SFF Committee

SFF-8414 Specification for

HPEI Passive Cable Assembly and PCB S-Parameter Measurements

Rev 10.1 January 24, 2007

Secretariat: SFF Committee

Abstract: This specification defines the requirements for measuring S-Parameters that are suitable for accurate characterization of passive HPEI cable assemblies and PCB's in the speed range that is compatible with test equipment and test fixtures that are available today. Such cable assemblies are used in most applications requiring high speed serial and serial-parallel electrical connections. HPEI is an acronym for high performance electrical interconnect.

This specification provides a common specification for systems manufacturers, system integrators, and suppliers of magnetic disk drives. This is an internal working document of the SFF Committee, an industry ad hoc group.

This document is made available for public review, and written comments are solicited from readers. Comments received by the members will be considered for inclusion in future revisions of this document.

The description of a test procedure in this specification does not assure that the specific hardware necessary for executing the procedure is actually available from instrumentation suppliers. If such hardware is supplied it must comply with this specification to achieve interoperability between suppliers.

Support: This document is supported by the identified member companies of the SFF Committee.

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EXPRESSION OF SUPPORT BY MANUFACTURERS

The following member companies of the SFF Committee voted in favor of this industry specification.

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EMC
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The following member companies of the SFF Committee voted to abstain on this industry specification.

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Foreword

The development work on this specification was done by the SFF Committee, an industry group. The membership of the committee since its formation in August 1990 has included a mix of companies which are leaders across the industry.

When 2 1/2" diameter disk drives were introduced, there was no commonality on external dimensions e.g. physical size, mounting locations, connector type, connector location, between vendors.

The first use of these disk drives was in specific applications such as laptop portable computers and system integrators worked individually with vendors to develop the packaging. The result was wide diversity, and incompatibility.

The problems faced by integrators, device suppliers, and component suppliers led to the formation of the SFF Committee as an industry ad hoc group to address the marketing and engineering considerations of the emerging new technology.

During the development of the form factor definitions, other activities were suggested because participants in the SFF Committee faced more problems than the physical form factors of disk drives. In November 1992, the charter was expanded to address any issues of general interest and concern to the storage industry. The SFF Committee became a forum for resolving industry issues that are either not addressed by the standards process or need an immediate solution.

Those companies which have agreed to support a specification are identified in the first pages of each SFF Specification. Industry consensus is not an essential requirement to publish an SFF Specification because it is recognized that in an emerging product area, there is room for more than one approach. By making the documentation on competing proposals available, an integrator can examine the alternatives available and select the product that is felt to be most suitable.

SFF Committee meetings are held during T10 weeks (see www.t10.org), and Specific Subject Working Groups are held at the convenience of the participants. Material presented at SFF Committee meetings becomes public domain, and there are no restrictions on the open mailing of material presented at committee meetings.

Most of the specifications developed by the SFF Committee have either been incorporated into standards or adopted as standards by EIA (Electronic Industries Association), ANSI (American National Standards Institute) and IEC (International Electrotechnical Commission).

If you are interested in participating or wish to follow the activities of the SFF Committee, the signup for membership and/or documentation can be found at:

www.sffcommittee.com/ie/join.html

The complete list of SFF Specifications which have been completed or are currently being worked on by the SFF Committee can be found at:

ftp://ftp.seagate.com/sff/SFF-8000.TXT

If you wish to know more about the SFF Committee, the principles which guide the activities can be found at:

ftp://ftp.seagate.com/sff/SFF-8032.TXT

Suggestions for improvement of this specification will be welcome. They should be sent to the SFF Committee, 14426 Black Walnut Ct, Saratoga, CA 95070.

SFF Committee --

HPEI Passive Cable Assembly and PCB S-Parameter Measurements

1. Scope

The SFF Committee was formed in August, 1990 to broaden the applications for storage devices, and is an ad hoc industry group of companies representing system integrators, peripheral suppliers, and component suppliers.

2. References

The SFF Committee activities support the requirements of the storage industry, and it is involved with several standards.

2.1 Industry Documents

The following interface standards are relevant to many SFF Specifications.

- X3.131R-1994	SCSI-2 Small Computer System Interface
- X3.253-1995	SPI (SCSI-3 Parallel Interface)
- X3.302-xxxx	SPI-2 (SCSI-3 Parallel Interface -2)
- X3.277-1996	SCSI-3 Fast 20
- asd;LAKJ	PIP (Passive Interconnect Performance)
- X3.221-1995	ATA (AT Attachment) and subsequent extensions
- EIA PN-3651	Detail Specification for Trapezoidal Connector 0.50" Pitch used with Single Connector Attach -2.
- X3.230-1994	FC-PH (Fibre Channel Physical Interface) and subsequent extensions FC-PH-3, FC-PI, FC-PI-2, FC-PI-3 and FC-PI-4
- ANSI-Y14.5M	Dimension and Tolerancing
- MIL-STD-1344,	Method 3008 Shielding Effectiveness of Multicontact Connectors.
- IEC 96-1,	Reverberation Chamber method for measuring the screening effectiveness of passive microwave components.

2.2 SFF Specifications

There are several projects active within the SFF Committee. The complete list of specifications which have been completed or are still being worked on are listed in the specification at ftp://ftp.seagate.com/sff/SFF-8000.TXT

2.3 Sources

Those who join the SFF Committee as an Observer or Member receive electronic copies of the minutes and SFF specifications (http://www.sffcommittee.com/ie/join.html).

Copies of ANSI standards may be purchased from the InterNational Committee for Information Technology Standards (http://tinyurl.com/c4psg).

Copies of SFF, T10 (SCSI), T11 (Fibre Channel) and T13 (ATA) standards and standards still in development are available on the HPE version of CD_Access (http://tinyurl.com/85fts).

2.4 Conventions

The American convention of numbering is used i.e., the thousands and higher multiples are separated by a comma and a period is used as the decimal point. This is equivalent to the ISO/IEC convention of a space and comma.

American:	ISO:
0.6	0,6
1,000	1 000
1,323,462.9	1 323 462,9

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3. Description

This document is about creating accurate and transportable S-parameter measurements on physical interconnect cable assemblies and PCB’s (termed IUT for Interconnect Under Test). Many features of using S-parameters impact the testing or measurement process so a description of what S-parameters are and what is involved with creating a complete set of S-parameters for IUT’s of interest is included.

This technology appears deceptively simple yet is truly mathematically elegant in its ability to describe very complex behaviors.

Use of S-parameters is becoming more widespread as different standards seek practical ways to specify complex signal performance without requiring ‘golden’ hardware and to mitigate the challenges of making accurate waveform measurements at very high frequencies. Previously there has not been a significant demand for transportable S-parameter files as most uses were for design. However, when using S-parameter based methods for compliance to standards and for using S-parameter based methods to allow accurate simulation of complex waveforms, the transportability property rises to the forefront.

This work complements other work in the T11 (Fibre Channel) committee under the signal modeling (FCSM-2) and signal performance specification (MSQS) projects by taking a pragmatic view of the measurement portion.

This document covers three broad areas:

- Thorough description of S-parameters and the general requirements for attaining adequate coverage

- Specifies the format for transporting S-parameter files, including the formats for transporting cross talk and other pair to pair (more than four single ended ports) interaction measurements.

- Specifies acceptance criteria for determining whether calibration structures accurately represent the test fixture.

This document does not provide detailed step-by-step instructions for making calibrations or measurements because these are usually determined by the specific test equipment and its related calibration software. The test equipment and software manufacturers provide calibration, test method step-by-step instructions, and application notes.

The procedures described in this document are not optimized for high volume production testing. They are primarily intended for use as reference methods that can resolve disputes and deliver adequate accuracy for use in compliance testing and simulation.

4. General statement of application space for this document

4.1 Physical components and frequency ranges

Physical implementations are passive cable assemblies up to 15 meters long, PCB based interconnects, and the compliance interconnects (both cable and PCB based) used by various standards to verify transmitter device compliance. The lower length limits are determined by the properties of the S parameter measurement set up (typically around one cm).

Signals used in the end application are between 1 GBaud and 12.75 GBaud serial NRZ stream (800 Mb to ~10 Gb/s using 8b10b encoding). The higher the frequency range for the S parameters the more complete the S-parameter description of the IUT properties an the more difficult the problem of obtaining transportable S-parameters. The methods described in this document are suitable for a frequency range of up to 20 GHz based on fundamental considerations required to generate eye diagrams using the S-parameter measurements with a suitable simulation tool.

These constraints lead to requirements on the frequency step size that depends on the length such that the frequency step causes less than 360 degree phase change.

See clause 6 for the explanation of the insertion loss and return loss terms used in the following paragraphs.

Insertion loss type measurements are assumed to have at least – 60 dB noise floor with lower floors attainable without excessive effort. This noise floor is well below the range of interest (around – 40 dB)

Return loss type measurements are expected to have values in the neighborhood of -10 dB at 9 GHz. A noise floor for return loss measurements of better than -20 dB is required at 9 GHz to achieve adequate accuracy for product characterization.

There is a belief that there is a fundamental challenge to making adequate return loss measurements in the 10 GHz range and this is the reason for the relatively high return loss target. Insertion loss measurements under these conditions appear to be reasonably attainable using well known methods and equipment.

4.2 Uses of S-parameters

4.2.1 Overview

The purpose of this document is to ensure that the basic measurement of the S-parameters adequately and accurately captures the behavior of the IUT and that these measurement results can be accurately repeated on the same IUT by other laboratories.

The S parameters measured for the IUT after removal of the test fixture contributions can be used for a number of purposes. One use is as a model of the behavior of the IUT without any concept of pass or fail. Other uses may involve specifying pass-fail criteria. The modeling/characterization use is straightforward. The pass/fail uses, however, are a subject of significant controversy in the industry.

Once the complete set of S-parameters are known for an IUT one may calculate or simulate waveform responses for the IUT. The properties of these waveforms may be criticized for compliance. Some standards choose to place limits on the values of the S-parameters themselves and others use a mixture of waveform properties and S-parameter values for compliance.

4.2.2 Pass/fail schemes

4.2.2.1 Overview

There are two pass/fail schemes in common use that are discussed in this clause. Both require the use of simple limit masks but one mask is specified in the time domain and the other mask is specified in the frequency domain. Masks can be arbitrarily complex and in the theoretical limit both methods yield equivalent results. In practice, however, the need for having simple masks drives significant differences between these pass-fail methods.

4.2.2.2 Time domain masks

One pass-fail scheme for S-parameter files is in creating eye diagrams or other simulated time domain responses by using a simulation tool with the S-parameter file as part of the simulation input. Pass or fail is indicated by whether the simulated signal violates a time domain limit mask (eye or other type of mask). This use appropriately indicates the suitability of the IUT for a specific signal without any over or under specification.

A different time domain mask is required for each behavior tested. For output differential signals an eye mask that may not be crossed is often used. By using multiple launched signals at different ports the combined effects of cross talk can be included in the output differential signals. For output common mode signals staying below a specified maximum time domain amplitude limit may be all that is required. For reflected signals a TDR type of time domain limit mask may be used.

However, just because a specific S-parameter file passes the time domain mask test for a particular signal with a set of properties does not automatically mean that some other signal with a different set of properties will also pass the time domain limit mask test with that same IUT. If the IUT is to be used for a range of applications then multiple signals, each representing a specific set of conditions within the allowed range of applications, are required to determine compliance for the IUT.

4.2.2.3 Frequency domain masks

The other pass-fail scheme for S-parameter files is to place a frequency domain limit mask directly on individual S-parameter files. Each different parameter has a different mask. If any specific S-parameter for the IUT exceeds its respective mask then the IUT fails. This pass-fail methodology is generally significantly over-conservative and does not allow for any trade-offs between parameters.

For example, an insertion loss suckout at some frequency may be perfectly fine if there is little frequency content in the signal at that frequency. But the insertion loss limit mask would probably fail the perfectly good IUT (for that signal).

In another example an IUT might have better insertion loss but more cross talk and the two parameters trade off to yield a good IUT. A limit mask would fail the good IUT (for that signal) for high cross talk.

A benefit of the limit mask approach is that if the complete set of (simple) limit masks for all S-parameters for the IUT can all be met then it is likely that the IUT will work for a fairly broad range of applications. It may require significant cost increases or design constraints for the IUT to meet this set of requirements.

4.2.2.4 Closed eyes

It is worth noting that closed eyes on differential signals that may be seen at the end of lossy links are no problem for using the eye mask scheme for pass-fail purposes. With closed eyes one must simply apply a reference receiver to the signals before applying the eye diagram acceptance criteria (mask). The reference receiver processes the signal in a specified and standard way such that the processed eye is open. Such reference receivers are being specified in a number of standards and also have the benefit that they allow the link signal budget (jitter/amplitude etc.) to attain ‘credit’ for the signal processing done in receivers that process the signal (for example using equalization). Having a closed eye going into the reference receiver is not a valid reason to require the use of limit masks on the individual S-parameters.

4.2.3 Summary

It is not the purpose of this document to recommend which method should be used for compliance purposes as each has benefits and drawbacks. One key drawback to using limits on S-parameter values is the tendency to over specify performance; local deviations over a small frequency range may not harm the application. Engineering tradeoffs cannot easily be incorporated into the acceptance limits because there is no relationship to the actual application requirements. One key benefit to using the s-parameter limit method is ease of implementation without needing a signal simulation tool.

5. Definitions

Bilateral: the ability of an IUT to remain invariant in all electrical properties upon end to end reversal of the IUT. Bilaterality is only possible if the connectors on the IUT have the same design.

Calibration - the process of removing instrumentation errors at a specific point in the system called the reference plane, which may be located as shown in Figure 13 and Figure 14 in 8414 depending on the method. Use of known standards and/or defined reference structures is required.

Calibration enabling structure – Special structures required in the instrumentation calibration process

De embedding – the process of removing test fixture effects by using matrix algebra where the Sij of the test fixture is known.

Instrumentation – the collection of hardware and software that is used to excite and detect signals applied to or detected from the reference plane used during the IUT measurement. Instrumentation may or may not include test fixtures depending on the method used. Instrumentation may or may not include internal calculations.

