



IEEE Standard for Electrical Characterization of Printed Circuit Board and Related Interconnects at Frequencies up to 50 GHz

IEEE Electromagnetic Compatibility Society

Developed by the
Standards Development Committee

IEEE Std 370™-2020

STANDARDS

IEEE Standard for Electrical Characterization of Printed Circuit Board and Related Interconnects at Frequencies up to 50 GHz

Developed by the

Standards Development Committee
of the
IEEE Electromagnetic Compatibility Society

Approved 24 September 2020

IEEE SA Standards Board

Abstract: Standard and recommended practices for ensuring the quality of measured data for high-frequency electrical interconnect at frequencies up to 50 GHz are provided. This might include, but is not limited to recommending design of test fixtures, as well as methods and processes for ensuring the accuracy and consistency of measured data for signals with frequency content up to 50 GHz. The standard and general practice should be applicable for frequencies higher than 50 GHz as well. The methods and techniques contained herein have been validated only to 50 GHz as of this writing.

Keywords: causality, consistency tests, de-embedding electrical measurement, fixture, IEEE 370, interconnect, passivity, reciprocity, S-parameters, verification

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 978-1-5044-7063-6 STD24412
Print: ISBN 978-1-5044-7064-3 STDPD24412

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Introduction

This introduction is not part of IEEE Std 370-2020, IEEE Standard for Electrical Characterization of Printed Circuit Board and Related Interconnects at Frequencies up to 50 GHz.

As high-speed serial link data rates increase (beyond 25 Gbps), the need for accurate interconnect measurements becomes critical. However, standard practices are lacking on how to measure interconnects at high frequencies.

Most high-frequency instruments, such as vector network analyzers (VNAs) and time-domain reflectometers (TDRs), can make good measurements at the end of a coaxial interface. Typical devices to be tested do not have coaxial interfaces, so test fixtures are often required to be inserted between an instrument's coaxial interface and the device under test (DUT), such as a printed circuit board (PCB), package, connector, cable, etc. There are various de-embedding approaches already commercially available, however, the de-embedding algorithms are often proprietary, and verification of the accuracy of the de-embedded S-parameters is left to the user.

A poorly designed test fixture can lead to inaccurate de-embedded S-parameters. There is no IEEE standard that specifies the electrical requirements of a properly designed test fixture to achieve high-quality de-embedded results.

The quality of measured S-parameters of DUT can vary widely. There is no IEEE standard to check and validate the quality of S-parameters before they are distributed for use. This has created many complications for engineers who are utilizing the measured S-parameters for high-speed interconnect analysis. An IEEE standard is needed to check post measurement S-parameter data.

The IEEE P370 workgroup was established to address the above issues. Three task groups (TGs) were formed under the workgroup:

- TG1: Fixture Design Criteria
- TG2: De-embedding Verification
- TG3: S-parameter Integrity

This document is the outcome of the joint efforts of P370 members.

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IEEE Standard for Electrical Characterization of Printed Circuit Board and Related Interconnects at Frequencies up to 50 GHz

1. Overview

1.1 Introduction

This document provides standard practices for ensuring the quality of measured data for high-frequency electrical interconnects at frequencies up to 50 GHz. This includes, but is not limited to: recommended design of test fixtures, as well as methods and processes for ensuring the accuracy and consistency of measured data for signals with frequency content up to 50 GHz. Annexes are included in this document comprise the following:

- Examples
- Best practices
- Tutorials
- Definitions
- Reference information

1.2 Scope

This document addresses the quality of measured S-parameters for electrical printed circuit board (PCB) and related interconnect at frequencies up to 50 GHz. This might include, but is not limited to: test fixtures, as well as methods and processes for controlling the accuracy and consistency of measured data for broadband signals with frequency content up to 50 GHz. The standard is applicable to:

- PCB and related interconnects (including package, connector, cable, etc.) used in high-speed digital applications, operating with signals at frequencies up to 50 GHz
- Most industries using such interconnects

- Major measurement approaches (time domain or frequency domain) for collecting scattering (S-parameter) data
- Significant methods of removing/de-embedding fixture and instrumentation effects

1.3 Purpose

The purpose of this standard is to define methodologies by which high-quality scattering parameters (S-parameters) can be obtained for electrical interconnects that are intended to operate at microwave frequencies (up to 50 GHz). The standard includes requirements for designing test fixtures, evaluating measured data, removing test fixture and instrumentation effects, and verifying the quality of the S-parameters. The primary focus of this standard development is measured S-parameters. However, the methodology is applicable to simulated S-parameters as well.

Note that this standard defines a set of metrics to be calculated and reported to the recipient of the S-parameter data. In order to comply with this standard, the values of the metrics shall be included in S-parameter data file. However, the determination of pass/fail status of the results is out of the scope of this standard, and is left to the recipient of the data.

Although the highest frequency of interest is set at 50 GHz in this document, the methodology is generally applicable to higher frequencies. The methods and techniques contained herein have been validated only to 50 GHz as of this writing.

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1, 2}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IBIS Open Forum, Touchstone File Format Specification version 1.1.

¹ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

² The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

IBIS Open Forum, Touchstone File Format Specification version 2.0.

IEEE Std 287™, IEEE Standard for Precision Coaxial Connectors (DC to 110 GHz).^{3, 4}

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁵

2X-Thru: A de-embedding structure composed of directly connected replicas of left fixture and right fixture for a given device under test (DUT).

2X-Thru de-embedding: A de-embedding method that utilizes the 2X-Thru structure to remove the fixture effects when measuring a device under test (DUT).

calibration: The process of characterizing the systematic errors of the instrument by measuring known devices (calibration standards). Subsequently, the effects of the characterized systematic errors are mathematically removed from raw measurements.

calibration standard: A structure used for calibration of the test equipment. Typical standards are a *load*, an *open*, and a *short* (circuit). Such a device may be included in the test fixture.

causality: The property of a physical system in which the output depends only on past and current inputs but not future inputs.

de-embedding: The process by which the characteristics of the test fixture are mathematically removed from the measured data, leaving the characteristics of the device under test (DUT).

device under test (DUT): The interconnect that is to be measured; examples include a connector, a cable, a printed circuit board trace or trace pair, or an active electronic device.

direct measurement: Measurement of a device under test that does not require the use of a fixture.

fixture: See test fixture.

front delay: The time at which the front of a signal should appear relative to time of the applied stimulus signal. It is impossible to exactly calculate front delay unless frequency response is given for all frequencies. The methodology described in the standard approximately calculates front delay.

group delay: The transit time of a signal through a device under test as a function of frequency.

impulse response: The time-domain response of an interconnect to the application of an ideal impulse function at its input.

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⁵ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

insertion loss: The loss of signal power from one port of the device under test (DUT) to another port, resulting from the insertion of the DUT. It is also used synonymously with S_{21} .

launch: A connector, typically coaxial, by which a signal is propagated from the test equipment cable into the test fixture at the first interface of the fixture before the first uniform transmission line region.

line-reflect-match (LRM): A calibration method that utilizes transmission line, reflect (short or open), and matched load standards.

load: A structure that provides purely resistive impedance for the purpose of calibration of the fixture with the test equipment, typically 50 Ohm in value.

microstrip: A type of transmission line that is fabricated using printed circuit board technology. It consists of a conducting metal trace separated from a reference plane by a dielectric layer, and is typically constructed as the top or bottom layer of a printed circuit board.

mixed-mode S-parameters: The S-parameter data describing the response of an interconnect to the application of either a differential-mode signal or a common-mode signal.

multi-chip module (MCM): An electronic package on which multiple integrated circuit die are mounted and interconnected.

National Institute of Standards and Technology (NIST): The U.S. federal agency responsible for developing and maintaining measurement methods and standards.

passivity: Property of an interconnect that does not generate energy.

phase delay: The difference between the phase of a sinusoidal input signal and the output signal from a device under test (DUT).

port: A structure, typically a coaxial connector, by which a test signal is applied to or observed at the interface to a test fixture or device under test (DUT).

post-processing: The process by which measured data are manipulated into the user's desired format for interpretation or other usage.

printed circuit board (PCB): A planar structure used to interconnect electronic components, typically constructed of alternating layers of dielectric (such as glass-epoxy) and conductive materials (such as copper foil) that are etched to form conductive paths.

reciprocity: A property of an interconnect in which the transmission of a signal between any two ports does not depend on the direction of propagation such that input and output ports are interchangeable (scattering parameter $S_{21} = S_{12}$, $S_{13} = S_{31}$, etc.).

reference plane: The location within the interconnect where the user calibration is performed. It is the plane at which the measurement is typically made.

return loss: The loss of power in the signal returned/reflected by a discontinuity in an interconnect, measured at a given port. It is often used synonymously with S_{11} , while in some other literature, it is used synonymously with the inverse of S_{11} .

S-parameter: A numerical matrix that quantifies how radio frequency (RF) energy propagates through a multi-port network, at specified frequencies. Each component of the matrix defines the ratio of the output voltage wave to the incident voltage wave for a given pair of input port and output port, and at a given frequency. The resulting ratio is typically a complex value.

stripline: A transmission line composed of a signal line that is between two solid reference planes, separated from each plane by a dielectric layer.

test fixture: Structure used to connect test equipment cables, typically coaxial, to a non-coaxial device under test (DUT). The fixture is in many cases constructed using a printed circuit board (PCB).

