Advanced Signal Equalization Methods for 448G

Abstract: The progression to 448G interfaces necessitates substantial enhancements in critical link components, including SerDes, packaging, channels, and connectors. Additionally, it may demand the adoption of advanced equalization and error correction techniques. This presentation evaluates the applicability of existing equalization strategies for 448G transmissions. Specifically, it examines the integration of Continuous Time Linear Equalizer (CTLE), Feed-Forward Equalizer (FFE), Decision Feedback Equalizer (DFE), and Maximum Likelihood Sequence Detection (MLSD), as initially defined in OIF-CEI-224G-LR and PIEEE 802.3dj standards for 224G interfaces, in the context of 448G links utilizing 224Gbaud PAM4 or 180Gbaud PAM6 modulation schemes. The discussion will incorporate state-of-the-art channel designs to assess the feasibility and performance of these equalization techniques in meeting the stringent requirements of 448G data transmission.

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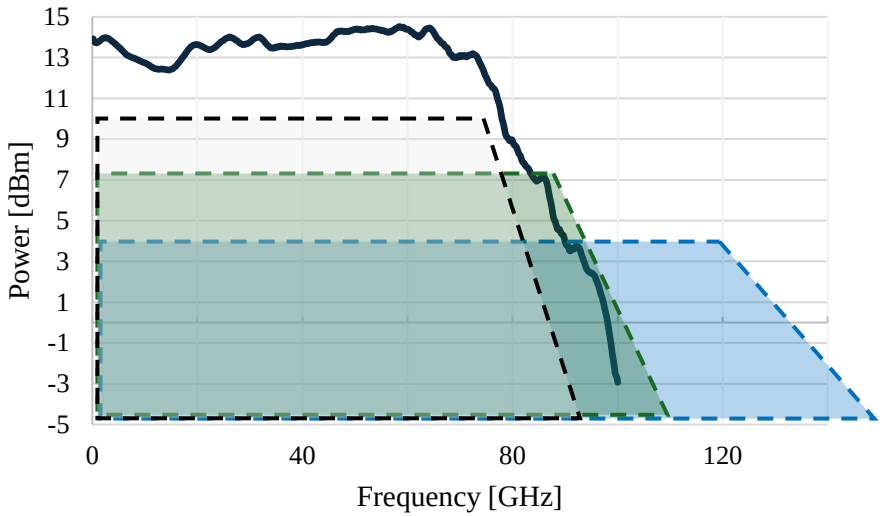
Presenter: John Calvin (john.calvin@keysight.com)

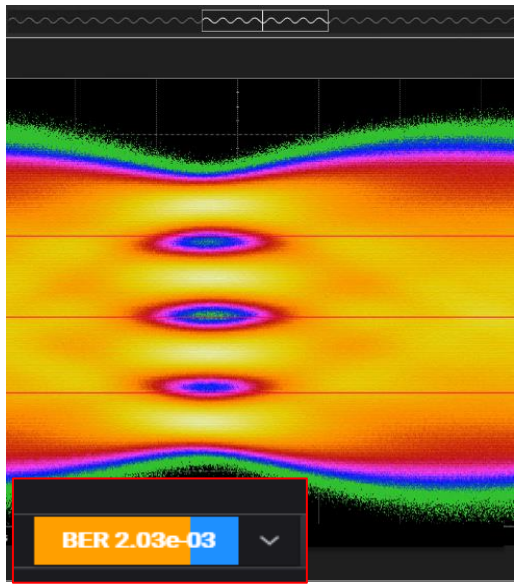
448G Channel Considerations (M8199B/UXR Instrumentation grade setup)

Spectral Power envelope of a M8199B Arbitrary Waveform Generator



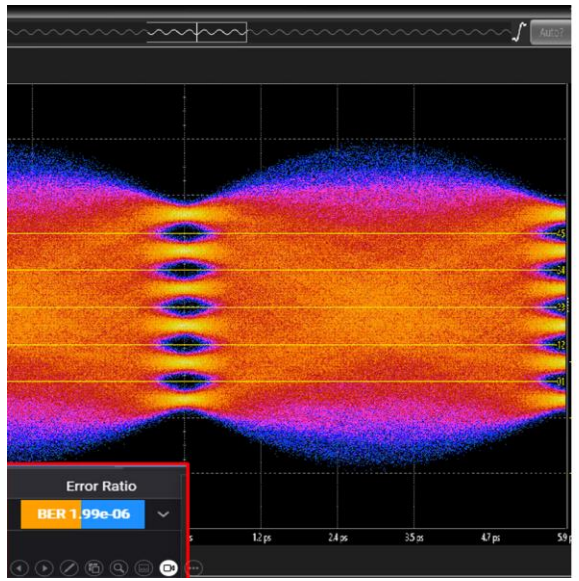
220GBd PAM4 (440Gb/s)

- 2e-3 BER
- Main limitation: Non-compensable signal distortion (also impacting the CDR scheme)



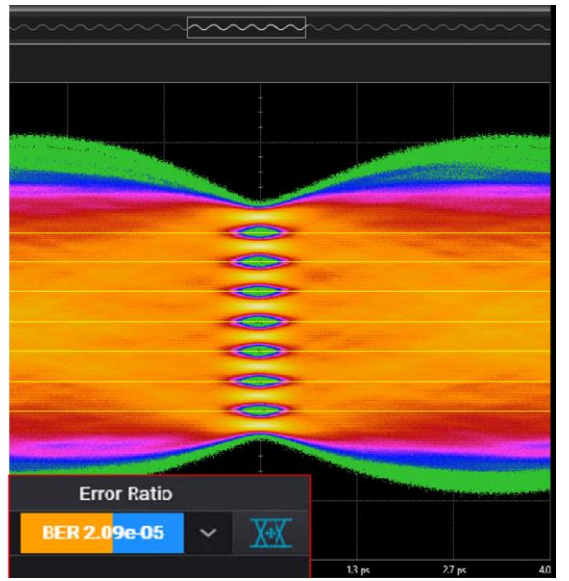
176GBd PAM6 (440Gb/s)

- 2e-6 BER
- Main limitation: SNR (Tx)



150GBd PAM8 (450Gb/s)

- 2e-5 BER
- Main limitation: SNR (Tx & Rx)



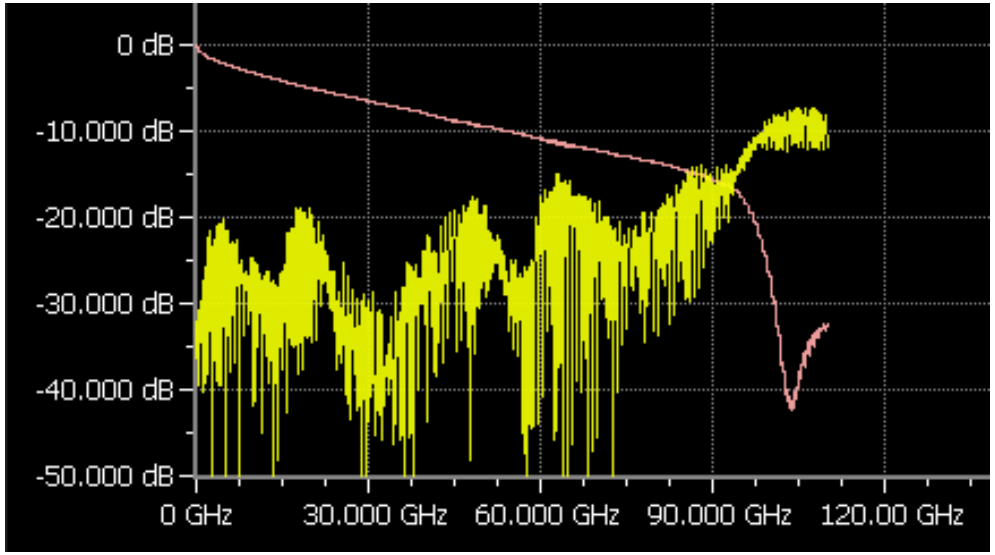
448G Electro/Optic Requirements
Higer-Order Modulation tradeoffs

	PAM4	PAM6	PAM8
FEC	6.25%	6.25%	6.25%
Min. Signal Rate [Gbd]	212.5	170	141.6
Nyquist [GHz]	106.25	85	71
ΔSNR [dB] (relative PAM4)	0	3.6	6.1

Fractional Symbol Rate
- Breaks conventional KP4 FEC

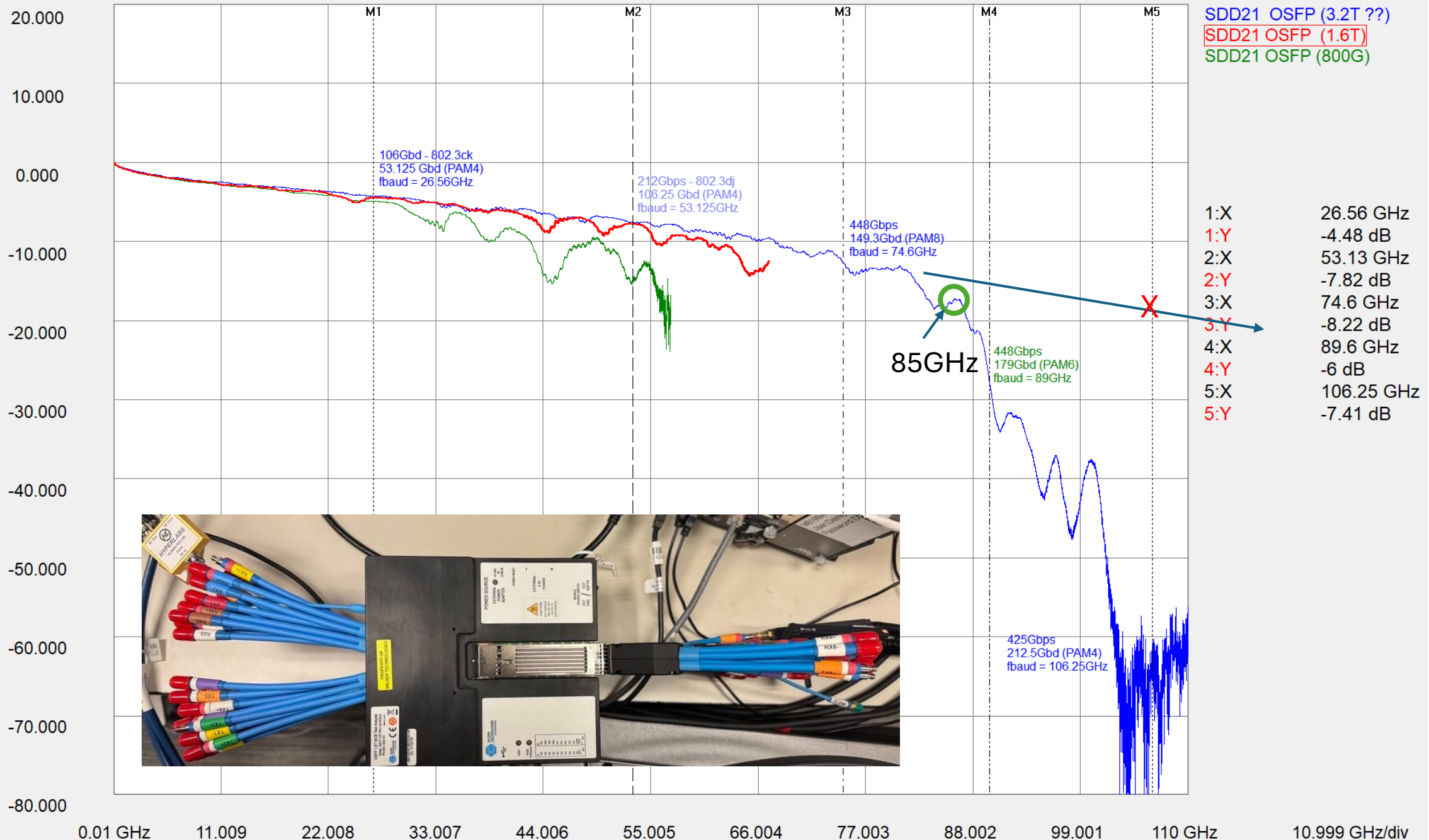
Challenging for optical links
- Higher laser power
- Improved Rx sensitivity
- New FEC (power, latency)

