

A Simple, Powerful Method to Characterize Differential Interconnects

Abstract

The Automatic Fixture Removal (AFR) process is a new technique to extract accurate, high bandwidth models of interconnects that is both simple and accurate. This technique can be applied to all interconnects such as connectors, IC packages, cables, circuit board traces and even vias. It has comparable accuracy to traditional TRL techniques, but is much simpler to implement. This app note describes the AFR technique and why you will want to use it in your next measurement project.

Measurements in Perspective

Every high-speed digital product designed and built today, operating above 50 MHz, has one problem in common: the interconnects between the chips are not transparent.

This means if they are not optimized right from the beginning of the design process, the product probably will not work. In fact, the chance of success, if you do not optimize the interconnects, diminishes rapidly as data rates exceed 1 Gbps. This is the high-speed digital regime.

The ability to accurately simulate the performance of the interconnects is a critically important capability to assure optimized cost-performance before you build the product. The key element here is “accurate”. How do you know how accurate your models, material properties or simulation tools really are? The only way to gain this sort of information is by comparison to measurement, your anchor to reality.

While measurements are not a substitute for simulation, they can compliment simulations, for example, by using them to:

- Emulate system performance using a measured behavioral model
- Characterize a component
- Verify a component to a spec
- Validate a simulation/model to hardware
- Extract material properties
- Debug a problem

But all measurements, especially at high frequency, have a critical limitation: what you want to measure is often buried deep inside an interconnect and not easily extracted.

The Chief Problem with all Measurements

Figure 1 shows a small via structure in the middle of a uniform transmission line with SMA launches on the ends. We want the measured properties of the via, our real device under test (DUT), not the long transmission line feeding it, or the SMAs and via launches where the VNA cables attach.

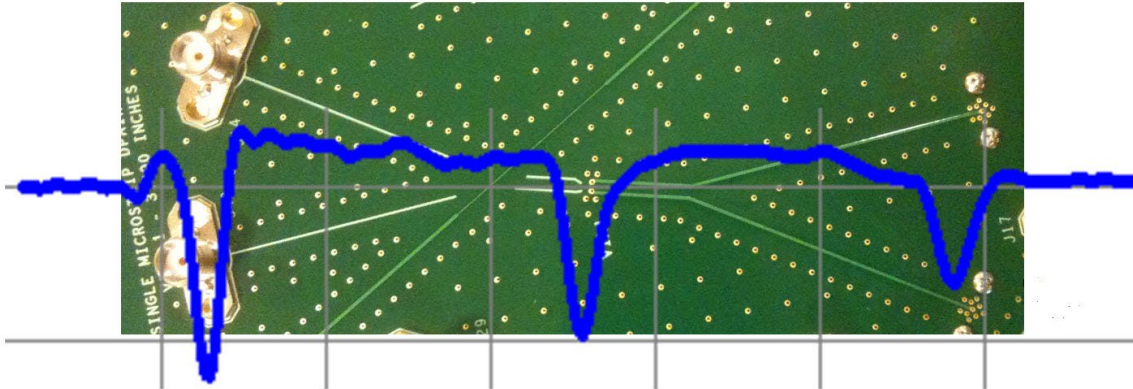


Figure 1. Example of a via structure as the DUT, but embedded in a fixture, with the measured TDR response superimposed.

In this example, the DUT we care about is the via. It is embedded in the middle of a fixture, the launches and uniform transmission lines in the board feeding into it. As apparent in the TDR response superimposed on the picture of the interconnect structure, the via pad stack at the launches introduce a considerable discontinuity and the uniform transmission lines are not so uniform, showing some impedance variation down their length, and of course introducing loss.

The fundamental problem in all measurements is this: how do we separate out just the DUT we want from the total measurement of the DUT + fixture. This is where the Automatic Fixture Removal (AFR) technique, a new calibration routine recently introduced by Keysight Technologies, Inc. can play an important role.

There are already a number of calibration techniques commonly used in the industry, such as

- SOLT (short, open load, thru)
- TRL (thru, reflection, line)
- LRM (line, reflect, match)

They each offer a balance between complexity to implement and ability to extract the DUT properties from a DUT + fixture measurement. Unfortunately, for TRL and LRM, while they are widely used to remove the fixture effects from a measurement, they are difficult to implement correctly and have a number of subtle opportunities for artifacts to be introduced.

Historically, calibration techniques have followed the old saying, “The better a medicine is for you, the worse it will taste.” The more accurate a calibration technique, the harder it has been to implement. The Automatic Fixture Removal (AFR) technique breaks this pattern and offers both accuracy and ease of use.

