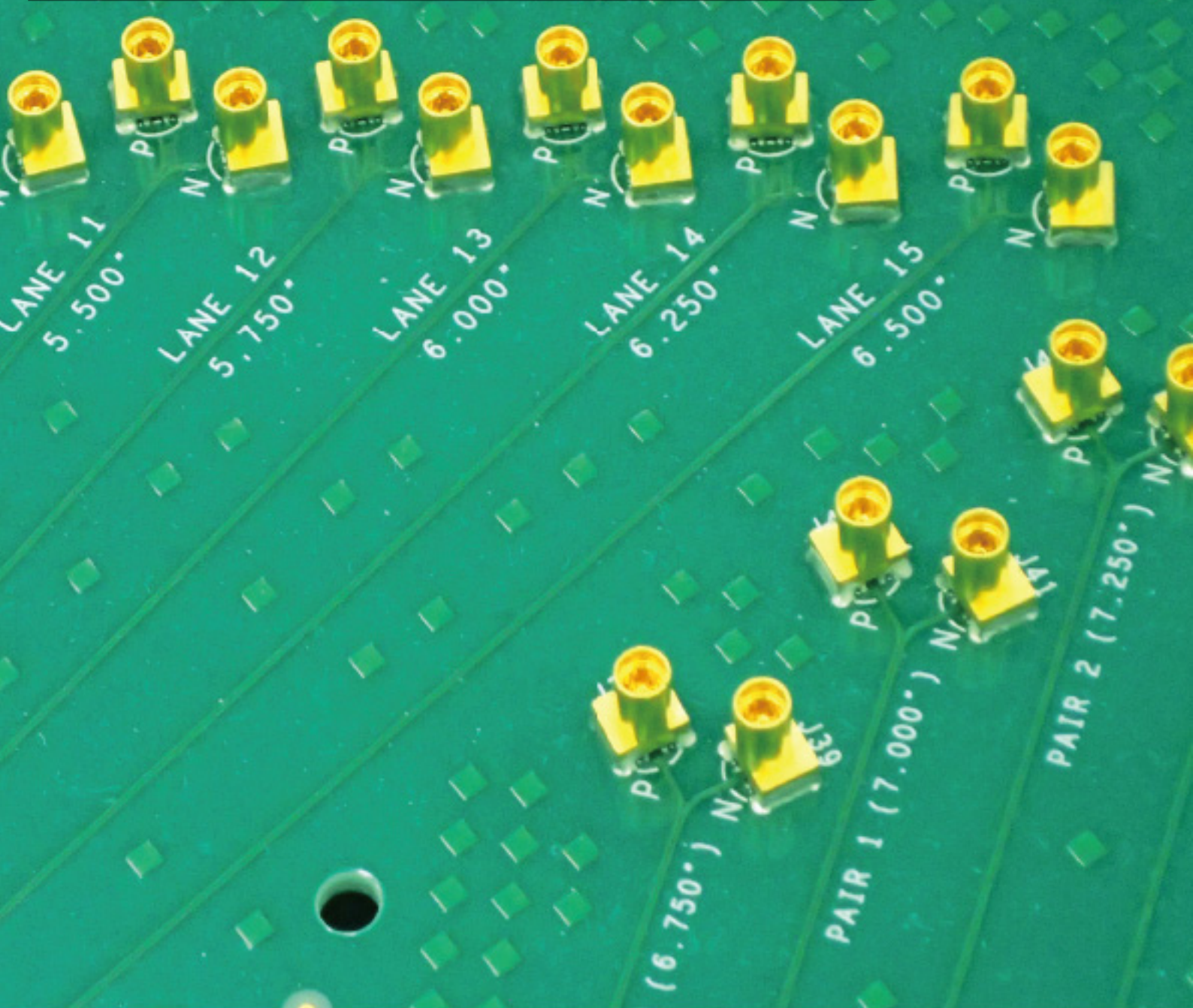




PAM4 Demands Accurate S-parameters



1. Introduction

With the increase in high-speed serial data rates to 200 Gb/s and greater, conventional logic-emulating Non-Return-to-Zero (NRZ) signaling is replaced by a 4-level Pulse Amplitude Modulation (PAM4) scheme that requires only half the bandwidth to transmit the same payload as the equivalent NRZ signal. Note that PAM4 requires precise measurements to ensure accuracy. Design verification must occur before production, and simulations and measurements must align on a point-by-point basis. Since the Signal-to-Noise Ratio (SNR) for PAM4 is approximately 10 dB weaker than that of NRZ, qualitative agreement is insufficient. Rather, accurate S-parameter measurements are essential for ensuring the reliability of the simulation accuracy and channel evaluation.

This document discusses the impact of PAM4 on signal integrity and the challenges faced by test and design engineers responsible for the Serializer/Deserializer (SERDES) components, interconnects, backplanes, cables, connectors, circuits, and complete systems. The next section introduces the details of PAM4. Section 3 will discuss S-parameters in terms of inter-symbol interference and crosstalk. Section 4 gives a short introduction to IBIS-AMI simulation, the keys to creating models that you can trust, and the use of S-parameters to evaluate equalization schemes, de-embed test fixtures from signal integrity analyses, and measure the channel operating margin. Section 5 concludes with guidance on how to achieve Vector Network Analyzer (VNA)-quality S-parameter measurements on a tight budget. This document will help you understand how to use scattering (S)-parameters, how to consider channel response and crosstalk in terms of S-parameters, and where problems that may be caused by inaccurate measurement of the S-parameters are most likely to occur.

2. NRZ and PAM4 Bandwidth Demands at High Data Rates

Conventional, logic-emulating NRZ signaling has reached a bandwidth limitation caused by a high insertion loss, which can be 35 dB or even more for a typical trace at next-generation data rates.

The limits of NRZ signaling were first approached with 100 GbE (Gigabit Ethernet) with its 25-Gb/s to 28-Gb/s signals on 4 channels that combine to give 100-Gb/s data payloads. Since each bit period covers half a cycle, the fundamental frequency of a 26.6-Gb/s NRZ signal is 13.3 GHz. The insertion loss of conventional copper traces on a standard flame-retardant, type-4 printed circuit board (FR-4 PCB) typically falls at about 10 dB/decade of frequency, depending on its length. Considering the effects of the connectors, vias, ball grid arrays (BGAs), and various impedance mismatches in a real circuit, the resulting frequency response exhibits both resonant peaks and absorption valleys, as illustrated in Figure 1.

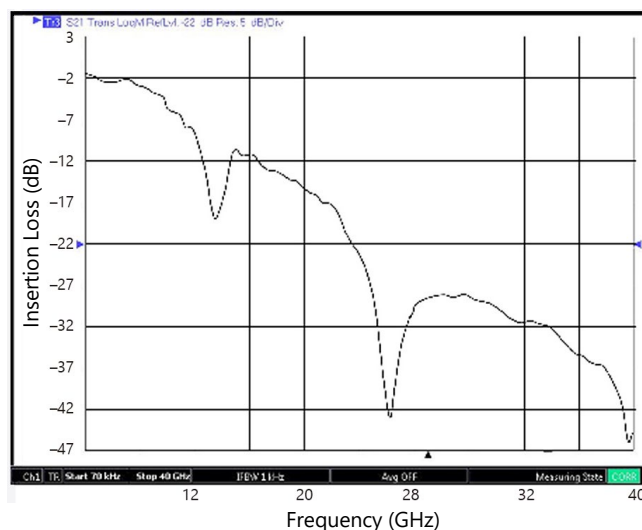


Figure 1 Frequency Response of a Typical 100 GbE Channel, $S_{dd21}(f)$ or IL (f).