Challenging for electrical channels
- Max frequency ~100GHz
- ERL, IL, FEXT/NEXT are real physical issues
- Need better (higher BW) connection technology



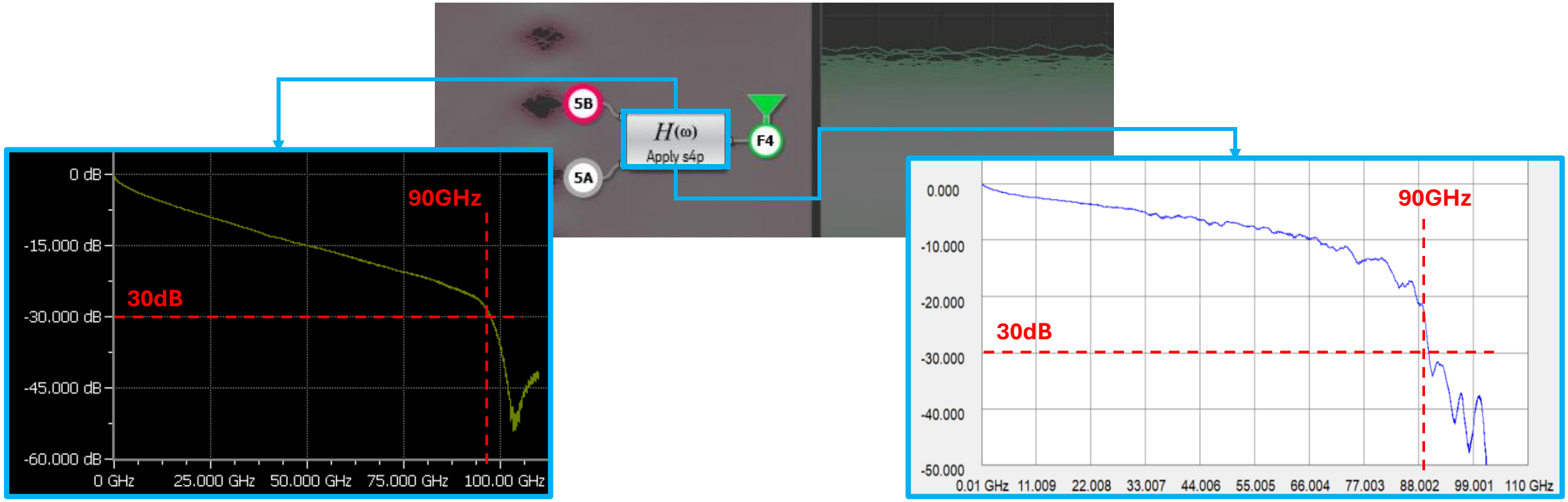
e.g. state-of-the art 10 cm channel with compression connectors

OSFP MTF (HCB+MCB) SDD21



425Gb/ Electrical - Investigation

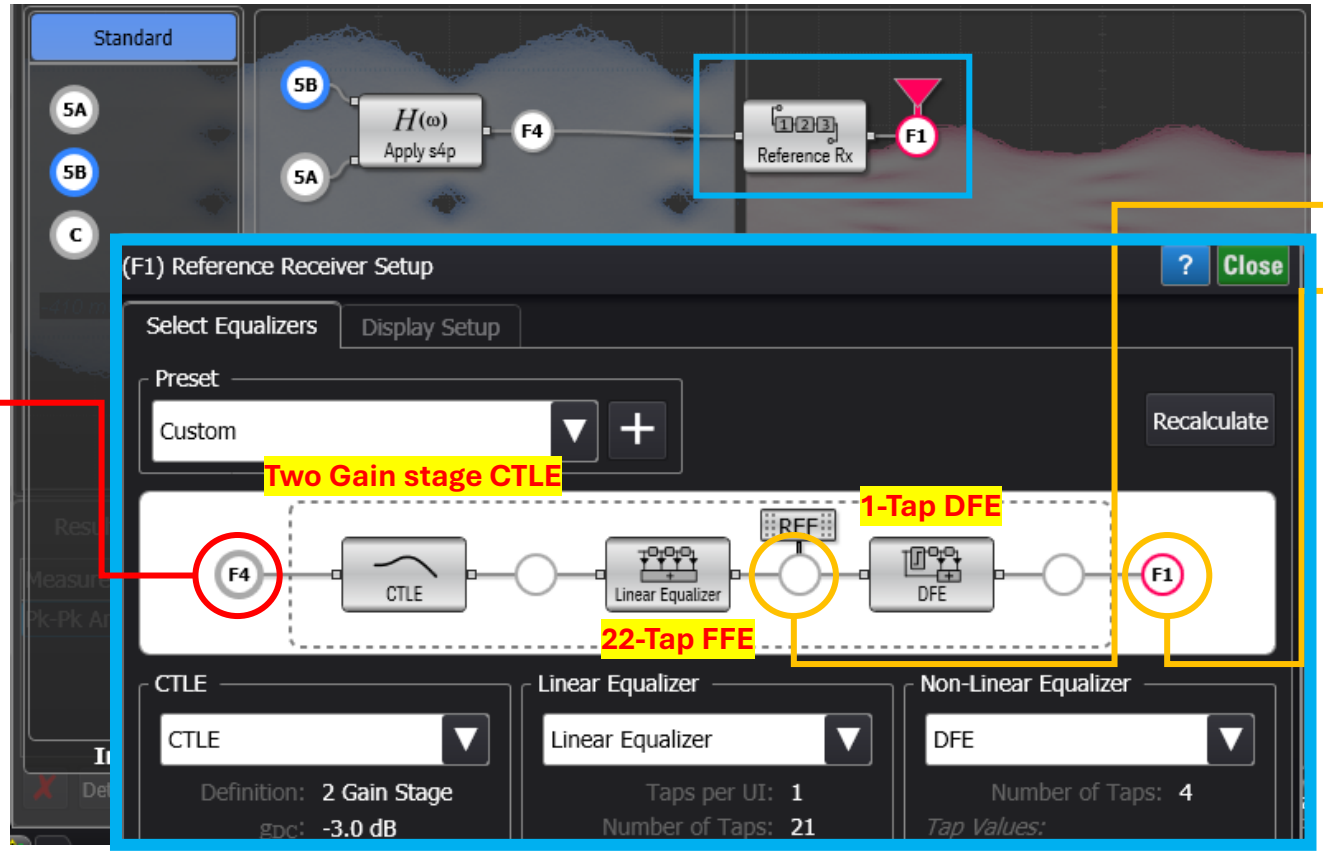
- Emulated channel



240mm Samtec-BE90 compression connector

1mm OSFP MTF

425Gb/ Electrical – Equalizer Investigation



Matlab post processing

- PR-MLSD
- SER

PR-MSLD

- 15-Tap pre-shaping filter (in addition to 22-Tap FFE)
- 1-transistion memory
- Trellis length: 10 symbols

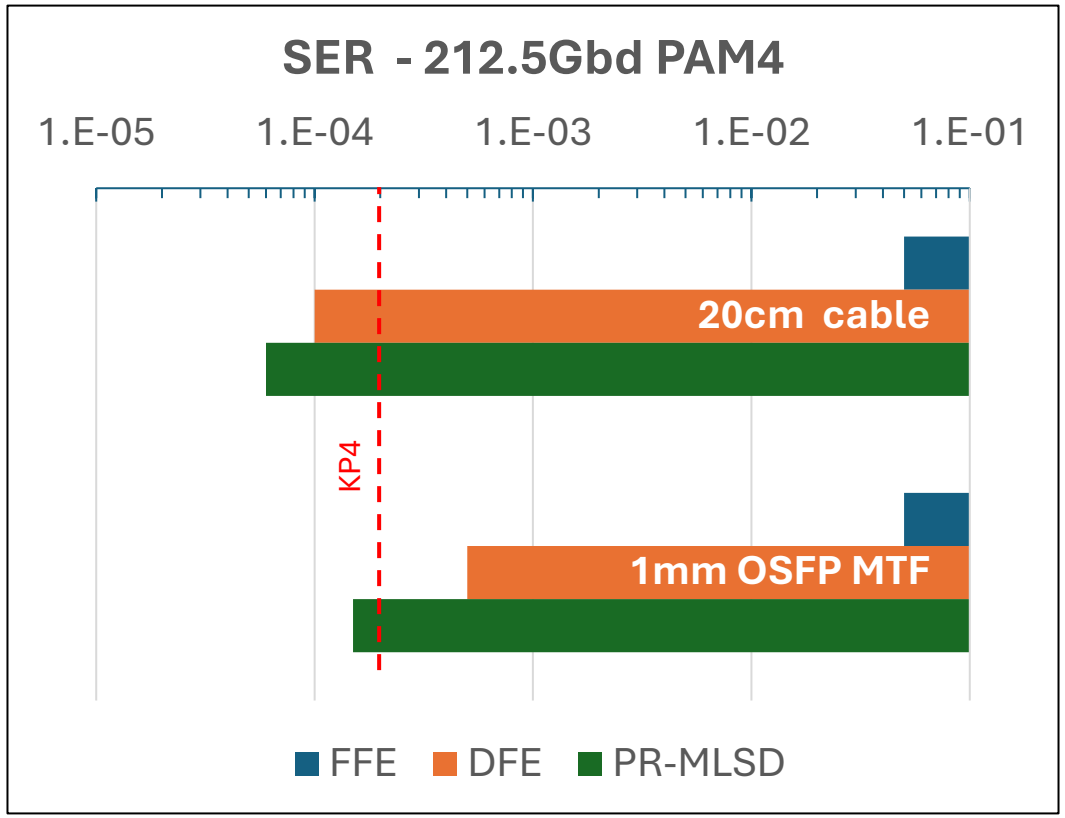
Important note

- No input referred noise (eta_0=0)
- SNR does not degrade after the channel

FFE & DFE are co-optimized (pulse Response & MMSE)

425Gb/ Electrical - Investigation

- PAM4 results



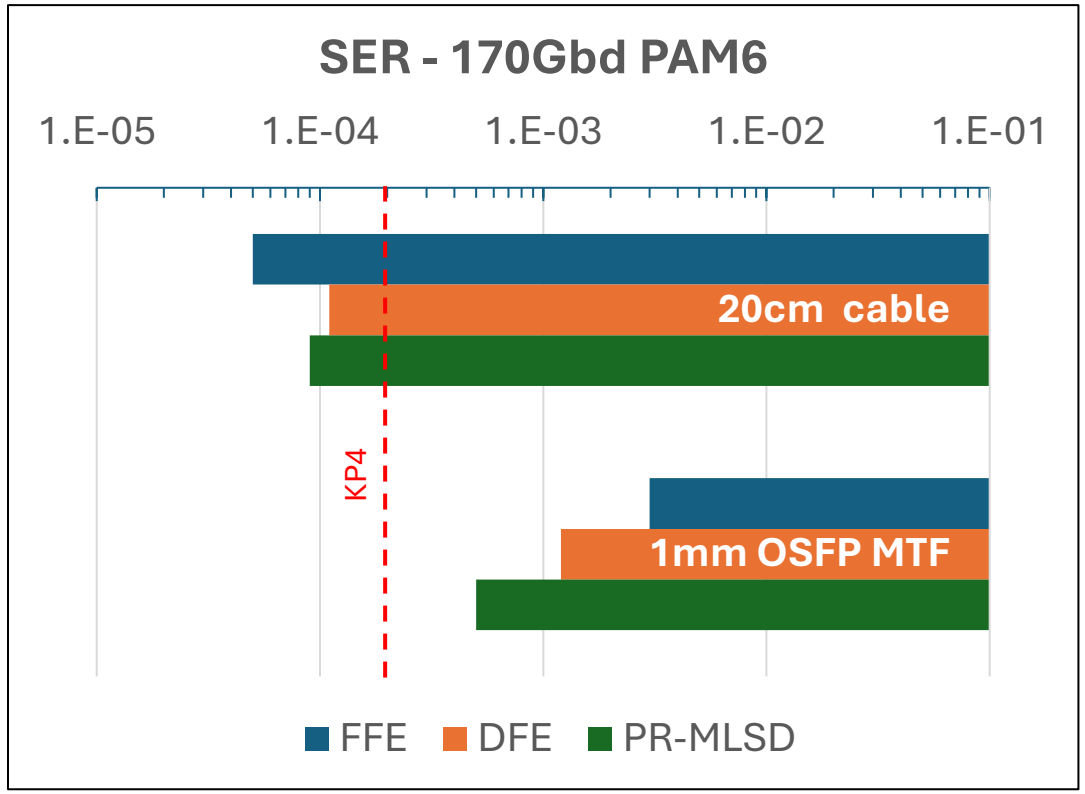
425Gb/s PAM4

- CTLE+FFE not capable of equalizing the signal
- CTLE+PR-MLSD has slightly better performance than CTLE+FFE+DFE
- Operation below KP4 FEC Threshold is possible but no margin
- Operation below 1E-5 BER not possible