IUT – Interconnect under test

Normalization: a term used to describe a process of accounting for the test fixture insertion losses for the magnitude of the IUT insertion loss and for the phase effect of the test fixtures. This process is only accurate for test fixtures that produce no reflections.

Reciprocal: the property of having identical waveshapes at the receiver and transmitter if the position of the transmitter and receiver are reversed. Often the impedance of the transmitter and receiver make it impractical to access the points in the system where the ideal transmitter and receiver exist. Waveshapes determined only by the insertion loss properties are generally reciprocal even when the connectors are different on each end of the IUT if the transmitter and receiver impedance are identical as required for S-parameter measurement. Even though IUT's with different connectors have the same insertion loss in either direction (i.e., S21=S12) this same IUT will not have the same return loss on either end and therefore is not bilateral. The return loss is, however, still reciprocal even in the presence of unequal reflections on both ends of the IUT because by definition the transmitter and the receiver are at the same place on the same end for return loss. And the IUT is also reciprocal even with unequal return loss because the total effect of the reflections is the same at the ports even though the losses occur at different places in the two directions.

Reference plane: a defined location in the physical setup where measurements are assumed to apply. Formally reference planes require TEM (Transverse ElectroMagnetic) transmission mode (where the electric and magnetic fields are both perpendicular to the direction of propagation) at the reference plane. This assumption is often not satisfied due to practical physical constructions of connectors. Only very high quality straight transmission lines offers close to actual TEM conditions. The coaxial construction is the closest. Within a PC board a straight trace is another example. Non TEM constructions and imperfections in the construction are sources of measurement error that cannot be fully corrected. In addition to practical design constraints of making TEM structures there is an error source because a fixture without the IUT does not have the same construction or imperfections as when the IUT is attached. Errors from this source all have higher order propagation modes as the root cause.

SOLT - short open load thru; an acronym for a set of defined steps for calibrating and removing the effects of the test fixture. This process involves sequentially measuring the properties of the test fixture under different conditions of special short, open, load, and thru connections in place of the IUT. A separate set of calculations using these results is required to account for the test fixture in the IUT measurement.

Symmetry – having identical properties with respect to a defined point, line, or plane. Symmetry requires a modifier to be unambiguous. For example, mirror symmetry describes an object whose reflection with respect to a plane is identical to the object. Other types may include: end to end, rotational, axial, etc.

Test fixture – the exact same hardware (same trace, same wire, same connector etc.) that is used to physically connect to the IUT. The test fixture may or may not be part of the instrumentation depending on the method.

Test fixture characterization structure – Special structures used to allow removal of the test fixture effects from the measurement.

Time domain gating - a process of using only information the time domain response in the time region where the IUT exists

TRL - thru, reflect, line; an acronym for a set of defined steps for calibrating and removing the effects of the test fixture. This process involves building a special calibration test fixture that is ‘identical’ to the test fixture to be used with the IUT. This special test fixture has structures that emulate the thru, reflect, and line conditions. A separate set of calculations using these results is required to account for the test fixture in the IUT measurement.

6. Framework for S-parameter measurements

6.1 General concept of S-parameters

6.1.1 Overview

S-parameters or scattering parameters are one of many possible ways to represent the behavior of a linear system. S-parameters are the ratio of the output amplitude to the input amplitude and the difference between the output phase and the input phase. Equivalently the real and imaginary properties of the respective signals may be used. In S-parameters the signal description includes the propagation direction. Thus it is possible to have an S-parameter for a single port by relating the reflected signal to the incoming signal.

S-parameters assume a perfect resistive termination (e.g., most systems use 50 ohms single ended, 100 ohm differential) is attached to all ports. This includes active ports where the signal is applied (signal source has perfect source impedance), the response port where the signal is measured and any ‘not connected’ ports that are not being used for the measurement. As such, S-parameters measurements are intrinsically 'laboratory' measurements. The reference impedance for the S-parameter shall be explicitly stated if not 50 ohms single ended or 100 ohms differential.

While S-parameters can be measured for a single frequency their utility is limited to IUT properties only at that frequency. Since IUT's are called on to transport complex data patterns and waveforms that contain a wide range of frequencies it is necessary to examine S-parameters across the range of frequencies that are important to the end use application. When the term 'S-parameter', or one of the specified symbols that identify the S-parameter, is used in this document it refers to the entire set of properties across the frequency range and is actually a large number of discrete values that individually describe the signal level (or sinusoidal signal amplitude, rms or dB), the phase, and the frequency.

S parameters are defined by a subscript system where the first numerical subscript defines the port number for the outbound response signal from the IUT and the second numerical subscript defines the port number for the applied incident signal to the IUT. The applied incident signal is always propagating into the IUT and the outbound response signal is always propagating out of the IUT.

It is not sufficient to only describe an S-parameter by the two numbered port subscripts because both differential and common mode signals may be described by S-parameters. The basic terminology is 'D' for differential and 'C' for common mode.

Maintaining the convention that the first subscript always describes the outbound response signal from the IUT and the second subscript always describes the applied incident signal into the IUT, a four subscript convention results, S_{ABij}.

For example S_{DC14} defines the ratio of the differential signal coming out of differential port 1 to the common mode signal applied at differential port 4. To avoid the inconvenience of creating, accommodating, and reading small subscripts the 'subscripts' are often raised to full font characters added after the letter 'S'. For example, the S_{DC14} could also be written as SDC14.

If no 'D' or 'C' is present then it is assumed that the signals are single ended.

It is common to calculate differential and common mode S-parameters from the measured single ended responses to single ended applied signals.

The port numbering scheme and the IUT description scheme can be complex as discussed in 6.3. The port numbering scheme shall be clearly specified in the description of the IUT in all cases.

Regardless of whether an S-parameter port is single ended or differential (two single ended ports per differential port) the description of the IUT defines the port numbering. For example, an IUT could have differential port 1 consisting of single ended port 1 and single ended port 3. In this case the IUT access points have multiple accurate numbering – one set for the differential ports and another set for the single ended ports.

However, even if only differential ports are assigned numbers is it still necessary to separately identify each leg of the differential pair so that the common mode and mode conversion properties are captured.

Differential port identification is usually assigned according to the single ended port pairs connected to a single wire pair (e.g., twisted pair or twinax) in the IUT. However, mathematically, S-parameters allow assignment of differential ports to arbitrary pairs of single ended ports. If the full S-parameter set is measured for the IUT then all the information for the IUT will be in the results. It may require careful mapping of ports numbers to actual construction to make much sense of the data unless an intelligent port numbering scheme is used up front.

6.1.2 Theoretical requirements for S-parameters at the measurement system interface

A reference plane is defined as the location in the physical setup where measurements are assumed to apply. The formal definition of a reference plane requires TEM (Transverse ElectroMagnetic) transmission (where the electric and magnetic fields are both perpendicular to the direction of propagation) at the reference plane. This assumption is often not satisfied due to practical physical constructions of connectors. Only very high quality straight transmission lines offers close to actual TEM conditions. The coaxial construction is the closest. Within a PC board a straight trace is another example. Non TEM constructions and imperfections in the construction are sources of measurement error that cannot be fully corrected. In addition to practical design constraints of making TEM structures there is an error source because a fixture without the IUT does not have the same construction or imperfections as when the IUT is attached. Errors from this source all have higher order propagation modes as the root cause.

6.2 Basic S parameter signal measurement definitions

Figure 1 shows the connections, 1, 2, 3, and 4, made to a four port instrument such as a vector network analyzer (VNA) or a time domain network analyzer (TDNA) for measuring S parameters on a four single ended port ‘black box’ device. Such a device could be a single differential pair in an IUT. The instrumentation recognizes signals going into the ‘black box’ denoted by the ‘a’ subscript and signals coming out of the ‘black box’ denoted by the ‘b’ subscript. These instruments may do this separation via directional couplers, for example, but how they do it is not part of this document. S-parameters use only the voltages with the a and b subscripts since propagation direction is required to be known. In the absence of directional separation the total voltage, V_i, is observed.

All the measurements specified in this document relate to differential signal pairs. It requires all four single ended instrumentation ports to measure the properties of two differential ports.

Instrumentation ports may be single ended with the differential and common mode properties for differential ports calculated, typically internal to the instrument. Some instruments may also directly measure and detect differential and/or common mode signals. No instruments are presently known that extract the single ended behaviors from differential and common mode measurements.

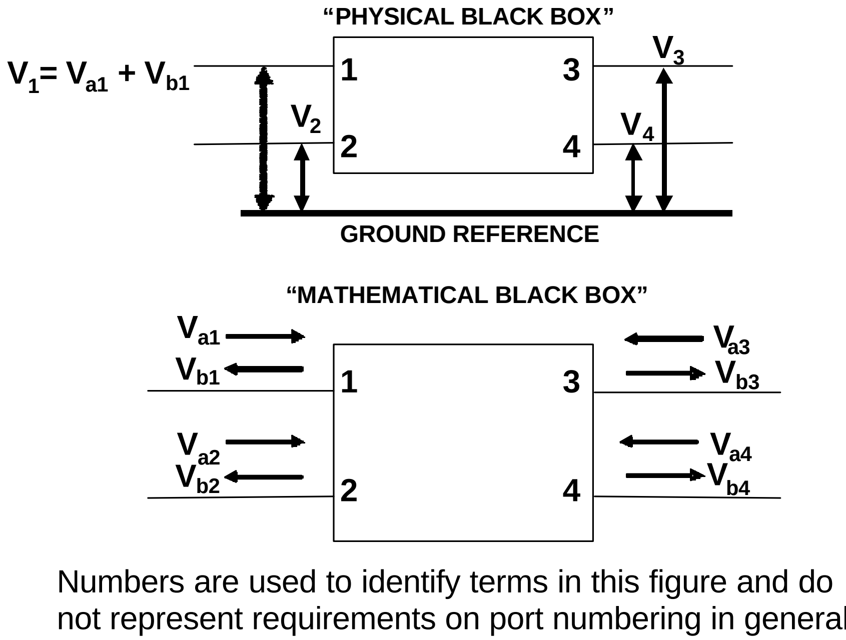


Figure 1 - Architecture of a 4 port measurement (single ended measurements)

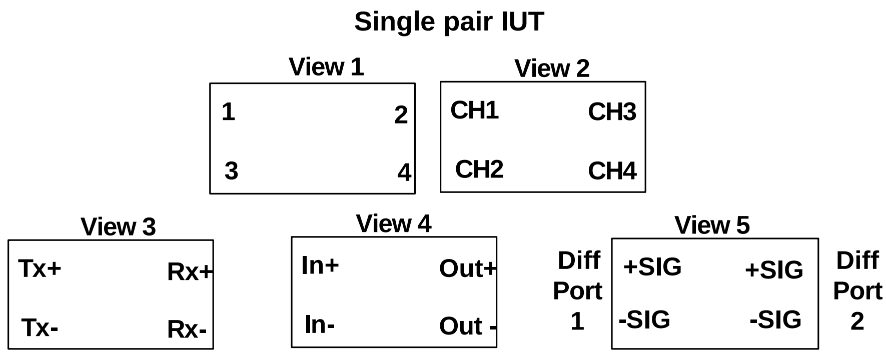
6.3 Definition of S parameter naming conventions

6.3.1 IUT port identification

Subclause 6.1 defined the general naming conventions but there is another dimension to this topic, namely, defining specifically which port gets which number for a real IUT. There is general agreement that the downstream side of the IUT for normal signal flow in service is generally assigned the higher differential port numbers. The single ended port numbering may not follow this rule rigorously but usually the highest single ended port number will be on the downstream side and the lowest single ended port number will be on the upstream side. So for identification of ports with numbers the problem is straightforward – simply make sure that the following information is provided:

- The DD,CC,DC,CD, or none for single ended, conventions are used for all data
- A clear picture of the IUT is provided with the file that shows which connector contact (or contacts for differential) belongs to which port number
- A statement of the normal signal flow direction in service for the IUT being measured.

There are several other legitimate port identification schemes in use. Figure 2 shows five different schemes each following a logical (but different) pattern.
When the S-parameter files are finally created a numbering scheme shall be used in the file so a translation between the contact naming scheme used for the physical IUT and the port numbering scheme used in the data file must be done and clearly documented.



IUT port (pinout) identification conventions – five equivalent views:

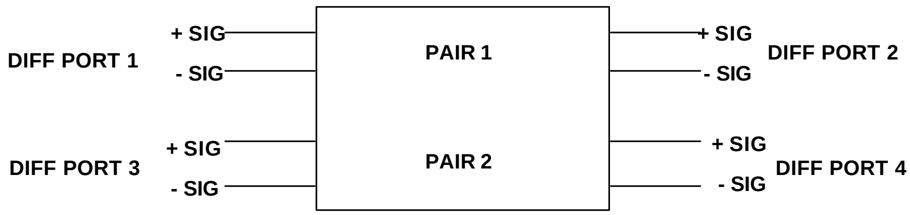
View 1: IUT ports are identified according to the VNA port numbering scheme (Agilent numbers shown, other numbers may be used for other instruments)
View 2: IUT ports are identified according to the TDNA channel numbering scheme
View 3: IUT ports are identified according to the function provided by the device that is connecting to the IUT in normal service
View 4: IUT ports are identified according to the signal flow through the IUT
View 5: IUT ports are identified according to SFF-84xx conventions using +SIG and –SIG and differential port numbering

Figure 2 - Different schemes used for identifying IUT ports

This document does not require any specific port identification or port numbering scheme for the physical IUT but compliance with this document does require that the three bulleted items above be delivered with the S-parameter data files that apply to the IUT. It is worth noting that the In+, In-, Out+, Out- scheme provides the best overall independence from specific service application and specific measurement method. The signal flow direction and the differential sense are explicitly defined. Since some IUT's may not directly connect to transmitter devices or receiver devices the Tx,Rx scheme is less desirable.

