Characterizing Non-Standard Impedance Channels with 50 Ohm Instruments

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Introduction

- **Emerging systems are moving from the familiar 50 Ohm Single-Ended and 100 Ohm Differential Pair environment.**
  - Traditional 75 Ohm SE video applications are becoming digitized and moving to 3-6 Gbps driven by demand for High Definition and switched distribution.
  - New 85 Ohm DP based high speed data protocols are being implemented such as Intel QuickPath Interconnect ™.
- **But the vast majority of modern test instrumentation is 50 Ohm.**
  - Many long standing industry standards and test procedures are based on 50 Ohm measurements.
  - Most model extraction processes were developed using native impedance measurements.

Introduction

- **We're presented with several challenges:**
  - How do we measure non-50 Ohm components to ensure adherence to specifications?
  - How can we use this data to accurately simulate non-standard impedance channels?

Introduction

- We'll present several approaches for characterizing non-standard impedance components using standard, 50 Ohm based instruments, 50 Ohm calibration standards, and familiar calibration techniques.
- We'll compare data obtained with these approaches to data obtained from traditional dedicated test instruments.
- We'll establish guidelines for determining which procedures are appropriate for particular applications.
- We'll show how to use this data to create S-parameter models for use in channel simulations.

Introduction

- We'll present a brief background on the mathematics and theory.
- We'll demonstrate several basic procedures and approaches using a 6 GHz 75 Ohm coaxial cable assembly, and compare 50 Ohm measurement results with those made with a dedicated 75 Ohm network analyzer.
- We'll follow that with an example using an 85 Ohm differential cable assembly.
- We'll demonstrate how to extract S-parameters for this assembly, and use them in channel simulations.

Two Key Concepts

- **There are two key theoretical concepts at the core of non-standard impedance measurements:**
  - Impedance Mismatch Uncertainty Error
  - Mathematical Impedance Transformations
- **We discuss these topics with some detail in our paper, but we'll only briefly touch upon them today.**

Mismatch Error

- **A “mismatch error” occurs anytime a device in the test path deviates from its assumed ideal impedance.**
  - In the real world, very few components present ideal impedance across a wide frequency range.
  - For example, even in a high end 50 Ohm VNA, few internal components are truly 50 Ohm real + 0 Ohm imaginary across the instruments entire bandwidth range.
- **The amount of potential error caused by a non-ideal device can be quantified and used to mathematically determine bands of reasonable measurement uncertainty.**
- **Many calibration techniques have been developed to minimize or remove mismatch error in modern test instruments from the test port inward.**

Mismatch Error

- The greater the difference between the test port and the DUT, the greater the measurement uncertainty.
- Mismatch error = 1/(1+/-(ps*pl))^2 where ps and pl are the magnitudes of the source and load reflections. See reference (5).
- Assuming a 10% uncertainty boundary as acceptable, a 50 Ohm instrument can provide useful data for a DUT impedance between 2 Ohms and 1.5 Ohms. See reference (11).

Impedance Transformations

- **Within certain reasonable constraints, it is straightforward to mathematically convert data obtained at one reference impedance to represent data taken at a different reference impedance.**
  - This is a standard tool provided in most modern RF design and simulation software packages
  - Can be applied to performance parameters such as Return Loss, Insertion Loss, VSWR, and S-Parameters
  - For theoretical development, see references (2) and (3)
- **With care in test set up, validity constraints can easily be met for many components.**

Transformations Outside the Box

- **Mathematical approaches similar to those used in calibration routines can be extended from the test port outward to minimize errors when testing non-50 Ohm devices.**
  - Time Domain Gating
  - Re-normalization
  - Model De-embedding

Time Domain Gating

- **A user selected non-ideal section of the transmission path is "removed" and mathematically replaced with an ideal length of transmission line between "gate" start and stop points.**
- **Pros:**
  - Easily visualized in Time Domain
  - Can remove long length discontinuities
- **Cons:**
  - Only accounts for reflection anomalies, and phase uncertainties are not easy to quantify
  - Gate placement subject to human interpretation
  - Large discontinuities can have propagating effects that are not intuitively obvious
  - Limited suitability for developing models for circuit simulations

Renormalization

- **A calibrated measurement made in one impedance environment is mathematically transformed to another impedance environment.**
- **Pros:**
  - Vast array of off the shelf calibration methods and standards are available
  - Math is straightforward and easily automatable
- **Cons:**
  - Best suited to devices with a near instantaneous change from measurement port impedance to secondary impedance. Otherwise, multiple reference plane extensions may be required, with each extension adding uncertainty

Model De-embedding

- **A procedure based on circuit simulation techniques where a model is created for the impedance transition regions, and the effects of which are then removed via circuit simulation.**
- **Pros:**
  - Software and procedures are often familiar to RF engineers
  - Model of transition can be extracted from other measurements or through field solver simulations
  - Well suited for developing models for use in further circuit simulations
- **Cons:**
  - Accuracy of measurement is highly dependant upon accuracy of model, so uncertainty can be very difficult to quantify

External Hardware Based Approaches

- **Some approaches to non-standard impedance measurements are based upon various hardware enhancements. Some are stand-alone options, but others are often combined with mathematical approaches to offer improved accuracy.**
  - Custom Calibration Standards
  - Impedance Matching Transformers
  - Minimum Loss Matching Networks (Pads)

Custom Calibration Standards

- **Custom calibration standards can be created for most any impedance of interest. They may be based on traditional calibration methods such as SOLT or more recent approaches such as TRL.**
- **Pros:**
  - Can be extremely accurate with proper care in design and manufacture of standards
- **Cons:**
  - Design, construction, and characterization can be time consuming and costly with multiple iterations often required
  - Uncertainties in manufacturing tolerances, material properties, and computational accuracy can lead to unquantifiable measurement accuracy

Impedance Matching Transformers

- **The use of transformers (baluns or un-uns) is common at frequencies below 1 GHz.**
- **Pros:**
  - \- Very straight forward use
  - – Works well with differential measurements
- **Cons:**
  - – Stability issues can lead to repeatability problems
  - – Potential non-linearity can cause calibration mathematical assumptions to become invalid
  - – Typically limited to narrow frequency bands

Impedance Matching Pads

- **Impedance matching networks can be used to practically eliminate all reflection effects across certain frequency ranges.**
- **Pros:**
  - Can be quite accurate if the calibration is made after the impedance transformation point
  - Simple to implement
- **Cons:**
  - Limited bandwidth
  - Measurement noise floor and directivity are negatively effected in direct proportion to the loss of the pads

