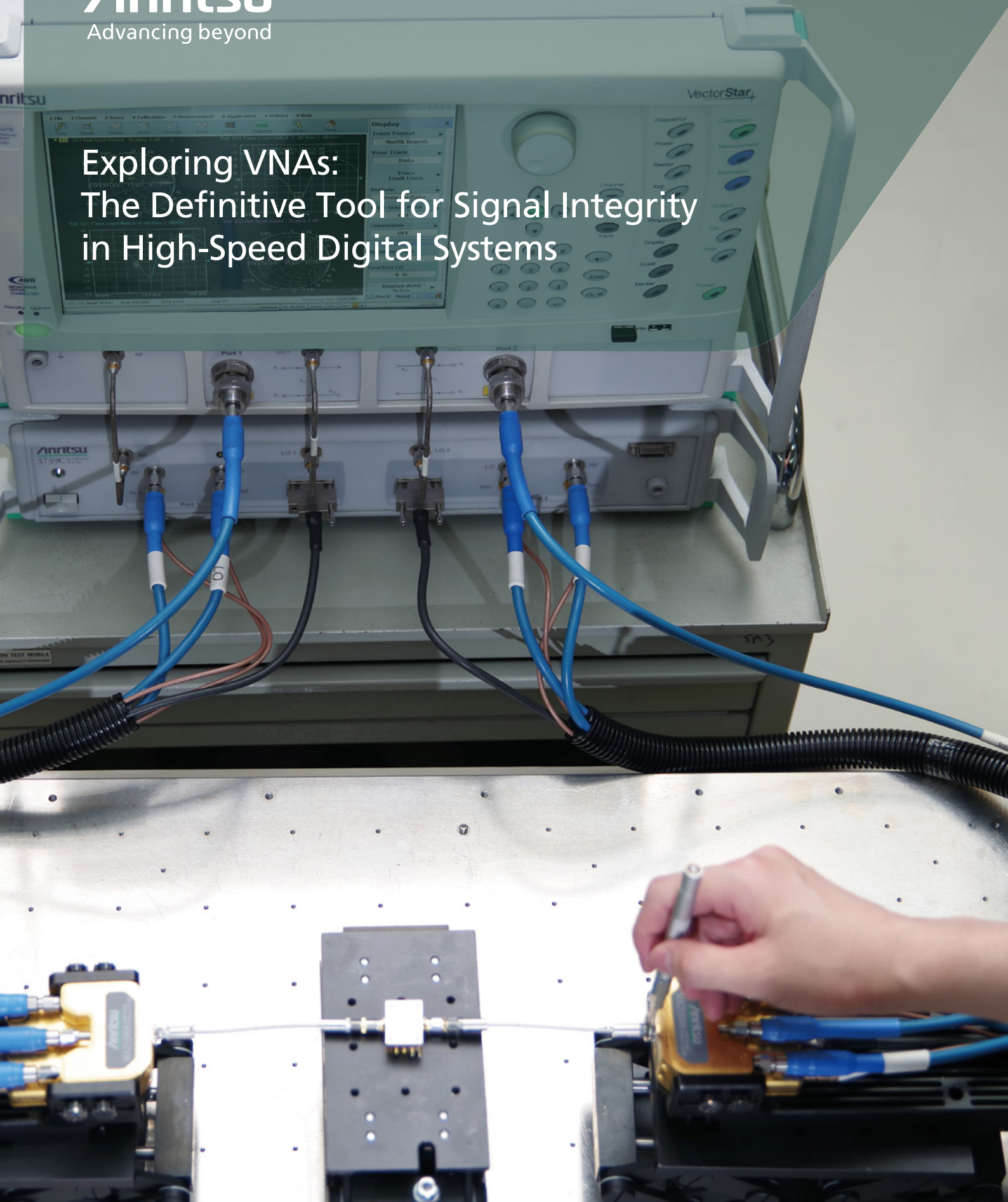


Anritsu
Advancing beyond

Exploring VNAs: The Definitive Tool for Signal Integrity in High-Speed Digital Systems



Overview

Digital signal transmission systems are increasingly demanding, requiring high-frequency handling, due to the increasing speeds in these systems. The components of these systems include chip packages, PCB traces, connectors, cables, and backplanes (hereafter "channels" in this document). The accurate design, simulation, and characterization of transmission lines demand a new set of test tools.

This document examines the role of Vector Network Analyzers (VNAs) in maintaining signal integrity in high-speed digital systems. It provides an in-depth explanation of the advantages of VNA measurements, methods for utilizing VNAs as a tool, the conversion from frequency domain to time domain, the time-domain mode of VNAs, the evaluation criteria for S-parameter quality, channel characterization, measurement frequency, network extraction, and de-embedding procedures.

