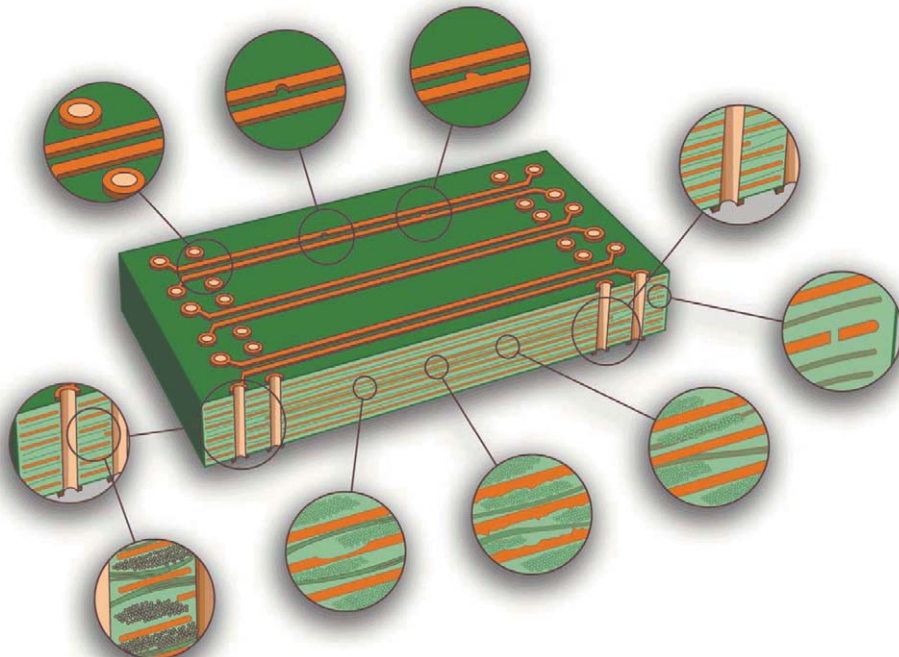
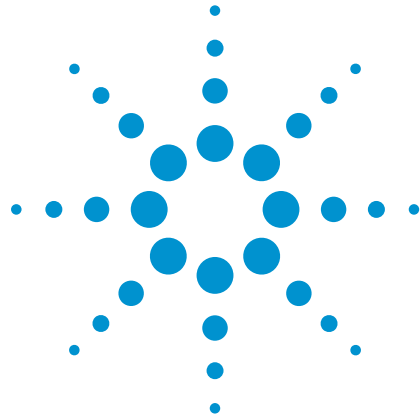


# Agilent Signal Integrity Analysis Series

## Part 3: The ABCs of De-Embedding

Application Note



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## Introduction

No test equipment is perfect, including a vector network analyzer (VNA). However, using a powerful tool box of special operations enables the measurement errors to be dramatically minimized. These operations improve the laboratory measurement data turning it into an excellent representation of the device under test (DUT). While calibration is a pre-measurement step which minimizes errors, the most important operation to reveal information about just the DUT is a post-measurement process called de-embedding. Traditionally, de-embedding has been used only by experienced users. By understanding the principles and how to use the new generation of built in de-embedding features of VNAs, this powerful technique can be leveraged by all users and the quality of information extracted from all measurements dramatically improved. This practical guide to de-embedding will enable all users to take advantage of this important feature.

## Why De-Embedding?

Although a VNA is a powerful tool for component characterization, it can only measure between well calibrated reference planes. Often there is a some type of fixture that makes the physical connection between the reference plane of the VNA to the ends of the device under test (DUT).

Figure 1 shows an example from Altera Corporation. The DUT is a ball grid array (BGA) component on the back side of the board, which is accessed from the edge where there are SMA launches and traces on the circuit board. The SMA and traces on the board contribute a larger measured impact than the DUT itself.

How do you isolate the DUT performance when all you have are the DUT and the fixtures?

This is the value of de-embedding techniques. When you have a composite measurement of a DUT/fixture combination, you can isolate the performance of the fixture and use de-embedding to extract or de-embed the fixture from the measurements.

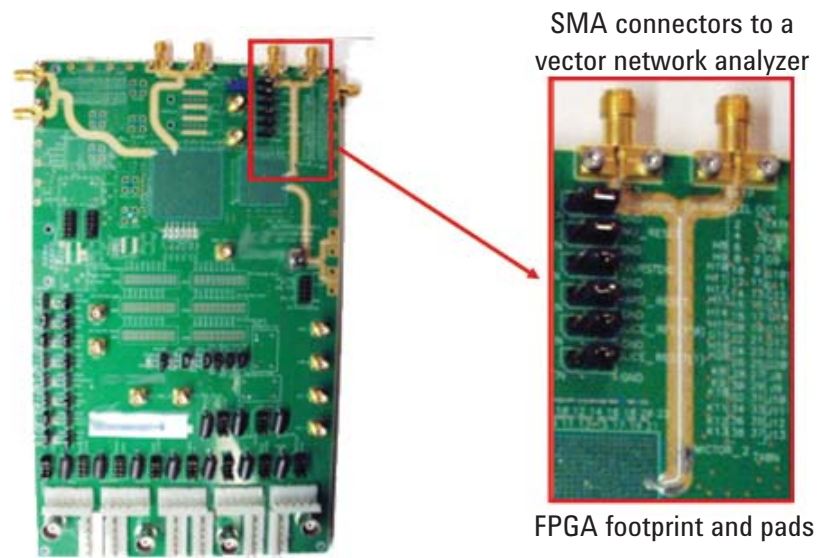
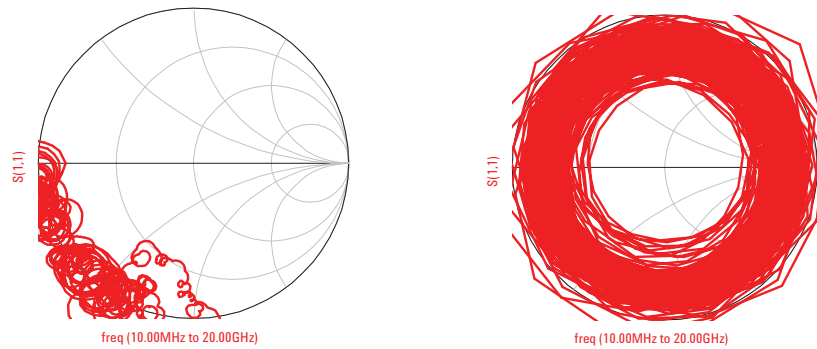


Figure 1. De-embedding: removing fixture effects from a measurement.

Measured short at front of VNA:  
No cable  
No calibration

Measured short at end of 1 m cable:  
No calibration



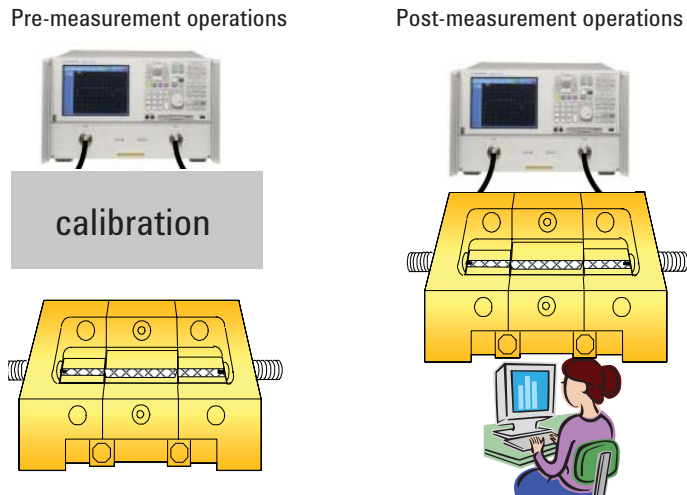
**Figure 2. Why calibration and de-embedding are important**

Between the sources and receivers at the core of the VNA are directional couplers, switches and connectors, all designed to make the measurement of the S-parameters of the DUT effortless and transparent to the user. Each of these internal components contributes to measurement artifacts which hide and obscure the intrinsic measurement of the DUT.

For example, an ideal short on a Smith chart should be a dot on the left hand side of the chart. The actual measured Smith chart of a short connected directly to the front connector of the VNA is shown on the left of Figure 2. This measurement is basically on the left side of the Smith chart, but other than that, is nothing like an ideal short. Clearly, the internal interconnects of the VNA are hiding the true nature of the device under test.

It is virtually impossible to connect a DUT directly to the front panel of test instrumentation. To further complicate measurements, cables and other mounting fixtures are almost always used to interface the DUT to the test instrumentation. Even the most precise interconnects will dramatically distort the measured response of the DUT.

The Smith chart on the right of Figure 2 shows the measured  $S_{11}$  response from a short located at the end of a meter long, precision 50 ohm, low-loss cable. Deciphering any information about the DUT is virtually impossible from this measured response.



**Figure 3. Error correction techniques**

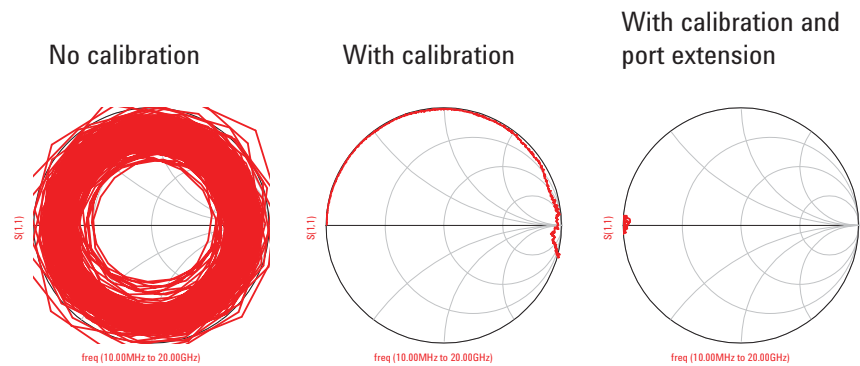
Over the years, many different approaches have been developed for removing the effects of the internal VNA features and the test fixtures from a measurement to reveal the behavior of just the DUT. They fall into two fundamental categories: pre-measurement and post-measurement operations.

Pre-measurement operations require specialized calibration standards that are inserted at the ends of the test fixture and measured. This process moves the calibration plane to the end of the fixture. All the effects of the fixture are calibrated out up to this plane. The accuracy of the subsequent device measurement relies on the quality of these physical standards. This is why most VNA calibration kits include very precise air dielectric coaxial standards with calibration coefficients of inductance and capacitance that are read into the VNA firmware. Using any 50 ohm loads out of lab stock is not recommended.

Post-measurement operations involve taking a measurement of the DUT and all the fixturing leading up to it, then mathematically removing the fixturing leaving only the DUT behavior. Of course, the essential ingredient to a post measurement operation is to have accurate information about the fixture. This process is called de-embedding. The intrinsic DUT behavior is embedded in the total measurement and de-embedding removes the fixture effects leaving just the DUT behavior.

This powerful technique can be used when the DUT is remote from the calibration plane or when there are non-coaxial connections from the VNA cables to the DUT. De-embedding is commonly used with circuit board traces, backplane channels, semiconductor packages, connectors and discrete components.

In signal integrity applications, de-embedding is the most important technique besides calibration for obtaining artifact-free device measurements. It is noteworthy to mention that full de-embedding requires all s-parameters for the fixture. With a differential fixture, this means the .s4p Touchstone file with all 16 elements in the 4x4 matrix.



**Figure 4. Impact of calibration on a short at the end of a 1 m precision cable**

With the use of pre- and post-measurement compensation techniques, you can turn a network analyzer with all the artifacts from the cabling and fixturing into a nearly ideal network analyzer which can display the intrinsic S-parameters of the DUT.

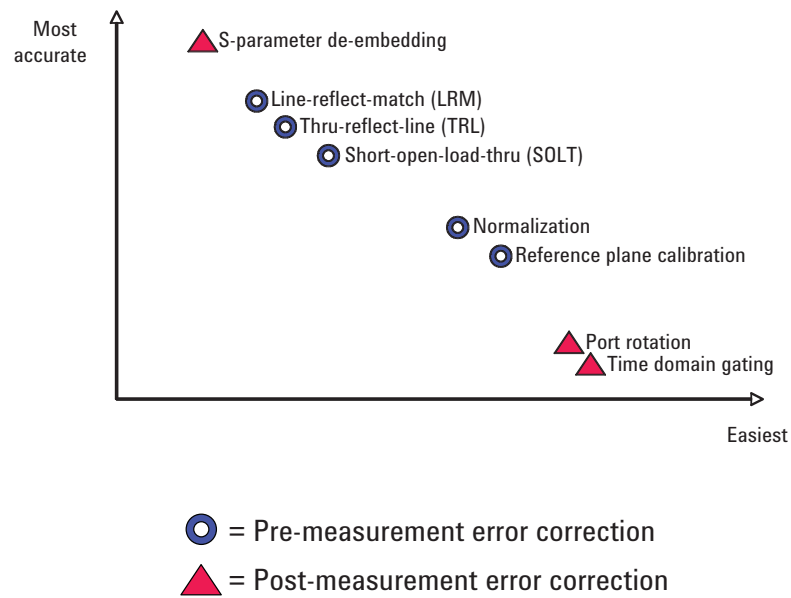
With no calibration, a short at the end of a cable connected to a VNA looks anything but ideal. See the Smith chart measurement on the left of Figure 4. By applying the pre-measurement calibration process to the end of the cable, the resulting measured response of the short looks closer to what is expected for a short. See the center measurement. However, the real short is not an ideal short. As a calibration standard, it doesn't have to be. It just has to be a known standard. In this case, the real short is a very good coaxial short connected to the end of a coaxial transmission line that is approximately 100 mil long.

For measurements up to 20 GHz, the real short actually looks like an ideal, lossless transmission line shorted at the far end with a time delay of 13 psec. This is why it loops around the Smith chart in the clockwise direction. The coaxial short can be de-embedded from the measurement.

If you assume the connection to the short is an ideal, lossless, 50 ohm transmission line segment with a time delay of 13 psec. Then the S-parameter performance of this interconnect can be calculated analytically. The fixture S-parameters are used to "de-embed" the short from the composite measurement. This technique is called port extension.

The last Smith chart on the right of Figure 4 shows an almost ideal short. This has the internal VNA circuitry, the cable effects, and the transmission line of the DUT all de-embedded. This is why de-embedding is such a powerful technique; it removes the unwanted artifacts of the system and fixtures to reveal the true characteristics of the DUT.

Pre- and post-measurement compensation techniques enable you to routinely make accurate S-parameter measurements of interconnect structures such as backplane traces, semiconductor package leads, surface mount components and circuit board traces.



**Figure 5. Fixture error correction techniques**

The various methods of turning real laboratory measurements into a close approximation of ideal measurements of the DUT are summarized in Figure 5.

The simplest to understand and implement is time domain gating. It involves converting the frequency domain return loss measurements into a time domain response (TDR). A narrow region of the TDR response is selected and only this TDR response is converted back into the frequency domain to be interpreted as the return loss from a specific region of the DUT. Though it is easy to implement in virtually all network analyzers, it is limited in application to just the return loss measurement and decreases in accuracy with increasing loss in the interconnect. It is most useful when the DUT dominates the total measurement such as when a connector adaptor is used with the DUT.