With a 20-dB loss at the 13.3-GHz fundamental harmonic, the channel depicted in Figure 1 can function with NRZ signaling at a Bit Error Rate (BER) of less than 1E-12, which satisfies the 100 GbE standard. However, this is achievable only if equalization is optimally tuned at both the transmitter and receiver.

At 53 Gb/s (the channel rate required by 400 GbE), as shown in Figure 2, the fundamental frequency is 26.5 GHz. At this frequency, the channel experiences over 40 dB of loss. In the presence of crosstalk, no amount of equalization can pull the NRZ signals out of this noise.

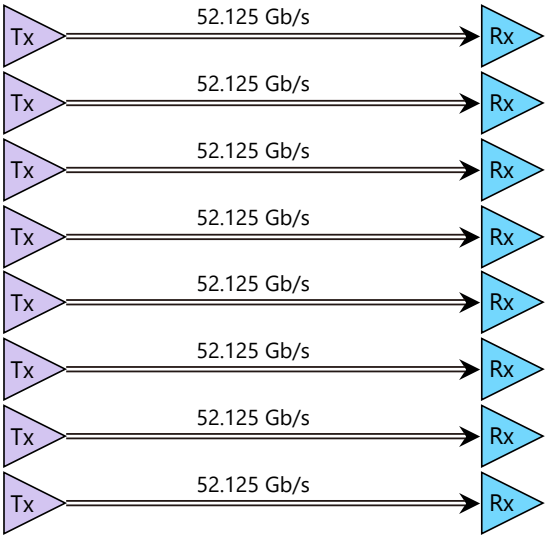


Figure 2 Diagram of the 8×53 Gb/s Version of 400 GbE.

The solution is to pack twice as many bits into each transmitted symbol. Where NRZ encodes a single bit, either 0 or 1, in each symbol, PAM4 uses four separate levels to encode two bits — 00, 01, 10, 11 — in each symbol, as shown in Figure 3. By encoding two bits per symbol, a 53-Gb/s signal can be transmitted at 26.5 Gbaud with a fundamental frequency (Nyquist frequency) of 13.25 GHz.

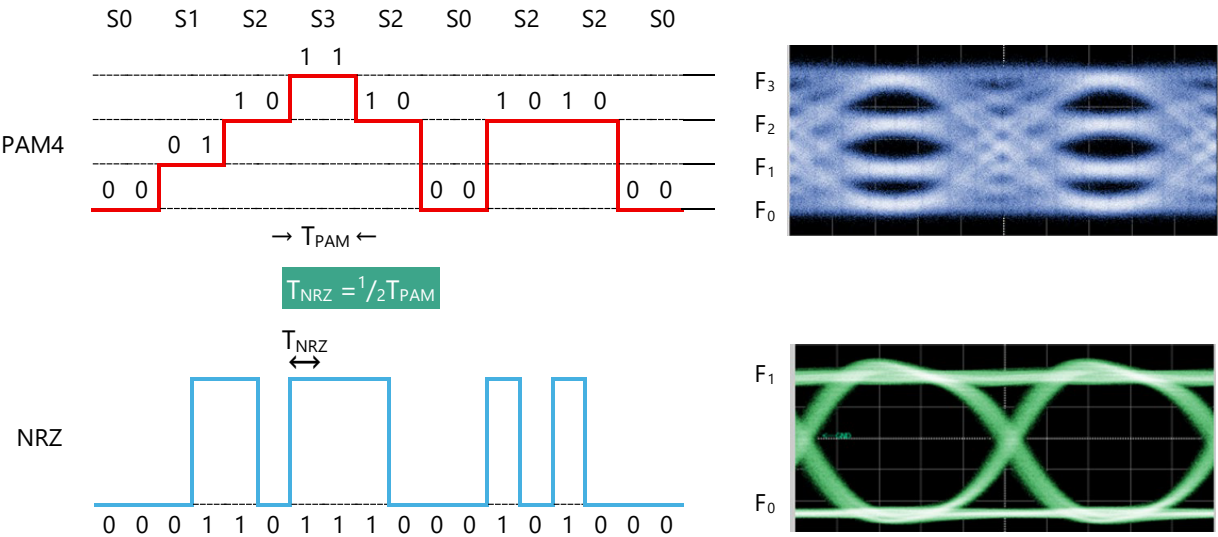


Figure 3 NRZ Waveform Compared to PAM4.

2.1 PAM4 Complexity

PAM4 reduces loss to manageable levels. However, it introduces a significant increase in signal complexity: 12 distinct symbol transitions compared to NRZ, which has only three eye diagrams per bit period. Additionally, the Signal-to-Noise Ratio (SNR) is degraded by at least 9 dB.

PAM4 also introduces potential nonlinearities that have not been faced in the past. The variations in the heights of the three eye openings are called “eye compression.” Similarly, a “timing skew” occurs when the centers of the three eyes are misaligned. Figure 4 shows an eye diagram that exhibits both eye compression and timing skew.

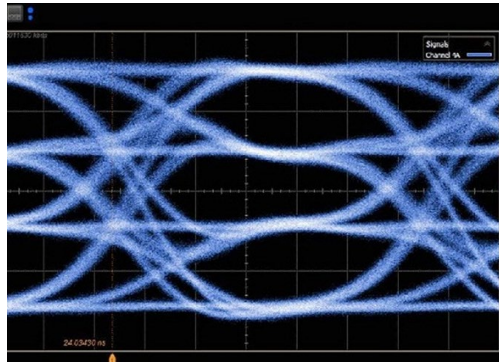


Figure 4 Potential PAM4 Nonlinearities: (a) Eye Compression and (b) Timing Skew.

To effectively address jitter, noise, and crosstalk, it is essential to utilize super-clean clocks, robust clock recovery circuits, and highly sensitive symbol decoders or voltage slicers. To decode the four possible symbols, three slicers are now required. Additionally, enhanced equalization techniques at both the transmitter and receiver sides are crucial to mitigate Inter-Symbol Interference (ISI) caused by the channel.

2.2 PAM4 ISI and Equalization

The frequency content of both the NRZ and PAM4 signals consists of square wave harmonics and sub-harmonics from the sequences of identical symbols. The frequency components have precisely coordinated amplitudes and phases. Consider Figure 1 again. The channel affects the amplitudes and phases of each frequency component differently. By de-correlating the frequency and phase structure, the channel causes ISI. Equalization removes ISI by inverting the channel response. Like everything else, equalization in PAM4 systems is more complicated than in NRZ systems.

Transmitter equalization, also known as emphasis or Feed-Forward Equalization (FFE), pre-distorts the signal to compensate for the gross features of the channel response. Two types of equalization are applied at the receiver: Continuous-Time Linear Equalization (CTLE) and Decision-Feedback Equalization (DFE). CTLE attenuates the low-frequency components and amplifies the high-frequency components to compensate for the channel’s low-pass nature (Figure 5).

