White Paper

Using VNA's as a Tool for Signal Integrity in High Speed Digital Systems

Frequency Domain Tools and Time Domain Transformation Performance

Overview:

As bit rates in serial communications systems increase the signal paths that carry these signals must be treated as high frequency transmission lines. These signal paths can include chip packages, PCB traces, connectors, cables and backplanes and will be referred to as channels in this paper. The fact that these channels must now be treated as transmission lines means that engineers might need a new set of tools to use to design, simulate and characterize them.

VNAs make measurements in the frequency domain and can be used to supplant the information that native time domain instruments, like fast oscilloscopes, Signal Quality Analyzers (BERTs) and Time Domain Reflectometers/Transmission instruments (TDR/TDT's) already provide.

VNA measurement advantages:

Native time domain instruments can provide S-parameters by doing a Fast Fourier transformation (FFT) on the time domain data. Making high quality S-parameter measurements in the frequency domain has some inherent advantages over time domain based instruments, namely dynamic range (DR).

Time domain based instruments are inherently broadband in nature. This bandwidth does net some speed advantages in the measurements, but the very broadband nature of these means that they have 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. The net effect is a reduction in the DR of S-parameters provided by these instruments.

VNAs on the other hand are inherently narrow band instruments and have lower noise floors because the bandwidth driven kTB noise is much lower. VNAs can measure to an instantaneous IF bandwidth of 10s of Hz which provide very high S/N ratio data and yield higher DR S-parameter measurements.

As a practical example, S-parameters provided by a typical TDR/TDT instrument have on the order of 40 dB DR, where the typical DR of VNA S-parameters is typically greater than 100 dB. This higher quality data can be important when correlating measured and simulated results for channels used in signal integrity applications.

VNA's as a tool:

VNAs are useful in characterizing channels as a means of comparing measured S-parameters to the ones that have been modeled in an EDA software package like HFSS or Microwave Office. Having high quality S-parameters are key in making the measured and modeled results agree; more on determining the quality of S-parameters later in the article

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

Frequency to time domain transformations:

When making the transition from frequency domain to the time domain, Inverse Fourier Transformations (IFT) are used. The general form of an IFT is as follows:

The time domain terms are on the left side and the frequency domain terms are on the right side of this equation. There are several important considerations in making this transformation.

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

Low frequency S-parameters: The low frequency terms (small values of fk in the exponential) define the slowly varying time terms (tn) in the transformation. These slowly varying time terms define the flat top portions of the time domain transformation and can affect how things like step responses and eye diagram simulations look. 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 no VNA can measure this value directly due to the coupling structures used. This DC approximation is used as an integration reference in the transformation. If it is not correctly approximated, the time domain step response can have slope associated with it.

These two considerations mean that the quality of the low frequency data and an accurate extrapolated DC point are very important in making this time domain transformation. This means that having high DR low frequency data is crucial.

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 made 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 becomes important when looking at long structures like cables or high dielectric constant (Dk) materials with slow 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 by the propagation velocity of the media in question. In this article, concentration will be placed on distance.

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

Distance resolution (in mm) = 150 mm/VNA BW (in GHz)

If another medium is used, this resolution is divided by the square root of the Dk for that medium. A practical resolution example for a typical PCB with a Dk of 4 is shown below for different VNA measurement bandwidths:

Time domain resolution vs VNA BW for a PCB with a D_k of 4						
VNA BW	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

Having high TD resolution is important in being able to resolve small defects or defects that are close together.

VNA Time Domain Modes available:

Anritsu VNA’s have 2 Time Domain modes available. They are Band Pass (BP) and Low Pass (LP) modes.

Band Pass mode is useful in looking at tuned structures that are not DC coupled, like tuned amplifiers, band pass filters and structures like waveguide. You can look at the impulse response of these structures using the band pass mode. Impulse response is useful in characterizing capacitive or inductive changes in the channel as a function of distance but no impedance information can be derived.