Port rotation is a lesser form of de-embedding in which a phase shift, increasing linearly with frequency, is subtracted from a measurement. The phase shift corresponds to a short length of ideal, 50 ohm interconnect between the calibration plane and the DUT. Port rotation is a built in feature in all network analyzers and can compensate for extra lengths in both the return loss and the insertion loss measurements. In modern network analyzers, the skin depth and dielectric losses of a uniform transmission line can also be simply and routinely removed from a measurement by de-embedding. In typical applications, the accuracy of port rotation drops off significantly as the length of the transmission line length increases. When a port rotation of more than 360 degrees is needed, non uniformities in the interconnect often limit the accuracy of the resulting measurement.

While many of the calibration techniques listed here are straight forward, some of them such as Thru-Reflect-Line (TRL), require careful design in the fixturing. This can often be a challenge in both fabricating the calibration standards and implementing their measurements in the calibration procedure.

Historically, the limitation of de-embedding techniques has not been in the technology used to implement it, but in the challenges faced by the user due to its complex nature. This application note will lower this user barrier.

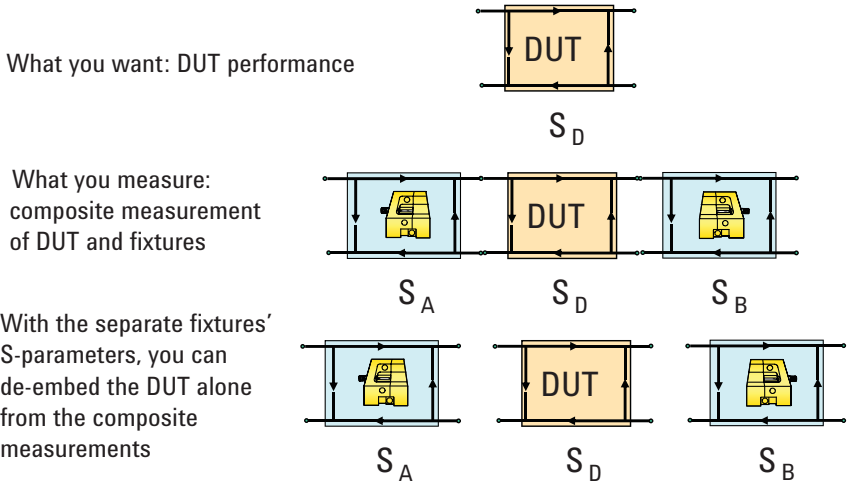


Figure 6. What is de-embedding?



## Principles of De-Embedding

The goal in any measurement is to extract an accurate value of the S-parameter of the device under test with minimum effort and artifacts. The DUT can be measured directly when it is connected directly to the calibration plane. Unfortunately, this is rarely possible.

There is usually some type of connection between the calibration plane and the DUT. This can be a coaxial to microstrip transition, stripline traces and even some intervening vias. If you can obtain an accurate description of the S-parameters of the fixture, you can mathematically take the measured composite S-parameters of the DUT and fixtures and extract just the DUT performance.

These five general principles are the foundation for de-embedding measurements.

- Definition of a port on a DUT
- Definition of the S-parameter
- S-parameter in power flow and matrix notation
- Cascading S-parameter networks with T-parameter matrices
- De-embedding T and S-parameter networks

**Figure 7. The five principles to de-embedding**

These principals are also useful for general S-parameter measurements.

The sections that follow introduce five simple principles that will explain the process of de-embedding the DUT from the measurements of a composite structure. With a brief glimpse into what goes into de-embedding, the requirements on setting up a measurement system to de-embed will be clearer.

## Definition of a port on a DUT

The first principle is the definition of a port. The definition of each S-parameter comes from the idea of a port. The popular way of describing the signal flows into a network based on the S-parameter is the basis of concatenated networks. The interactions of the S-parameter in a cascaded collection of multiple networks is the starting place for the actual de-embedding process.

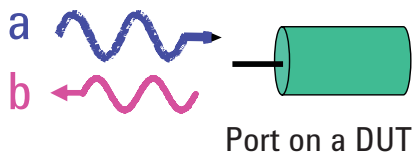


Figure 8. Principle #1: The port

Any device to be measured has some number of signal-return path connections, referred to as ports. Though the connections can be any transmission line geometry, such as microstrip, stripline, coplanar or even twisted wire, it is easiest to conceptually think about a port as coaxial. This emphasizes that every port ALWAYS has a signal and return connection, and just one signal and return connection.

At each port, there may be two signals present simultaneously. One will be moving toward the DUT while the other signal, superimposed on the same conductors, will be moving away from the DUT toward the VNA. Part of the formalism of S-parameter is using the letter "a" to designate signal sine waves moving into the DUT and the letter "b" to designate signal sine waves moving away from the DUT. A subscript with the port index number identifies at which port the signal sine wave is present.

- Ports define the interface to a DUT
- A Port is a signal-return path connection
- Into each port are simultaneously, in going and out going sine waves, superimposed on the same conductors. They do not interact on the port
- 'a' voltage waves enter the DUT
- 'b' voltage waves leave the DUT

## Definition of the S-parameter

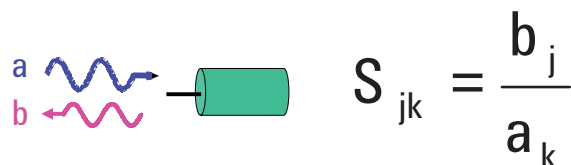


Figure 9. Principle #2: S-parameters

The second important S-parameter principle is the definition of each S-parameter. The “S” stands for scattering. The S-parameter values describe how the DUT scatters incoming “a” waves into outgoing, “b” waves.

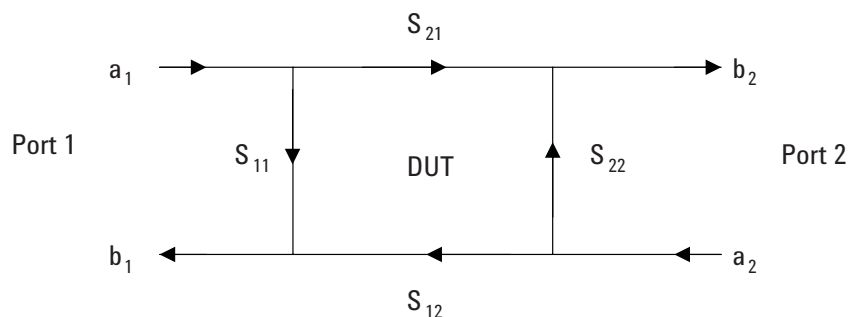
Every combination of a wave going in at one port to a wave coming out at another port has an S-parameter value. Each S-parameter is defined as the ratio of the outgoing b wave at one port to the incoming a wave at another port, provided there are no incoming waves at any other ports.

To keep track of all the combinations of waves going out at each port and waves coming in at each port, subscripts corresponding to the port where the action is, are used and are carried over to the S-parameter index. An “a” wave coming in on port 1 would be designated as “a1”. An outgoing “b” wave on port 2 would be designated “b2”.

Each S-parameter is the ratio of a “b” wave to an “a” wave and the indices of each S-parameter identifies the two ports involved. But, there is one subtle and confusing twist to the order of the indices for the S-parameter.

It would be convenient if in the definition of each S-parameter, the index was read in the order the signal moved. If the signal came into port 1 and went out of port 2, it would be reasonable to expect the S-parameter element which described this to be labeled as  $S_{12}$ . This is not the case. In order to take advantage of the power of matrix algebra, the order is reversed. The S-parameter that describes how the network transforms a1 into b2 is designated  $S_{21}$ . The S-parameter which describes how a network transforms the a3 wave into the b1 wave is  $S_{13}$ .

## S-parameter in power flow and matrix notation



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad b_j = S_{jk} a_k$$

Figure 10. Principle #3: Signal flow diagrams

The flow of the signals from an input to an output of any DUT can be illustrated using a signal flow diagram.

This is a schematic way of illustrating the flow of sine waves into and out of ports. Of course, since each port is really like a coaxial connection, the input and output waves flow over the same conductors in each port. If the signal paths were shown with arrows in the same location as their actual position, the diagram would be confusing with arrows on top of each other.

For this reason, the convention is to space apart the incoming and outgoing signal arrows. All arrows along the top flow in the same direction, from left to right. All arrows on the bottom flow from right to left.

At a glance, you can see that  $S_{11}$  transforms the  $a_1$  wave into the  $b_1$  wave, and  $S_{21}$  transforms the  $a_1$  wave into the  $b_2$  wave. There is no additional information content in a signal flow diagram, it is just a convenient visual aid to display the function of each of the S-parameter elements.

When an S-parameter is used to describe a device, the device is represented as a network that converts incoming sine waves into outgoing sine waves. It doesn't matter how physically complex the device is, the network description is simply related to how it transforms the various incoming waves into outgoing waves at each of the ports.

Though the values of the S-parameter are affected by the nature of the network, the formalism to describe what happens at each port is completely independent of what the interconnect network between the ports looks like. It's all described by its S-parameters.

## Cascading S-parameter networks with T-parameter matrices

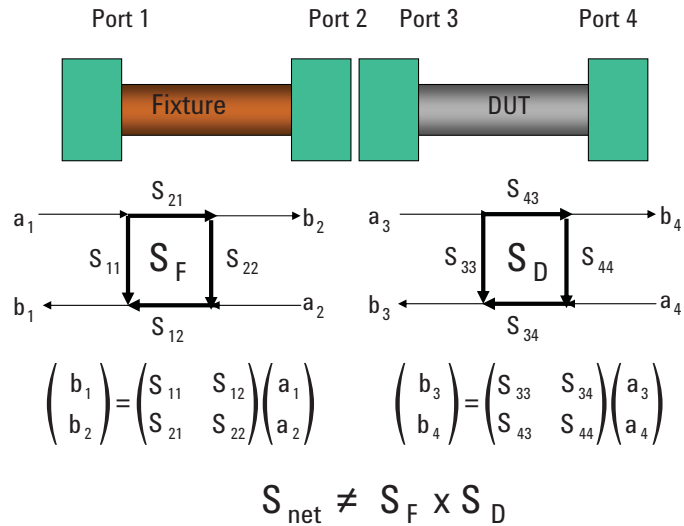


Figure 11. Principle #4: Cascading signal flow diagrams

An important property of the signal flow diagram is its ability to show the signal flow for devices that are connected in series or cascaded. When two 2-port networks are connected in series, for example, a small fixture and a DUT or two DUTs, the signal flows from one into the other.

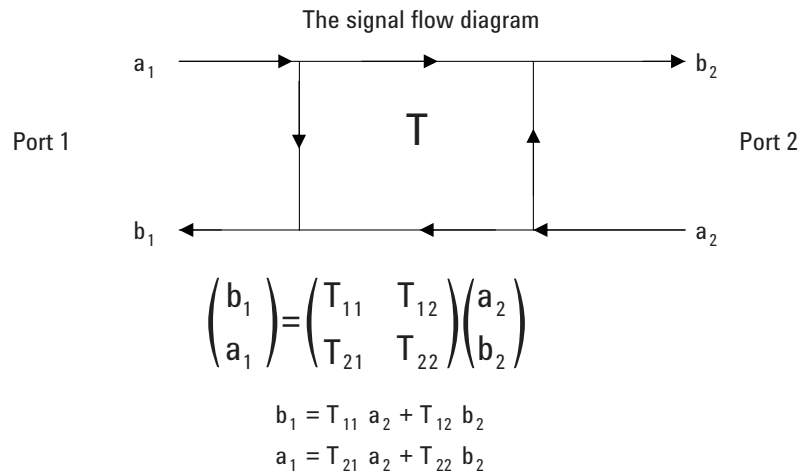
In this example, the connection is between ports 2 and 3. Port 1 is the entrance to the first structure and port 4 is at the far end. Using this formalism for the signal flow diagram, multiple networks can be cascaded in series. Two 2-port networks in series are equivalent to one 2-port network with the two outermost ports defining its ends. This is shown in the cascaded signal flow diagram in Figure 11. There is a new S-parameter matrix that describes the two networks in series. It would be defined based on ports 1 and 4 in this example.

Though the formalism of signal flow diagrams makes it easy to cascade multiple networks in series, unfortunately, the definition of the S-parameter matrix does not provide a simple process to calculate the equivalent series combination of the S-parameter of two networks.

The S-parameter matrix is defined by how incoming waves are transformed into outgoing waves. At the interface between the networks, an outgoing b wave from the first network is transformed into an incoming a wave of the second network.

The formalism for signal flow diagrams is designed to illustrate this series connection. As the b2 wave exits port 2, it becomes the a3 wave entering port 3. Likewise, the b3 wave leaving port 3 becomes the a2 wave entering port 2.

As it is defined, you cannot take the two S-parameter matrices and simply multiply them together. This makes the calculation of cascaded networks difficult if you are limited to the S-parameter matrix.



**Figure 12. The transfer-parameter or T-parameter matrix**

To be able to describe the equivalent network performance of two networks in series as the product of their two matrices, you need a matrix that relates the inputs and outputs at port 1 to the inputs and outputs at port 2. This way, the output of network 1 can become the input to network 2 in the matrix representation.

The “transfer” scattering matrix, or T-parameter matrix is designed to translate the input and output waves at port 1 to the input and output waves at port 2. The T matrix elements are defined so that the inputs and outputs on port 2 are the inputs and outputs to the next network at port 3.

With this definition of the T-parameter matrix, each of its element can be defined in terms of the a and b sine-wave signals. Unfortunately, it is sometimes difficult to understand what each element means.

For example,  $T_{22}$  is the ratio of  $a_1$  to  $b_2$ , when  $a_2 = 0$ . The  $T_{12}$  term is the ratio of  $b_1$  to  $b_2$  when  $a_2 = 0$ . Likewise, the  $T_{11}$  term is  $b_1$  divided by  $a_2$  when  $b_2 = 0$  and  $T_{21}$  is  $a_1$  divided by  $a_2$  when  $b_2 = 0$ .

When the interconnect is transparent, the T-parameter matrix has a special form. To be transparent to the interconnect must have a 50 ohm input and output impedance, no loss and no phase shift.

In this case,  $T_{11}$  is 1. Everything goes right through.  $T_{12}$  is 0 since  $b_1$  has to be 0 as nothing reflects.  $T_{21} = 0$  as  $a_2$  is 0 and  $T_{22} = 1$ , since everything in the reverse direction goes through. The T-parameter matrix for a transparent interconnect is the identity matrix.

The purpose of the T-parameter matrix description of a network is to facilitate the calculation of multiple networks in a series. It is important to keep in mind that the S-parameter matrix and the T-parameter matrix description of the same network use the same content. They are just different combinations of the same features.