VNA Measurement Advantages

VNAs can be utilized for frequency-domain measurements, serving as an alternative to the time-domain measurement results obtained through high-speed oscilloscopes, signal quality analyzers (Bit Error Rate Tester: BERT) such as MP1900A, or Time-Domain Reflectometry/Transmission instruments (TDR/TDT). Conversely, time-domain instruments generate S-parameters by applying the fast Fourier transform (FFT) to time-domain data. There are certain inherent advantages associated with time-domain instruments, particularly in terms of Dynamic Range (DR), for obtaining high-quality S-parameter measurements in the frequency domain.

Time-domain instruments are inherently broadband in nature. While this broadband characteristic can provide advantages in terms of measurement speed, it also introduces significant noise (noise power = kTB , where k is Boltzmann's constant, T is temperature in Kelvin, and B is noise bandwidth). This increases the noise floor and reduces the Signal-to-Noise (S/N) ratio. Consequently, the net effect is a reduction in the DR of the S-parameters obtained from these instruments.

On the other hand, VNAs are inherently narrowband instruments and have lower noise floors because the bandwidth-driven kTB noise is much lower. VNAs can measure an instantaneous Intermediate Frequency (IF) bandwidth of tens of Hz, which provides exceptionally high S/N ratio data and yields higher DR S-parameter measurements.

As a practical example, S-parameters provided by a typical TDR/TDT instrument generally exhibit a DR of approximately 40 dB, whereas the typical DR of S-parameters using a VNA achieves greater than 100 dB. This significant improvement in data quality is crucial when correlating measured results with simulated ones for channels for signal integrity applications.

VNAs as a Tool

VNAs are instrumental in characterizing channels by facilitating the comparison of measured S-parameters with those modeled using high-frequency electromagnetic simulation software, such as HFSS or Microwave Office®. Ensuring the acquisition of high-quality S-parameters is integral to achieving consistency between measured and simulated results; the evaluation of S-parameter quality will be discussed later in this document.

Using the time-domain mode, VNAs are useful as a troubleshooting and verification tool for defects in channels. They can also be used to probe these channel structures for actual impedance measurements of inaccessible structures, such as PCB vias, which helps detect internal cable and connector defects.

Frequency to Time-domain Transformations

Transitioning from the frequency domain to the time domain involves the use of Inverse Fourier Transformations (IFT). The general form of an IFT is expressed as follows:

$$X(t_n) \propto \sum_{k=1}^N X(f_k) e^{j2\pi f_k t_n}$$

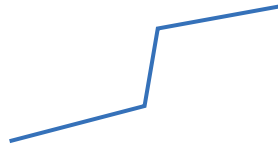
The time-domain terms are represented on the left side, while the frequency-domain terms appear on the right side of the equation. Proper care must be taken to ensure accuracy during this transformation.

Low-frequency S-parameters

The low-frequency terms (small values of f_k in the exponential) define the slowly varying time terms (t_n) in the transformation. These slowly varying time terms define the flat-top portions of the time-domain transformation and can affect how the likes of step responses and eye diagram simulations appear. Any noise or instability in these low-frequency terms will show up as noise and instability in the flat tops of time-domain transformations.

DC Value

The DC term must be approximated since a VNA cannot measure this value directly due to the coupling structures used. This DC approximation serves as a reference for integration in the transformation. If it is not correctly approximated, the time-domain step response can have a slope associated with it.



These two considerations mean that the quality of the low-frequency data and an accurately extrapolated DC point are crucial to making this time-domain transformation. This means that having high-DR, low-frequency data is vital.

Alias-Free Range

The time-domain transformation is a circular function and repeats at a value called t_{max} . This is related to the frequency step size (f_s) used in the calibration and measurement, in that:

$$t_{max} = 1/[(2f_s)]$$

The time-domain transformation repeats at that value and can obscure any step or impulse responses that occur after that value. This factor becomes critical when analyzing extended structures, such as cables or materials with a high dielectric constant (D_k) that exhibit slower propagation velocities.

VNA Time-domain Resolution

The resolution of the time-domain transformation in VNAs provides the ability to resolve features or defects in either distance or time. These are related to the propagation velocity of the media in question. This document focuses on distance.

The distance resolution is inversely proportional to the frequency span of the VNA being used to make the measurement. A rule of thumb widely used for measurements made in air is:

$$\text{Distance resolution (mm)} = 150 \text{ mm/VNA BW (GHz)}$$

If another medium is used, this resolution is divided by the square root of D_k for that medium. A practical resolution example for a typical PCB with a D_k of 4 is shown below for different VNA measurement bandwidths (BW). A high Time-Domain (TD) resolution is essential for accurately identifying minor defects or closely spaced imperfections in a system.

Table 1 Time-domain Resolution vs. VNA Bandwidth for a PCB with a D_k of 4.