→ **We hitting a fundamental limitation for PAM4** (BTB SER < 1e-6)

425Gb/ Electrical - Investigation

- PAM6 results



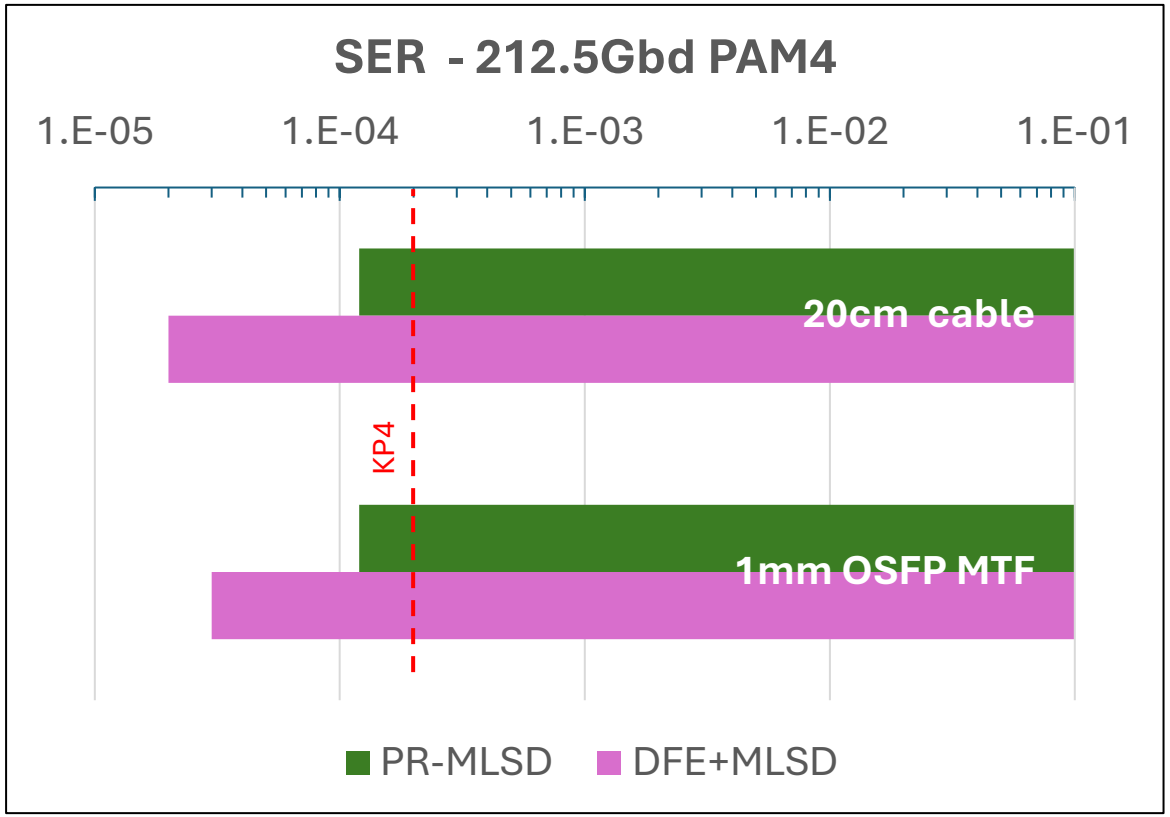
425Gb/s PAM6

- No significant improvement using DFE/MLSE vs FFE → why?
- Operation below KP4 FEC Threshold is possible only for one channel
- Operation below 1E-5 BER not possible

→ **Is PAM6 link mainly limited by SNR**
(BTB SER = 3e-5)

425Gb/ Electrical - Investigation

- Improvements on the equalizer side are possible



Current setting far from optimal

- CTLE not included in the optimization
- DFE tap and sampling time probably not optimum

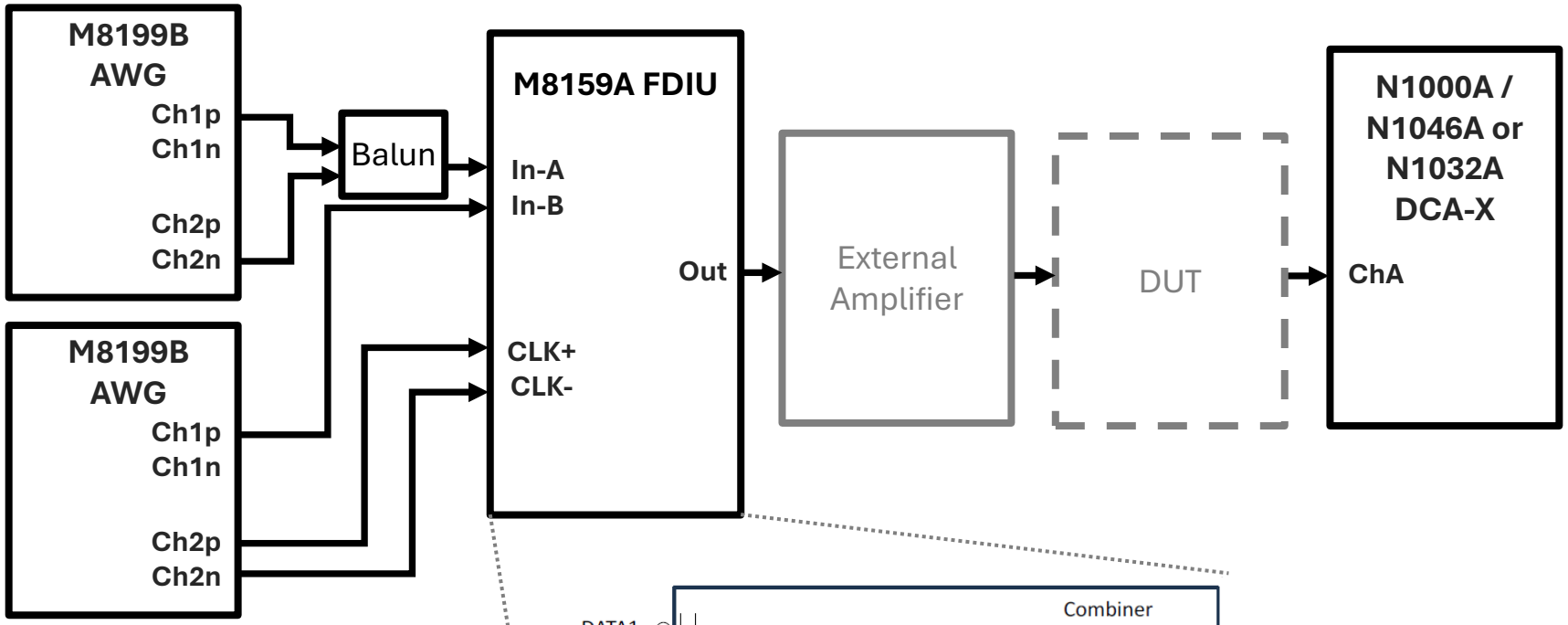
Further improvement

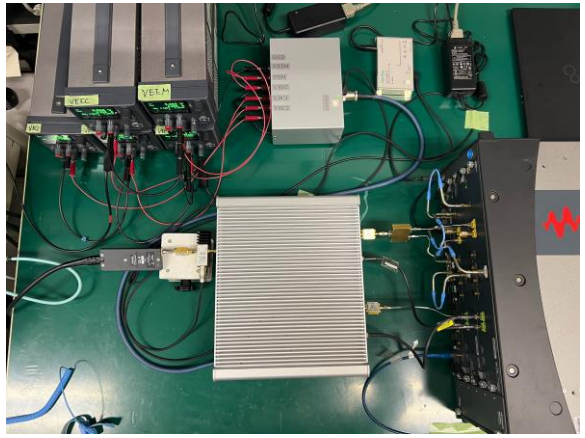
- Combining DFE followed by PR-MLSD enables almost one order of magnitude in BER (is MLSD mitigating DFE burst behavior, tbc)

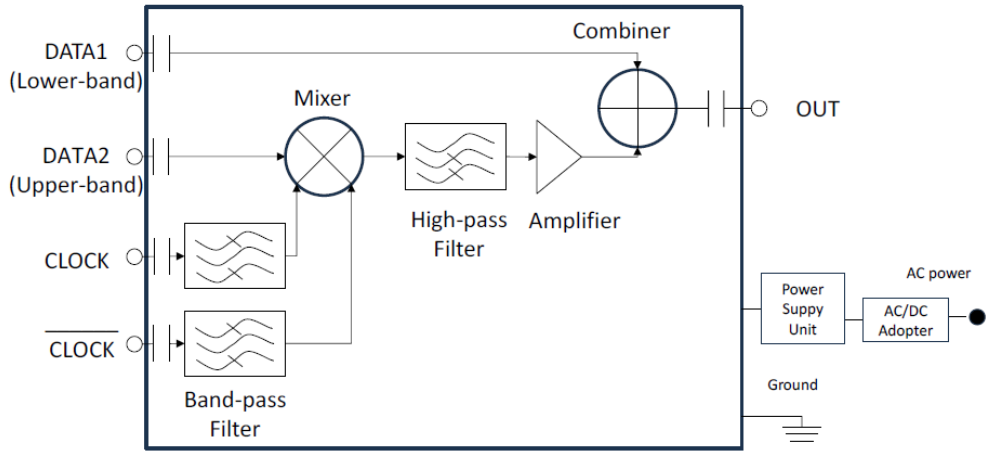
→ Good chances that improved equalizer architectures make 425G PAM4 work for these channels