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

LP Time Domain Mode - TDR Like display:

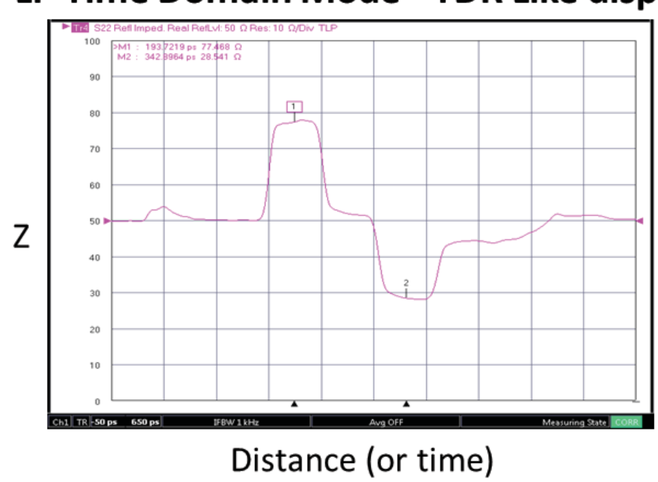


Figure 1. VNA TDR-like display shows impedance vs Distance for a stepped impedance line.

Performing a LP time domain calibration and measurement requires a set of harmonically related frequencies in that the start frequency and step size are the same value. This leads to symmetry around DC and allows the algorithm to use twice the number of points used in Band Pass mode. Effectively this symmetry leads to the transformation using the negative frequencies. This symmetry is illustrated in Figure 2.

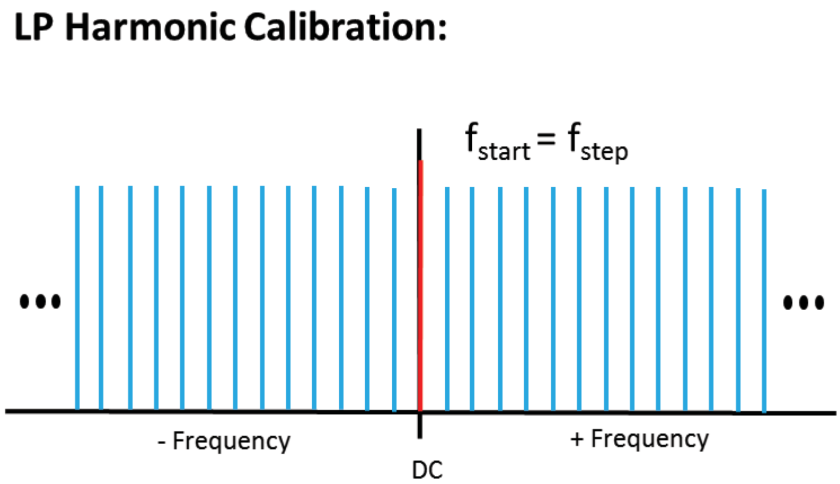


Figure 2. Low Pass Harmonic Calibration and Measurement frequencies showing symmetry around DC.

S-Parameter Quality Metrics:

There are three Parameter metrics that are important to SI applications. They are Reciprocity, Passivity and Causality.

Reciprocity: TThis metric is a measure of the forward and reverse transmission parameters (S12 and S21) and states that they should be equal in both magnitude and phase for a passive system. This is typically not a problem for VNA's because the stimulus that is used is a single switched synthesizer or a number of phase-locked synthesizers used to measure S12 and S21. This can be more of a problem for TDR's and TDT's 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 is a gage of how well a measurement represents a passive device. Having good passivity means that a passive device cannot show gain anywhere in its measured S-parameters. A lossy device showing gain at any frequency has S-parameter passivity issues. There can be several causes of passivity problems. Receiver saturation is often the issue. VNA users need to be certain that the receiver is not compressed at all when doing a calibration or measurement. In addition, contact or connector repeatability can cause passivity issues. De-embedding can also cause passivity issues when too much loss is attributed to the structures being de-embedded like connectors or fixtures. This is especially prevalent in systems with low loss DUT's and high loss fixturing. A simple way to check for passivity issues is to measure a low loss high quality thru, like an air-line. This thru should show only loss across the measurement band.

Causality: This is a more abstract S-parameter quality metric. It measures how correlated measurement response are to stimuli. One symptom of a system with causality issues is that an output occurs before an input to the system happens.

All VNA's have causality issues primarily because they do not provide a complete characterization of the network or DUT. In this instance, a complete characterization means having an infinite number of frequencies from DC to daylight. VNA's have a start and stop frequency and a user defined number of points which determine a finite step size. This incomplete data set leads to causality issues. Any increase in the frequency coverage (BW) or number of measurement points will make the S-parameters more causal.

