PAM4 in 400G/200G/100G/50G Networking Technology

(NOTE: Some standards still in development)

Optical Standards						Key Optical Measurements of IEEE 802.3bs, 802.3cd D3.2				
	Modulation Format	Distance	Data Rate	Multiplex	Signaling Rate	**AOP** Average launch Optical Power: key to safety and achieving transmission distance objectives.	**OMAouter** Optical Modulation Amplitude level 0 to level 3: basic TX amplitude (i.e. w/o ISI problems, noise, or offset).	**$RIN_{22.8}OMA$** RIN<x>OMA of an optical signal is a ratio of optical Relatitve Intensity Noise to **OMA** when backreflection is **<x>** dB.	**ER** Extinction Ratio: in PAM4, the ratio of certain high level to certain low level.	**TDECQ** Transmitter and Dispersion Eye Closure: characterizes the TX ISI, noise, and dispersive Quaternary eye closure.
200GBASE-SR4 (802.3cd) similar: 100GBASE-SR2, 50GBASE-SR	PAM4	70 m, 100 m	n lane x 50 Gbps	<n> parallel MMF	26.56 GBd	-6 … 4 dBm	-4 … 3 dBm	[-]	≥ 3 dB	≤ 4.9 dB
200GBASE-DR4 (802.3bs)	PAM4	500 m	4 lanes x 50 Gbps	4 parallel SMF	26.56 GBd	-5.1 … 3 dBm	-3 … 2.8 dBm	≤ -132 dB/Hz, with -21.4 dB refl.	≥ 3.5 dB	≤ 3.4 dB
400GBASE-DR4 (802.3bs) similar: 100GBASE-DR	PAM4	500 m	<n> lane x 100 Gbps	4 parallel SMF	53.125 GBd	-2.9 … 4 dBm	-0.8 … 4.2 dBm	≤ -136 dB/Hz, with -21.4 dB refl.	≥ 3.5 dB	≤ 3.4 dB
400GBASE-FR8 (802.3bs) similar: 200GBASE-FR4, 50GBASE-FR	PAM4	2 km	<n> lanes x 50 Gbps	1 SMF 8λ WDM	26.56 GBd	-4.2 … 4.7 dBm	-1.2 … 4.5 dBm	≤ -132 dB/Hz, with -16.5 dB refl.	≥ 3.5 dB	≤ 3.3 dB
400GBASE-LR8 (802.3bs) similar: 200GBASE-LR4, 50GBASE-LR	PAM4	10 km	<n> lanes x 50 Gbps	1 SMF 8λ WDM	26.56 GBd	-3.4 … 5.3 dBm	-0.4 … 5.1 dBm	≤ -132 dB/Hz, with -15.1 dB refl.	≥ 3.5 dB	≤ 3.4 dB
Key Aspects of Measurement						Output power is within receiver and safety requirements.	Sufficient modulation swing.	Laser noise.	Limits signal offset.	Replaces TDP and mask test to ensure signal interoperability.

Note: Optical 400GBASE-SR16 at 25 GBd PAM2 NRZ not shown

(NOTE: Standards still in development)