How to extend the bandwidth of the M8199B Arbitrary Waveform Generator

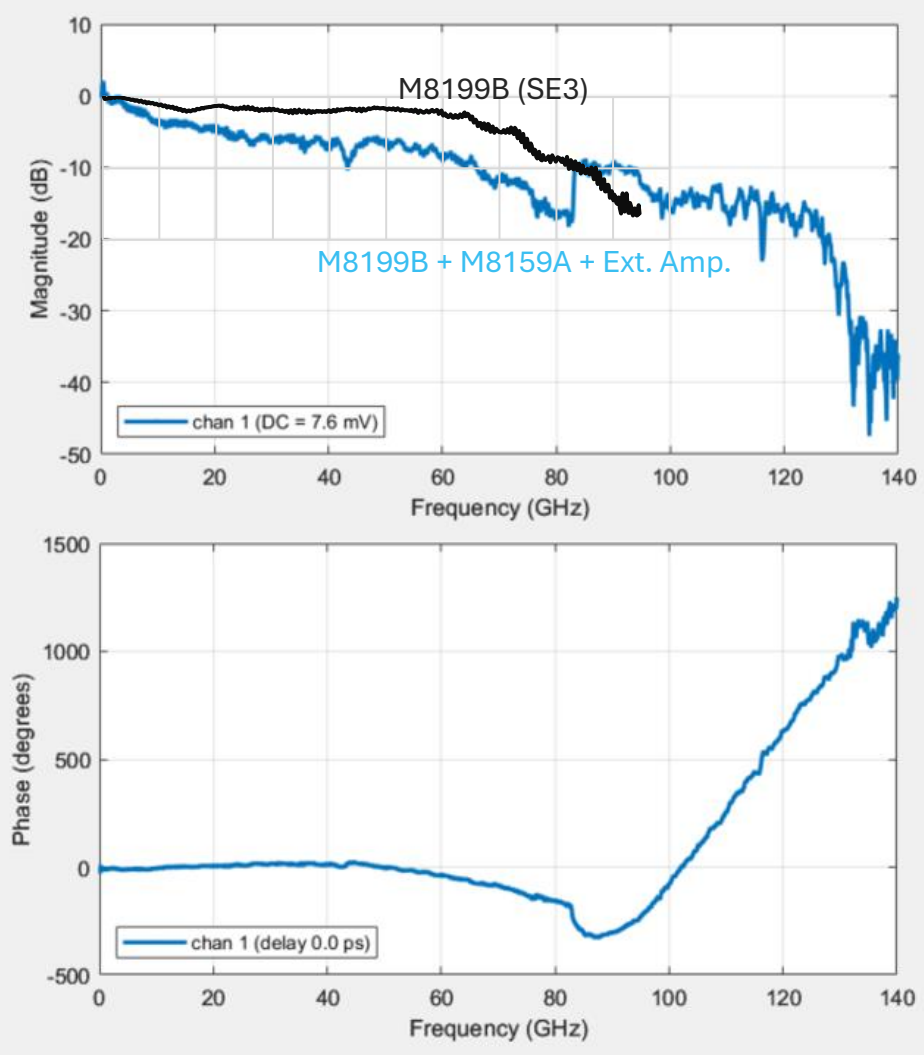
Reference Setup





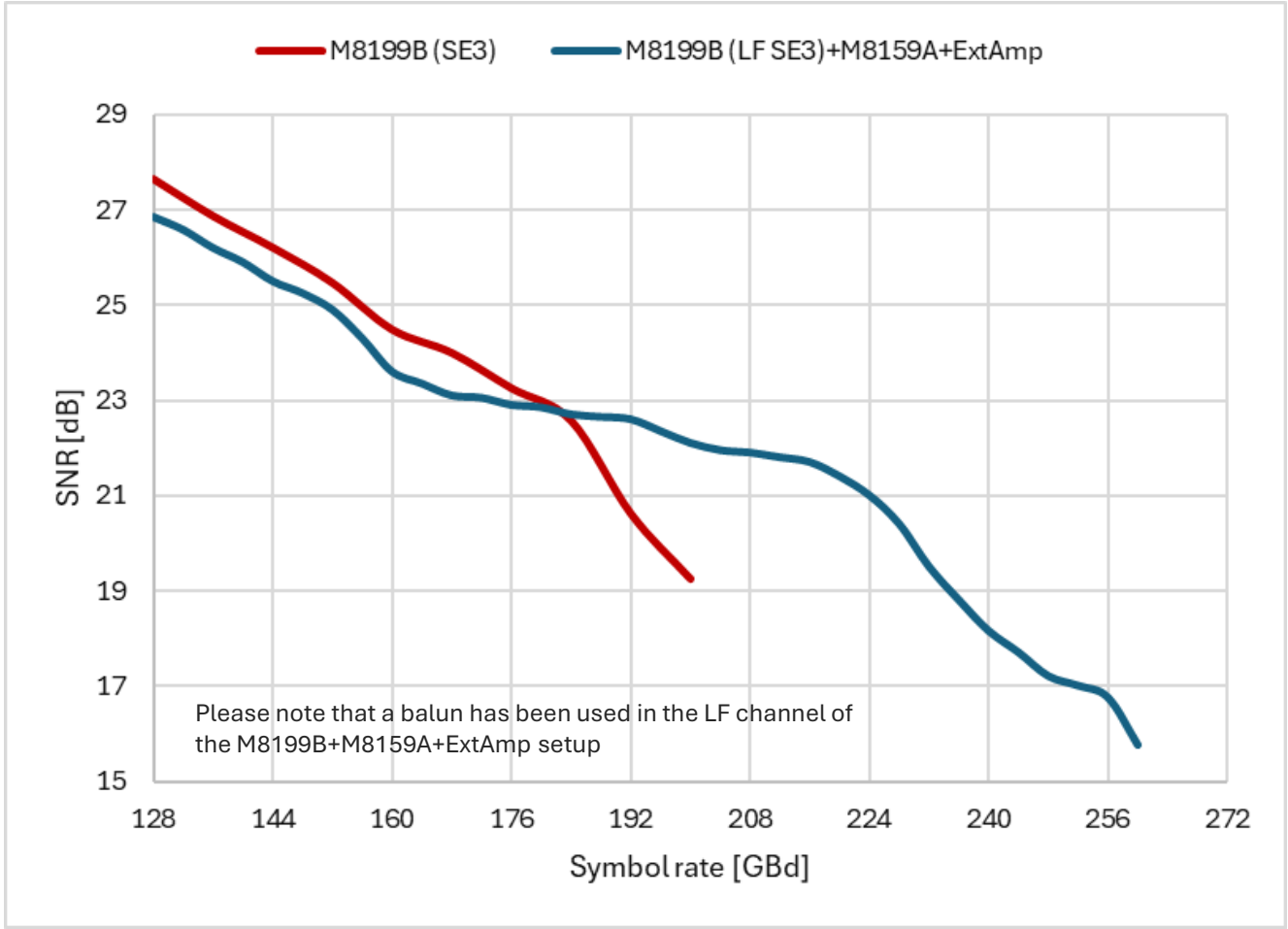


M8199B AWG + M8159A FDIU + External Amplifier



SNR @224 Gbaud: ≥ 20 dB

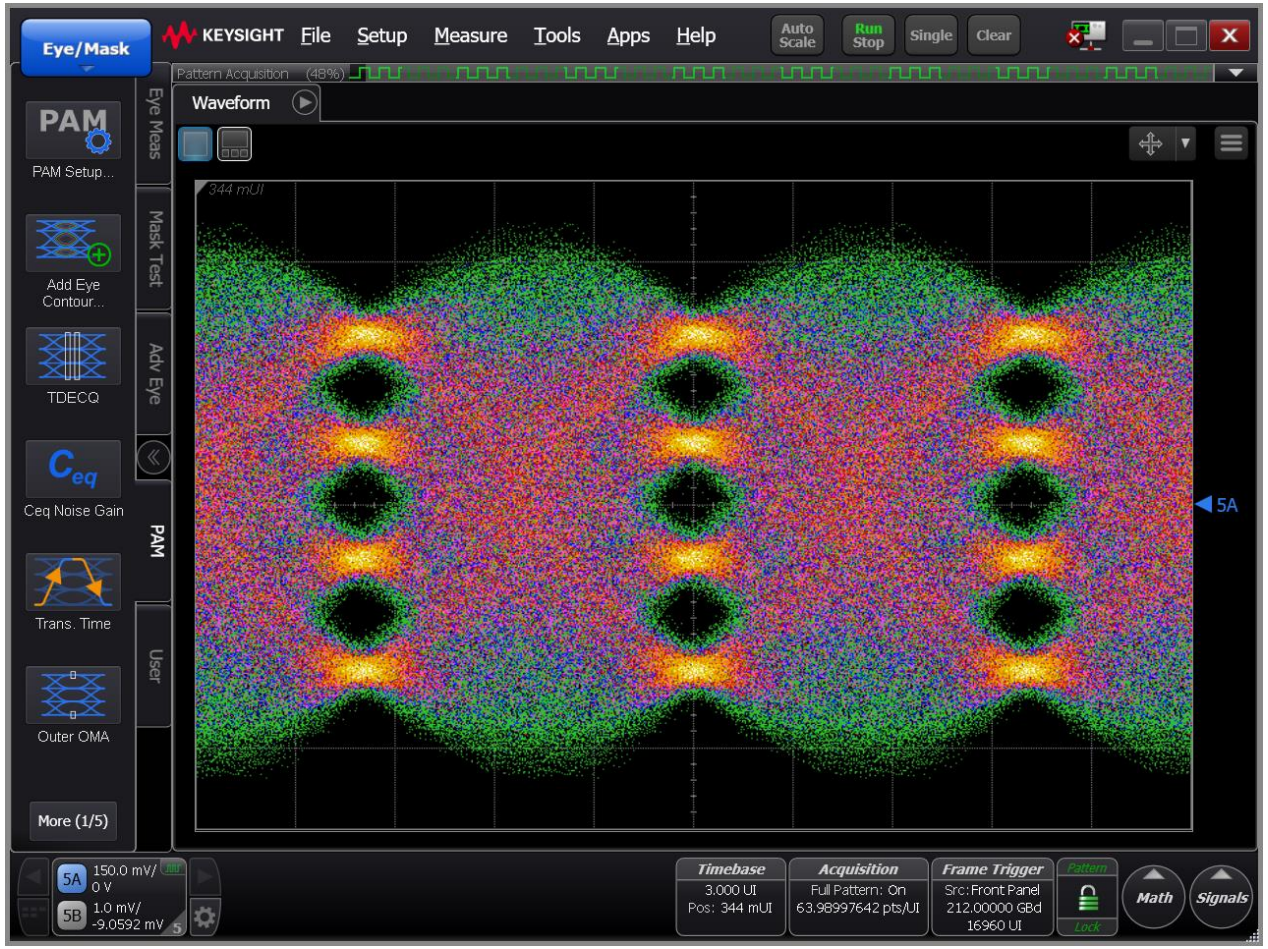
Output amplitude @224 Gbaud: ~700 mV_se (OMA)



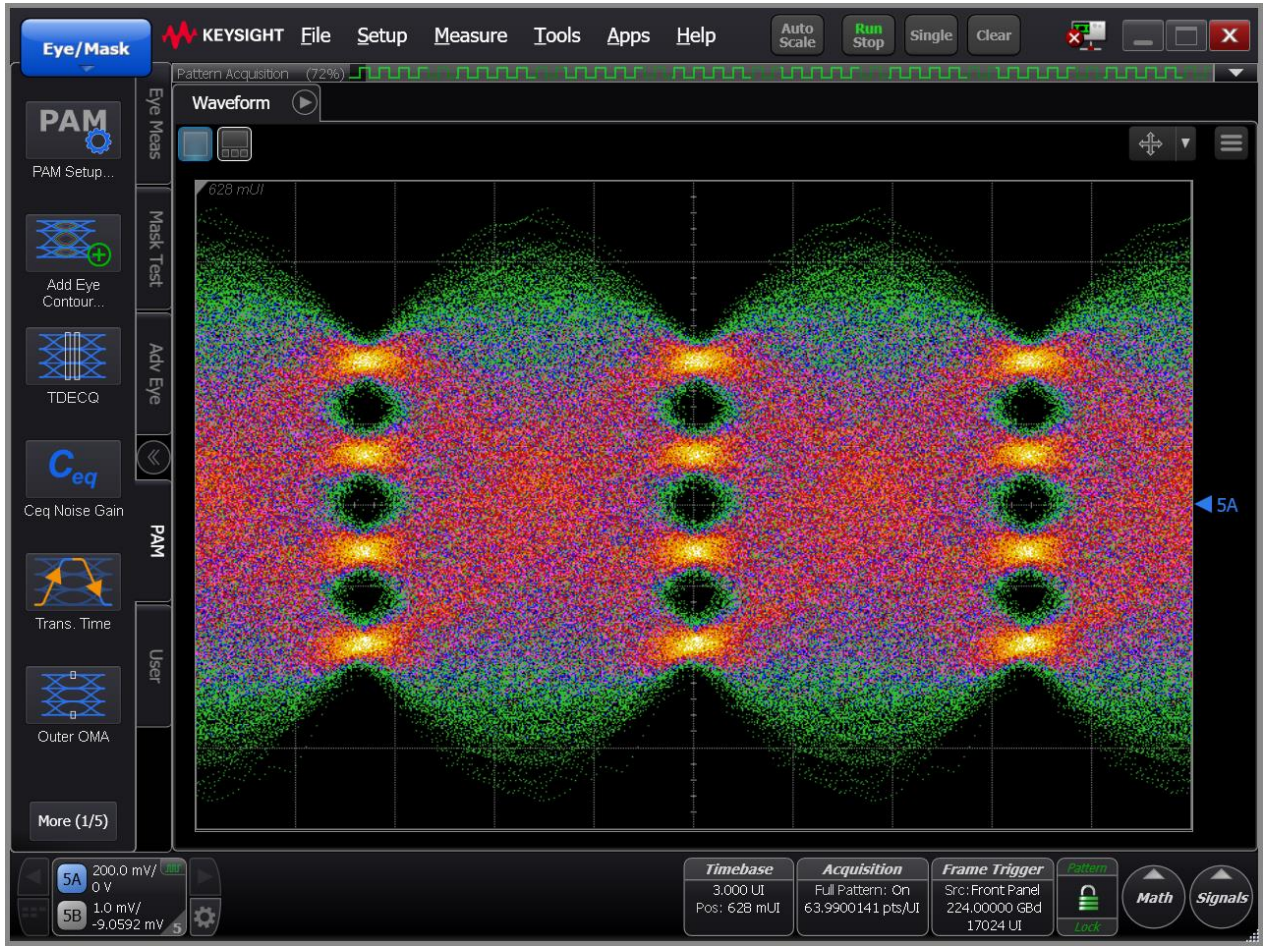
M8199B AWG + M8159A FDIU + External Amplifier

