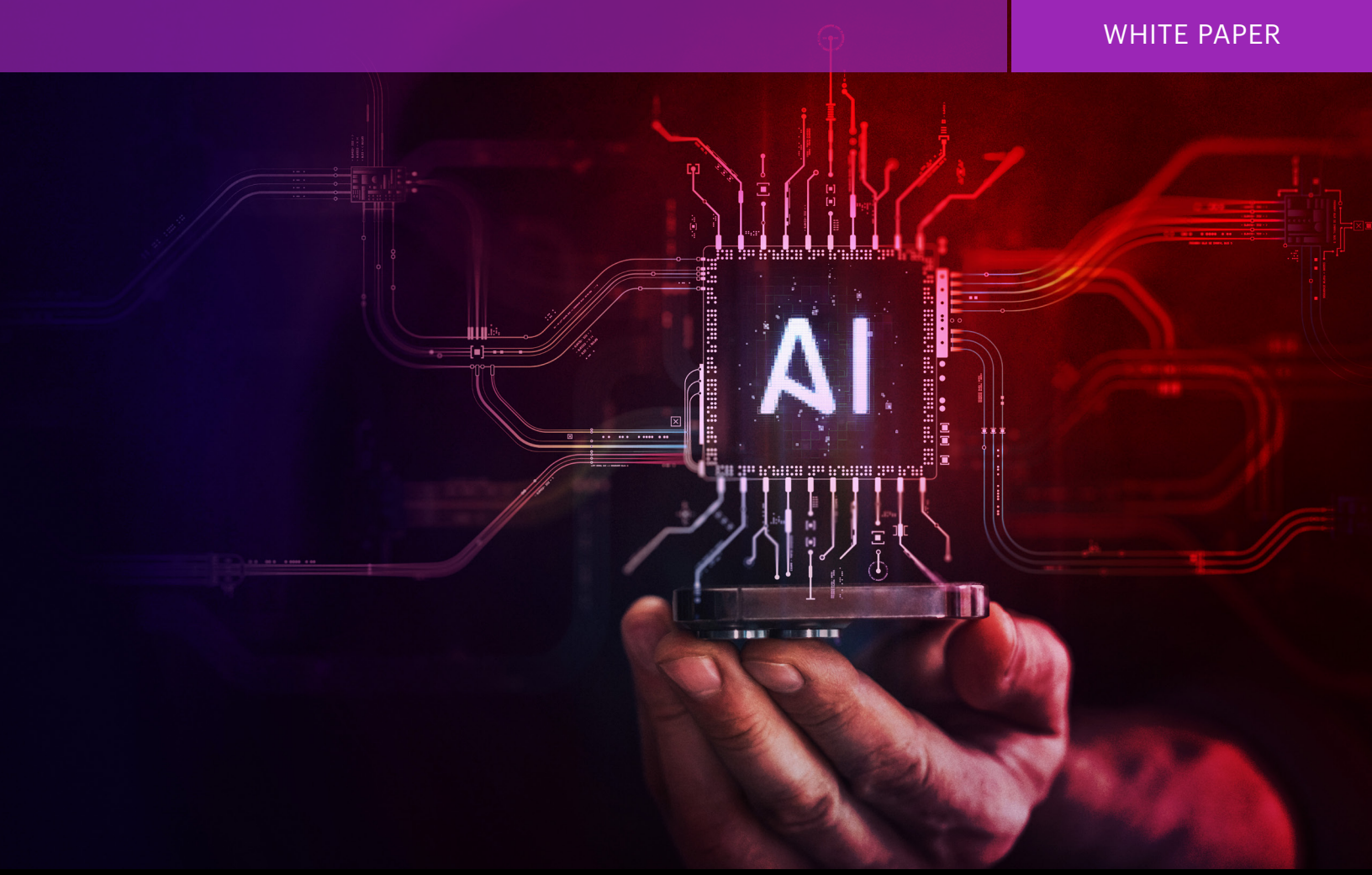
WHITE PAPER



Race to 448 Gbps

Pushing the limits and examining tradeoffs for high-speed signaling

KEYSIGHT

Introduction

Enabling next-gen data center and AI performance through advanced modulation and test innovation

The accelerating demand for bandwidth is pushing data transmission technologies to their limits. As the industry looks beyond 400 Gbps, researchers are turning to advanced modulation formats and high-performance test equipment to meet the requirements of next-generation networks. AI workloads are straining existing copper and optical interconnects as models become larger and more complex. Training large-scale models, such as GPT-5 and others, depends on distributed computing infrastructures, where current 400/800G links are becoming a bottleneck. Scaling interconnect speeds to 1.6T and 3.2T (or 224/448 Gbps per lane) is crucial for meeting the performance demands of future AI clusters.

This white paper outlines the technological path toward achieving 448 Gbps transmissions, detailing the role of advanced instrumentation, system configurations, and real-world experimental validation.