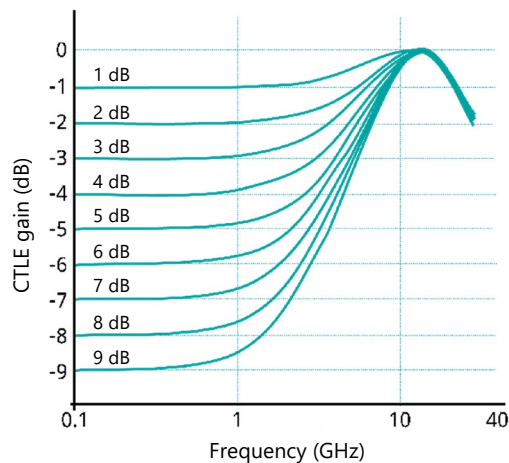


Figure 5 CTLE Frequency Response for Different Levels of Gain.

The CTLE typically precedes the clock recovery circuit in the receiver as shown in Figure 6. DFE, a type of Infinite Impulse Response (IIR) filter, feeds symbol decisions back into the decision circuit. With PAM4, which utilizes 4 symbols, the complexity of DFE increases. However, this added complexity also offers greater flexibility and opportunities for innovations that could enhance PAM4 DFE compared to its NRZ counterpart.

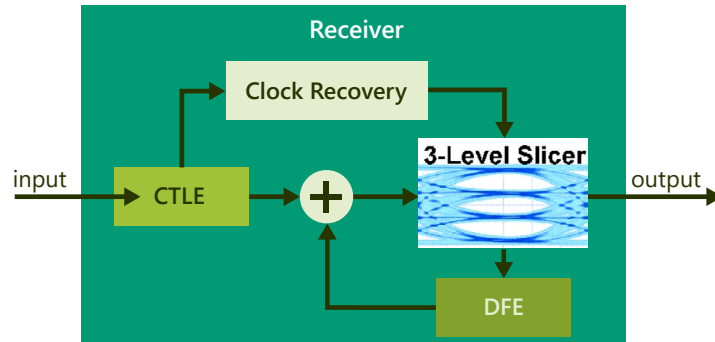


Figure 6 PAM4 Receiver.

3. Importance of Accurate S-parameters in the Development and Manufacturing of PAM4 Components and Systems

Customers' goals include optimizing and verifying designs, reducing time to market, manufacturing high-quality components, and assembling systems that perform at least as well as the required BER.

While equalization can compensate for the ISI caused by channel frequency and phase response, it causes problems in the presence of crosstalk. Crosstalk is predominantly high-frequency interference. To compensate for the low-pass channel response, transmitter emphasis and CTLE amplify high-frequency signal components. In so doing, they also amplify crosstalk noise. Since DFE operates at the symbol level, crosstalk is not affected, either way.

The parameters affecting ISI, crosstalk, and equalization present a multi-variable optimization problem. This can be thought of as a multi-dimensional design space where the goal is to identify the point at which the BER is minimized. S-parameters serve as tools to predict the combined effects of ISI, equalization, and crosstalk.

ISI and impulse response

Let's start with ISI. Figure 7 shows how a sharp impulse is affected by a channel. A perfect, infinite amplitude, infinitesimal width — Dirac delta function — impulse propagates through the channel. Different frequency components experience different losses and phase variations. The output is the "impulse response."

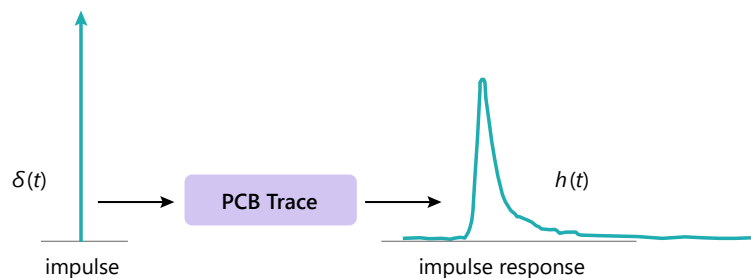


Figure 7 Impulse Response.

Every characteristic of the channel is encoded in the impulse response: every impedance variation, all the reflections and losses, however tiny. The impulse response is the time-domain equivalent of the frequency response. The output of any channel can be calculated by convolving the impulse response with the input:

$$R_X(t) = \int T_X(t') h(t - t') dt'$$

where $h(t)$ is the impulse response, $T_X(t)$ is the transmitted signal, and $R_X(t)$ is the received signal. Think of the impulse response as being a smearing function: $h(t)$ smears every symbol in the transmitted waveform, causing them to overlap and, as a result, interfere with each other.

Of course, an impulse signal with infinite bandwidth and infinitesimal width cannot be produced. An alternative approach involves using a step function rather than an impulse, since the derivative of an ideal, zero-rise-time step is a Dirac delta function. By transmitting a small rise-time step and measuring the transmitted and reflected responses, the impulse response can be approximated. This technique is used in Time Domain Transmission/Time Domain Reflectometry (TDT/TDR) measurements. Since TDT/TDR are broadband measurements and the noise of an instrument is proportional to the instrument bandwidth, they tend to have a high noise floor and a low dynamic range. This can act as an effective analysis tool for low-rate, low-loss NRZ systems. Unfortunately, this is too noisy and lacks the dynamic range necessary for high-data-rate, high-loss PAM4 analysis.

There is, however, a better approach. The wide, flat frequency spectrum from DC to infinite frequency makes an ideal impulse response, as shown in Figure 8.

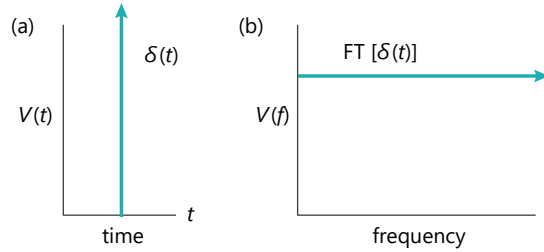


Figure 8 Perfect Impulse Response, Dirac Delta Function, in (a) the Time Domain, and (b) the Frequency Domain.

Creating a signal that closely matches the desired spectrum is possible, even if generating a perfect impulse or step remains unattainable. It's fairly simple to generate sinusoidal waveforms from very low to very high frequencies. Instead of measuring the impulse response in the time domain, we can measure it at one frequency at a time in the frequency domain.

VNAs characterize channels with unprecedented accuracy by transmitting a series of sine waves and measuring the resulting signals and their reflections. VNAs build up the frequency-domain equivalent of the impulse response one frequency at a time. Since their measurements are performed in sequential steps, each in a narrow intermediate frequency bandwidth, (as low as 1 Hz in the case of Anritsu's VectorStar VNA), VNAs have extremely low noise floors (typically -100 dBm), high bandwidths (up to 220 GHz in a single coaxial connection), and a broad dynamic range (over 100 dB).

In the frequency domain, a convolution reduces to a simple product:

$$R_x(f) = T_x(f) H(f)$$

Where $T_x(f)$ and $R_x(f)$ are the frequency-domain expressions of the transmitted and received signals, respectively, and $H(f)$ is the transfer function, the frequency domain equivalent of the impulse response.

Once we've measured an accurate transfer function, $H(f)$, we can transform it to the time domain and get the impulse response, $h(t)$.

