IEEE P370: A fixture design and data quality metric standard for interconnects up to 50 GHz

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Abstract

Most high frequency instruments such as Vector Network Analyzers (VNAs) and Time Domain Reflectometers (TDRs) can make very good measurements at the end of a coaxial interface. However, interconnects used in complex systems rarely have coaxial interfaces. The design and implementation of the fixtures used to characterize these devices can have a significant influence on the measured data, and therefore the observed characteristics of the Device Under Test (DUT). The extent of these influences can potentially corrupt the measured data in ways that are not necessarily obvious to the user. Hence some method is needed to ascertain the quality and usability of the measured data. The P370 standard committee was chartered with the task of solving these problems for measurement of interconnects up to 50 GHz.

The P370 committee is comprised of approximately 60 members from 25 companies and universities. It has three task groups: Test Fixture Design Criteria, De-embedding Verification, and S-parameter Integrity and Validation. Task Group 1 is drafting guidelines for fixture design to ensure that devices measured with fixtures meeting the design criteria will produce accurate measurement data for the DUT after removing ("de-embedding") the fixture effects. A design kit of reference structures has been designed and built for use in this process, and extensive measurements have been taken. TG1 has also published a sample software tool for performing the de-embedding process. Task Group 2 has developed an S-parameter library for the various structures, is working on the verification process for the de-embedded data when compared to the library data. Error data have been generated and evaluated. Task Group 3 is working on metrics and software tools for checking the integrity of the S-parameter data, including passivity, causality, and reciprocity. This paper will provide a preview of the fixture design guidelines, reference structures, de-embedding techniques, and S parameter quality metrics and validation methods that is being developed as part of the P370 standard.

Major test equipment manufacturers and universities have participated in the committee's work to date. The committee is making good progress, and the draft specification is currently in review. The target date for the draft to be ready for ballot vote in early 2019. Note that since the P370 standard is still an unapproved draft, any material included from it in this paper is subject to change.

Test Fixture Design Criteria

The quality of the measured data for a given fixture is highly dependent on the design of the fixture. The P370 standard establishes requirements for both the structures included in the fixture design and their electrical characteristics. The following structures are included in the draft standard:

1. A 2x thru structure as shown in Figure 1 is required for measurement of fixture insertion loss and return loss.

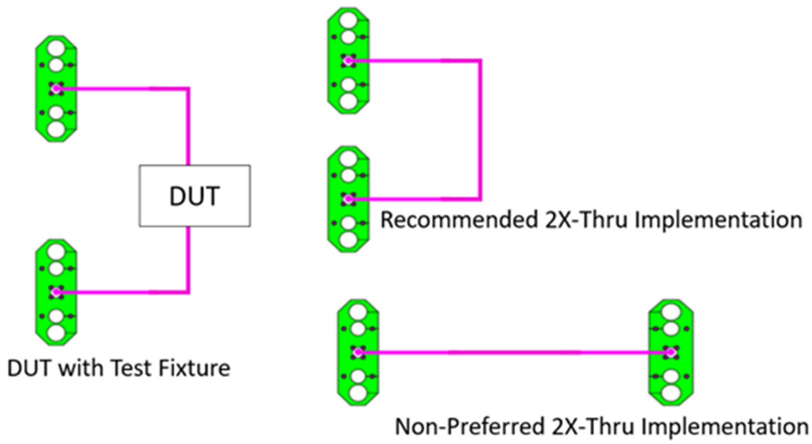


Figure 1. 2x thru structure for measuring fixture insertion loss

There are a number of proposed requirements for the 2x thru structure that are intended to ensure usable, accurate measurements from this structure:

- 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 in Table 1.

Fixture Class	Minimum 2x thru insertion loss, dB
A	-10
B	-15
C	-15

Table 1. Minimum insertion loss for the 2x thru, by fixture class

2. A "dog leg" structure as shown in Figure 2Figure is required for measurement of fixture crosstalk in the case of a single-ended DUT. The purpose of these structures is to quantify the crosstalk induced by the test fixture, which is typically not considered in most de-embedding tools.