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \frac{T_{12}}{T_{22}} & \frac{T_{11}T_{22} - T_{12}T_{21}}{T_{22}} \\ \frac{1}{T_{22}} & -\frac{T_{21}}{T_{22}} \end{bmatrix}$$

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} -\frac{S_{11}S_{22} - S_{12}S_{21}}{S_{21}} & \frac{S_{11}}{S_{21}} \\ -\frac{S_{22}}{S_{21}} & \frac{1}{S_{21}} \end{bmatrix}$$

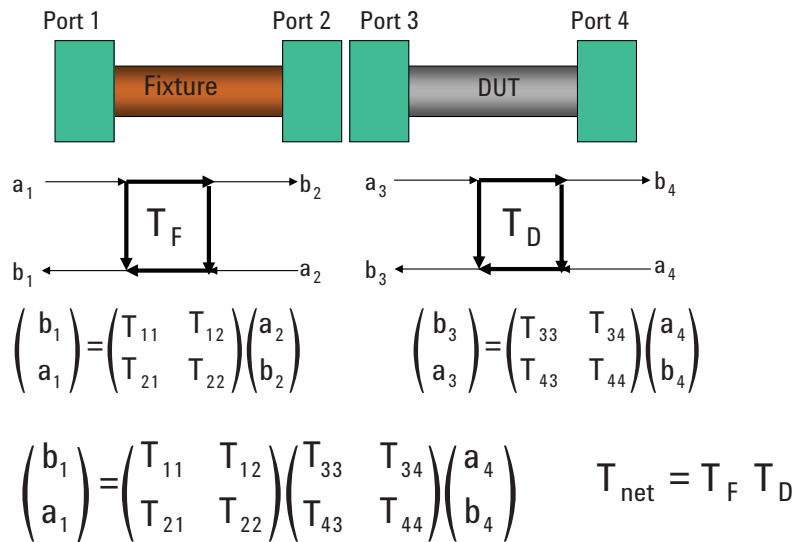
**Figure 13. Converting between S-parameter and T-parameter matrices**

With a little algebra, each T element can be translated from the S-parameter matrix and each S-parameter element can be converted into the T-parameter matrix.

Given the translations shown here, it is possible to perform this conversion with a spreadsheet. However, the conversion is also built in to most network analyzers and is a key feature in Agilent's Advanced Design System (ADS). In practice, there should never be a need to manually transform a T-matrix into an S-matrix.

Each matrix has its use. When you want to describe the electrical properties of a DUT, it is most convenient to use the S-parameter representation. When you want to cascade multiple networks in series and find a resulting network, use the T-parameter matrix representation of the network. Depending on the application, you can transparently go back and forth without gaining or losing any information.

This transformation is similar to the transformation performed in a time domain or frequency domain description of interconnect behavior. They both have exactly the same information content, it's just that depending on the question asked, one format will get you to the answer faster.



**Figure 14. Cascading T-parameters**

The special format of the T-parameter matrix is designed so that the equivalent T-parameter matrix of 2 networks in series, is just the product of the T-parameter matrices of each of the two networks. The output of one T-parameter matrix is the input to another T-parameter matrix.

In Figure 14, you can see that the a2 wave is the same as the b3 wave and the b2 wave is the same as the a3 wave. This lets you substitute the a2, b2 vector for the b3, a3 vector which results in the product of the two T-parameter matrices.

With this formalism, the net T-parameter matrix of two separate networks is the product of the two T-parameter matrices of each individual network. This is an incredibly powerful principle and is the basis of all calibration and de-embedding methods.

$$T_M = T_F T_D$$

$$T_F^{-1} T_M = T_F^{-1} T_F T_D = T_D$$

**Figure 15. Matrix math for 1 port**

This definition of the T-parameter matrix description of a 2-port network makes describing the de-embedding process simple and concise. When you perform a 1-port measurement of a DUT which has a fixture in series with it, you will have two S-parameter matrices.

First you will see the 2-port S-parameter of the fixture and the 1-port S-parameter of the DUT. Each of these S-parameter matrices can be converted into T-parameter matrices using algebra.



The resulting measured T matrix ( $T_M$ ) is the series combination of the fixture matrix (TF) in series with the device under test matrix (TD). The series combination is calculated by the product of the two T-matrices, as  $T_M = T_{F1} \times T_D$ .

The de-embedding process uses matrix algebra to de-embed the DUT matrix from the measured matrix and the fixture matrix.

As shown in Figure 15, applying matrix algebra, it is a simple matter of multiplying each side of the equation by the inverse matrix of the TF matrix. This results in the T matrix for the DUT alone as the inverse of the fixture T matrix times the measured T matrix.

$$T_M = T_{F1} T_D T_{F2}$$

$$T_{F1}^{-1} T_M T_{F2}^{-1} = T_{F1}^{-1} T_{F1} T_D T_{F2} T_{F2}^{-1} = T_D$$

Figure 16. Matrix math for 2 ports

With 2 ports, the DUT is embedded between two series 2-port fixture matrices. To de-embed the TD matrix, multiply each side of the measured T matrix by the inverse of each fixture T matrix.

Using algebra, the T matrix of just the DUT can be extracted. Of course, from the T-matrix, it is a simple step to convert this into the S-parameter matrix.

This is the basic de-embedding process.

**De-embedding T and S-parameter networks**

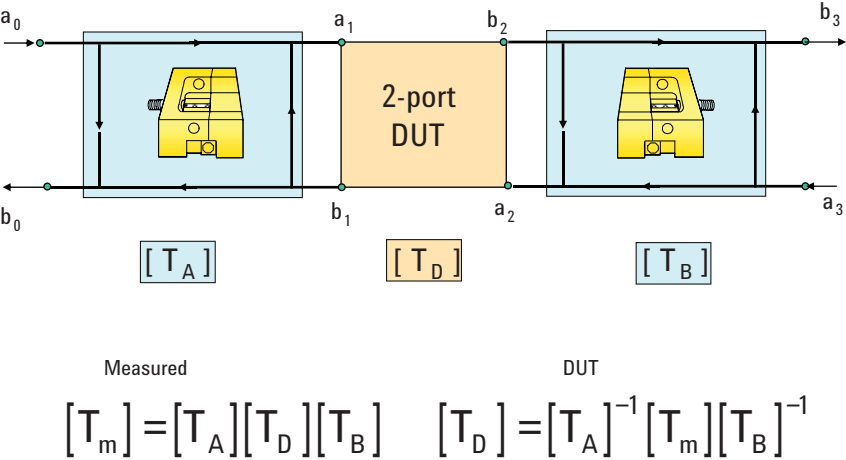


Figure 17. Principle #5: De-embed fixtures from measurements using T-parameter matrices

Principle number 5 of the de-embedding process tells you how to de-embed the DUT. If you have the description of the performance of each fixture in terms of their T-parameter matrix and the performance of the composite of the DUT and the fixtures on either side as a T matrix, then the T matrix of the device under test can be extracted mathematically.

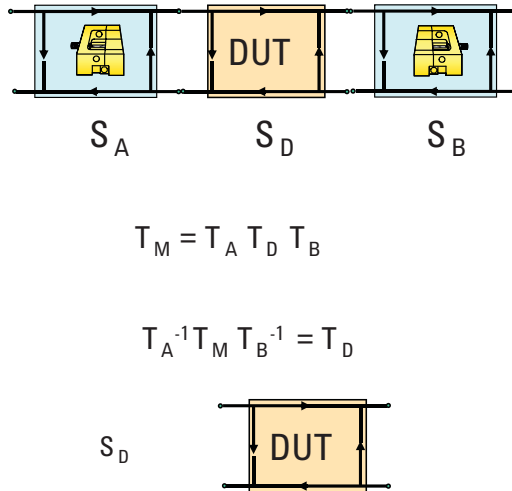


Figure 18. The de-embedding process

**There are six basic steps to perform a de-embedding operation.**

- Step 1.** Measure the composite system of the DUT and the fixtures.
- Step 2.** Obtain the 2-port S-parameters of each fixture. Obtain the 2-port S-parameter of each fixture; this is usually the most challenging part of de-embedding.
- Step 3.** Convert each of the S-parameter matrices into T-parameter matrices, which is just a mathematical process.
- Step 4.** Perform the matrix math to convert each of the fixture T matrices into their inverse matrices
- Step 5.** Multiply the measured T matrix by the inverse of the fixture T matrices using matrix math.
- Step 6.** Convert the de-embedded DUT's T-matrix into a S-parameter matrix using matrix math.

In most network analyzer and processing software, such as Agilent's Physical Layer Test System (PLTS) and Advanced Design System (ADS), the matrix operations are completely hidden from the user. You simply supply the combined series S-parameter and fixture S-parameter measurements, and the conversions and matrix math are performed automatically. In practice, there is no need to understand the details of how the matrices are combined together.

## Obtaining the S-Parameter of the Fixture

The secret to successful de-embedding is to obtain a good value of the S-parameters of the fixture. There are basically four methods used for obtaining S-parameters. These work on any size network, 2-port, 4-port or more.

- Direct measurement
- Extracting equivalent model from a measurement
- Calculate S-Parameters from a scalable, analytical approximation
- Calculate S-Parameters from a 2D or 3D field solver model

### Direct measurement

The first method is direct measurement. This requires being able to connect to both ends of the fixture at the calibration plane of the VNA. While not the most common configuration, it is the simplest and most direct way of getting the S-parameter measurement of the fixture.

### Extracting equivalent model from a measurement

When a direct measurement of the fixture is not possible, the next best solution is to perform a measurement of the fixture in such a way that a circuit model can be fit to the measurement and the S-parameters of just the fixture created.

### Calculate S-parameters from a scalable, analytical approximation

Sometimes, the fixture can be as simple as a uniform, lossy transmission line. Or a part of the fixture could be a uniform, lossy transmission line. In such cases, an accurate analytical model can be used to generate the S-parameter of the line segment. The advantage of this sort of model is that it can be scaled to any appropriate length. This is the basis of the port extension calibration procedure.

### Calculate S-parameters from a 2D or 3D field solver model

Finally, the S-parameters of the fixture can be calculated using a 3D planar or full-wave field solver. Most full-wave tools are accurate enough to extract S-parameters for practical use, if their geometry can be accurately described and the material properties of the fixtures are well known.

When designing the fixturing for the DUT, it is important to think about how the S-parameter of the fixture can be generated.

One of the most important concerns is the accuracy of the fixture S-parameters. The fixture connected to the DUT must be identical to the structure which is measured and the S-parameter extracted to be used for de-embedding. This is always a concern for all cases of calibration or de-embedding.

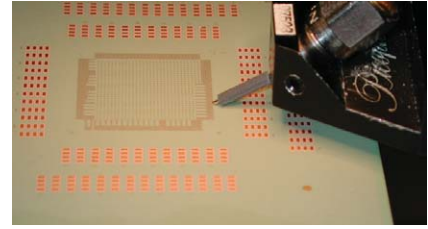
The following case studies illustrate the principles of de-embedding and show that a routine process can be used to generate S-parameter files that can then be used to provide direct measurements of the DUT.

## Direct Measurement of Fixture S-Parameters

Microprobe



Probing an LTCC package



**Figure 19. Example #1: De-embedding microprobes**

In Figure 19, the fixture is a microprobe used to make contact with circuit boards and semiconductor packages. On one end is a standard 3.5 mm coaxial connector and the other is a coplanar S-G tip. The path between these two ends is a short length of rigid coaxial cable.

In most typical applications, the microprobe is calibrated at the probe tip using reference calibration structures. This is perfectly acceptable and is the common practice. In general, there are three calibration measurements, an open, short and load, performed on each port. Then for multiple ports, there are  $n-1$  thru measurements plus one isolation measurement. For  $n$  ports ( $n$  = number of ports, this is a total of  $4 \times n$  individual measurements in the calibration process.

In a 2 port measurement, this equals 8 measurements. There are 8 chances to break a probe tip. In a 4 port measurement, there will be 16 measurements in the calibration procedure. In a 12-port measurement, there are 48 chances to break a tip, just in the calibration process.

By leveraging de-embedding, the calibration procedure using microprobes can be dramatically simplified.

## Using de-embedding in the calibration procedure

The calibration procedure with de-embedding is simple. The ends of the 3.5 mm connectors on the cables from the VNA are connected to an e-cal module, in this case an Agilent N4433A. With one mouse click, the calibration plane of the VNA is moved to the ends of the 3.5 mm cables.

Next, the microprobes are attached to the ends of the cable and the measurements of the semiconductor package performed. These measured S-parameters have the DUT with fixtures on all sides. However, if you have a good set of S-parameters for the fixtures, their influence can be removed from the measurements.

The de-embed operation can be started from the calibration menu tool bar of the VNA. The S-parameter files for the fixture are selected and the VNA now displays the S-parameter for just the semiconductor package leads.

For a 4-port measurement, the calibration process has changed from 16 different measurements, which might take 3 or 4 hours and introduce opportunities for mistakes and damage to the delicate probes, to literally a 3 minute, automated operation with robust connectors.

## Steps for using de-embedding in Calibration



Figure 20. Step 1. Calibrate all ports at the end of the coax cable using the electronic calibration module



Figure 21. Step 2. Attach microprobes to the ends of the VNA cables  
Step 3. Perform all the measurements with microprobes

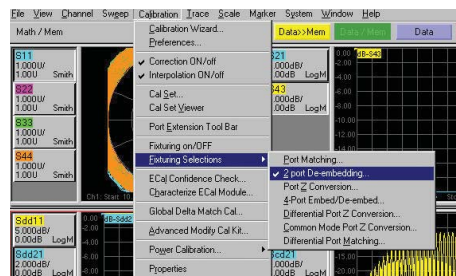


Figure 22. Step 4. De-embed the microprobe S-parameters

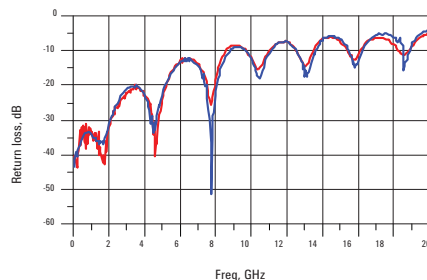


Figure 23. Step 5. Analyze the measurements of the DUT

Microprobe to measure



Thru connection, with the microprobe to be measured inserted, using unknown thru calibration

One port cal

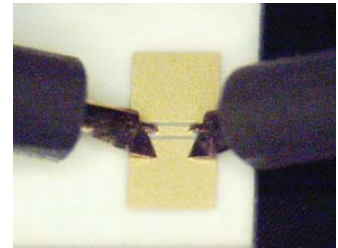
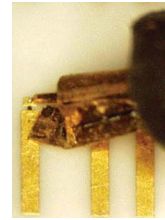


Figure 21. Measuring microprobe S-parameters

### De-embedding the microprobe in series

A 2-port model of the microprobe is required to de-embed the microprobe in series with the DUT from a composite measurement. This is accomplished using a very straight forward, three-step process. A 2-port VNA is used to perform the fixture measurement.

First, one port of the VNA is set up with a precision cable ending with a 3.5 mm connector. The other port has a precision microprobe on the end of a cable that has the same pitch as the microprobe to be measured.