Causality can be checked in two ways on the VNA. The S-parameters can be viewed on a polar display and should always rotate in a clockwise sense. 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 look at causality issues is to view the energy that occurs prior to the stimulus at time<0. Fortunately this can be seen on a VNA screen and causality of different measurements can be compared. See Figure 3 for a comparison of a 20 and 40 GHz BW measurement on the same structure. Clearly the 20 GHz BW measurement has more energy occurring before t=0 and as such has lower causality.

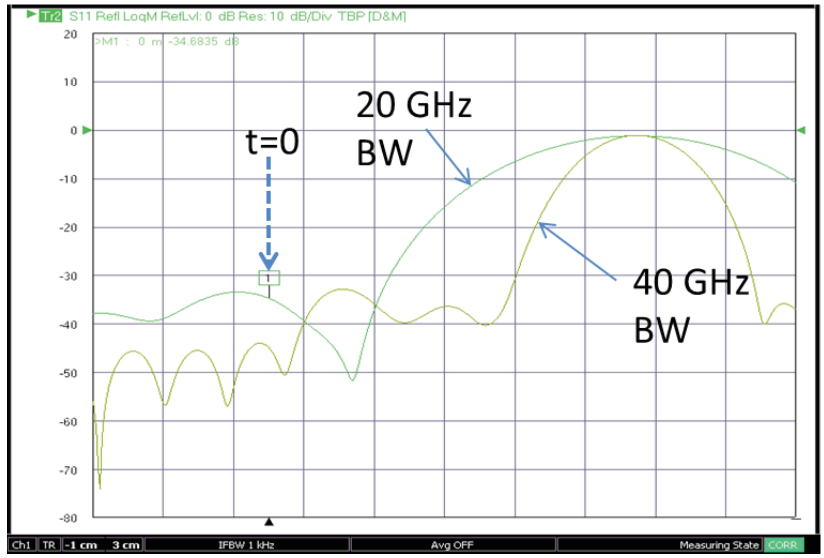
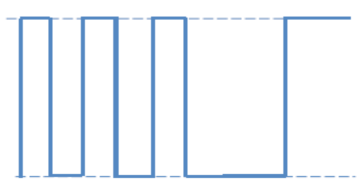


Figure 3. Causality is affected by measurement BW. Note the response levels before t<0.

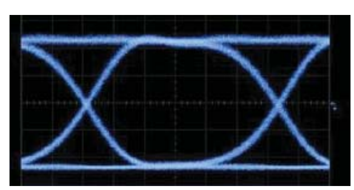
Channel Characterization and Measurement Frequencies:

The question often comes up as to what frequency range is needed to measure and characterize high speed channels to capture all relevant data and channel effects. This is dependent on the bit rates and encoding of the bit stream. NRZ and PAM4 encoding will be explored, since these are currently the most popular encoding schemes right now.

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

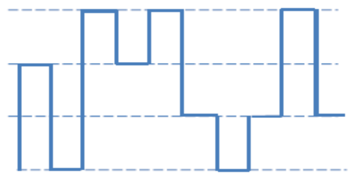


NRZ Encoding Levels

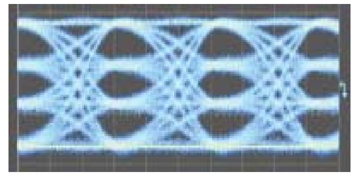


NRZ Eye Diagram

<u>PAM4 Encoding:</u> This encoding is popular because of its spectral efficacy and its ability to encode more bits into the same signal bandwidth. PAM4 has the ability to double the NRZ encoding levels from 2 to 4 and thereby increase throughput by a factor of 2 for the same clock rate. There is a penalty to encode this many levels and a 6 dB signal loss penalty occurs. The eye openings are also smaller in the eye diagram, compared with NRZ, so jitter and S/N are important in these systems.



PAM4 Encoding Levels



PAM4 Eye Diagram

To understand what frequencies are needed to measure and characterize these channels, the spectral content of the bit streams and clock signals will be examined.

It is well known that a square wave can be synthesized by adding together a sine wave of the same frequency and its odd harmonics. The more harmonics included, the closer the approximation to a square wave, see Figure 4 below.