VNA Bandwidth	20 GHz	40 GHz	50 GHz	70 GHz	110 GHz	145 GHz
TD Resolution	3.75 mm	1.88 mm	1.50 mm	1.07 mm	0.68 mm	0.52 mm

Supported VNA Time-domain Modes

Anritsu's VNAs offer two time-domain modes: Band Pass (BP) and Low Pass (LP).

Band Pass mode helps examine tuned structures that are not DC coupled, such as tuned amplifiers, band-pass filters, and structures such as waveguides. The impulse response of these structures can be checked using the Band Pass mode. The impulse response helps characterize capacitive or inductive changes in the channel as a function of distance. However, no impedance information can be derived.

Low Pass mode is more flexible and allows for greater time-domain resolution compared to the Band Pass mode. This mode is very useful for structures affecting signal integrity, since most of those structures tend to be DC-coupled. Channels, including micro-strips, strip-lines, and cables, can be looked at in this mode using either impulse or step responses. Step responses enable the examination of impedance information versus distance or time, similar to a Time-Domain Reflectometer (TDR). This display is shown in Figure 1.

LP Time Domain Mode – TDR Like display:

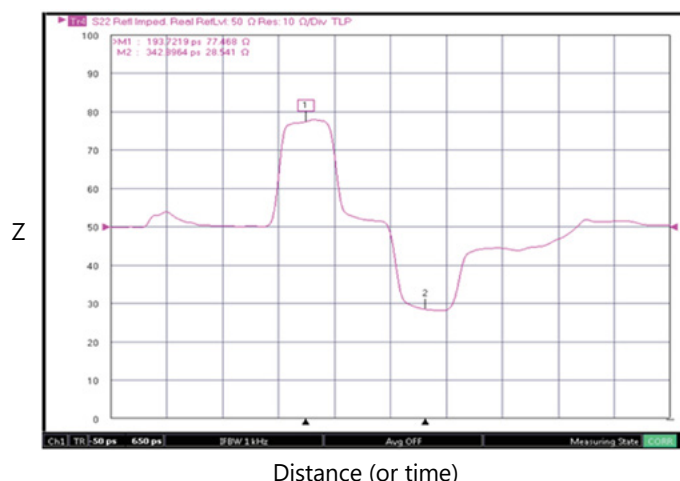


Figure 1 Impedance vs. Distance Display for Stepped Impedance Line.

An LP time-domain calibration and measurement procedure requires the use of a set of frequencies that are harmonically related. Specifically, the starting frequency and the frequency step size must be identical. This leads to symmetry around DC and allows the algorithm to use twice the number of points as that used in the Band Pass mode. Effectively, this symmetry leads to the transformation using the negative frequencies. This symmetry is illustrated in Figure 2.

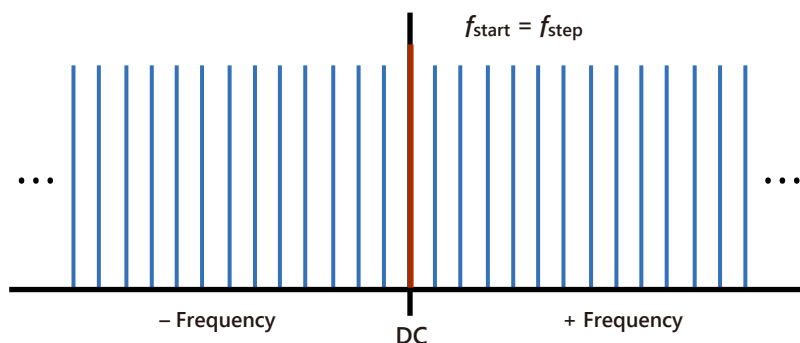


Figure 2 Symmetry of Low-pass Harmonic Calibration and Measurement Frequencies Around DC.

S-parameter Quality Metrics

The three key parameter metrics essential for signal integrity applications are Reciprocity, Passivity, and Causality.

Reciprocity

This metric measures the forward and reverse transmission parameters (S_{12} and S_{21}) and states that they should be equal in both magnitude and phase for a passive system. This is typically not a problem for VNAs, since the stimulus that is used is a single switched synthesizer or several phase-locked synthesizers used to measure S_{12} and S_{21} . This can be more of a problem for TDRs and TDTs because the stimuli that they use are pulses in the time domain, and there can be jitter and synchronization issues in the forward and reverse directions.

Passivity

This metric evaluates how accurately a measurement reflects the characteristics of a passive device. Proper passivity requires that a passive device does not exhibit gain in any of its measured S-parameters. If a lossy device demonstrates gain at any frequency, this indicates an S-parameter passivity issue.

