Rapid Characterization of High Speed Digital Channels using a Multiport VNA

Application Note

Products:

- R&S®ZNBT

Vector Network Analyzers (VNA) are gaining popularity in the Signal Integrity community as time domain measurement and analysis tools. VNAs with 8 ports or more can provide significant decreases in test time by migrating from a 4-port measurement system to an 8-port measurement system. For tight tolerance DUTs that are barely within the test limit lines, small increases in accuracy can be realized by testing all of the test parameters at once, because the entire test setup is at the same temperature. This application note discusses the thermal advantages of testing an 8-port DUT with the R&S ZNBT VNA. The use of the ZNBT to assess and debug two differential pairs in a 20-inch backplane is presented.

Application Note
Rohde & Schwarz
3.2020– 1EZ83_0E

ROHDE&SCHWARZ

Table of Contents

1 Introduction

Vector Network Analyzers (VNA) are gaining popularity in the Signal Integrity community as Time Domain Measurement and Analysis tools. Modern Vector Network Analyzers offer Time Domain analysis tools including Eye Diagrams and Time Domain Reflectometers (TDR) as illustrated in Figure 1 and Figure 2 respectively. Eye diagrams allow users to quickly assign a Pass or Fail criteria to a Device Under Test (DUT) with a specification mask, while TDR data plots can allow for the location of design issues to be quickly identified.

VNAs also provide accurate Frequency Domain data, or S-parameters, which provide valuable information and insight into a design. A thorough review of logarithms, dBs and S-parameters are provided for engineers and technicians who are new to working in the Frequency Domain with S-parameters in decibels (dB’s). VNAs generate very accurate data because they are able to maintain very high Signal to Noise Ratios (SNR) over very low Receiver Noise Floors. A brief review of SNR and Receiver Noise Floor is also provided for readers who are new to high Dynamic Range VNA measurements.

VNAs with 8 ports or more can provide significant decreases in test time by migrating from a 4-port measurement system to an 8-port measurement system. For tight tolerance DUTs that are barely within the test limit lines, small increases in accuracy can be realized by testing all of the test parameters at once, because the entire test setup is at the same temperature. This thermal advantage of testing an 8-port DUT is discussed.

The use of a VNA to assess and debug two differential pairs in a 20-inch backplane is also presented. One of these backplane circuits is fabricated from Rogers 3003 while the other Backplane is fabricated from Rogers 6202. There are two variants of each backplane, a “degraded” version and a “healthy” version. The degraded version of the backplane has been deliberately degraded to “close the eye” diagram. The Time Domain Features and the Frequency Domain features of an 8-port R&S ZNBT-20 are used to perform a real-world design troubleshooting scenario. This design debug is performed to identify the root cause of the “Closed” Eye Diagram in Figure 1 to arrive at the “Open” Eye Diagram of Figure 1. While the Time Domain data are more intuitive for some engineers, the frequency domain data provide engineers with information about the design issue(s) that are not are not possible with Time Domain data alone. These Frequency Domain features are briefly introduced.

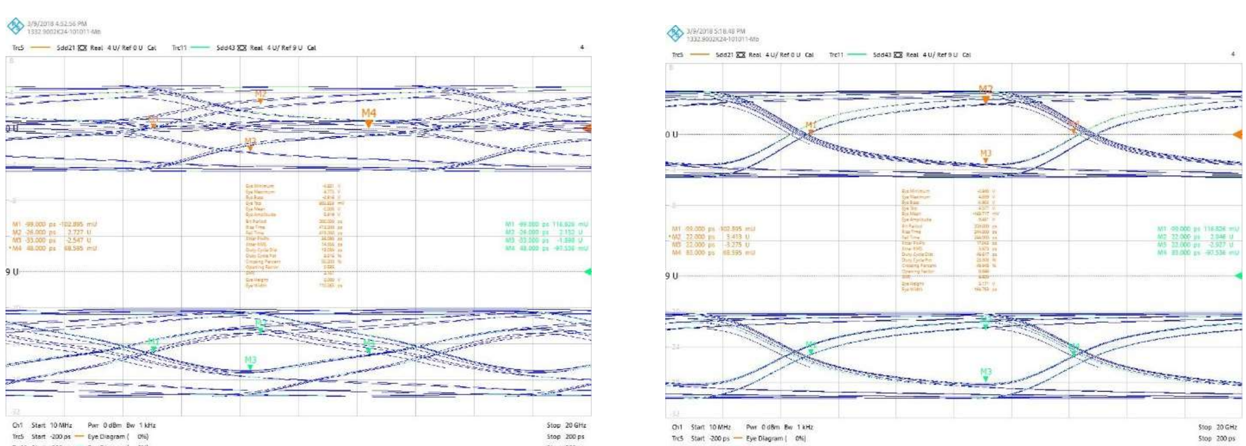


Figure 1: Degraded Backplane vs Clean Backplane Eye Diagrams for a PRBS 2^{5-1} at 5 Gbps (2.5 GHz)

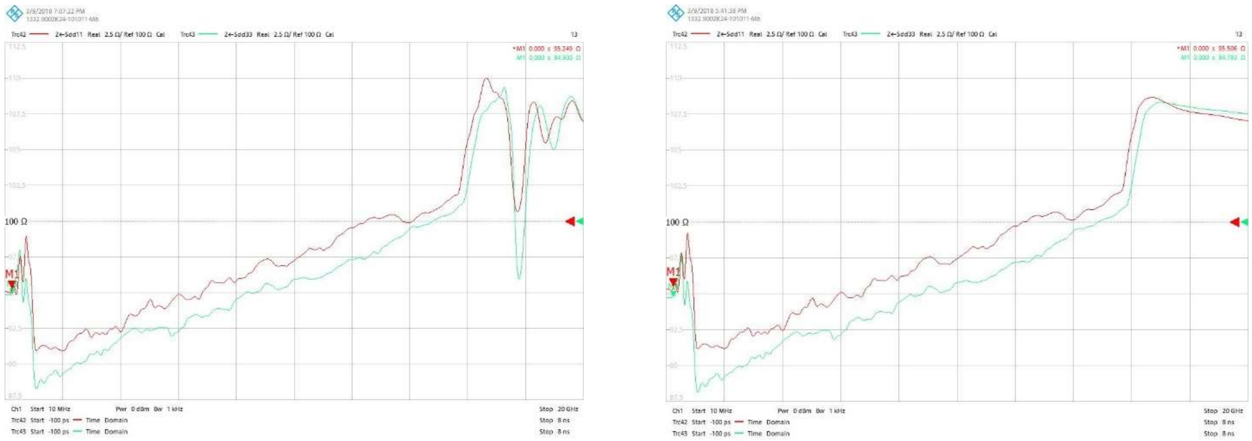


Figure 2: Degraded Backplane Time Domain Reflectometer (TDR) vs Clean Backplane TDR

An 8-port VNA can be used to thoroughly characterizer a two-lane High Speed Digital channel in a single test setup as illustrated in Figure 6. Taking the Inverse Fourier Transform of the VNAs Frequency Domain data allows one to arrive in the Time Domain. This Includes Eye Diagrams as illustrated in Figure 1 and TDR data plots as illustrated in Figure 2. Frequency Domain data includes Near End Cross Talk (NEXT), Far End Cross Talk (FEXT), Intra-Pair Skew, Inter- Pair Skew, Differential to Common Mode Conversion, Common Mode to Differential Mode Conversion, Insertion Loss and Return Loss. Knowing a full characterization of a high-speed digital backplane in the frequency domain (e.g. S-parameters) provides engineers with all of the information they need to assess and debug a design.

2 A Review of Decibels

The decibel, or dB, is one of the most widely used units when working with S-parameters in the frequency domain. If you are already familiar with decibels, and you can readily convert to and from them, you can skip this section and move onto the next section. If you are used to working in Volts or millivolts and you are not used to working in dB's, then you will find that spending a few minutes learning dBs is a worthwhile investment of time. Understanding decibels is the first of two steps to understanding VNA data. The second step is to understand S-parameters, which is covered in the next section.

The decibel is a logarithmic unit that is used to express ratios and compress scales. Several features of the decibel make it very useful to a High-Speed Digital Engineer. First, it greatly reduces the size of numbers required to express large ratios. A Power ratio of 2 to 1 is 3 dB, while a ratio of 100,000,000 is 80 dB. Since the power levels encountered in VNA measurements can cover 1,000,000,000,000 (120 dB) or more, the compression of the magnitude of the numbers that decibels provide is extremely valuable. Specifically, Power Ratio in dB

dB = 10 * Log_{10} (P_2 / P_1)

where P2 and P1 are two power levels being compared.

For the case of circuits that amplify signals, gain is defined as

Gain in dB = 10 * Log_{10} (Output Power / Input Power)

For the case of lossy circuits that attenuate signals (e.g. backplanes), Loss is defined as

Loss in dB = 10 * Log_{10} (Input Power / Output Power)

For example, if a 10 mW is transmitted and a 1 mW signal is received,

10 * Log_{10} (P_2 / P_1) = 10 * Log_{10} (1 mW / 10 mW) = -10 dB

The negative sign indicates a loss of power. Also notice that dividing mW / mW = 1 and the result is a dB.

Additionally, if 1mW is transmitted and 10 mW is received,

10 * Log_{10} (P_2 / P_1) = 10 * Log_{10} (10 mW / 1 mW) = 10 dB of gain

Where the positive sign indicates a gain of power.

When working in units of mW, the result is compared to 1 mW = 0 dBm.

10*Log_{10}(Power mW) = Power dBm
10*Log_{10}(10 mW) = 10 dBm, which is 10 dB greater than 0 dBm.
Since 1000 mW = 1 Watt, 30 dBm = 0 dBW

Another advantage of logarithms is the ability to multiply two numbers by adding them in dB. For example, multiplying 2500/1 by 63/1 in your head is not particularly easy. When these two numbers are converted to dB they are simply added together

34 dB + 18 dB = 52 dB

If one desires to work in Voltage the following property of logarithms can be used:

$$\mathbf{Log_{10}N^x = X * Log_{10}N.}$$

Since Power is proportional to the square of the voltage,

$$\mathbf{10 * Log (P_2 / P_1) = Log_{10} [(V_2^{\,2}/R) / (V_1^{\,2}/R)] = 20 * Log_{10} (V_2 / V_1)}$$

$$\mathbf{20*Log_{10}(Voltage\ V) = Power\ dBV}$$

60 dBmV = 0 dBV

When working in Radio Frequency (RF) the Resistance R is assumed to be 50 Ω unless otherwise stated.