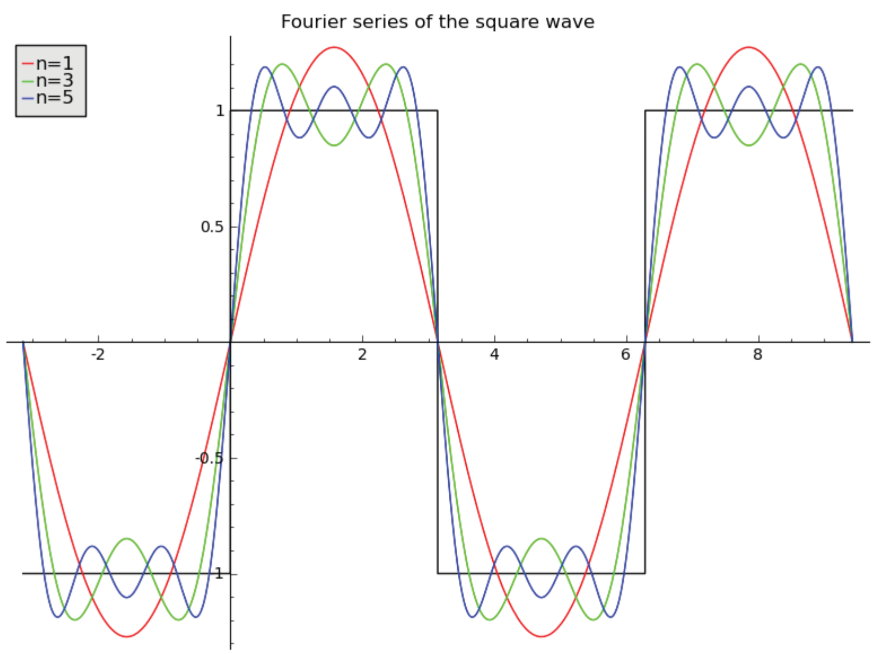


Figure 4. Fourier series of a square wave with different harmonic contributors.

This concept is useful in looking at a practical upper frequency limit for channel characterization.

While Anritsu has the highest frequency broadband VNA's on the market and our ME7838D system is capable of 70 kHz to 145 GHz in a single sweep, this upper frequency might not be needed. The bit rates and encoding of the system need to be considered.

It is recommended that measurements be made to the 5th clock harmonic to capture sufficient spectral content to characterize channel performance properly, but 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.

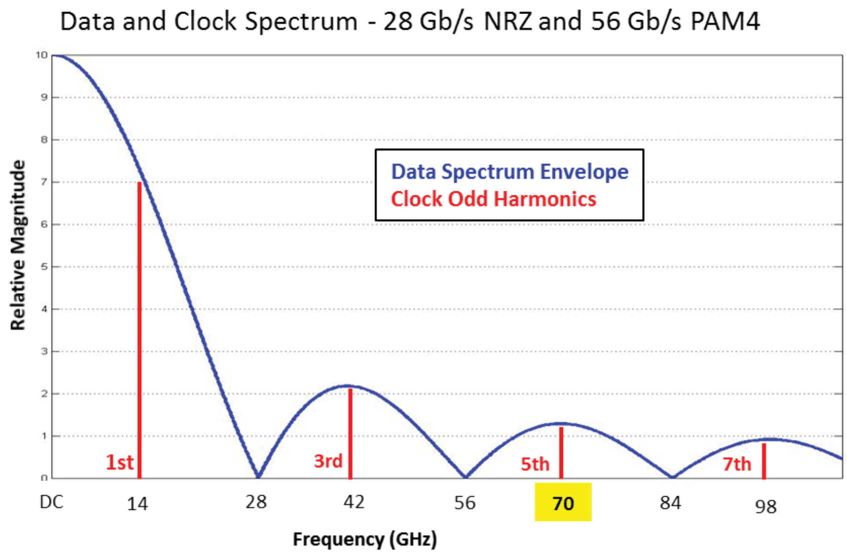


Figure 5. Spectral envelope of 28 Gb/s NRZ and 56 Gb/s PAM4 signals showing the 5th clock harmonic at 70 GHz.