Breaking the 400G Barrier: Bandwidth vs. SNR

The transition to 448 Gbps transmission is driven by the urgent need for faster data rates in data centers, high-performance computing, and next-generation telecommunications systems. At the core of this challenge lies Shannon's Law, which defines the theoretical maximum data rate (channel capacity) of a communication system based on its bandwidth and signal-to-noise ratio (SNR):

$$C = B * log_2(1 + SNR)$$

Where: C = Channel capacity in bps, B = bandwidth in Hz, SNR is the signal-to-noise ratio (linear).

While Shannon's Law describes the ultimate ceiling of what's theoretically possible with ideal coding, real-world systems must also contend with Symbol Error Rate (SER), which is directly impacted by the chosen modulation format and the actual SNR of the channel. Shannon's Law defines the limit, but SER reflects whether a system performs reliably enough to be practical and commercially viable.

In practice, if the SNR is too low for a selected modulation scheme, the resulting SER becomes unacceptably high, making bit error correction, by practical forward-error-correcting (FEC) codes, impossible, therefore jeopardizing data integrity. The SER for PAM-L (two-sided noise spectrum) in an Additive White Gaussian Noise (AWGN) channel is generally given by:

$$SER_{PAM-L} \approx \frac{2(M-1)}{M} * Q\left(\sqrt{\frac{3 * SNR_s}{(M^2-1)}}\right)$$

Where: M = levels (e.g., 4 for PAM4, 8 for PAM8), Q(x) = tail probability, SNR=Es/(N0/2) (linear)

For example, achieving an SER below 10^{-3} using PAM4 requires an SNR of approximately 17.1 dB. That same SNR would result in significantly worse performance if PAM6 or PAM8 were used, yielding SERs of 10^{-2} and 10^{-1}. To maintain equivalent error rates, PAM6 or PAM8 would require SNRs of roughly 20.9 dB and 23.5 dB, respectively. This clearly illustrates the trade-off: while PAM6 and PAM8 offer higher data throughput per symbol, they are also more susceptible to noise and require cleaner, higher-SNR channels to operate effectively.

$$SER_{PAM4} \approx 1.5 * Q\left(\sqrt{\frac{SNR}{5}}\right) \quad \text{and} \quad SER_{PAM8} \approx 1.75 * Q\left(\sqrt{\frac{SNR}{21}}\right)$$

The figure below visualizes this relationship. As modulation order increases, so does the SNR required to maintain a fixed error rate. For instance, to achieve an SER of 10^{-5}, PAM8 demands about 6.3 dB more SNR than PAM4, highlighting the increasing sensitivity to noise at higher modulation levels.

This trade-off becomes even more pronounced at higher symbol rates, where timing jitter, bandwidth constraints, and inter-symbol interference further degrade signal quality. As data rates increase, systems require not only higher SNR for a given modulation format but also faster, more precise instrumentation to maintain low error rates.