Sample measurements

200 Gbaud PAM4

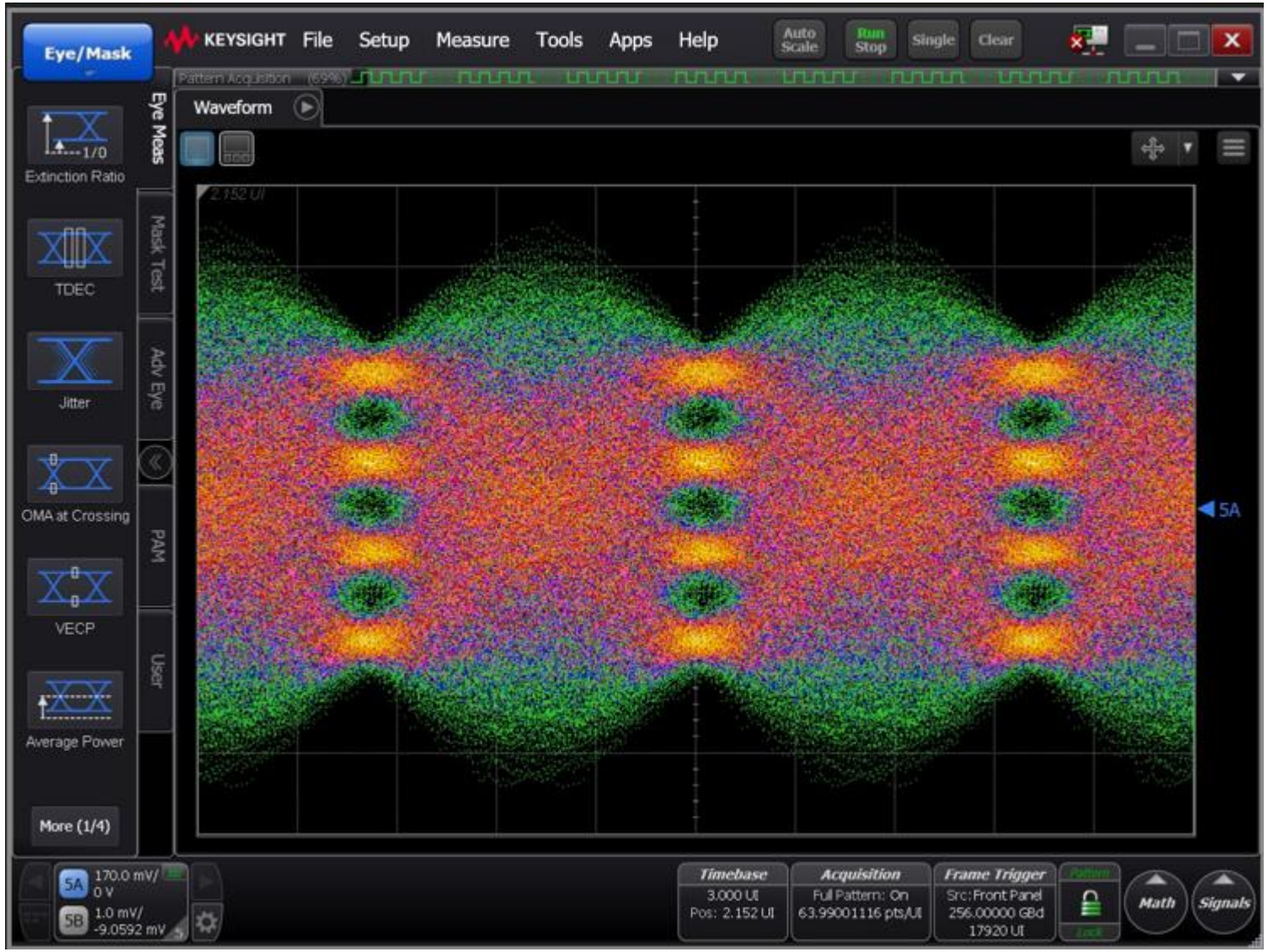


224 Gbaud PAM4



Anything worth doing is worth over-doing

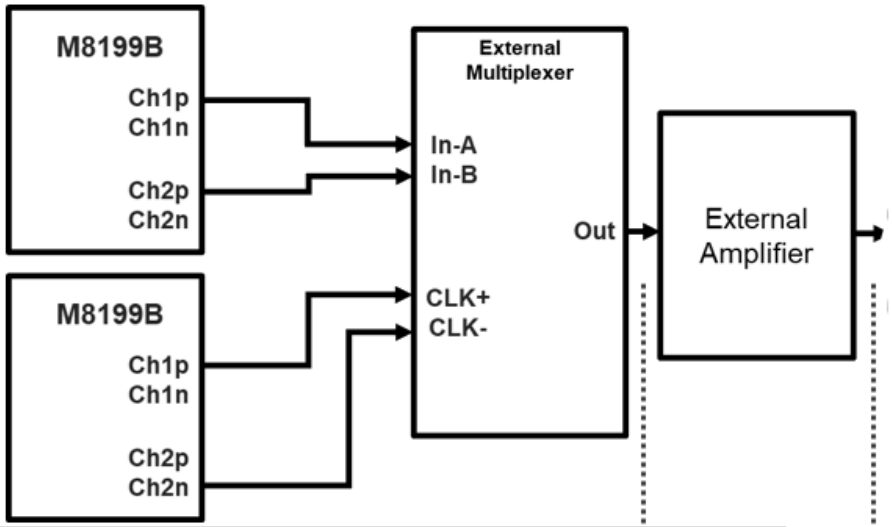
- Likely the fastest electrical signal ever recorded at 512Gbps PAM4.

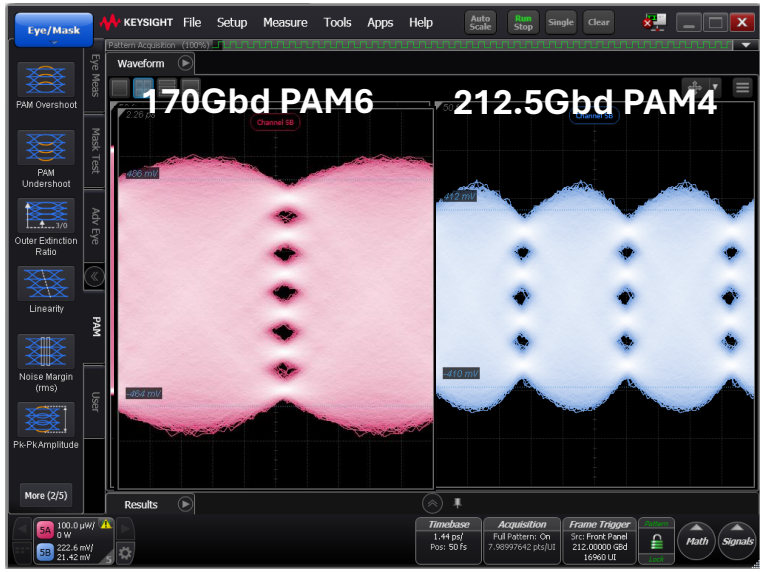


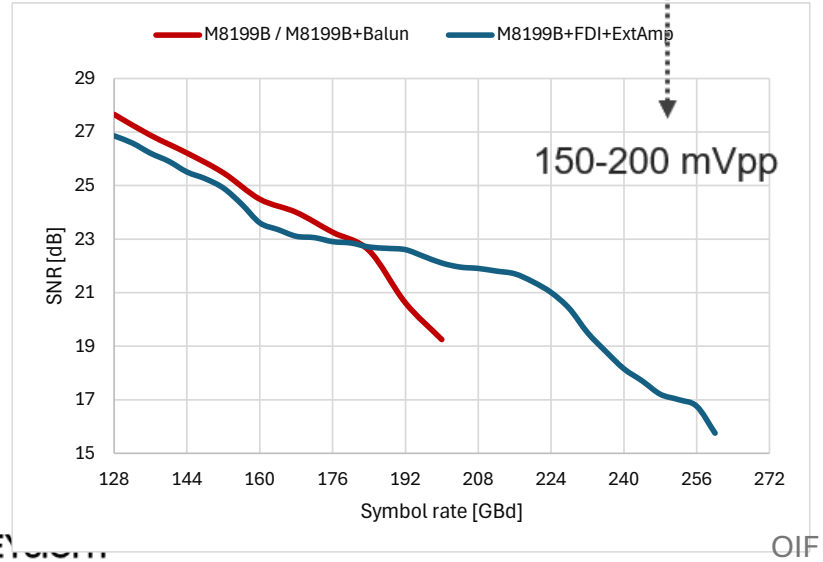
Summary

- The 448Gbps design problem is well within the operational limits of contemporary signal generation and signal acquisition instruments today. New instrumentation and measurement science is being developed today to serve this rapidly approaching need.
- Bandwidth of channels/connectors is likely to determine the preference of modulation order.
  - Optics is not BW limited
  - Electrical channels are very limited.
- PAM8 at 150 GBd or PAM6 at 174Gbd satisfies many of the current channel limitations, however the fractional symbol rate (PAM6) will likely break KP4 FEC models.
- Compound use of FFE/DFE in serries with MLSD shows almost an order of magnitude improvement in reducing BER, and curiously works best on sub nyquist channels.
- PAM4 practicality requires real 40% improvement to current connector technology. The 90GHz prominent resonance needs to be pushed up to 110GHz at minimum.
- Additional equipment details in backup slides.

Backup: Instrumentation details







425Gbs

- 400Gbps net rate
- 6.5% KP4 FEC overhead
- FEC threshold 2.2e-4

N1046A 100 GHz Electrical Remote Sampling

1, 2 and 4 channel configuration options

Head Module

Item	
Bandwidth[1], 3 dB (user selectable)	Options 11F, 12F, and 14F
100 GHz	•
122 GHz (Characteristic)	•
Transition Time (10% to 90% calculated from t_r = 0.35/BW)	Options 11F, 12F, and 14F
100 GHz	3.5 ps
122 GHz (Characteristic)	< 3.2 ps
RMS Noise	Options 11F, 12F, and 14F
100 GHz	1400 µV *1050 µV (Characteristic)*
122 GHz (Characteristic)	*2000 µV (Characteristic)*

[1]Fourth-Order Bessel-Thompson Response

Maximum specified: 100 GHz

Maximum characteristic: 122 GHz

Maximum SIRC[2] BW setting: 130 GHz

[2]System Impulse Response Correction

N1046A Frequency Respons

Data from ONE module – not specification, but informative

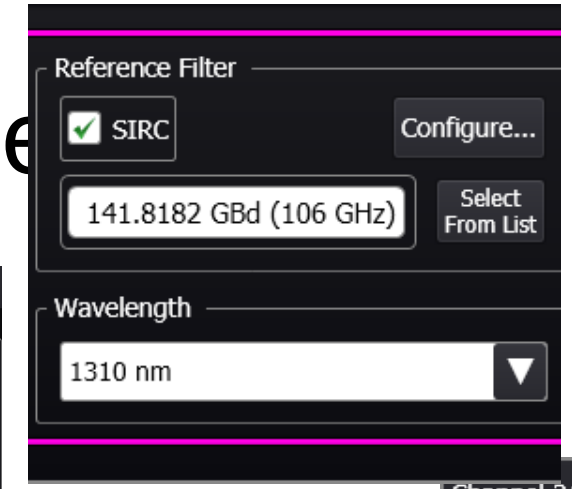
N1032A/B 120 GHz Optical Modules

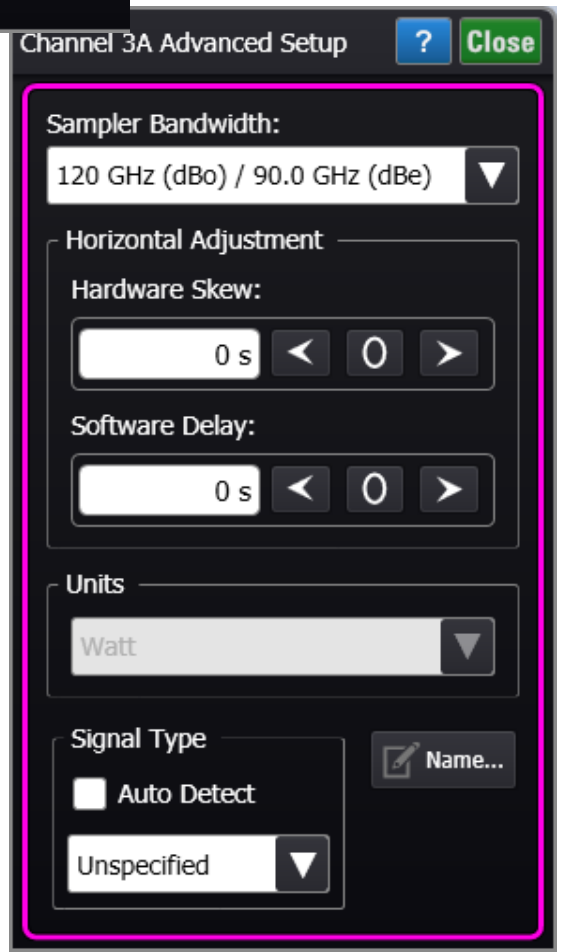
N1032A Single Channel | N1032B Dual Channel