Measurement Examples

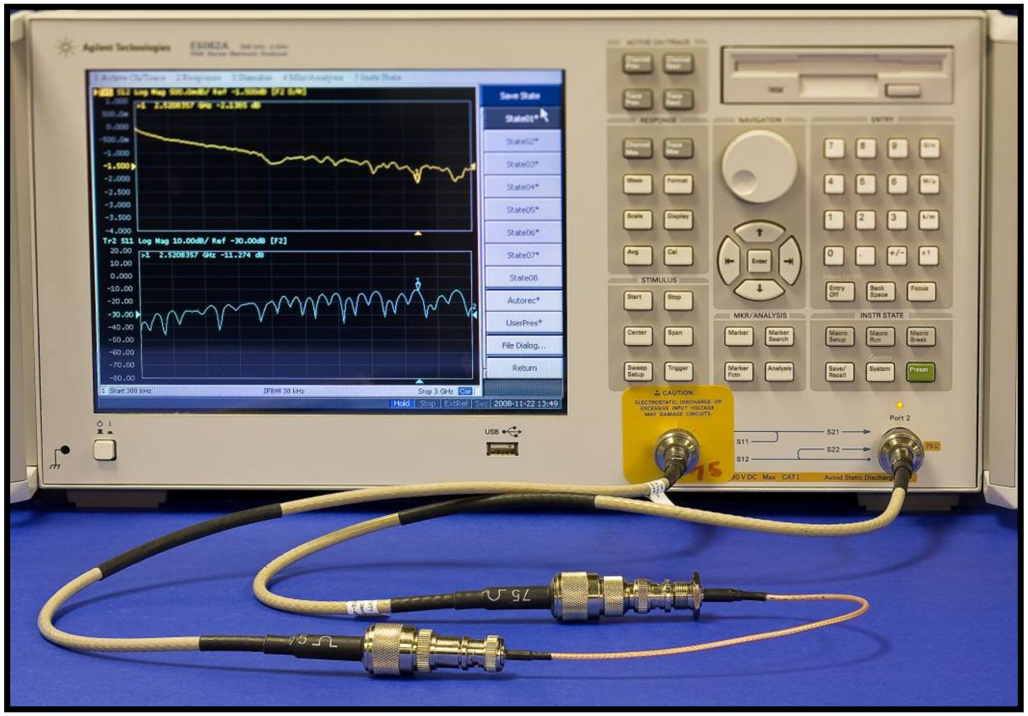
- **Now we'll demonstrate some real world tests, and hopefully validate some of the theories.**
- **75 Ohm BNC Coaxial Cable assembly**
  - Goal is to "test to spec" for Return Loss to 3 GHz
  - We'll examine several methods using a 75 Ohm VNA system
  - We'll follow that with similar testing on a 50 Ohm VNA, and compare the results to validate our method
- **85 Ohm Differential High Speed Multi pair cable assembly**
  - Goal is to extract S-parameter model to use in channel simulations up to 8.5 GHz (6 Gbps)
  - We'll test using a TRL calibration method on a 4 port VNA system

BNC Cable Assembly

- 75 Ohm Male and Female BNC connectors on RG-179 cable, specked to 6 GHz.
- Must meet Return Loss requirements of SMPTE 424M-2006: 15 dB max, to 3 GHz, in 75 Ohm environment.
- Test procedure as specified is ambiguous.

Measuring with a 75 OHM VNA

- **The “Golden Standard” Method**

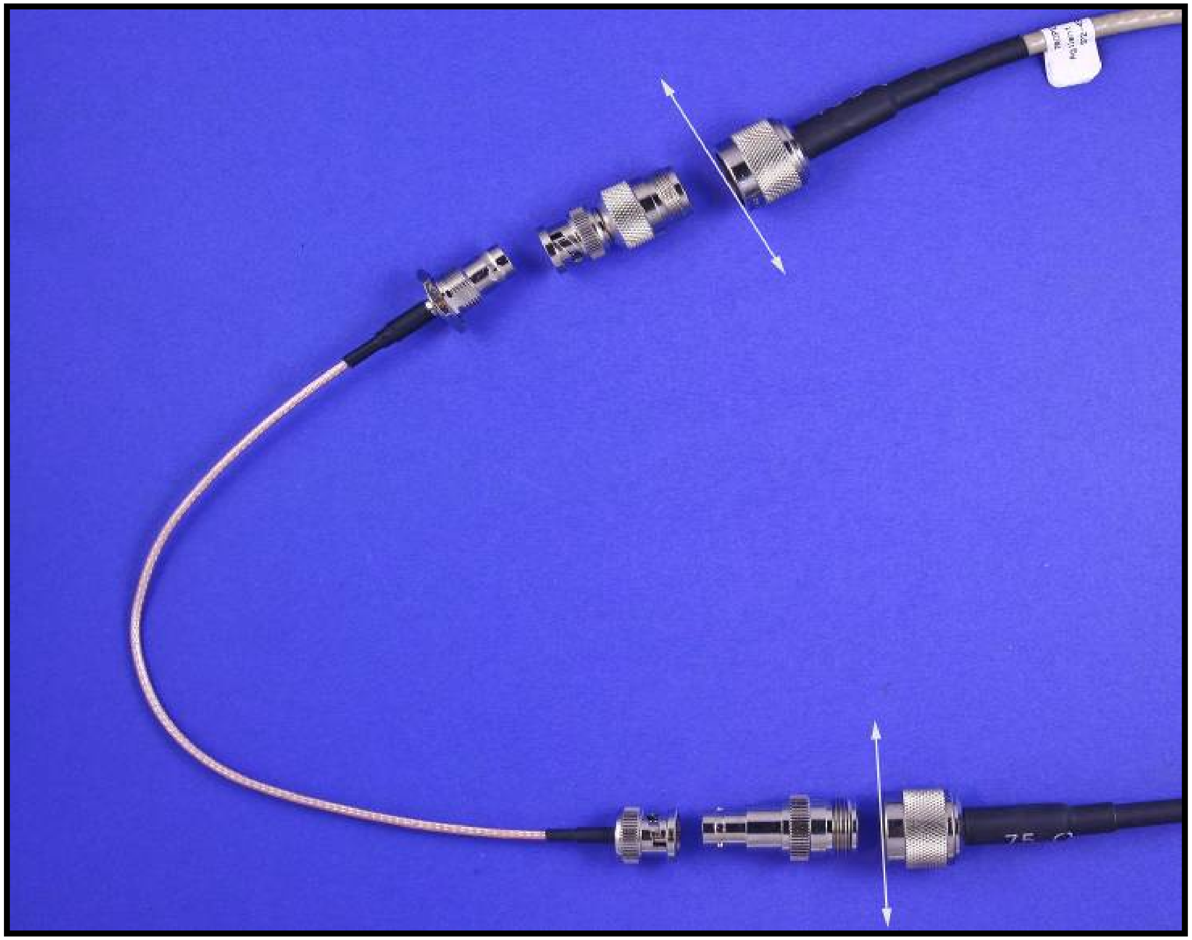


- **300 kHz-3 GHz, 75 Ohm Type N connector test ports, Type N cal kit.**

First Challenge: Adapters

- We plan to perform a traditional SOLT cal at the end of the Type-N test cables using the cal standards pictured here.
- However, we must use some sort of adapters to attach the BNC connectors to the N connectors.