Introduction to S-parameters

S-parameters describe how a signal is "scattered" by an object. For us, the object is a transmission channel. The S-parameters are functions of both amplitude and phase over frequency.

A two-port network, like that shown in Figure 9, is characterized by a 2×2 matrix of S-parameters. The channel frequency response in Figure 1 is also called the insertion loss as a function of frequency, $IL(f)$, and is given by the magnitude of an S-parameter, $|S_{21}|$.

The return loss as a function of frequency, $RL(f)$, is given by $|S_{11}|$.

In addition to being straightforward to measure accurately, the S-parameters account for all the partially reflected and transmitted signals that bounce around a network, including crosstalk. Since they're matrices, they fit perfectly in models.

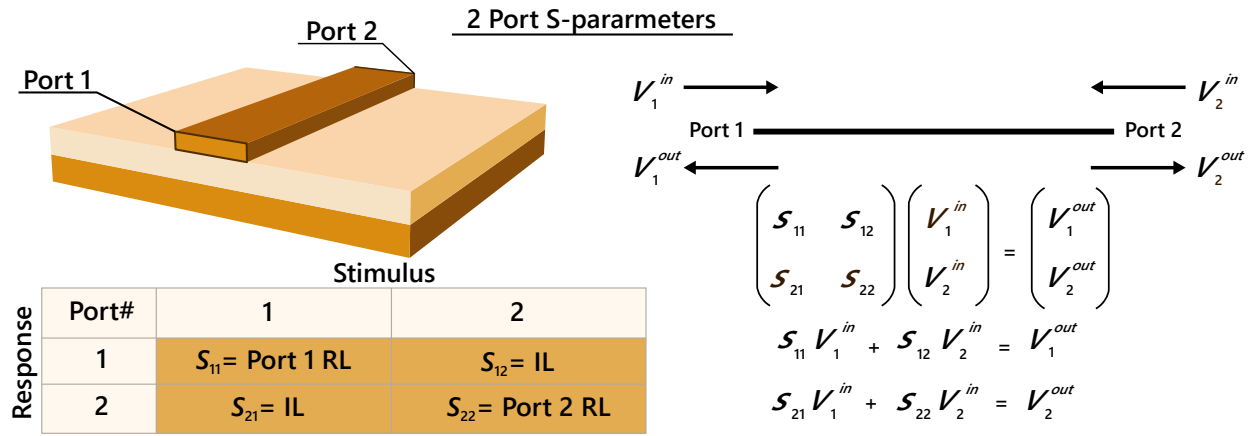


Figure 9 Two-Port Network and Its S-parameters.

Crosstalk S-parameters

Figure 10 shows two channels, that is, a “4-port network” in S-parameter terms: two input ports plus two output ports. Consider S_{23} , the signal emerging from the right side of the top channel, port 2, due to a signal being input to port 3, the left side of the bottom channel. Since port 3 is on the far side of the network from port 2, S_{23} gives the Far-End Crosstalk (FEXT) phase and frequency response. Similarly, S_{24} parameterizes the Near-End Crosstalk (NEXT) response of the output on port 2 due to a signal being input to port 4.

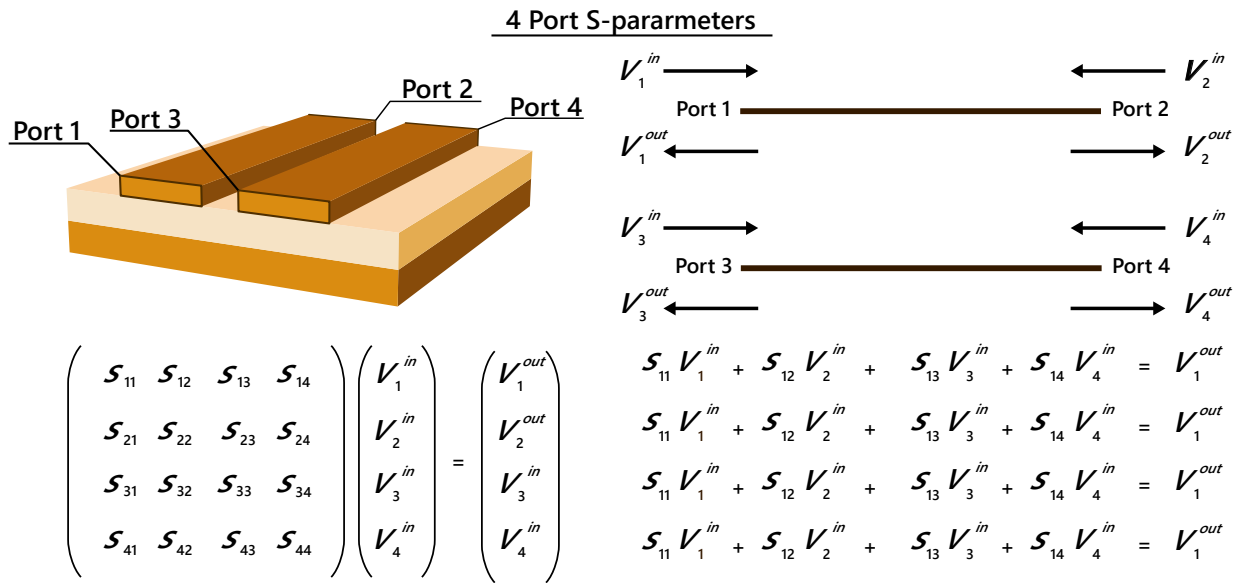


Figure 10 Four-Port Network and Its S-parameters.

Notice that NEXT and FEXT calculated from the S-parameters include all multiple reflections, not just the forward wave contribution to FEXT and the reverse wave contribution to NEXT, but the net signal that emerges from port 2 due to the signals being input to port 3 for FEXT and port 4 for NEXT.

Differential S-parameters

Differential channels consist of pairs of conductors with minimal skew. Differential pairs reduce the crosstalk both radiated by and picked up by a channel. The S-parameters for a differential channel are derived from the two-channel system by transforming the simple 4-port matrix to a combination of differential and common-mode S-parameters. Differential mode signals have a signal on one trace and its opposite on the other. Common-mode signals have identical signals on both traces. Any signal can be composed of a combination of differential and common-mode signals. The transformation is equivalent to a coordinate rotation in geometry: no information is gained or lost; it is merely rotated. The resulting S matrix is shown in Figure 11.