2.1 Working with Decibels

When working with power the following conversions are the only conversions that need to be remembered:

1 dB ≈ 1.25/1 ≈ 1.25	-1 dB ≈ 1/1.25 ≈ 0.8 = 80%
3 dB = 2	– 3dB = ½ = 0.5 or 50%
10 dB = 10	-10 dB = 1/10 = 0.1 or 10%

Using these basic conversions,

2 dB = 3 dB – 1 dB = 2 * 0.8 = 1.6	-2 dB = 1 / 1.6 = 0.625
4 dB = 3 dB + 1 dB = 2 * 1.25 = 2.5	-4 dB = 1 / 2.5 = 0.4
5 dB = 3 dB + 3 dB – 1 dB = 4 * 0.8 = 3.2	-5 dB = 1 / 3.2 = 0.3125
6 dB = 3 dB + 3 dB = 2 * 2 = 4	-6 dB = 1 / 4 = 0.25
7 dB = 3 dB + 3 dB + 1 dB = 4 * 1.25 = 5	-7 dB = 1 / 5 = 0.2
8 dB = 6 dB + 2 dB = 4 * 1.6 = 6.4	-8 dB = 1 / 6.4 = 0.156
9 dB = 6 dB + 3 dB = 4 * 2 = 8	-9 dB = 1 / 8 = 0.125
13 dB = 10 dB + 3 dB = 10 * 2 = 20	-13 dB = 1 / 20 = 0.05
16 dB = 10 dB + 6 dB = 10 * 4 = 40	-16 dB = 1 / 40 = 0.025

If a circuit is excited with 0 dBm (1 mW) and it has 20 dB of loss its output is – 20 dBm or 0.01 mW. If a circuit is excited with 0 dBV (1 V) and it has 20 dB of loss its output is – 20 dBV or 0.1 V. Regardless if one is working in units of power or voltage, 20 dB of loss is 20 dB of loss. The difference occurs when converting to the factor form of power levels or voltage levels. 20 dB is a factor of 100 for power, while it is a factor of 10 for Voltage. Either way the circuit has 20 dB of loss.

If a circuit is excited with 0 dBm (1 mW) and it has 6 dB of loss its output is – 6 dBm or 0.25 mW.

If a circuit is excited with 0 dBV (1 V) and it has 6 dB of loss its output is – 6 dBV or 0.5 V.

6 dB is a factor of 4 for power, and a factor of 2 for Voltage. Either way the channel has 6 dB of loss.

3 A Review of S-parameters

The S-parameter is one of the most widely used ratios when working with VNAs in the frequency domain. S-parameters contain a Real and Imaginary component, and there are several ways this can be expressed. Real Imaginary, Magnitude and Phase or dB Magnitude and Phase. If you are already familiar with S-parameters you can skip this review and move onto the next section. If you are used to working in Volts or Millivolts vs time then you will find that spending a few minutes learning S-parameters is a worthwhile investment of time. Understanding S-parameters is the second step in understanding VNA data.

A 2-port network (e.g. device) is defined by the following diagram:

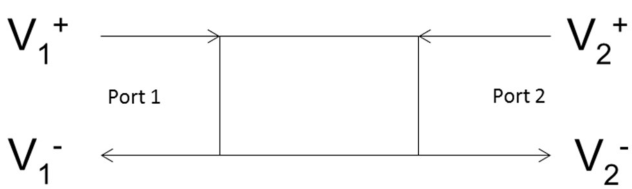


Figure 3: Voltage Definition of a S-parameters for a 2-port network

NOTE: Voltage V_1^+ and V_1^- are not Differential Voltages, they are Incident and Reflected Voltages

If a Voltage V_1^+ is applied to port 1 the energy can be reflected back to the generator as V_1^- or it can be transmitted through the network and arrive at port 2 as V_2^-. NOTE: Always use the voltage definition in Figure 3 when defining S-parameters. Also note that Voltage V_1^+ and V_1^- are not Differential Voltages, rather they are Incident and Reflected Voltages, respectively. Similarly, if a Voltage V_2^+ is applied to port 2 some of the energy can be reflected back to the generator as V_2^- or it can be transmitted through the network and arrive at port 1 as V_1^-. S-parameters for a 2-port network are defined as the following:

$S_{ii} = V_i^- / V_i^+ = \Gamma_i$

Γ is the Reflection Coefficient

$S_{11} = V_1^- / V_1^+ \mid V_2^+ = 0$

$S_{21} = V_2^- / V_1^+ \mid V_2^+ = 0$

$S_{22} = V_2^- / V_2^+ \mid V_1^+ = 0$

$S_{12} = V_1^- / V_2^+ \mid V_1^+ = 0$

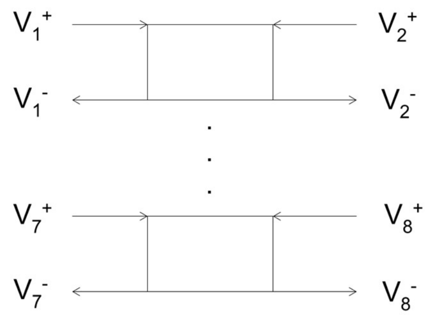
S_{11} is commonly called Return Loss. S_{21} is commonly called Insertion Loss.
Symmetry is defined for a 2-port network as:

$S_{11} = S_{22}$

and reciprocity is defined for a 2-port network as:

$S_{21} = S_{12}$

As seen in the definitions, S-parameters are ratios of numbers. Logarithms are also ratios of numbers and units of dBs work naturally with S-parameters. Figure 4 provides a voltage definition of an 8-port network and Figure 5 illustrates the Scattering Matrix of an 8-port network.



$$S_{88} = V_8^- / V_8^+ \qquad S_{87} = V_8^- / V_7^+$$

Figure 4: Incident and Reflected Voltage Definition of a S-parameters for an 8-port network

$$\begin{matrix} S_{11} & S_{12} & S_{13} & \cdots & S_{18} \\ S_{21} & & & & \vdots \\ S_{31} & & & & \\ \vdots & & & & \\ S_{81} & & \cdots & & S_{88} \end{matrix}$$

Figure 5: The Scattering Matrix for an 8-port VNA

If a 1 Volt signal is applied to Port 1 of a passive device S-parameters can be used to quickly and easily identify where the energy has gone. For example,

S_{11} = - 18 dB at 2.5 GHz

S_{21} = - 20 dB at 2.5 GHz

S_{11} = - 18 dB = -6 dB – 6 dB – 6 dB = 1/2/2/2 = 0.125 * 1 = 0.125 V is reflected back to the generator from port 1. This means that 0.875 V is transmitted into the device and a fairly good impedance match has been achieved per the definition of Γ the refection coefficient. S_{21} = - 20 dB = 0.100* 1 V = 0.1 V. This means that 0.1 V is transferred through the DUT to port 2 of the device and 0.775 V was lost in the device. Notice: the Law of Conservation of Energy expressed in S-parameters results in the formula

$S_{11}^2 + S_{21}^2 \leq 1$

For a passive device this equation is valid in the following formula:

Loss in [%] = $(1 - (S_{11}^2 + S_{21}^2)) \times 100\%$

4 Signal to Noise Ratio and System Dynamic Range

Signal to Noise Ratio and System Dynamic Range is a topic that is very detailed and requires a lot of training to understand. This section is meant to serve as a brief introduction to the topic to illustrate a major advantage of a VNA. The VNA offers the measurement advantage of high Signal to Noise ratios and High System Dynamic Range.

Signal to Noise Ratio = SNR = S/N

The theoretical noise floor of a receiver can never be lower than this simple Noise Power definition

Noise Power = P^n = kTB

where k = Boltzmann's Constant = 1.38×10^{-23} J/K

T = Temperature in Kelvin = 290 K for room temperature

B = Bandwidth in Hz

Vector Network Analyzers are capable of achieving very low noise floors when using a 1 Hz and 10 Hz Intermediate Frequency Bandwidths. The noise floor that is calculated using this equation is the smallest value that can be achieved, and a real noise floor will be 25 to 40 dB higher than this value.

A general definition of Dynamic Range is the desired (usually linear) operational range of a component or system. VNAs are capable of achieving high dynamic ranges because the Test Signal is large when compared to the receiver noise floor. Nonetheless, Linear System Dynamic Ranges of 140 dB are possible with VNAs. If one excites a Device Under Test with 10 mW (e.g. 10 dBm), a Signal to Noise Ratio of 120 dB is achievable (1,000,000,000,000 = 120 dB).

When using a 20 GHz bandwidth, as is common with a High-Speed Scope, one can calculate that the Noise Power is about 102 dB higher than a VNA with a 1 Hz Intermediate Frequency. VNAs are much more capable of "seeing though" high losses of DUTs and with high accuracy because a high SNR is maintained. If a 20 GHz Bandwidth Time Domain Scope has 30 dB of Dynamic Range, and a DUT with 30 dB of loss is being measured, a SNR of 0 dB is achieved and no intelligible data can be recovered from this measurement.

5 Benefits of an 8-port VNA

5.1 Reduction in Test Time

A significant reduction in test time by at least a factor of 3 can be achieved on a DUT that has two differential pairs by migrating from a 4-port measurement system to an 8-port measurement system. For example, 2 differential pairs that requires Differential Insertion Loss (SDD21), Differential Return Loss (SDD11), NEXT, Intra-Pair Skew, Inter-Pair Skew requires a minimum of 3 test setups as Illustrated in Figure 7. Using an 8-port VNA reduces 3 test setups to 1 test setup as illustrated in Figure 6. There can be additional test setups when debugging a design, and all of these test setups already exist in the 8-Port VNA test setup.