Thru-reflect-line (TRL): A calibration method developed by the National Institute of Standards and Technology (NIST) that uses transmission lines of various lengths, which are used over specified frequency ranges.

time-domain reflectometer (TDR): A special-purpose measurement instrument that applies a finite rise time step wave to a device under test (DUT), and typically displays the measured response in terms of impedance versus time or distance.

time-domain reflectometry (TDR): A measurement technique used to determine the characteristics of electrical lines by observing reflected waveforms.

traceable: Measurement data that were taken using calibration standards whose accuracy have been verified to devices maintained by the National Institute of Standards and Technology (NIST) or another internationally recognized standards organization.

transverse electromagnetic (TEM): A mode of wave propagation in which both the wave's electric and magnetic fields are perpendicular to the direction of propagation.

vector network analyzer (VNA): An instrument that applies a stimulus signal to a device under test (DUT) that is swept across a range of frequencies while the response of the DUT is measured.

3.2 S-parameter terms and labeling conventions

3.2.1 Introduction

The following subclauses identify common terms used with S-parameters and their recommended usage. These recommendations are intended to reduce ambiguity of S-parameter interpretation. Refer to Annex B for information regarding network parameters in general, including S-parameters.

3.2.2 Port index labeling

3.2.2.1 Introduction

A significant source of confusion when evaluating the S-parameters of any structure is the identification of which port indices correspond to which physical port of the interconnect. This document offers a recommendation for a specific labeling scheme. It is recommended that the port index assignment be verified before an S-parameter file is used.

3.2.2.2 Port assignment for two-port interconnects

In a two-port device under test (DUT), there is no ambiguity of the port labeling. Port 1 is connected to one end and port 2 is connected to the other end of the DUT. S_{11} is the ratio of the amplitude of the reflected voltage wave at port 1 to the amplitude of the incident voltage wave at port 1, each divided by the reference

impedance. Likewise, S_{21} is the ratio of the amplitude of the outflowing voltage wave at port 2 to the amplitude of the incident voltage wave at port 1, each divided by the reference impedance. S_{11} is therefore the reflection coefficient at port 1, S_{22} is the reflection coefficient at port 2, and S_{21} is the transmission coefficient from port 1 to port 2.

3.2.2.3 Port assignment for four-port interconnects

In a four-port structure, such as a differential pair interconnect, there are multiple ways of assigning index labels to the four ports. For example, it is possible to assign the port configuration such that port 1 connects to port 2, and port 3 connects to port 4. This would place ports 1 and 3 on one end of the differential pair, and ports 2 and 4 on the other end, as shown in Figure 1.

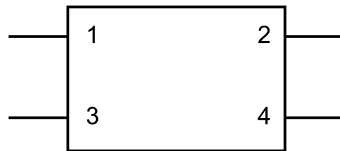


Figure 1—One labeling scheme for a four-port interconnect

In this configuration, the single-ended transmission coefficient of one line is S_{21} , consistent with the case of having just a single transmission line. The insertion loss of the first line in the pair is S_{21} , and the insertion loss of the second line in the pair is S_{43} . This assignment scheme is consistent with the two-port scheme described above and is also easily extendable to interconnects with larger numbers of ports. Odd-numbered ports are on the “left” side of the interconnect, and even-numbered ports are on the “right” side. This is the naming convention used in this standard.

An equally correct configuration is labeling the ports with port 1 connected to port 3 and port 2 connected to port 4, as shown in Figure 2. This places ports 1 and 2 on one side of the differential pair, and ports 3 and 4 on the other side. In this case, S_{31} is the insertion loss of the first line in the pair, and S_{42} is the insertion loss of the other line in the pair. While this labeling is perfectly correct, it makes the interpretation of each S-parameter different from the previous case. S_{21} in the first case is insertion loss, while S_{21} in the second case is near end crosstalk (NEXT). As described above, there are multiple port ordering schemes. De-embedding tools must be able to handle both port ordering conventions shown in Figure 1 and Figure 2.

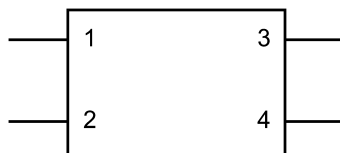


Figure 2—Alternate port labeling scheme

Identification of the port labeling scheme of the DUT is very important. Assuming one configuration when another one is actually used will result in misinterpreted results.

The port configuration shall be documented in the comment field of the S-parameter Touchstone file as described in 3.5.7. As an important consistency test, it is recommended that the S-parameters always be checked to identify which terms are the insertion loss and verify the assumed port labeling. This is done by examining the magnitude of the loss of the presumed transmission path (e.g., S_{21} or S_{31}). For a passive interconnect, this is often a small dB value at low frequency.

3.2.2.4 Mixed-mode S-parameter labeling

When characterizing differential interconnects, the measured single-ended S-parameters are often converted to mixed-mode S-parameters, using the equations in Annex C. Characteristics of differential interconnects may be described using mixed-mode ports composed of pairs of single-ended ports as follows:

- Mixed-mode port 1, which is composed of single-ended ports 1 and 3 (see Figure 1)
- Mixed-mode port 2, which is composed of single-ended ports 2 and 4

The name of the S-parameter indicates the configuration: S_{DD21} (or S_{D2D1}) is the S-parameter associated with the signal measured at mixed-mode port 2 due to a stimulus at mixed-mode port 1. The return loss of differential port 1 would be contained in S-parameter S_{DD11} (or S_{D1D1}). Likewise, S_{DC21} is the S-parameter associated with the signal measured at differential port 2 due to a common stimulus at port 1. If the alternate port numbering scheme of Figure 2 is used, mixed-mode port 1 would be composed of single-ended ports 1 and 2, while mixed-mode port 2 would be composed of single-ended ports 3 and 4.

3.2.3 Labeling fixtures with two or four ports

3.2.3.1 Introduction

In this document the fixture names are based on the index number of the DUT port to which they attach.

3.2.3.2 Labeling and identifying the fixture names

This standard recommends a specific labeling method for each fixture connected to the DUT, referred to as FIX-1, FIX-2, etc., and the port indices attached to each FIX. This is only a recommendation, as there are alternative approaches in wide use that are also correct. There is no industry-accepted method, and the user must verify in each application how the fixture is connected to the DUT and the port indices.

A DUT may have more than one fixture attached to it. On every DUT port that has a fixture to de-embed, the fixture is labeled based on the DUT port index number to which it connects.

In the case of a two-port DUT, for example, the fixture attached to the single-ended DUT port 1 is labeled as FIX-1. The fixture attached to the single-ended DUT port 2 is labeled as FIX-2.

In the case of differential ports with differential fixtures, FIX-D1 is connected to the differential DUT port D1, and FIX-D2 is connected to the differential DUT port D2.

3.2.3.3 Labeling and identifying the ports of the fixture

This standard recommends labeling the fixture's higher number port index as the one attached to the DUT and the lower number port index connected to the outside.

For example, in a 2X-Thru, composite structure, FIX-1 port 2 is connected to DUT port 1 and FIX-2 port 2 is connected to DUT port 2.

On each fixture, port 2 of the fixture is connected to the DUT and port 1 of each fixture is connected to the outside. These labels are illustrated in Figure 3.

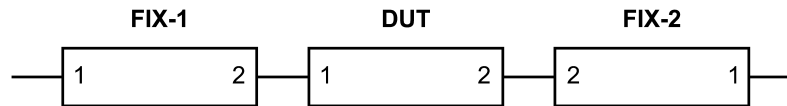


Figure 3—Illustration of a DUT with two fixtures correctly labeled

It is very important that the port labeling of the fixture assigned by the de-embedding tool is checked to verify that it is consistent with expectations. Not all tools may automatically label fixture ports the same way.

3.2.3.4 Naming of the fixture-DUT-fixture

The name of the fixture may be shortened to FIX. For example, the composite structure could be referred to as the FIX-DUT-FIX structure.

The combination of the DUT and fixtures on either end is referred to as the composite structure or the FIX-DUT-FIX structure. The combination of just the two fixtures, such as a FIX-1 connected to a FIX-2, is referred to as a FIX-FIX structure or a 2X-Thru.

In the case of a single port DUT, the composite structure is referred to as a FIX-DUT. This labeling scheme removes some of the ambiguity of the specific structure. In this standard, a FIX-DUT structure is described, but not recommended.

3.2.3.5 Labeling fixtures for DUTs with multiple ports

When a fixture connects to the DUT with more than one port, the name of the fixture should contain the multiple DUT ports connected, separated by underscores. For example, the specific differential fixture connected to ports 1 and 3 of the DUT should be labeled as FIX-1_3. The fixture connected to the other end of the DUT should be labeled as FIX-2_4.

If the differential port scheme were used to identify the DUT, the two fixtures should be identified as FIX-D1 and FIX-D2.

A fixture connected to two differential DUT ports should itself have four ports. These should be labeled with port 1 as an outside port on one fixture and port 1 as an outside port on the other fixture. In a differential fixture, the same convention is recommended, in which port 1 is connected to port 2 and port 3 is connected to port 4.