6.3.2 Extension to a 2-pair IUT

Figure 3 shows the definition of the differential ports and the differential-to-differential S parameters that may be acquired from a two pair IUT. If using a four single ended port instrument only two differential ports may be measured at one time. The physical reconfiguration required to access all the differential S parameters listed in Figure 3 is shown in Figure 4.



SDD11 = DIFFERENTIAL RETURN LOSS FROM DIFF PORT 1
SDD22 = DIFFERENTIAL RETURN LOSS FROM DIFF PORT 2
SDD33 = DIFFERENTIAL RETURN LOSS FROM DIFF PORT 3
SDD44 = DIFFERENTIAL RETURN LOSS FROM DIFF PORT 4
SDD21 = DIFFERENTIAL INSERTION LOSS AT DIFF PORT 2 FROM DIFF PORT 1
SDD31 = DIFFERENTIAL NEAR END CROSS TALK AT DIFF PORT 3 FROM DIFF PORT 1
SDD41 = DIFFERENTIAL FAR END CROSS TALK AT DIFF PORT 4 FROM DIFF PORT 1
SDD42 = DIFFERENTIAL NEAR END CROSS TALK AT DIFF PORT 4 FROM DIFF PORT 2
SDD43 = DIFFERENTIAL INSERTION LOSS AT DIFF PORT 4 FROM DIFF PORT 3
SDD32 = DIFFERENTIAL FAR END CROSS TALK AT DIFF PORT 3 FROM DIFF PORT 2
SDD34 = DIFFERENTIAL NEAR END CROSS TALK AT DIFF PORT 3 FROM DIFF PORT 4
SDD12 = DIFFERENTIAL INSERTION LOSS AT DIFF PORT 1 FROM DIFF PORT 2
SDD13 = DIFFERENTIAL NEAR END CROSS TALK AT DIFF PORT 1 FROM DIFF PORT 3
SDD14 = DIFFERENTIAL FAR END CROSS TALK AT DIFF PORT 1 FROM DIFF PORT 4
SDD23 = DIFFERENTIAL FAR END CROSS TALK AT DIFF PORT 2 FROM DIFF PORT 3
SDD24 = DIFFERENTIAL NEAR END CROSS TALK AT DIFF PORT 2 FROM DIFF PORT 4

Figure 3 - Definition of differential-to-differential S parameters

In Figure 3 a partial mapping between the S-parameter names and the common verbal descriptions that may be used is given.

In general for the SABij shown in Figure 3:

- If i=j, and A=B then the parameter is a RETURN LOSS (going into and out of the same port with the same mode in and out)

- If i j, and A=B then the parameter is an INSERTION LOSS between ports i and j for the same mode in and out.

  However for the special cases where the same wires are not connected between ports i and j in the IUT then this type of insertion loss is called CROSS TALK

  Cross talk is NEAR END when ports i and j are on the same end of the IUT and FAR END when ports i and j are on the opposite ends of the IUT

- If A B (not shown in Figure 3) then the parameter is a MODE CONVERSION

CAUTION: S-PARAMETERS ARE A MEASURE OF GAIN (OUTPUT REFERRED TO INPUT) BY DEFINITION. HOWEVER COMMON USAGE HAS INCORRECTLY IMPLEMENTED THE WORD ‘LOSS’ INSTEAD OF GAIN. PARAMETERS WHOSE AMPLITUDE IS EXPRESSED AS A NEGATIVE DB VALUE REPRESENT A GAIN LESS THAN ONE OR A POSITIVE ‘LOSS’. PLEASE EXERCISE CAUTION IN THIS AREA AND UNDERSTAND THAT DATA MAY BE PRESENTED OR LABELED INCORRECTLY (i.e, GAINS BEING LABELED AS LOSSES).

Figure 3 and Figure 4 list only the differential-to-differential S-parameters (SDDij). The common mode-to- common mode (SCCij), the common mode-to-differential (SDCij), and the differential-to common mode (SCDij) are also required for creating the complete set of 64 S-parameters for the IUT.

6.4 Coverage of the S-parameter matrix

6.4.1 Theoretical coverage

For an N-port IUT a complete set of all S-parameters is required to fully represent the behavior of the IUT. For an IUT with N differential ports this includes:

SDDij
SCCij
SDCij
SCDij

where both i and j are the differential port numbers and both i and j are fully and independently varied from 1 to N to cover all of the differential ports on both ends of the IUT.

It requires a lot of work and time to measure a full S-parameter set even if the IUT is only as complex as two differential pairs. Even in this ‘simple’ 2-pair case, it requires an 8-port single ended instrument to access all the single ended ports with a single IUT physical connection. The practical limit for most instruments is a single differential pair (that requires 4 single ended ports).

For the simple one pair case where N = 2 there are four single ended ports (two per pair). Let us temporarily call these single ended ports 1+, 1-, 2+ and 2- where the number is the number of the differential port and the + - is the leg of the pair. Each single ended port requires four frequency sweeps to cover all the cases where that single ended port is the source. So if single ended port 1+ is the source the complete set is S1+1+, S2+1+, S1-1+, S2-1+. Each port must act as source in turn so it requires 16 sets of single ended data to completely populate the S-parameter matrix for an IUT with a single pair. Fortunately, most 4-port instruments available today automatically connect the appropriate source, measure at the appropriate output and keep track of all the data that results.

It should be even more obvious at this point that clear port numbering is VITAL.

For a 2-pair IUT having 8 single ended ports and using an 8 port (single ended) instrument the number of frequency sweeps is 64. The general formula is:

$$\text{Number of frequency sweeps} = (2N)^2 = (4P)^2$$

where N is the number of differential ports and P is the number of pairs in the IUT.

See also 6.7 for discussion of partial coverage.

6.4.2 Practical issues relating to coverage

Figure 4 shows all the test configurations required for measurement of a complete S-parameter set for a 2-pair IUT when using a 4-port instrument. Although Figure 4 shows the connections for a VNA, the same information may be obtained by using time domain measurements to acquire time domain waveforms. Practical coverage of a two-pair IUT with a 4 port instrument requires 6 different IUT connections with 6 different sets of 4 port measurement results. Note that termination is required on all differential ports that are not connected to the instrument during the measurement.

Post processing of the 6 data sets is required to assemble the complete S-parameter set for the 2-pair IUT into a single matrix set.
In Figure 4 only the SDDij are specifically called out. The SCCij, SCDij, and SDCij may also be obtained with these same 6 physical IUT connections.

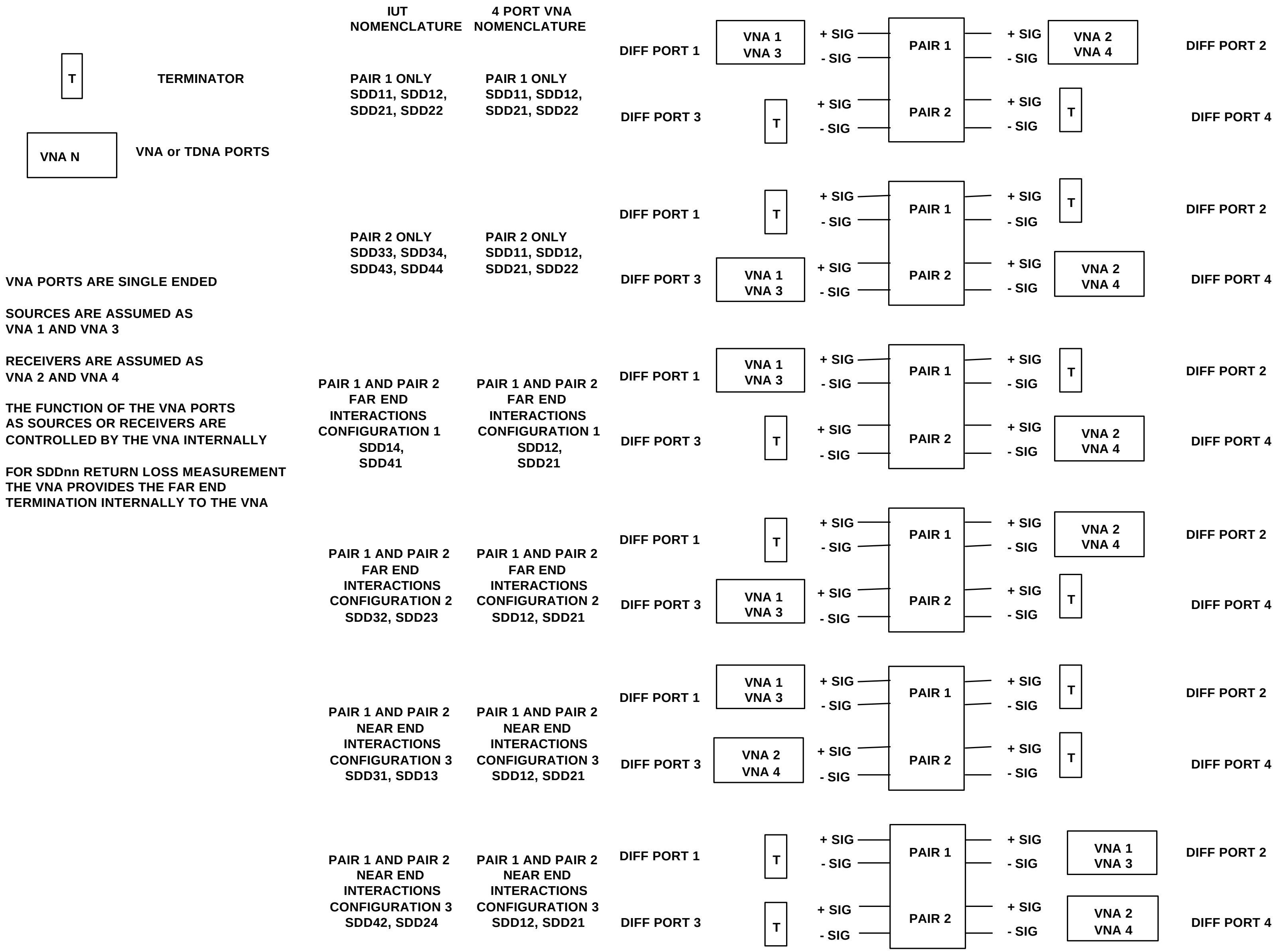


Figure 4 - Test configurations required when using a 4-port VNA or TDNA instrument with a 2-pair IUT

An 8-port instrument would be better than the 4-port instrument shown because there are intrinsic inefficiencies and risks listed below that are built into doing the multiple IUT connections shown in Figure 4:

- Every IUT needs to be connected and reconnected to the instrumentation multiple times – this is not only time consuming but every connection and reconnection action moves the IUT, may damage the IUT and takes time
- The instrumentation may lose calibration while executing the full coverage measurements
- There is an increased chance of connection error due to multiple connections
- There is an increased chance of data mismanagement since several complex data sets are produced and must be recombined later to form the overall S-parameter file set for the IUT
- There are a multiplicity of measurements that are duplicated. All the measurements into and out of the same port and all the measurements across the same differential port in both directions is duplicated 8 times in the example used in Figure 4.

In the case shown in Figure 4 there are 6 measurement configurations each with 16 frequency sweeps for a total of 6 X 16 = 94 frequency sweeps collected. There are also 8 cases where ports are measured into and out of and across themselves that were also measured elsewhere. In each of these cases 4 frequency sweeps were recorded. When these redundant measurements are accounted for we end up with 96 – 32 = 64 unique frequency sweeps which is the same as that for the 8-port instrument that did not have the duplications. However, there may be value in this duplication in that one can compare these supposedly redundant frequency sweeps to determine how repeatable the measurements are and whether the assumptions of ‘perfect’ termination on all ports was satisfied.

Clearly there are many IUT’s that have more than two differential pairs. The amount of testing, data management, and post processing required for complete coverage goes up roughly as N^2 with the pair count. So there is a practical consideration with the measurement of S-parameters of how much of the complete S-parameter set is necessary to measure and how much can be ‘assumed’. The issues associated with executing a reduction in coverage are discussed more fully in sub-clause 6.7.

6.5 Relationship between frequency domain and time domain instrumentation

6.5.1 General relationships

This sub-clause defines the relationship between the measurement types involved.

The frequency domain measurements excite and detect the properties of sine waves at a single frequency. Multiple frequencies are measured in a sweep across a defined frequency range. The time domain measurements excite and detect waveforms. The waveforms contain all the signal level, frequency, and phase information found in the frequency domain methods though in a different form. These waveforms may then be converted to S parameters using a suitable software package typically using a version of Fourier transforms. Similarly the frequency domain measurements contain all the time domain waveform information.

If the time domain waveform is excited and detected from the same port it is called a time domain reflection measurement or TDR. If the waveform is excited at one port and detected at another port it is call a time domain transmission measurement or TDT. Time domain measurements involve comparing the differences between the excited and detected waveforms.

6.5.2 Mapping between S-parameters and time domain measurements

The following three figures contain 4 x 4 matrices that show all the differential, common mode, and mode conversion S parameters that are possible from a differential 2-port (single ended 4 port) IUT. The kind of time domain measurements used to create the specific kind of frequency domain S parameters is shown with the double headed arrows.

In Figure 5 the differential only portions are shown in larger font. In Figure 6 the common mode only portions are shown in larger font. In Figure 7 the mode conversion responses are shown in larger font. Transmission responses acquired via TDT and reflection responses acquired via TDR are noted.

Return loss uses TDR methods. Insertion loss (including cross talk) and mode conversion uses TDT methods.