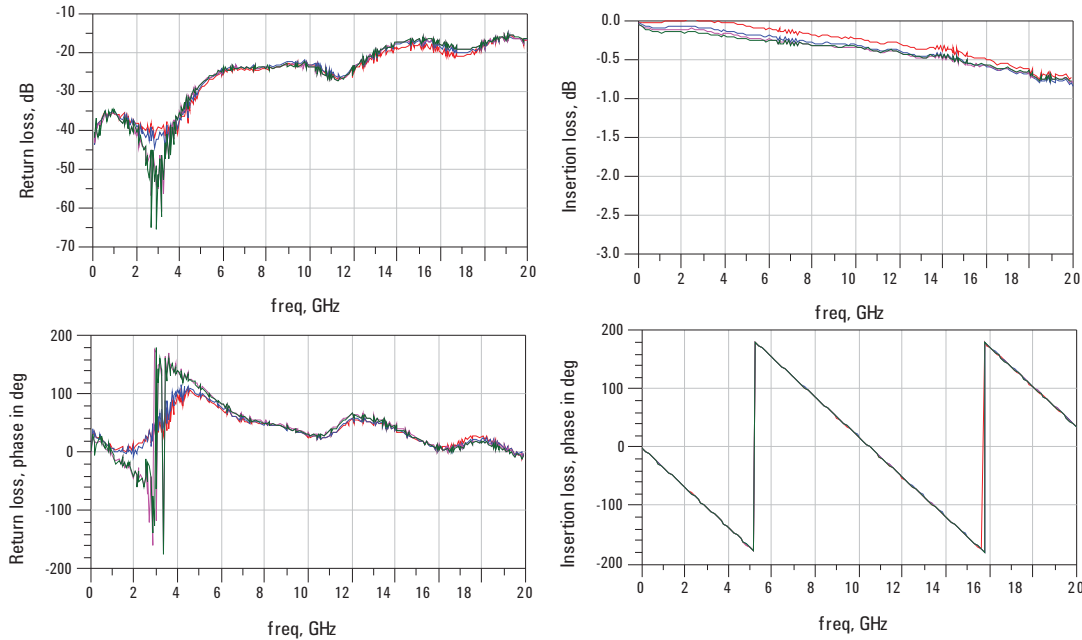
Next, the VNA is calibrated with this configuration. To calibrate a VNA with different adaptors on the ends, a standard "two port with unknown thru" technique is used. This requires first an open, short and load calibration on each port. On the coaxial port, coaxial standards are used. On the microprobe end, a precision calibration substrate is used as the reference. This is the standard process for calibrating with a microprobe.

Next the thru path is calibrated. All the latest VNA models, and PLTS, have a new integrated calibration routine called “unknown thru” calibration. This is a breakthrough technology that enables the use of “non-insertable” connectors on the ends of the cables connected to the VNA ports. This calibration procedure allows the use of different connector sizes, types or geometries on the ends. This could be a 2.4 mm connector on one end and 3.5 mm connector on another, for example, or in this case, a coaxial connector and a microprobe.

All that is required is a thru connection with only a few dB of insertion loss between the two connectors and a small phase delay at the lowest frequency. In Figure 21, the unknown thru connection is made with a second microprobe on the cable end, and the tips of the two probes are in contact with a very small thru connection pad. This is the same configuration as used in the thru calibration of the microprobes.

Using this calibration process, the reference planes of the VNA are moved to the end of the coaxial cable for one port and the end of the microprobe on the other.

Finally, the 2-port S-parameters of a microprobe are measured by inserting the microprobe to be measured between the coax on one port and the other, calibrated microprobe tip, on the other. This is just the unknown thru calibration configuration. After the calibration, a measurement of the 2-port S-parameter in this configuration is a direct measurement of the return and insertion loss of the second microprobe itself.



**Figure 22. Measured performance of a four different microprobes**

Using this routine procedure, the 2-port S-parameter of any microprobe can be measured. Figure 22 shows an example of the measured performance of four individual microprobes with the same geometry. The return loss, sensitive to impedance discontinuities, is very similar in all four units. This indicates that they are physically indistinguishable.

The insertion loss shows identical phase up to 20 GHz, indicating very similar lengths. There is a slight variation in insertion loss between the microprobes. This could be due to slight variations in how the probes are touching down on the substrate or the quality of the thru connection between the two tips.

The variation apparent among these four probes is small enough that one average value set of S-parameters can be used for all the nominally identical probes.

In fact, it is routine now for probe suppliers to provide an .s2p file for each of the probes they sell. These 2-port S-parameter data sets are created using this procedure.

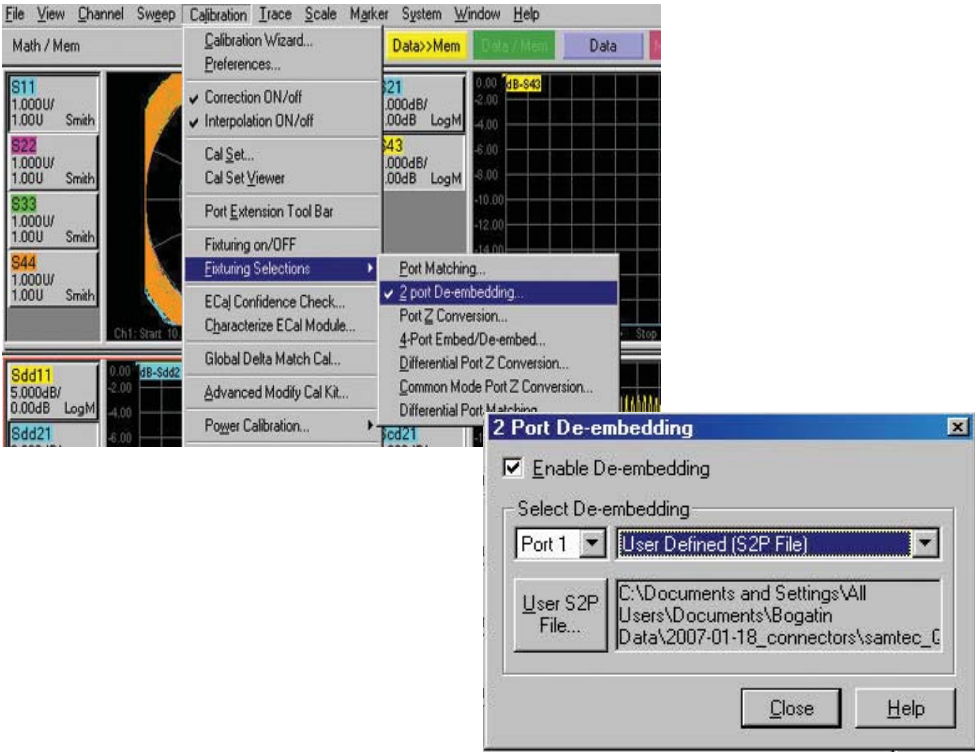


Figure 23. De-embedding on the VNA

Since the actual de-embedding operation which extracts just the DUT behavior is performed after the measurement, there is flexibility in how it is performed. Since the actual de-embedding operation which extracts just the DUT behavior is performed after the measurement, there is some flexibility in performing this type of error correction. There are three different ways to accomplish de-embedding: using the vector network analyzer firmware internal to the hardware, specialist signal integrity software (PLTS) or modeling software (ADS).

**De-embedding using a vector network analyzer**

De-embedding a DUT directly on the Agilent VNA is as simple as selecting **Calibration > Fixturing Selections > 2-port De-embedding**. Once this is selected, a new window opens up allowing the user to select the .s2p file of the fixture on each of the two ports.



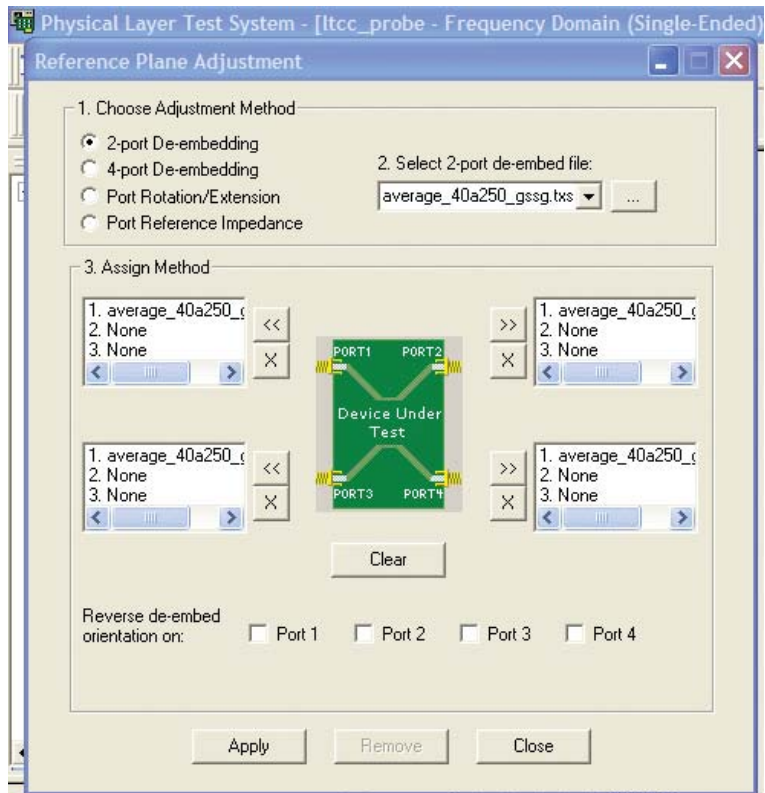


Figure 24. De-embedding in PLTS

## De-embedding using PLTS software with the VNA

This same process can be implemented using Agilent's Physical Layer Test System (PLTS) to control the VNA and collect the measurement results, or in post processing of the measurements. In PLTS, de-embedding can be accessed by selecting the **Utilities > Reference Plane Adjustment**. The .s2p de-embed file is selected for each port required and then the de-embedded measurement of the DUT is displayed in the user window.

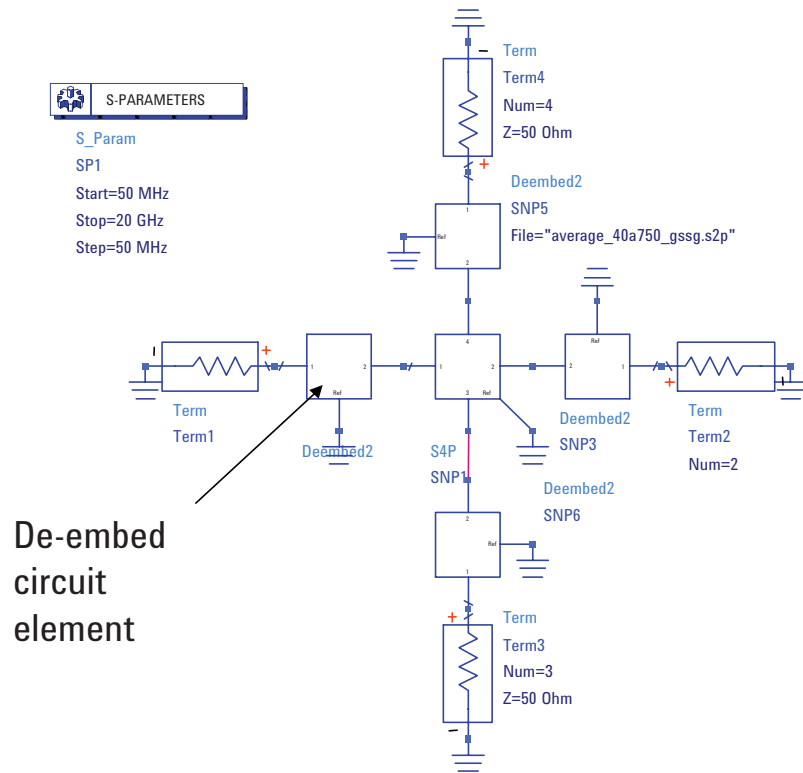
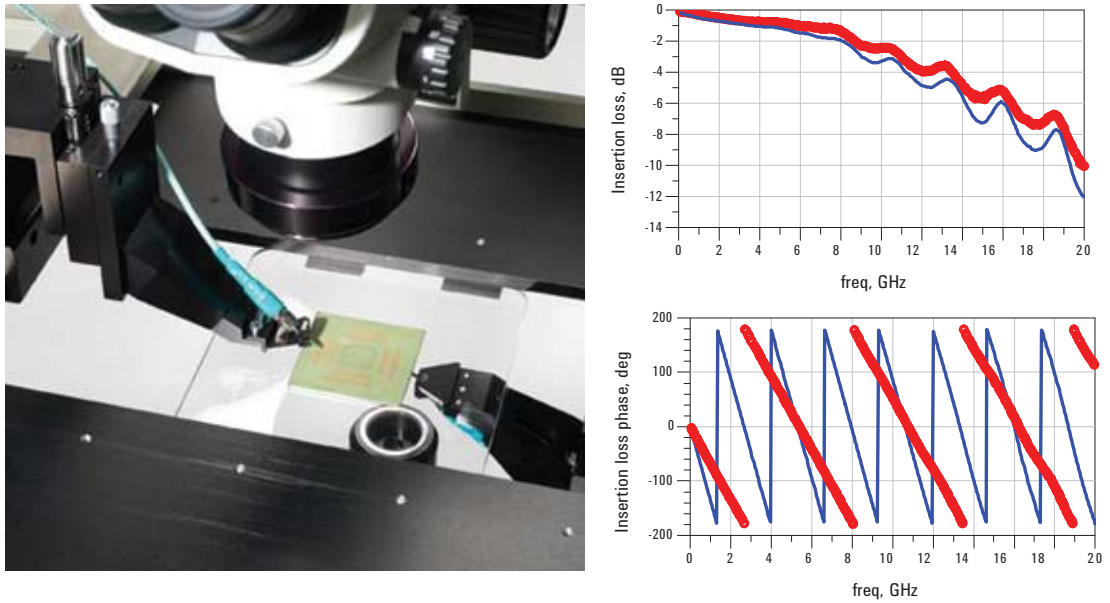


Figure 25. De-embedding in ADS

## De-embedding using ADS modeling software

In addition, de-embedding can be performed using Agilent's Advanced Design System (ADS). The measured, 4-port data file of the DUT with the microprobes in series can be brought into the ADS simulation environment. The 2-port de-embed circuit element, native to ADS, is loaded with the measured .s2p file of the microprobe and the resulting simulated S-parameters are of just the DUT with the microprobes removed.

These new 4-port S-parameter data sets can be used in all the typical operations, such as transient simulation, eye diagram simulation and model building through optimization.



**Figure 26. Impact of the microprobe**

The microprobes on each end of the cable add a significant amount of phase to a thru measurement of a package interconnect. As seen in Figure 26, the measured insertion loss of a package interconnect is obtained by probing opposite sides of the package, from the C4 pads on one side to the land grid array pads on the other side.

The calibration plane of the VNA was moved to the end of the cables. Then microprobes were attached to the cables and the DUT measurement performed. The blue trace is the measured insertion loss with the microprobe fixtures in the measurement. The red trace is the same measurement with the microprobe fixtures removed from the measurement and the package interconnect de-embedded. The red trace is a better approximation to the package interconnects alone.

The large impact on the phase is the result from the fixture adding length to the measurement. The magnitude of the insertion loss is only slightly affected by the probe, since the probes are designed to be as transparent as possible. However, the impact on the 3 dB bandwidth is important. With the fixture in the measurement, the 3 dB bandwidth of the package interconnect is measured as about 8 GHz. With the fixture effects removed, the 3 dB bandwidth is 11 GHz. This is a 20% increase in bandwidth.