De-embedding Techniques

Most DUT + fixture structure can be described with a set of S-parameters, S_D , for the DUT only, and a set of S-parameters associated with the fixture elements on each side of it, S_A and S_B , as shown in Figure 2.

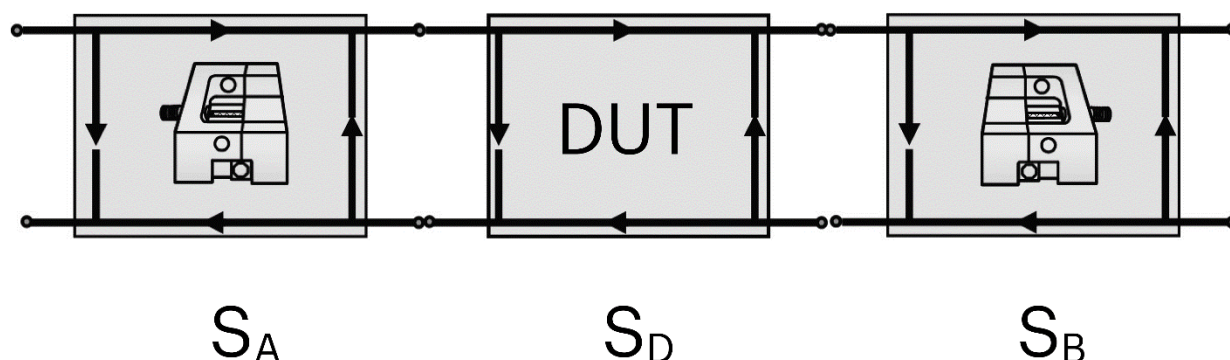


Figure 2. S-parameter description of the DUT surrounded by an A and B fixture on either side

The challenge for all calibration techniques is to extract the S-parameters for the DUT from the total measurement of the S-parameters of the entire DUT + fixture composite structure. The general process of extracting just the DUT performance from the composite performance is called de-embedding, as we “de-embed” the DUT from the total measurement.

The secret to successful de-embedding of the DUT S-parameters from the total S-parameters is knowing the S-parameters of the two fixture sections. If we have the total measurement of the cascaded network of the three S-parameter networks, (S_A , S_D , S_B) and we have the values of the two sets of S-parameters of the fixture, S_A and S_B , using matrix math, we can extract just S_D .

The mathematics for doing this is tedious and complicated, but still straightforward and is implemented in all VNA instruments and many simulation tools such as Keysight’s ADS and PLTS. These operations happen, “under the hood” and can be invisible to the user who does not want to get “grease under their fingernails.”

The difficulty implementing a de-embedding technique has traditionally been in obtaining accurate values of the fixtures’ S-parameters. This is where complex techniques such as TRL come in. They are designed to extract S-parameter models of the fixture.

Any technique which enables you to extract accurate S-parameter models of the fixtures can be used to de-embed the DUT from the S-parameters of the composite structure. The Automatic Fixture Removal (AFR) technique dramatically reduces the complexity of directly measuring the S-parameters of the fixture, which are then used to de-embed the S-parameters of just the DUT from the total S-parameter measurement.

The Automatic Fixture Removal (AF) Technique

The most accurate results of the AFR technique are realized if the fixture elements on the two ends of the DUT are mirror symmetric. Furthermore, it's necessary to have a separate structure that is just the two fixtures connected together as a single thru. Since this thru reference structure is twice the length of either fixture connected to the DUT, it is often referred to as a 2x thru reference fixture. Figure 3 shows an example of a 2x thru reference fixture.