With this recommendation, the differential fixture ports should be labeled:

FIX-D1_1, FIX-D1_2, FIX-D1_3 and FIX-D1_4

If a differential port labeling were used for the fixture, the ports should be labeled:

FIX-D1_D1, FIX-D1_D2 and the other fixture should be labeled as FIX-D2_D1, FIX-D2_D2

In all cases, port 1 of the fixture always connects to the test equipment, and port 2 of the fixture always connects to the DUT.

While this labeling scheme may seem detailed, having unambiguous labeling for each component and their ports will dramatically reduce confusion and reduce risk when interpreting the three S-parameter files:

- The composite, FIX-DUT-FIX
- The 2X-Thru, FIX-FIX
- The de-embedded DUT

Figure 4 shows an example of a four-port DUT and two fixtures with the part labeling and an example of the port labeling of each. A similar diagram should be included with the documentation of every DUT.

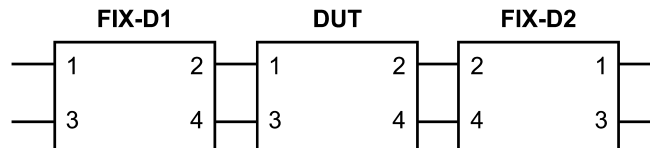


Figure 4—Four-port DUT and fixture example

3.2.3.6 Fixture S-parameter file naming

Part of the de-embedding process is to generate S-parameter data of just the fixture that is presumed to be attached to the DUT. The file that includes extracted S-parameters of a fixture should be named by appending the suffix “_calc” to the fixture label. For example, the files with the fixture models created to de-embed from the FIX-DUT-FIX structure are referred to as FIX-1_calc and FIX-2_calc.

This model can be created from a 2X-Thru structure for use in a 2X-Thru de-embedding algorithm, from the FIX-1 structure attached to the DUT, in an impedance-corrected 2X-Thru algorithm, or from a direct measurement of the FIX-1 structure if it is designed to be separable.

In the last case, the FIX-1 measurement is the same as the FIX-1_calc.

3.3 Defining the calibration method used and the component measured

3.3.1 Introduction

Refer to Annex D for a discussion of calibration and de-embedding basics.

3.3.2 Calibration methods

There is a number of different calibration methods used in the industry, a subset of which is discussed in this document:

- Short-open-load-thru (SOLT)
- Thru-reflect-line (TRL)

3.3.3 Traceable calibration method

There are a variety of standard methods that can be used to calibrate to the end of the coaxial test cables that are used to connect to the measurement equipment, using a mechanical calibration kit or an electronic calibration (ECal) module. Calibration standards of these types are typically used when the connection to the test fixture is made using precision coaxial connectors, such as those described in IEEE Std 287™ [B21]⁶.

Precision coaxial cables and standard calibration structures can be used during the calibration process to establish the measurement reference plane at the end of the coaxial cable. IEEE Std 287 provides electrical and mechanical specifications for precision coaxial connectors covering the range of dc to 110 GHz. Coaxial connectors are often defined by the nominal inside diameter of the outer conductor, such as 3.5 mm and 2.92 mm connectors. Table 1 lists some typical precision coaxial connector sizes.

Table 1—Precision coaxial connector characteristics

Inside diameter of outer conductor	7 mm	3.5 mm	2.92 mm	2.4 mm	1.85 mm	1.0 mm
Rated minimum upper operating frequency, GHz	18	33	40	50	65	110

Lower precision coaxial connectors with non-air dielectrics, such as those described in MIL-STD-348 Rev. B [B23], can be used for fixtures, but typically require an additional adapter to be added to the fixture for mating with the precision connector at the measurement reference plane. To avoid damage to precision connector interfaces, it is always advised to use the proper adapter to transition between connector types.

3.3.4 Using a traceable calibration with microprobes

When the fixture does not have a coaxial connector, such as pads on a circuit board for probing by a microprobe, it is more challenging to move the reference plane to the beginning of the fixture.

There are two recommended approaches to measuring the fixture:

- Calibrate to the end of the microprobe tip using a calibration substrate. There will always be some ambiguity about the tip's fringing fields to the calibration substrate being different than to the DUT. This will always limit the accuracy to some high-frequency limit.
- Calibrate to the end of the coaxial cable that is connected to the microprobe, using either mechanical coaxial calibration standards or an ECal unit. In that case, the microprobe is treated as part of the fixture. The microprobe + fixture is measured in the 2X-Thru and the FIX-DUT-FIX measurements and is part of the de-embed model.

The ambiguity in this case is the reproducibility of the connection of the microprobe to the fixture pads between the 2X-Thru measurement and the FIX-DUT-FIX measurement. Good measurement practices should be employed to keep this connection reproducible and preserve the quality of the resulting data.

With the impedance-corrected 2X-Thru method defined in D.6.3, the de-embedded DUT is less sensitive to the discontinuity at the tip of the microprobe.

⁶ The numbers in brackets correspond to those of the bibliography in Annex A.

3.4 De-embedding method

There are a number of different S-parameter de-embedding methods used in the industry, a subset of which is discussed in this document. These de-embedding methods use different techniques to obtain the S-parameter of the fixture first, and then utilize a general procedure involving T-matrix (also called ABCD matrix) manipulation to recover the S-parameter of the DUT, as described in Frei, Cai, and Muller [B14].

Annex D details the following techniques:

- 1X-Reflect
- 2X-Thru
- Impedance-corrected 2X-Thru
- General S-parameter file

A de-embedding process generally involves the following steps:

- a) Connect calibration structures to end of coaxial cables from a vector network analyzer (VNA)
- b) Perform calibration on VNA with calibration structures
- c) Disconnect calibration structures and connect fixtures to VNA
- d) Acquire and verify s-parameter for the test fixtures
- e) Acquire and verify s-parameters for the DUT with attached test fixtures

De-embed fixture s-parameters and acquire and verify DUT S-parameters.

Notes:

- Steps d) and e) can be reversed in order.
- Refer to Annex D and Annex E for more details.

3.5 Normative header information in the Touchstone^{TM7} file

3.5.1 Introduction

S-parameter data shall be stored in the Touchstone file format defined in *Touchstone File Format Specification version 1.1* or *Touchstone File Format Specification version 2.0*. Subclause 3.5 defines the keywords and values that shall be included in the header of the Touchstone file in order to comply with this standard. Comment lines (a line preceded by a ! character) should be added to provide IEEE 370 compliance information. For IEEE 370-compliant Touchstone files, quantities contained in brackets between lines “! [IEEE 370 Start]” and “! [IEEE 370 End]” are normative keywords.

⁷ Touchstone is a registered trademark of Keysight Technologies.

3.5.2 Data source

This field indicates the source of the data. Types include the following:

- Measured
- Simulated
- Synthesized
- Other

3.5.3 Post-processing

This field specifies the type of post-processing that was applied to the data. Types include the following:

- Raw (no post-processing)
- De-embedded
- Other

3.5.4 Component type

This field indicates the type of the structure measured, calculated, or simulated. Types include the following:

- De-embedding structures
 - De-embed structure: 1X-Reflect-Short
 - De-embed structure: 1X-Reflect-Open
 - De-embed structure: 2X-Thru
- Calibration structures
 - Calibration structure: Short
 - Calibration structure: Open
 - Calibration structure: Load
 - Calibration structure: Primary Thru
 - Calibration structure: TRL Line 1
 - Calibration structure: TRL Line 2
 - Calibration structure: TRL Line <x>
- DUT
 - DUT: DUT
- Composite structures
 - Composite structure: Fixture-DUT-Fixture
 - Composite structure: Fixture-DUT
- Fixture
 - Fixture: Fixture

3.5.5 Calibration method

This field indicates the calibration method used to acquire the data. Types include the following:

- SOLT
- TRL
- User specific

3.5.6 De-embedding method

This field indicates the de-embedding method used to acquire the DUT data.

- 1X-Reflect
- 2X-Thru
- Impedance-corrected 2X-Thru
- Direct de-embedding with S-parameter file

3.5.7 Port assignment

Port assignment information shall be included in the Touchstone file to avoid misuse of S-parameters. The format of the port assignment information is informative, but should be easily interpreted by the user. Below is an example of port assignment information describing a four-port network from Pin 04 and Pin 05 of a Base Board to Pin 04 and Pin 05 of a Load Card:

```
!* BASE BOARD (end a) ->>- (end b) LOAD CARD *  
!* -----  
!* Port 01 (Pin 04) ->>- (Pin 04) Port 03  
!* Port 02 (Pin 05) ->>- (Pin 05) Port 04
```

3.5.8 Fixture electrical requirements

The fixture class, as defined in 4.3.3, shall be reported.

3.5.9 S-parameter quality metrics

In order to claim compliance with the requirements of this standard, the provider of the S-parameter data shall calculate the normative S-parameter metrics defined in Clause 7, and report the results in the comments in the Touchstone file header, along with the name and version of the tool used to generate them.

3.5.10 Touchstone file header reporting requirements summary

Table 2 summarizes the reporting requirements for the Touchstone file header.

Table 2—Touchstone file header reporting requirements

Item	Subclause	Normative?	Comments
Keywords	3.5.2 through 3.5.6	Yes	Keywords shall be included in the Touchstone header to define an overview of the de-embedding methods, data source, etc.
Fixture electrical requirements (FER) compliance	4.3.3	Yes	Fixture quality is defined in terms of a “Class.” This shall be computed and reported in the Touchstone header.
Quality metrics	7.4.3, 7.4.4, 7.4.5	Yes	The quality values for the S-parameters shall be computed and reported in the Touchstone header.
Port assignment	3.5.7	Yes. (Note: format is informative.)	The port assignment info shall be included, but the format is not normative.