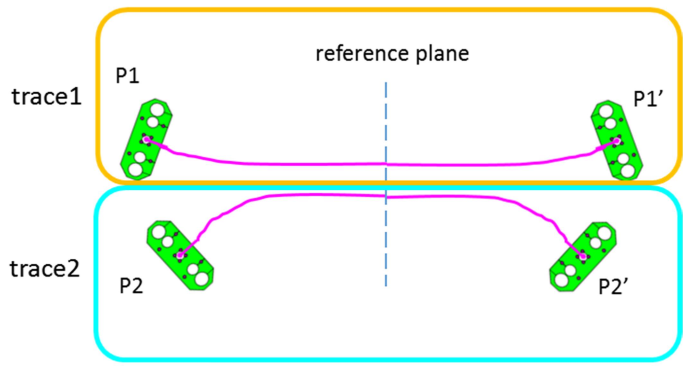


Figure 2. “Dogleg” structure for measuring single-ended fixture crosstalk

3. For differential DUTs, the “spiderleg” structure shown in Figure 3 is used.

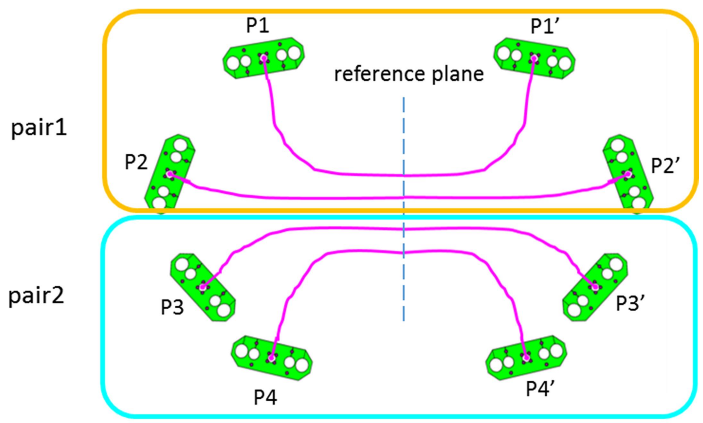


Figure 3. “Spiderleg” structure for measuring fixture crosstalk for differential DUTs

4. An optional 1x reflect (Open or Short) structure as shown in Figure 4 is needed when the 1x-reflect algorithm is used for de-embedding. This is not the recommended algorithm when the 2x-thru is available. Therefore, it is just an informative specification, when a 2x-thru structure cannot be constructed in certain applications.

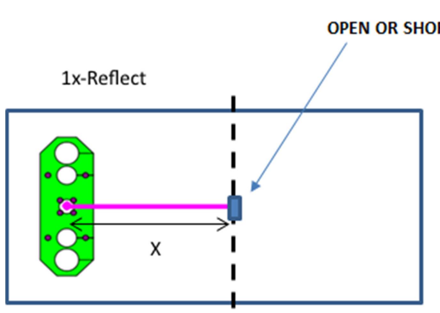


Figure 4. 1x reflect structure for fixture calibration

Verification Structures

Two structures are recommended to be included on PCB-based test fixtures to provide the data needed for verification of fixture de-embedding. These are the Line and Beatty structures. The line structure provides a qualitative approach to verify the de-embedding results, as the S-parameter of de-embedded line structure should follow the ideal behavior of a transmission line. The Beatty structure, described in [2] and shown in Figure 5, is a resonant network that provides insight into the fabrication process as well as the quality of the calibration. The increased line width creates a large low impedance discontinuity and a standing wave with resonances at frequencies defined by equation 1.

$$f = \frac{N \times c}{4L\sqrt{\varepsilon_r}}\ , N \epsilon \ \{1, 2, 3, \dots\} \qquad [1]$$

where
c is the speed of light,
L is the length 2X as shown in **Error! Reference source not found.**,
ε_r is the effective dielectric constant (DK) of the PCB material

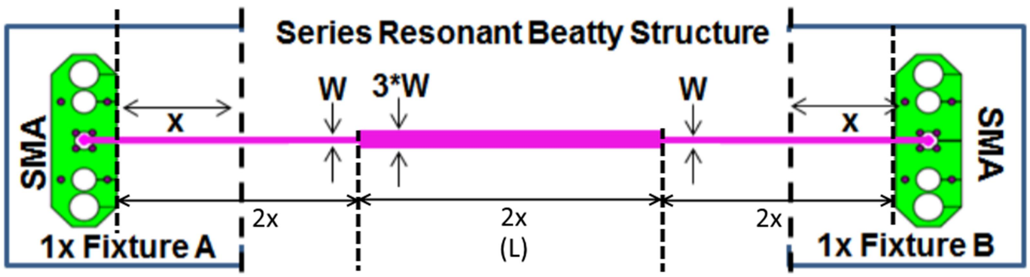


Figure 5. Physical design of a resonant Beatty structure

The insertion and return loss characteristics of such a structure are shown in Figure 6.

