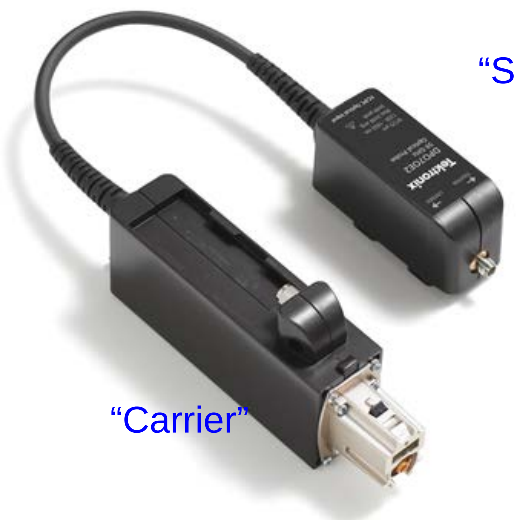
PAM4 Optical Measurements	
Error Analysis	• Symbol Errors, • SER • BER
Linearity	
Jitter	• Rj • Dj • Tj@BER
Statistical Eye Analysis	• Vertical Eye Closure • EW6 / EW5 • EH6 / EH5 • V_{upp} / V_{mid} / V_{low} • H_{upp} / H_{mid} / H_{low}
Optical	• ER • OMA • AOP
IEEE Specific	• TDECQ
Correlated Waveform	• Level Deviation • Level Thickness • Time Deviation • Rise and Fall

PAM4 Electrical Measurements	
Error Analysis	• Symbol Errors, • SER • BER
Linearity	
Jitter	• Rj • Dj • Tj@BER
Statistical Eye Analysis	• Vertical Eye Closure • EW6 / EW5 • EH6 / EH5 • V_{upp} / V_{mid} / V_{low} • H_{upp} / H_{mid} / H_{low}
SNDR	• SNDR • P_{max} • σ_e • σ_n
OIF-CEI	• UUGJ • UBHPJ • EOJ
IEEE Specific	• Jrms • J4 • EOJ • Rise Time • Fall Time • SNR_ISI
Correlated Waveform	• Level Deviation • Level Thickness • Time Deviation • Rise and Fall

PAM4 Testing - Optical Probe

Introducing DPO7OE2 Optical Probe

- Optimized for 56G Data Center Network App’s
- 59 GHz Optical bandwidth, DC coupled
- Single mode, 1200nm – 1650nm
- Compatible with TekConnect and ATI inputs
- Use with DPO70kSX