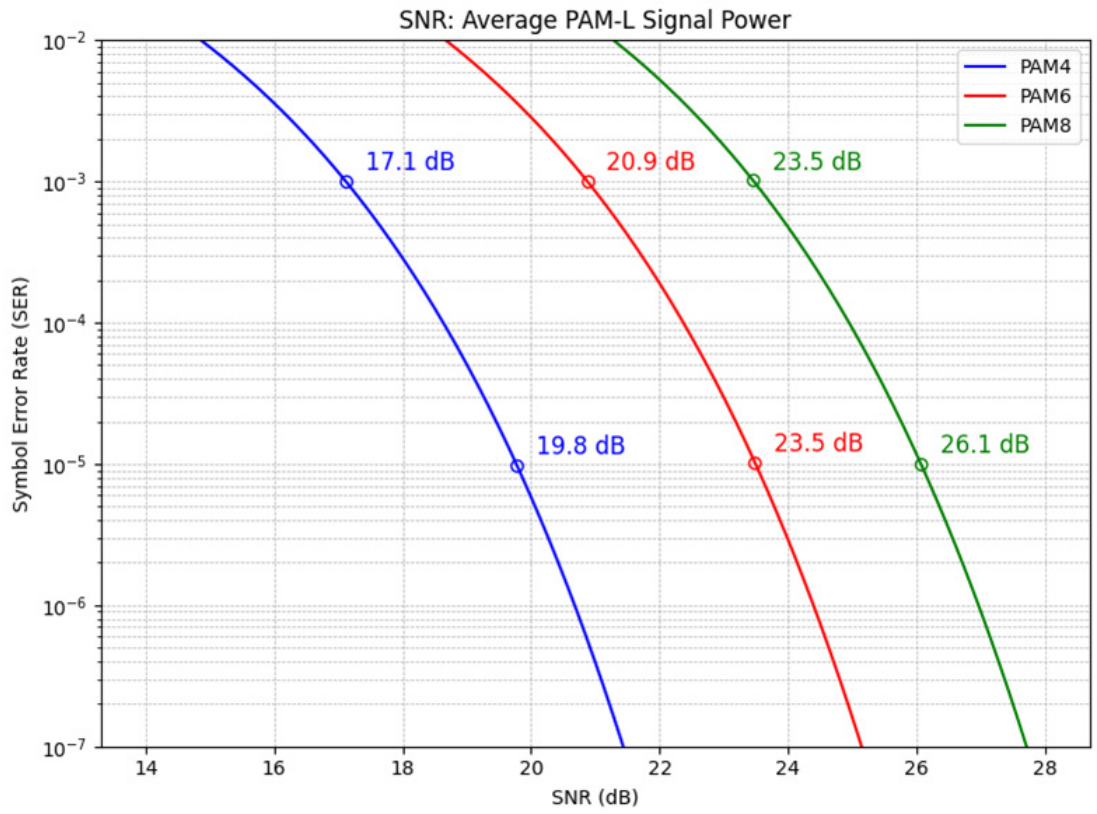


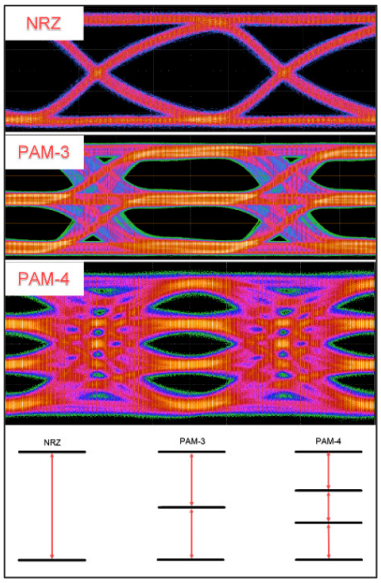
Figure 1. Required SNR (dB) vs. Symbol Error Rate (SER) for PAM4, PAM6, and PAM8 modulation schemes

Ultimately, this trade-off represents a key roadblock to scaling beyond 400 Gbps: reaching 448 Gbps and beyond requires balancing higher symbol rates (which demand more bandwidth) with higher-order modulation (which requires a greater signal-to-noise ratio, or SNR), while also improving signal quality using better components, shorter interconnects, and advanced equalization and coding techniques.

Modulation Advancements Enabling Higher Throughput

To overcome the limitations of bandwidth and signal quality, the industry is turning to more efficient modulation formats. By encoding more bits per symbol, higher-order PAM schemes—such as PAM3, PAM4, PAM6, and PAM8—enable faster data transmission without necessarily increasing the symbol rate.

As discussed, each step up in modulation complexity improves throughput but introduces greater sensitivity to noise and demands more sophisticated signal integrity and equalization techniques. The table below compares these modulation formats, highlighting their respective trade-offs, performance characteristics, and current deployment status.



Comparison of modulation schemes

Modulation	Bits / Symbol	Key characteristics	Example use cases
NRZ	1	Simple, lowest SNR requirement, uses more bandwidth for the same data rate	USB 2.0
PAM3	~1.58	3-level modulation, moderate gain over NRZ, balances between complexity and efficiency	USB 4 v2
PAM4	2	4-level modulation, widely adopted, reduces channel bandwidth needs by about half vs. NRZ	IEEE 802.3ck/dj, PCIe 6/7
PAM6	~2.58	6-level modulation, ~29% more throughput than PAM4 at the same symbol rate	Research and proof-of-concept systems
PAM8	3	8-level modulation, 50% more data rate than PAM4; more susceptible to noise	Research and proof-of-concept systems

Navigating the complexities of higher-order modulation

As shown in Figure 2, roadmaps for Ethernet, interconnects, PCIe, and memory are converging on lane rates well above 200 Gbaud for AI-class data centers. While PAM4 has become the standard for many high-speed links, scaling it beyond 200 Gbaud presents real physical design challenges. Channels and connectors must support frequencies exceeding 100 GHz, demanding ultra-low-loss materials and refined signal paths. Keysight has demonstrated a 448 Gbps PAM4 rate, equivalent to 224 Gbaud, proving that these limits can be pushed.

Researchers are also turning to PAM6 and PAM8 to achieve 448 Gbps without the need to double the symbol rate. PAM6 offers a 1.29× improvement over PAM4, and PAM8 boosts it by 1.5×, achieving 448 Gbps using lower symbol rates, such as 174 Gbaud (PAM6) and 150 Gbaud (PAM8). These approaches reduce the stress on bandwidth but require much tighter control over signal integrity.