3.5.11 Touchstone file header example

An example Touchstone file header is shown in Figure 5.

```

!This data was taken in accordance with the requirements defined in IEEE P370
!Date 4 June 2020
# GHz S MA R 50
! [IEEE-370 Start]

! [Number of Ports] 16
! [Number of Frequencies] 1601
! [Data Source] measured
! [Component Type] DUT
! [Calibration Method] SOLT
! [De-embedding method] Impedance corrected 2X-Thru
!
!The normative metrics defined in Clause 7 of IEEE Std 370-2020 are as follows:
!PQMa=1e-5V, RQMa=2e-6V, CQMa=1e-4mV.
!The open source Matlab code, https://gitlab.com/IEEE-SA/ElecChar/P370/-tree/v1.0.0-beta (version 1.0.0-
! beta), was used to compute these S-parameter quality metrics
!Please refer to IEEE Std 370-2020 for interpretation of these quality metrics.
!
!The test fixture achieved Class A compliance to 23 GHz, Class B compliance to 30 GHz and Class C
compliance to 50 GHz. Please refer to IEEE Std 370-2020 for interpretation of these classes.
!The physical length of the 2X-Thru cal. structure is 1100 mils
!
!The diagram/description below shows the port mapping of the S-parameter file to the DUT
!*****
!* MANUFACTURER = SAMTEC *
!* INTERCONNECT = BEC5-XXX-02-X-X-V-A + Load Card *
!* [Vertical Mount, 1.57 mm load card thickness] *
!* BOUNDARY = Boundary 2 *
!* [Mated Connector + PCB Footprint] *
!* *
!* SEQUENCE = **Important Note** - FOR ACCURATE RESULTS: *
!* end A represents the [Base Board] side *
!* end B represents the [Load Card] side *
!*
!* BASE BOARD (end a) ->>- (end b) LOAD CARD *
!* ----- *
!*
!* Port 01 (Pin 04) ->>- (Pin 04) Port 09 *
!* Port 02 (Pin 05) ->>- (Pin 05) Port 10 *
!* Port 03 (Pin 16) ->>- (Pin 16) Port 11 *
!* Port 04 (Pin 20) ->>- (Pin 20) Port 12 *
!* Port 05 (Pin 28) ->>- (Pin 28) Port 13 *
!* Port 06 (Pin 32) ->>- (Pin 32) Port 14 *
!* Port 07 (Pin 07) ->>- (Pin 07) Port 15 *
!* Port 08 (Pin 11) ->>- (Pin 11) Port 16 *
!* [IEEE-370 End]

```

Figure 5—Touchstone file header example

4. Test fixture design criteria

4.1 Overview

Clause 4 presents requirements, guidance, and best practices to enable successful test fixture design, including features and details for single-ended and differential fixture de-embedding. This includes the following:

- Fixture design requirements (FDR) for structures needed for de-embedding

- Fixture electrical requirements (FER) related to the electrical performance criteria for the structures
- Design considerations, such as critical design aspects and best practices
- A design documentation template for creating de-embedding structures
- Measurement guidance for making, verifying, and correlating measurements

4.2 Fixture design requirements (FDR) (normative)

4.2.1 Introduction

Subclause 4.2 describes the details to implement the required or recommended de-embedding test structures for the PCB test fixture de-embedding. The subclause also presents a series of validation structures that may be used to correlate measurement and simulation or tune the manufactured PCB parameters.

4.2.2 Single-ended de-embedding

Single-ended refers to individual uncoupled transmission lines including a signal conductor and its return path; de-embedding is the process of removing fixture effects from the measured S-parameters. A single-ended 2X-Thru standard is needed to create the fixture models; the following subclauses include the requirements for this standard. “X” is the structure between the reference plane and the DUT; i.e., TP1 to TP2 or TP3 to TP4, as illustrated in Figure E.1 and Figure E.2.

4.2.3 2X-Thru

The 2X-Thru de-embedding method (see Keysight Technologies [B22] and Annex D) bisects the data for the 2X-Thru to generate S-parameters of the test fixtures. This method has been shown to produce results that are equivalent or better than those obtained using TRL calibration (Moon, Ye, and Smith [B25]). The design of a 2X-Thru structure is illustrated in Figure 6. Bisection is achieved through several means described in Annex D.

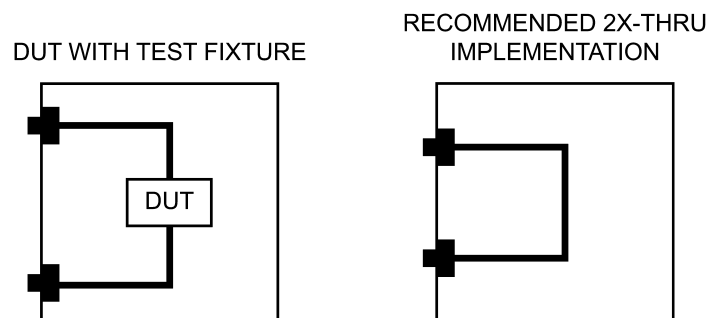


Figure 6—2X-Thru implementation

In order for the 2X-Thru to replicate the electrical behavior of the test fixture and allow accurate de-embedding of the fixture, the 2X-Thru shall meet the following requirements:

- The 2X-Thru should be fabricated on the same PCB as the test fixture.

- The 2X-Thru shall be routed on the same PCB layer as the test fixture traces.
- The 2X-Thru shall incorporate the same layer transitions and test point launch as the test fixture.
- With the measurement reference plane set at the coaxial test point, the insertion loss of the 2X-Thru shall meet the requirements of 4.3.4 for insertion loss.
- With the measurement reference plane set at the coaxial test point, the return loss of the 2X-Thru shall meet the requirements of 4.3.5 for return loss.

The 2X-Thru and test fixture traces should be oriented in the same direction on the PCB panel as illustrated in Figure 6.

4.2.4 Mixed-mode de-embedding

The 2X-Thru method described in 4.2.3 is applicable to mixed-mode (differential) de-embedding structures as well, except that differential ports are used instead of single-ended ports.

However, differential transmission lines that have intentional coupling require additional design considerations. For example, test fixture traces for differential de-embedding have areas that are transitioning from single-ended to differential routing due to the physical size of the coaxial connectors or probing footprint. Ensure that the transition from a single-ended to coupled transmission line does not cause large return loss that may degrade de-embedded results. This issue is addressed in 6.4.

4.2.5 Single-ended fixture crosstalk

Fixture crosstalk may remain in the measured data after calibrating or de-embedding, and measured crosstalk can be larger than DUT crosstalk. If crosstalk is a parameter to be measured and the fixture crosstalk cannot be de-embedded, a “dogleg” structure shall be included in the fixture to measure the trace-to-trace fixture crosstalk directly. Those results should then be compared against the total measured crosstalk to determine whether the fixture crosstalk is large enough to compromise the results. A dogleg structure for measuring trace-to-trace crosstalk is designed as follows (see Moon et al. “Fixture” [B24]):

- Pick one pair of traces in close proximity, the worst case (smallest spacing).
- If the input and output side traces are on the same wiring plane, remove the DUT portion of the test board design and connect the traces together, as shown in Figure 8. If the input and output side traces are not on the same routing layer, copy the input side traces and mirror them to create the output side traces for the first layer, and connect them directly to the input side traces. Then copy the output side traces from the second layer to create the input side traces for the second layer, and connect them directly together. This will create two dogleg structures.
- Construct the trace lengths of the dogleg to be the same as the 2X-Thru length. Terminate all unused ports with 50 Ohm loads when measuring crosstalk. For example, when the far end crosstalk (FEXT) is measured from P1 to P2', terminate ports P2 and P1'.

Terminate all unused ports when measuring crosstalk.