Several factors can lead to passivity problems. Receiver saturation is a common cause; users of VNAs should ensure that the receiver remains within its linear operating range during calibration and measurement. Additionally, variations due to contact or connector repeatability can introduce passivity errors. De-embedding can also result in passivity issues, particularly when excessive loss is attributed to the de-embedded structures, such as connectors or fixtures. This is especially problematic when testing low-loss devices with high-loss fixture environments.

Causality

This is a more abstract S-parameter quality metric. It measures the correlation between the measurement responses and the stimuli. One symptom of a system with causality issues is that an output occurs before an input to the system.

All VNAs inherently exhibit causality issues due to their inability to provide a complete characterization of the network or DUT. In this context, complete characterization entails capturing data across an infinite range of frequencies, from DC to high frequencies. VNAs, however, operate within a defined frequency range determined by the start and stop frequencies, as well as a finite number of measurement points, which results in a specific step size. This limitation in data acquisition introduces discrepancies in causality. Expanding the frequency coverage (bandwidth) or increasing the number of measurement points can enhance the causality of the S-parameters, making them more reflective of actual system behavior.

Causality can be checked in two ways on the VNA. The S-parameters can be viewed on a polar display and should rotate continuously in a clockwise direction. If there are some frequencies where the S-parameters appear to rotate counterclockwise, then there might be causality issues at the frequencies where this occurs.

Another way to examine causality issues is to consider the energy that occurs before the stimulus at time $t < 0$. Fortunately, this can be observed on a VNA screen, allowing for the comparison of causality between different measurements.

Figure 3 compares 20 GHz and 40 GHz bandwidth measurements conducted on the same structure. The 20 GHz bandwidth measurement exhibits a higher amount of energy occurring before $t = 0$, indicating lower causality.

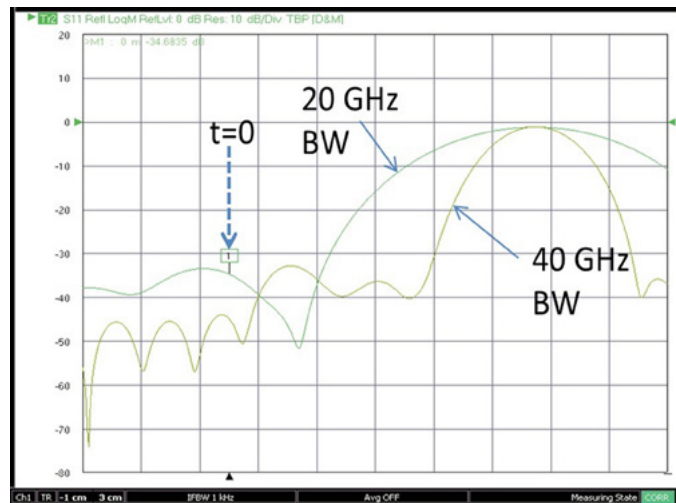


Figure 3 Causality Affected by Measurement Bandwidth. Note the Response Levels Before $t < 0$.

Channel Characterization and Measurement Frequencies

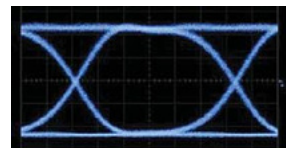
The required frequency range for measuring and characterizing high-speed channels often raises questions about capturing all relevant data and channel effects. The appropriate range depends on the bit rates and encoding schemes of the bit stream. NRZ and PAM4 encoding will be examined, as these represent the most widely used encoding methodologies in current systems.

NRZ Encoding

This encoding utilizes a half-rate clock and encodes 2 bits per complete clock cycle. A 28 GB/s bit stream has a clock rate of 14 GHz. There are two levels of encoding used in this scheme, with a single eye opening in the eye diagram as shown below:



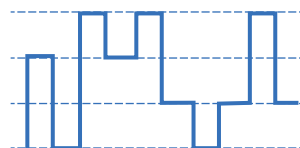
NRZ Encoding Levels



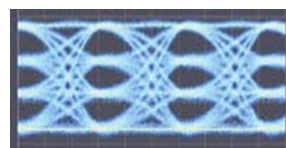
NRZ Eye Diagram

PAM4 Encoding

This encoding is widely adopted due to its spectral efficiency and its ability to encode more bits into the same signal bandwidth. Unlike NRZ encoding, PAM4 increases the encoding levels from 2 to 4, effectively doubling the throughput for the same clock rate. However, this method introduces a trade-off: a significant 6-dB signal loss penalty. Additionally, the eye openings in the PAM4 eye diagram are notably smaller than those for NRZ, making parameters such as jitter and the signal-to-noise ratio critical for system performance.



PAM4 Encoding Levels



PAM4 Eye Diagram

To understand the frequencies that are needed to measure and characterize these channels, the spectral content of the bit streams and clock signals is examined. It is well known that a square wave can be synthesized by adding a sine wave of the same frequency and its odd harmonics. The more harmonics that are included, the closer the approximation to a square wave. See Figure 4 below.