Race to higher baud rates: Next-gen ethernet, interconnects, PCIe and memory

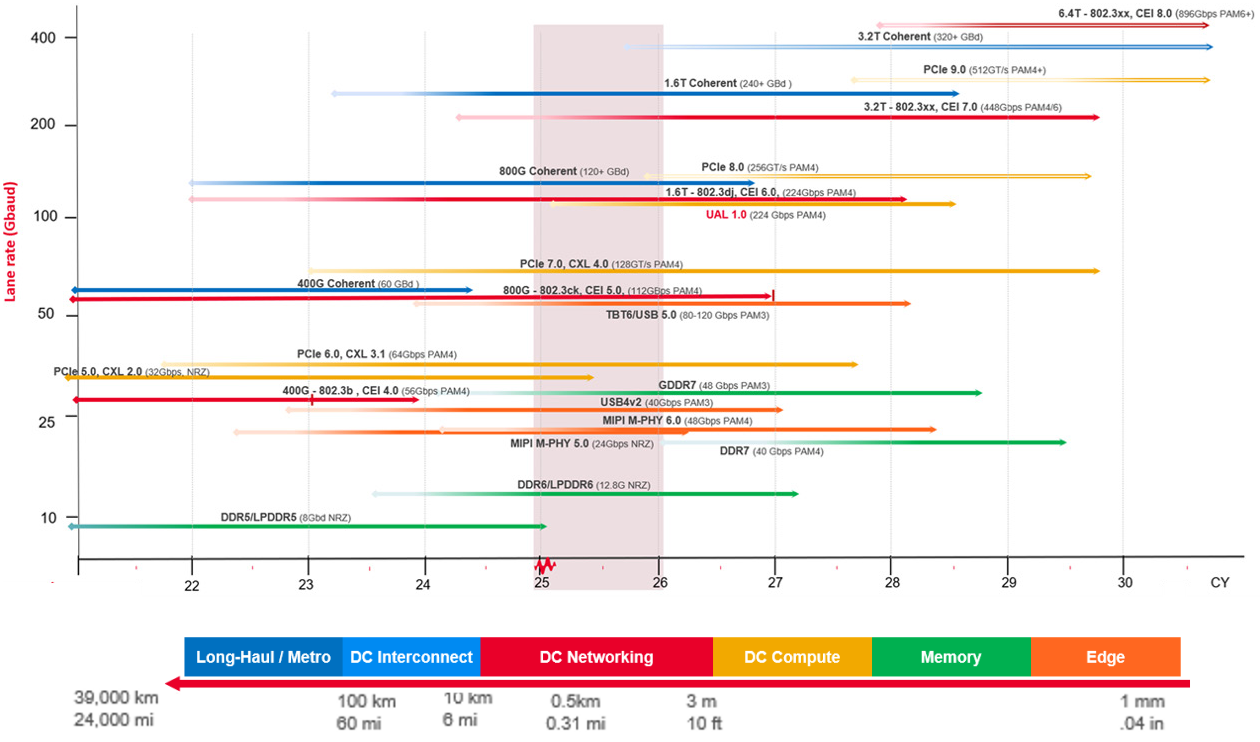


Figure 2. Lane-rate (Gbaud) vs. calendar year for next-gen Ethernet, interconnects, PCIe, and memory, highlighting the industry's shift into the 224–320+ Gbaud era and the modulation formats driving it.

The trade-off is clear: PAM6 and PAM8 increase system complexity. Their additional amplitude levels introduce greater susceptibility to noise, jitter, and ISI (inter-symbol interference). Maintaining performance requires advanced equalization techniques, including Continuous Time Linear Equalizer (CTLE), Feed Forward Equalizer (FFE), and Decision Feedback Equalizer (DFE).

Figures 3 through 5 visualize how eye opening diminishes, and SNR sensitivity increases with higher-order modulation schemes. As modulation complexity increases, so too does the need for high-fidelity signal generation, advanced measurement tools, and robust equalization capabilities, which Keysight's platforms are uniquely positioned to deliver.