For differential measurements differential stimulus signals are used with differential response measurements. For common mode measurements common mode stimulus signals are used with common mode response measurements. For mode conversion measurements differential stimulus with common mode response or common mode stimulus with differential response is used.

$$\begin{bmatrix} S_{DD11} \text{ « } TDR_{DD11} & S_{DD12} \text{ « } TDT_{DD12} & S_{DC11} \text{ « } TDR_{DC11} & S_{DC12} \text{ « } TDT_{DC12} \\ S_{DD21} \text{ « } TDT_{DD21} & S_{DD22} \text{ « } TDR_{DD22} & S_{DC21} \text{ « } TDR_{DC21} & S_{DC22} \text{ « } TDR_{DC22} \\ S_{CD11} \text{ « } TDR_{CD11} & S_{CD12} \text{ « } TDT_{CD12} & S_{CC11} \text{ « } TDR_{CC11} & S_{CC12} \text{ « } TDT_{CC12} \\ S_{CD21} \text{ « } TDT_{CD21} & S_{CD22} \text{ « } TDT_{CD22} & S_{CC21} \text{ « } TDT_{CC21} & S_{CC22} \text{ « } TDR_{CC22} \end{bmatrix}$$

Figure 5 – Differential TDR stimulus, differential response

$$\begin{bmatrix} S_{DD11} \text{ « } TDR_{DD11} & S_{DD12} \text{ « } TDT_{DD12} & S_{DC11} \text{ « } TDR_{DC11} & S_{DC12} \text{ « } TDT_{DC12} \\ S_{DD21} \text{ « } TDT_{DD21} & S_{DD22} \text{ « } TDR_{DD22} & S_{DC21} \text{ « } TDR_{DC21} & S_{DC22} \text{ « } TDR_{DC22} \\ S_{CD11} \text{ « } TDR_{CD11} & S_{CD12} \text{ « } TDT_{CD12} & S_{CC11} \text{ « } TDR_{CC11} & S_{CC12} \text{ « } TDT_{CC12} \\ S_{CD21} \text{ « } TDT_{CD21} & S_{CD22} \text{ « } TDT_{CD22} & S_{CC21} \text{ « } TDT_{CC21} & S_{CC22} \text{ « } TDR_{CC22} \end{bmatrix}$$

Figure 6 – Common mode TDR stimulus, common mode response

$$\begin{bmatrix} \begin{array}{cc} S_{DD11} \text{ « } TDR_{DD11} & S_{DD12} \text{ « } TDT_{DD12} \\ S_{DD21} \text{ « } TDT_{DD21} & S_{DD22} \text{ « } TDR_{DD22} \end{array} & \begin{array}{cc} S_{DC11} \text{ « } TDR_{DC11} & S_{DC12} \text{ « } TDT_{DC12} \\ S_{DC21} \text{ « } TDT_{DC21} & S_{DC22} \text{ « } TDR_{DC22} \end{array} \\ \begin{array}{cc} S_{CD11} \text{ « } TDR_{CD11} & S_{CD12} \text{ « } TDT_{CD12} \\ S_{CD21} \text{ « } TDT_{CD21} & S_{CD22} \text{ « } TDR_{CD22} \end{array} & \begin{array}{cc} S_{CC11} \text{ « } TDR_{CC11} & S_{CC12} \text{ « } TDT_{CC12} \\ S_{CC21} \text{ « } TDT_{CC21} & S_{CC22} \text{ « } TDR_{CC22} \end{array} \end{bmatrix}$$

Figure 7 – Mixed mode, two cases shown in one matrix for convenience

6.5.3 Practical full coverage comparison for time domain and frequency domain methods

Some practical time domain instruments are capable of directly measuring and detecting differential and common mode signals as well as the single ended signals. These time domain instruments produce full coverage with a different set of measurements than frequency domain instruments.

The number of measurements required for full coverage (frequency sweeps or waveform captures) is the same for both frequency domain and time domain. There are 16 measurements required for a 1-pair IUT. This applies whether single ended or differential signals are used by the instrument. However, the time to collect the data may be significantly less with the time domain because the time domain instruments use real time waveforms while the swept frequency methods use a ‘lock and roll’ technique where each frequency is locked on using an IF detector and measured separately before rolling to the next frequency.

The time required for frequency domain frequency sweeps is determined mostly by the number of frequency points required which in turn is determined by the application.

The number of frequency points required is specified in several places. For example, for bulk cable testing SFF-8416 specifies how to determine the number of frequency points. The Fibre Channel FCSM-2 document has requirements applying to signal modeling applications. Others probably exist in other standards and industry documents. Compliance with SFF-8414 requires implementing the properties specified following in this sub-clause unless otherwise specified in other application documents.

Compliance with the following requirements

- Assures that any insertion loss suckouts and return loss and cross talk peaks will be detected with good resolution
- Assures that the electrical length (defined immediately below) and phase content is adequately represented for the IUT – no missing points due to instrument limitations of reporting only values in the +- 360 degrees range – IUT’s with more than 360 degree phase rotation are at risk of being mis-represented otherwise.

Electrical length is defined as the number of degrees of phase rotation at the output of the IUT at a given frequency. Electrical length is expected to vary with frequency. Electrical length in degrees may be converted to electrical length in time with the equation: electrical length (s) = phase /

[2*pi*frequency (Hz)]. Values of phase are reported by practical instruments as numbers between zero and 360 degrees, therefore a phase rotation of 380 is reported by the instrument as a phase rotation of 20 degrees.

It is vital to the effective use of S-parameter files that the actual phase rotation be known. This can be guaranteed by knowing the actual phase at the lowest frequency and taking frequency steps that yield less than 360 degree phase rotation. The actual phase is: (n*360 + reported value), where n is the number of complete 360 degrees phase rotations within the IUT at the measured frequency.

At the lowest frequency n should be zero. If n is not zero at the lowest frequency the supplier of the data must determine and report n at the lowest frequency. Known physical properties of the IUT (relative dielectric constant and physical length) may be used to derive n. For example, for equipment with a lowest start frequency of 50 MHz the maximum electrical length for n = zero is 20 nanoseconds (e.g., 4.0 meters with relative dielectric constant = 2.15 yields 20 nanoseconds); if electrical length of the IUT is longer than 20 nanoseconds at 50 MHz then the supplier of the data must report the value of n at 50 MHz.

The electrical length of the IUT is used when selecting time window in the time domain or the frequency step in the frequency domain such that the frequency step yields less than 360 degrees phase change. In general test methods that use mathematics to convert between time domain and frequency domain require that the delta phase between frequency data points be less than 360 degrees.

The basic requirement is that the frequency step size be less than 360 degrees of phase change for the electrical length of the IUT. This maximum frequency step size (Hz)is given by 1/(IUT electrical length in seconds). Older test equipment may have a limitation in that this step size needs to be less than 180 degrees, in which case divide the step size found above by 2.

6.6 Documentation of the S-parameter file

6.6.1 Overview

S-parameter files shall be documented according to the format specified in this sub-clause.

6.6.2 Documentation of a single pair IUT file

The ASCII format to be used for single pair IUT's is specified below. The commented material, denoted by '!' shall be included and completely filled out for every file.

The data portion of this file shall conform to the Touchstone® File Format Specification rev 1.1 (IBIS open forum).

In the example shown in this sub-clause the single ended S-parameters from a 1-pair IUT is shown. This may be clearly seen from the exclusion of the DD, CC, CD, and DC in the S-parameter listing.

```
! The material between !!!!!!!!!!!!!  and !!!!!!!!!!!!!! shall be added by the provider of the file
!
! Material following the second !!!!!!!!!!! is the file provided by the IUT modeling tool or measurement of the IUT
!
!The actual format of the material following the second !!!!!!!!!!!!! shall follow the Touchstone format defined in
!version 1.1 of the Touchstone specification as shown in the example below.  Mote that the S11, S21, etc map needs
to !be explicitly shown for compliance to this requirement.  The naming conventions described in sub-clause 6.1.1
shall be used.
!
!Use dB and angle, magnitude and angle, or real and imaginary forms.
!
!!!!!!!!!!!!!!!
!
! The IUT for this file is [provide a physical description of the IUT including whether fixtures, pads, etc are
included]
!
!   contact #,  contact gender      in+ >--+--+--> out+   contact gender, contact #
!                                          |  |
!   contact #,  contact gender      in- >--+--+--> out-   contact gender, contact #
!
! Use the above diagram to fill in the following expression:
!
! param.ports:[{in+} {in-} {out+} {out-}]    ! This expression is used to describe the actual connection of port
!   numbers to terminals of a differential in / differential out DUT.  Replace the port names in {} with the number
!   used in the file.  This expression as a comment is read by some tools - the expression shall be placed exactly
!   as shown.
!
! Example valid configuration lines are: (The two dots are included to avoid accidental matches.)
! example1.param..ports[1 3 2 4] Input is {1,3} output is {2,4}
! example2.param..ports[1 4 3 2] Input is {1,4} output is {3,2}
!
! This file [does/does not chose one] conform to the passivity and causality tests defined by T11
! This file [does/does not chose one] conform to the requirement of the phase shift from D.C. to the start
! frequency being less than 360 degrees.  If the file does not conform to this requirement, then the file may not
! yield accurate results.
! If there are known reversals in the phase vs frequency, then frequency steps corresponding to phase shifts much
! less than 180 degrees may be required.
!
!!!!!!!!!!!!!!!!
```

```
# MHZ S DB R 50.00
!
! FREQ          S11                      S12                      S13                      S14
!               S21                      S22                      S23                      S24
!               S31                      S32                      S33                      S34
!               S41                      S42                      S43                      S44
!           DB       ANG          DB        ANG          DB        ANG          DB        ANG
   0.000      -58.94   -0.000000    -66.06    0.000000     -0.00    0.000000    -70.87    0.000000
              -66.00    0.000000    -59.38   -0.000000    -71.30   -0.000000     -0.01    0.000000
               -0.00    0.000000    -70.94    0.000000    -63.53   -0.000000    -62.96   -0.000000
              -70.25    0.000000     -0.01    0.000000    -62.87   -0.000000    -81.79   -0.000000

  50.000      -41.33   81.382332    -39.49   86.017905     -0.00   -1.856410    -47.12  -92.722304
              -39.49   85.981293    -41.07   81.785583    -47.14  -92.750495     -0.01   -1.833449
               -0.01   -1.848768    -47.12  -92.462204    -40.90   83.808603    -39.65   85.250282
              -47.08  -92.182704     -0.01   -1.835249    -39.65   85.162887    -40.32   86.429201

 100.000      -35.09   83.685011    -33.37   85.843012     -0.01   -3.697857    -41.43  -99.953779
              -33.37   85.840106    -34.85   83.633309    -41.45  -99.864809     -0.01   -3.680551
               -0.01   -3.691578    -41.44  -99.827424    -34.87   84.084605    -33.44   85.804287
              -41.42  -99.884793     -0.01   -3.682022    -33.44   85.793616    -34.44   84.002183
```

6.6.3 Documentation of a 2-pair IUT file

Figure 8 shows an example of a complete set of differential to differential S-parameters from a 2-pair IUT as produced by a commercial simulation tool. In this figure the notation should have indicated SDDij but the ‘DD’ is not shown. CARE MUST BE EXERCISED TO BE CERTAIN OF THE TYPE OF S-PARAMETER DATA BEING PRESENTED AS NOT ALL TOOLS FOLLOW THE CONVENTIONS REQUIRED BY THIS DOCUMENT FOR IDENTIFICATION OF S-PARAMETERS.

The i and j in this example refer to the DIFFERENTIAL port numbers. If this were single ended data then the numbers from 5 through 8 would be required to identify all of the single ended ports on this 2-pair IUT. Following the conventions in this document the example data as literally shown would describe single ended S-parameters and half of the single ended ports in the IUT would not be represented.

Similar plots of SCCij, SDCij, and SCDij are required for a complete S-parameter set for this example IUT type.

Documentation of the S-parameter file follows the same rules as specified in sub-clause 6.6.2 except that the complete set of S-parameters (either differential form or single ended form) shall be included.

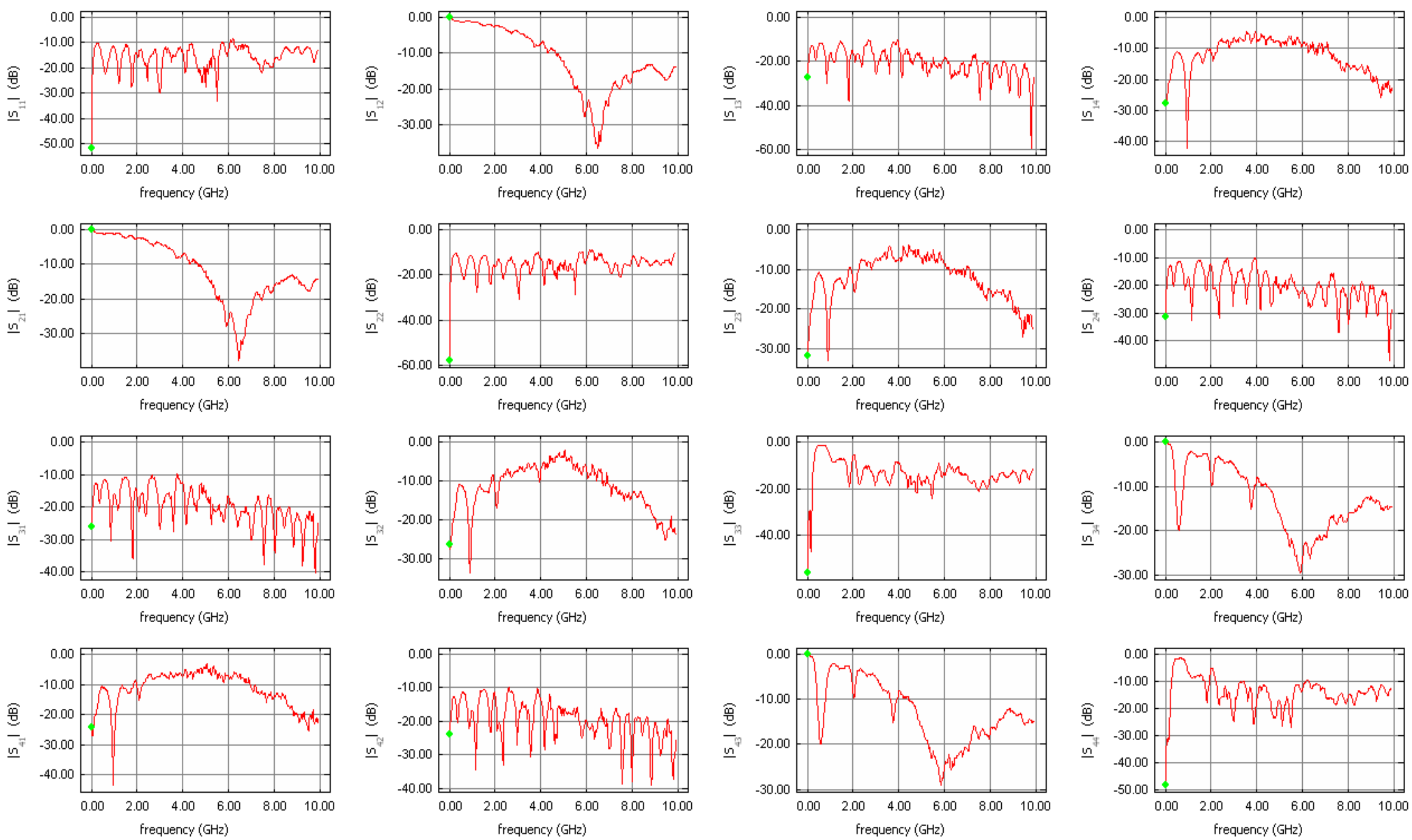


Figure 8 - Example of the differential S-parameters from a two pair IUT

6.7 Partial coverage of the S-parameter matrix

6.7.1 Overview

It is a common practice to use only part of the full S-parameter matrix for specific purposes. An example of a partial S-parameter set that is commonly used is the insertion loss only. However, insertion loss alone does not describe the IUT’s behavior. This sub-clause describes the considerations and issues when one needs to reduce the number of measurements required for full coverage.