Item	Description	
Optical Channel Count	1 (N1032A) 2 (N1032B)	
Optical Channel Bandwidth, −3 dBo [1, 8]	Option 09U	Option 13U
BW (unfiltered)	60 GHz	60 GHz
	80 GHz	80 GHz
	90 GHz	90 GHz
		110 GHz
		120 GHz (characteristic)
RMS Noise *(Characteristic)* [7]	1310 nm	1550 nm
Unfiltered 80 GHz (−3 dBo)	*65 µW*	*120 µW*
Unfiltered 90 GHz (−3 dBo)	*90 µW*	*155 µW*
Unfiltered 110 GHz (−3 dBo)	*130 µW*	*235 µW*
Unfiltered 120 GHz (−3 dBo)	*175 µW*	*300 µW*
RMS Noise (Maximum) [7]	1310 nm	1550 nm
Unfiltered 80 GHz (−3 dBo)	80 µW	135 µW
Unfiltered 90 GHz (−3 dBo)	105 µW	165 µW
Unfiltered 110 GHz (−3 dBo)	150 µW	235 µW
Unfiltered 120 GHz (−3 dBo)	185 µW	315 µW

N1032A Frequency Response

Data from ONE module – not specification, but informative

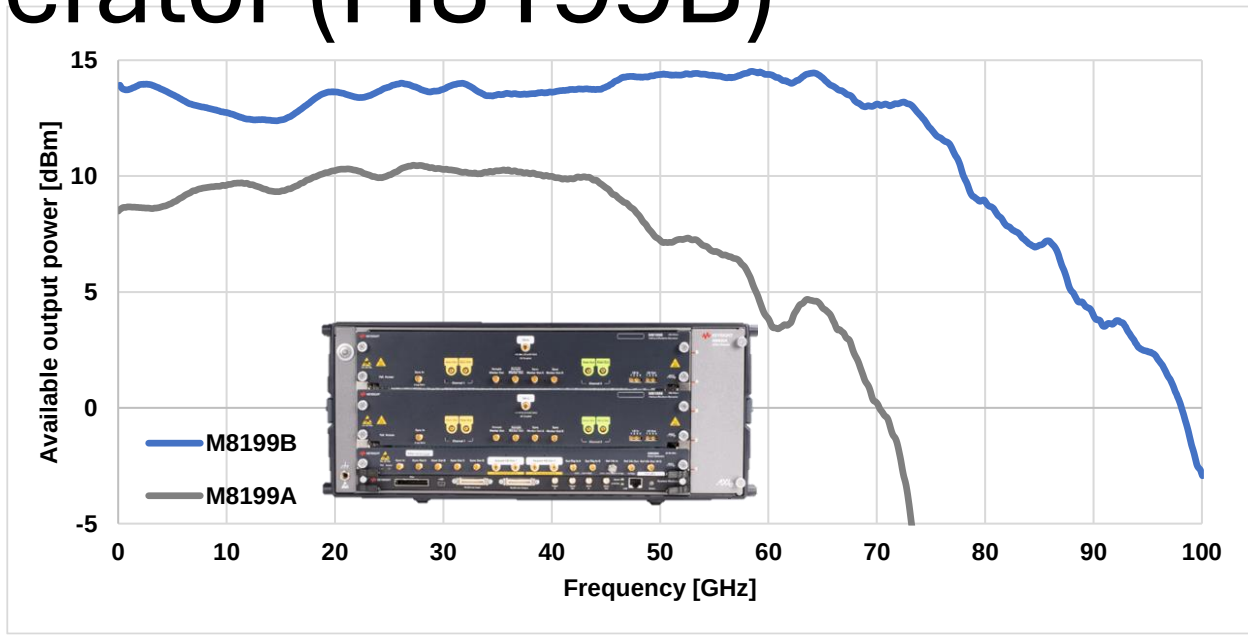


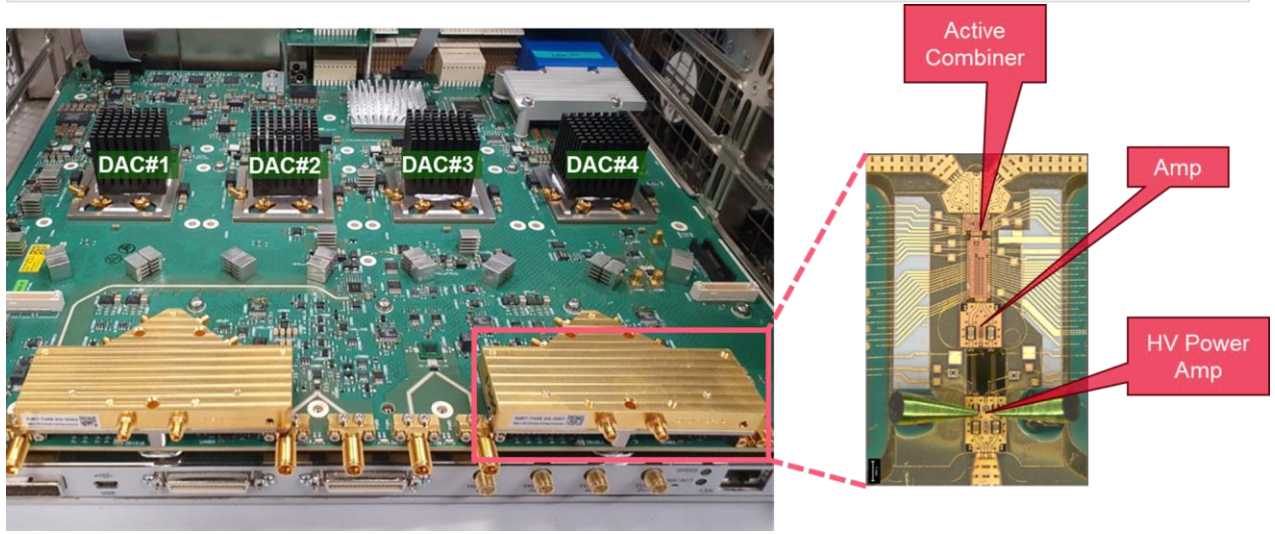


Arbitrary Waveform Generator (M8199B)

The AWG for development of 160 GBaud designs

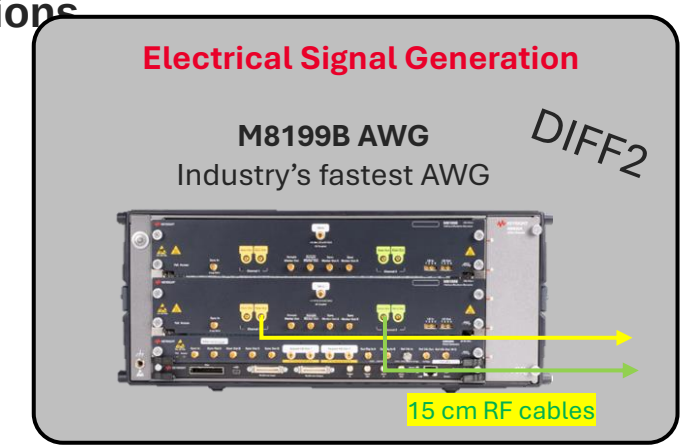
- Continuous sample rate from 200 to 256 GSa/s
- 1 MSa of waveform memory per channel
- Analog bandwidth exceeding 80 GHz
- Synchronization of up to 8 channels across 4 modules
- Up to 2.2 Vpp differential output voltage at 160 Gbaud
- 5.0 Vpp amplitude at 400 MHz
- Built-in frequency and phase response calibration for clean output signals
- The only AWG in the industry allowing to generate 200 Gbaud signal