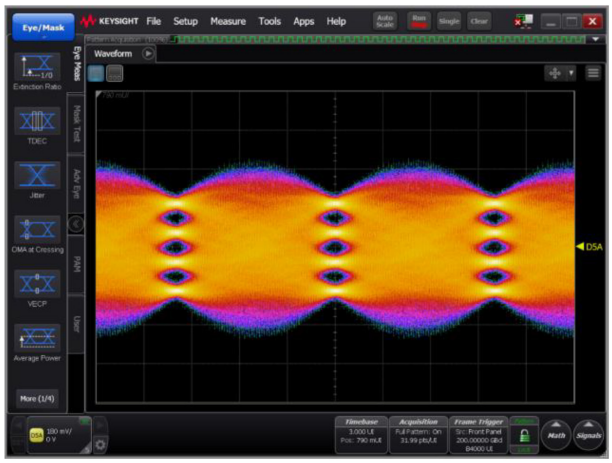


Figure 3. Example Eye Diagram at 448 Gbps - 200 GBaud using PAM4

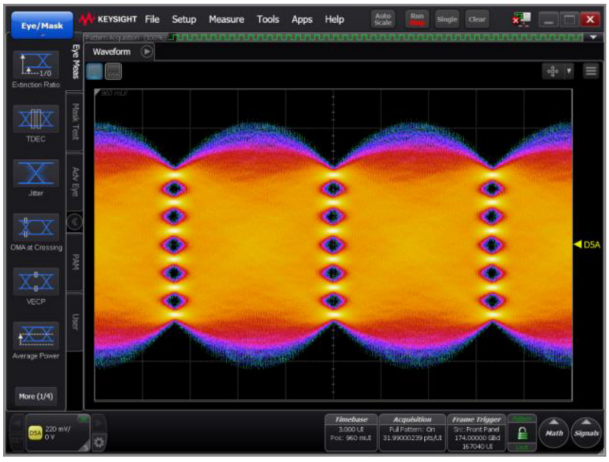


Figure 4. Example Eye Diagram at 448 Gbps - 174 GBaud using PAM6

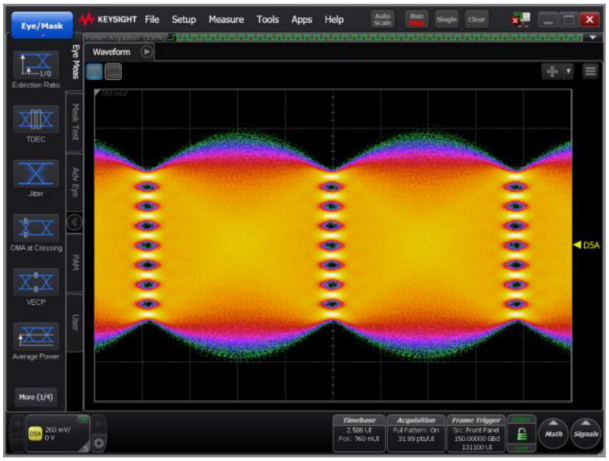


Figure 5. Example Eye Diagram at 448 Gbps - 150 GBaud using PAM8

Pushing the Limits of Symbol Rate and Signal Integrity

As the industry drives symbol rates beyond 100–120 Gbaud toward 150–240 Gbaud, raw transmission speeds up to 448 Gbps per lane are becoming achievable. Reaching and validating such performance requires not only higher SNR but also more advanced test strategies to ensure signal fidelity and system reliability at scale.

Transitioning to higher-speed PAM4—and especially to complex formats like PAM6 and PAM8—requires oscilloscopes with ultra-wide bandwidths, ideally 110 GHz or more. These instruments must offer low intrinsic jitter, high vertical resolution, and the ability to capture rapid transitions and subtle waveform distortions accurately. Without such capabilities, diagnosing and correcting signal degradation at elevated data rates becomes increasingly difficult.

As modulation formats advance, so must measurement methodologies. Eye diagram analysis, transmitter equalization tuning, and compliance metrics like Transmitter Dispersion Eye Closure Quaternary (TDECQ) must evolve to address narrower eye openings and tighter timing margins. This is especially critical for PAM6 and PAM8, which require greater measurement precision to ensure interoperability and compliance.

To meet these demands, test solutions must not just keep pace; they must lead. This requires signal generation and analysis tools with bandwidth, fidelity, and precision to validate high-speed, high-complexity designs. At these performance levels, optimized SNR and bandwidth are no longer advantages; they're essential.

Optimizing bandwidth and SNR for hero performance

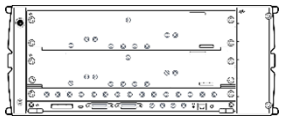
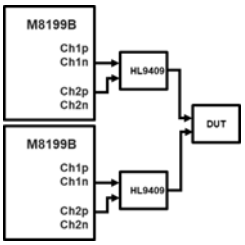
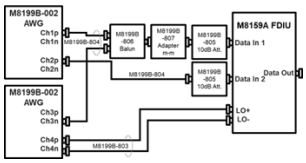
Building on these test requirements, Keysight's solutions are engineered to deliver the SNR, sample rate, and bandwidth needed to validate cutting-edge modulation formats at the highest symbol rates.

The following table illustrates how Keysight's Arbitrary Waveform Generator (AWG) solutions are optimized for these next-generation testing challenges. It compares three high-performance AWG industry-leading configurations—including the standalone M8199B, the PAM6/8-optimized solution, and the PAM4-optimized configuration requiring the M8159A Frequency-Domain Interleaving Unit (FDIU). These systems offer different trade-offs between amplitude, SNR, sample rate, and bandwidth, supporting up to hero experiments beyond 240 Gbaud.

The most advanced system delivers a sample rate of 512 GSa/s and over 120 GHz of usable bandwidth, enabling signal generation at unprecedented speeds. With SNR exceeding 20.5 dB at 224 Gbaud and flexible support for PAM4, PAM6, and PAM8. Keysight's AWG platforms are purpose-built for high-speed interconnect R&D, characterization and validation testing.

Together with Keysight's ultra-broadband analysis tools, these signal generation solutions enable a complete end-to-end test environment to push data rates to 448 Gbps and beyond, bridging the gap between theoretical performance and real-world implementation.