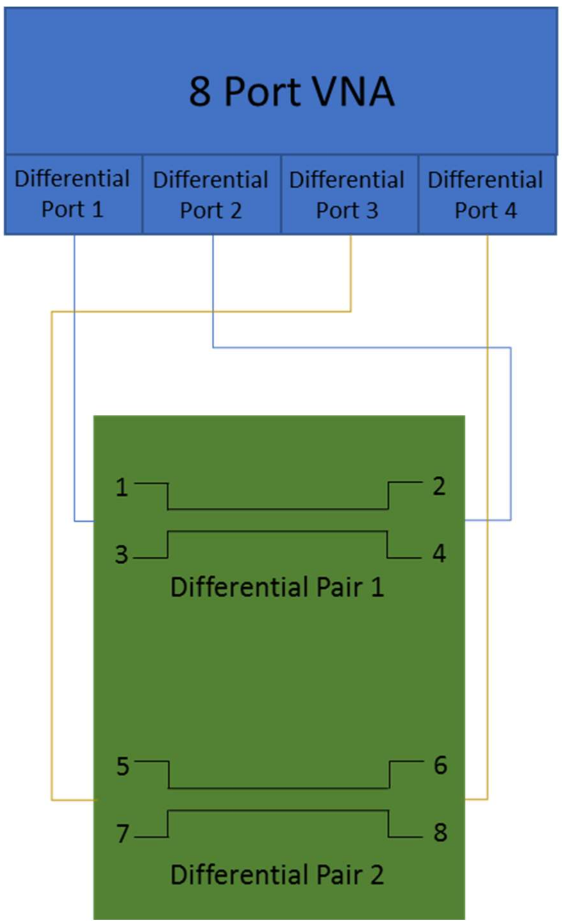


Figure 6: 8-port VNA Test Setup on 2 Differential Pairs

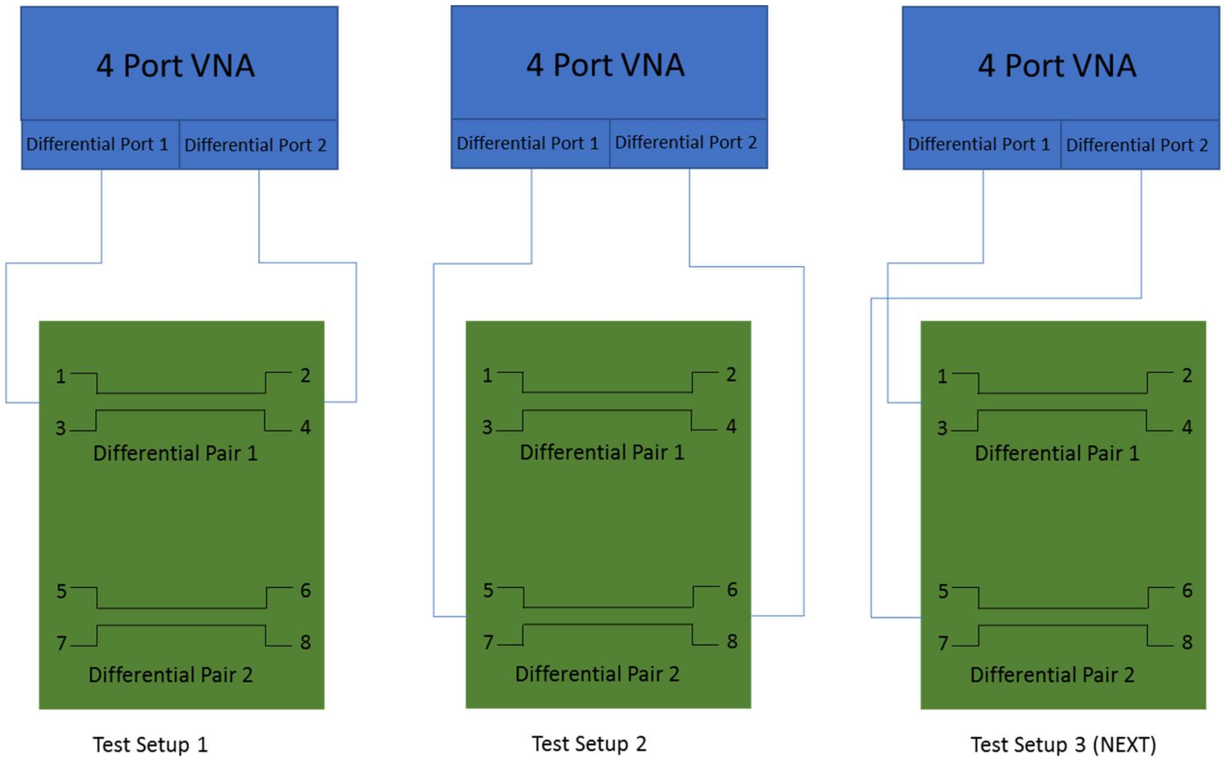


Figure 7: Basic Test Setups using a 4-port VNA for 2 Differential Pairs

Differential Insertion Loss (SDD21), Differential Return Loss (SDD11) and Near End Cross Talk (NEXT) require 3 test setups using a 4-port test set as illustrated in Figure 7. Each Differential Port requires 2 Single Ended Ports, and two differential ports require a total of 4 Single Ended Ports. Test Setup 1 in Figure 7 can be used to evaluate Differential Insertion Loss (SDD21), Differential Return Loss (SDD11), Differential to Common Mode Conversion (SCD21), Common Mode to Differential Mode Conversion (SDC21) and Intra-Pair Skew on Differential Pair 1. Test Setup 2 in Figure 7 can be used to evaluate SDD21, SDD11, SCD21, SDC21, and Intra-Pair Skew on Differential Pair 2. Test Setup 3 in Figure 7 can be used to evaluate Near End Cross Talk (NEXT). These 3 test setups can be replaced with a single test setup as shown in Figure 6.

When migrating from 3 test setups to 1 test setup, time savings of greater than 3 times can be achieved. Engineers and technicians are encouraged to evaluate their situation and come to their own conclusion by performing evaluations with VNA demonstration units. This can also reduce the number of mating cycles of the test cables and increase their life, thus decreasing the probability of damage to them. Similarly, this can reduce the number of mating cycles of the Device Under Test (DUT) or it’s test fixture and decrease the probability of damage to it.

5.2 Increased Measurement Accuracy from Reduced Thermal Drift

Measurement accuracy due to thermal drift (e.g. changes in room temperature) can also be increased by migrating from a 4-port VNA to an 8-port VNA. The temperature of test laboratories can vary by 1 or two degrees over the course of a day and this can result in small errors that can have a significant impact. The temperature of production settings can vary by several degrees or more over the course of a day and this can also result in small errors that can have a significant impact on product scrap rates.

For example, a DUT can have an Intra-Pair Skew requirement of < 10 ps and the expected skew can range from 7.5 ps to 9.5 ps. If lane 1 is measured in the morning on test setup 1 and lane 2 is measured in the afternoon, small changes in mechanical dimensions of the DUT due to thermal change (e.g. metals expand and contract with changing temperature) can result in small changes in propagation delay. This small change in mechanical dimension can occur in the DUT as a result in temperature change. While the VNA is temperature-stabilized and can be re-calibrated, the DUT behavior may change. Dielectric constants can also change with temperature, and dielectrics (e.g. insulators) expand and contract differently than metals.

While trying to predict what will happen to a DUT as temperature changes can be difficult, the situation can be avoided altogether by migrating to an 8-port VNA. All of the measurements are made at the same time with an 8-port VNA and one can assume the temperature of the DUT is constant over the course of the measurement. [NOTE: This comparison is being made to a 4-port test setup where one differential pair can be tested in the morning, and the other differential pair may be tested in the afternoon, or the next day, or some other time in the future] For an extremely tight tolerance component having an Intra-Pair Skew requirement of < 10 ps, having the entire device tested at a single moment in time (< 1 millisecond), at a single temperature, can be very advantageous to product scrap rates. Engineers and technicians are encouraged to evaluate their situation and come to their own conclusion by performing evaluations with VNA demonstration units.

A single test setup also eliminates connecting, disconnecting and reconnecting test cables to different DUT or DUT Test Fixture connectors. This has multiple advantages. The movement and flexure of the test cables to change test setups is eliminated. This helps to minimize phase and amplitude changes in the test cables due to cable movement and increases the life of the test cables. While cable movement results in small errors, it can cause extremely tight tolerance components with Intra-Pair Skew requirement of < 10 ps to fail a production test.

A hypothetical system level use of a Skew budget is illustrated in Figure 8. An Intra-Pair Skew requirement of < 10 ps may seem ridiculous to some engineers, but in many cases, it is necessary. If an end-to-end Intra-Pair Skew budget is 150 ps and 50 ps are used in each circuit board, that leaves 50 ps of Intra-Pair Skew for everything that connects the two circuit boards (connectors, backplane connector pinfield, cables, etc.). In many cases, DUTs are passing by very small margins. Migrating from a legacy test system to a new test system, and the increased accuracy that comes with it, can have a significant impact on product scrap rates. If a good Signal to Noise Ratio is maintained, a legacy test set that has a phase accuracy of +/- 2 degrees can be replaced with a modern test set that has a better phase accuracy of 0.4 degrees (see Table 1).
The phase accuracy can be converted into a runtime difference $\Delta\tau$ if the frequency span Δf is known:

$$\Delta\tau = \Delta\varphi(\text{radian}) / \Delta\varpi = \Delta\varphi(\text{degree}) * 2\pi / (360^\circ\ 2\pi * \Delta f) == 0.4^\circ / 360^\circ / 2\ \text{GHz} = 0.5\ \text{ps}\ (\text{with}\ \Delta f = 2\ \text{GHz})$$

The time difference can be 10 ps vs 9.5 ps. For DUTs that are testing just under the test limit line this can make the difference between scrap rates. Engineers and technicians are encouraged to evaluate their situation and come to their own conclusion by performing evaluations with VNA demonstration units.

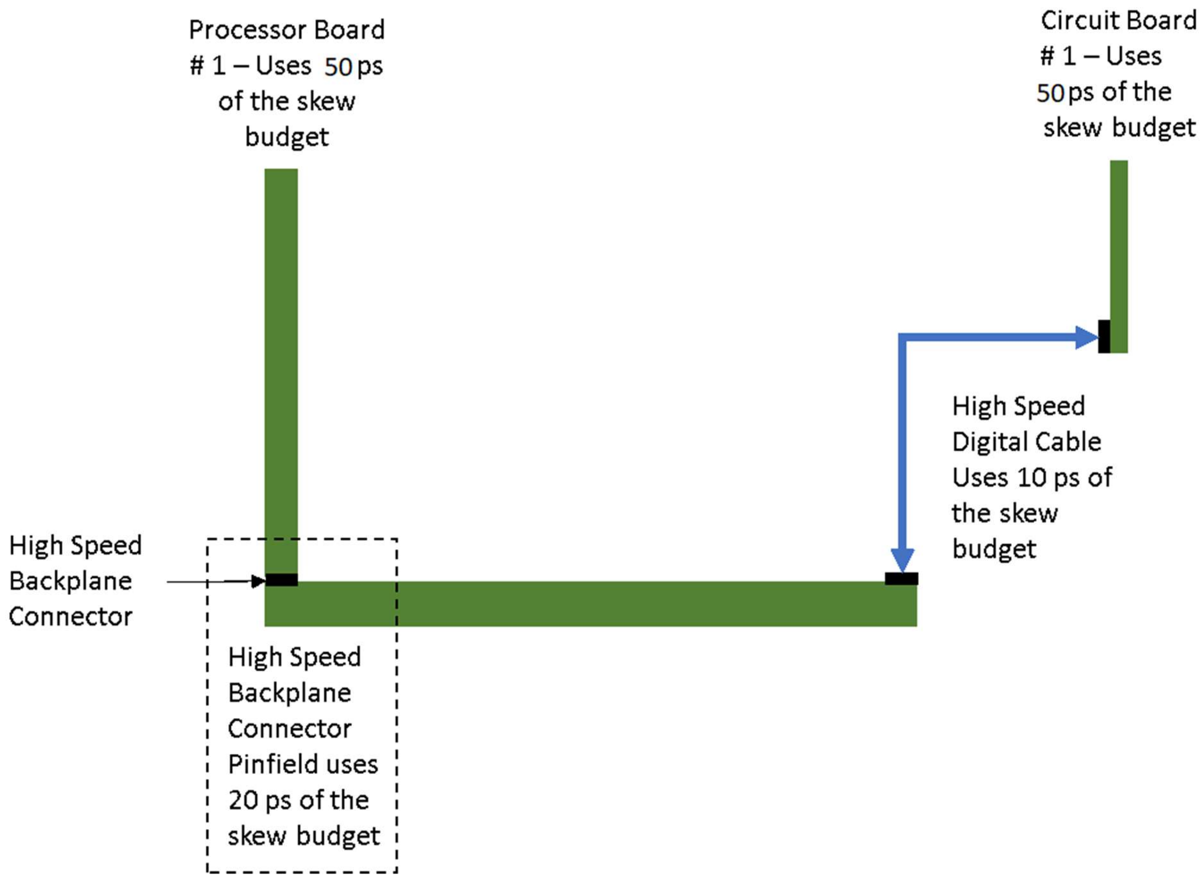


Figure 8: Illustration of System Level use of the Skew Budget

Table 1: Amplitude and Phase Accuracy of a Rohde and Schwarz ZNBT 20

Accuracy of transmission measurements		Magnitude	Phase
100 kHz to 10 GHz	+5 dB to –35 dB	≤ 0.05 dB	≤ 0.4°
	–35 dB to –50 dB	≤ 0.15 dB	≤ 1.0°
	–50 dB to –60 dB	≤ 0.25 dB	≤ 1.7°
10 GHz to 18 GHz	+5 dB to –35 dB	≤ 0.06 dB	≤ 0.4°
	–35 dB to –50 dB	≤ 0.15 dB	≤ 1.0°
	–50 dB to –60 dB	≤ 0.25 dB	≤ 1.7°
18 GHz to 20 GHz	+5 dB to –35 dB	≤ 0.06 dB	≤ 0.4°
	–35 dB to –50 dB	≤ 0.15 dB	≤ 1.0°
	–50 dB to –60 dB	≤ 0.25 dB	≤ 1.7°
Specifications are based on a matched DUT, a measurement bandwidth of 10 Hz and a nominal source power of –10 dBm.			