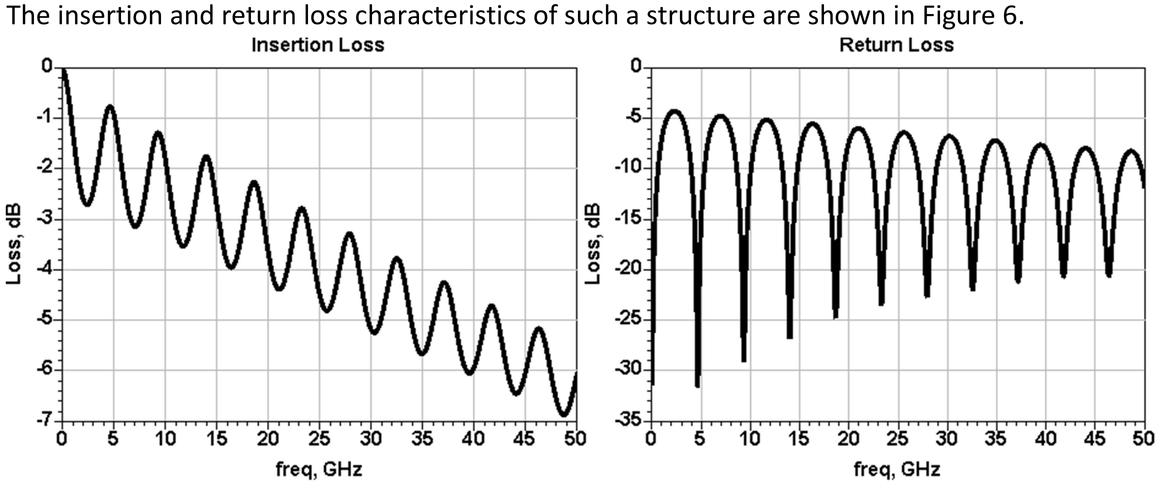


Figure 6. Insertion and return loss of a resonant Beatty structure

Fixture Electrical Requirements

The P370 standard proposes a number of requirements on the electrical performance of the fixtures described. The concept of compliance “Classes” is introduced. These Classes represent the quality of the electrical performance of a fixture relative to an ideal, or relative to the characteristics of the DUT. Fixtures with good electrical performance will result in better de-embedded DUT data than fixtures with poor electrical performance. Performance parameters included in the class definition include insertion loss, return loss, insertion and return loss separation, crosstalk, and differential to common mode conversion (in the case of a differential fixture). Table 2 summarizes the class definitions.

Performance metric	Class A limit	Class B limit	Class C limit	Comment
Insertion loss	-10 dB	-15 dB	-15 dB	
Return loss	-20 dB	-10 dB	-6 dB	
Insertion and return loss separation	5 dB	0 dB	0 dB	
Impedance variation	±2.5%	±5%	±10%	Between 2X thru and FIX portion of FIX-DUT-FIX (see Figure 7)
Intra fixture crosstalk	Lower than DUT crosstalk			
Differential to Common Mode conversion loss		-15 dB		

Table 2. Fixture Class definitions

Note that some de-embedding algorithms do not account for fixture crosstalk. A given fixture is described as Class A up to the maximum frequency at which it conforms to the Class A limit, Class B from that frequency to some other higher frequency at which the Class B limit is met, and Class C up to some other yet higher frequency at which it conforms to the Class C limit.

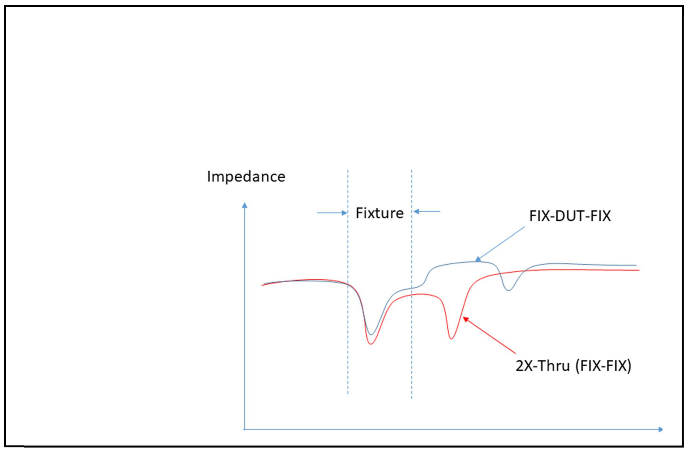


Figure 7. Fixture impedance variation

De-embedding methods

Traditional de-embedding has been done using the cascaded T matrix method described in [3]. This method uses cascaded matrices for the Left fixture, DUT, and Right fixture, as shown in Figure 8. The matrices are mathematically manipulated to remove the fixture contributions and produce the S-parameters of the DUT alone, as described in [3]. The draft P370 standard recommends use of what is being called the “Impedance-corrected 2X” method. This method, which is described in [4], eliminates the errors introduced when the fixture impedance varies from that of the test equipment, the structures used for the calibration, or even between the two halves of the fixture.