Specifications	M8199B	PAM6 / 8 Solution	PAM4 Solution
			
Max. sample rate	256 GSa/s	256 GSa/s	512 GSa/s
Bandwidth (incl. sinc roll-off)	75 GHz @–3 dB 80/90 GHz @-6/–10 dB	Reduced respect of M8199B because of balun and cables	> 120 GHz (usable)
DAC Resolution	8 bits	8 bits	8 bits
Output	Differential	Differential (single-ended with an additional balun)	Single-ended (differential with an additional balun or with an additional M8199B and M8159A FDIU)
Max. Amplitude (diff.)	2.2 V_{pp} @ 160 GBd	0.5 V_{pp} @ 200 GBd	0.15 V_{pp} @ 224 GBd (single-ended), with external amplifier up to 0.7 Vpp
Memory	1024 kSa per channel	1024 kSa per channel	1024 kSa per channel
SNR	15 dB @ 200 GBd	20 dB @ 200 GBd	20.5 dB @ 224 GBd
Channels per system	Up to 8	Up to 2	Up to 2
Form-factor	1x M9505A: 2-slot AXIe + 1-slot AXIe for M8008A	1x M9505A: 4-slot AXIe + 1-slot AXIe for M8008A	1x M9505A: 5-slot AXIe + external box
Application	Up to 160-180 GBd, hero experiments up to 200 GBd	Best system in the industry for 448 Gbps based on 150 GBd PAM8 and 174 GBd PAM6, 200 GBd PAM4 is also possible	Best system in the industry for 448 Gbps based on 224 GBd PAM4, ≥ 240 GBd hero experiments also possible
Reference document	Link	Link	

Extending Bandwidth for 448 Gbps and Beyond

To validate 448 Gbps and beyond, test systems must deliver ultra-wideband, high-fidelity signals. Figure 6 shows how to extend the bandwidth of the M8199B Arbitrary Waveform Generator (AWG) using a setup demonstrated at OFC 2025. The goal here is to generate ultra-broadband signals that go beyond the limits of a single AWG channel, which is essential for testing next-generation high-speed devices.

At the center of the setup is the M8159A FDIU. Based on the frequency domain interleaving approach, two AWG outputs are used in parallel, each responsible for generating a spectral sub-band of the overall signal. The lower-frequency band contains signal information from DC up to ~80 GHz. The rest of the spectrum is contained in the upper-frequency band, depending on the symbol rate to be generated. This sub-band is upconverted by means of a local oscillator signal generated from another AWG channels and combined in the analog domain to form a wideband signal. The concept of balun is used for the lower-frequency band to improve the SNR, since this band contains most of the frequency content of the wide-band signal.

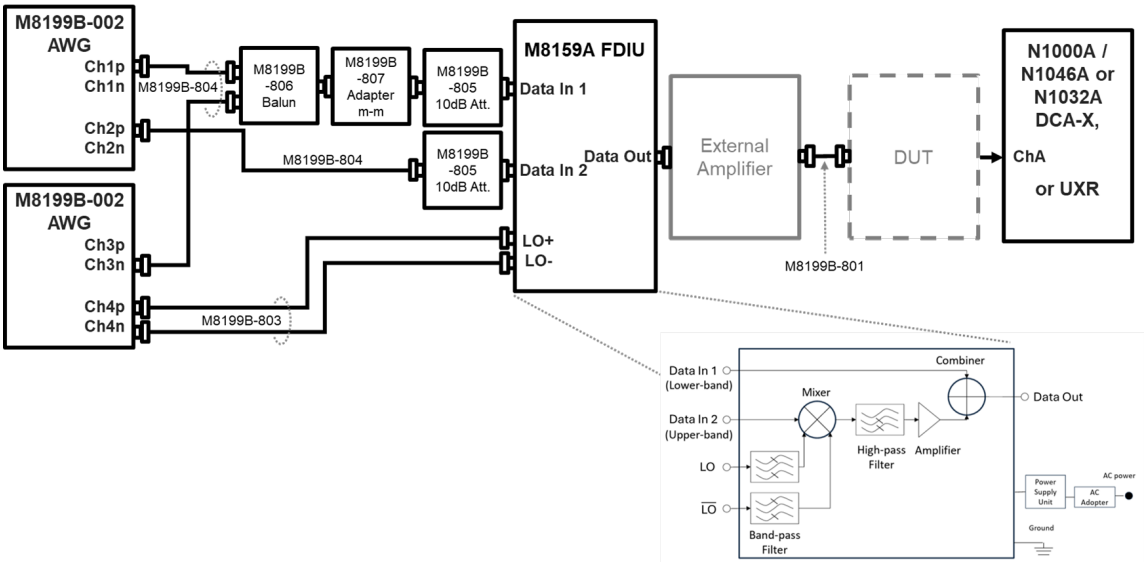


Figure 6. Extended Bandwidth Signal Generation Setup for 448 Gbps Testing

The output signal from the M8159A FDIU can be sent to different devices under test (DUT), such driver amplifiers, and a variety of optical modulators. If need an external amplifier can be used to boost the driving voltage to the DUT.

To measure the results, the setup utilizes high-speed instruments, such as the N1000A DCA-X, N1046A, N1032A, or UXR oscilloscopes. These tools can analyze high-speed signals and are crucial for validating advanced modulation formats, such as PAM4, PAM6, and PAM8, at speeds of up to 448 Gbps.

Figure 7 shows the frequency response at the output of the M8159A. A complementary view of this setup's performance is shown in Figure 8, which plots signal-to-noise ratio (SNR) versus symbol rate. The chart compares the baseline M8199B (SE3) output with the extended configuration using the M8159A and an external amplifier.