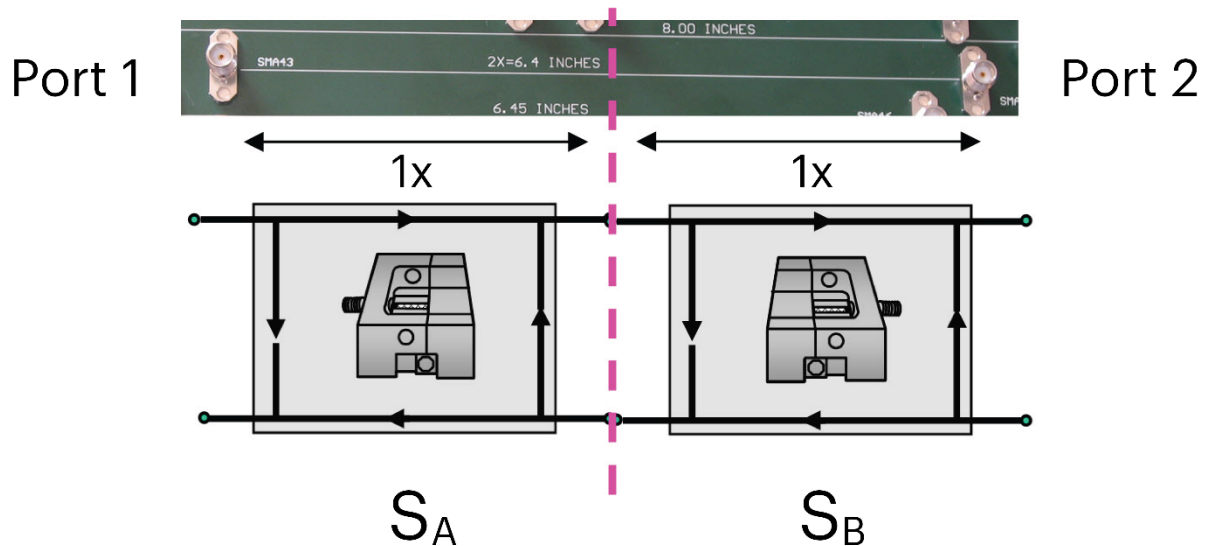


Figure 3. Example of a 2x thru reference fixture with mirror symmetry and how it is described by the two sets of S-parameters.

Each fixture end by itself may not be symmetric. For example, one end of the fixture on port 1 has an SMA connector, while the other end of this fixture connects to the DUT with a section of uniform transmission line. However, when the two fixture pieces are connected together, end to end, the resulting 2x thru reference fixture is mirror symmetric.

The resultant measurement is the composite S-parameters of the 2x thru reference fixture. This is described in terms of the two S-parameter sets that make up the fixture, as illustrated in Figure 4.

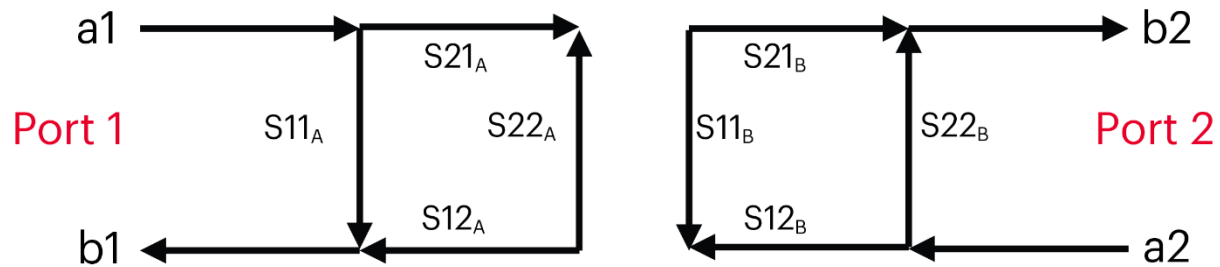


Figure 4. S-parameter network diagram showing the S-parameter sets for each half fixture and how they combine together in the 2x thru reference fixture.

In this example of a single-ended fixture, the measurement is the composite S-parameters of the series combination of the two fixture sections, S11, S22, S21 and S12. These four S-parameter elements and the fact the structure has mirror symmetry is still not enough to uniquely extract the S-parameters of each fixture half.

An essential element to the AFR technique is leveraging signal processing in the time domain to extract the unique values of S11_A and S22_B. With these three features, each element of the S-parameters of each fixture can be uniquely extracted.

Of course, once the measurement of the 2x thru reference fixture is performed, these operations are all done automatically by the AFR software built into PLTS. The intuitive user interface of AFR transforms this normally complex error correction algorithm into a simple task.

The process going on “under the hood” is illustrated in the following Figures.