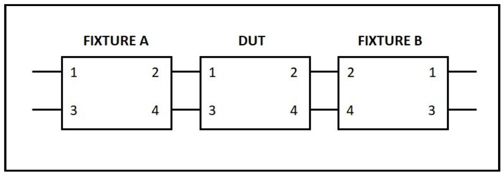


Figure 8. Cascaded FIX-DUT-FIX model**De-embedding Verification**

Once the de-embedding method has been developed or selected, it is desirable to verify its accuracy prior to use. The P370 standard suggests three methods for verification of a de-embedding method:

1. Use of synthesized libraries
2. Use of Plug and Play test boards
3. Use of user-manufactured demonstration boards

The first option allows the user to compare the de-embedded DUT data to those from synthesized data obtained from a field solver and/or circuit simulator. The P370 committee has generated a library of synthesized data for this purpose that includes coaxial launch connectors, single-ended and differential lead-in traces, and DUT structures. Structures using various combinations of design parameters such as dielectric constant, dielectric loss tangent, trace width, and trace spacing, are included, the result of which is varying line or pair impedance. Different launch via geometries are also included, as shown in Figure 9, which are combined in various configurations with the sample DUTs shown in Figure 10. Due to the performance dependence on the via geometry, the combined test fixtures will have different electrical properties as described in Table 2. The synthesized S-parameter library can be used for EDA tool vendors to test the capability of their tools.

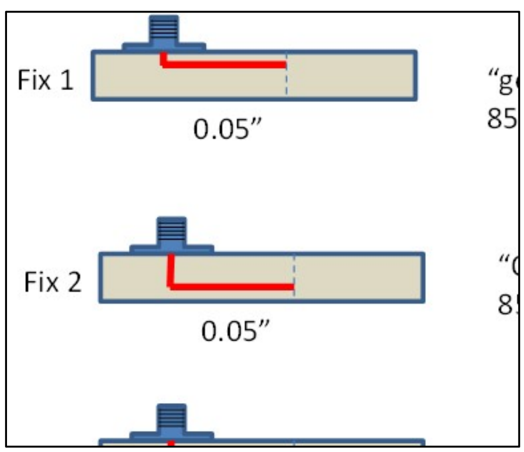


Figure 9. Launch via geometries included in the S-parameter library with different topologies

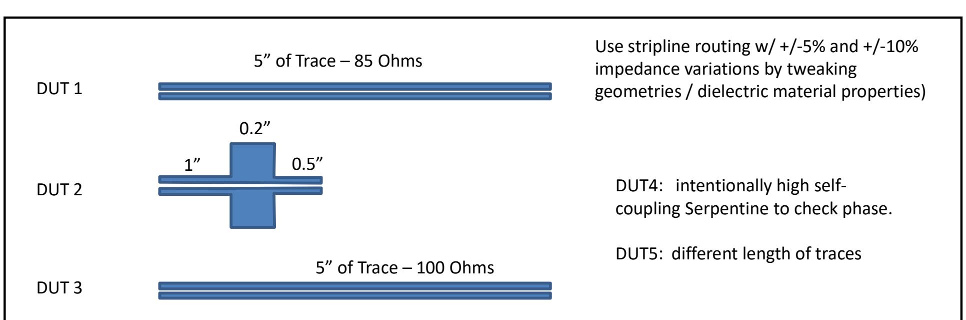


Figure 10. Sample DUTs included in the S-parameter libraryA summary of the contents of the S-parameter library is shown in Table 2.

Parameter	Min.	Max.
Dielectric constant (Dk)	3.33	4.07
Loss tangent (Df)	0.002	0.002
Layer 1 lead-in trace width, mils	6.1275	7.095
Layer 1 impedance, Ohms	50.71 (SE), 82.19 (diff.)	54.72 (SE), 87.53 (diff.)
Layer 3 lead-in trace width, mils	5.598 (diff. 85 Ohm), 3.78 (diff. 100 Ohm)	6.842 (diff. 85 Ohm) 4.62 (diff. 100 Ohm)
Layer 3 impedance, Ohms	81.07 (diff. 85 Ohm), 95.7 (diff. 100 Ohm)	89.63 (diff. 85 Ohm), 105.8 (diff. 100 Ohm)
Layer 8 lead-in trace width, mils	4.041	4.939
Layer 8 impedance, Ohms	58.6 (SE), 97.21 (diff.)	62.69 (SE), 103.12 (diff.)