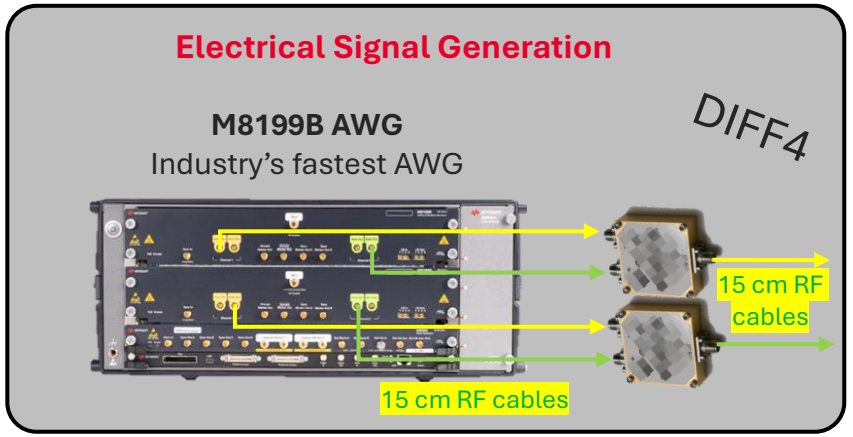




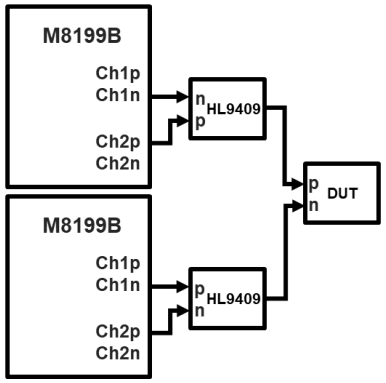
448 Gbps Electrical Measurements

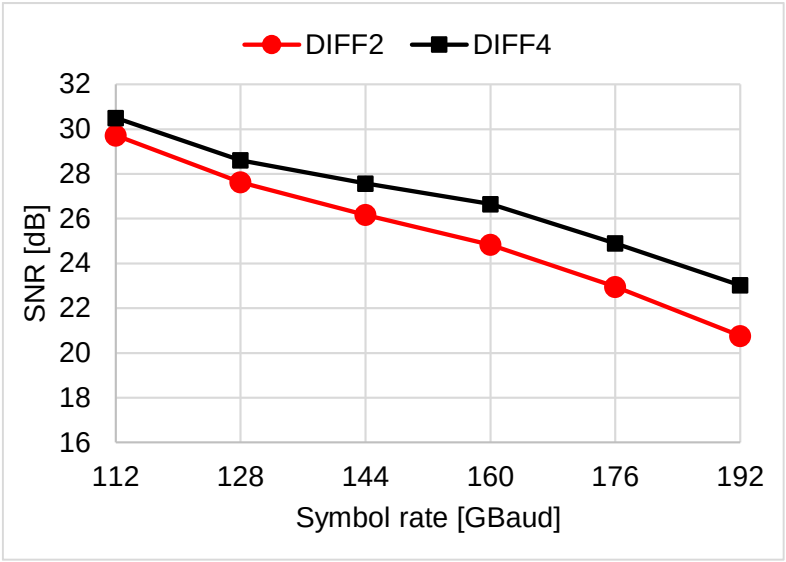
Pathfinding Solutions

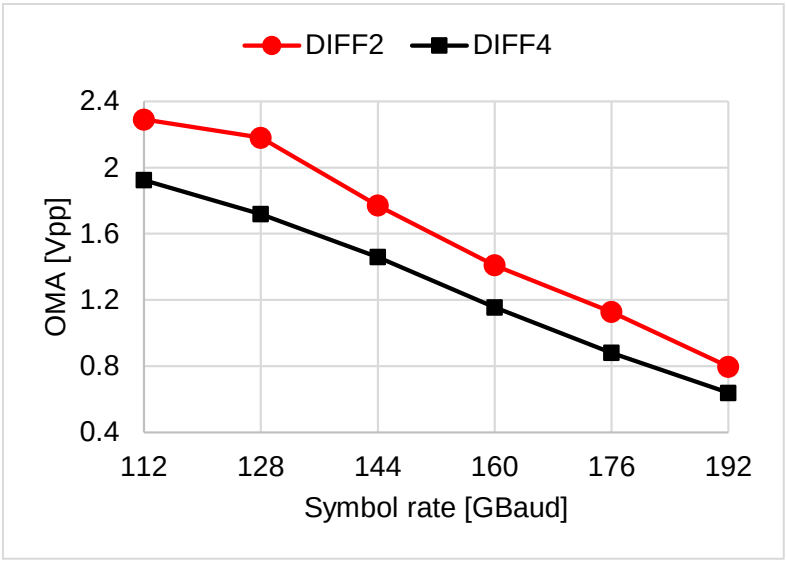




DIFF4: Multi-module virtual diff. channel







Differential signal generated with two M8199B AWGs (for each module, ch1p and ch2n connected to a high-bandwidth balun). Electrical signal measured with an N1046A DCA electrical channel module. A 10dB attenuator at each AWG output is used. Digital pre-distortion of AWG, 15 cm RF cables and balun applied at the transmitter side. No equalization is applied in FlexDCA.

448 Gbps Electrical BER Measurements

Pathfinding Solutions

Electrical Signal Generation

M8199B AWG
Industry's fastest AWG

15 cm RF cables

Electrical Signal Detection

30 cm RF cables

Infiniium UXR-Series Oscilloscope
The world's most advanced real time oscilloscope.

Differential signal generated with two M8199B AWGs. Electrical BER measured with a 110 GHz UXR real-time oscilloscope. Digital pre-distortion of AWG, RF cables and balun applied at the transmitter side. No equalization is applied in Infiniium UXR software.

448 Gbps Electrical BER Measurements

Pathfinding Solutions

Electrical Signal Generation

M8199B AWG
Industry's fastest AWG

15 cm RF cables

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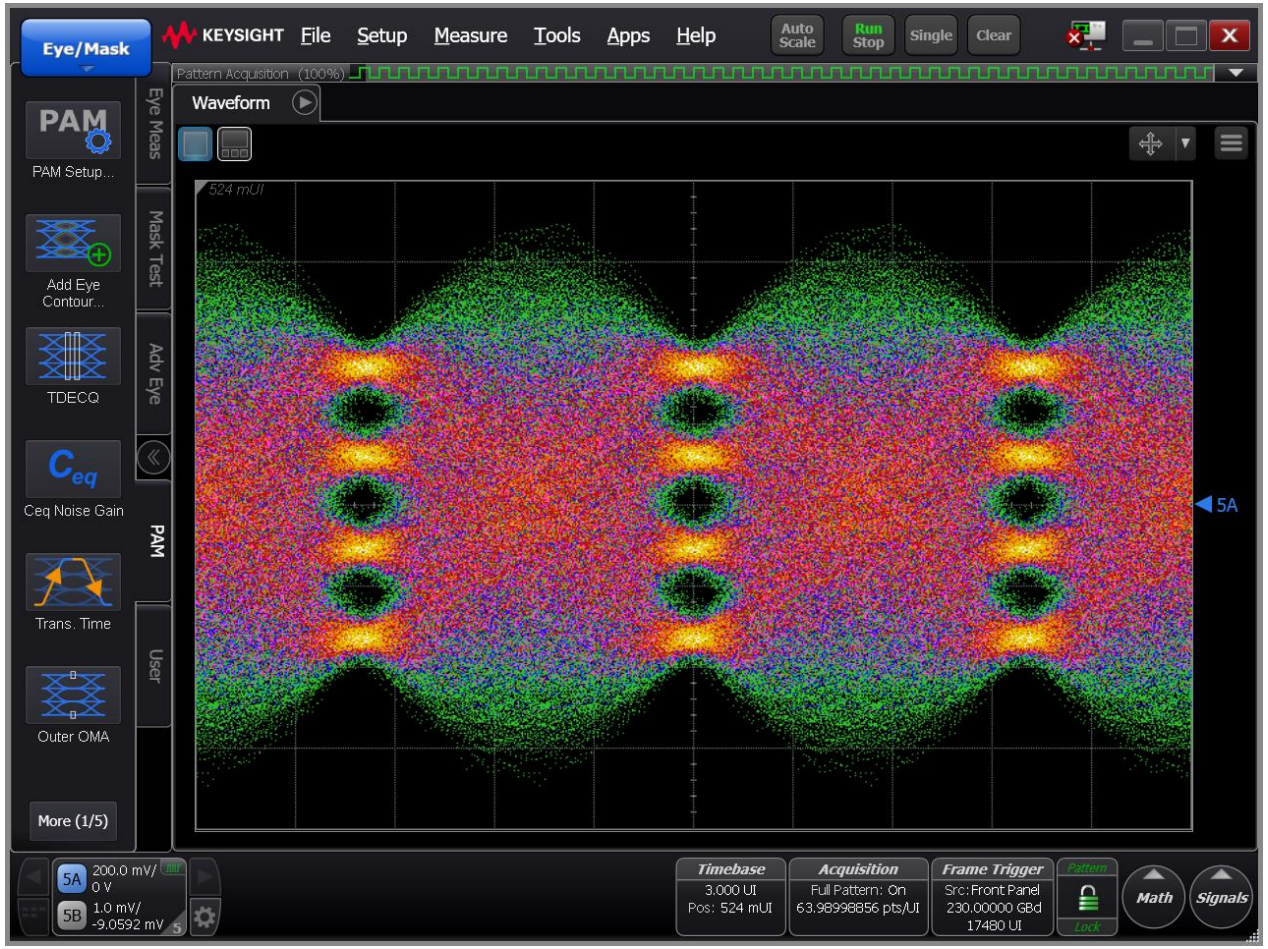
Differential signal generated with two M8199B AWGs. Electrical BER measured with a 110 GHz UXR real-time oscilloscope. Digital pre-distortion of AWG, RF cables and balun applied at the transmitter side. No equalization is applied in Infiniium UXR software.

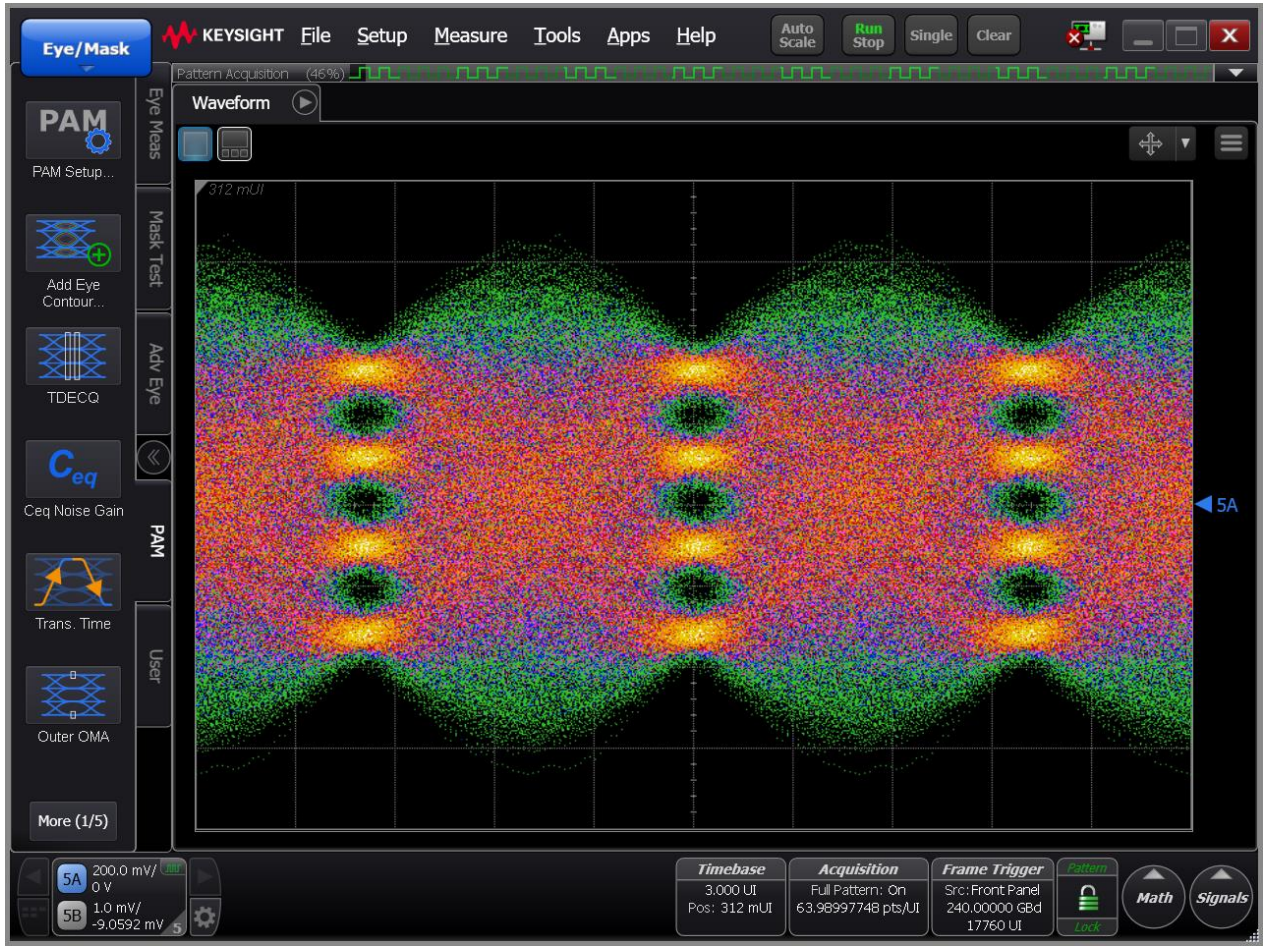
M8199B AWG + M8159A FDIU + External Amplifier