Figure 5 shows the data spectral envelope as well as the clock odd harmonics for either a 28 Gb/s NRZ signal or a 56 Gb/s PAM4 signal. The data spectrum envelope is a sin(x)/(x) shaped sinc function. In reality, one would see a series of spectral lines whose spacing depends on the word length, but the spectral lines would fall within this envelope. In this example, the 5th clock harmonic is 70 GHz

Looking at higher bit rate NRZ systems, the frequency needed to characterize associated channels to can go up dramatically 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. As can be seen, the 5th clock harmonic for this system is 140 GHz. This would require a broadband VNA system capable of measuring from as close to DC as possible to 140 GHz, such as Anritsu's previously mentioned ME7838D VNA system.

Network Extraction and De-embedding:

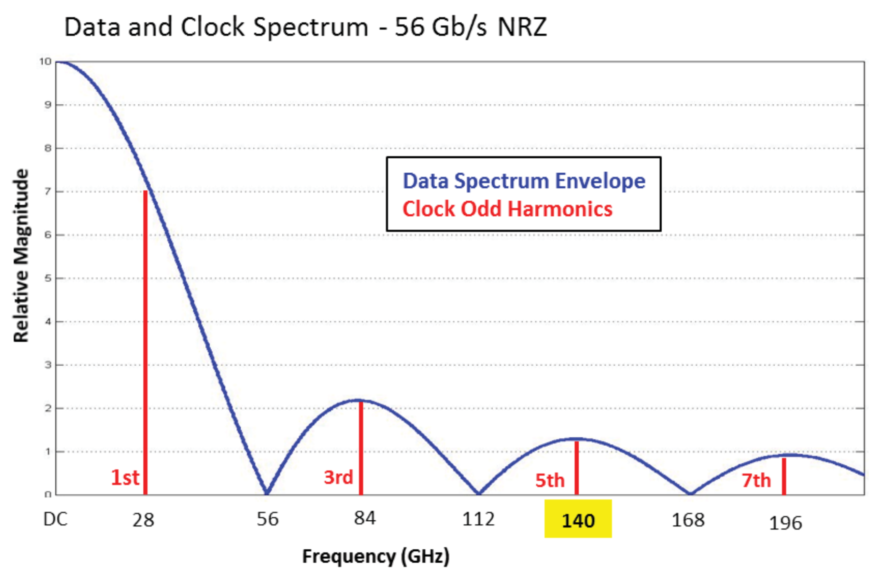
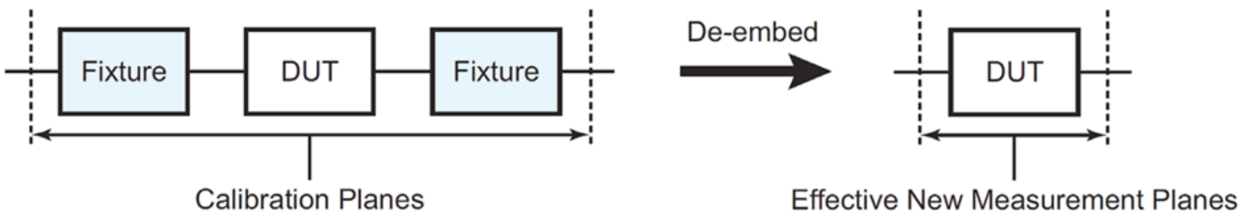


Figure 6. Spectral envelope of 56 Gb/s NRZ signal showing the 5th clock harmonic at 140 GHz.

Many channels used in SI applications have fixtures or connectors required for measurement that 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 do this, one needs to determine the S-parameters of these features. This can be done in several ways. These features can me modeled by building a network of discrete resistor, inductor and capacitor components on the VNA, a known or vendor supplied S-parameter file can be used, or the VNA canuse a suite of network extraction tools native to the instrument. There are seven types of network extraction available on Anritsu VNA's to accomplish this. Please see reference #2 for more info**.**



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 VNA's with two different architectures. The VNA's used were as follows.

Anritsu's VectorStar VNA: Unlike other VNAs, this VNA provides excellent low frequency S-parameters as well as high frequency S-parameters because of its unique architecture. It uses the only hybrid RF/Microwave VNA structure in the industry. This is accomplished by using bridge based reflectometers and mixer based receivers below 2.5 GHz. 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 avoids a common problem with most VNA's on the market (which only utilize directional couplers), where the measurement quality significantly rolls-off below 500 MHz. The reduction in quality can be seen increased measurement uncertainty and lower dynamic range of the low frequency S-parameters. VectorStar is capable of making high quality S-parameter measurements as low as 70 kHz; see Figure 7 for a schematic of this unique architecture.