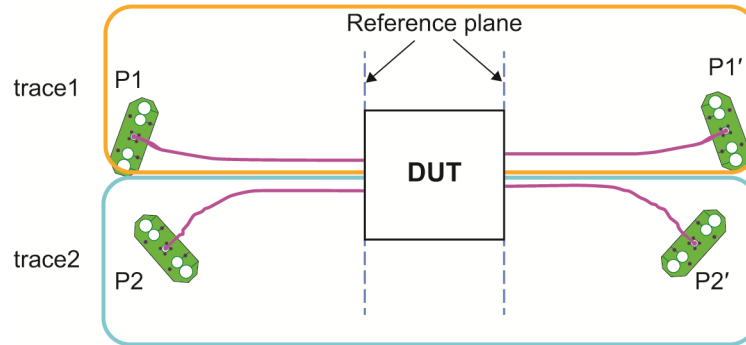


Figure 7—Single-ended test board layout

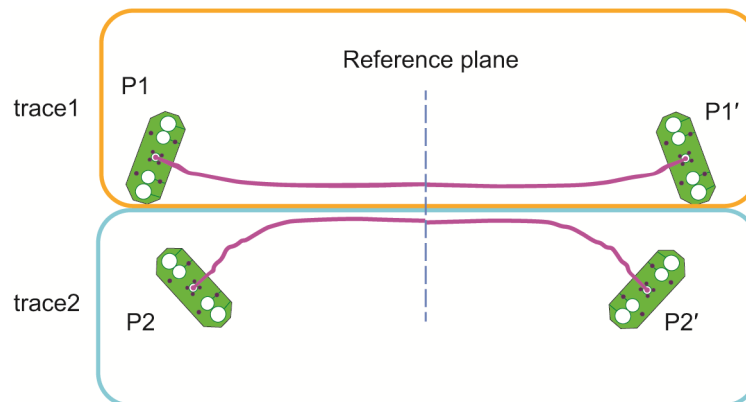


Figure 8—Single-ended dogleg structure

4.2.6 Interpair (pair to pair) fixture crosstalk

As in the single-ended case, the interpair fixture crosstalk of a mixed-mode fixture may remain in the measured data after calibrating or de-embedding, and measured crosstalk can be larger than the DUT crosstalk. The topology of a typical mixed-mode test fixture is shown in Figure 9. If crosstalk is a parameter to be measured, and the interpair fixture crosstalk cannot be de-embedded, a “spiderleg” structure (see Moon et al. “Fixture” [B24]) shall be included in the fixture to measure the interpair crosstalk. It is also required for measurement of the common-mode conversion of the fixture. A spiderleg structure is illustrated in Figure 10. It consists of four traces and eight ports. To design a spiderleg structure:

- Pick two pairs in close proximity.
- Remove the DUT portion of the test board design within the reference planes, copy the traces exactly, and connect the Thru traces directly, as described in 4.2.5 (see Figure 10).

Terminate all unused ports when measuring crosstalk.

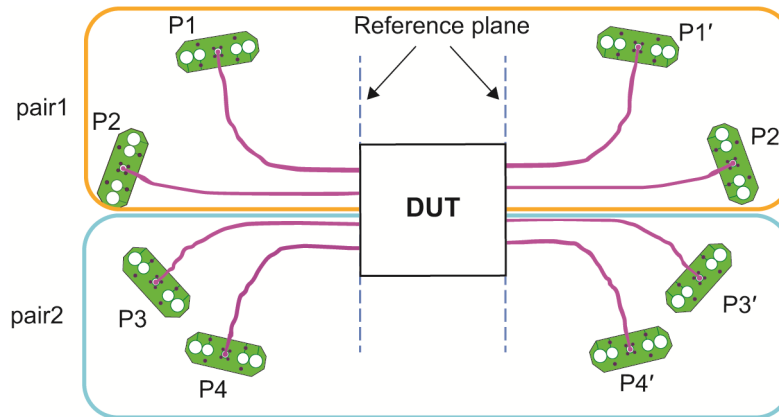


Figure 9—Mixed-mode test board layout

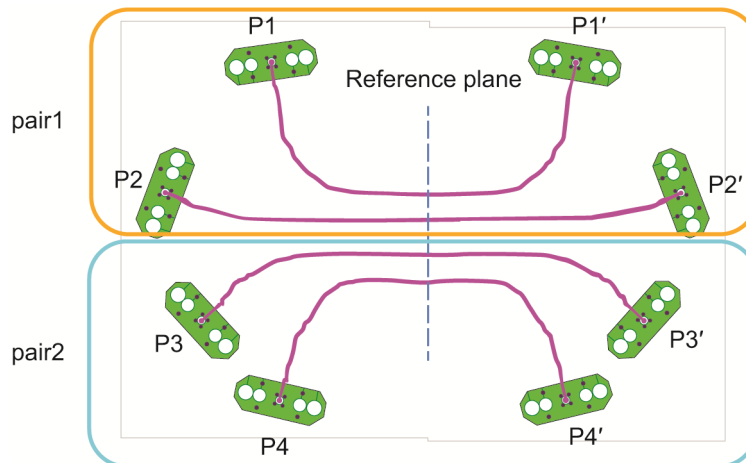


Figure 10—Spiderleg structure of mixed-mode 2X-Thru with fixture crosstalk included

4.3 Fixture electrical requirements (FER)

4.3.1 Introduction

As a fixture deviates from a perfect lossless transmission line, removing the effects of the fixture becomes more difficult. Subclause 4.3 places limitations on how much a fixture may deviate from ideal based on how well contemporary techniques remove the non-ideal characteristics.

4.3.2 Class definitions

The test fixture performance is identified by Class A, B, or C. Class A has the most stringent design requirements, and Class C has the least stringent. Obtaining the best possible data from a Class C fixture will require the use of the most sophisticated de-embedding tool available, such as the impedance-corrected 2X-Thru method. On the other hand, a less sophisticated de-embedding technique may be sufficient for use with a Class A or Class B fixture.

4.3.3 FER compliance

The class of a fixture may vary by frequency and DUT performance. For example, a fixture measured from 10 MHz to 50 GHz with 10 MHz steps may fail a Class A requirement at 10 GHz and fail a Class B requirement at 40 GHz, and fail a Class C requirement at 50 GHz. That fixture is deemed Class A compliant for frequencies below 10 GHz, Class B for frequencies below 40 GHz, and Class C for frequencies below 50 GHz. A fixture is deemed non-conforming for all frequencies higher than the frequency of its first class C failure.

Throughout this document, insertion loss is expressed as a negative value in dB, to specify the amount of attenuation.

4.3.4 FER1: Insertion loss of 2X-Thru

- Class A minimum: -10 dB at all frequencies of interest
- Class B minimum: -15 dB at all frequencies of interest
- Class C minimum: -15 dB at all frequencies of interest

Justification: As fixture insertion loss increases, de-embedding becomes more unreliable and unstable.

4.3.5 FER2: Return loss of 2X-Thru

- Class A maximum: -20 dB at all frequencies of interest
- Class B maximum: -10 dB at all frequencies of interest
- Class C maximum: -6 dB at all frequencies of interest

Justification: Return loss values of fixtures above this value result in unreliable calibration or removal. This specification is for single-ended, differential, and common-mode return loss.

4.3.6 FER3: Insertion loss and return loss separation

- Class A minimum: 5 dB at all frequencies of interest
- Class B minimum: 0 dB at all frequencies of interest
- Class C minimum: 0 dB at all frequencies of interest

Justification: There is a relationship between insertion-return loss separation and quality of de-embedding.

4.3.7 FER4: Intra-fixture crosstalk

Class A, B, and C maximum fixture crosstalk is lower than that of the DUT at all frequencies of interest.

Justification: For cases when fixture crosstalk is not negligible, and the de-embedding algorithms to be used cannot remove it, the fixture crosstalk shall be measured and compared to the DUT crosstalk to evaluate whether or not it will compromise the de-embedded results.

4.3.8 FER5: Impedance variation: Difference between the FIX in 2X-Thru and the FIX-DUT-FIX

Measure the point-by-point difference between the impedance of the 2X-Thru and the impedance of the FIX-DUT-FIX from the start of the fixture to the time of the midpoint of the 2X-Thru, using a 20% to 80% rise time of $1/f_{\max}$ with a Gaussian edge, as defined in Annex S.

- Class A maximum: $\pm 2.5\%$ difference from the reference impedance
- Class B maximum: $\pm 5\%$ difference from the reference impedance
- Class C maximum: $\pm 10\%$ difference from the reference impedance

This measurement shall be done from both ends of the fixture. Refer to Figure 11.

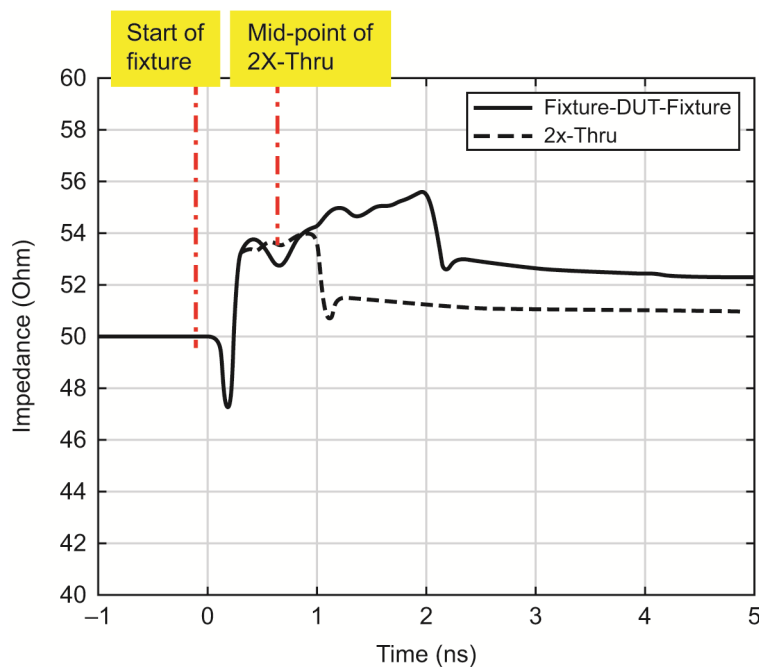


Figure 11—Idealized impedance plots of the 2X-Thru and FIX-DUT-FIX

Justification: Post-de-embedding broadband error occurs in the reflection coefficient when the transmission line of the DUT test fixture deviates beyond the specified limit of the standard transmission line.