Remark:
Due to time domain transformation phase values cannot be calculated directly into skew values.

One should also not depend on measurement error to pass a test. One may expect that a measurement error of 2 degrees can work in their favor and help them to pass a test. In reality, measurement error doesn't work this way. Sometimes it is 2 degrees in your benefit, other times it is 2 degrees that is not to your benefit, and anywhere in between.

An increase in the life of a test cable occurs when migrating from a 4-port VNA to an 8-port VNA. This occurs because the test cable connectors have a finite number of mating cycles. A connector pair mating cycle is defined as each time the cable connectors are connected to a test setup and disconnected. When testing 2 Differential Pairs with a 4-port VNA, there are 3 test setups and 3 mating cycles. When testing 2 Differential Pairs with an 8-port VNA, there is 1 test setup and only one mating cycle. Reducing the number of mating cycles will increase the life of the test cables and the DUT or the life of its test fixture.

Decreasing the number of mating cycles also decreases the probability of damage to a test fixture or a DUT. When a test fixture connector is worn out or damaged failures can be intermittent. When intermittent connections occur one test can fail and the very next test can pass, making intermittent issues very difficult to detect. Replacing worn out test fixtures is used as preventive maintenance to prevent issues. Migrating to an 8-port VNA from a 4-port VNA can decrease the frequency of preventive maintenance.

6 Real World Troubleshooting Scenario using an 8-port VNA

The following two sections are composed of a Differential section and a Single Ended section. The Differential Data and Troubleshooting section contains the Undesired Degraded Backplane vs. the Desired Clean Backplane Differential VNA Data measured on an R&S®ZNBT20 in the Differential measurement configuration. The Single Ended Data and Troubleshooting section contains the Undesired Degraded Backplane vs. the Desired Clean Backplane Single Ended VNA Data measured on an R&S®ZNBT20 in the Single Ended measurement configuration.

6.1 Differential Data and Troubleshooting

A heavily degraded eye and a clean eye were measured on an 8-port R&S®ZNBT20 Vector Network Analyzer and are illustrated in Figure 1. Figure 2 shows the TDR data plots of the degraded and clean backplane differential pairs measured on the same VNA. While Time Domain data provide valuable information, the data do not provide all of the information needed to assess a High-Speed Digital Channel. Using a Fourier Transform of the Time Domain Data allows one to calculate the Frequency Domain data, and the Inverse Fourier Transform of the Frequency Domain allows one to calculate the Time Domain. The advantages of using a VNA and working in the Frequency Domain are listed in the previous sections. The features of VNA Frequency Domain S-parameter data will now be used to quickly and easily identify the issues that are causing the degraded eye of Figure 1. The Degraded Eye will be the starting point and multiple S-parameter data plots will be analyzed. NOTE: Fractions of decibels are disregarded in this discussion and whole number decibel values are used to facilitate a rapid understanding of the concepts put forth.

Figure 9 is a larger image of the Degraded Eye Diagram in Figure 1 to allow more detail to be seen (eye maximum, eye minimum, etc.). While not present, the Eye Mask can easily be defined against any test standard and displayed in the diagram.

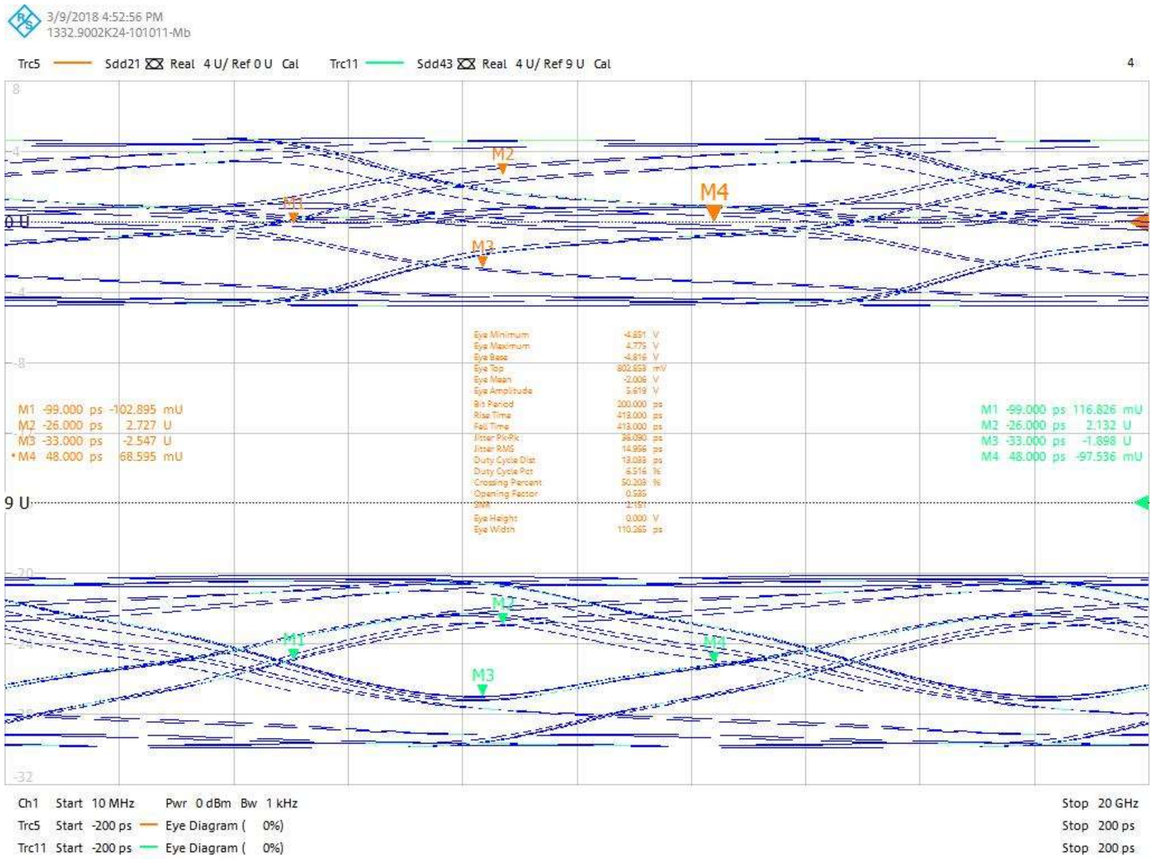


Figure 9: Degraded Eye Diagram of a 20” Backplane measured with a R&S®ZNBT20

The Differential Return Loss SDD11 in Figure 10 is showing poor performance on Trace 8 (light green trace). It can be seen that there is an issue with this differential pair because the Differential Return Loss is approximately -5 dB (-5 dB = 0.32) where indicated by the red arrow. On closer examination, it can be seen that the performance of Trace 6 is also worse than Trace 2 and Trace 7. Trace 2 and Trace 7 have consistent behavior while Trace 6 is more erratic, while Trace 8 is very erratic. This illustrates a major advantage of working with S-parameters; one can clearly see there is something wrong with Trace 8 by simply noticing that Trace 8 is performing about 15 dB worse than the other traces at about 11 GHz. This is a significant advantage of working with S-parameters in the frequency domain. Time Domain Analysis does not accommodate this intuitive insight.

At the fundamental frequency of 2.5 GHz (5 Gbps) the Differential Return Loss is about -12 dB as indicated by the dashed turquoise line.

An SDD11 of – 12 dB means that a significant amount of power is being transferred into the DUT and very little power is being reflected back to the VNA. 63 mW of every Watt injected into the DUT is reflected back to the VNA signal generator. Similarly, 0.3V of every 1 Volt is reflected back to the VNA signal generator.

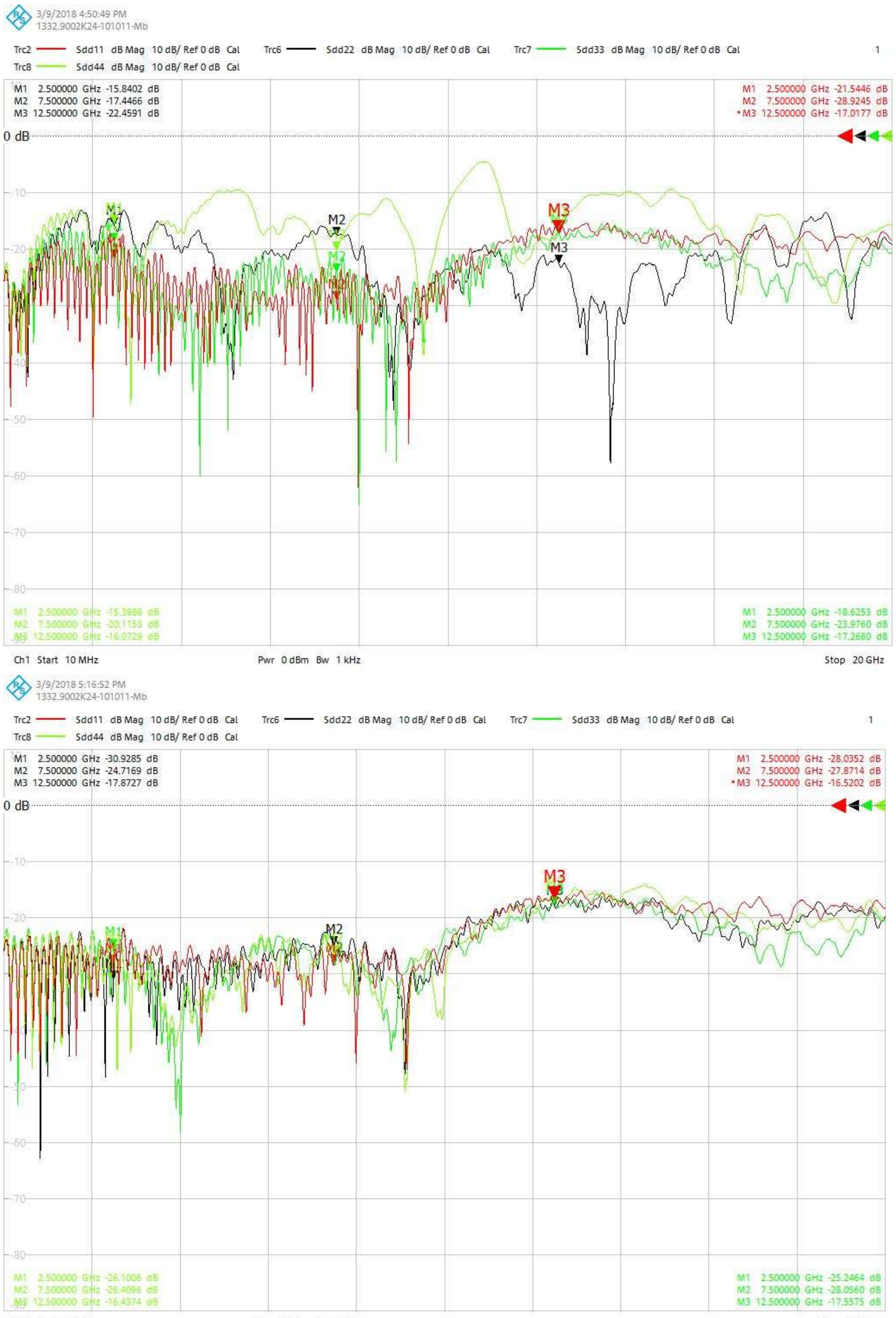


Figure 10: Differential Return Loss SDD11 of the Undesired Degraded Backplane vs. the Desired Clean Backplane

The Differential Insertion Loss SDD21 of the green Trace 3 of Figure 11 shows there is 15 dB of loss at 2.5 GHz as indicated by Marker 1. Marker 1's value is displayed in the bottom right corner of the left image of Figure 11. A loss of 15 dB means approximately 31 mW of every 1 Watt launched into the DUT is propagated through the DUT. Similarly, 178 mV of every 1 Volt launched into the DUT is propagated through the DUT.