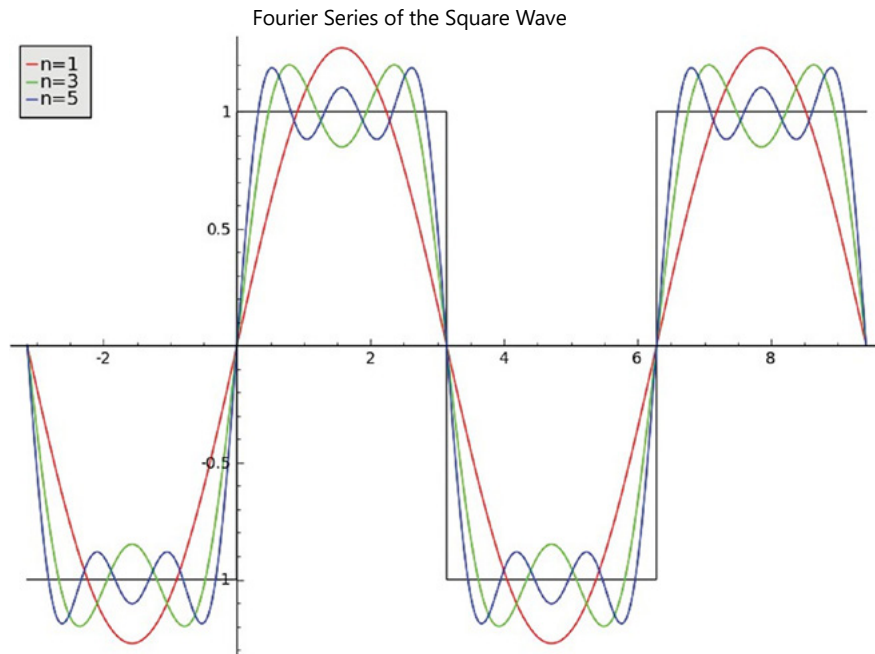


Figure 4 Fourier Series of a Square Wave with Different Harmonic Contributors.

This concept helps us consider a practical upper frequency limit for channel characterization.

Anritsu offers the highest-frequency broadband VNAs, and the ME7838 Series is capable of 70 kHz to 110, 125, 145, and 220 GHz in a single sweep. The bit rates and encoding of the system need to be considered.

Anritsu recommends performing measurements up to the fifth clock harmonic to ensure sufficient spectral content is captured for accurate channel characterization. However, this is somewhat dependent on the data signal rise and fall times. Systems with faster rise and fall times typically have higher frequency spectral content due to the microwave energy associated with these fast transitions. One might only require measurement to the 3rd clock harmonic on systems with slower rise and fall times.

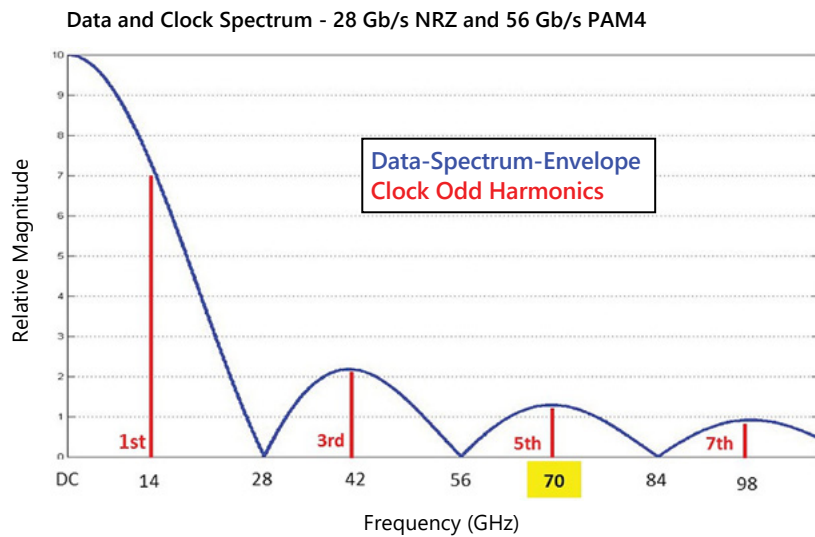


Figure 5 Spectral Envelope of 28 Gb/s NRZ and 56 Gb/s PAM4 Signals.