Adapter Decisions



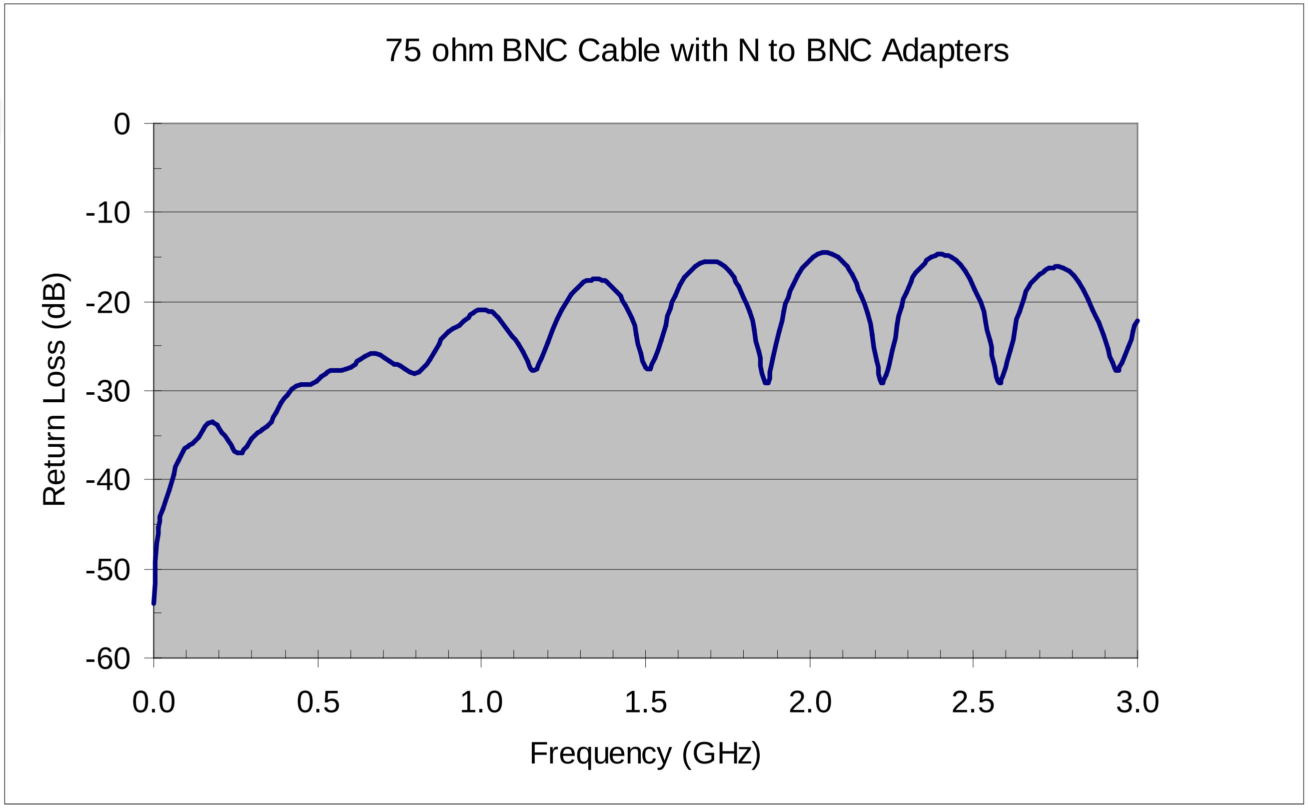
Custom Adapters and BNC Cal Kit

- **With an insertable DUT such as this, we could purchase or construct precision 75 OHM BNC to N adapters of the appropriate sexes, and then use a 75 Ohm BNC calibration kit to calibrate at the end of the BNC adapters.**
- **Pros:**
  - Very accurate
  - Familiar and straight forward process
  - Calibration plane is effectively located at mid point of mated BNC pair. Thus, data literally represents performance of the cable assembly only. Good procedure when only one half of mating interface will be specified
- **Cons**
  - Precision adapters and cal kits very expensive to design and build
  - Procedure not straight forward with a non-insertable DUT

A Second Approach

- **Calibrate at N connectors, but leave adapters in measurement.**
- **Pros:**
  - Very straight forward, inexpensive
  - OK for testing to spec. It is likely that if assembly meets spec with adapters in place, it will also meet spec with out them. I.E., in most cases they won't make DUT look better than in the real world
- **Cons:**
  - True upper limits of assembly performance will be unknown. Not good if you are marginally failing spec
  - Not suitable for accurate model extraction (OK at lower frequencies though)

Results With Adapters In Measurement



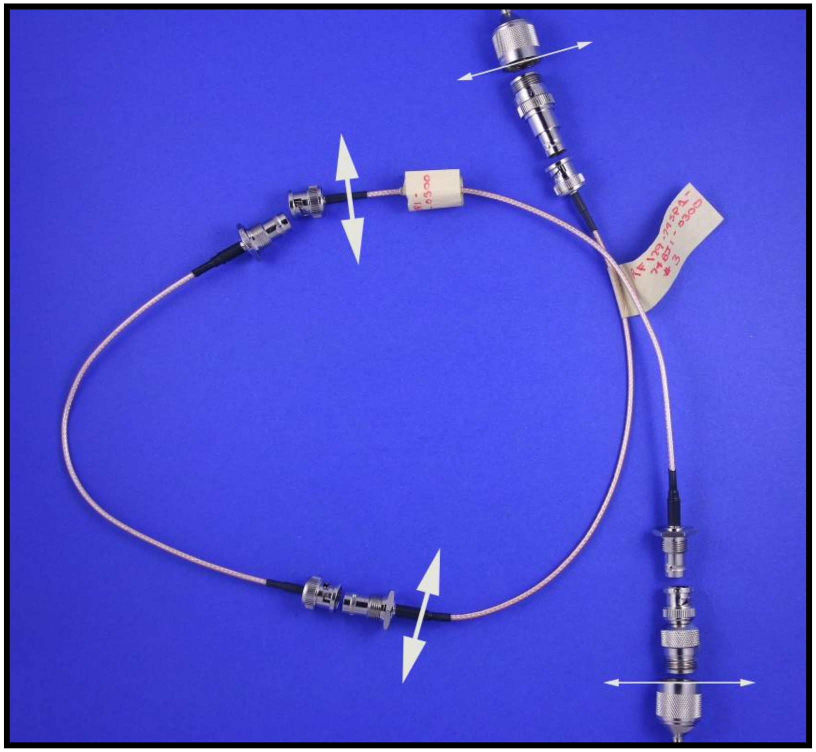
The assembly meets the 15dB requirement, even with the adapters in the test path

Time Domain Gating Approach

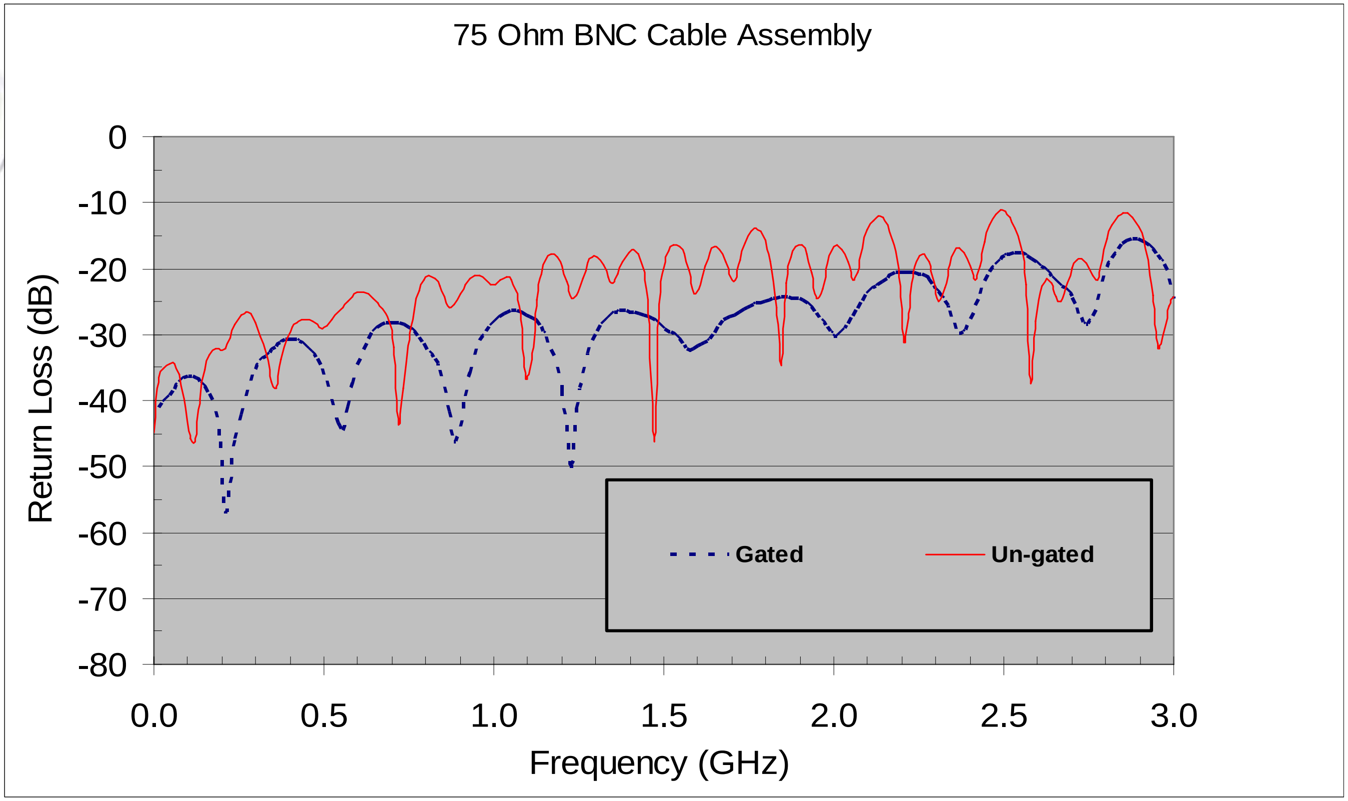
- **Next, we made an attempt to gate out the adapter effects.**
- **VNA did not have internal gating capabilities, so gating was performed in post processing using Agilent PLTS software.**
- **We used custom cable assemblies as adapters**
  - Allowed us to more clearly discern the impedance transition in the test path, so made gate placement easier and more repeatable
  - Relatively quick and inexpensive way to create adaptors for multiple connector types

Time Domain Gating

- Small arrows depict calibration plane.
- Large arrows depict gating plane.
- Also note with this method, both full connector pairs will be in the DUT path.