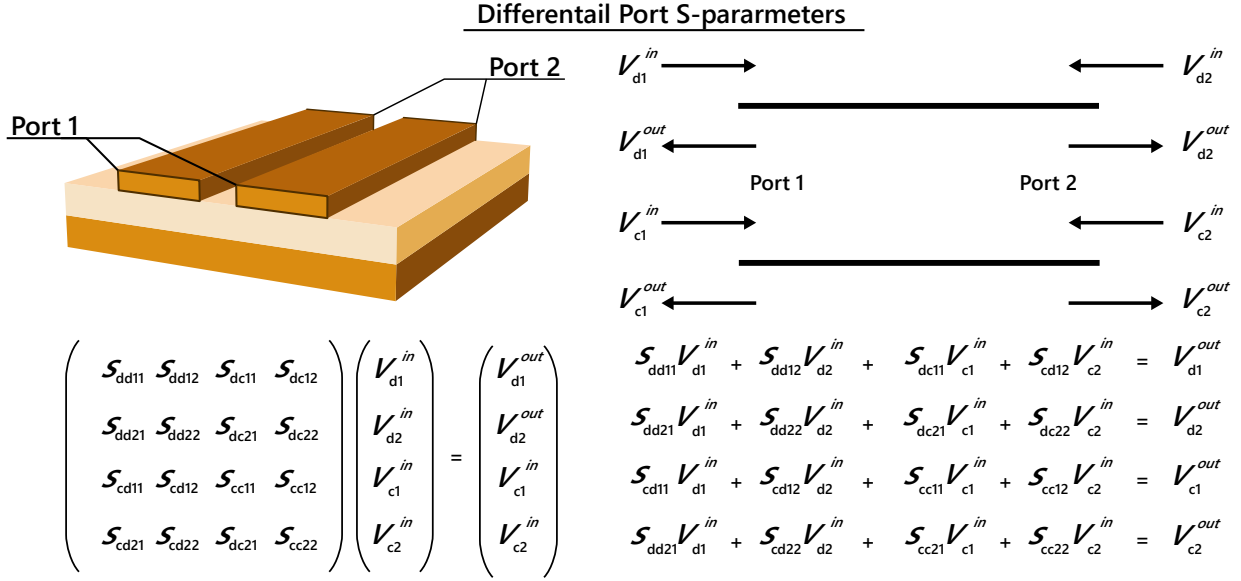


Figure 11 Differential Channel and its S-parameters.

The transformed S-parameter matrix consists of four sectors. The top-left 2×2 submatrix consists of purely differential elements, while the bottom-right 2×2 submatrix consists of purely common-mode elements. For example, S_{dd21} describes the response of a differential signal that emerges on the right, port-pair 2, from a differential signal transmitted on the left, port-pair 1. Similarly, S_{cc21} describes the transmission properties of the pair of conductors for common-mode signals.

The top-right and bottom-left 2×2 submatrices consist of mixed terms. For example, S_{dc21} describes the differential response of the channel at port-pair 2 due to a common-mode signal being input to port-pair 1.

Since crosstalk is picked up by both differential lines, it is primarily a common-mode signal. A key feature of differential signaling is the ability to cancel common-mode signals at the receiver. The Common Mode Rejection Ratio (CMRR) is measured in decibels and is given by:

$$CMRR = 20 \log \frac{|S_{dd21}|}{|S_{cc21}|}$$

S-parameter requirements of interconnects

Many standards specify masks for the channel S-parameters to assure minimum acceptable performance. Figure 12 shows the PAM4 masks for insertion loss, differential return loss, and differential-common mode conversion.

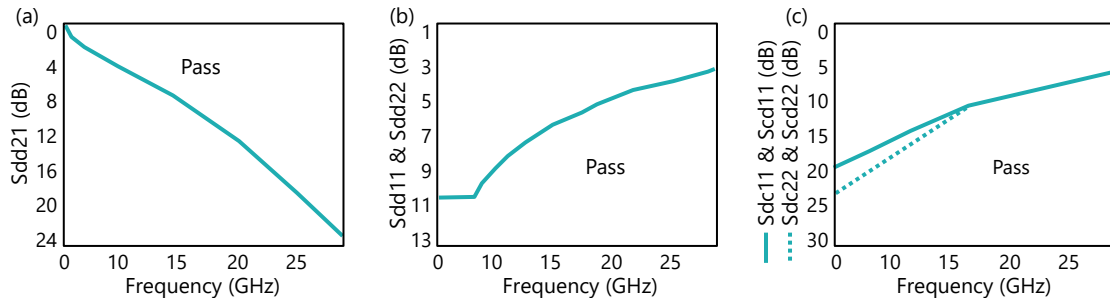


Figure 12 Examples of S-parameter Mask Requirements: (a) Channel Insertion Loss, (b) Return Loss, (c) Differential to Common and Common to Differential Mode Conversion.

S-parameters for a multi-channel system

In a 400-GbE system that consists of eight separate differential channels operating at 53 Gb/s (Figure 2), the entire system is described by a 32×32 S-parameter matrix. It includes every pair-wise crosstalk response. We would seldom need to look at the full matrix, especially given that it's made of 1024 separate complex functions. However, by plotting the magnitudes of specific elements, we can learn a great deal about how a system will perform, the balance of crosstalk and insertion loss that it can tolerate, and the degree to which our equalization schemes will be challenged.

Figure 13 shows the insertion loss, return loss, NEXT, and FEXT for a differential channel in a two-channel differential system.

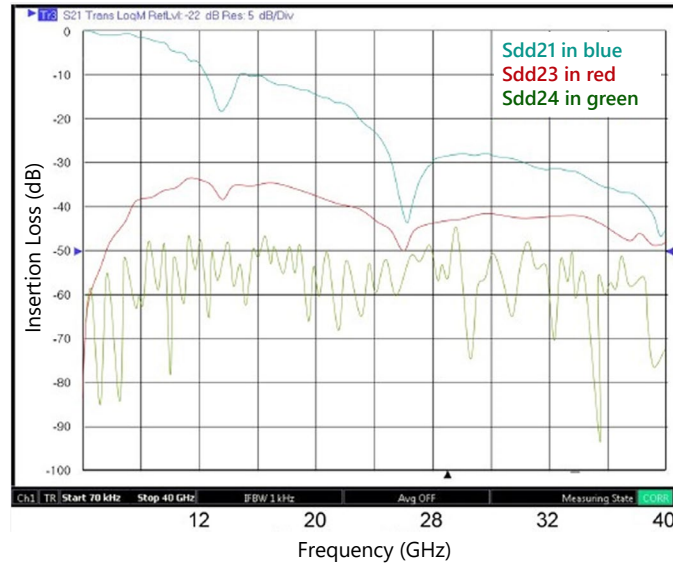


Figure 13 S_{dd21} , S_{dd24} (NEXT), and S_{dd23} (FEXT).

4. Modeling and Simulation of SERDES, Interconnects, and Circuits

The use of models to optimize and verify designs radically reduces cost and development time. By modeling a system, we can find the optimum ISI-crosstalk tradeoff in the huge design space that includes the number of transmitter emphasis and DFE taps and CTLE gain, plus differential pair coupling, channel spacing, and all the other circuit design considerations like reference planes, via locations, coupling capacitors, etc.

To model the eye diagrams, eye height, and width for each of PAM4's three eye diagrams and the Symbol Error Rate (SER) and BER performance of each design, it is necessary to determine the response of a system to millions of PAM4 symbols.

4.1 Essentials of IBIS-AMI Modeling

IBIS-AMI (Input/Output Buffer Information Specification-Algorithmic Modeling Interface) models integrate analog simulation with algorithm calculations that run fast enough for designers to experiment with multiple design variations.

IBIS defines the interface between ASCII files that describe system components and simulation platforms. "Touchstone" files contain the model's network parameters. S-parameters are stored in ASCII Touchstone files with the extension ".sNp", where N represents the number of ports. For example, the S-parameters of a single differential channel are saved as ".s4p", while those of the eight-channel 400 GbE, 8×26.6 -Gbaud PAM4 topology are saved as "<filename>.s32p".