Sample measurements

230 Gbaud PAM4



240 Gbaud PAM4

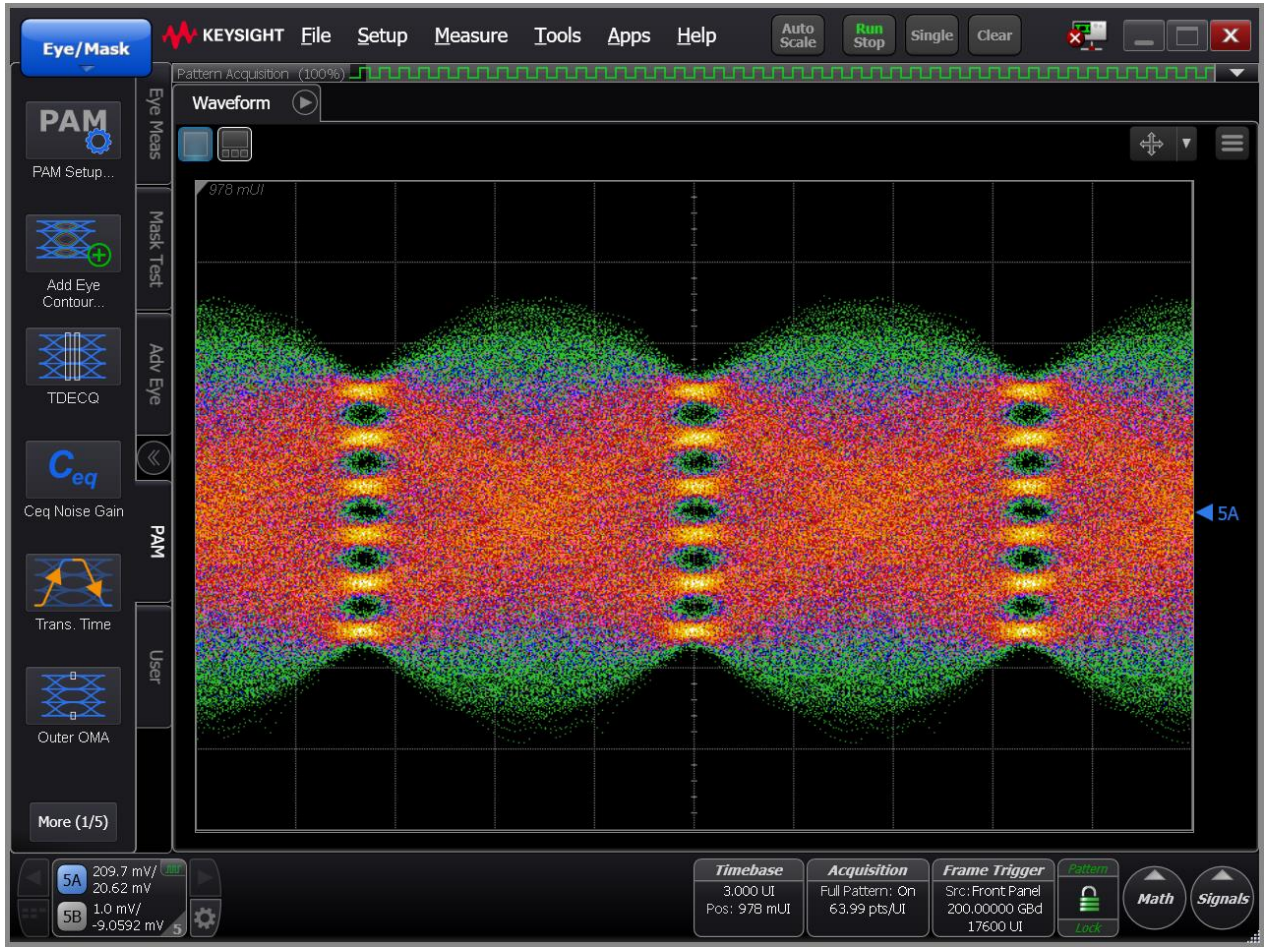


M8199B AWG + M8159A FDIU + External Amplifier

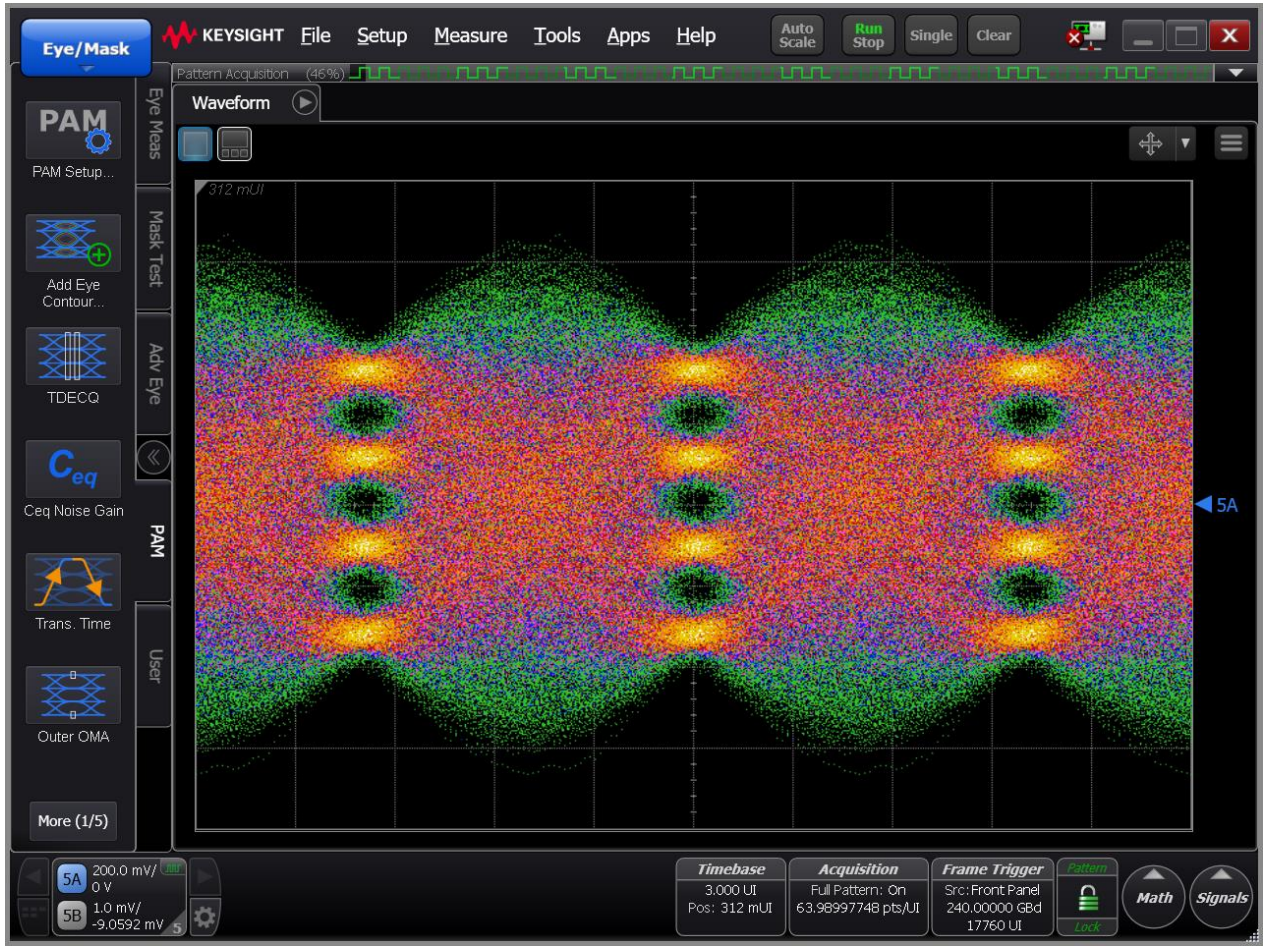
Sample measurements

Relevant for R&D targeting 1600ZR

200 Gbaud PAM6 (tributary for **1.6T** with **DP-32QAM**)



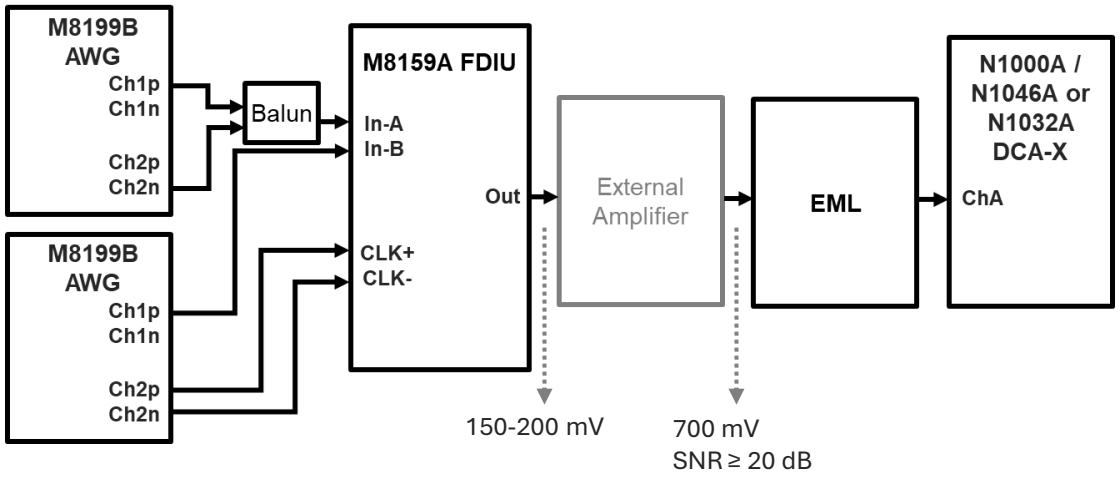
240 Gbaud PAM4 (tributary for **1.6T** with **DP-16QAM**)

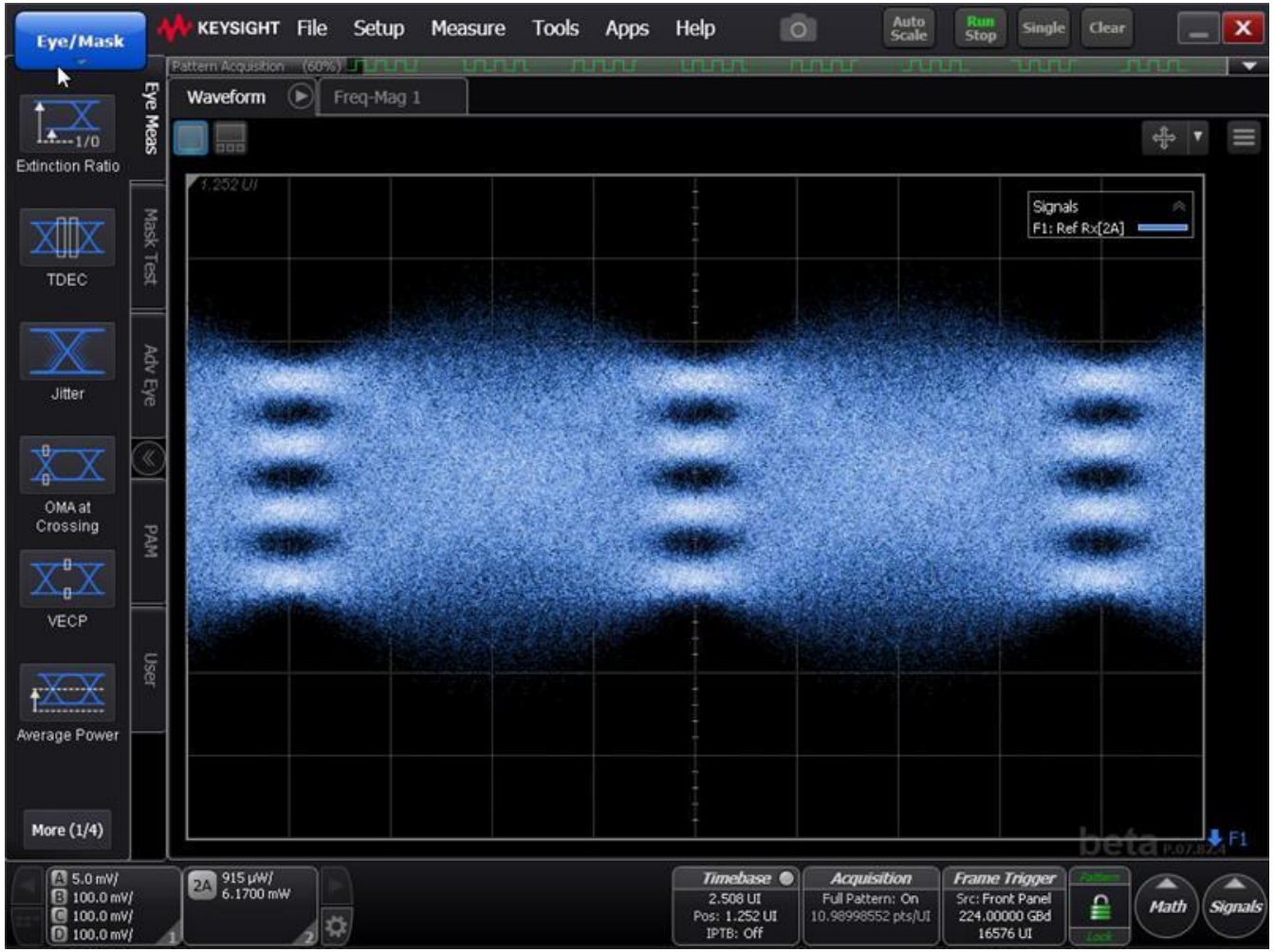


448 Gbps Optical Research

Demo at OFC25, Keysight booth 1301

OFC 50
Celebrating 50 Years of Optical Networking and Communications





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