Table 2. Synthesized data library summary

Option 2, use of Plug and Play boards, enables the user to compare the results of the de-embedding process with results from direct measurements of a fixture and sample DUT components. In this case, coaxial connector adaptors are inserted between DUT and Fixtures, so that a direct measurement of DUT (without de-embedding) is readily available, to be compared against the de-embedded results. The Plug and Play board set has been developed by the P370 committee, and the test data for it are available for use in verifying de-embedding algorithms. An example of an implementation of this board kit is shown in Figure 11.

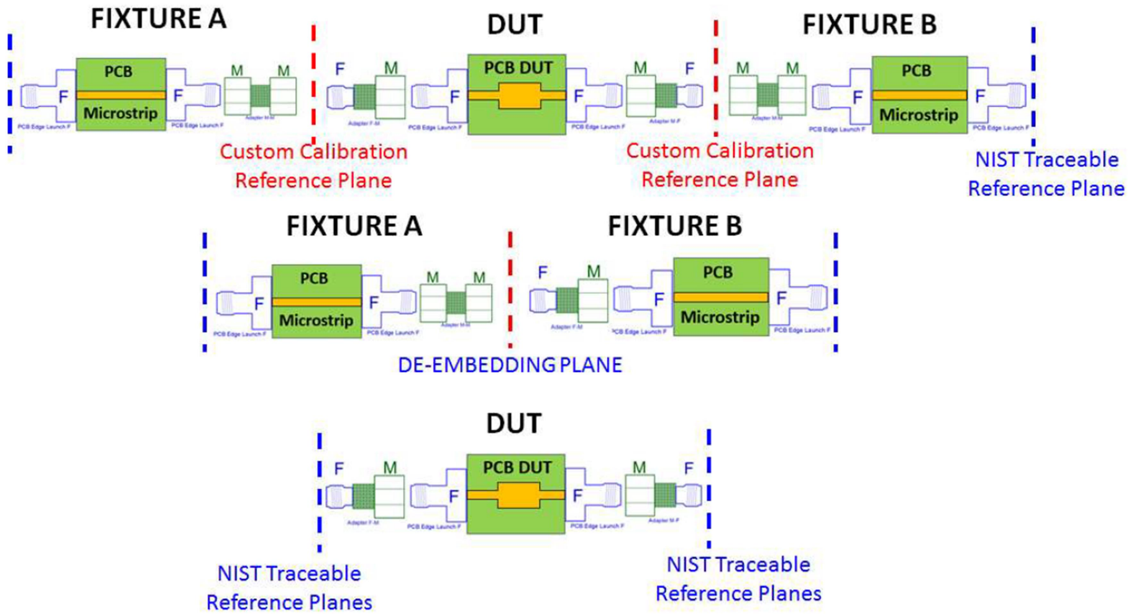


Figure 11. Plug and Play board kit example

Option 3, use of demonstration boards, provides a way to verify the results of de-embedding across multiple samples of the same structure on the same board. This is useful to quantify the differences in measured results due to manufacturing process variations. Figure 12 shows the layout of a typical demonstration board, where multiple DUTs and multiple fixtures (similar to the simulation library) are built are the same board. This includes the variation from manufacturing of the same 2x thru reference, the fixture attached to the DUT, and the DUT itself. In addition, the sensitivity of the de-embed process to variations in fixture features, such as impedance, launch, loss and delay can be explored in this test board.