4.3.9 FER6: Difference between differential to common mode conversion loss and insertion loss

Class A, B, and C maximum: The difference between differential to common-mode conversion and insertion loss is lower than -15 dB at all frequencies of interest. Justification: Differential to common-mode conversion (S_{CD21}) represents the imbalance within a differential pair. Typical mixed-mode de-embedding techniques assume negligible S_{CD21} . In that case, any difference between differential to common-mode conversion loss and insertion loss higher than the specified value may result in significant error. Note that the requirement does not apply to de-embedding methods that take mode conversion into account (which should be verified by user).

4.3.10 FER7: Line to line or pair to pair phase skew

In some fixture designs, a single 2X-Thru structure may be used to de-embed multiple DUT input/output signal lines (single-ended or differential). For accurate de-embedding, it is necessary to keep all FIX structures identical with respect to the corresponding FIX structure in the 2X-Thru. However, it is challenging to validate after the board is manufactured, since a direct measurement of the FIX-only structure is not feasible for the FIX-DUT-FIX structure. Therefore, it is critical to ensure that at the board layout stage, the lead-in routing lengths for all the FIX structures in FIX-DUT-FIX are the same. The difference in phase delay (time-domain skew) of the lead-in traces or pairs should be no more than 2 ps for all fixture classes.

4.3.11 FER8: Minimum length of 2X-Thru

The 2X-Thru de-embedding method often uses a fast Fourier transform (FFT) to convert frequency domain S-Parameters into a time-domain reflectometry (TDR)/time-domain transmissometry (TDT) waveform. In order to have enough resolution, the length of the 2X-Thru should be at least three wavelengths at the highest measured frequency. For a 50 GHz maximum frequency, this corresponds to 60 ps minimum electrical length (which is 0.9 cm in PCB stripline with $D_k = 4$) for the 2X-Thru. For a 20 GHz maximum frequency, this corresponds to 150 ps minimum electrical length (which is 2.25 cm in PCB stripline with $D_k = 4$) for the 2X-Thru.

4.3.12 FER summary

Table 3 summarizes the fixture electrical requirements found in the previous subclauses for single-ended applications. Measurement methods for these parameters are beyond the scope of this document. For details, refer to Barnes et al. (“S-Parameter” [B3]).

Table 3—Fixture electrical requirement summary for single-ended interconnects

Metric	Structure	Equation	Class A limit	Class B limit	Class C limit
Insertion loss (FER1)	2X-Thru	$20 \times \log_{10} S_{21} $	−10 dB	−15 dB	−15 dB
Return loss (FER2)	2X-Thru	$20 \times \log_{10} S_{11} $	−20 dB	−10 dB	−6 dB
Difference between insertion and return loss (FER3)	2X-Thru	$20 \times \log_{10} S_{21} $ $-20 \times \log_{10} S_{11} $	5 dB	0 dB	0 dB
Fixture crosstalk (FER4)	Dogleg structure; see 4.2.5	$20 \times \log_{10} S_{xy} $, where y is the aggressor port number, and x is the victim port number. In the case in which two dogleg structures (A and B) are needed, the equation becomes $20 \times \log_{10} \frac{ S_{xy} _A + S_{xy} _B}{2}$	FIX-FIX crosstalk shall be 6 dB lower than measured FIX-DUT–FIX crosstalk.		
Fixture impedance variation ^a (FER5)	All	Difference in impedance between the 2X-Thru and FIX-DUT-FIX curves in the Fixture region; see Figure 11.	±2.5%	±5%	±10%
Line to line skew (FER7)	All DUT traces	N/A	$1/(10 \times f_{\max})$ ps ^b	$1/(10 \times f_{\max})$ ps	$1/(10 \times f_{\max})$ ps
Minimum length of 2X-Thru (FER8)	2X-Thru	N/A	Three wavelengths at highest measured frequency	Three wavelengths at highest measured frequency	Three wavelengths at highest measured frequency

^a Apply this equation to the example Gaussian step response defined by Annex S.

^b $f_{\max}$ is the maximum frequency of interest.

Table 4 summarizes the fixture electrical requirements found in the previous subclauses for mixed-mode applications.

Table 4—Fixture electrical requirement summary for mixed-mode interconnects

Metric	Structure	Equation	Class A limit	Class B limit	Class C limit
Insertion loss (FER1)	2X-Thru	$20 \times \log_{10} S_{DD21} $	−10 dB	−15 dB	−15 dB
Return loss (FER2)	2X-Thru	$20 \times \log_{10} S_{DD11} $	−20 dB	−10 dB	−6 dB
Difference between insertion and return loss (FER3)	2X-Thru	$20 \times \log_{10} S_{DD21} $ $-20 \times \log_{10} S_{DD11} $	5 dB	0 dB	0 dB
Fixture crosstalk (FER4)	Spiderleg structure; see 4.2.6	$20 \times \log_{10} S_{DDxy} $, where y is the aggressor port number, and x is the victim port number. In the case in which two spiderleg structures (A and B) are needed, the equation becomes $20 \times \log_{10} \frac{ S_{ddxy} _A + S_{ddxy} _B}{2}$	FIX-FIX crosstalk shall be 6 dB lower than measured FIX-DUT–FIX crosstalk		
Fixture impedance variation ^a (FER5)	All	Difference in impedance between the 2X-Thru and FIX-DUT-FIX curves in the Fixture region; see Figure 11.	±2.5%	±5%	±10%
Difference between differential to common-mode conversion loss and insertion loss ^b (FER6)	Spiderleg structure; see 4.2.6	$20 \times \log_{10} S_{CD21} $ $-20 \times \log_{10} S_{DD21} $	−15 dB	−15 dB	−15 dB
Line to line or pair to pair skew (FER7)	All DUT traces/pairs	N/A	$1/(10 \times f_{\max})$ ps ^c	$1/(10 \times f_{\max})$ ps	$1/(10 \times f_{\max})$ ps
Minimum length of 2X-Thru (FER8)	2X-Thru	N/A	Three wavelengths at highest measured frequency	Three wavelengths at highest measured frequency	Three wavelengths at highest measured frequency

^a Apply this equation to the Gaussian step response defined by Annex S.

^b This metric is for mixed-mode de-embedding only.

^c $f_{\max}$ is the maximum frequency of interest.

Table 4 addresses the FER limit when a differential excitation is applied. For cases when the primary excitation is common mode, the FER limits are not defined at this time.

4.4 Design documentation

Thorough and accurate documentation of any test fixture design is necessary to ensure good quality measurement results. This subclause outlines the documentation necessary for a successful design. The following information should be specified for the test fixture in as much detail as possible:

- The PCB test fixture part number, manufacturing date, and a unique identification number of the PCB test fixture. If the document is intended to address multiple test fixtures, it needs to explicitly state which PCB test fixture identification number was used on the presented data.

- The VNA instrument and calibration kit manufacturer and model number, calibration date for the VNA and calibration kit, and the cable manufacturer and model number(s) used for the acquired measurements.
- The IF bandwidth used, number of points, and whether averaging or smoothing were used.
- Description of the DUT to be used with the PCB test fixture.
- The trace geometry, trace length, dielectric material, PCB cross-section (stackup), vias, and backdrilling, if used.
- The launch connector(s) used on the board, including manufacturer, part number, number of guaranteed matings, and bandwidth specification.
- Measurements of the insertion and return loss of the 2X-Thru standard. Plot the data on a single graph indicating the exact frequency supported by the test fixture based on the standard requirements.
- The S-parameter quality metrics per Clause 7.
- TDR plot of the 2X-Thru path using the step response in Annex S.
- Measured results for any available verification structures; e.g., line or Beatty structure (see Barnes, Schaefer, and Moreira [B5] and Annex F.1).

5. De-embedding verification

5.1 Introduction

The purpose of de-embedding verification is to measure and report the absolute accuracy of the de-embedding tool. The accuracy is measured by comparing the result of the tool with a known result. There are three kinds of known results:

- Option 1: Using synthesized DUT and fixture models based on simulated values
- Option 2: Using separately measured fixture and DUT S-parameters from special test structures
- Option 3: Using the measurements from an evaluation board

Using synthesized S-parameter models tests the absolute accuracy of the de-embed tool limited by numerical simulation noise. Using a separately measured set of fixture and DUT boards tests the accuracy of the measurement process and the de-embedding tool to the accuracy of the real world measurement process. Using an evaluation board tests the de-embedding tool, the measurement process, and the manufacturing variations of typical boards. These tests are recommended as a standard process to verify the accuracy of a de-embedding tool and process.

5.2 Overview

5.2.1 Introduction

Verification of the accuracy of the process of de-embedding the fixture(s) from measured and simulated data has three aspects:

- Verification of the accuracy of the de-embedding software tool. This is accomplished through the use of S-parameters for the composite FIX-DUT-FIX and 2X-Thru FIX-FIX calculated using a numerical simulator, the results from which are compared to the de-embedded results.
- Verification of the agreement between the de-embedded DUT model and the measured data of the DUT alone. This second type of verification test applies to the combination of a measurement process and a de-embedding tool. This method utilizes specially designed and fabricated circuit boards with coaxial connectors that allow the boards to be measured separately and then in combination to create composite FIX-DUT-FIX structures and 2X-Thru FIX-FIX structures. In this way the embedded DUT can be measured directly and the results of this measurement compared to the de-embedded DUT S-parameters to verify the measurement and de-embedding process.
- Verification of the accuracy of the de-embedded data across the manufacturing process variations under which a number of tested samples were made. This involves fabricating various structures on an evaluation board to test the reproducibility of the same structure repeated with different fixture features.