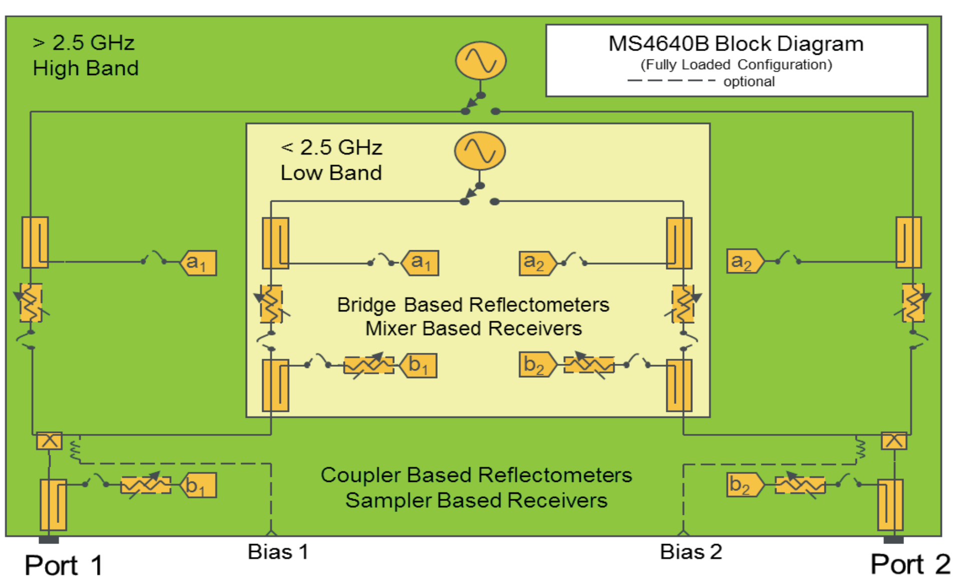


Figure 7. The unique VectorStar VNA architecture provides very high quality low frequency S-parameters.

Traditional Architecture VNA: This VNA uses couplers for the entire band which exhibit roll off below 500 MHz. At these frequencies, users will see higher measurement uncertainty, reduced DR, and higher noise levels. This architecture is representative of most VNA's on the market today. The VNA in this example has a low frequency limitation of 40 MHz because of its architecture. For this case study we used Anritsu's previous generation Lightning VNA system.

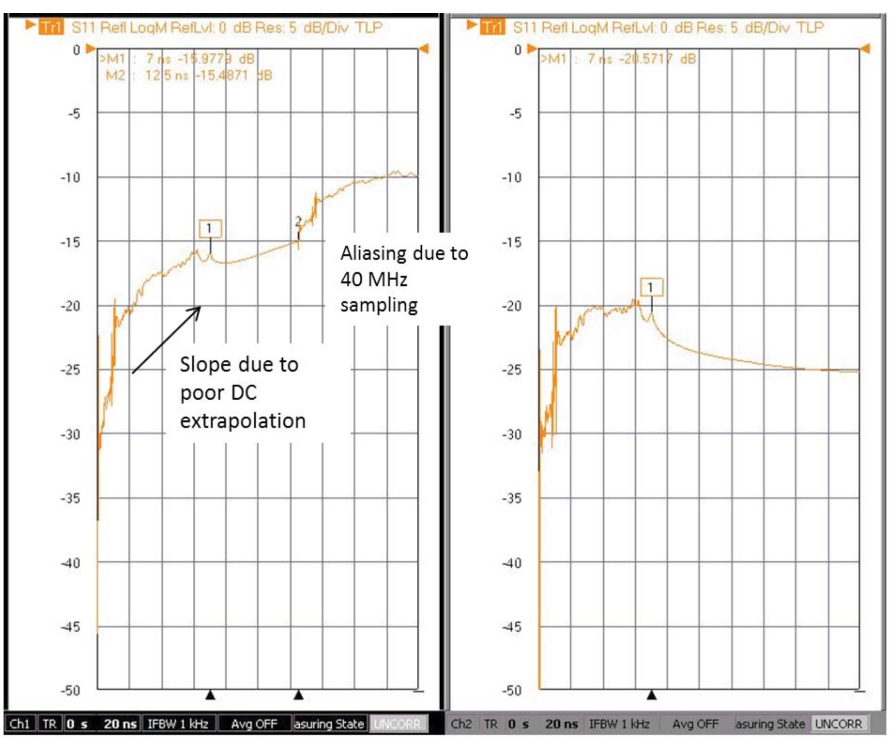
A low pass time domain transformation was then done on these S-parameters and the results will be examined below. A summary of the measurements is shown below:

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

There are several significant things in the two S-parameter files generated as a part of these measurements. These can have a significant difference when 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 for the VectorStar. This will yield 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 (IFT) was the applied to the two resultant S-parameter files with the results shown in Figure 8.



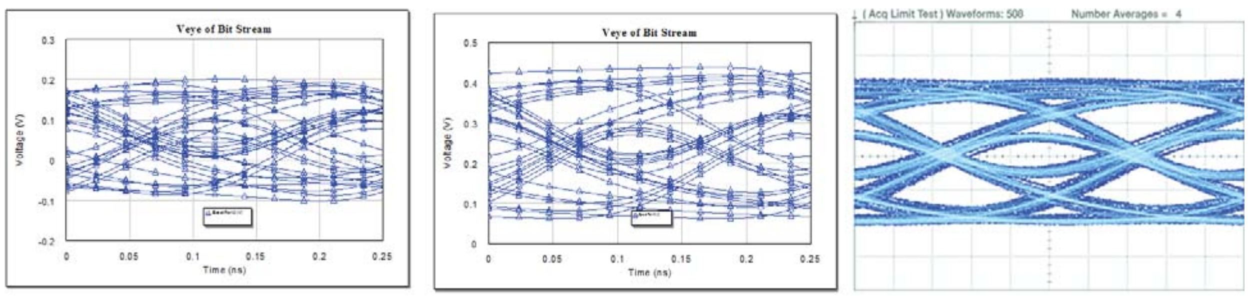
Traditional VNA: 40 MHz to 40 GHz data
fs=40 MHz, 1,000 points

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.

One can clearly see the differences in the step responses of the two files. The traditional VNA response shows a slope due to a poor DC point extrapolation. The effect of aliasing is observed as well (the step response repeats) because of the larger step size. None of these artifacts are present in the step response from the VectorStar S-parameters.

Finally, an eye diagram simulation (another form of a time domain transformation) was generated from these S-parameter files with the results shown in Figure 9.



Traditional VNA Simulated Eye diagram | VectorStar VNA Simulated Eye diagram | Measured Eye diagram

Figure 9. Eye Diagram Simulations compared with actual measurements.

You can see that there are differences in these simulations with the VectorStar simulation more closely matching the actual measurement.

Summary:

This paper described the difference in how VNA's and time domain based instruments generate S-parameters. There was an examination of VNA time domain transformations and how they are affected by VNA bandwidth, frequency step size and low frequency S-parameter quality. S-parameter quality metrics were also described, including indications of measurement issues. There was discussion on channel characterization and measurement frequencies as it applies to bit rates and encoding. VNA de-embedding and network extraction tools were also touched on as a way to simplify measurements. The net result is verification that VNAs are an excellent tool in signal integrity applications.

There is recommended additional reading in the references shown below.

1. Anritsu Application Note 11410-00722 "Time Domain Measurements Using Vector Network Analyzers"

2. Anritsu White Paper 11410-0666 "Higher Data Rates Require New De-embedding Techniques"

3. Anritsu Application Note 11410-00817 "Creating Eye Diagrams using VectorStar SnP files and AWR Microwave Off ice®"

4. Anritsu Application Note11410-00534 "Multiport Vector Network Analyzer Measurements"

5. Anritsu Application Note 11410-00794 "True Mode Stimulus Measurements"

6. Anritsu Application Brief 11410-00654 "Signal Integrity Measurement Challenges"

7. Anritsu White Paper 11410-0658 "Overcoming High-speed Interconnect Challenges"

8. Anritsu White Paper 11410-0659 "Superposition vs. True Balanced: What's Required for Your Signal Integrity Application"

9. Anritsu White Paper 11410-0728 "True Mode Stimulus and Stability"

Specifications are subject to change without notice.

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