Figure 5 shows the data spectral envelope and clock odd harmonics for either a 28 Gb/s NRZ signal or a 56 Gb/s PAM4 signal. The data spectrum envelope follows a sinc function, represented as $\sin(x)/x$. One can observe a series of spectral lines with a spacing determined by word length, with the spectral lines contained within this envelope. In this example, the 5th clock harmonic is 70 GHz. When examining high-bit-rate NRZ systems, the frequency required to characterize associated channels can increase dramatically when using the same methodology as in the previous example. Figure 6 shows the spectral content of a 56 Gb/s NRZ clock and data signal. Notably, the 5th clock harmonic for this system is 140 GHz. This would require the use of a broadband VNA system capable of measuring from as close to DC as possible to 140 GHz, such as Anritsu's previously mentioned ME7838 Series.

Network Extraction and De-embedding

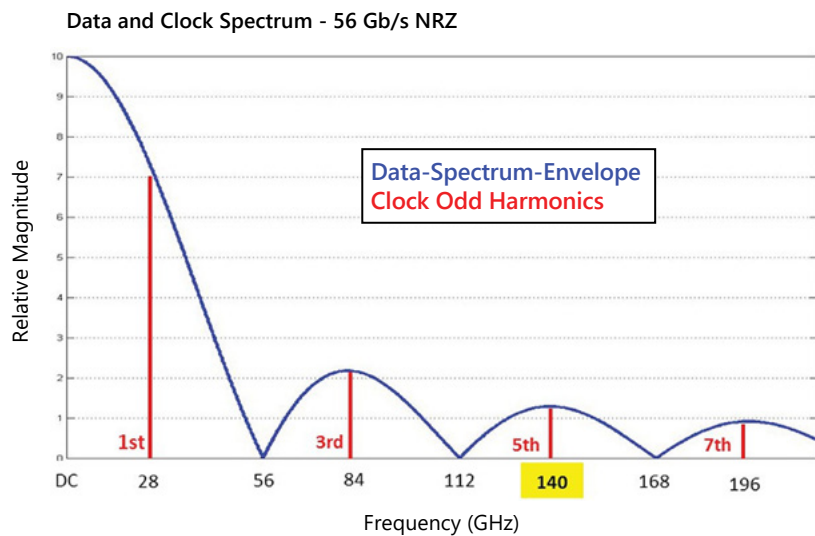
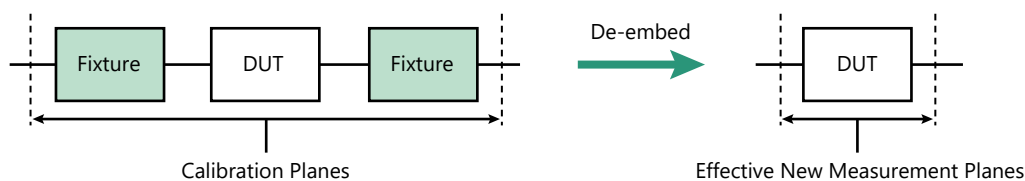


Figure 6 Spectral Envelope of 56 Gb/s NRZ Signal.

Many of the channels used in signal integrity applications have fixtures or connectors required for measurement. These will affect the measured S-parameters. Typical fixtures include Baluns, connectors, and/or PCB traces. Having a way to remove these features and structures from the measurement is often very useful. Network extraction is the process of determining the S-parameters for the features that we want to de-embed from (or embed into) the measurement.

To achieve this, it is necessary to determine the S-parameters of these features. This can be done in several ways. These features can be modeled by building a network of discrete resistors, inductors, and capacitors on the VNA. A known or vendor-supplied S-parameter file can be used, or the VNA can utilize a suite of network extraction tools native to the device. Anritsu VNAs support seven types of network extraction to accomplish this. See reference #2 for more information.



VNA Case Study – Two Different VNA Architectures:

As an example, to demonstrate many of these concepts, measurements were made on the same 40-inch line using VNAs with two different architectures. The VNAs used were as follows.

Anritsu's VectorStar VNA

The unique architecture of Anritsu's VNA allows it to support excellent low-frequency S-parameters as well as high-frequency S-parameters. It utilizes the only hybrid RF/Microwave VNA structure in the industry. It uses bridge-based reflectometers and mixer-based receivers below 2.5 GHz. For frequencies above 2.5 GHz, it uses a more conventional architecture of directional coupler-based reflectometers and Anritsu's proprietary non-linear transmission line (NLTL) sampler-based receivers. This architecture effectively addresses a common problem with most VNAs on the market, which only utilize directional couplers. Such reliance often results in significant performance degradation below 500 MHz, as characterized by increased measurement uncertainty and reduced dynamic range of low-frequency S-parameters. In contrast, Anritsu's VectorStar ensures high-quality S-parameter measurements as low as 70 kHz. Figure 7 is a schematic of this unique architecture.