Time Domain Gating



Note improved margin versus method with adapters in the test path

Measurements with 50 Ohm VNA

- The procedures used with the 75 Ohm VNA are easily transferred to a 50 Ohm VNA with one additional step of impedance transformation.
- It should be noted that it is often difficult to find adapters with 50 Ohm connectors on one end and 75 Ohm on the other, but this shortcoming can often be addressed by using the custom cable assembly approach discussed earlier.
- Next, we’ll attempt to reproduce our previous measurements with a 50 Ohm VNA.

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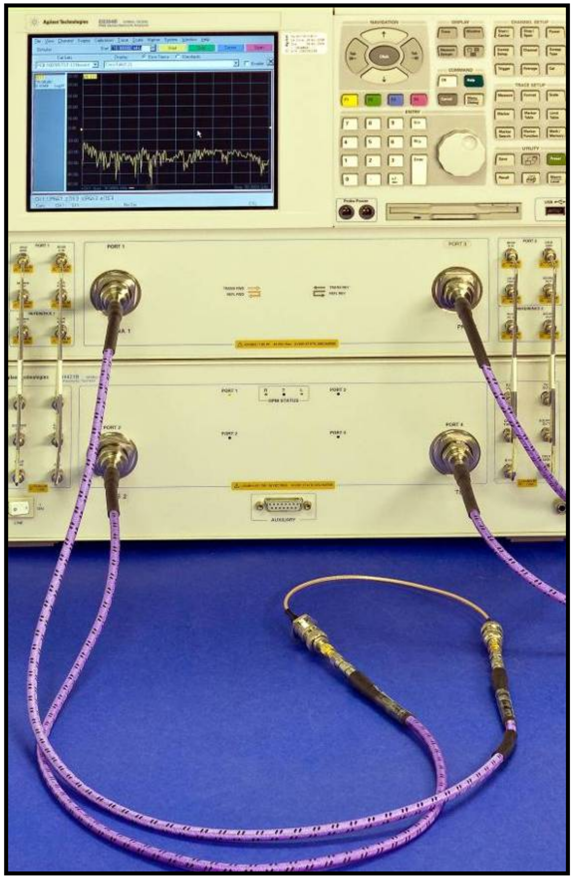
50 Ohm Measurements

- For the 50 Ohm measurements, we used a 10 MHz to 50 GHz 4-port VNA system controlled by external Agilent PLTS measurement control and post processing software.

- A 50 Ohm 3.5 mm calibration kit was used to perform the SOLT calibration.



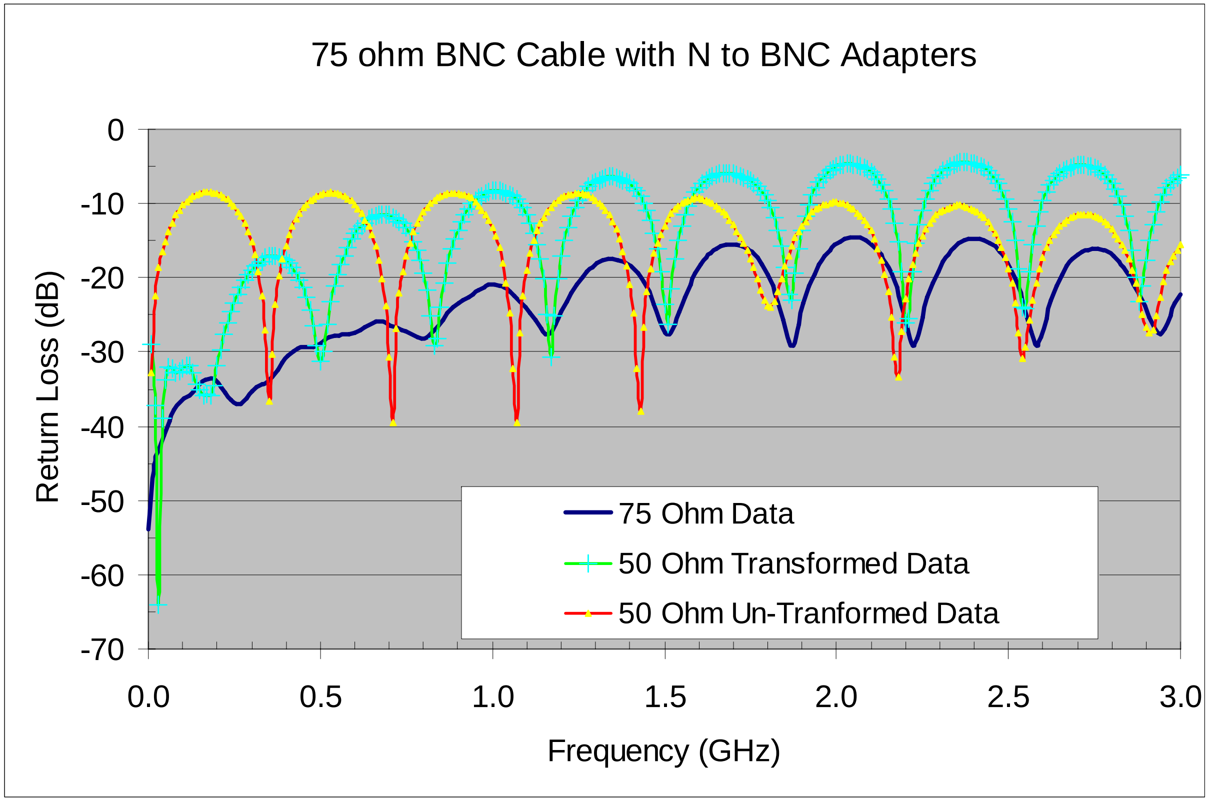
50 Ohm Measurement with Adapters Included

- We first attempted to duplicate our previous "adapter included" measurements.
- A unique feature of the BNC connector is that certain types of 50 Ohm and 75 Ohm connectors are physically intermateable.
  - Always check connector specifications carefully since not all designs or combinations are intermateable, and serious connector damage may occur
  - Electrical performance of 50/75 Ohm BNC combinations is often acceptable at lower frequencies (to 500 MHz or so), but can degrade rapidly with increasing frequency

50 Ohm Adapter-In Measurements

- Sample as tested.
- Small arrows represent calibration planes.
- 2.9 mm to 3.5 mm adapters (gold color) were, in effect, calibrated out of the measurement.