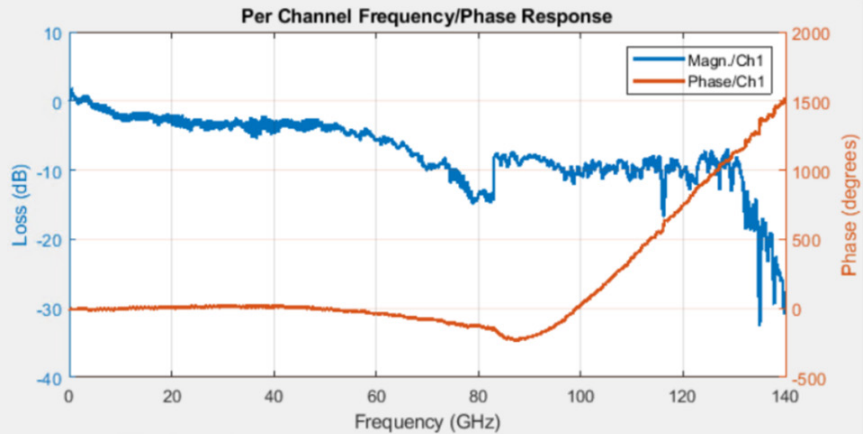


Figure 7. Signal-to-Noise Ratio (SNR) vs. Symbol Rate for M8199B Configurations

While the basic setup performs well up to ~180 Gbaud, the enhanced setup maintains SNR levels above 20 dB even at 224 Gbaud—a key threshold for reliable high-speed modulation. This extended configuration also achieves output amplitudes near 700 mV single-ended modulation amplitude, making it well-suited for pushing the limits of current interconnect technologies.

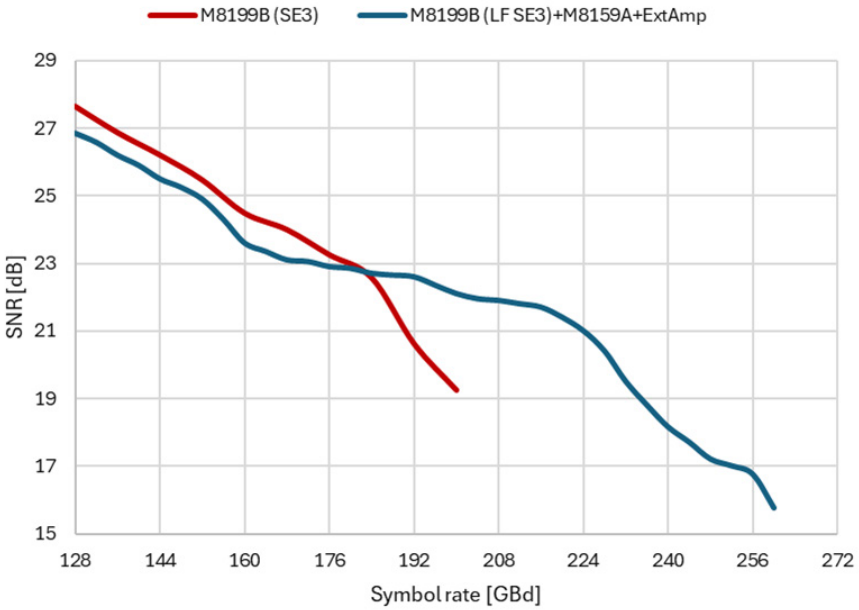


Figure 8. Signal-to-Noise Ratio (SNR) vs. Symbol Rate for M8199B Configurations

Electrical and Optical Measurement Setups

Electrical measurements

Electrical testing remains essential for early-stage development and validation of high-speed interconnects. The configurations below combine Keysight's Arbitrary Waveform Generators (AWGs) with precision analysis tools to ensure clean, high-fidelity signal generation and accurate capture of signal impairments.

Electrical signal generation	Bit Error Ratio Testers (BERT)	Electrical signal analysis
M8199B 1–2 channel AWG with up to 256 GSa/s, 80 GHz bandwidth	M8050A 120 Gbaud High-Performance BERT	UXR-Series Oscilloscopes with 5 to 110 GHz of bandwidth
M8199A Up to 4 channels with 128 GSa/s, 55 GHz bandwidth		N1000A DCA-X Oscilloscope Mainframe with N1046A 75 / 85 / 100 GHz
M8198A 1–2 channel AWG with 128 GSa/s and 58 GHz bandwidth		N1094A 30 / 50 GHz Dual Electrical Channel (N1094B, 4 ch.)