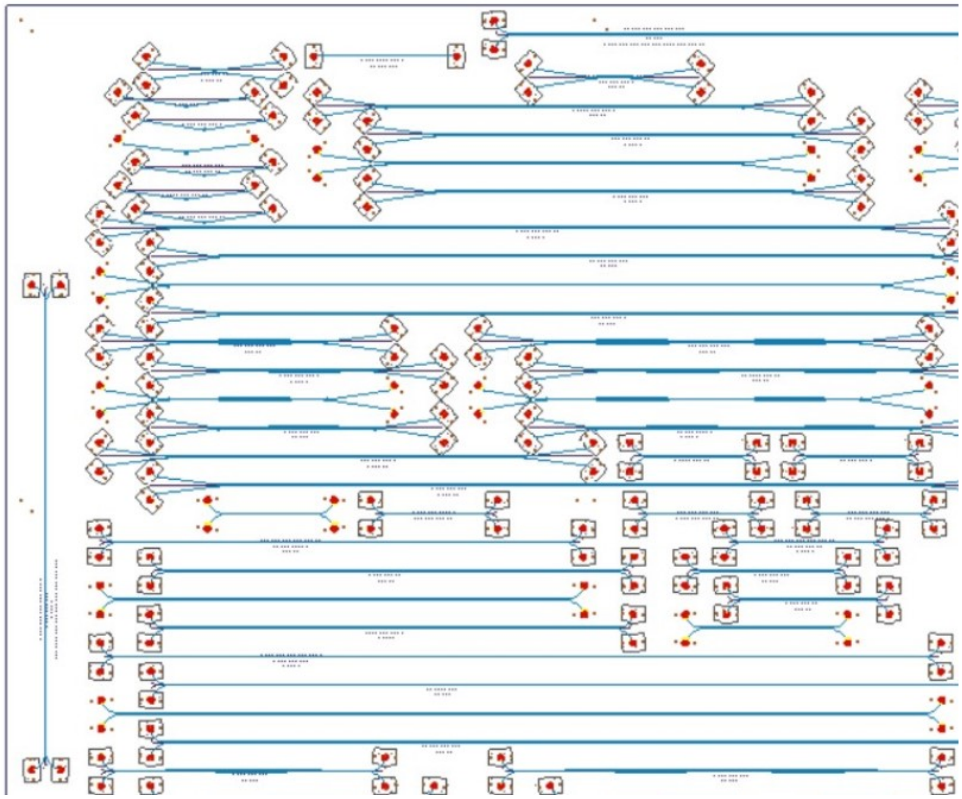


Figure 12. A demonstration board with multiple DUT and fixture structures

S-parameter Integrity and Validation

Accurate simulation depends on accurate models or data for the components in the system being simulated. If the extracted or de-embedded DUT data are inaccurate or of poor quality, the results of the simulation will be inaccurate. This is of greater impact as the frequencies of interest increase. There are many potential sources of problems in dealing with S-parameter data, some of which may not be immediately obvious. Some of these sources include:

- Differences in naming of ports, especially with differential DUTs
- Differences in frequency range or step size
- Mismatches in normalizing impedance
- Poor S-parameter quality, including non-causal, non-passive, and non-reciprocal data

The draft P370 standard deals with each of these. A preferred method is suggested for naming of ports, with odd-numbered ports on the input side of the DUT or network, and the even-numbered ports on the right or output side, as shown in Figure 13a. Thus with the simple case of a single-ended two port DUT, port 1 is the input and port 2 is the output, and s21 describes the “through” behavior of the DUT or network. This is consistent with conventional usage. In the case of a four port DUT or network, the differential input port 1 consists of single-ended ports 1 and 3, while the differential output port 2 consists of single-ended ports 2 and 4, as shown in Figure 13b.

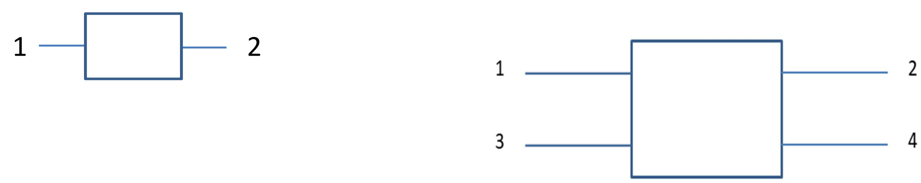


Figure 13. Preferred port numbering for single ended (a) and differential two port (b) DUTs or networks

Misinterpretation of S-parameter data is a common cause of errors. In order to address many of the causes of misinterpretation of data, a number of new keywords have been proposed for inclusion in the Touchstone file header, and will be requested to be incorporated in the Touchstone file standard that is maintained by the IBIS Open Forum. These include:

- Data source – measured, calculated, or simulated
- Component type – de-embedding structure, calibration structure, DUT, composite (fixture-DUT-fixture or fixture-DUT), or fixture
- Calibration method – SOLT or TRL
- De-embedding method – 1X Reflect, 2x Thru, Impedance-corrected 2x thru, or General S-parameter file

Differences in frequency ranges of the models or S-parameters used in a simulation can generally be dealt with by the simulator, but the maximum frequency for the simulation will be that of the lowest maximum frequency of the models and/or data being used. Differences in step sizes also can be handled through interpolation, but there may be some inaccuracy introduced in the results, especially if the step sizes are large.