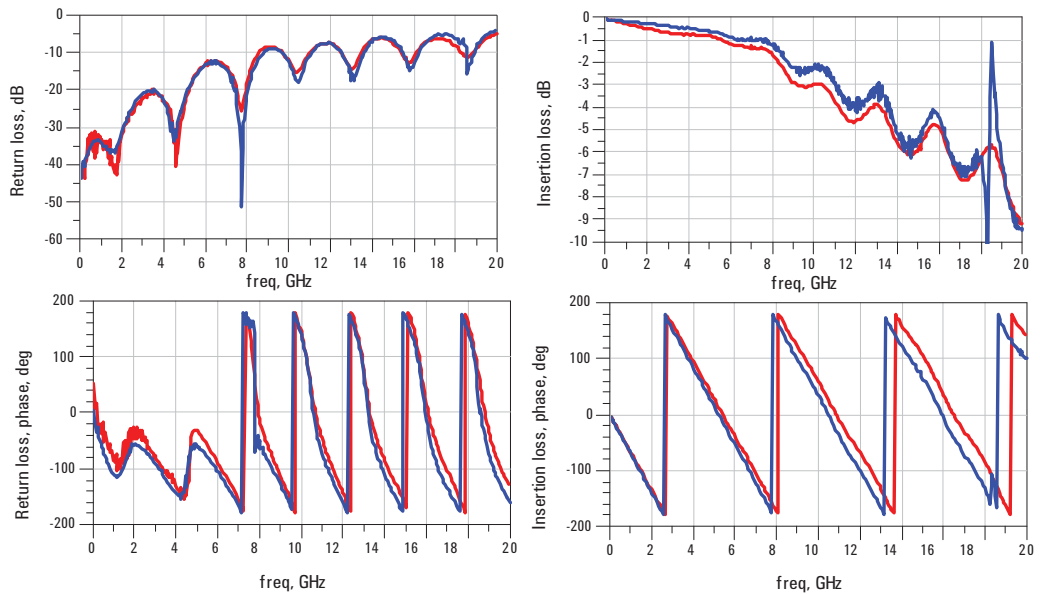


750 micron pitch probes

25 micron pitch probes

**Figure 27. Measuring the differential pair of a LTCC**

As a final verification of this technique, two methods were used to measure the same differential pair in a low temperature co-fired ceramic (LTCC) package. First, the differential channel was measured using microprobes that were calibrated directly at their tips. Then the same differential channel was measured using the new calibration technique of first calibrating to the cable, and then using the .s2p file for the microprobe to de-embed the package interconnect from the composite measurement.

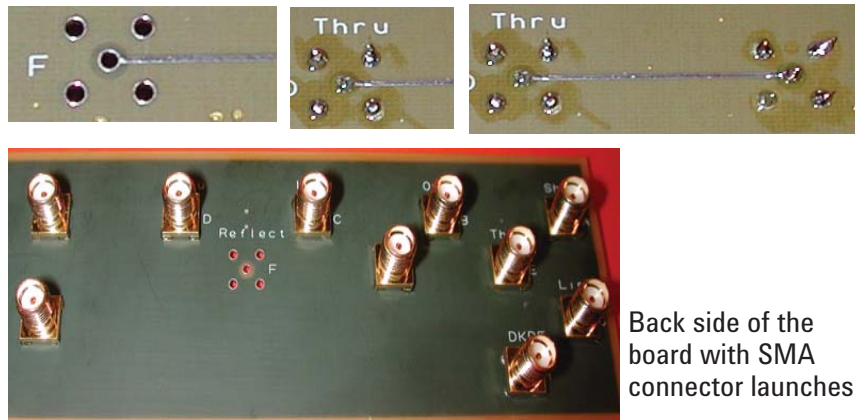


**Figure 28. Final verification**

In these measurements, up to 20 GHz, the agreement is seen to be excellent. See Figure 28. The return loss, which is a measure of the impedance matching, is nearly identical. The insertion loss has a very small difference, which can easily be due to the differences in the probe tips' compression. The measurement agreement, even at 20 GHz, is within 25 degrees.

This measurement also shows that the interconnect has a differential return loss of less than  $-13$  dB up to about 6 GHz. This is a typical acceptable specification. The  $-3$  dB insertion loss bandwidth is about 9 GHz.

## Building the Fixture S-Parameter by Fitting a Model to Measurement Data



Back side of the board with SMA connector launches

Figure 29. Example #2: De-embedding circuit board traces

Figure 29 shows the SMA launch to a 4 layer circuit board is the fixture to a uniform trace on a circuit board. The SMA is designed with four return pins surrounding one signal pin. The board is designed with plated holes that closely match the pin diameters. The SMA is soldered into the board with the pins connecting to internal ground layers and the signal pin to the top signal layer.

The clearance holes in the ground planes have been designed so that the launch is well optimized, but not a perfect match, to 50 ohms.

The goal is to generate an S-parameter file for the launch that can be used to de-embed any surface trace from a measurement of the SMA connections on the ends.

The process will be to measure a short length thru with two SMAs on either end and a long thru with two SMAs on the ends. The same SMA model will be used for each end. A topology based model will be extracted from the measurement and then used to simulate the S-parameters for just one SMA launch.

Using this S-parameter file, the intrinsic performance of any structure connected to a launch on the board can be extracted.

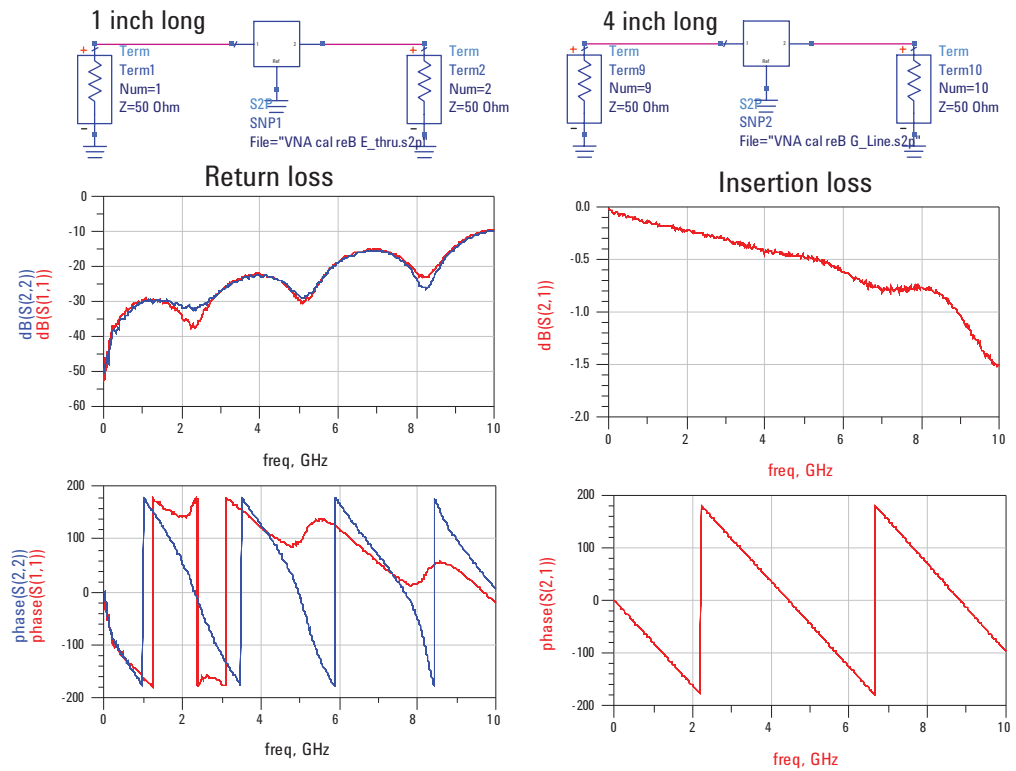


Figure 30. Measured return and insertion loss of the 1 inch long trace

The two sets of measurements taken are shown in Figure 30: a 2-port 1-inch long thru, and a 4-inch long thru. As can be seen by comparing the  $S_{11}$  and  $S_{22}$  performance of the 1-inch thru, the SMA launches are not identical. They are close, but there are clearly some differences between each end of the line. The same is true about the 4-inch long thru.

This means that there are limits to the accuracy of this de-embedding technique, which are due to variations in the launches from fixture to fixture.



Rule of thumb:  $BW = \frac{0.6}{Len}$  BW in GHz, len in inches

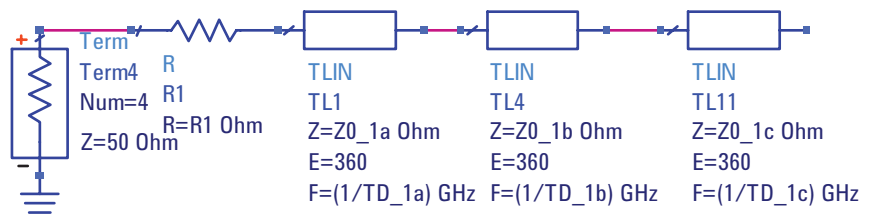


Figure 31. Building a model for an SMA launch

Any single-ended interconnect can always be approximated by a uniform transmission line. Of course, there is always a bandwidth limitation to how well all models work. The more uniform the interconnect, the higher the bandwidth of the model. When the interconnect is non-uniform, the interconnect can be modeled as a few uniform transmission lines in series. This is always a good model.

The question is always how many sections are needed for a given bandwidth. As a rough rule of thumb, the bandwidth of a single transmission line section will always be greater than 0.6 divided by the length of the line. If the line is 1-inch long, the minimum bandwidth of the model will be at least 0.6 GHz.

If you want a model with a bandwidth of at least 10 GHz, this means that for non-uniform regions, you need a new transmission line model for every 60 mils of interconnect. The SMA launch is comprised of a uniform barrel about 200 mils long and two shorter regions about 50 and 30 mils long corresponding to the pin in the board and the excess capacitance at the pin to trace interface.

As a good starting place a 10 GHz model for an SMA launch can be three uniform transmission lines. Each segment has a characteristic impedance and a time delay. In addition, due to the variable quality of the SMA connection, there maybe some contact resistance, on the order of 100 mohms, which is added to the model. This is the topology based model that will be used for the SMA launch. The identical model and parameter values will be used for all launches. To find the parameter values, take the measured results and fit this circuit topology to find the best parameter values.

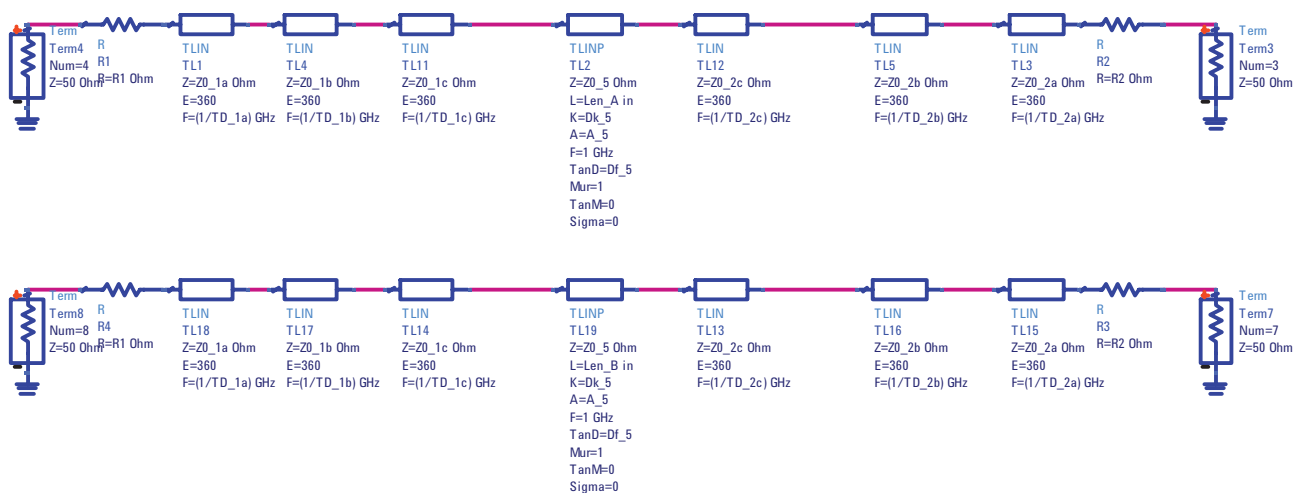
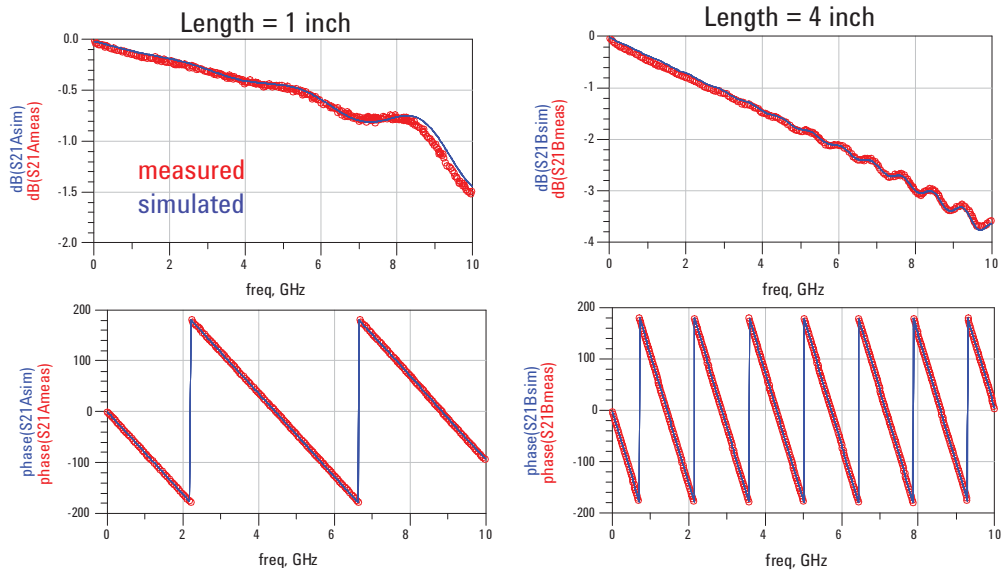


Figure 32. Two different length thru's

The two different thru interconnects are modeled as identical SMA launches on each end and a uniform transmission line. The only difference between the transmission line models for short and long thru is their length. They have the same characteristic impedance, effective dielectric constant and dissipation factor. The ideal, lossy transmission line model in ADS is a scaleable model. The variable between the two lines is only their length, 1 inch and 4 inches.

In this model there are ten parameters: there is a contact resistance for the SMA and two parameters for each of the transmission line models — the characteristic impedance and time delay. This makes seven. With the uniform transmission line thru path, there are three parameters: the characteristic impedance, the effective dielectric constant and the dissipation factor. This makes ten.

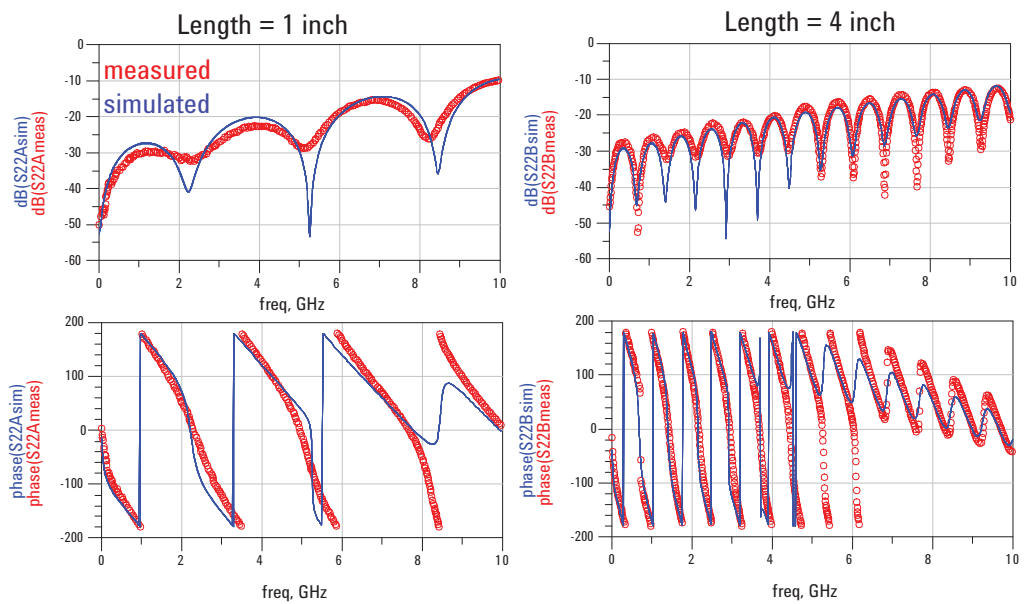
Using both sets of measurements as targets, these ten parameters are simultaneously optimized up to 10 GHz to find the best set of parameter values.