It is clear that full coverage can be expensive and error prone. Guidance on how to reduce full coverage without sacrificing the accuracy of the results for the application is therefore important.

The main variables in determining coverage are:

- Number of pairs per IUT
- S-parameters measured (insertion loss, return loss, cross talk, modes measured)

6.7.1.1 Measurements on a single pair

This sub-clause deals with coverage on a single pair only. No pair to pair interactions are involved. Pair to pair interactions are covered in the following sub-clause.

The only coverage variable available is which S-parameters to measure. Complete coverage requires 16 measurements (16 frequency sweeps or 16 waveforms).

The primary behavior is contained in the SDDij parameters. The least important are the SCCij and the SDCij since these both require common mode excitation. The SCDij may be important because of EMI and cross talk through differential to common mode conversion.

The requirements for differential frequency domain calculations that are derived from single ended measurements require that all 16 single ended measurements be executed so that the calculations will have the required inputs. There is no opportunity for further reduction. There may be a slight reduction in not calculating all the SABij parameters but since that is only algebraic computation this is minimal opportunity.

For time domain differential and common mode measurements, however, the AB quadrants are independently measured and this allows for elimination of some measurements. Elimination may proceed as follows:

- Elimination of SCCij and SDCij eliminates 8 measurements (total of 8 used)

- Elimination of SCDij eliminates another 4 measurements (total of 4 used)

- Within SDDij quadrant one may eliminate either SDD21 or SDD12 (utilizing reciprocity) because these will both be equal if the IUT is passive and linear (total of 3 used)

- If the IUT is expected to be bilateral or if the IUT has low insertion loss (e.g., less than 3 dB) at the highest frequency of interest, then either SDD11 or SDD22 is not needed (total of 2 used)

- If only insertion loss is required then only SDD12 or SDD21 is needed or if only return loss is required then only SDD11 or SDD22 is needed. (total of 1)

It may be desirable to check both ends for other reasons; use insertion loss to verify instrumentation and use return loss to verify that bilaterality actually exists in the IUT.)

Depending on the needs up to 15 measurements or a 16x reduction in number of measurements is possible using time domain methods.

Determination of which level of elimination is appropriate for the application is not addressed in this document.

6.7.1.2 Measurements on multiple pairs

Many IUT’s consist of more than one pair. Full coverage for N-pair IUTs was addressed in 6.4.1 where it was shown that the number of measurements required increases as the square of the port count. Reduction of this number of measurements is a primary target - especially for IUT’s with more than 2 pairs.

Considerations that lead to reductions in the number of measurements in multiple pair IUT’s:

- Realizing that all pair to pair interactions are a form of cross talk and that some pairs will not interact significantly due to proximity, shielding, etc
- Specifying the signal propagation direction in normal service allows elimination of cross talk measurements due to not ever having aggressors on half of the ends
- Some pairs may require less single pair coverage than others due to application details

Use of these considerations is highly dependent on the application. Large reduction in the number of measurements required is likely in many cases.

For example for the second bullet above, if all pairs interact but each pair only has one direction of propagation then the number of measurements required becomes:

$$\text{Number of measurements} = 16\ [N + (N-1) + \ldots + (N-N)]$$

This progresses as:

N (pairs in the IUT)	Full coverage number	Reduced coverage number
2	64	48
3	144	96
4	256	160

In addition to IUT construction details application properties include:

- Pass fail
- Transportability properties
- Simulation
- Standards compliance
- Design
- Design validation
- Trouble shooting

It is not the intent of this document to make the recommendations for specific applications.

6.7.2 Main variables in determining coverage cost

This sub-clause describes the main variables involved with the cost of measuring S-parameters.

It is assumed that using the method of stop testing on first failure to save testing time for pass fail applications is implemented and that basic performance has already been determined from continuity and hi pot and possible skew testing prior to S-parameter measurements.

Some considerations include:

- Time for data acquisition
- Time for equipment set up and calibration
- Cost of equipment
- Skill level required
- Cost and complexity of test fixtures
- Life of test fixtures
- Data management
- Accuracy required
- Measurement method used (see later clauses for details on measurement methods)

7. Identification of the IUT

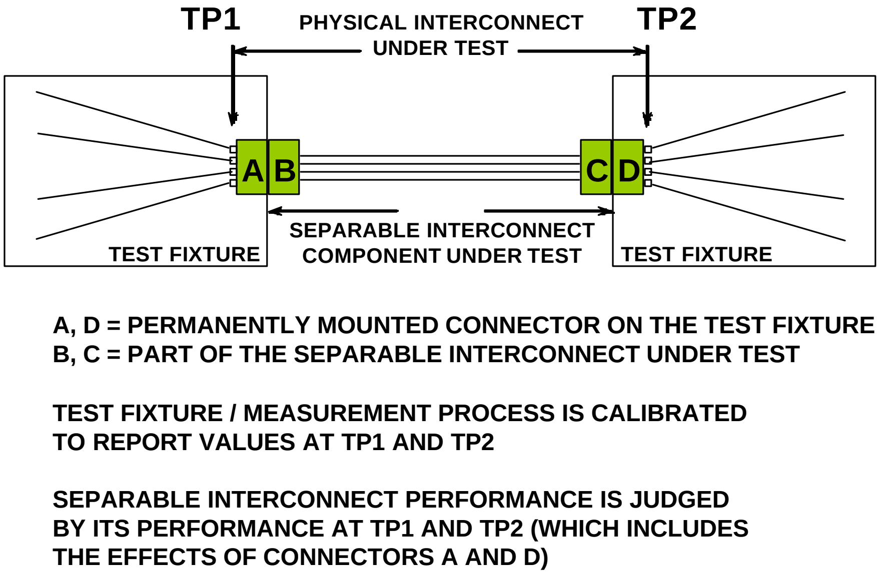
7.1 Overview

Clear identification of the physical entity whose performance is represented by the S-parameter file is required. This identification may be complex because of the theoretical requirements on reference planes may not match physical reality, and because the couplings present during measurement are different from the couplings present during calibration.

There are two major topics that together comprise the IUT identification: reference 'plane' definition and physical IUT boundary description.

7.2 Physical IUT boundary description

The IUT's of interest for this document typically have separable connectors on both ends of the IUT. Following the paradigm in SFF-8410, the IUT nominally begins and ends on the test fixture at the point where connector joins the substrate. Part of the IUT intrinsically involves connector halves that are not part of the separable IUT as shown in



.

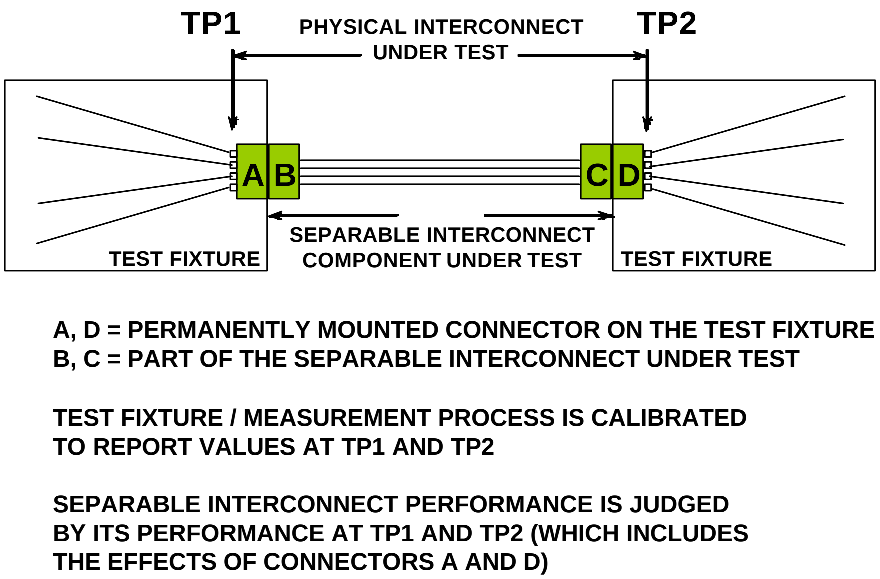


Figure 9 – Definition of the IUT

For IUT's that do not have separable connector (for example a connector by itself or a backplane trace) these same principles apply.

7.3 Reference plane

A reference plane is a physical boundary between the measurement system (including instrumentation cables, probes and fixtures) and the IUT. The reference plane is defined by the calibration process. A goal is to co-locate this reference plane with the desired physical boundaries of the IUT. Perfectly realizing this goal may not always be achievable.

The details of the position of the reference plane are important to avoid double counting and excessive penalty to the IUT or conversely causing the IUT to appear better than it really is. The document recommends that unavoidable residual errors should make the IUT appear worse rather than better.

The physical boundary of the IUT is the portions of the IUT that most closely approximate the location of the calibration point on the reference plane as determined by the calibration method.

7.4 Examples of reference planes and IUT boundaries

Figure 10 shows an example of the reference plane and the calibration point for a surface mount style of IUT connector.

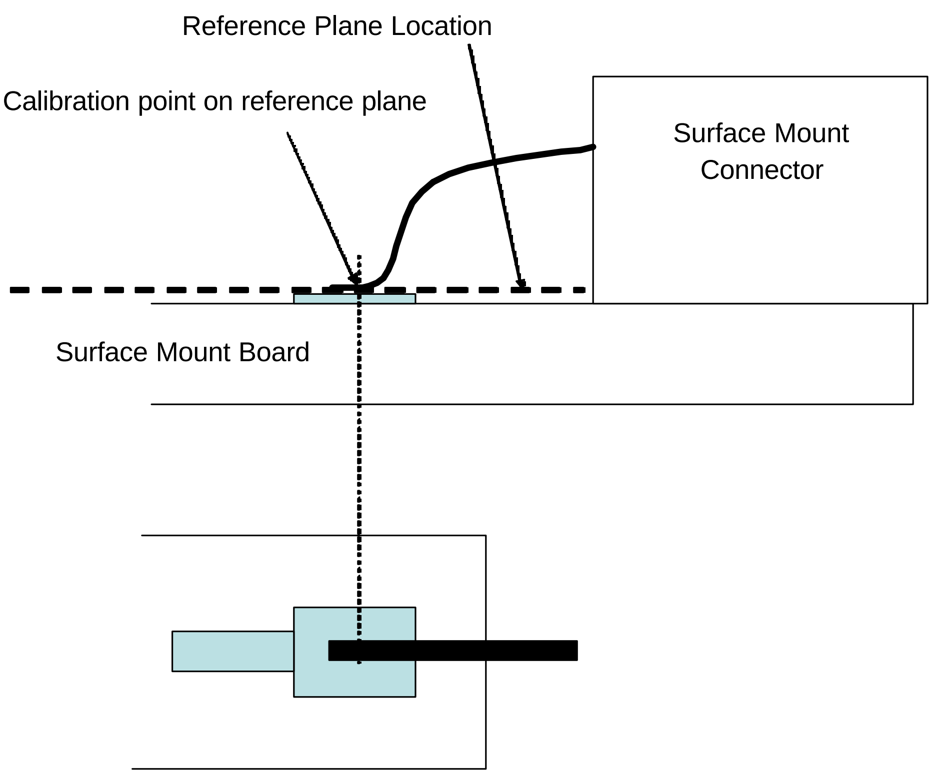


Figure 10 – Reference plane and calibration point for a surface mount style connector

Figure 11 shows an example of the reference plane and the calibration point for a through hole style of IUT connector.