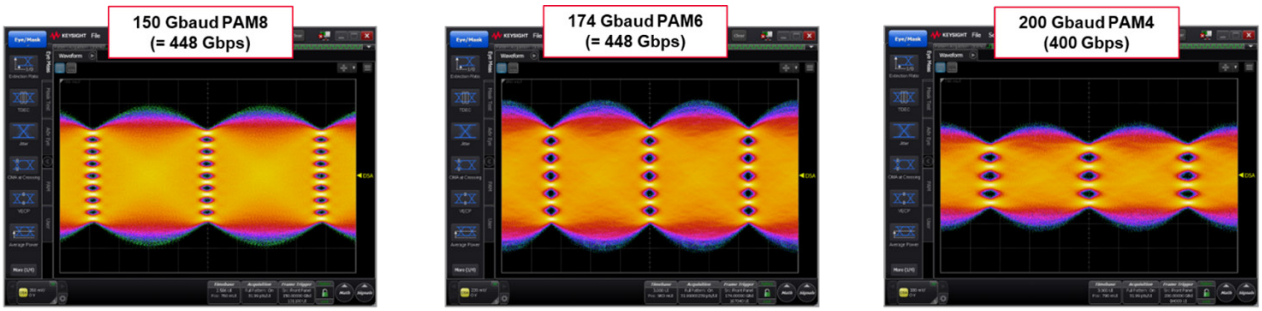


Figure 9. Differential signal generated with two M8199B AWGs (for each module, ch1p and ch2n connected to a high-bandwidth balun). Electrical signal measured with an N1048A DCA electrical channel module. A 10 dB attenuator at each AWG output is used. Digital pre-distortion of AWG output us used. Digital pre-distortion of AWG, 15 cm RF cables and balun applied at the transmitter side. No equalization is applied in FlexDCA.

Optical measurements

As interconnect technologies scale to higher speeds and longer reach, optical testing becomes increasingly critical. These optical configurations leverage the same signal generation backbone with specialized transmitters and analysis modules to enable end-to-end optical validation across complex link architectures.

Electrical signal generation	Optical signal generation	Optical signal analysis	Electrical signal analysis
M8199B 1–2 channel AWG with up to 256 GSa/s, 80 GHz bandwidth	N7718C Optical Reference Transmitter, 200G-per-lane design validation / 400G-per-lane research	N1000A DCA-X Oscilloscope with N1032A 90 / 120 GHz Single Channel Optical Module	UXR-Series Oscilloscopes with 5 to 110 GHz of bandwidth
M8199A Up to 4 channels with 128 GSa/s, 55 GHz bandwidth		N1000A DCA-X Oscilloscope with N1032B 90 / 120 GHz Dual Channel Optical Module	N1000A DCA-X Oscilloscope Mainframe with N1046A 75 / 85 / 100 GHz
M8198A 1–2 channel AWG with 128 GSa/s and 58 GHz bandwidth			N1000A DCA-X Oscilloscope Mainframe with N1060A 50 / 85 / Dual Channel

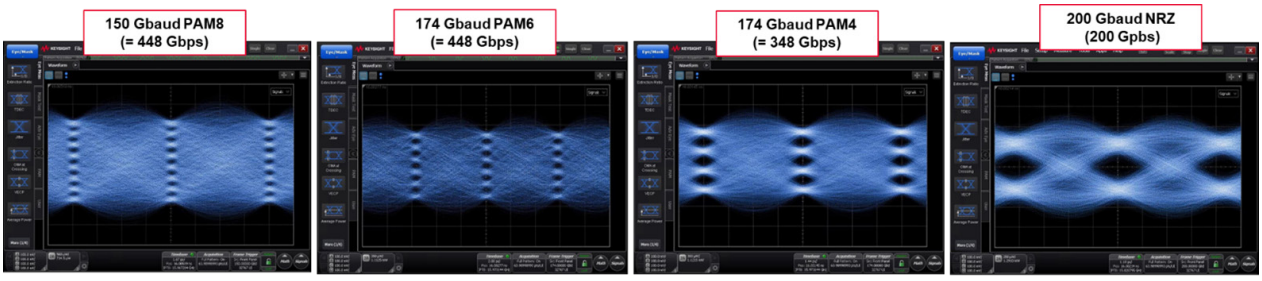


Figure 10. Signals generated with the N7718C reference transmitter driven by an M8199B AWG (ch1p and ch2n connected to a high-bandwidth balun). Optical signal measured with an N1032A DCA optical channel module. Digital pre-distortion of AWG, 30 cm RF cables and balun applied at the transmitter side. System impluse Response Correction (SIRC) with flat response and linear equali zation, also removing noise and interference components that are not correlated to the trigger signal, are applied in FlexDCA.

Conclusion: Enabling the Future of AI and High-Speed Connectivity

As AI workloads scale and data center demands intensify, the limitations of current 400/800G interconnects are becoming increasingly apparent. Achieving 448 Gbps per lane represents a critical step toward meeting the bandwidth, latency, and scalability requirements of next-generation infrastructure. While PAM4 remains a strong standard today, higher-order modulation schemes like PAM6 and PAM8 offer viable paths to greater throughput, if paired with improved SNR and precision test strategies.

Keysight's R&D and test innovations, including advanced AWG configurations and high-bandwidth analysis tools, are helping push past the barriers of symbol rate and signal integrity. These solutions bridge the gap between theoretical performance and real-world implementation, enabling the development and validation of interconnects capable of supporting 1.6T and 3.2T system architectures.

The road to 448 Gbps and beyond is not just about faster links — it's about unlocking the infrastructure needed to power the next wave of AI, cloud, and high-performance computing.

Keysight enables innovators to push the boundaries of engineering by quickly solving design, emulation, and test challenges to create the best product experiences. Start your innovation journey at www.keysight.com.

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