50 Ohm Adapter-In Measurement



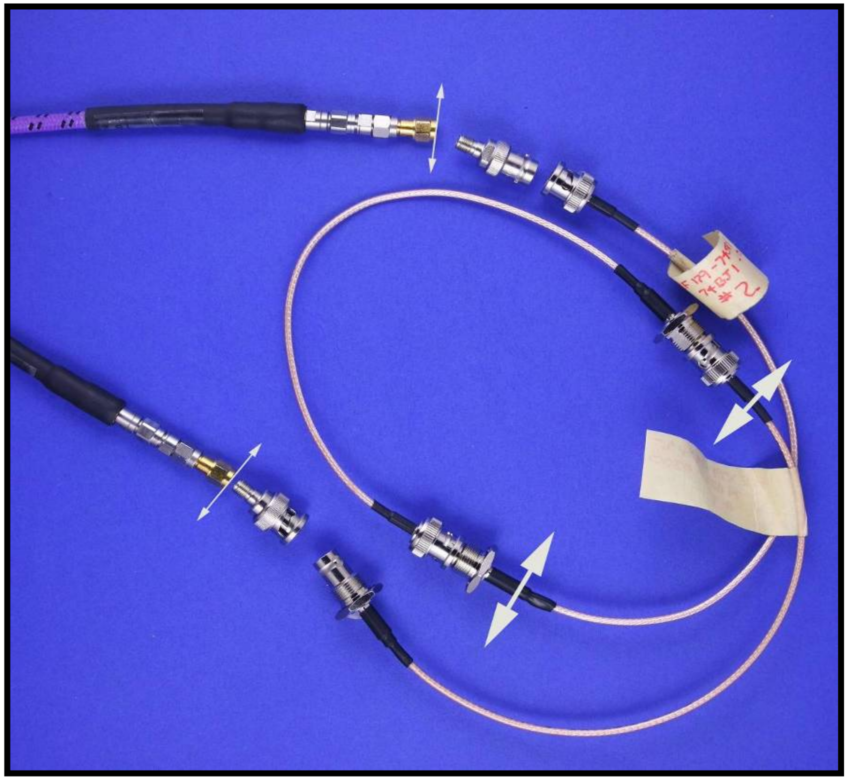
Plot with 50 Ohm data, transformed to 75 Ohms, and untransformed, versus previous data from 75 Ohm VNA

50 Ohm Adapter-In Measurement

- Based on the very poor performance at frequencies above a few hundred MHz, we concluded that the 50 Ohm SMA to BNC adapters did perform nearly as well as the dedicated 75 Ohm N to BNC adapters used in the earlier measurement.
- To address this issue, we constructed cable assembly based "adapters" to allow us to easily gate out adapter effects as discussed earlier, and repeated the measurements.
- After gating out the adapter effects, we transformed the reference impedance to 75 Ohms.

50 Ohm Gated Data with Adapters

- Set up with SMA-BNC adapters and additional cable assembly adapters.
- Small arrows indicate calibration planes.
- Large arrows gating planes.

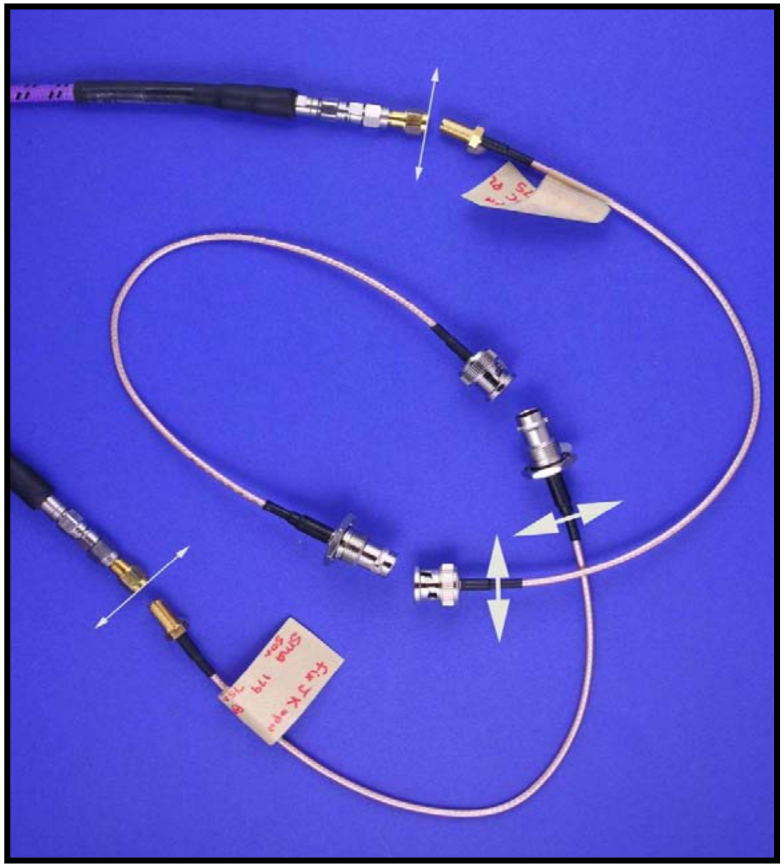


50 Ohm Gated Alternate Approach

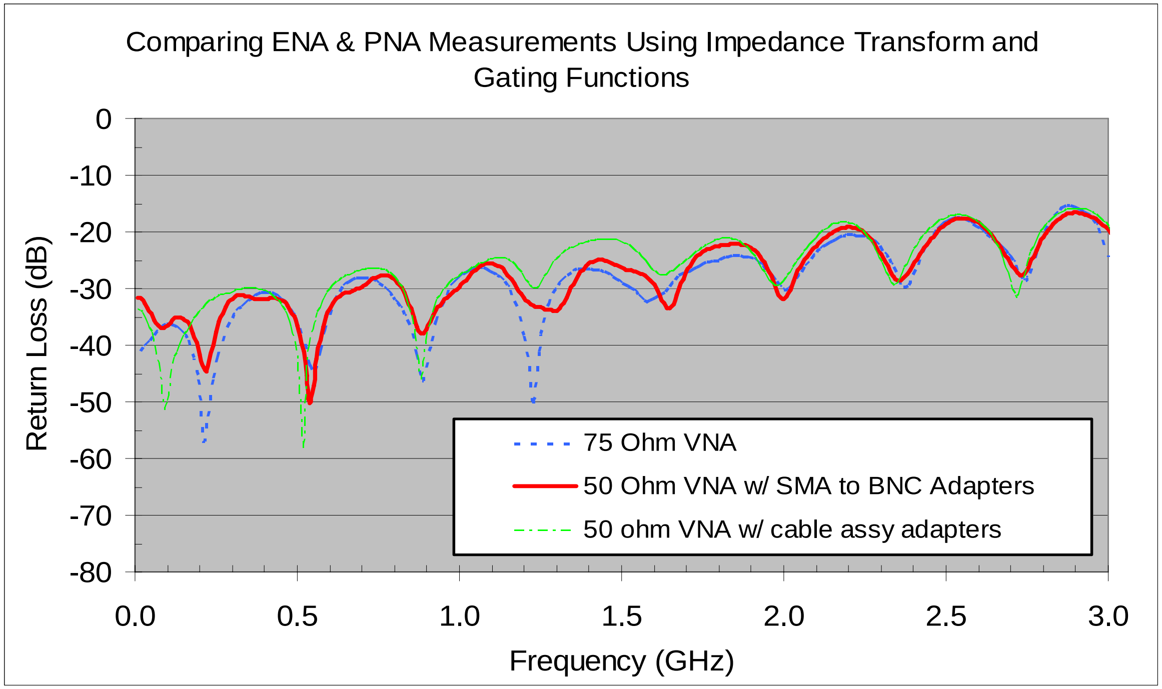
- To further “clean up” the test path, we constructed a set of cable assemblies with 50 Ohm SMA connectors on one end and 75 Ohm BNC connectors on the other.
- This approach eliminated the poor performing SMA/BNC adapters completely from the measurement.
- We then gated out the effects of the cable assembly “adapters” as before, and again transformed the reference impedance to 75 Ohms.