These three aspects are described in more detail in the following clauses.

5.2.2 Option 1 analysis: Synthesized libraries

Option 1 analysis verifies the de-embedding algorithm using synthesized S-parameter reference files. These S-parameter files are synthesized using field solver and circuit simulator tools. Files are supplied from both electromagnetic tools and open source simulation tools, the models for which any user can customize. Those files are available for download from <http://standards.ieee.org/downloads/>.⁸

Both simulated fixture and DUT files are provided with a variety of features to allow for testing the effects of different de-embedding scenarios. Combinations of composite FIX-DUT-FIX and 2X-Thru FIX-FIX structures can be composed by concatenating the individual S-parameter blocks. The de-embedding algorithm can be used to extract the DUT S-parameters, and these extracted values can be compared with the “correct” answer: the original DUT S-parameters.

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5.2.3 Option 2 analysis: Plug-and-play boards

Option 2 analysis verifies the measurement technique and the de-embedding algorithm using fabricated boards with coaxial connectors that are separately measurable. In this plug-and-play approach, each of the fixture and DUT boards is measured directly without any de-embedding. These board elements can be connected like building blocks as composite FIX-DUT-FIX or as 2X-Thru FIX-FIX configurations and measured. These boards, which are described in Barnes et al. ("A NIST" [B4]), are referred to as plug-and-play boards.

These measurements can be used with a de-embedding algorithm to de-embed the DUT to compare with the direct measurement. This approach verifies the general measurement technique and uses these measurements to de-embed the DUT. However, this approach is applied to these specific board measurements only.

5.2.4 Option 3 analysis: Demonstration boards

Option 3 analysis demonstrates a methodology using a test board with nominally the same DUT replicated over the surface of the board, with various fixture structures surrounding it. An example test board that can be used with this technique is described in 5.5. It is designed for testing with both micro probes and surface mount coaxial connectors.

Fixture combinations configured as 2X-Thru FIX-FIX structures are available across the board to provide a reference for use in de-embedding. The values of the various de-embedded DUT values can be compared as a rough measure of what might be expected in a typical manufactured test board process.

The variation between the different extracted DUT structures represents the combination of measurement variation, de-embedding tool accuracy, and manufacturing variation across the surface of the board. This is a practical example that illustrates the trends to be expected as the quality of the fixture degrades or insertion and return loss exceeds that of the DUT.

5.3 Option 1: De-embedding verification using the S-parameter library

5.3.1 Purpose

The purpose of this process is fourfold. First, it tests the absolute accuracy of the de-embedding algorithm. By using synthesized S-parameter models, the de-embedded DUT model should be compared with the starting DUT model. This is an absolute test of any de-embedding process.

Second, it is possible to use a variety of fixture models in the 2X-Thru reference structures and the same ones in the FIX-DUT-FIX structures. These may span the range of recommended fixture design specifications to violating the recommended fixture design specifications. This will test the robustness of a de-embedding process for conforming and non-conforming fixtures.

Third, it's possible to use a fixture model in the de-embedding algorithm that is different from the fixture attached to the DUT in the FIX-DUT-FIX structure. By controlling the differences, such as in impedance, loss, crosstalk, or delay, the sensitivity of the de-embedding process to possible manufacturing variations can be quantified.

Finally, the impact from manufacturing variation on the de-embedded DUT model can be quantified to set realistic expectations. By using corner cases in the ideal fixture models, the variation in the extracted DUT model can be established.

To increase the usefulness of this process, select or synthesize ideal fixture and DUT models that closely match the specific application. Two approaches are presented to synthesize the S-parameter models:

- Use 2D and 3D electromagnetic field solvers to generate the models for the fixtures, DUTs, and composite structures.
- Use simple circuit models simulated with a circuit simulator for all the S-parameter data.

5.3.2 Testing a de-embedding process with S-parameter library (approach 1)

A library of S-parameter files is available for download from <http://standards.ieee.org/downloads/> as reference structures for testing a de-embedding algorithm. The process of using the S-parameter library to test the de-embedding algorithm is described in Annex N. The library consists of three types of elements:

- Launches
- Uniform transmission lines from launches to DUT structures
- DUT structures

The user can mix and match any combination of elements, like building block elements, to build fixtures, FIX-FIX, and FIX-DUT-FIX structures.

A perfect de-embedding process results in an extracted DUT S-parameter that is exactly the same as the starting DUT model. A difference between the de-embedded DUT and the original DUT may indicate a non-optimal de-embedding process.

Subclause 6.6 outlines a method for quantifying the similarity between two S-parameters for the de-embedded DUT and the original DUT. This similarity metric shall be reported as a measure of the quality of the de-embedding algorithm.

There are two sources of ideal S-parameter library elements. One source of library elements has been synthesized from a combination of 2D and 3D full-wave electromagnetic field solvers. Another source is library elements synthesized from an open source, freely available circuit simulator, such as the Quite Universal Circuit Simulator (QUCS) discussed below.

The simulated S-parameters of all structures were synthesized based on a typical eight layer board stackup using low loss dielectric material. The details for this library of elements are in Annex P.

The three elements are created on various layers, and should be cascaded together to create composite FIX-DUT-FIX structures, such as shown in Figure 12.

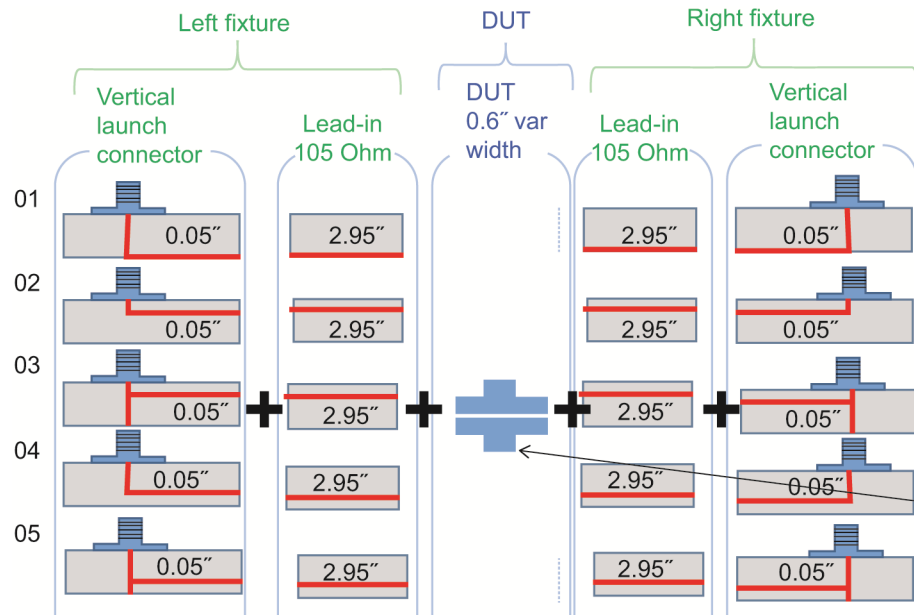


Figure 12—Example of a composite structure synthesized with combinations of the three building block elements

Launches are designed as coaxial, vertically launched connectors (VLC) from the top layer to some inner layer of the board. Surrounding the signal via are four return vias connecting all the planes in parallel, as shown in Annex J.

An example of the simulated output from a 2X-Thru FIX-FIX and the composite FIX-DUT-FIX for the case of a single-ended synthesized structure from this library is shown in Figure 13.

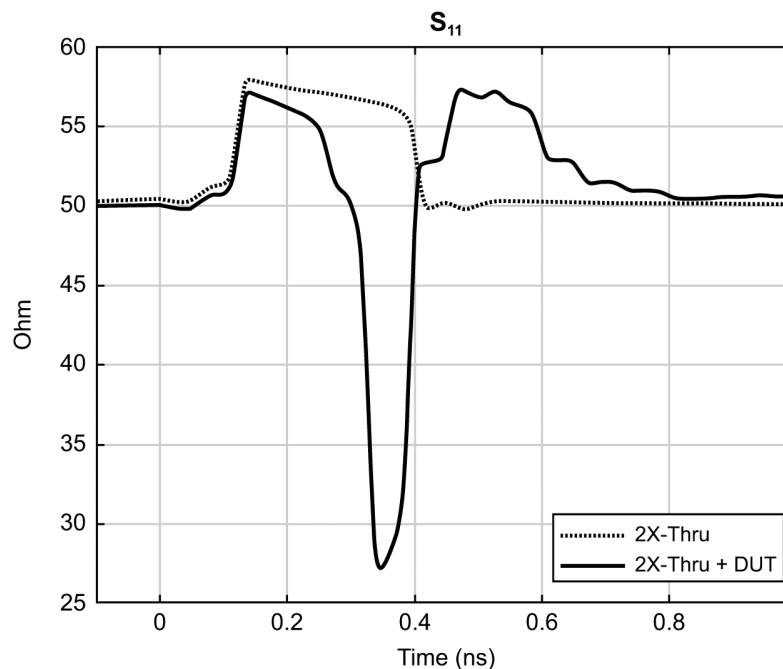


Figure 13—Example of simulated data from the S-parameter library that can be used to evaluate a de-embedding algorithm

Using the 2X-Thru simulated model, the DUT should be de-embedded from the composite structure using a candidate tool and the original and de-embedded DUT responses compared. An example is shown in Figure 14.