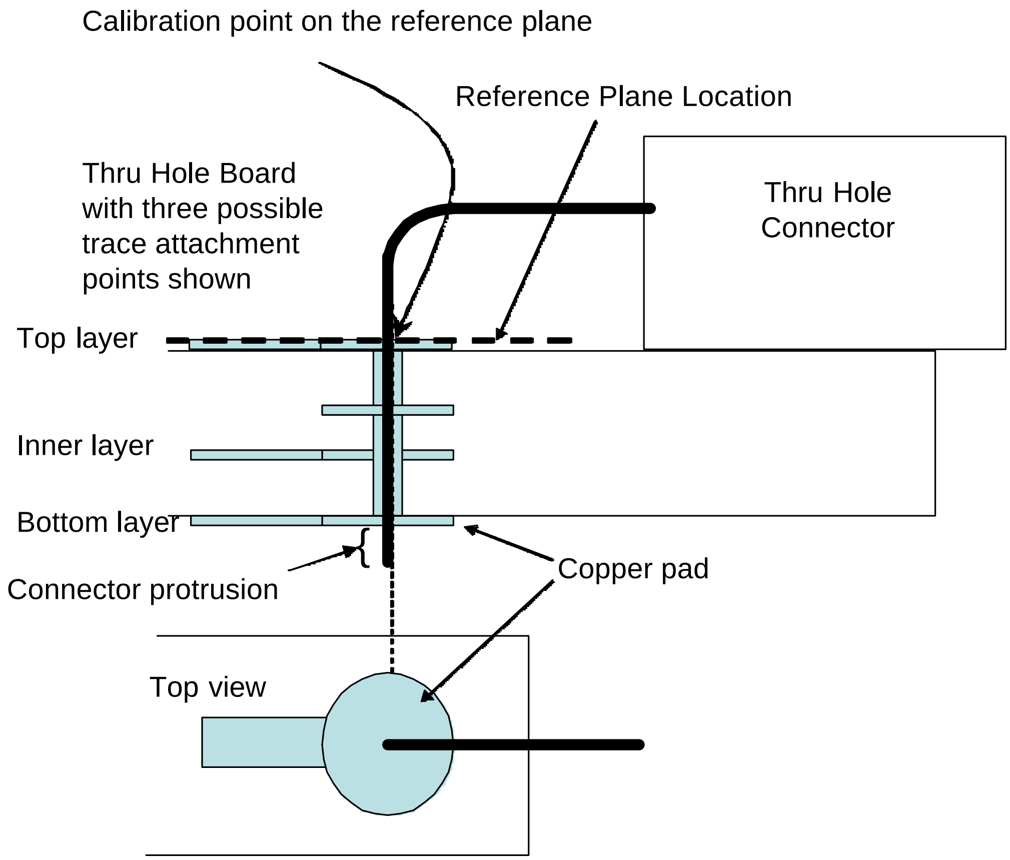
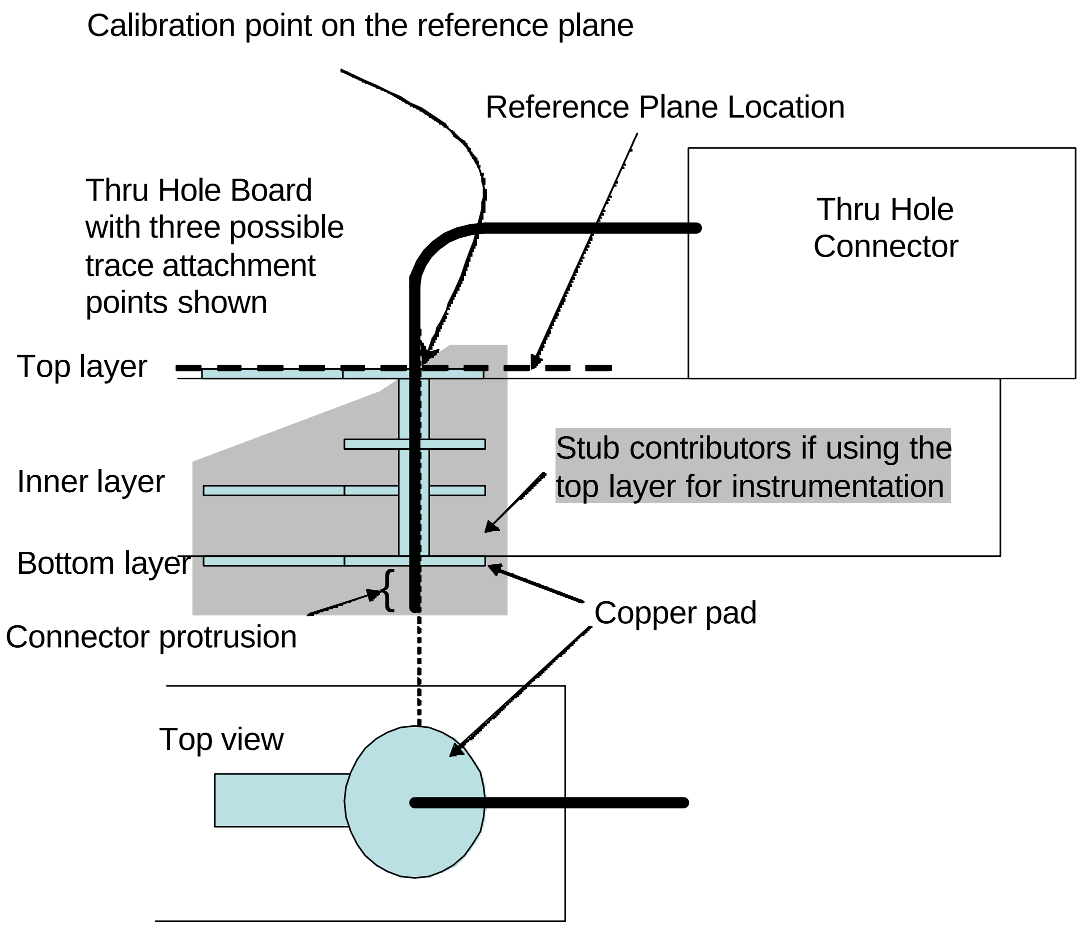


Figure 11 – Reference plane, calibration points, and protrusion for a through hole style connector

This construction is more complex than the surface mount construction particularly because of features that act as transmission line stubs and the fact that the physical boundary of the connector does not match the physical reference plane and calibration point.

Stubs are defined as any connection to the transmission path that is not part of the transmission path. With the construction in Figure 11 the choice of board layer used for the instrumentation attachment changes which features are stubs and which are not.

If the top layer is used for the instrumentation attachment then the stub contributors are as shown in Figure 12.



If the inner layer or bottom layer is used for instrumentation then the stub contributors are different. The least stub effects are seen when there is only a bottom layer connection and there is no connector protrusion.

Cleaner signals and less error in accounting for the test fixture contributions result if stubs are minimized. In any case, one must account for the entire test fixture construction as it will be used during IUT measurement.

The portion of the connector that enters the through hole at the calibration point (and possibly protrudes out the bottom of the board) is not considered part of the IUT. A significant source of error exists if the test fixture effects are calibrated without considering the effects of the connector protrusion. The best way is to have no connector protrusion at all. One way to do this is to clip or mill any protrusion after assembling the connector to the test fixture board and to do so without changing any other properties of the board. Otherwise calibration becomes problematic because it is only AFTER the connector is assembled to the text fixture board that the extent of the protrusion is known.

8. Accounting for the test fixture in S-parameter measurements

8.1 Overview

Clause 8 describes the ways that test fixtures may be treated in terms of the overall S-parameter measurement process.

8.2 Extraction of S-parameters from a practical measurement

In a general sense the challenge is to measure or determine the S-parameter of the IUT alone. In order to do this it is necessary to either remove the effects of the instrumentation and test fixtures or to include the instrumentation and test fixture effects as part of the calibration process.

Figure 12 shows a view of the separate measurement of the test fixtures (or of the calibration of the test fixtures + instrumentation) and the combination of the test fixtures with the IUT.

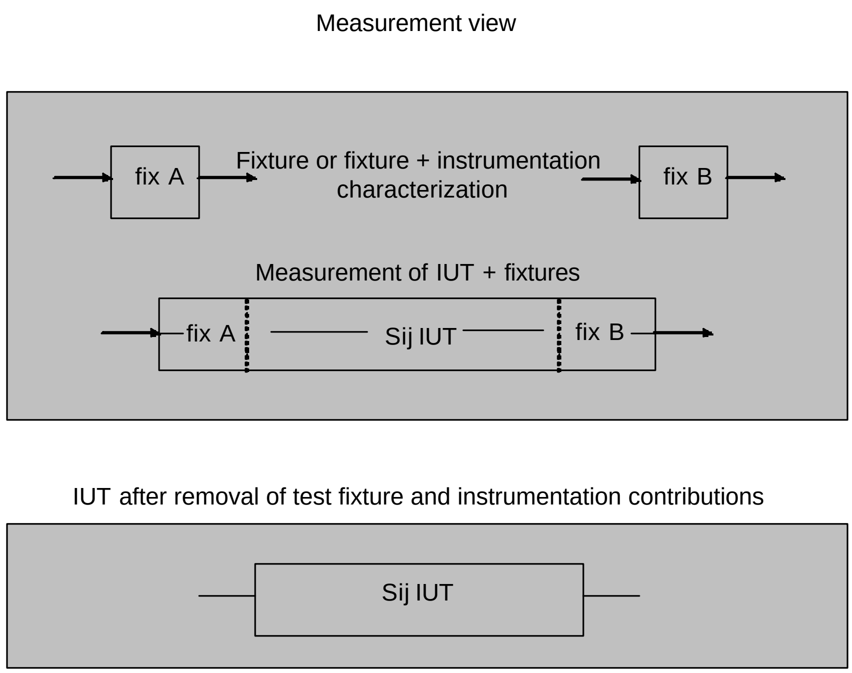


Figure 12 – General process for achieving an IUT Sij

Practically the determination of the Sij for the IUT uses one of the two basic methods illustrated in Figure 13 and Figure 14. Each uses a different reference plane position.

Figure 12 shows the configurations used when a separate set of characterizations / measurements are first done on the test fixtures. Then the test fixtures are attached to the IUT and the Sij for the composite is measured. The reference plane for both the IUT + test fixture and the separate test fixture measurement is at the instrumentation/test fixture interface. Subsequent removal of the test fixture contributions by matrix algebra is referred to as ‘de-embedding’.

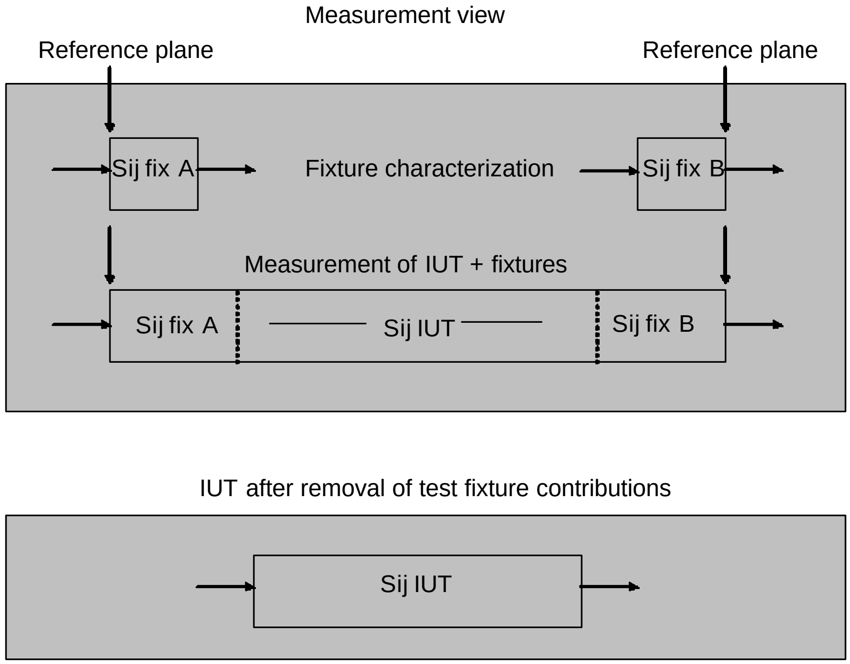


Figure 13 – Calibration reference plane at instrumentation side of test fixture

The equation below specifies the mathematical relationship for removing the test fixture effect by using T parameters. The de-embedding works best if the S parameters are first converted to T parameters

$[\text{Tij IUT}] = [\text{Tij fixA}]^{-1} * [\text{Measured Tij of IUT and fixtures}] * [\text{Tij fix B}]^{-1}$

The T parameters shall be converted to S parameters and vice versa using standard conversion equations.

Figure 14 shows the configuration used when the test fixture effects are included as part of the instrumentation as for example in the abbreviated SOLT, full SOLT, and TRL methods. In this method the reference plane is at the IUT/test fixture interface.

The test fixture effects are accounted for, not by direct measurement of the test fixtures but rather by inferring what these effects are from other measurements on artifacts that are intended to represent the actual test fixture under different idealized conditions.

The measurement of the IUT + test fixtures is done in essentially the same way as for the de-embedding method but the test fixture effects are accounted for differently.

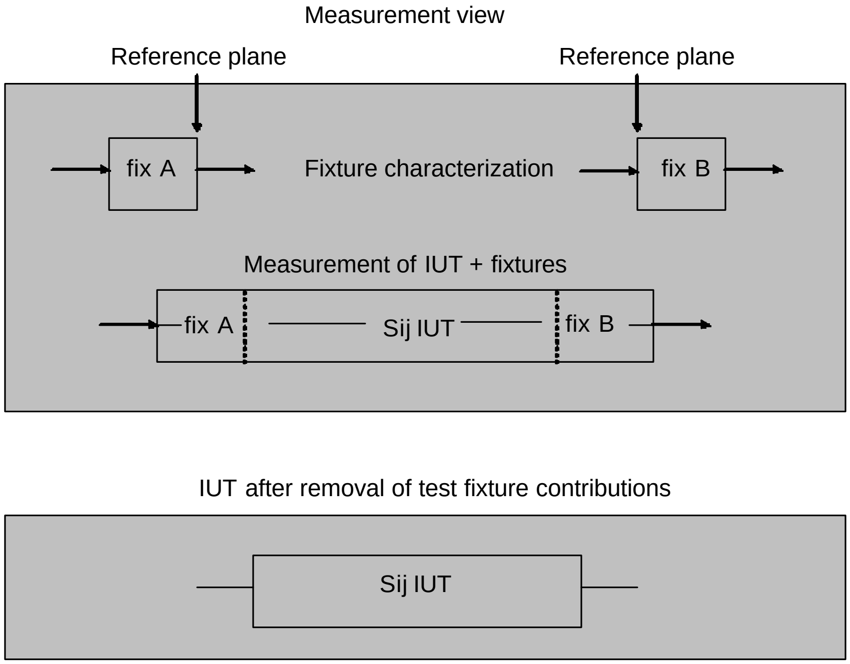


Figure 14 - Calibration reference plane at IUT side of test fixture

The mathematics of removing the test fixture effects in this method are complex but have been well documented, reviewed, and practically exercised. These mathematics are not specified in this document but typically are embedded in measurement equipment that uses this method of accounting for the test fixture effects.