Gated "Cable Assembly Adapters"

- **Gated set up with SMA/BNC adapters removed.**



50 Ohm Gated Measurement Results



Transformed, gated 50 Ohm VNA measurements
and 75 Ohm VNA gated measurement

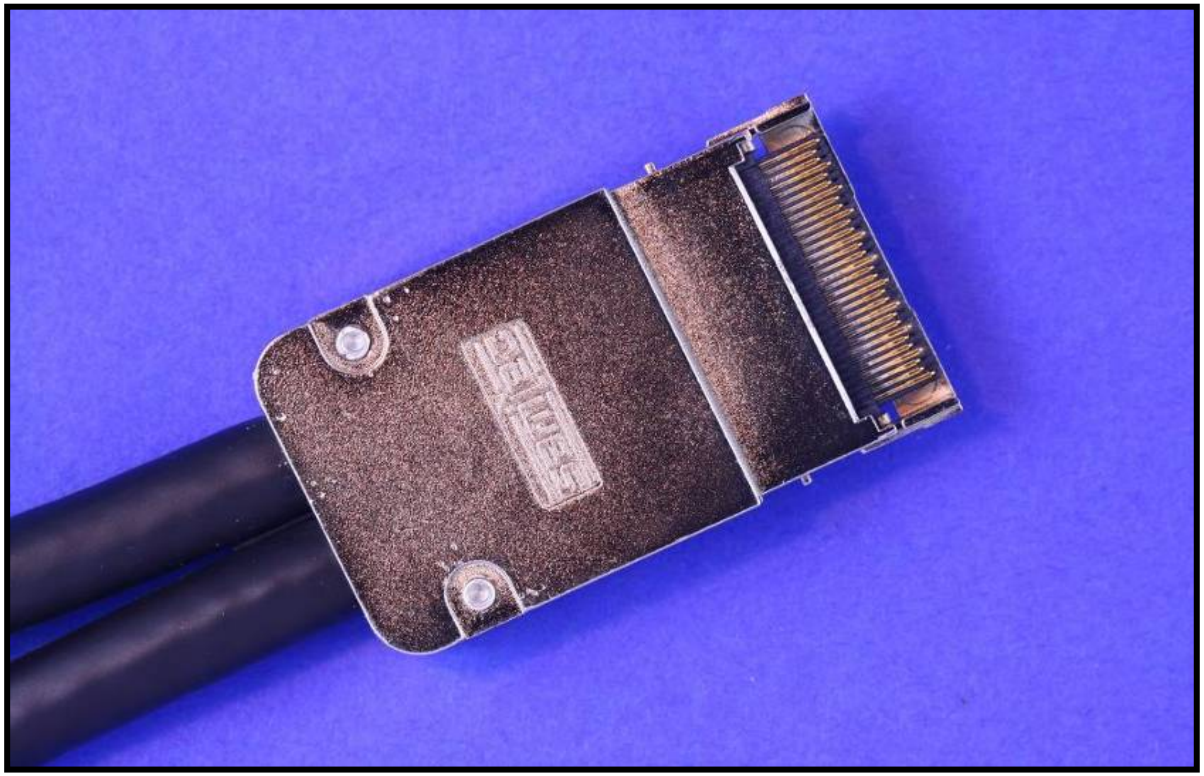
75/50 Ohm Experiment Conclusions

- Gating is effective in removing adapter effects, even with “ugly” adapters.
- “Cable assembly adapters” help in isolating gate locations.
- Impedance transformations work well to convert reference impedance.

85 Ohm Differential Example

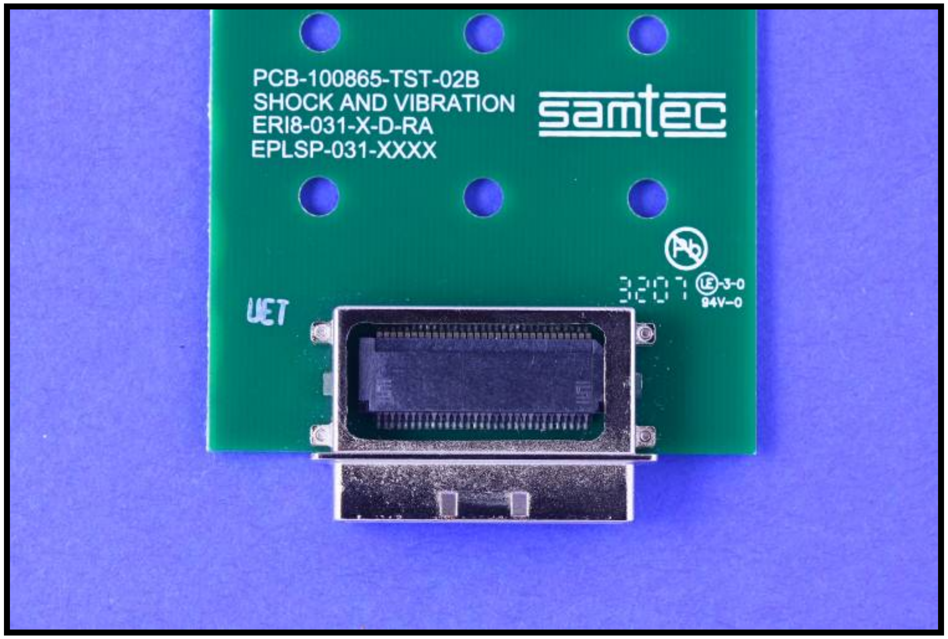
- After validating procedures with the 75 Ohm single-ended example, we built upon our lessons learned, and moved to an 85 Ohm differential case.
- Instead of “testing to spec” with this example, our goal was to extract a multi-port S-parameter model that could be used in an 85 Ohm channel circuit simulation.
- We pushed the high end to 8.5 GHz, which is suitable for most 6 Gbps applications.

85 Ohm Example



15 GHz 85 Ohm Multi-pair I/O cable assembly

85 Ohm Example



Board Mount I/O Connector included in test path
(note top of shield is cut away to allow view inside)

85 Ohm Example

- The goal of this measurement was to obtain a model of the interconnect channel path.
- The channel path includes the cable assembly with connectors, the PCB mount connectors, the PCB foot print effects, and the break out region of the PCB at each end of the channel.
- The break out region includes solder pads, vias, and traces in the vicinity of the connector out to the point where a uniform transmission line PCB trace is encountered.

A S-Parameter Overview

- **Since our objective is to create a S-parameter based model of this device, a brief overview of S-parameter reference impedance conventions is in order.**
- **“Generalized S-parameters” describe the behavior of a device when a perfect impedance match is present at all ports.**
  - This impedance is a complex value (with real and imaginary, or magnitude and phase components)
  - This impedance will most likely vary with frequency
- **In the signal integrity world, we typically work with “Normalized s-parameters”.**
  - The impedance of each port is defined at a constant reference value
  - 50 Ohm real, 0 Ohm imaginary is a traditional standard most often encountered
- **Mathematical impedance transformations previously discussed are used to convert from general to normalized reference impedance S-parameters.**

A S-Parameter Overview

- **S-parameters generated by most modern VNA’s will be referenced to the VNA test port impedance by default (50 Ohms in most cases)**
  - If a reference impedance isn’t specified with a certain set of s-parameters, it’s usually safe to assume it is 50 Ohms
  - However if the component is typically used in a 75 or 05 Ohm system, it’s best to verify the s-parameter reference impedance
- **Most simulation software can use s-parameters with any arbitrary reference impedance**
- **The reference impedance is typically defined in the header of several widely accepted standards for s-parameter file formats**