Additionally in the measurement shown in figure 11, an extremely large loss of approximately 27 dB in the green Trace 3 at 2.1 GHz is indicated by the red arrow. One should also notice that this minimum occurs at a periodic rate as indicated by the blue lines with arrows on both ends. Periodic behavior of the transmission indicates that there are two flaws on the line causing multiple reflections and interferences. Their distance from each other Δl can be calculated from the frequency period Δf: $\Delta l = c / (2^*\Delta f)$. With Δf here being around 4 GHz, a distance of about Δl = 38mm between two discontinuities results.

Additional analysis of the Differential Insertion Loss SDD21 of Figure 11 shows that there is an extremely large loss in blue Trace 9 at marker 2 at 7.5 GHz (e.g. third harmonic of 2.5 GHz). The value is approximately – 26 dB, or 26 dB of loss. This is an excessive amount of loss for a High-Speed Digital backplane and the third harmonic of the signal will be heavily attenuated by this Differential pair.

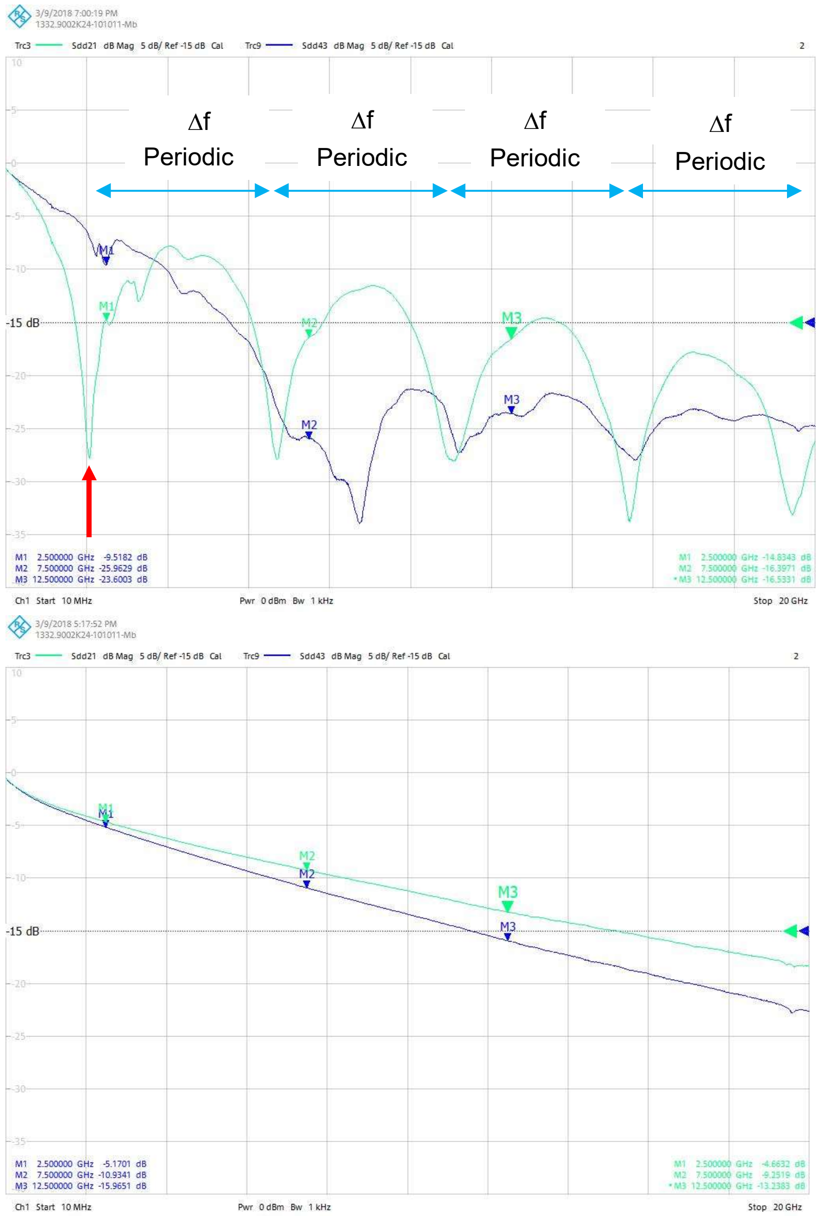


Figure 11: Differential Insertion Loss SDD21 of the Undesired Degraded Backplane vs. the Desired Clean Backplane

Figure 12 shows there is an extremely excessive amount of Differential Signal (e.g. Odd Mode) being converted to Common Mode Signal (e.g. Even Mode) by analyzing the Differential to Common Mode Conversion traces SCD21 and SCD43. A peak conversion occurs at approximately 2.1 GHz and its value from the data plot is approximately – 5dB, while its value at 2.5 GHz is approximately -7 dB as indicated by the marker. This peak value at 2.1 GHz correlates to the maximum loss that occurs in Trace 3 of Figure 11. One should also notice there is also a periodic nature in this trace as well as indicated by the turquoise arrows. Information about the distance of the two interfering discontinuities (flaws) that are causing the degraded eye can be determined from the periodicity of these frequencies. Additional analysis of the Differential to Common Mode Conversion of Figure 12 shows there is significant conversion of Differential to Common Mode signal in the entire backplane. This conversion translates to an excessive amount of loss for a High-Speed Digital backplane. Analysis of the backplane in the Frequency Domain is providing valuable information that the time domain simply cannot provide.

Further analysis of the Common Mode to Differential Mode Conversion SDC21 and SDC43 of Figure 12 shows that a significant amount of the Common Mode energy is being converted back to Differential Mode. From the SDC21 and SDC43 data plots of Figure 12 it can be seen these signals are approximately 12 dB below the fundamental amplitude of 0 dBm (1 mW). NOTE: The peak value just below 2.5 GHz is used for this discussion. This means that the best Signal to Noise Ratio that can be achieved in the communications system using this backplane is 12 dB. Additionally, one can accurately determine when these signals arrive at the receiver due to the undesirable design issues in the backplane using this same VNA test setup. As illustrated in Figure 13 the signals are arriving at the receiver separated by 43 degrees of phase (Trace 46 – Trace 44) and 36 degrees of phase (Trace 47 – Trace 45). Phase measurements that are performed by VNAs are extremely accurate and the phase accuracy of a R&S®ZNBT40 is illustrated in Table 1. The meaning of these data plots is now summarized.

The receiver has two signals arriving, a fundamental signal and a second signal that is 12 dB smaller in amplitude and arriving 40 degrees later than the fundamental signal. The SDC21 signal is an error signal because it is undesirable and it is interfering with the fundamental, or primary, signal. Since it has the same effect as stochastic noise, the best Signal to Noise Ratio that can be achieved in a communications link that uses this backplane is approximately 12 dB.

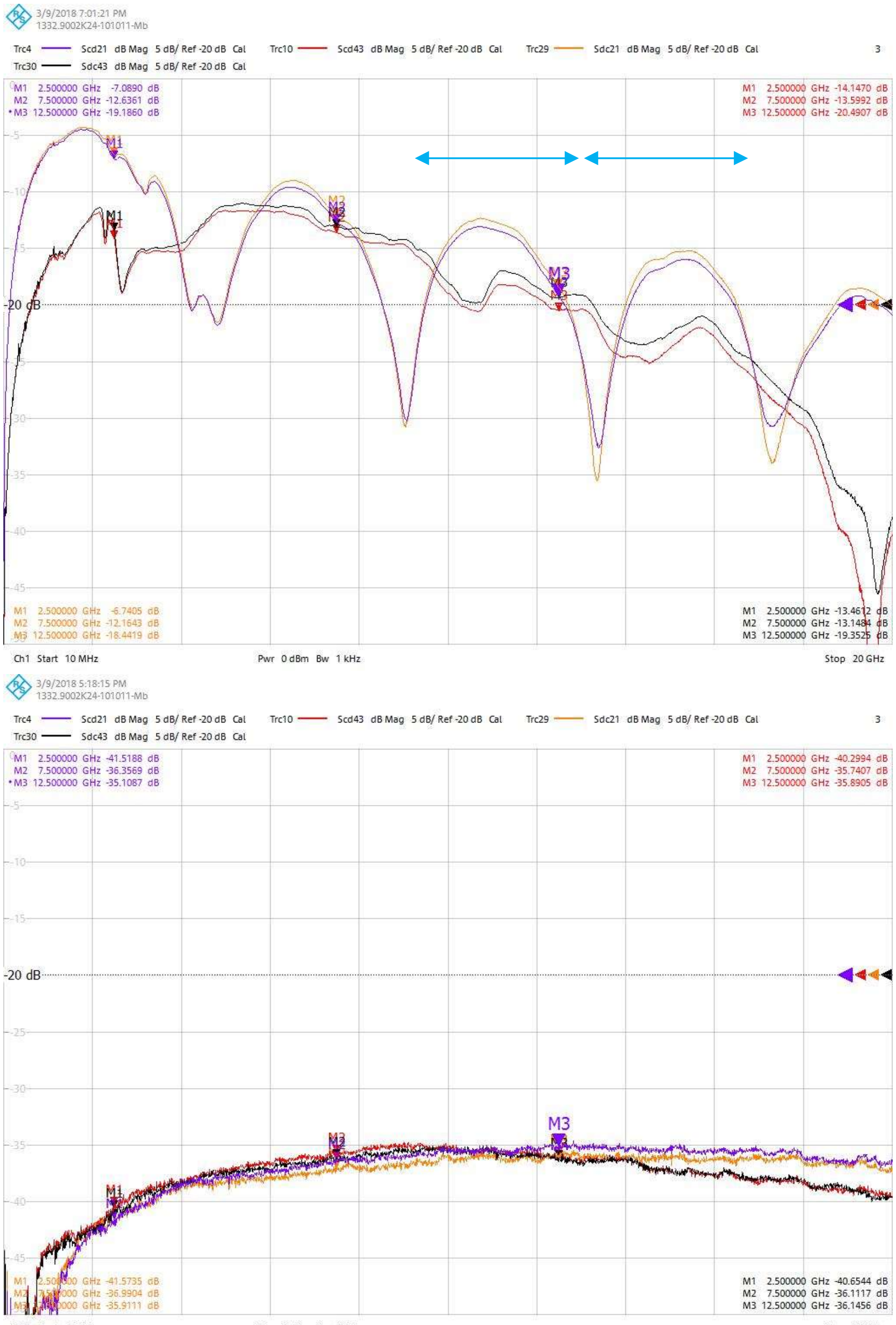


Figure 12: Differential to Common Mode Conversion SCD21 and SDC21 of the Undesired Degraded Backplane vs. the Desired Clean Backplane