Electrical Standards						Key Electrical Measurements				
	Modulation Format	Distance	Data Rate	Multiplex	Signaling Rate	**SNDR** Transmitter output Signal to Noise and Distortion Ratio: Describes the ratio (at the transmitter) of linear signal model amplitude to the sum of noise and non-linear components.	**Linear Fit Pulse Peak** The useful amplitude of the transmitter; found as the amplitude of a pulse that is a linear fit model of the transmitter.	**UBHPJ/J5/J4** Uncorrelated Bounded High Probability Jitter probability/deterministic jitter components.	**UUGJ/JRMS** Uncorrelated Unbounded Gaussian Jitter (Random Jitter RMS).	**EOJ/Even-Odd Jitter** F/2 Jitter asymmetry usually induced by imbalanced MUX.
CEI-56G-VSR-PAM4	PAM4	100 mm	n lane x 56 Gbps	1-n lanes	18-29 GBd	31 dB	0.75 Near-end-Linearity	0.05 UI_{pp}	0.01 UI_{RMS}	0.019 UI_{pp}
CEI-56G-MR-PAM4	PAM4	500 mm	n lane x 56 Gbps	1-n lanes	18-29 GBd	31 dB	0.83xT_Vf V	$T\_J_{4u} \le 0.118$ UI_{pp}	$T\_J_{RMS} \le 0.023$ UI_{RMS}	0.019 UI_{pp}
CEI-56G-LR-PAM4	PAM4	1 m	n lane x 56 Gbps	1-n lanes	18-29 GBd	31 dB	0.83xT_Vf V	$T\_J_{4u} \le 0.118$ UI_{pp}	$T\_J_{RMS} \le 0.023$ UI_{RMS}	0.019 UI_{pp}
400GAUI-8/200GAUI-4/ 100GAUI-2/50GAUI-1	PAM4	~250 mm	50 Gbps	1,2,4,8 lanes	26.56 GBd	31.5 dB	Eye Height Near End: 32 mV (host), 70 mV (module)	Eye Width ESMW Near End: 0.22 (host), 0.265 UI (module)	[-]	Far End: Precursor ISI r. -4.5 to +2.5 %
200GBASE-KR4/ 100GBASEKR2/50GBASE-KR	PAM4	<1 m	50 Gbps	1,2,4 lanes	26.56 GBd	SNRTX >= 32.5 dB	≥ 0.75xVf V	J3u ≤ 0.106 UI	$J_{RMS} \le 0.023$ UI	$0.019_{pk\text{-}pk} \le$ UI
200GBASE-CR4/ 100GBASECR2/50GBASE-CR	PAM4	<3 m	50 Gbps	1,2,4 lanes	26.56 GBd	SNRTX >= 32.2 dB	≥ 0.49xVf V	J3u ≤ 0.115 UI	$J_{RMS} \le 0.023$ UI	$0.019_{pk\text{-}pk} \le$ UI
Key Aspects of Measurement						Measurement which compares the useful amplitude of the signal to the un-compensable distortions and noise.	Lower limits on amplitude, ISI; noise limit.	OIF: un-correlated jitter. IEEE: jitter.	Limits the random jitter for a transmitter.	Limits the asymmetry of the transmitter.

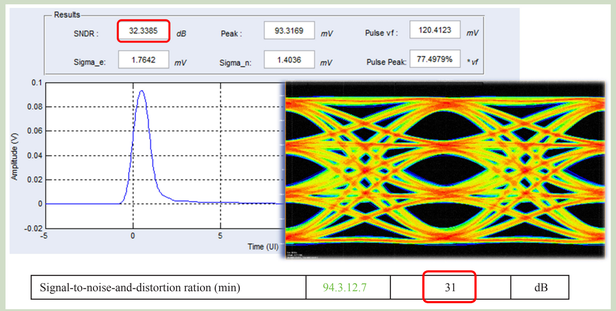
SNDR (PAM4)

The Signal to Noise Distortion Ratio (SNDR) measurement is the principal electrical measure of transmitter performance in all 400G specifications today.

$$SNDR = 10\log_{10}\left(\frac{p_{max}^2}{\sigma_e^2 + \sigma_n^2}\right) dB$$

The SNDR is a ratio of p_{max} (the maximum of the linear fit pulse response) to the sum of the linear fit error σ_e and σ_j and the noise extracted from consecutive long run lengths of symbols.

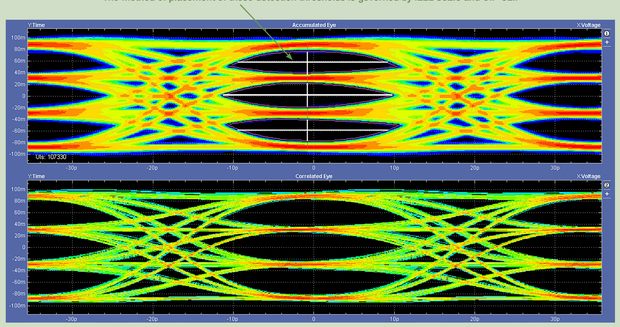
These three parameters have error contributions directly related to the instrumentation bandwidth, jitter noise floor and vertical noise floor. The combination of 70 GHz of instrument BW allows tracking a fourth order Bessel-Thomson electrical response to the -10dB point (at 69 GHz), which offers flat phase response and minimal instrument contributed data-dependent jitter. The σ_j term is heavily influenced by instrument contributed jitter noise floor, and that contribution on an ATI architecture can be as low as 40fs on some signals. The σ_e term is heavily influence by the instrumentations effective number of bits and overall vertical noise contribution. The key to the most accurate SNDR measurement performance is to maximize the p_{max} term (requires approximately 50 GHz bandwidth) and minimize the instrument contributed jitter and vertical noise components.