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S-Parameter File Example

- **!S4P File: Measurements: <S11,S12,S13,S14>,**
- **!<S21,S22,S23,S24>,**
- **!<S31,S32,S33,S34>,**
- **!<S41,S42,S43,S44>:**
- **# Hz S dB R *50***
- **10000000 -2.310623e+001 2.726391e+001 -2.171497e+001 5.360749e+001 -4.421907e-001 -2.869534e+001 -3.266447e+001 -1.569800e+002**
- **-2.169765e+001 5.354795e+001 -2.257862e+001 2.954361e+001 -3.257936e+001 -1.570860e+002 -4.615603e-001 -2.872216e+001**
- **-4.477470e-001 -2.868213e+001 -3.255874e+001 -1.571285e+002 -2.302687e+001 2.591842e+001 ....**

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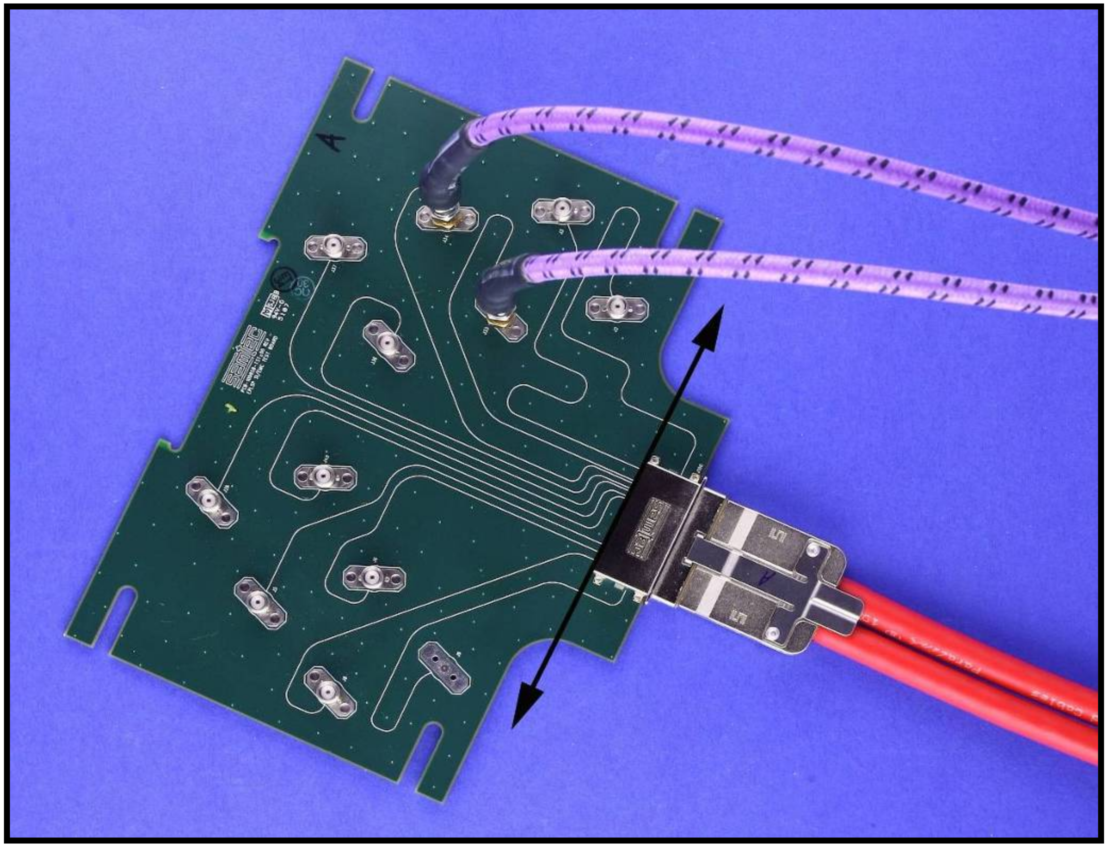
85 Ohm Example

- **Since 50 Ohm is the de facto S-parameter standard, it is convenient to characterize many devices in a 50 Ohm environment.**
- **Therefore, we chose to use 50 Ohm traces for our test board.**
  - Many designs for 50 Ohm traces are well established and characterized in the industry
  - Board houses are very familiar with producing well controlled 50 Ohm traces
- **This also allowed us to use a straight forward and familiar TRLM calibration technique to move the calibration plane to the edge of the break out region of the test board.**

85 Ohm Example

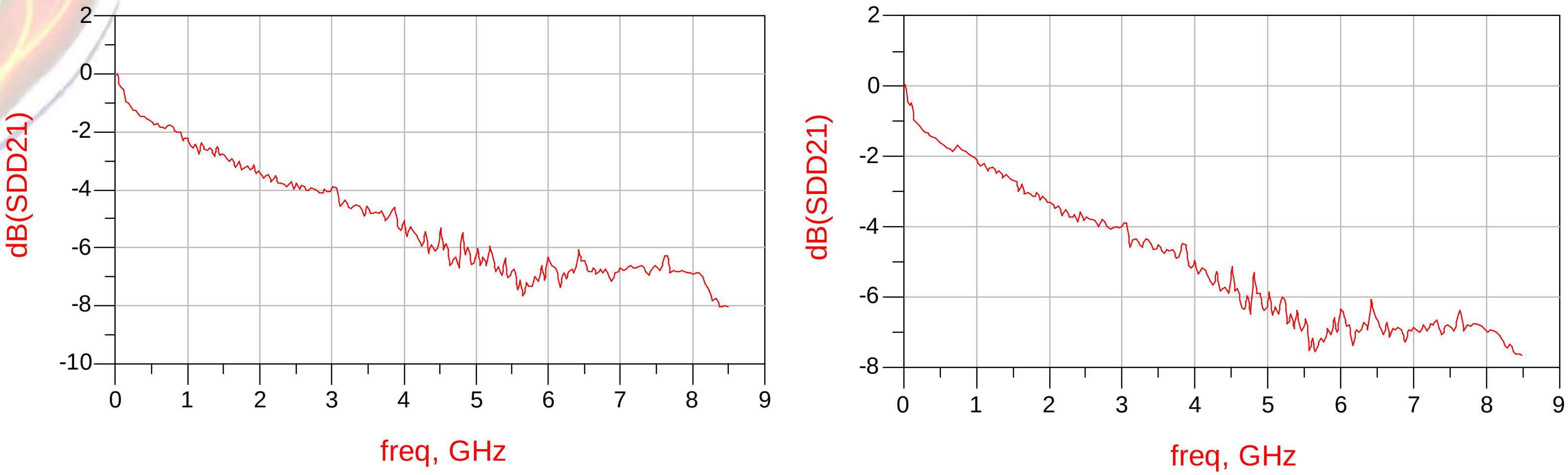


50 Ohm test board with reference plane denoted by arrows

85 Ohm Example

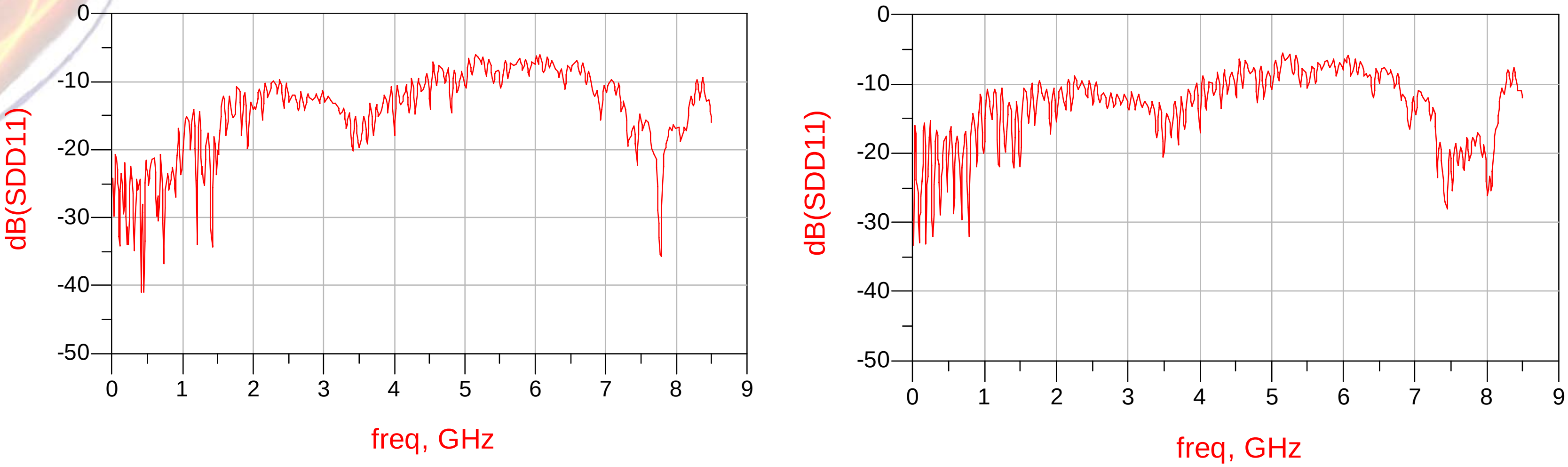
- After proper TRLM calibration, S-parameter files obtained from measurement were suitable for direct use in circuit simulation as they were already reference to 50 Ohms.
- Simulations in an 85 Ohm environment were performed with results as follows.