S-parameter quality

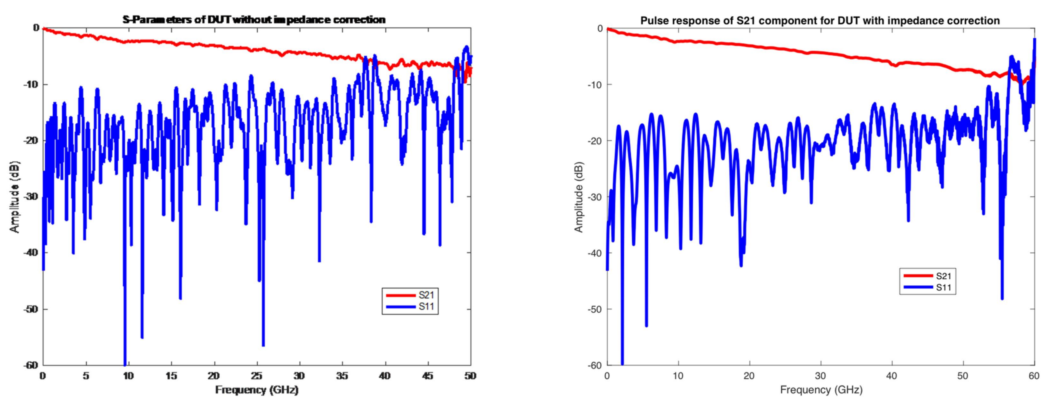
S-parameters can exhibit a number of behaviors that can cause problems with simulation, everything from inaccurate results to “crashing” the simulation tool. These undesirable behaviors often fall into one of three categories: non-causality, non-passivity, and non-reciprocity. Real, physical systems do not produce energy at their outputs prior to the application of an input. On the other hand, non-causal systems can produce outputs prior to the occurrence of the input. If the de-embedded S-parameter is non-causal, this will produce erroneous simulation results.

Similarly, real physical systems without internal energy sources do not produce any output if no input is applied. However, non-passive systems do not satisfy this requirement.

Real, passive physical systems are generally reciprocal, meaning that if the inputs and outputs of a DUT are reversed, the same output would be produced by the application of a given input as was obtained prior to reversing the input and output. With a non-reciprocal DUT, the output of the DUT with normal connections could be different than that obtained prior to reversal of the input and output.

Given that these undesirable behaviors often result from inaccurate de-embedding, the P370 committee has developed a set of metrics with which to gauge the quality of S-parameters. It is often difficult to gauge the quality of S-parameter data, given the large volume of data and the limited ability of the user to examine all the potential interactions. The only quality checks performed may be examining the magnitude of s21 and s11. This approach is incomplete in that it ignores some of the common problems that result from measurement and de-embedding errors which can result in non-passive, non-causal, or non-reciprocal behavior. The quality checking tools developed as part of the P370 standard effort give the user the ability to evaluate the S-parameter data and make decisions relative to the quality and usability of those data. These tools provide quantitative measures of three aspects of data quality, and are intended as an example implementation, but their use is not required for conformance to the standard.

The draft standard specifies metrics with specific ranges of numeric values that designate the quality level of a given S-parameter, on a scale of zero to 100. The respective metrics are the Passivity Quality Metric (PQM), the Causality Quality Metric (CQM), and the Reciprocity Quality Metric (RQM), with limits as defined in the draft standard. S21 and s11 for the two sample S-parameters are plotted in Figure 14. One was de-embedded with the traditional 2x method, while the seond used the impedance corrected method. Obvious differences between the two can be observed in the plots. The CQM value for the S-parameter in Figure 14a is 81 mV, while the value for the S-parameter of Figure 14b is 7 mV, indicating significant non-causal behavior for the first case.



3.

Figure 14. S21 and s11 plots for two S-parameters.**Application Based Quality Checking**

One new approach proposed in P370 is the application based quality checking. The goal is to estimate the quality of the given S-parameters in terms of passivity, causality and reciprocity in physical units. The process is as follows:

- First, , S-Parameters models will be created based on the original S- Parameters, for passivity, causality and reciprocity comparison
- Then the similarity metric will be defined in the time domain to get estimation in physical units
- Finally, the similarity metric in the time domain will be applied between the original and created models to get correspondingly passivity, causality, and reciprocity estimations in physical units.