Signal-to-noise-and-distortion ration (min)	94.3,12.7		31	dB

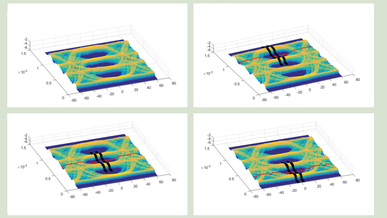
Eye Height at BER (Noise Decomp), T_{mid}, V_{mid}

The method of placement of these detection thresholds is governed by IEEE 802.3 and OIF-CEI.



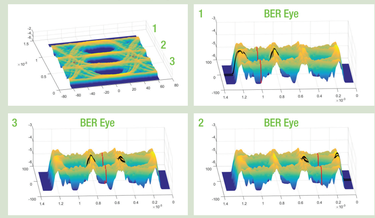
TDECQ Transmitter and Dispersion Eye Closure - Quaternary

TDECQ after Reference Equalizer



- Reference equalized PAM4 eye is sliced with two vertical histograms:
  - 0.1 UI apart, at 0.04 UI width
  - Target SER is e.g. 4.8e-4

TDECQ Example (Optical PAM4): 26GBaud

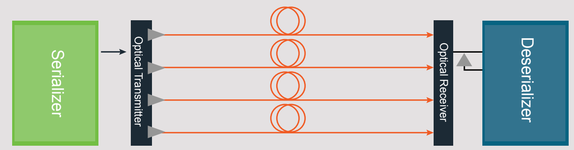


- For each vertical slice:
  - Capture histogram and calculate measured bathtub
  - Find bathtub opening in terms of RX noise, compare to ideal, express as a penalty (the smaller the better)

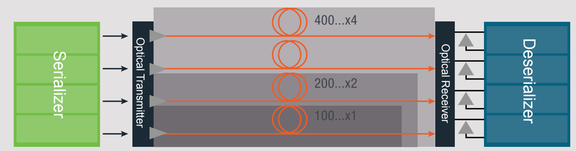
Optical - 50G, 200G, 400GBASE-LR/LR4/LR8, FR/FR4/FR8 WDM (Wavelength Division Multiplexing)

Optical - 100G, 400GBASE-DR/DR4 parallel single-mode fiber

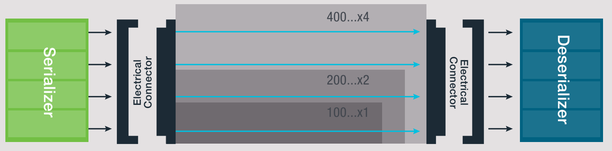
Optical - 200GBASE-DR4 parallel single-mode fiber



Optical - 50/100/200GBASE-SR/SR2/SR4 parallel multi-mode fiber



Electrical - 50, 100 or 200GBASE-CR/CR2/CR4 or KR/KR2/KR4



All diagrams: for clarity, only one direction of transmission is shown.
SMF: single-mode fiber. MMF: multi-mode fiber. WDM: wavelength div. multiplexing.

Note: Optical 400GBASE-SR16 at 25 GBd PAM2 NRZ not shown

Visit tek.com/400G-PAM4-Testing for additional resources and solutions in testing 50/100/200/400G designs.

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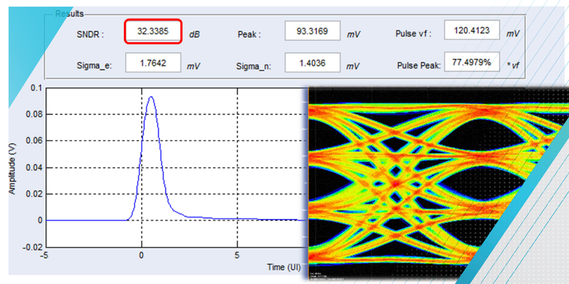

Signal-to-noise-and-distortion ration (min)	94.3.12.7

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