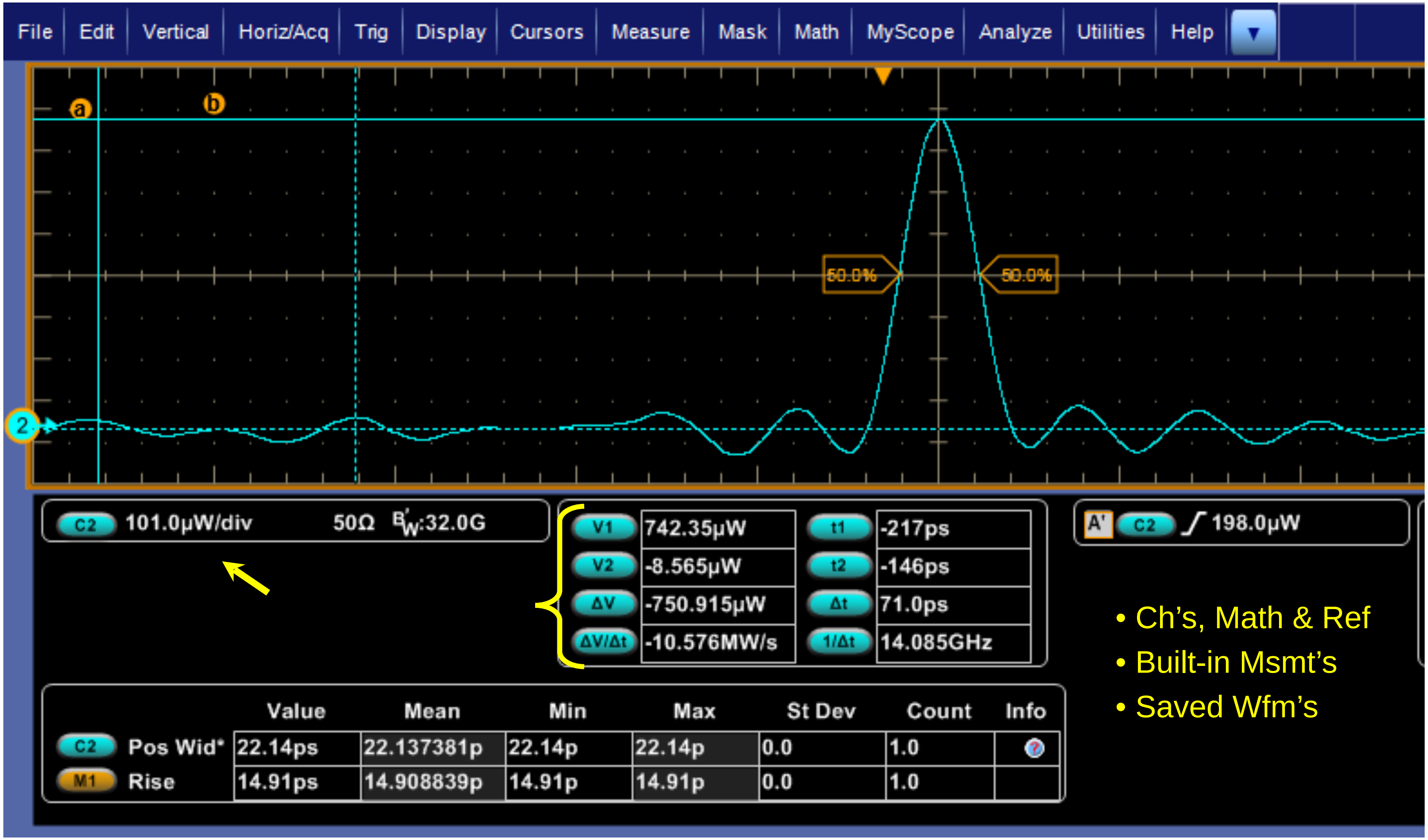
“Shuttle”

“Carrier”

ATI – 56G ORR

ATI – Mechanical support deck

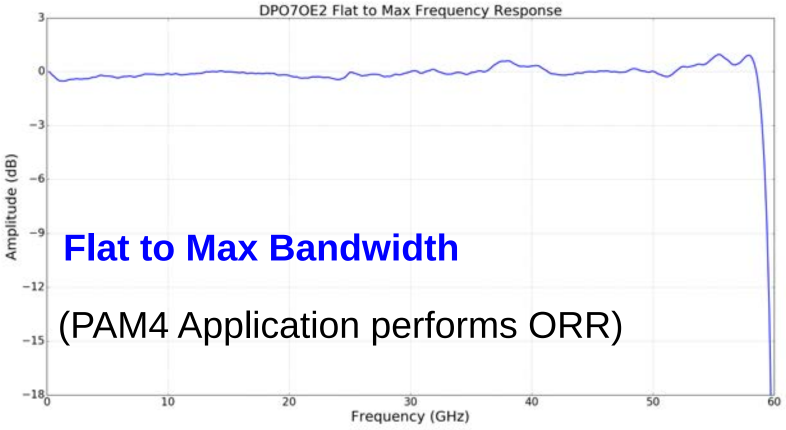
DPO7OE1/OE2 – Optical Power Scaled in Watts