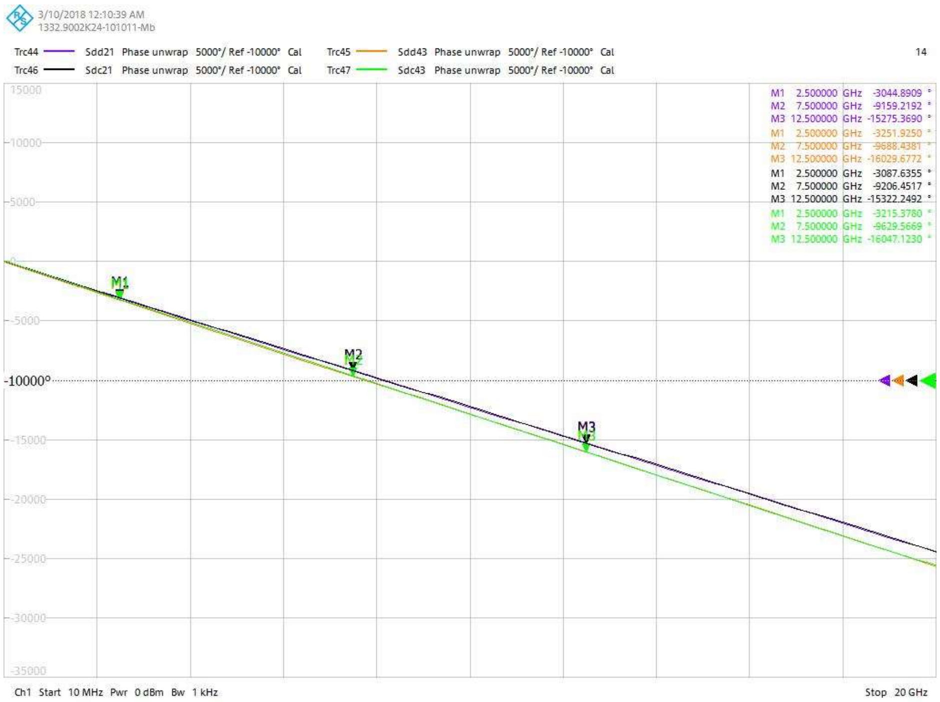


Figure 13: Common Mode to Differential Mode Unwrapped Phase (degrees)

The Near End Cross Talk (NEXT) and the Far End Cross Talk (FEXT) definition is

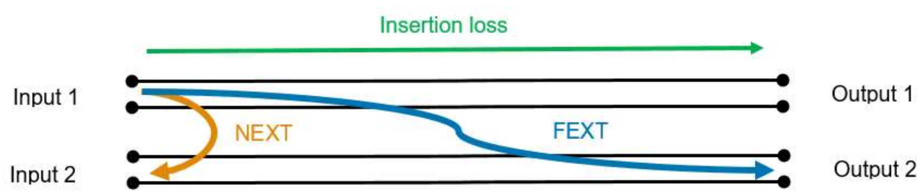


Figure 14 NEXT and FEXT definition for differential lines

illustrated in Figure 14. Analyzing the NEXT data plots of Figure 15 shows there is significant coupling between the two differential pairs of the High-Speed Backplane. The coupling between the two differential pairs is approximately - 15 dB in the green Trace 35 data plot, while the coupling between the two differential pairs is approximately - 26 dB in the red Trace 34 data plot. What is the Difference and what should one measure NEXT at both ends of the DUT? In order to understand what these data plots say; the test setup needs to be examined. Figure 16 illustrates the NEXT test setup, where the black arrow represents the coupling between the two differential pairs port 1 and port 3 at one end of the backplane, and the copper colored arrow represents the coupling between the two differential pairs port 2 and port 4 at the opposite end of the backplane. The Red Trace Sdd31 is the NEXT at one end of the Backplane, while the Green Trace Sdd42 is the NEXT at the other end of the backplane. The difference in amplitude between the two traces is approximately 11 dB. This difference tells us the coupling is occurring on the larger amplitude Sdd42 side (physical ports 2, 4, 6 and 8) - of the test setup in Figure 16.

Using an 8-port VNA allows these two measurements to be performed using a single test setup, while a 4-port VNA would require a 4th test setup.

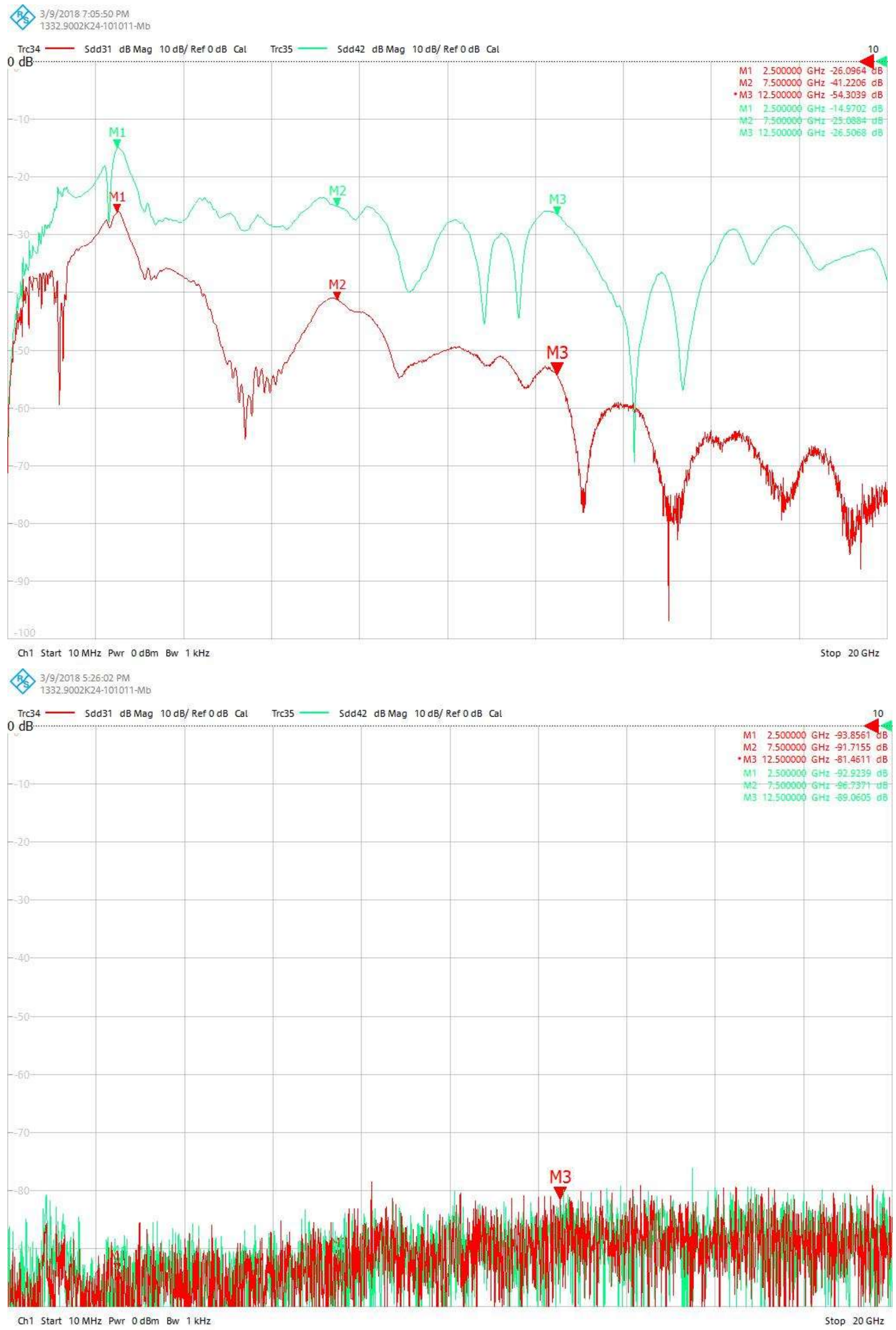


Figure 15: Differential Near End Cross Talk (NEXT) of the Undesired Degraded Backplane vs. the Desired Clean Backplane

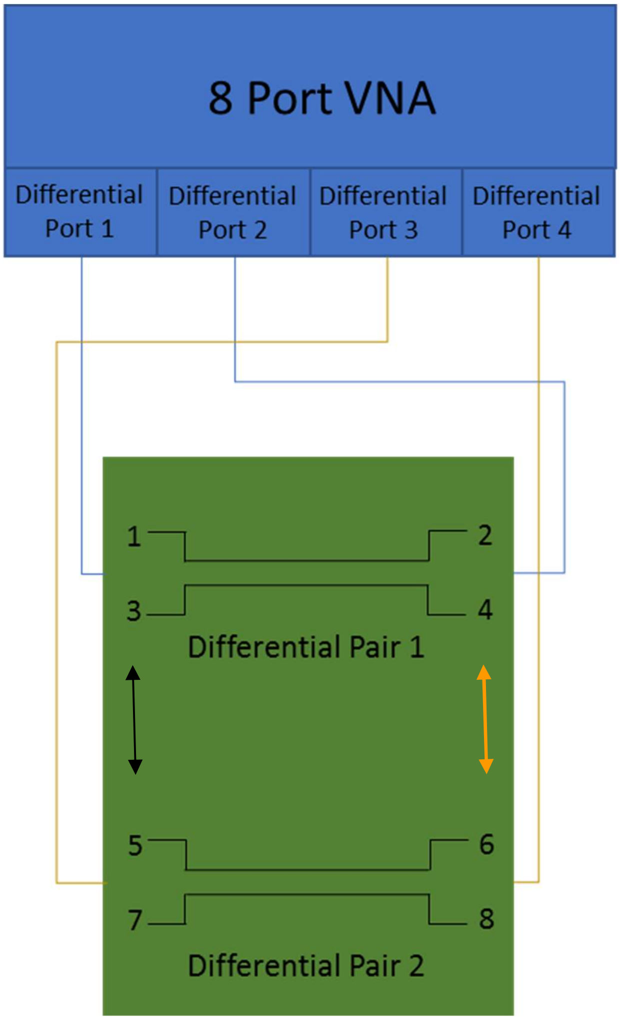


Figure 16: 8-port VNA and Backplane Near End Cross Talk (NEXT) Test Setup

Figure 17 illustrates the Far End Cross Talk (FEXT) that is present in the degraded backplane. While there aren't significant differences between the two traces at 2.5 GHz, these traces confirm there is something wrong with the backplane that is being measured. The FEXT measurement shows the two differential lanes are coupled at approximately 18 dB at 2.5 GHz. The purple Trace 36 of Figure 17 is represented by the copper arrow in Figure 18, while the gold Trace 37 of Figure 17 is represented by the black arrow in Figure 18.