9. Basic measurement requirements

9.1 General

There are three elements to a basic measurement: measurement instrumentation, hardware being measured, and measurement procedure. This clause describes each of these elements.

It requires complete specification of all three elements to produce an acceptable S-parameter file. Annex II uses an A, B, C,… scheme to identify specific combinations of the three elements.

9.2 Measurement instrumentation

9.2.1 Overview

Measurement instrumentation is the hardware and software that stimulates and detects responses from the hardware being measured. By convention the instrumentation ends where it attaches to the test fixture. However, depending on the measurement procedure, the calibration of the instrumentation may also include the test fixture.

When the instrumentation calibration includes the test fixture, as shown in Figure 14, the instrumentation formally ends at the IUT reference plane. See clause 8.

That notwithstanding, for the purposes of clarity and simplicity, this document treats the instrumentation as ending at the instrumentation side of the test fixture regardless of the calibration scheme used for the overall IUT measurement.

9.2.2 Definition of instrumentation type

Instrumentation provides time or frequency domain stimulus to the hardware being measured and provides a means to report the detected results. The type of instrumentation is defined by the type of stimulus – not by the form of the display of the measurement results.

Instruments that apply single frequency sinusoidal stimulus are frequency domain instruments. Instruments that apply time domain waveform stimulus are time domain instruments.

Instrumentation includes the instrumentation quality cables required to attach the instrumentation enclosure to the test fixture connectors.

Instrumentation also includes any software used to process the detected signals prior to displaying or otherwise exporting the results provided that this software is run in the same enclosure that provides the stimulus and does the raw signal detection.

9.2.3 Calibration of instrumentation

This document assumes that the supplier of the instrument and associated instrumentation quality cables specifies the calibration procedure up to the end of the cables. Further calibration to account for test fixture effects is part of the measurement procedure.

9.2.4 TDNA resolution and bandwidth considerations

The following applies when using time domain network analyzer instrumentation.

Record length or time window ns, T
# of data points, N (gives Δt between points)

$T = N(\Delta t)$

Upper frequency limit for measurement, Fmax is given by

$Fmax = 1/2\Delta t = N/2T$

Δf is the frequency step in the measured S parameter result.

$\Delta f = 1/T$

It is important to allow waveform captured from the IUT to settle to its steady state D.C. level. The low frequency content of the result is more accurate for longer settling times. The settling time depends strongly on the sample length, reflections, and losses.

The steady state value may be determined by observing the value at the end of the waveform observed with the waveform measuring instrument set to its widest time scale. Typically this time scale will have a range of hundreds of microseconds.

For IUT’s that have very small end point reflections and significant loss, steady state may be achieved with an acquisition window, T, that is 3 to 4 times the one-way electrical length of the IUT.

Δf may be made much smaller than the value given by 1/T by using well established zero padding methods. Values of Δf in the single Hertz range may be achieved.

9.2.5 VNA (frequency domain) set-up considerations

The following equipment settings are recommended by a major equipment supplier, other equipment suppliers may have different recommendations.

Start Frequency	10 MHz
Stop Frequency	20 GHz
Frequency step size	10 MHz (5 MHz for Time Domain conversions)
Number of points	2000 (3999 for Time Domain conversions)
IF Bandwidth	300 Hz
Power	-8 dBm
Averaging	1
Analyzer Sweep Type	Stepped

9.3 Hardware being measured

9.3.1 Overview

The hardware being measured consists of the test fixture that is required to adapt between the physical IUT and the instrumentation hardware. See subclause 9.3.2. As discussed in clauses 8 and 9 the additional measurements required to account for the test fixture are executed separately from the measurement done with the test fixture and the IUT connected together. Therefore, the overall measurement requires that both the IUT and the test fixture be part of the hardware being measured regardless of how test fixture effects are accounted for in the measurement process.

9.3.2 Test fixture and associated calibration structure design

9.3.2.1 Basic architecture

With the exception of cable assemblies that happen to use exactly the same connectors as provided with the instrumentation cables, all S-parameter measurements require a separate piece of hardware that allows connection of measurement equipment to the IUT. This piece of hardware is called a test fixture in this document. It is important to distinguish between the test fixture and the associated calibration structures. The calibration structures may or may not be part of the same board as the test fixture. Calibration structures are used to account for the effects of the test fixture on the measurement of the IUT.

Differential signals are assumed, so corresponding signal pairs shall be maintained between all calibration structures and the test fixture.

The connector half that mates to the IUT is part of the IUT in this document. The test fixture formally ends at the calibration points defined in 7.4.

In an architecturally ideal world there would be no need for any separate calibration structures and all calibration would be done directly on the actual test fixture to be used for the measurement. Unfortunately, due to the fine geometries required at the connector attachment points, present technology does not allow attachment of known standards or instrumentation cables to the calibration points defined in 7.4 without introducing unacceptable errors.

These errors are exacerbated at the 20GHz frequencies required for this document and methods that may have been useable at lower frequencies are no longer acceptable. The HPEI group that developed this document explored at length the possibility of using the actual test fixture for calibration because only that method does not require verifying the uniformity of the boards used. Because of these difficulties calibrating the actual test fixture was abandoned.

9.3.2.2 Example of a test fixture and associated calibration structures

Figure 15 shows a conceptual design for a test fixture and associated calibration structures that implements the full SOLT calibration schemes. Similar figures apply for the TRL, and abbreviated SOLT schemes.

The test fixtures consist of the portions highlighted in grey. Instrumentation connectors include any that are well controlled and calibrateable. High frequency probes are not excluded but may require extra care to use acceptably.

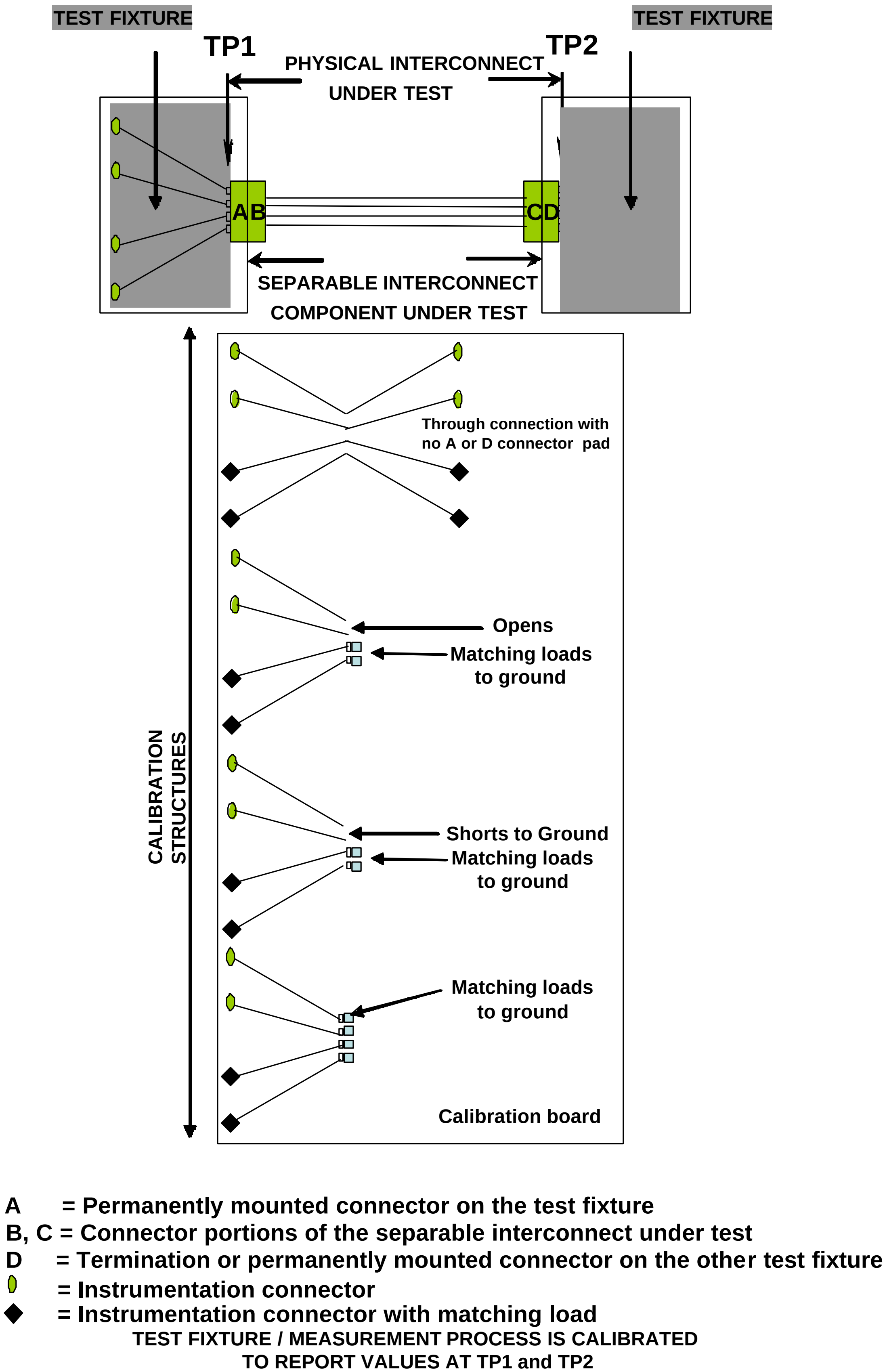


Figure 15 – Proper test fixture and calibration structure design concept

9.3.2.3 Special requirements for all test fixtures and associated calibration structures

One key requirement where separate calibration structures are used is that the calibration structures accurately represent the behavior of the test fixture. This is achieved by requiring that the calibration structures be designed to be electrically and physically the same.

Two important but often overlooked properties that must be considered in achieving this similarity are: (1) uniformity across boards and between boards and (2) electrical coupling between the measurement traces and other parts of the test fixture or calibration structure.

It is well known that properties of printed circuit boards can vary significantly across the same board and from board to board even if made from the same panel. Examples of causes for this variation include linewidth differences due to non uniform metal thickness and imperfect artwork, different contributions from the reinforcing glass fibers used for construction at different positions on the board, laminate thickness variations, and alignment shifts between layers during curing. For this reason it is required that tight specifications on the uniformity of the boards used be enforced.

An example of test fixture and calibration structure designs that do not have similar electrical coupling and may be problematic for S-parameter calibrations is shown where:

- The traces on the actual test fixture are coupled to other portions of the test fixture or other traces, while the calibration structures are typically isolated and do not have the same coupling to other traces as the actual fixture.
- Actual fixtures have many traces converging on the connector footprint while the calibration structure may have only one trace or pair of traces converging on the connector footprint.

Figure 15 shows calibration structures that rigorously apply only for the upper pair in the left test fixture. Terminations required for calibrating this pair are shown in Figure 15. However, if it is determined that the lower pair and the pairs in the right test fixture are the same according to the criteria specified in 9.3.2.3 then these calibration structures may be used for all the test fixture pairs.

Some complex test fixtures may have pairs that are different from other pairs. In this case a different set of calibration structures is required for each different pair.

This document requires the following properties from all test fixtures and associated calibration structures independent of the actual calibration and measurement scheme used.

The following requirements apply without connectors A and D in Figure 15 installed on the test fixture.

1) The single-ended impedance profile of the calibration structures (measured using a 30 ps rise time (20%-80%)) shall match the corresponding test fixture traces according to:

> Measured single-ended impedance of calibration structures shall be the same as the single ended impedance of the corresponding part of the test fixture

to within ± 1% at every time point across the profile between the launch point and the calibration point.

All traces except those under test shall be terminated on both ends with a matching load during the measurement. This termination is either hard wired into the calibration structure or is attached to an instrumentation connector.

This applies to all calibration structures needed for the measurement method being used. Notice that this is NOT a peak to peak requirement and that any reasonable variation that exists for BOTH the test fixture and the corresponding calibration structure is acceptable. For example if the impedance lowers in the same way for both the calibration structure and the test fixture as the calibration point associated with the connector is approached (as one would expect) this change in impedance level is acceptable. What is not acceptable is that the calibration structures impedance profile not match the test fixture impedance profile.

Non uniformity in properties due, for example, to non uniform fiber glass in boards may be a significant source of error. Board constructions using thin or thick film ceramics, other specialty materials or tightly controlled design and processing may be required to meet this requirement.

2) The single ended S-parameters of the calibration structures shall match the corresponding S-parameters of the test fixture (no connector installed) over the frequency range specified in 4.1 according to the following rules:

Magnitude of S21 (measured in dB) of the ‘through’ connection calibration structure equals the magnitude of S11 for the corresponding test fixture trace (with the traces open as they exist with no connector in place) within the greater of +/- 10% of the measurement or +/- 0.2 dB.

Magnitude of S11 (measured in dB) of the ‘short’ calibration structure equals the magnitude of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within the greater of +/- 10% of the measurement or +/- 0.2 dB.

Magnitude of S11 (measured in dB) of the ‘open’ calibration structure equals the magnitude of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within the greater of +/- 10% of the measurement or +/- 0.2 dB.

Magnitude of S11 (measured in dB) of the ‘load’ calibration structure before the load is mounted on the end of the ‘load’ calibration structure equals the magnitude of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within the greater of +/- 10% of the measurement or +/- 0.2 dB.

Angle of S21 (measured in degrees) of the ‘through’ connection calibration structure equals the angle of S11 for the corresponding test fixture trace (with the traces open as they exist with no connector in place) within +/- 20 degrees at all frequencies.

Angle of S11 (measured in degrees) of the ‘short’ calibration structure equals the angle of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within 180 +/- 20 degrees at all frequencies.

Angle of S11 (measured in degrees) of the ‘open’ calibration structure equals the angle of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within +/- 20 degrees at all frequencies.

Angle of S11 (measured in degrees) of the ‘load’ calibration structure before the load is mounted on the end of the ‘load’ calibration structure equals the angle of S11 of the corresponding test fixture trace (with the traces open as they exist with no connector in place) within +/- 20 degrees at all frequencies.