Comparison of S-parameters

In evaluating the accuracy of S-parameter data, it is often useful to compare two different S-parameters. These could represent two sets of DUT data, extracted and de-embedded measured data, or de-embedded data obtained by using two different methods. This has traditionally been qualitative, for instance comparing the shapes of two overlaid plots of s11 or s21 data. This approach is imprecise, and does not provide any quantitative measure of agreement between the two parameters. The P370 committee has also developed a software tool for comparing two S-parameters which provides a quantitative measure of the similarity of two S-parameters. Comparison metrics have been defined which allow classifying the degree of agreement, using the Error Vector Magnitude (EVM):

- the magnitude of the absolute error vector calculated at each frequency
- the magnitude of the relative error vector calculated at each frequency
- the magnitude of the composite error vector which is 0.9 x the magnitude of the absolute error 10 vector + 0.1 x the magnitude of the relative error vector
- the cumulative or integrated relative energy error up to each frequency value.

The error vector calculation is illustrated in Figure 15.

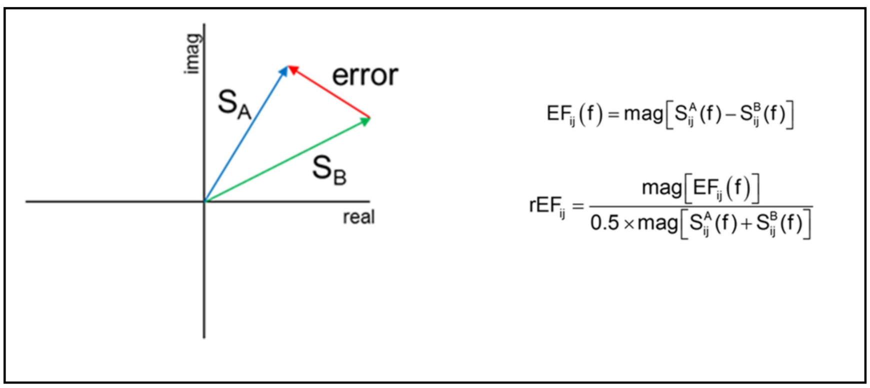


Figure 15. Error Vector Magnitude calculation

The degree of agreement is used to classify the results into three quality Levels, with the limit criteria for each level listed in the standard. The bandwidth of the S-parameter's level is the highest frequency at which the similarity metric meets the specified limit. Comparison may also be done of time domain (e. g., TDR) data. A sample frequency domain comparison is shown in Figure 16.

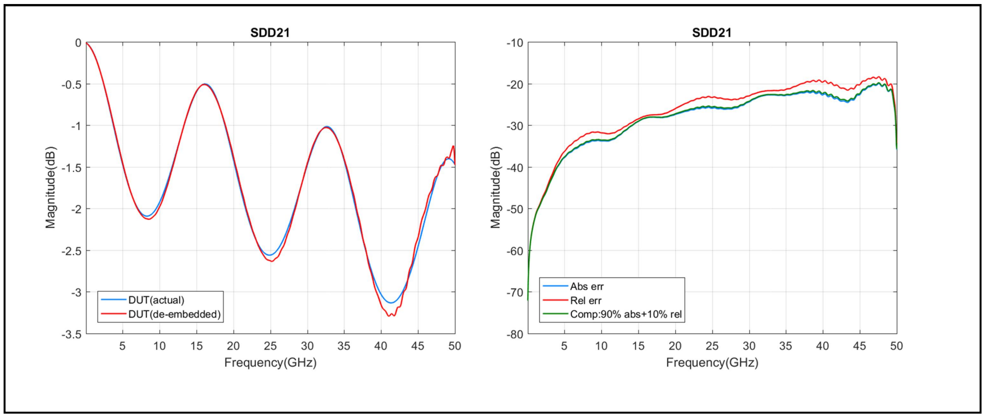


Figure 16. S-parameter comparison example

Tutorials

The draft P370 standard includes tutorial material on topics such as network parameters of multiport networks, calibration and de-embedding, and printed circuit board design and fabrication.

Best Practices

The P370 standard includes a description of best practices that provide guidance to the designer, to help avoid some of the common problems that one may encounter at these frequencies. These include fixture design, coaxial launch connector footprints, via designs, frequency extrapolation to DC, and generation of Gaussian pulses for use in simulation.

Conclusions

The IEEE P370 standard provides guidance on fixture designs, best practices, a data library for use in verifying de-embedding tools, and sample tools for evaluating and comparing S-parameter data. Designing fixtures and measuring devices for use up to 50 GHz is non-trivial, and it is hoped that this standard will provide users with the means to obtain accurate, usable results for use in their designs.

Acknowledgements

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