At the fundamental frequency of 2.5 GHz, the coupling of -18 dB means 125 mV of noise is induced into the second differential pair by the first differential pair, and vice versa, for every 1V that is propagated down the transmission lines. What is the difference between the NEXT and the FEXT measurements? The NEXT measurement is evaluating the Odd Mode Coupling while the FEXT is evaluating the Even Mode Coupling.

The phase of the FEXT can also be measured and used to determine when this signal will arrive at the receiver, relative to the Primary Signal and the SDC21 Component of the Signal. This is similar to the unwrapped phase measurement that is provided in Figure 13.

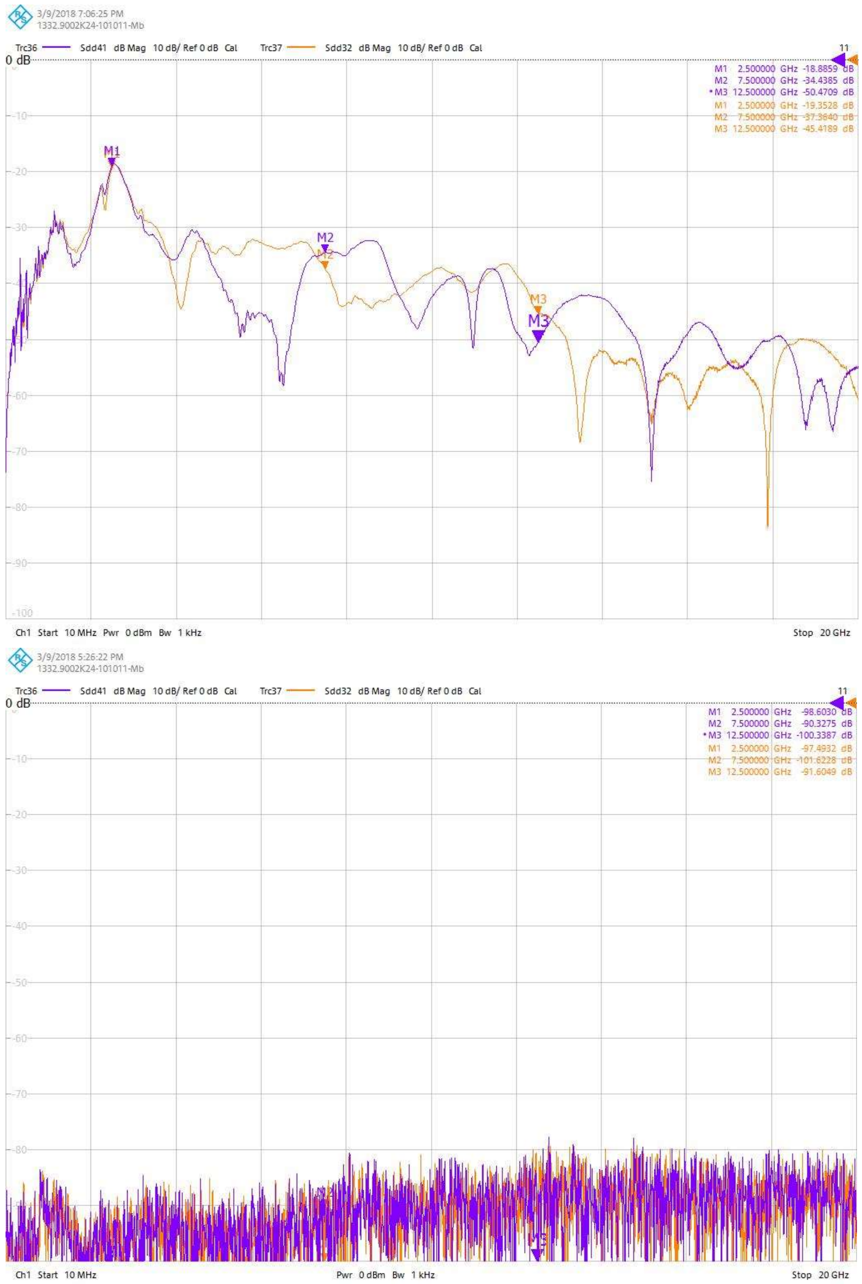


Figure 17: Differential Far End Cross Talk (FEXT) of the Undesired Degraded Backplane vs. the Desired Clean Backplane

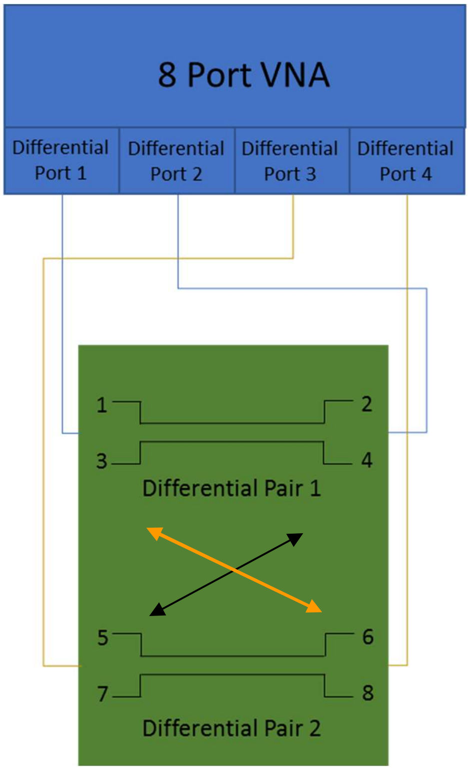


Figure 18: 8-port VNA and Backplane Far End Cross Talk (FEXT) Test Setup

6.2 Single Ended Data and Troubleshooting

Differential S-parameters were analyzed in the previous sections. While valuable, they do not provide information about exactly which member, or trace, of the differential pair is causing an issue. It can be one trace or the other, or both. Single ended S-parameters can be used to determine if one member of a differential pair is worse than the other. This can greatly assist a design engineer in determining exactly where a design issue is located.

The Single Ended Return Loss S_{11} is illustrated in Figure 19. One can immediately see there is a significant impedance mismatch on two of the conductors that are being represented by the blue Trace S_{55} and the red Trace S_{77}. This plot shows the ratio of the reflected energy to the incident energy is approximately 4 dB at 2.5 GHz. This is a high amount of Return Loss, and these single ended data plots allow one to determine the individual trace of the differential pair that is causing the Eye Diagram to close. From this data plot it can be seen that there are two traces that have an issue.

Figure 19: Single Ended Return Loss S11 of the Undesired Degraded Backplane vs. the Desired Clean Backplane

The Single Ended Insertion Loss S_{21} is illustrated in Figure 20. One can immediately see there is significant loss on two of the conductors that are being represented by the purple Trace S_{65} and the golden Trace S_{87}. This plot shows the ratio of the transmitted energy to the incident energy is approximately -14 dB. This is a high amount of loss, and these single ended data plots allow one to determine the individual trace of the differential pair that is causing the eye diagram to close. From this data plot it can be seen that there are two traces that have an issue, and these data plots confirm the conclusions drawn from Figure 19.

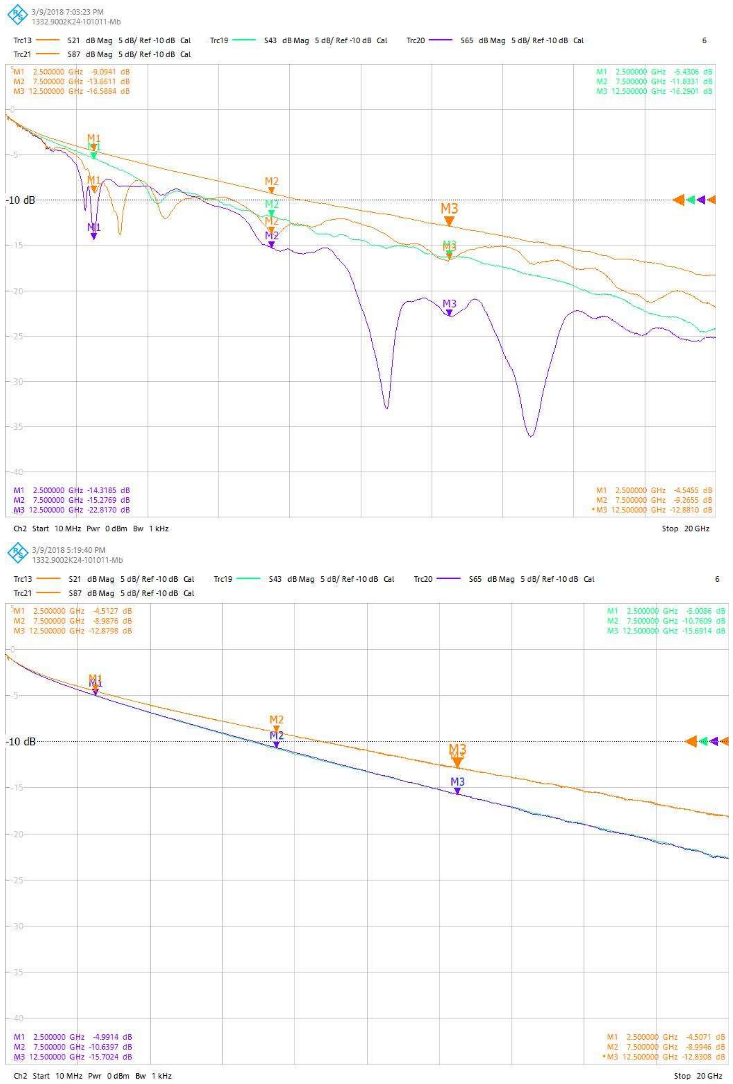


Figure 20: Single Ended Insertion Loss S_{21} of the Undesired Degraded Backplane vs. the Desired Clean Backplane

An accurate way to evaluate the propagation delay through a transmission line, or differential pair, is to analyze the Single Ended Insertion Loss S_{21} Unwrapped Phase as illustrated in Figure 21. The Single Ended Insertion Loss Unwrapped Phase is the time delay of a signal in degrees of signal phase that propagates down a single conductive member of a differential pair. This is an extremely accurate method to determine the electrical length, or time delay, of a transmission line. From these data plots it can immediately be seen that there are multiple significant issues with two members of a differential pair. The first thing one notices are the misalignment of the traces in the upper data plot of Figure 21. Upon closer inspection one can see that the violet trace is approximately 160 degrees of phase faster than green trace. For a digital NRZ signal a bit period is 180 degrees of phase and this delay is 160 degrees of phase. This signal arrives almost an entire bit period ahead of its differential partner. This phase delay will manifest itself as the high differential to common mode conversion that is seen in Figure 12. This gross misalignment of signals in time forces the signals to become “skewed” in time and helps to “close the eye” that is seen in Figure 9.