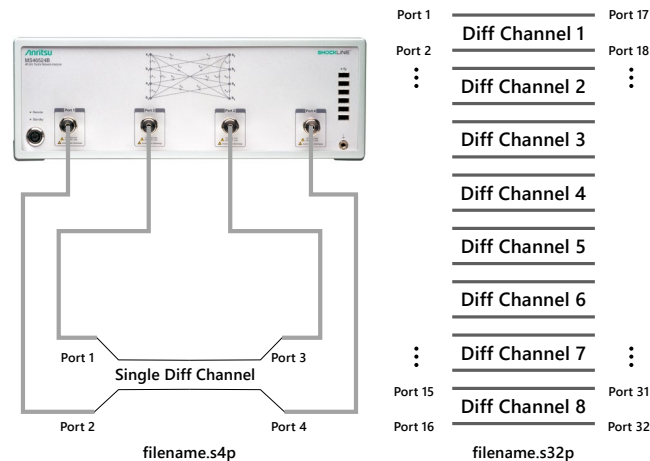


Figure 14 Example Mapping of Ports to Differential Channels.

AMI extends IBIS so that algorithm-driven SERDES subsystems like clock recovery, CTLE, DFE, and symbol decoding can be tested. Other IBIS-AMI input files include the symbol scheme, PAM4 or NRZ, the baud rate, signal characteristics like voltage levels, rise and fall times, and the data pattern. Many IC manufacturers provide IBIS models for their components.

IBIS-AMI models allow us to analyze performance in the time and frequency domains at any point from the transmitter to the interconnect and inside the receiver. For example, you can look at eye diagrams before and after CTLE and/or DFE.

Two categories of IBIS-AMI modeling provide different insights. The "statistical flow" processing mode assumes Linear Time Invariant (LTI) behavior. While statistical flow offers quick, high-statistics results, it's not capable of predicting nonlinear problems like voltage compression and timing skew that can plague PAM4 systems. The "bit-by-bit" mode is considerably slower, but it can simulate nonlinearities.

Since IBIS-AMI is standardized, Anritsu's "sNp" files can be used seamlessly with any IBIS-based Electronic Design Automation (EDA) simulator. Anritsu's VNAs can be purchased with optional signal integrity applications. Anritsu's VectorStar VNAs can perform live updating of eye diagram simulations from S-parameter data on a sweep-by-sweep basis (Option 047). Anritsu's ShockLine VNAs have Advanced Time Domain software (Option 022), which can post-process S-parameter files to do eye diagram simulations as well as perform signal integrity analysis from S-parameter files.

4.2 IBIS-AMI Evaluation of Transmitter and Receiver Equalization Schemes

Since eye-closure due to ISI varies widely for different sequences of symbols, we need large statistical samples to evaluate equalization schemes. Fortunately, interconnects are passive LTI systems, so we can use statistical flow IBIS-AMI models.

Clock recovery presents a challenge because the clock circuit derives the data rate clock used to time the logic decision circuit from the edges in the PAM4 signal. With four symbol levels, those edges are not as well defined as in NRZ systems, and nonlinear timing skew aggravates the problem. A bit-by-bit IBIS-AMI model should be used to check the accuracy of the clock-timing in the equivalent statistical flow model. The DFE performance relies on the accuracy of the four-level symbol decoder. If there's a timing skew, the DFE taps derived from the statistical flow model must be questioned and should be confirmed with a bit-by-bit model. With four different symbols to feed back, tuning DFE is more complicated for PAM4 than NRZ.

Most first-generation PAM4 symbol decoders consist of three synchronized voltage slicers, each with its slice threshold: lower, middle, upper. In IBIS-AMI, we can offset the relative timing of each slicer to determine whether a more flexible receiver is necessary for a given transmitter/interconnect/receiver combination.

4.3 Accurate Models Require Accurate S-parameters

The accuracy of an IBIS-AMI model depends on the accuracy of the “sNp” input file. A few simple concepts will help you understand the strengths and weaknesses of S-parameter measurements.

Frequency Resolution and Aliasing

VNAs make the most accurate S-parameter measurements possible, but the measurements are made at discrete frequencies. Accurate modeling requires high-resolution S-parameters, so the step-size, Δf , between adjacent S-parameter frequency measurements should be small. Another reason for using small spacing has to do with aliasing.

When a discrete function is transformed from the frequency domain to the time domain, the time domain function becomes periodic: It repeats, or aliases, in time intervals called the alias-free range, $T_{alias} = 1/(2\Delta f)$. If the time delay of the channel is $T_{channel}$, the alias-free range must be at least $T_{alias} > T_{channel}$, which translates to a step size $\Delta f < 1/(2T_{channel})$. To account for impedance mismatches that could cause multi-path effects, the frequency step size should include at least one point per 90 degrees of return loss phase angle change to assure accurate interpolation; the maximum frequency step size should be $\Delta f \leq 1/(8T_{channel})$.

Causality

The biggest potential weakness associated with transforming frequency-domain measurements to the time domain stems from the limited bandwidth of the measurement equipment.

The Fourier transform from frequency to time requires integration over frequencies from 0 to infinity, that is, from DC to very high frequencies. Since the frequency content of a real PAM4 signal rarely exceeds the fifth harmonic, $5/2$ fbaud, where fbaud is the baud rate and $1/2$ fbaud is the fundamental, we can approximate the upper integrand, $\infty \approx 5/2$ fbaud or larger. The main issue arises at the bottom end. Since we can't generate a DC sine wave, we can't measure the S-parameters down to DC: the DC limit of the S-parameters must be extrapolated. The best that we can do is to use equipment that gets as close to DC as possible.

High start frequencies cause causality problems that give the appearance of effects preceding their causes, like an output that occurs before its input, and convergence problems in the transformation to the time domain. Anritsu VNAs reduce the causality and convergence risks by reaching down to the lowest frequency in the industry.

Anritsu's VectorStar ME7838x series broadband VNAs offer the widest single sweep coverage from the lowest start frequency of 70 kHz to the highest stop frequency of 220 GHz. This industry-leading, widest single-sweep coverage ensures that DC extrapolation errors and causality issues are minimized, allowing your simulations to match reality.

Reciprocity

The S-parameters of passive devices are reciprocal; for example, S_{12} should be the same as S_{21} in both phase and magnitude.

S-parameters measured on VNAs rarely suffer from these “reciprocity” problems. One way to estimate the uncertainty of S-parameter measurements is to compare reciprocal S-parameters. If the uncertainty is high, you may need to recalibrate.

Reciprocity is a much greater concern for TDT/TDR-based S-parameters. In addition to their timebase jitter and noise problems, the fast rise-time step voltage used by TDT/TDR equipment can cause synchronization problems in both the forward and reverse directions.

Passivity

Passive devices like interconnects shouldn't have any gain, but gain can appear when the receiver is saturated. It's easy to eliminate passivity problems when you measure S-parameters on a VNA. VNAs are precise instruments that require careful calibration.

Passivity problems can be eliminated simply by exercising good lab techniques. Check that the VNA receivers are not compressed during calibration and measurement, and that all the connectors are in good condition and tightened to the proper torque, and verify that any cables used in the measurement are in good condition and are properly de-embedded.