**Figure 33. Insertion loss: measured and modeled**

When the best parameter values have been found, the agreement in the simulated and measured performance for both the 1-inch and 4-inch interconnects is excellent. Figure 33 shows a comparison of the insertion loss for each thru. The agreement to 10 GHz is excellent.

This supports the idea that the model has the right topology and the right parameter values.



**Figure 34. Return loss: measured and modeled**

The return loss measurements and simulations are also excellent. This agreement is all based on assuming the exact same SMA model for each end and a simple, uniform transmission line for the thru path.



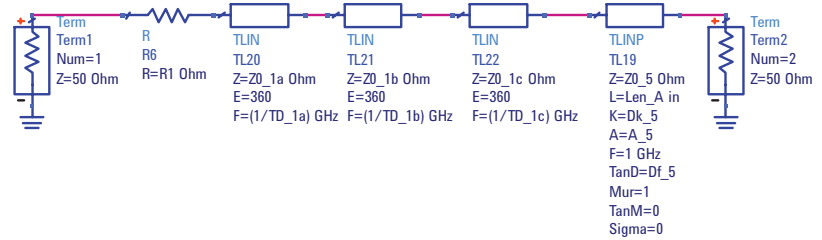


Figure 35. Model for one SMA launch and uniform line

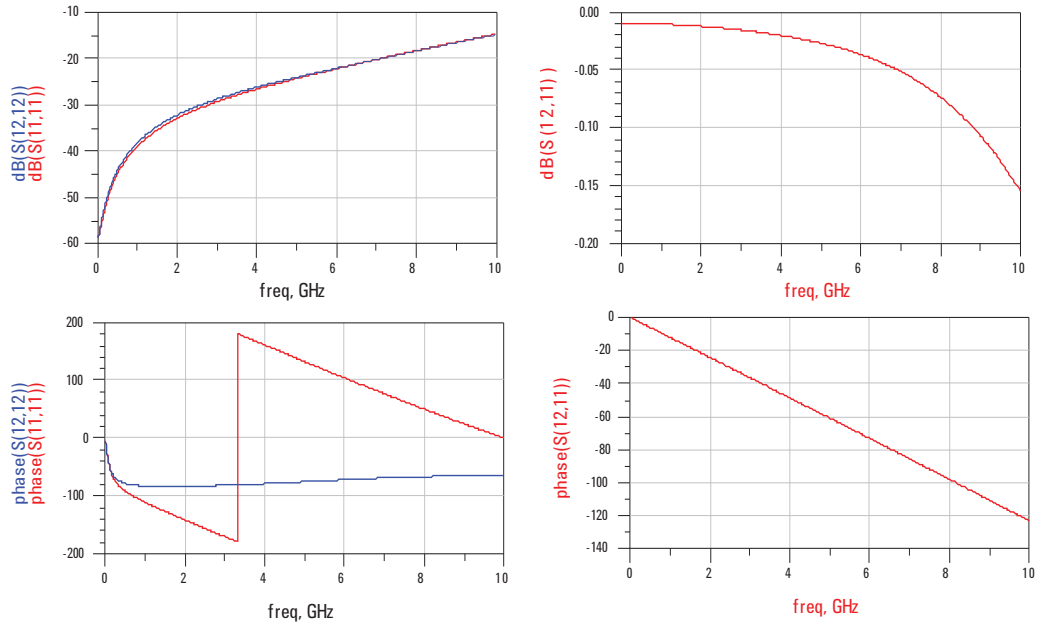


Figure 36. S-parameter of the SMA launch with a zero length transmission line segment

After the model has been optimized, the section that is the SMA launch can be pulled out and its S-parameter simulated directly. This 2-port S-parameter data set now becomes the SMA launch file which will be used to de-embed any structure in the path.

In addition, to make it a more generic model, you can add a scaled length of uniform transmission line corresponding to the microstrip line to the three section transmission line model of the SMA launch. Using the analysis of the two different length lines, determine the values of the three parameters that define a uniform line, the characteristic impedance, the effective dielectric constant and the dissipation factor. The length of the line becomes the scaling factor.

The model shown in the Figure 37 is the de-embed generator engine which can produce a 2-port S-parameter file for any scaled line segment length. This engine is used to build the .s2p file that connects the SMA into any DUT on the circuit board.

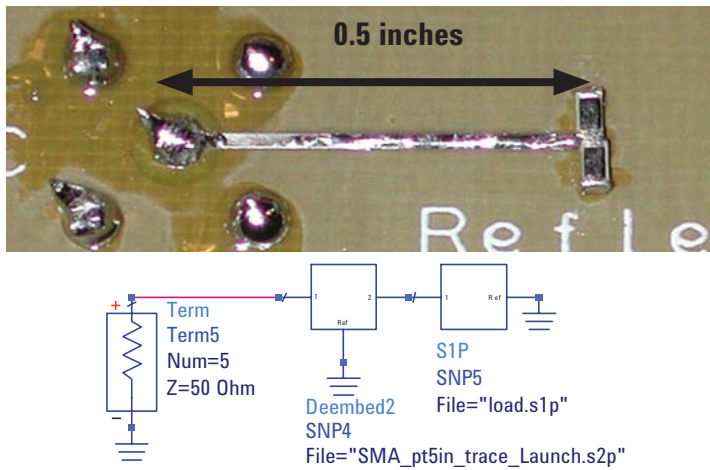


Figure 37. Model for a 50 Ohm load

In this example, a standard SMA launch feeds a ½ inch surface interconnect trace to a pair of 100 ohm resistors acting as a termination resistor. At the end of each resistor is a via to the return path, located on the plane directly below the signal layer.

Perform the measurement of the composite structure, and then build a .s2p file consisting of the SMA model and a ½ inch length of surface trace. This .s2p file becomes the data set which will be used to de-embed just the terminating resistors from the composite measurement.

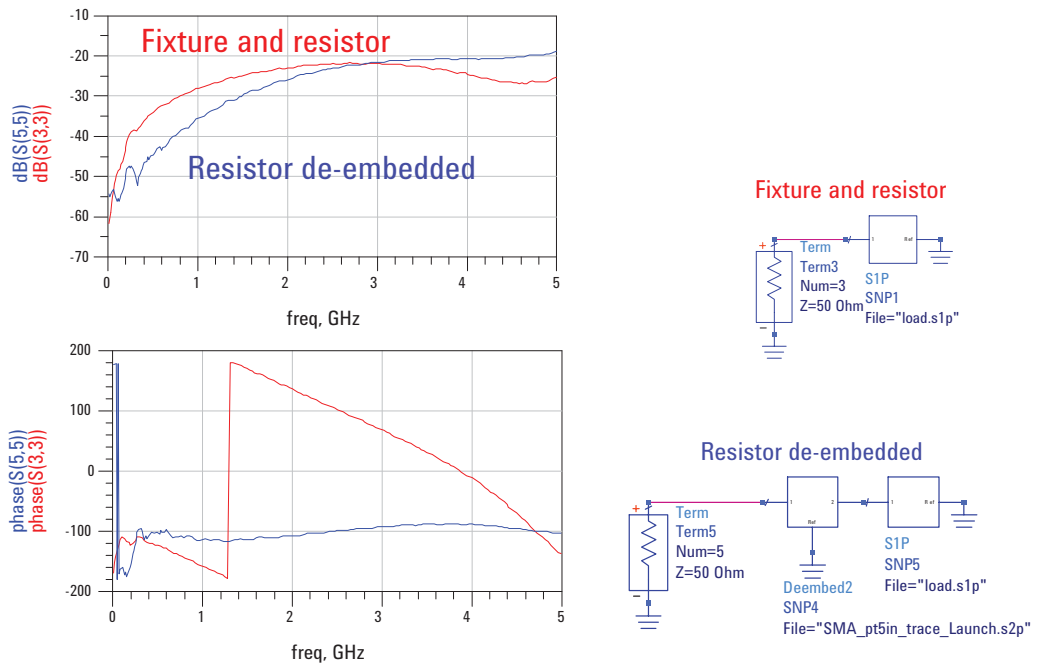


Figure 38. De-embedded termination

The .s2p file generated from the SMA and 0.5 inch trace model is added to the de-embed element in ADS and the composite data of the fixture and resistor is plotted along with the de-embedded data of just the resistor.

The magnitude of the return loss is different and the phase is very far off. Since the SMA launch has been somewhat optimized, and the interconnect is roughly 50 ohms, the magnitude is not strongly affected. The phase is affected since it contributes half an inch of interconnect.

The de-embedded data can now be used to build a model for the termination resistor. To first order, you might have expected a model to be an ideal resistor. This would give the low return loss. However, the phase is comparable to a capacitor as the data is in the southern hemisphere of the Smith chart. Up to the 5 GHz bandwidth of the measurement, a simple resistor is not enough.

A very good starting place for any component is an RLC model. This model can be used with an optimizer to fit the parameter values.

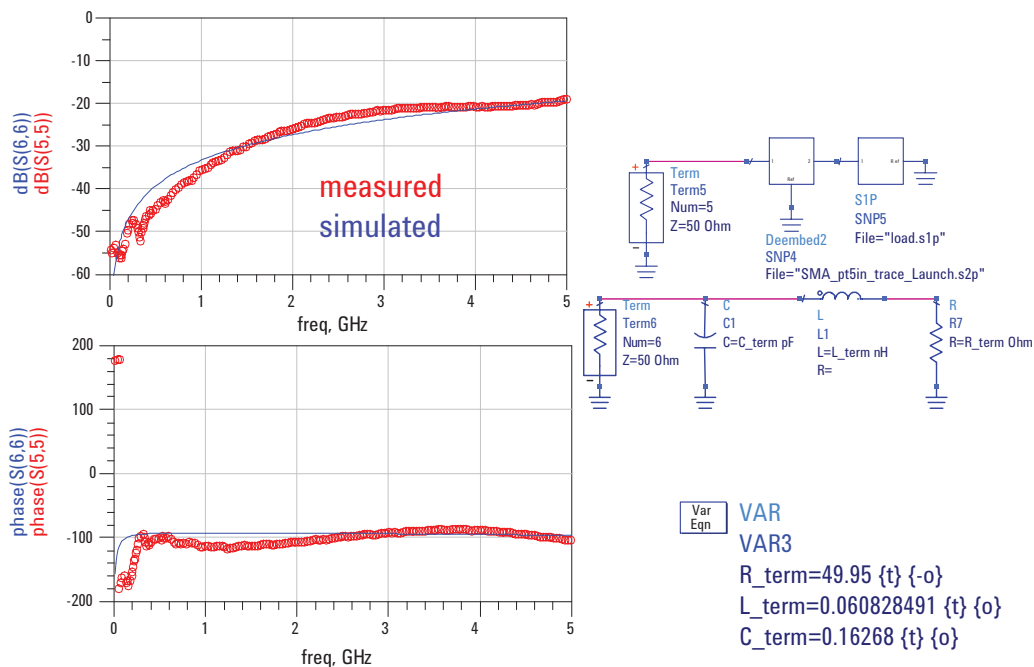


Figure 39. Modeling the terminating resistor

The model for the real terminating resistor is a simple RLC model with the three parameters of the ideal R, L and C.

These values are adjusted, comparing the simulated return loss of this model to the de-embedded return loss of the actual component. When the optimization is complete, the values of the parameters that best fit the data are  $R = 49.95$  ohms,  $L = 0.06$  nH and  $C = 0.16$  pF.

Figure 39 shows a comparison of the simulated and measured values; the model is excellent up to 5 GHz.

Now that you understand the de-embedding process, you can look at what you want in an ideal fixture to facilitate its removal from a measurement to de-embed just the DUT.

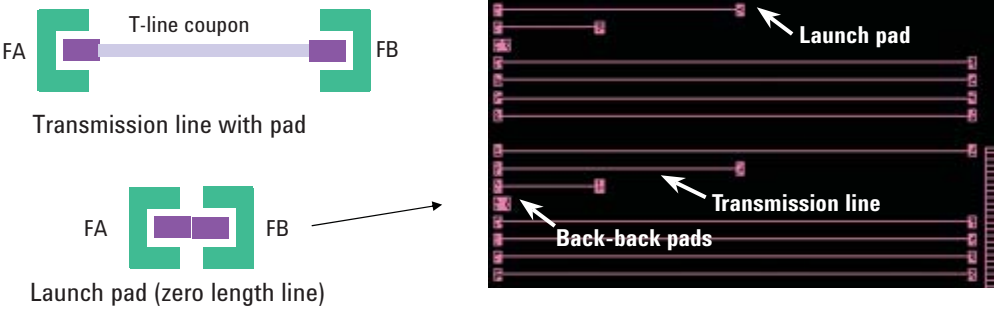
### Optimized fixture design

- Minimize the impact on the transfer matrix-
  - Short
  - 50 ohms
  - Low loss
- Allow easily obtaining the 2 port S-parameters
- The S parameters of the fixture when measured should be identical to when the fixture connects to the DUT

In the design of the fixturing, you want to make sure the fixture has minimal impact on the DUT by designing it to be as transparent as possible. This will make the T matrix values as close to the unity matrix as possible and introduce the minimum numerical error. This means that the fixture should be short, 50 ohms and low loss.

The fixture should be designed so that its S-parameters, and hence its T-parameters, can be easily obtained. Finally, the fixture must be mechanically stable enough so that its S-parameters are the same when connected to the DUT as when they were originally obtained. This will reduce the measurement error in the de-embedding.

When a circuit board is part of the fixturing, care should be taken in the design of the fixturing to make it as identical as possible in all instances. The reference structures for the reference and the fixture to the DUT must be as similar as possible.



**Figure 40. FPGA test fixture de-embedding**

Figure 40 shows an example of a fixture design that is optimized for de-embedding. In this example, microstrip traces are fabricated in a substrate used to construct BGA packages. The launch pads are designed for a ground-signal-ground (G-S-G) microprobe with two return pads on either side of the signal pad.

The idea is to perform a 2-port measurement of the uniform line and extract the material properties from the substrate which could then be used as input to a field solver for package design analysis.

The design of the fixture uses a launch pad that is effectively a zero length thru. The thru measurement is performed. Then a model is extracted for the two pads and the S-parameters of the launch pad is used to de-embed the S-parameter of the other longer thru lines, as ideal transmission lines, without the role of the pads in the material measurement.