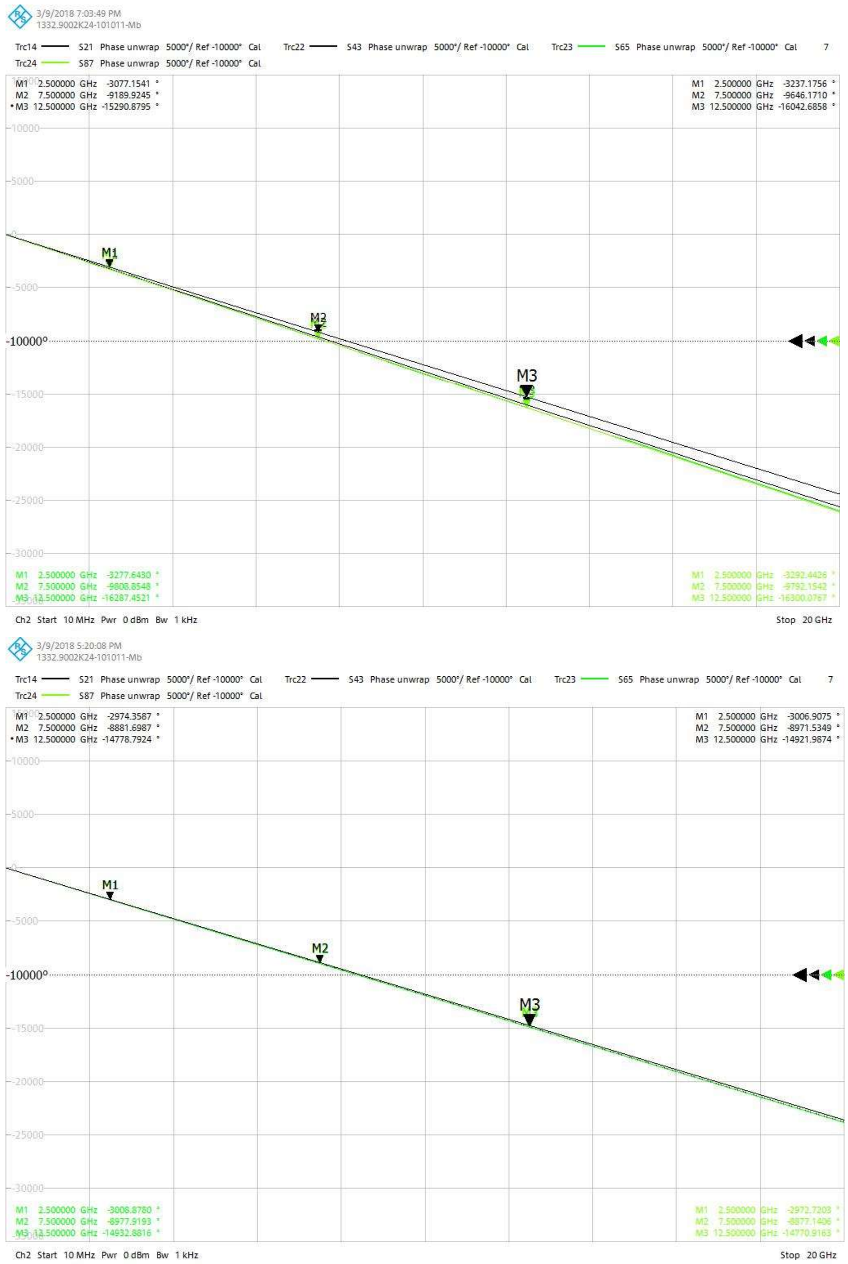


Figure 21: Single Ended Insertion Loss S_{21} Unwrapped Phase of the Undesired Degraded Backplane vs. the Desired Clean Backplane

6.3 Summary of the Frequency Domain Data.

One can conclude there are multiple significant issues with this backplane. In Figure 19 it was shown the Single Ended Return Loss is significant and this indicates a serious impedance mismatch by using $S_{11} = V_1^- / V_1^+$. In Figure 20 it was shown that there is significant loss in the single ended insertion loss plots. In Figure 21 it was shown that there is significant misalignment of the signals in time that results in excessive differential to common mode conversion and signal skew. This results from a physical length difference, and a delay caused by a coupling issue. All of the frequency domain S-parameter data plots can be taken in a single measurement set using an 8-port VNA. Time domain data including the eye diagrams and TDR plots can be derived from very accurate ZNBT-20 frequency domain data.

TDR Plots are presented in Figure 22 and Figure 23. They show the single ended impedance profiles at the input side (ports 1, 3, 5, 7). These data plots exhibit capacitive regions, relative to 50 ohms, at the ends of 3 out of 4 traces. These kinds of issues can be caused by a number of factors including traces being too close together (inductively coupled), traces running over top of one another (capacitive coupled), connector issues, dielectric issues and others. While the eye diagram is the “final test” that a DUT will undergo, it does not provide any insight into design issues. Frequency domain data provide valuable insight, such as SCD21 and SDC21, while the time domain data do as well. Having the complete time domain and frequency domain data set allows engineers to make good decisions that result in faster time to market schedules.

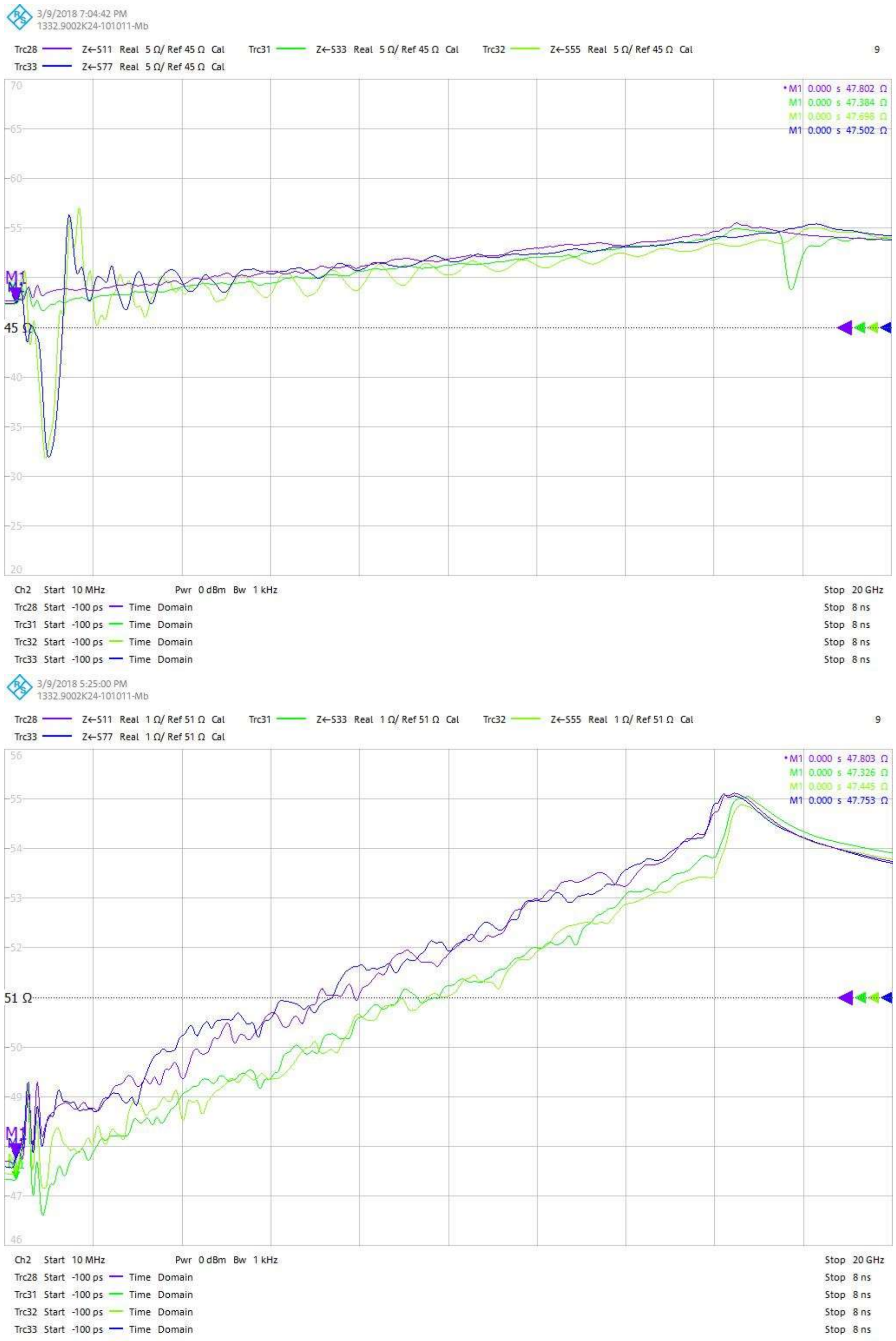


Figure 22: TDR Plots of Ports 1, 3, 5 and 7

Figure 23: TDR Plots of Ports 2, 4, 6 and 8

7 Multiport VNAs from Rohde & Schwarz

The R&S®ZNBT is the first multiport vector network analyzer offering up to 24 integrated test ports. The instrument can simultaneously test multiple DUTs or measure one DUT with up to 24 ports. It offers short measurement times even in scenarios with a large number of ports. In addition, it includes a wide dynamic range, high output power levels and inputs featuring high power-handling capacity.

The instrument is available in two different frequency ranges:

- The R&S®ZNBT8 operates in a range from 9 kHz to 8.5 GHz
- The R&S®ZNBT20, R&S®ZNBT26 and R&S®ZNBT40 operates from 100 kHz to 20 GHz, 26.5 GHz and 40 GHz, respectively.

These features make the R&S®ZNBT ideal for applications in the mobile radio, wireless communications and signal integrity. The instrument is primarily used in the development and production of active and passive multiport components such as GPS, WLAN, Bluetooth® and frontend modules for multiband mobile phones. Its outstanding performance also allows efficient analysis of base station filters and other highly selective components.

The R&S®ZNBT outperforms switch matrix based multiport systems. Its high integration density makes it a very compact solution for analyzing components with up to 24 ports while requiring no more rack space than an R&S®ZNB.

The convenient user interface makes it easy to handle even very complex multiport measurements. The R&S®ZNBT supports various remote control options and is easy to integrate into automated test systems, for example for carrying out phased-array antenna measurements. A 24 Port Rohde and Schwarz ZNBT Vector Network Analyzer is illustrated in Figure 24.

Figure 24: Rohde and Schwarz 24-Port ZNBT Vector Network Analyzer

The following are the features and benefits of an R&S®ZNBT Vector Network Analyzer.

- Platform for challenging multiport measurements
  - True multiport network analyzer
  - Multiport measurements made easy
  - Measurements at high power levels
- When speed counts
  - Short test times with a large number of ports
  - Data transfer simultaneously with sweep
  - Fast switchover between instrument setups
  - Test sequence control via TTL signals
  - Handler I/O interface for control of external parts handlers
  - Simultaneous testing of multiple DUTs
  - Segmented sweep for optimized speed and accuracy
  - Extended dynamic range for fast measurements on high-blocking filters
- Excellent measurement characteristics
  - Fast and accurate
  - High long-term stability for long calibration intervals
  - Calibration methods for every application
  - Calibration units speed up multiport calibrations
- Complex analysis of active and passive components
  - More than 100 traces and channels for characterizing complex components
  - Wide range of virtual matching networks for realtime embedding/deembedding
  - Frequency-converting measurements on amplifiers and mixers
  - Simple and fast characterization of balanced DUTs
  - Time domain analysis with gating function and display of eye diagrams
  - Voltage and current measurements
  - Measurements on frontend modules (FEMs)

For more information on the Rohde and Schwarz ZNBT Vector Network Analyzers:

https://www.rohde-schwarz.com/us/product/znbt

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management ISO 9001

Certified Environmental Management ISO 14001

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com