4.4 De-embedding and Embedding

S-parameters can also be used to remove the effects of cables, connectors, and traces from measurements. The process is called de-embedding. For example, assume we are interested in how a signal looks at the test point in Figure 15. If we measure the S-parameters of everything between the test equipment and the compliance point, we can “de-embed” the effect of the test fixture and reveal how the signal appears at the compliance point.

Anritsu VectorStar and ShockLine VNAs come with advanced de-embedding network extraction software. Most high-bandwidth oscilloscopes can be purchased with de-embedding software compatible with Anritsu's sNp files.

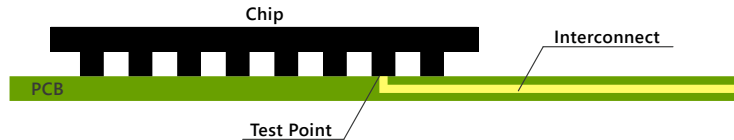


Figure 15 The Test Fixture must be De-embedded From Measurements so that we can evaluate the signal at the compliance point.

De-embedding requires that the S-parameters be measured with a dynamic range that well exceeds the test fixture's loss profile; each de-embedded element brings the measurement closer to the noise floor. With 100+ dB of dynamic range, Anritsu VNAs can de-embed quite long backplanes, cables, and traces.

Embedding is the process of adding the frequency response of a network element to a measurement. Embedding is useful for including the effects of internal components like equalizers and clock recovery to visualize a signal inside a SERDES.

4.5 Accurate COM Requires Accurate S-parameters

At high data rates, we can't reasonably expect open eye diagrams at the receiver, so we need sophisticated tools to analyze signal quality. The Channel Operating Margin (COM) is a signal-to-noise-like quantity that combines jitter, noise, crosstalk, and ISI, plus the effects of equalization, into a single figure. It gives us a measure of the effective SNR at the receiver input.

Measuring COM is an involved process based on S-parameters. The differential S-parameters of the channel, Sdd21, are used to calculate the ISI signal impairment and the extent to which it can be removed by equalization. The resulting signal amplitude is given by A_s .

FEXT is calculated from the crosstalk elements of the system S-parameters. Along with crosstalk and the remaining effects of ISI after equalization, the transmitter distortion, random jitter, and noise are all combined and used to estimate the vertical eye closure defined for a specified SER. An. COM is the ratio of the signal amplitude to the vertical eye closure.

$$COM = 20 \log \frac{A_s}{A_{ni}}$$

The use of COM high-speed standards permits design flexibility. Most standards require $COM > 3$ dB.

Since COM neglects common mode noise and NEXT approximates the interaction of equalization and crosstalk, it's not a substitute for a proper model.

5. PAM4 Analysis Requires VNA Measurements

The introduction of PAM4 signaling adds complexity to the design and testing of high-speed components and systems at every stage, from design and development through to manufacturing. Accurate S-parameter measurements, which are essential for key evaluations, can only be obtained using VNAs. Since VNAs are precision instruments that represent a significant investment, it is crucial to select equipment that best meets your needs.

Anritsu offers a comprehensive range of VNAs, including the ultra-high-performance VectorStar ME7838x4 Series of 4-port VNAs with bandwidths up to 220 GHz, as well as the more economical ShockLine VNAs with 2-4 ports, available in various bandwidth configurations.

SERDES and interconnect design will usually require a full-featured VectorStar VNA. For system design and development, a 4-port ShockLine Performance VNA, MS4652xB, is probably more than adequate, while for verification and manufacture, a ShockLine Economy VNA will likely be all that you need. Table 1 lists the important features of PAM4 applications for two VNA models; the VectorStar and ShockLine families of VNAs offer many other configurations. Table 1 is merely indicative of the available models. The Anritsu field team can provide the guidance you need to make the best choice for your applications and budget.

Table 1 Features of a VectorStar and a ShockLine Configuration That are Important for PAM4 Signalling.

	VECTORSTAR ME7838A4	SHOCKLINE MS46524B
Bandwidth	125 GHz	43.5 GHz
Typical Dynamic Range	110 dB	125 dB
Typical Noise Floor	-100 dBm	-115 dBm
Minimum Frequency	70 kHz	50 kHz
Number of Measurement Points	100,000	20,000

5.1 Advantages of VNA over TDT/TDR

We've already discussed several reasons why VNA measurements are more accurate in both the time and frequency domains than TDT/TDR measurements:

- Noise floor:

The noise floor of any measurement is proportional to the bandwidth over which the quantity is measured. By converting a step response to an impulse response, TDT/TDR systems make measurements over 35+ GHz, whereas VNAs make many narrowband measurements, each over tens of hertz, making TDT/TDR measurement noise floors inherently higher.

- Dynamic range:

The typical dynamic range of a TDT/TDR test set is around 40 dB. The dynamic range of Anritsu's VectorStar and ShockLine VNAs is typically around 100 dB, a million times that of TDT/TDR.

- Reciprocity:

With their short rise-time voltage steps and intrinsic timebase uncertainty, TDT/TDR measurements suffer synchronization problems that can lead to inconsistent S-parameters and make it impossible to model PAM4 problems like timing skew.

While TDT/TDR can be used to measure crosstalk S-parameters, at least in principle, their limited dynamic range and high noise floors make it difficult for them to access the weak coupling between victims and aggressors with any accuracy. Without accurate NEXT and FEXT S-parameters, we can't create accurate IBIS-AMI models or make COM measurements.

5.2 The Most Accurate and Economical VNAs on the Market

Since PAM4 signaling is used at high data rates in high-loss environments, the dynamic range and accuracy of a VNA are essential. The VectorStar and ShockLine VNAs offer typical dynamic ranges over 100 dB and noise floors below -70 dBm. Figure 16 shows Anritsu's VectorStar ME7838D dynamic range from 70 kHz to 145 GHz.