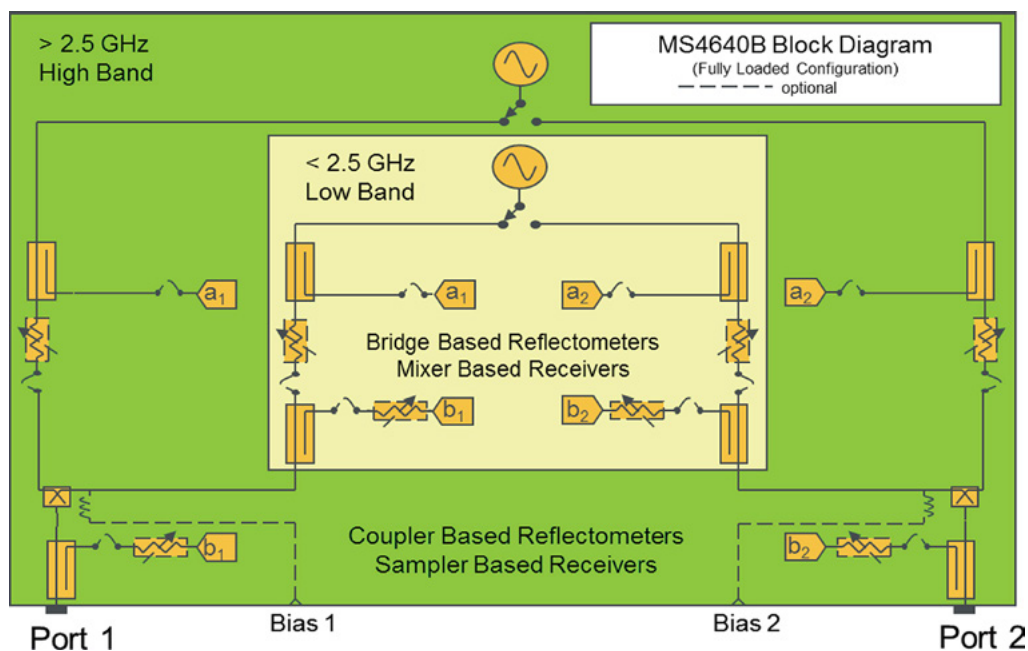


Figure 7 Unique VectorStar VNA Architecture Providing High-quality Low-Frequency S-parameters.

Traditional-architecture VNA

This type of VNA utilizes couplers for the entire band, exhibiting roll-off below 500 MHz. At these frequencies, users will experience higher measurement uncertainty, reduced dynamic range (DR), and increased noise levels. This architecture is representative of most VNAs on the market today. The VNA in this example has a low-frequency limitation of 40 MHz due to its architecture. For this case study, we used Anritsu's previous generation Lightning VNA system.

A low-pass time-domain transformation was then applied to these S-parameters, the results of which are discussed below. The following table summarizes these measurements:

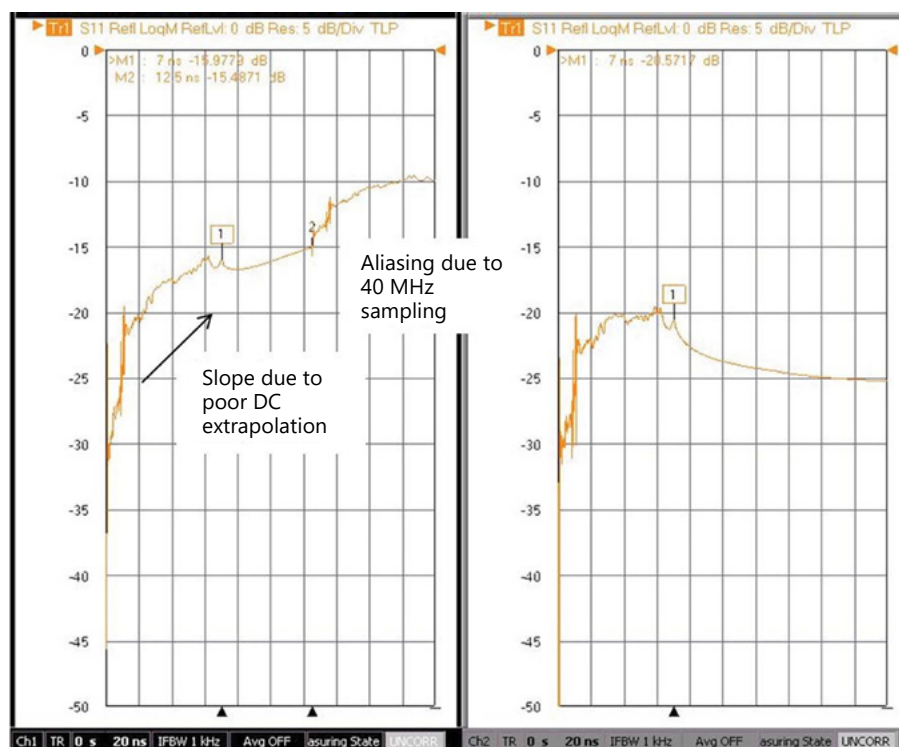
Table 2 VNA Measurement Results.