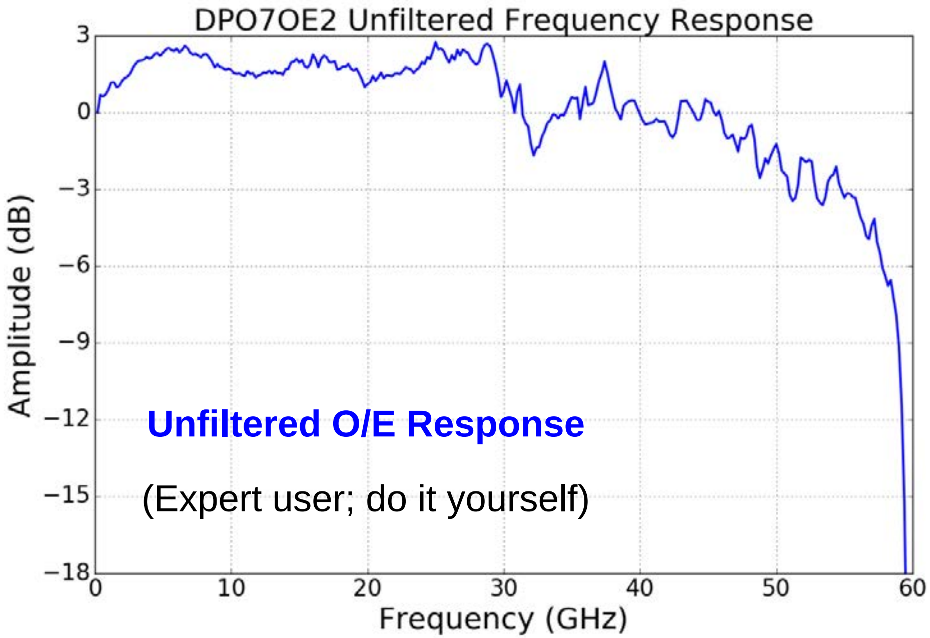


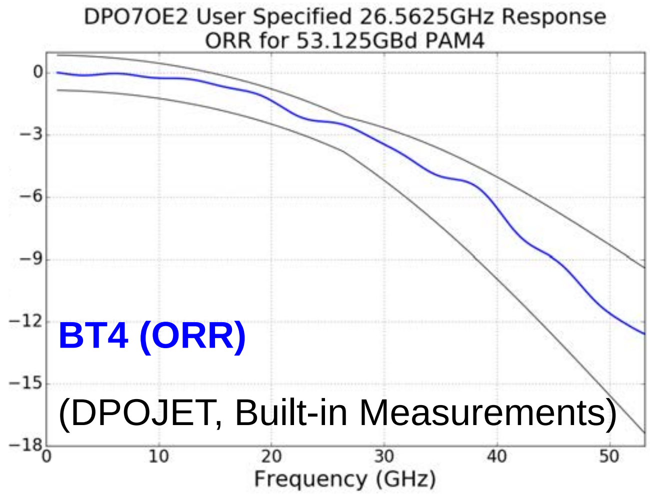
DPO7OE2 – Frequency Response Selection

APPLICATION-SPECIFIC CHOICES

- Frequency Response
  - Unfiltered O/E response
  - Flat to maximum bandwidth
  - BT4: User-specified electrical BW