All traces except those under test shall be terminated on both ends with a matching load during the measurement. This termination is either hard wired into the calibration structure or is attached to an instrumentation connector.

Non-uniformity in properties due, for example, to non-uniform fiberglass in boards may be a significant source of error. Board constructions using thin or thick film ceramics, other specialty materials or tightly controlled design and processing may be required to meet these requirements.

These requirements depend on the fact that the test fixture traces are open for this measurement and that this open, though not ideal, will reflect nearly all of the signal that reaches the open. Since the length of the path for the open measurement approximates the length of the insertion loss measurement for the through connection the value for S11 (open) should be approximately the same as the insertion loss for the through calibration structure.

9.3.2.4 Some examples of poor calibration structure design

Several examples of calibration structures that do not accurately represent the test fixture are shown in Figure 16.

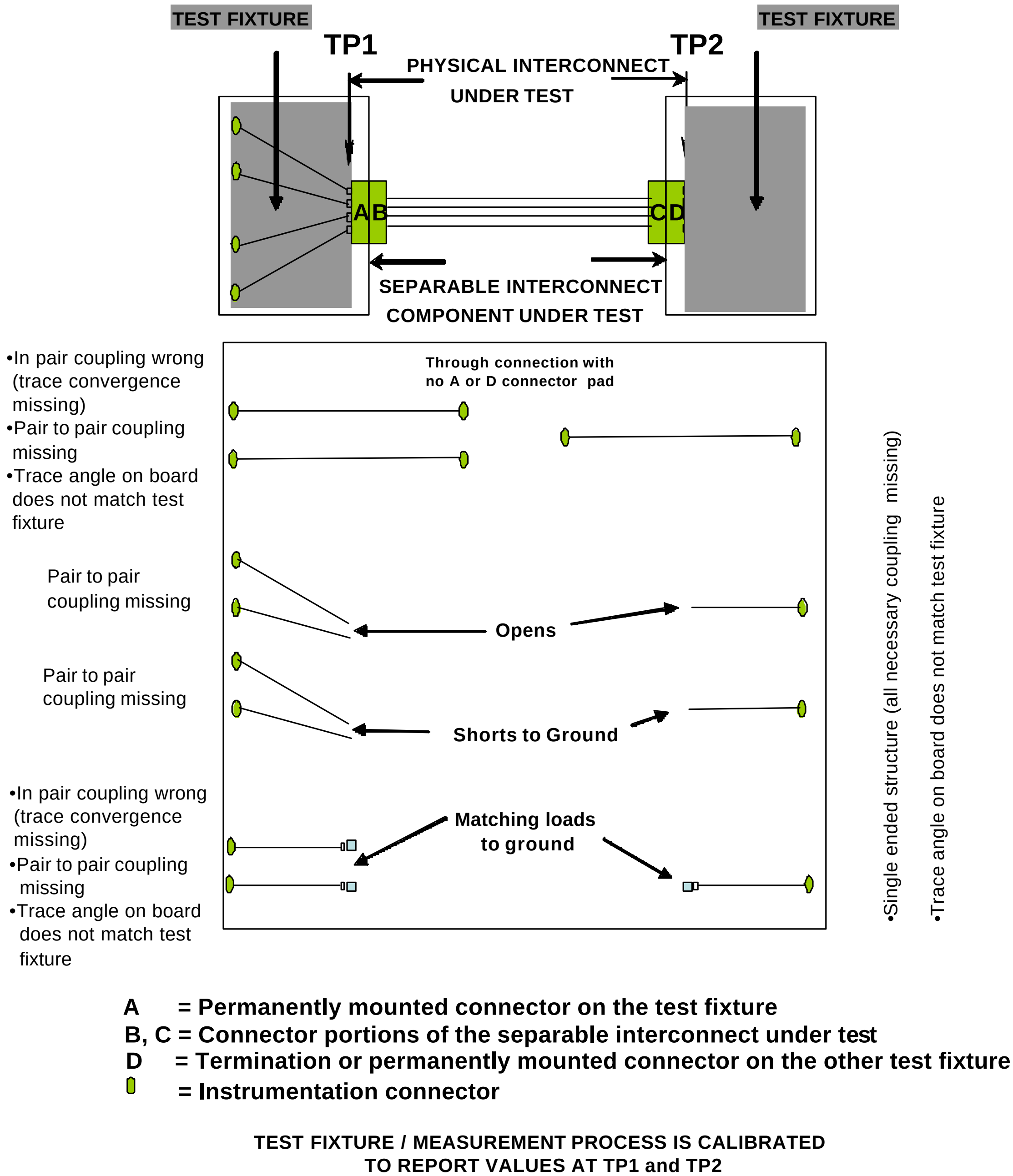


Figure 16 – Examples of poor calibration structure designs

9.4 Measurement procedures

9.4.1 Overview

This section describes three measurement procedures that may be used for S-parameters: SOLT (including abbreviated SOLT), TRL, normalization, and de-embedding.

There are many different acronyms (TRL, SOLT, TRM, LRM, abbreviated SOLT, etc.) for various test methodologies supplied by test equipment manufacturers. Each acronym represents a different way of approaching calibration. These differences range from small to very large. The error term each calibration standard is addressing, the measurement parameter being measured with the standard, and the parameter the calibration standard is correcting is different for each acronym.

The test methodology industry for S-parameters is changing very quickly, and no document can be released that will not be outdated by the release date if the document attempts to go into the step-by-step details of each acronym. The detailed methodology associated with each acronym has different requirements for how accurately the calibration structures must represent the actual fixtures that are being used in the actual measurements and whose effects need to be removed.

This document does not list the step-by-step instructions for each measurement method as those instructions are readily available from the instrument and software manufacturers. Rather, this document details a set of tolerances for how accurately the calibration structures must represent the actual fixtures. This document also details a format for exporting S-parameter data that does not exist elsewhere in the industry.

For each test method (acronym) selected by a user, the equipment and software manufacturer gives detailed step-by-step instructions during the calibration and test process. For example, “connect ‘short’ calibration standard to port 1”. Refer to the equipment and software manufacturer for detailed instructions during the calibration process.

Compliance with the requirements specified in 9.3.2.3 is possible using high quality processes and design and specification methods. However, it is easy to do what appears to be a high quality design and specification and not meet these requirements because details not traditionally specified are critical. For example, copper thickness and dielectric constants variation across the board and from board to board play a key role in matching the test fixture and the calibration structure.

Compliance with all of the requirements specified in 9.3.2.3 assures that any measurement method chosen is capable of achieving accurate S-parameters.

Some specific test methods may allow relaxing some of these requirements for some calibration structures. Then the supplier of the measurement technique and data shall demonstrate that the deviation is tolerable to the accuracy level of the S-parameter measurement claimed for the IUT.

If for any other reason a test fixture and its calibration structures do not comply with the requirements specified in 9.3.2.3 then the fact that such a deviation exists shall be included in the test report along with a caution that a guard band is needed when using the measured S-parameters. The amount of the deviation and its required guard band shall be determined between the supplier of the measurement and the user.

9.4.2 SOLT method

The SOLT method (Short, Open, Load, and Through) is actually a name for two similar methods: the full SOLT and the abbreviated SOLT both requiring some of all of Short, Open, Load, and Through calibration measurements.

This method requires making prescribed measurements on calibration structures and the test fixture + IUT. The test fixture effects are removed via a complex set of mathematics that has been developed for many years and is now mature. This document accepts that this mathematics is valid. Errors come largely from implementing inadequate calibration structure discipline.

The abbreviated SOLT method requires only one or two of these calibration measurements. The choice of these calibration measurements depends on the kind of IUT measurement desired and the kind of calibration structures available. In general, abbreviated SOLT insertion loss IUT measurements are best done using the through calibration measurement and abbreviated SOLT return loss IUT measurements are best done using the open and short calibration measurements. The load condition is used to improve the accuracy of the return loss measurements.

9.4.3 TRL method

The TRL method (Through, Reflect, Line) is actually one acronym amongst many that use similar assumptions about error sources and what calibration standards are needed to obtain correction values.

This method requires making prescribed measurements on special TRL calibration structures not described in this document and the test fixture + IUT. The test fixture effects are removed via a complex set of mathematics that has been developed for many years and is now mature. This document accepts that this mathematics is valid. Errors come largely from implementing inadequate calibration structure discipline. The equipment and software manufacturers give design details for the calibration standards, and step-by-step instructions for connecting the calibration standards during the calibration process.

9.4.4 De-embedding

De-embedding obtains all the S-parameters (including insertion and reflected losses and phase properties). The S-parameters are obtained by the following process:

1) Calibrate the test system on a well known reference plane with well established calibration standards and methods for verifying measurement accuracy
2) Measure or model the actual fixture, or measure reference standards that represent the actual fixture
3) Use post processing mathematics on a measurement of IUT plus fixture to remove the fixture effects.

Measurements of reflection and loss standards are required, and are specified by the equipment and/or software manufacturer.

9.4.5 Normalization method

Normalization obtains only insertion loss S-parameters. This method does not obtain corrected reflection S-parameters. The insertion loss S-parameters are obtained by 1) measuring or modeling either the actual fixture, or reference standards that represent the actual fixture (note this does not need to be a “calibrated” measurement if the IUT plus fixture measurement is made in the same set-up), and 2) use post processing mathematics on a measurement of IUT plus fixture to remove the fixture effects. Typically a “2X” through calibration structure is measured and subtracted from the measurement of IUT plus fixture.

There are no known schemes that allow adequately accurate separate extraction of the test fixture properties as required by this method. This is essentially the same problem as using the actual test fixture as the calibration fixture. The SOLT and TRL methods essentially integrate this measurement requirement into their respective methods.

Annex I – Example of a partial S-parameter based specifications

This annex is provided to give an example of one specification currently in use by a system specification. It may be interesting as an exercise for the reader to evaluate its effectiveness against the criteria provided in this document.

Insertion Loss and Return Loss
Measurement Method

Test fixture calibration:

1. Calibrate test system with the reference plane defined as the SMA or 3.5 mm interface. This step is not necessary if using a time domain system to obtain insertion loss.
2. Measure insertion loss of a thru calibration structure. All transmission line characteristics in the fixtures and test leads on both ends of an IUT must be included in the thru calibration structure. Include a discontinuity at the center of the thru calibration structure where the two halves of the calibration structures meet. The discontinuity shall have the same dimensions as the nominal mounting provisions of the IUT. For example if the IUT is via mounted then place the same via at the discontinuity where the two calibration structures meet. A thru calibration structure represents the entire test system without the IUT.

When two different fixtures are used on each end of the IUT:

Option 1: make a non-symmetrical thru calibration structure that represents the two different fixtures,

Option 2: Use two different thru calibration structures.
For scalar the combined insertion loss of the two fixtures is the average insertion loss of the two thru calibration structures. This average is subtracted from the insertion loss measurement of the IUT plus fixtures to obtain the insertion loss of the IUT.
For vector the combined insertion loss of the thru calibration structures is the square root of the insertion loss of each of the two thru calibration structures multiplied together.

Insertion loss:

1. Measure insertion loss of the IUT plus fixtures.
2. Determine scalar insertion loss by subtracting the insertion loss measurement of the thru calibration structure from the insertion loss measurement of the IUT plus fixtures.

Or, determine vector insertion loss by dividing the insertion loss measurement of the IUT plus fixtures by the insertion loss measurement of the thru calibration structure.

Return loss:

1. Measure the return loss of the IUT plus fixtures.
2. Determine scalar return loss by subtracting the insertion loss measurement of the thru calibration structure from the return loss measurement of the IUT plus fixtures.

Or, determine vector return loss by dividing the return loss measurement of the IUT plus fixtures by the insertion loss measurement of the thru calibration structure.

This method does not de-embed the fixtures’ return loss from the measurement, it only removes the fixture insertion loss from the IUT return loss measurement.

Annex II - Trade off / properties summary matrix for measurement methods

The following table provides a summary of some tradeoffs between measurement methods. The methods are labeled A, B, C… because more than the calibration scheme is involved in the differentiation between the overall measurement methods.

Method	Reference plane location	Calibration Method	IUT connection method	Test Fixture Characterization structures not part of test fixture	Standards / known reference structures attached in place of IUT	Frequency range	Comments	Apparent overall attractiveness based on inputs from 05/24/06 meeting (1 to 3, 3 best)
A	At IUT	SOLT 1	SMA* to IUT connector	Separate structures on the same board	Short open load thru	Depends on quality of standards,d.c. to 20GHz+ possible	Must trust the complex internal calculations required, higher frequencies may be a problem, test fixture cal not on the same traces used for measurement	2-3
B	At IUT	TRL	SMA* to IUT connector	Special TRL structures	None	d.c. to 20GHz+	Must trust the complex internal calculations required, special structures may not represent tests fixture	2
C	At IUT	SOLT 2	Probe	none	Short open load thru	??	Needs investigation re: connector attach Probes at IUT connector not shown to work reliably, grounding issue	1
D	At IUT	ABBREVIATED SOLT	SMA to IUT connector	none	Optional loads	d.c. to 20GHz+	Requires time domain calibration, VNA methods not presently available	3

Method	Reference Plane location	Calibration Method	IUT connection method	Test Fixture Characterization structures not part of test fixture	Standards / known reference structures attached in place of IUT	Frequency range	Comments	Apparent overall attractiveness based on inputs from 05/24/06 meeting (1 to 3, 3 best)
E	At non IUT side of test fixtures	Probe De-embed (Calibrate to the end of the SMA connectors)	SMA to IUT connector	Actual test fixture is characterized	None	??	Calibrated probe required to access IUT connection point on the test fixture to characterize the test fixture	1-2
F	At non IUT side of test fixtures	Test Fixture Model (Calibrate to the end of the SMA connectors)	SMA to IUT connector	Model uses measured test fixture properties	None	??	Validation of model is not possible	1

*SMA is a generic term used to describe any instrumentation quality connector used to attach test equipment to the test fixture