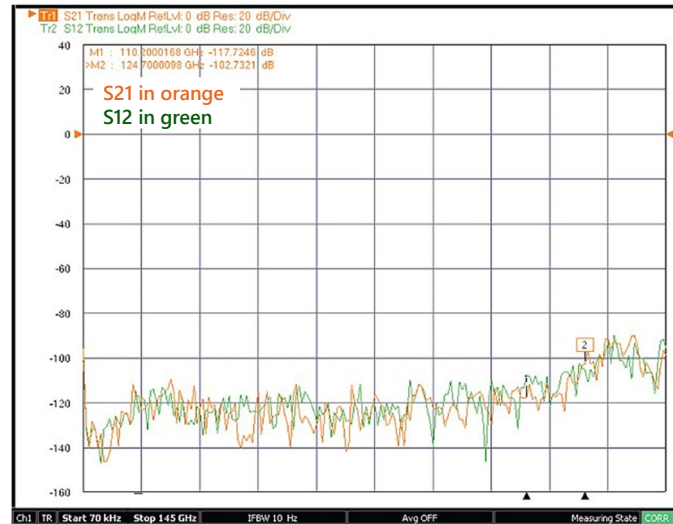


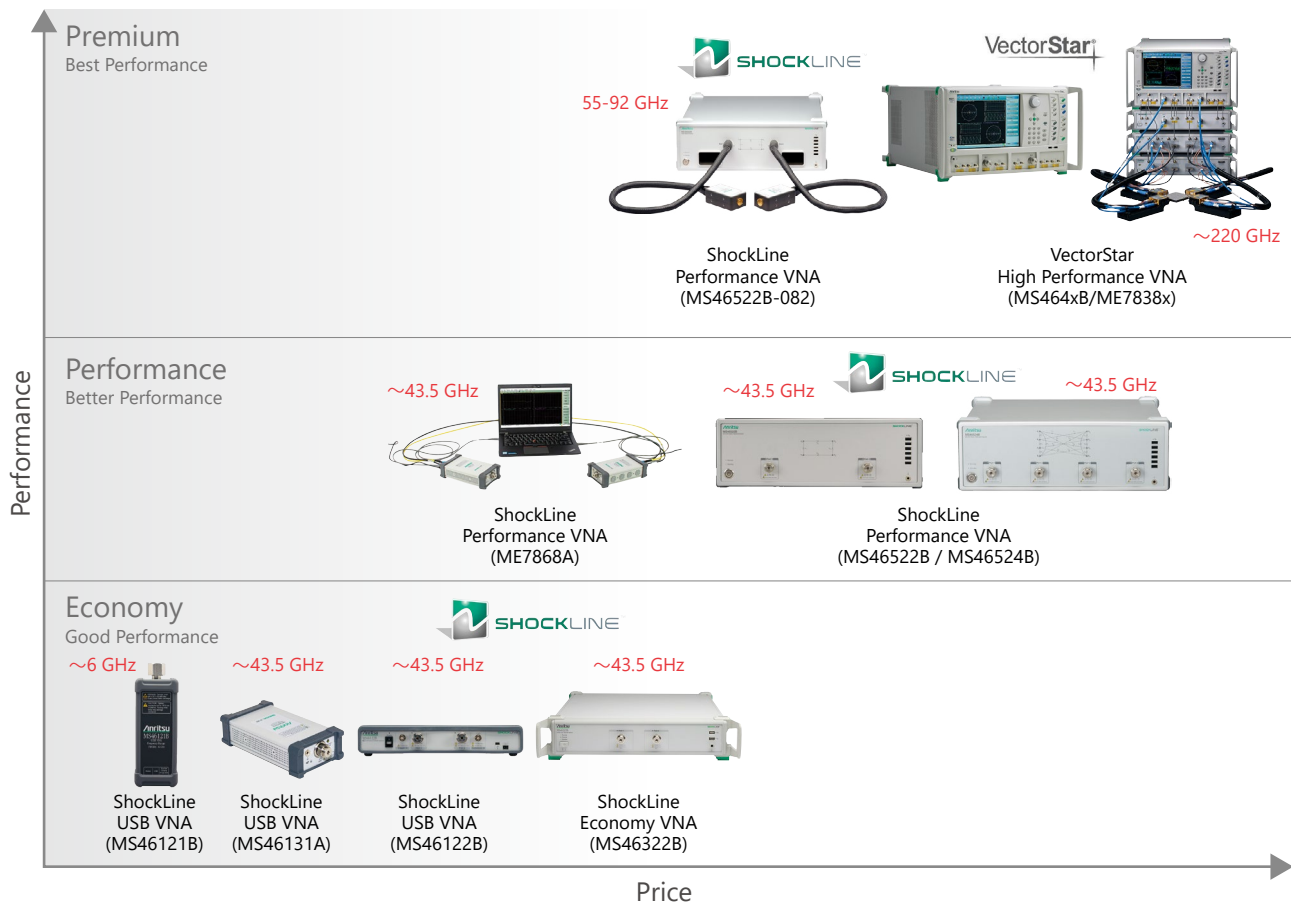
Figure 16 Measurement of the VectorStar ME7838D dynamic range from 70 kHz to 145 GHz.

VectorStar VNAs offer the best time domain measurement accuracy available. The combination of unique low-frequency coverage and up to 100,000 measurement points makes VectorStar VNAs all but immune to aliasing and causality problems. The more economical ShockLine VNAs also have excellent low-frequency coverage and up to 20,000 measurement points.

The ShockLine and VectorStar VNAs share common test software that makes it easy to verify a device with a performance VNA model on the bench, and test it with an economy model during manufacture.

Anritsu's VNA Solutions

Anritsu offers a lineup of VNAs that precisely meet a variety of measurement needs, including a compact and easy-to-use economy-type model with a single port configuration and a performance-type model with high output power, as the Shockline series. Anritsu also offers multifunctional premium-type models in the VectorStar series.



The ShockLine family of vector network analyzers (VNAs) achieves a new level of capability, flexibility, and value for signal integrity, electronic circuit board, RF, and microwave network analysis applications. ShockLine VNAs deliver excellent performance for wide band measurements from 50 kHz up to 43.5 GHz and banded E-band measurements from 55 GHz to 92 GHz. These are ideal for testing passive and many active components with general-purpose VNA requirements.

ShockLine™ 4-Port Performance Vector Network Analyzer MS46524B

The ShockLine™ MS46524B series are 4-port performance vector network analyzers (VNAs). Delivering an unprecedented level of value and performance in a multiport VNA, this series lowers the cost-of-test and speeds time-to-market in numerous test applications.

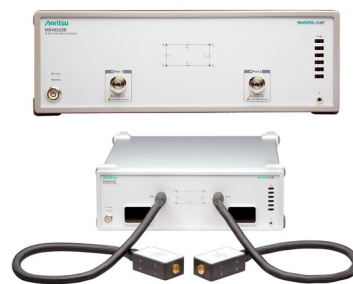
- RF and microwave VNAs are ideal for testing differential and multiport passive devices
- Available in three frequency models – 50 kHz to 8.5/20/43.5 GHz
- Delivers a great combination of speed, dynamic range, and 4-port measurement performance with an independent source per port in a space-efficient package



ShockLine™ 2-Port Performance Vector Network Analyzer MS46522B

The ShockLine™ MS46522B series Vector Network Analyzer is optimized for measuring S-parameters and time domain characteristics of passive RF and microwave devices

- Performance series of 2-port VNAs available in wide band (from 50 kHz to 8.5/20/43.5 GHz) and tethered E-band (55 to 92 GHz) models
- Ideal for passive and linear active device testing with variable output power control, fast sweep speed, high dynamic range, and wide IFBW
- ShockLine™ software supports SCPI command programming and has software driver support for the most common programming environments



Economy Vector Network Analyzer

MS46322B

Packaged in a compact 2U high rack mountable chassis, the ShockLine™ MS46322B includes an internal PC and power supply, making it self-contained and easy to integrate into rack mount test systems.

- Complete 2-port VNA packaged in a convenient 2U high chassis
- Available in three frequency models – 8/20/43.5 GHz
- Shares a common GUI and remote control interface with the rest of the ShockLine™ family, reducing switching costs to other models



Compact USB Vector Network Analyzer

MS46122B

A laptop PC-sized unit that conserves bench and test rack space, and makes it very portable and convenient to share between test locations.

- 2-port VNA packaged in a compact 1U chassis
- Available in three frequency models – 8/20/43.5 GHz
- Externally controlled via USB from a user-supplied PC running the same GUI software as the rest of the ShockLine™ family
- Data is stored only on the control PC and not in the VNA, making it great for secure environments



For further details, please visit:

<https://www.anritsu.com/en-us/test-measurement/solutions/basic-instruments/network-analyzers>