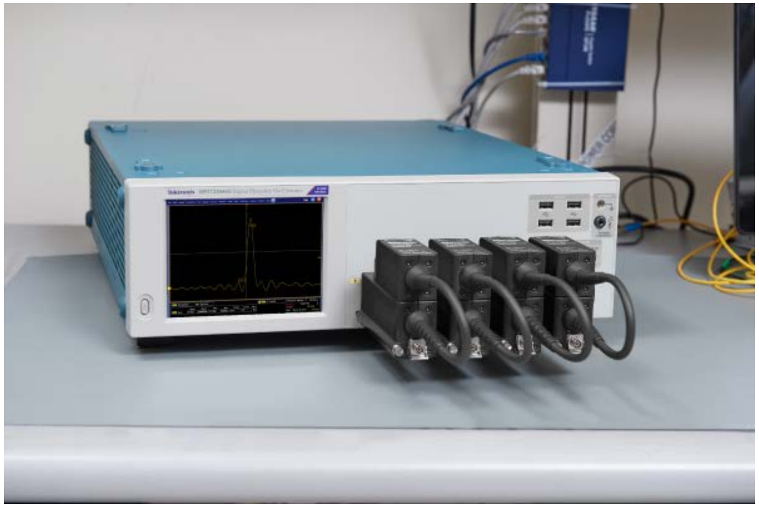


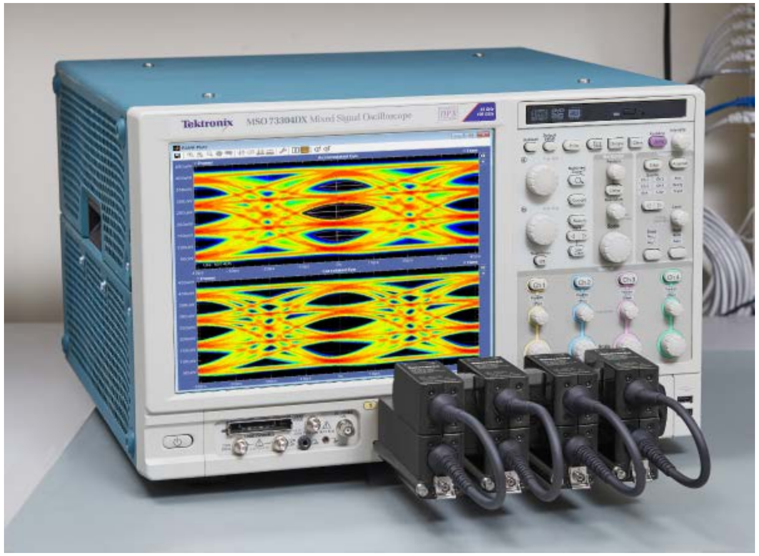


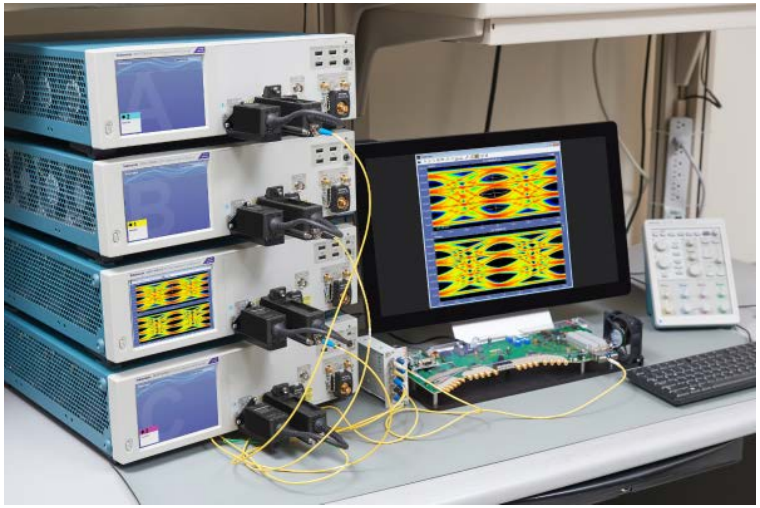


DPO7OE1/OE2 – Typical Configurations

MSO/DPO70KC/D/DX AND DPO70KSX - ATI OR TEKCONNECT







PAM4 TX Optical – Real Time

Only with the Tektronix DPO7OE1/OE2 …

Robust Clock Recovery

- PAM4 clock recovery that works reliably in the presence of higher ISI or noise found in PAM4 signaling
- PAM4 analysis even if you don't have access to a clock
- Fully configure clock recovery parameters for rates up to 64GBd

PAM4 Bit-Error Detection and Rate Analysis

- Overcome Low PAM4 Signal-to-Noise Ratio and Channel Effects
- Perform powerful PAM4 error rate analysis including debug of individual bit errors