Measurement	Traditional VNA	VectorStar VNA
Low frequency (DR)	40 MHz (92 dB)	4 MHz (115 dB)
High frequency	40 GHz	40 GHz
Step size	40 MHz	4 MHz
Number of points	1,000	10,000

There are several significant features in the two S-parameter files generated as a part of these measurements. These can differ significantly when a low-pass time-domain transformation is applied to these S-parameter files.

1. The lower start frequency for the VectorStar S-parameters allows better DC point extrapolation because you are closer to DC.
2. The dynamic range of the low-frequency S-parameters is better with Anritsu's VectorStar. This will yield a lower measurement uncertainty profile at those frequencies.
3. The higher number of points for the VectorStar will yield better causality in the S-parameters.

A low-pass time-domain transformation was applied to the two resultant S-parameter files. The results are shown in Figure 8.



Traditional VNA: 40 MHz to 40 GHz data
fs = 40 MHz, 1,000 points

VectorStar VNA: 4 MHz to 40 GHz data
fs = 4 MHz, 10,000 points

Figure 8 LP Time-domain Transformation Applied to the Two S-parameter Files.

The differences in the step responses of the two files are evident. The traditional VNA response shows a slope due to inadequate DC point extrapolation. In addition, aliasing effects are observed as well (the step response repeats) because of the larger step size. These artifacts, however, are absent in the step response derived from the VectorStar S-parameters.

Finally, an eye diagram simulation, which represents another form of time-domain transformation, was generated from these S-parameter files. The results are shown in Figure 9. The differences in these simulations are evident, with the VectorStar simulation demonstrating closer alignment with actual measurements.

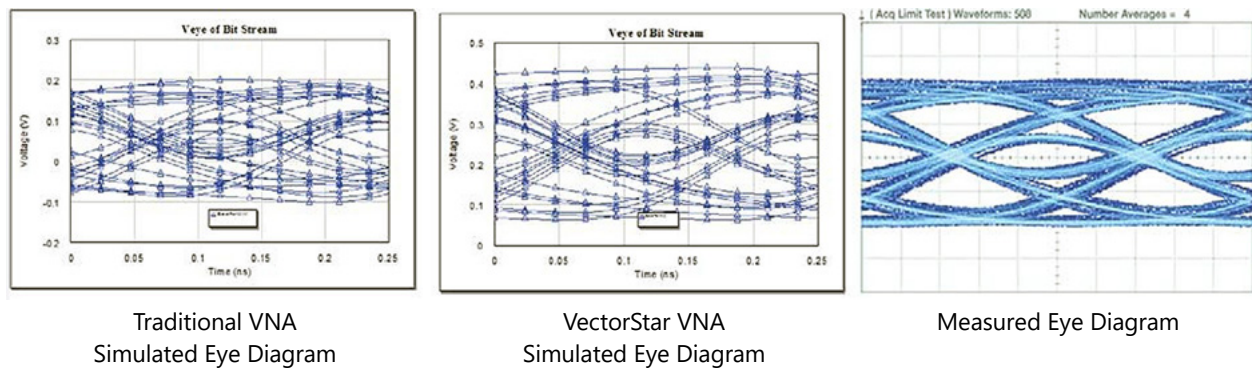


Figure 9 Comparison Between Eye Diagram Simulations and Practical Measurements.

Summary

This document has described the differences in how VNAs and time-domain-based instruments generate S-parameters. We examined VNA time-domain transformations and their dependence on VNA bandwidth, frequency step size, and low-frequency S-parameter quality. This document also explained S-parameter quality metrics, including indications of measurement issues. The document then went on to discuss channel characterization and measurement frequencies as they apply to bit rates and encoding. VNA de-embedding and network extraction tools were also touched on to simplify measurements. The net result was verification that VNAs are an excellent tool in signal integrity applications.

Recommended additional reading can be found in the following references.

1. Anritsu Application Note 11410-00722 "[Time Domain Measurements Using Vector Network Analyzers](#)"
2. Anritsu White Paper 11410-06666 "[Higher Data Rates Require New De-embedding Techniques](#)"
3. Anritsu Application Note 11410-00817 "[Creating Eye Diagrams using VectorStar SnP files and AWR Microwave Office®](#)"
4. Anritsu Application Note 11410-00794 "[True Mode Stimulus Measurements](#)"
5. Anritsu Application Brief 11410-00654 "[Signal Integrity Measurement Challenges](#)"
6. Anritsu White Paper 11410-00658 "[Overcoming High-speed Interconnect Challenges](#)"
7. Anritsu White Paper 11410-00659 "[Superposition vs. True Balanced: What's Required for Your Signal Integrity Application](#)"

For further information, go to:

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