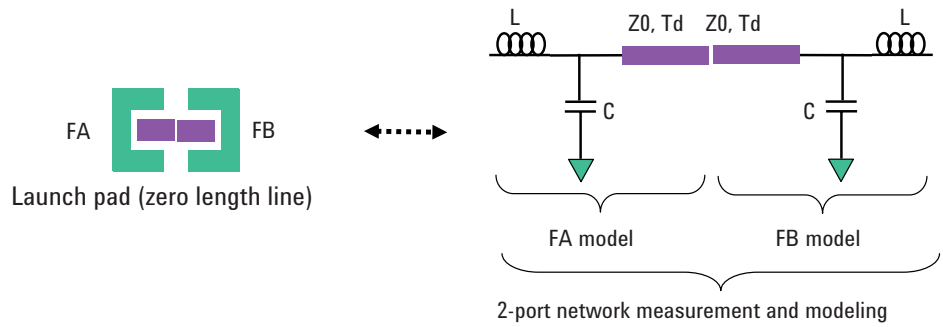


Figure 41. FPGA test fixture de-embedding

The model for the pads is a symmetric LC model with a single, short length, uniform transmission line. With symmetry, there are really only four parameters in this model. The parameter values are extracted from the 2-port measurement of the thru pads and then the 2-port model of just half of this circuit is simulated to create the S-parameter file used to de-embed the longer lines.

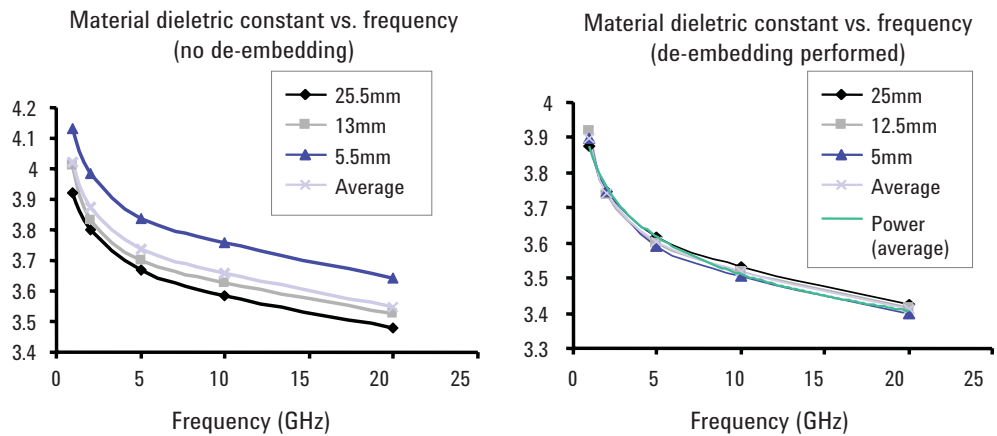


Figure 42. FPGA test fixture de-embedding

From the de-embedded uniform trace measurements, the dielectric constant as a function of frequency can be extracted based on the phase delay and the physical lengths. In the three different length lines, the dielectric constant should be independent of line length.

Without using de-embedding, but including the effect of the launch area, you can see a wider variation into the extracted dielectric constant and a higher dielectric constant for shorter lines. This is consistent as the capacitance of the launch will skew the phase delay toward higher dielectric constant. This is an artifact.

However, when the launch pads are removed, the skew between the three line lengths is dramatically reduced. The measurements are much more consistent. In this material system, there is some frequency dependence on the dielectric constant.

## Simulating the Fixture S-Parameter with a 3D Field Solver

- **Problem:** simulate the performance of a via field and extract the performance of the via only

- **Solution:** use a differential pair fan out to allow the return currents to stabilize and de-embed the differential pairs from both ends.

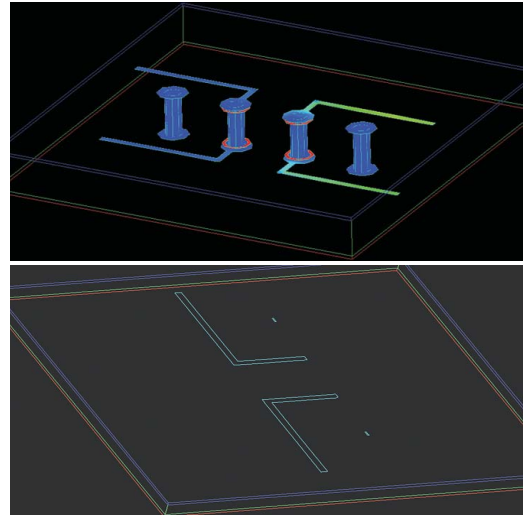


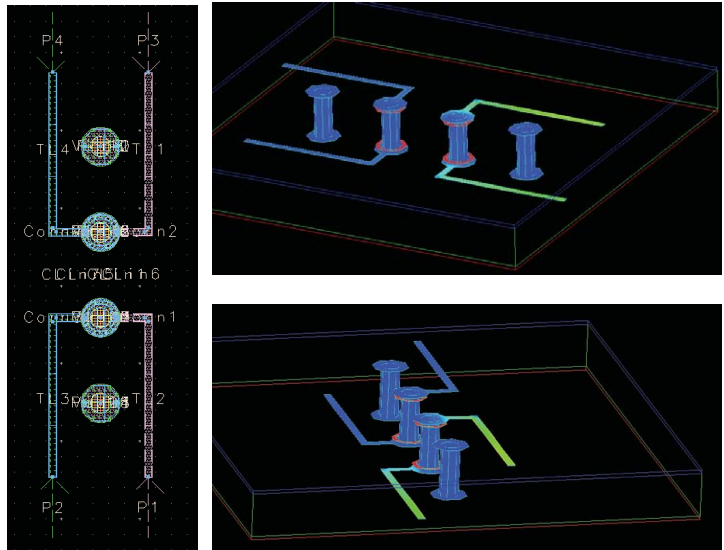
Figure 43. Example #3: The role of de-embedding in simulations

De-Embedding processes can play an important role in simulations, as well as in measurements. In this example, the performance of a via field is simulated with Momentum, a 3D planar field solver tool integrated into the ADS environment. The problem is to evaluate the performance of a pair of signal vias that connect between the top layer and the bottom layer of a 4-layer board. There are two planes between the signal layers acting as return planes, also with vias connecting between them.

You could attach ports to the top and bottom of the vias with no signal paths. However, this will create an artificial return current path because the signal line path is not present. The signal line feed will affect the return current distribution feeding into the signal via.

However, when you add the signal line feed to the via, you simulate not just the via but also the signal paths. While the magnitude of the insertion and return loss is not much affected by the feed lines, the phase is affected by the feed lines. The phase will affect the circuit model extracted from the simulated S-parameters. De-embedding can be used to take the simulated S-parameters of the composite structure, and by building a model of just the signal feeds, de-embedding just the via performance.

- Nominal conditions:
- G-S-S-G vias
  - 50 mil centers
  - 13 mil hole
  - 25 mil capture pad
  - 5 mil capture pad ring
  - 5 mil clearance in plane
  - 50 ohm signal line
  - 5 mil wide trace
  - 30 mil dielectric between planes



**Figure 44. Nominal via configuration**

The first step is to build the model of the vias with the signal line feeds. To simulate crosstalk, two adjacent signal vias are used and the signal feeds separate in opposite directions to minimize the coupling into the surface traces.

As an initial set up, the nominal conditions are used of a 50 mil grid for the vias, 13 mil drilled hole, and 50 ohm microstrip. The plane to plane separation is 30 mils, which is very typical.

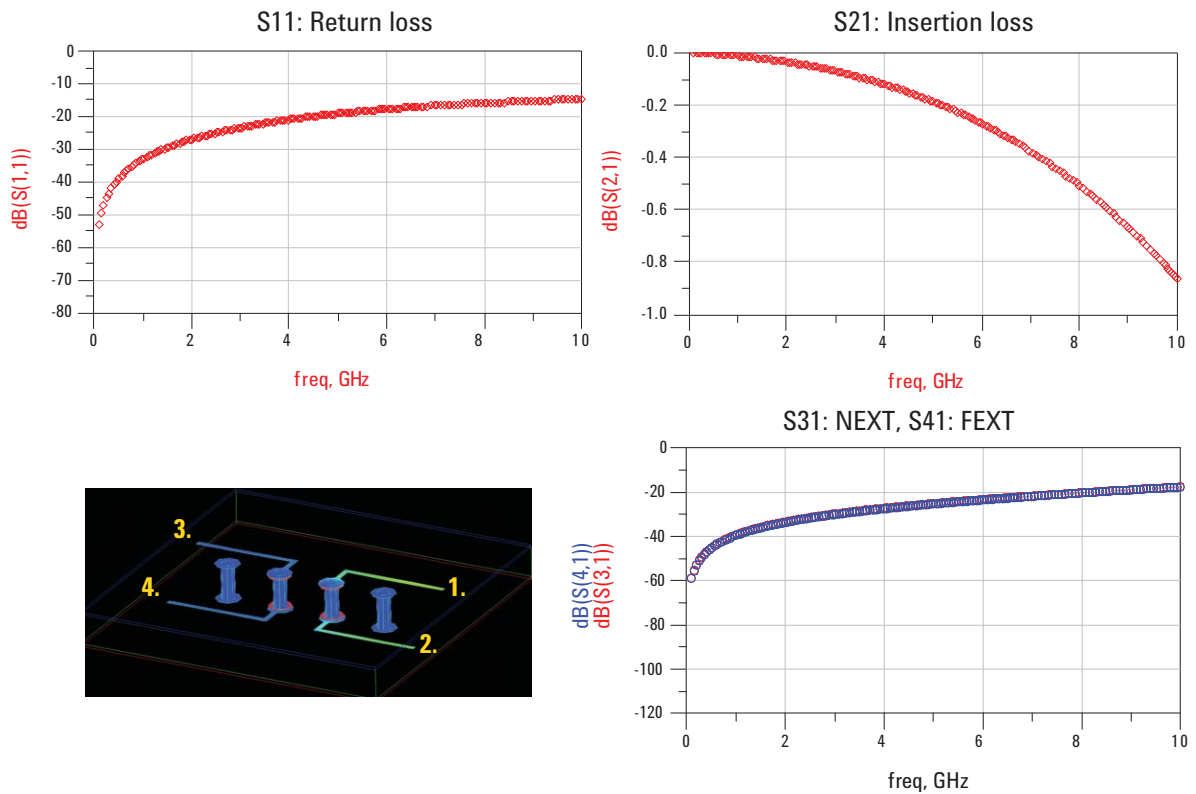


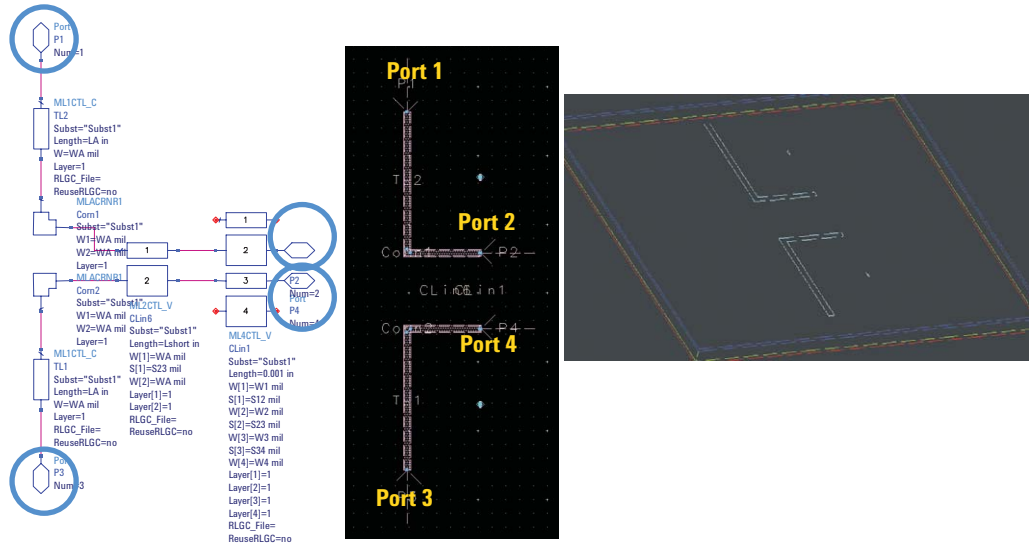
Figure 45. Example of simulated return and insertion loss of 1 signal via

Using the Momentum software package, the 4-port S-parameter of this via field configuration can be calculated. Since this structure is so small, you should expect to see an insertion loss that is pretty close to 0 dB. The crosstalk, which would be the S31 or S41 terms, should be fairly large, negative dB values, as there should be a small amount of crosstalk between these signal vias.

Figure 45 shows the results of this nominal case simulation. The return loss is as expected. It starts with very little, and then creeps up to as high as  $-20$  dB at 4 GHz, a surprisingly large amount. The insertion loss is also fairly large, and the higher the frequency, the worse the insertion loss becomes.

The crosstalk is also larger than might be expected. These values suggest the nominal via built is not so transparent. Of course, another possible explanation is that some of this behavior is due to the fixture, not the via. You can isolate and de-embed just the via from the composite measurement and eliminate this possible artifact by de-embedding it from the measurement.





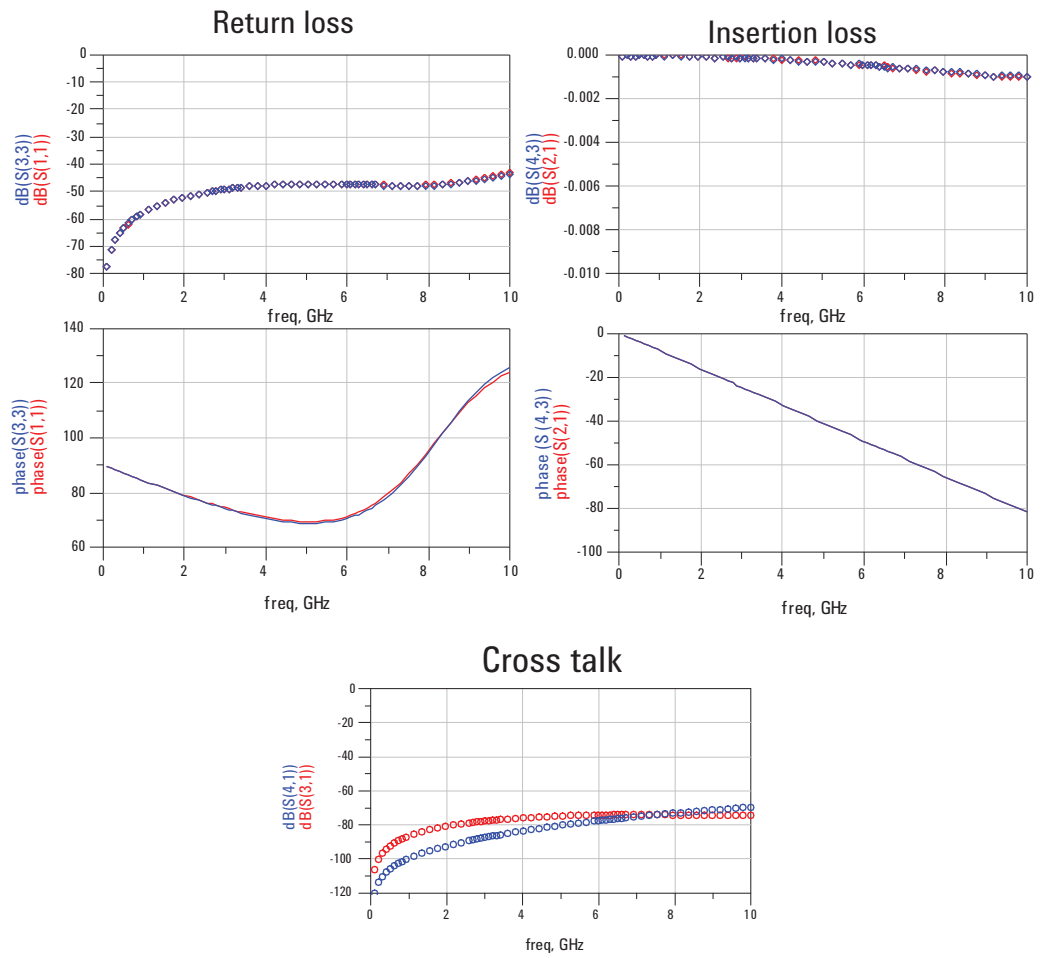
**Figure 46. De-embed file**

The first step in de-embedding the fixture is to create a model for the fixture on each end of the vias. Then simulate the S-parameters of the fixture and use this to mathematically subtract out or de-embed it from the composite simulation.