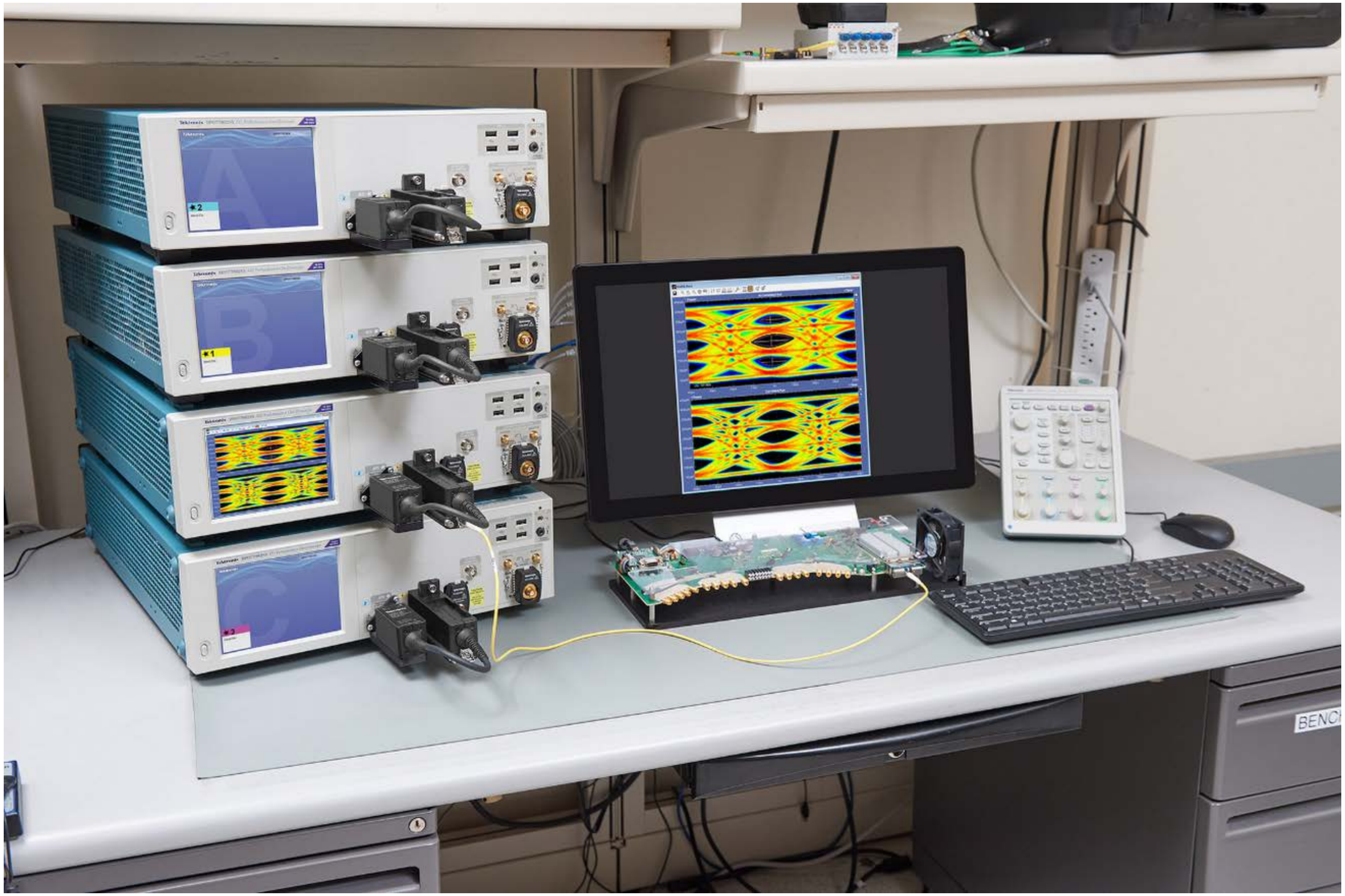
PAM4 Optical Signal Measurements

- ORR (Optical Reference Receiver) performance for 28GBd & 56GBd PAM4/NRZ
- Optical measurements for both NRZ & PAM4 signals: ER, AOP, OMA, Eye Height, and Eye Width
- PAM4 IEEE and OIF-CEI standard specific measurements including TDECQ with best in class optical sensitivity and noise

Advanced Debug Capability

- Use Visual Triggering to isolate PAM4 events of interest
- Full-bandwidth long-time capture and a time-correlated/contiguous record of your signal allowing offline DSP analysis

Comprehensive PAM4 & NRZ Optical Analysis Solution



Tektronix