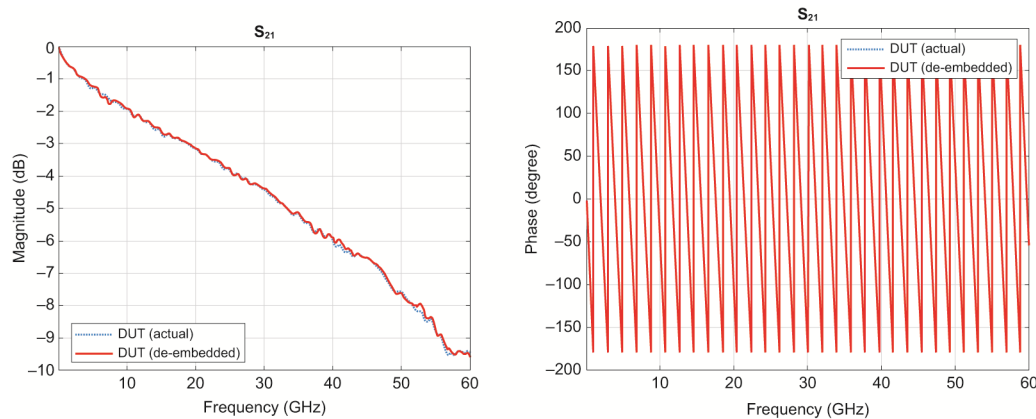


Figure 14—Comparison of the de-embedded DUT with the actual DUT for the SDD21 term from the S-parameter library

5.3.3 Testing a de-embedding algorithm with S-parameter library (approach 2)

Another source of S-parameter data for reference structures is by use of an open source simulation tool, such as QUCS. This tool, which is available at <http://qucs.sourceforge.net/>, can generate S-parameter library elements as .s2p and .s4p files. The generating circuit files are available for download at <http://standards.ieee.org/downloads/> so users can customize their own examples. Each of the three structures, VLC, transmission lines, and DUT can be synthesized from parameterized models. Figure 15 shows an example of the complete simulation environment (circuit schematic and results plot) for single-ended (SE)-VLC with lead-in structures.

NOTE—These S-parameter data can be exported and used in any combination to create a variety of FIX-DUT-FIX structures.⁹

⁹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

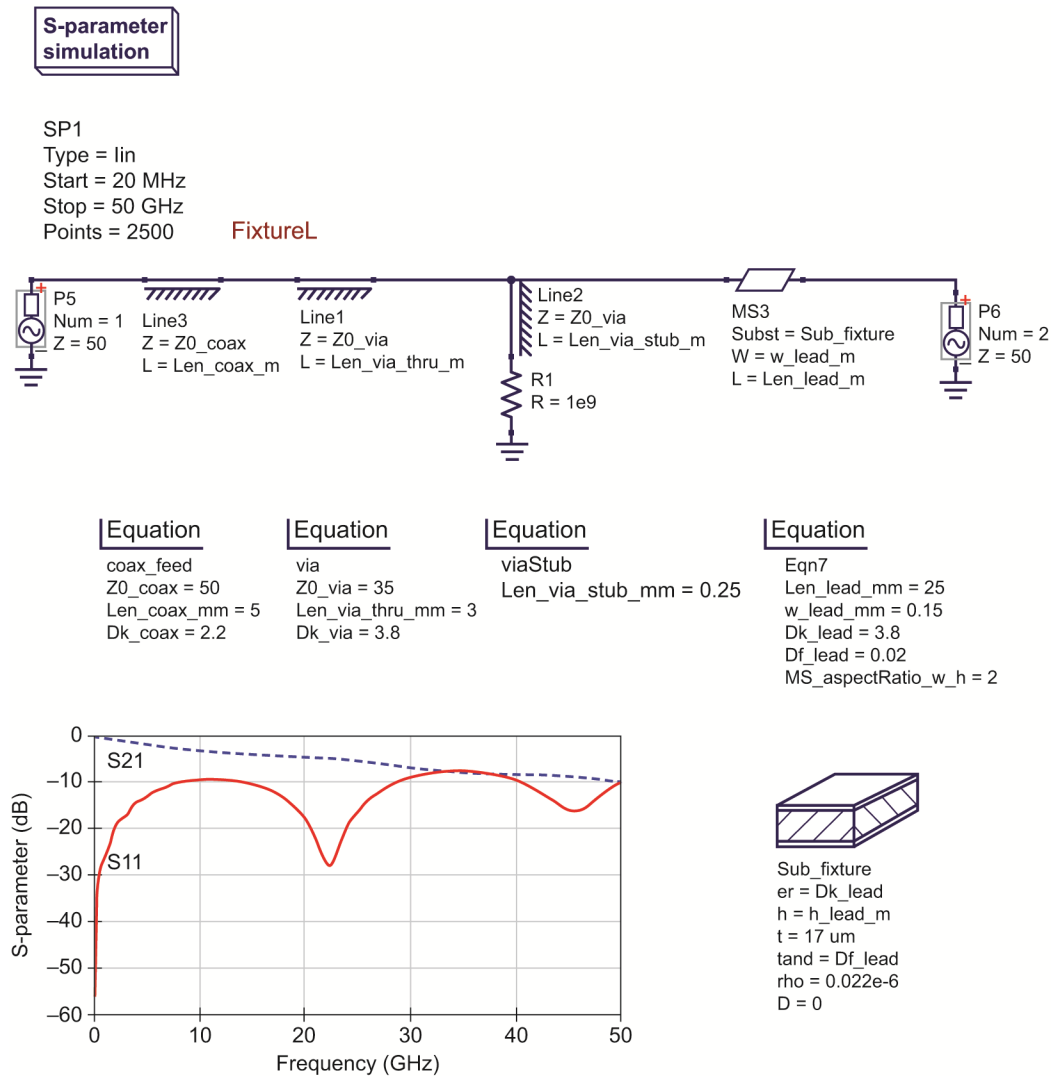


Figure 15—Example of the simulation environment for SE-VLC structures

In addition to using QUCS as a simulation environment to synthesize any fixture or DUT structure, QUCS can also be used as an environment to concatenate many circuit elements or even S-parameter files to create a single .s2p or .s4p file to emulate a 2X-Thru or FIX-DUT-FIX structure. Figure 16 shows an example of a circuit environment that creates a FIX-DUT-FIX model.

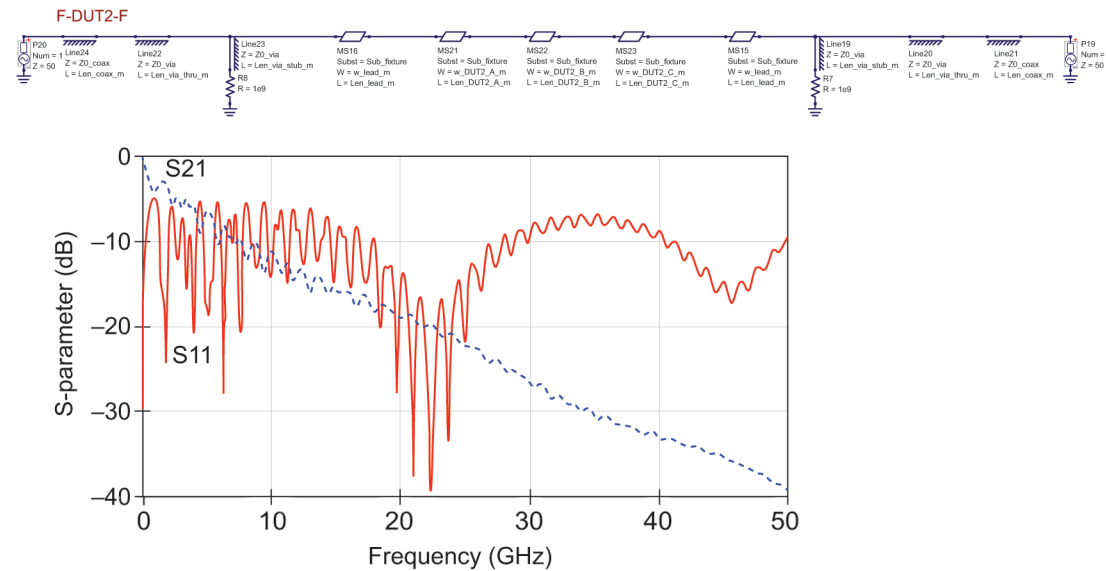


Figure 16—Example of a circuit that cascades S-parameter files into one composite structure

These S-parameter data can be used to test the de-embed algorithm in the same way as the library elements generated from the 2D and 3D simulation tools. One additional feature of the QUCS model is the opportunity for the user to synthesize specific models to emulate the features close to the specific application they want to test.

5.4 Option 2: De-embedding verification using separately measurable component test board measurements (plug-and-play modules)

5.4.1 Overview

This process uses specially designed and fabricated test boards that can be separately measured, connected together, and re-measured as composite structures. From the measured composite structure and fixture reference structures, the DUT is de-embedded. This DUT model can be compared with the measured DUT model.

In Figure 17, the three different board elements—FIX-A, FIX-B, and DUT—that make up a measurement are illustrated.