Break the model off where the signal lines enter the vias. Then place a port at the ends of the signal lines which define the interface to the fixture. There will be one of these on either side of the via field. Since both ends of the fixture are identical, you only need one S-parameter file, just make sure you have the ports connected correctly.

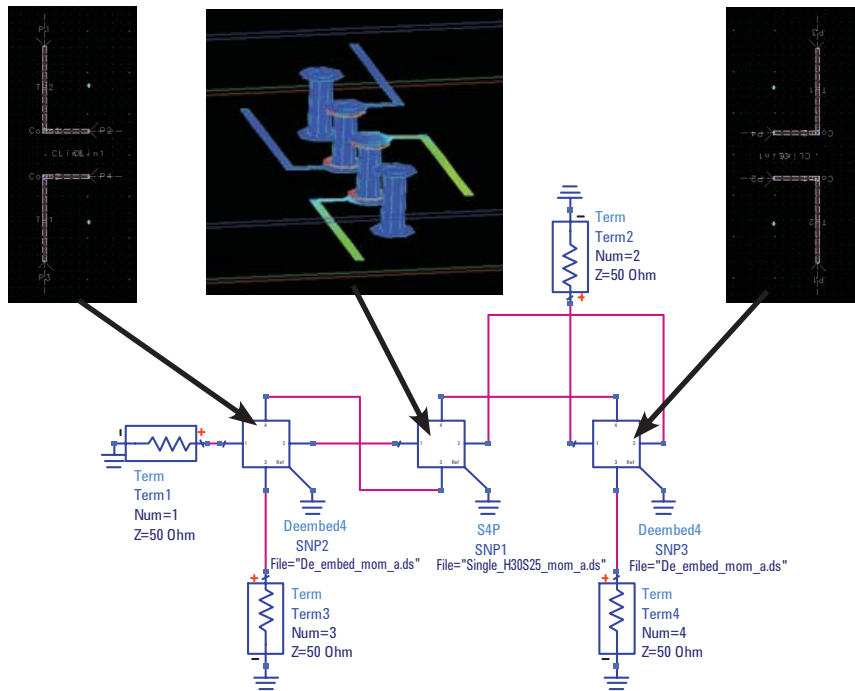
Take this section of the fixture and bring it into Momentum as a 3D structure and simulate the 4-port S-parameters from the ends.

This file becomes the part you will remove from the composite simulation of the via and the fixture.



**Figure 47. De-embed data**

Figure 47 shows the simulated file that will be subtracted off the composite simulated S-parameters. It has very low return loss, very low insertion loss and low crosstalk, but it does contribute phase in each term.

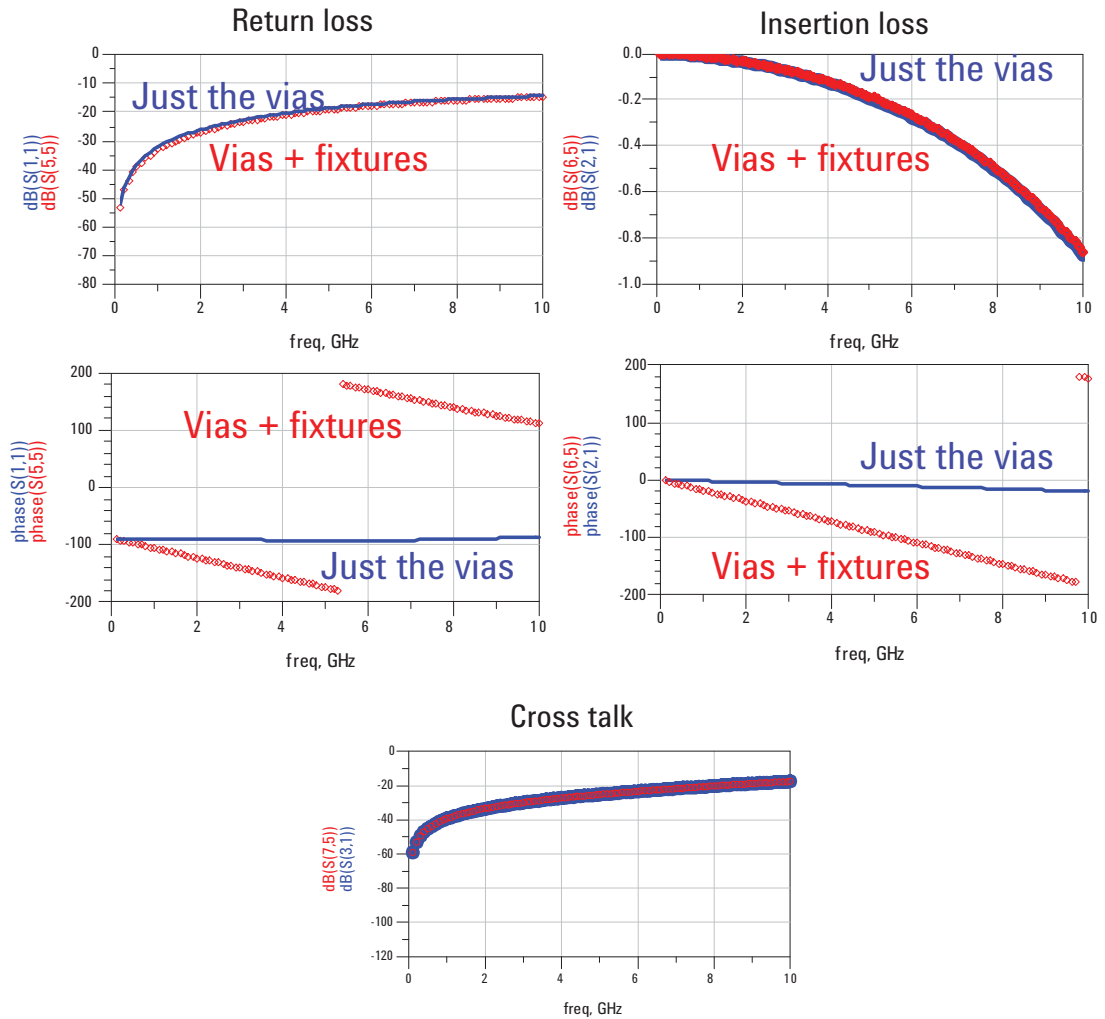


**Figure 48. De-embedding the 4-port data**

This is how ADS is set up to de-embed the vias from the composite simulation. You start with the data set file that has the 4-port S-parameters of the composite measurement. In ADS, there is a de-embed element that can be used to mathematically de-embed another data set.

Load the fixture only with the correct ports connected as a through path into this de-embed element. Do the same thing on the other end of the composite dataset. Now you simulate the S-parameters of this series combination.

The de-embedded S-parameter behavior is really the residual behavior of the complete structure that cannot be fully accounted for by just the transmission line feeds. This would include any return current re-distribution effects in the via field.

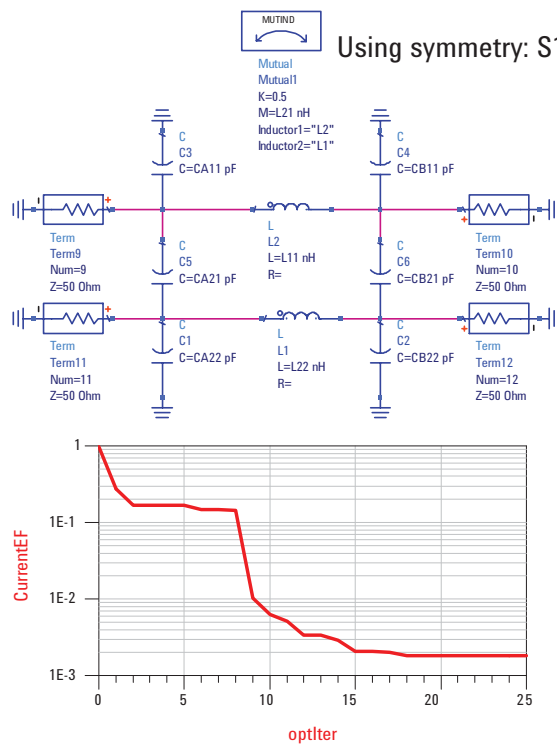


**Figure 49. Impact of de-embedding: de-embedding is critical for accurate phase simulation**

Now you can compare the de-embedded performance of just the via with the composite performance of the via and fixture. As expected, there is little impact on the fixture in the magnitude of the return or insertion loss, but a large impact on the phase. Using de-embedding, you are able to get the S-parameters of just the influence from the vias.

Of course, it might have been possible to get similar results in this case, if the ports were moved closer to where the via started. This would have minimized the impact from the fixture. But, then you could miss any return current re-distribution effects when the return vias are moved apart. This technique is a powerful technique for more complex fixture structures that are needed to feed the vias and to evaluate the impact on the region close to the vias. When you do use a long feed fixture, and you don't de-embed, the phase is mostly dominated by the fixture and you may get misleading results.

In addition, while the 3D planar field solver will take into account the return path in the planes which may re-distribute in the presence of the return vias and the planes, when you simulate just the fixture, the return path is well behaved under the signal lines. Any impact on the current re-distribution in the fixture and via case will be left as part of the de-embedded via data set.



Var Eqn

- Optimize 6 parameters to
- insertion loss,
  - return loss
  - cross talk

VAR  
 VAR1  
 CA11=0.0715631 {o}  
 CA22=CA11  
 CA21=0.0644762 {o}  
 CB11=0.0240905 {o}  
 CB22=CB11  
 CB21=0.0213518 {o}  
 L11=0.101908 {o}  
 L22=L11  
 L21=1.93179e-008 {o}

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{100 \text{ pH}}{0.095 \text{ pF}}} = 34 \Omega$$

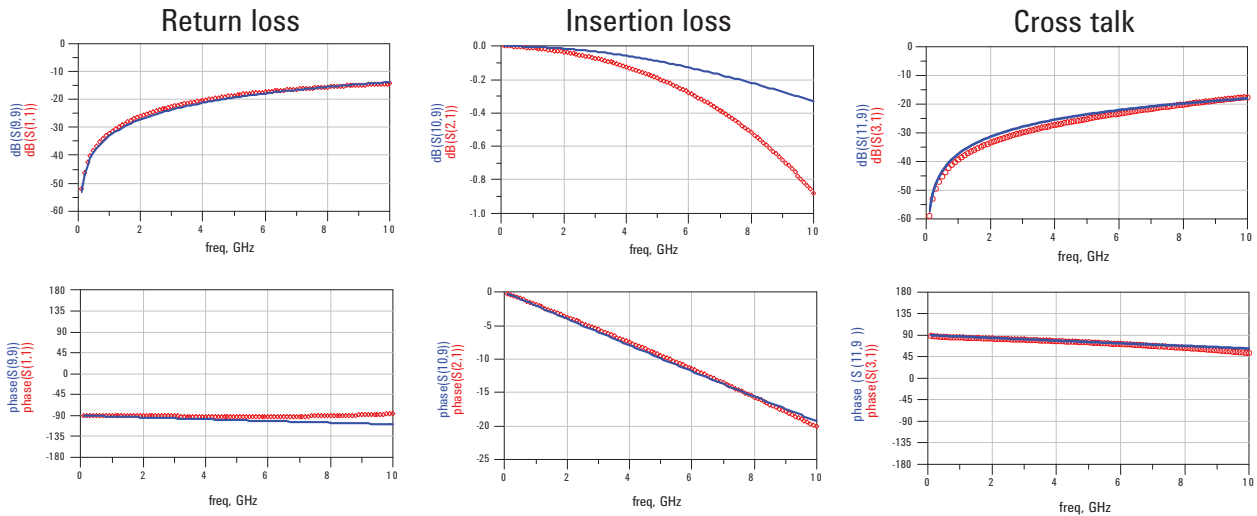
Figure 50. Building a simple C-L-C model of the vias

Using the de-embedded S-parameters of just the vias, you can now build a simple lumped circuit model and begin to analyze the results. The simplest model of a via is a C-L-C topology. When you want to include coupling, you need to add the coupling capacitors and the mutual inductance between the two signal paths.

Figure 50 shows the simple model of the two coupled signal vias. The presence of the return path vias is included in the capacitance to ground and the loop inductance of the signal vias. There are nine terms that define this model. However, by using symmetry, you can reduce this to only 6 terms. Use the built in optimizer to have ADS find the best set of parameter value that match the simulated S-parameters of the via field.

The convergence is shown in Figure 51. You can find the best values in less than 20 iterations. Here are the actual model parameter values when the optimizer is done. What do the values mean? What do they tell you about the behavior of the via? As a rough starting place, you can estimate the single-ended impedance of one signal via by taking the square root of the inductance to the capacitance of the via. In this case, the numbers are about 34 ohms. This says the single-ended impedance of this short via is about 34 ohms- lower than 50 ohms. It looks capacitive, and this is why the return loss is about -25 dB at 2 GHz- it has a mismatch.

But, before you read too much into this number, you should check to see how well this simple model matches the actual, simulated S-parameters.



**Figure 51. Model verification**

Figure 51 shows the comparison of the 3D planar simulated S-parameters of the two signal vias, in red, and the simulated s-parameters of the CLC model in blue for the return loss, the insertion loss and the crosstalk.

- Observations:
  - Return loss suggests, excellent model topology and parameters to 10 GHz
  - Cross talk match suggests excellent modeling of coupling- capacitive dominated
  - Insertion loss suggests another loss mechanism not include in the lumped circuit model, but included in the 3D planar field solution: possibly coupling into the plane to plane cavity

It's clear that the return loss is a great match, as is the crosstalk. This says that the model is a pretty good model for the behavior of the two signal vias. But, the insertion loss is not such a good match. The 3D planar simulation shows more insertion loss than the simple CLC model predicts. The fact that the insertion loss and crosstalk are such a good fit suggests that there is a real effect here. What could it be?

One possible explanation is that as the signal current switches through the region between the planes and the return current flows between the planes capacitively and then to the return vias, there is coupling of energy from the signal into the cavity made up of the planes. The energy that couples into this cavity is lost as radiation into the cavity. This is simulated by the 3D planar tool, but not by the CLC model.

The process of de-embedding the intrinsic via performance from the composite measurement is a generic process you can use to generate a dataset of just the vias of interest which can then be used for further analysis.

## Summary

De-embedding is a powerful tool that should be in the tool box of every characterization engineer. It requires the S-parameters of the fixture to be known. They can be obtained by direct measurement, fitted with parameterized circuit topology based models using measured results as the target, or by simulation with a 3D full-wave field solver

For best results, it is important to minimize the fixture effects by using short sections in the fixture and trying to optimize the design to match to 50 ohms.

Once you have the S-parameter file for the fixture, the built in de-embedding features of the VNA, PLTS or ADS can be used to separate the true performance of the device under test from the artifacts introduced by its fixturing.



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