85 Ohm Example



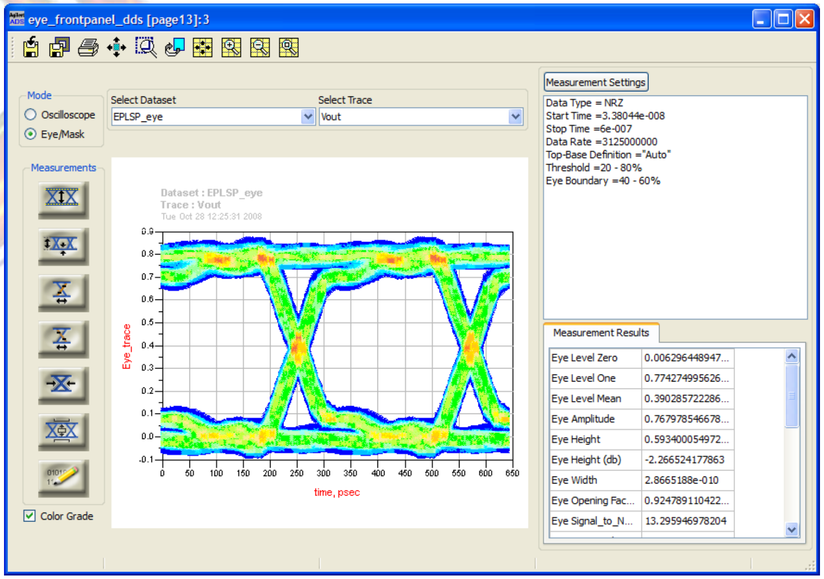
Channel Insertion Loss in 85 Ohm system (left) and 100 Ohm system (right) (Note difference in scales)

85 Ohm Example



Return Loss in 85 Ohm system (left) and 100 Ohm system (right)

85 Ohm Example

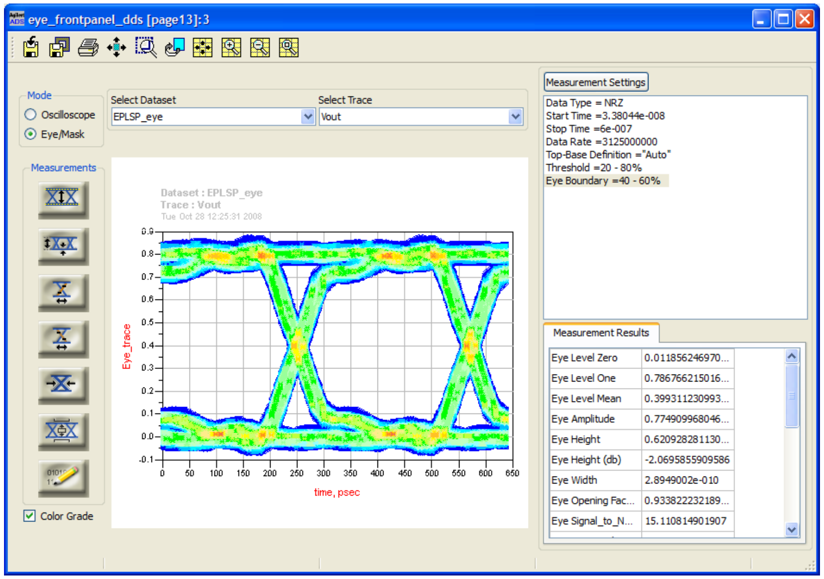


Select Dataset: EPLSP_eye

Select Trace: Vout

Data Type = NRZ
Start Time =3.38044e-008
Stop Time =6e-007
Data Rate =3125000000
Top-Base Definition ="Auto"
Threshold =20 - 80%
Eye Boundary =40 - 60%

Eye Level Zero	0.006296448947...
Eye Level One	0.774274995626...
Eye Level Mean	0.390285722286...
Eye Amplitude	0.767978546678...
Eye Height	0.593400054972...
Eye Height (db)	-2.266524177863
Eye Width	2.8665188e-010
Eye Opening Fac...	0.924789110422...
Eye Signal_to_N...	13.295946978204



Select Dataset: EPLSP_eye

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Data Type = NRZ
Start Time =3.38044e-008
Stop Time =6e-007
Data Rate =3125000000
Top-Base Definition ="Auto"
Threshold =20 - 80%
Eye Boundary =40 - 60%

Eye Level Zero	0.011856246970...
Eye Level One	0.786766215016...
Eye Level Mean	0.399311230993...
Eye Amplitude	0.774909968046...
Eye Height	0.620928281130...
Eye Height (db)	-2.0695855909586
Eye Width	2.8949002e-010
Eye Opening Fac...	0.933822232189...
Eye Signal_to_N...	15.110814901907

Eye patterns at 3.125 Gbps, 85 Ohm system left, 100 Ohm right

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Conclusions

- The need for quality, high frequency characterization of non-50/100 Ohm impedance components continues to grow.
- A typical modern 50 Ohm VNA can be used to characterize many components of arbitrary impedance. In many cases it is actually the preferred instrument.
- Excellent correlation has been demonstrated between measurements made with 50 and 75 Ohm systems.
- In many applications, connector adaptors are a larger source of error than impedance mismatch between the DUT and instrument test port.
- Custom “adapters” made from short cable assemblies offer advantages with some gating based procedures.

Conclusions

- For most applications, a 50 Ohm instrument is suitable for DUT's between 2 Ohms and 1.5 Kilo Ohms.
- Modern data post processing routines allow for the removal of significant adapter and fixture effects.
- Non-50 Ohm instrumentation and fixturing may be appropriate in environments where large volumes of non-50 ohm components are typically tested.
- A 50 Ohm VNA is an ideal instrument for many characterizing arbitrary impedance devices to obtain S-parameters for use in circuit simulations.

References

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- [10] Maxim Integrated Products, Appl.[6] MAXIM Application Note 3250, “: Characterizing the S-Parameters of 75W Circuits using 50W Lab Equipment.”
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Resources

- Agilent E5062A 75 Ohm VNA
- Agilent E8364B 10 MHz - 50 GHz PNA Series Analyzer with an N4421B 10 MHz – 50 GHz S-Parameter Test Set
- Agilent Physical Layer Test System software (PLTS) version 4.50
- Agilent ADS 2008 Update 1, Advanced Design System
- Samtec 5 GHz True 75 Ohm Male to Female BNC cable assembly
- Samtec Edge Rate™ EPLSP Series cable assembly
- Samtec cable prototype 85 Ohm twinax cable
- Samtec Final Inch ® ® PCB reference design