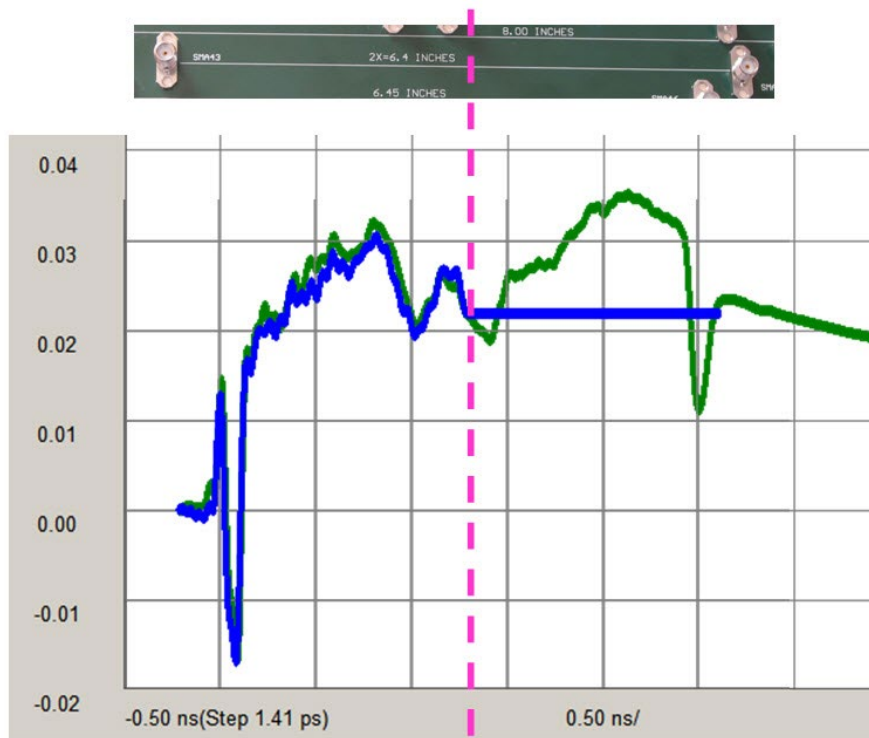


Figure 5. Step 1: The measured S11 and S21 elements of the composite 2x thru reference fixture are transformed from the frequency domain into the time domain. The time delay of the thru signal from the T21 measured response is used to define the exact one way time delay of the 2x thru reference fixture. This time is used to gate the TDR response looking into port 1. The gated TDR response looking into port 1 is the TDR response of just the T11 of fixture, T11_A.

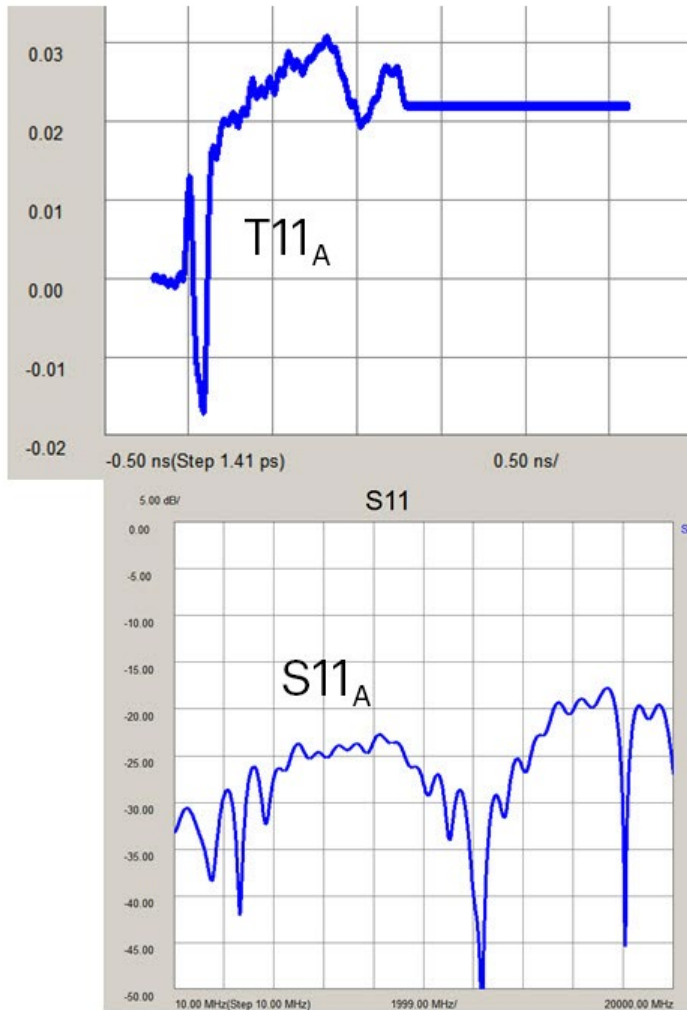


Figure 6. Step 2: the gated $T11_A$ response of the fixture is transformed back into the frequency domain as the $S11_A$ term. If the fixtures are mirror symmetric, $S11_A = S22_B$. In later versions of PLTS, the AFR technique calculates separately $S11_A$ and $S22_B$ using this time domain gating technique. However, AFR still requires the fixture on each side of the DUT to be of equal length.

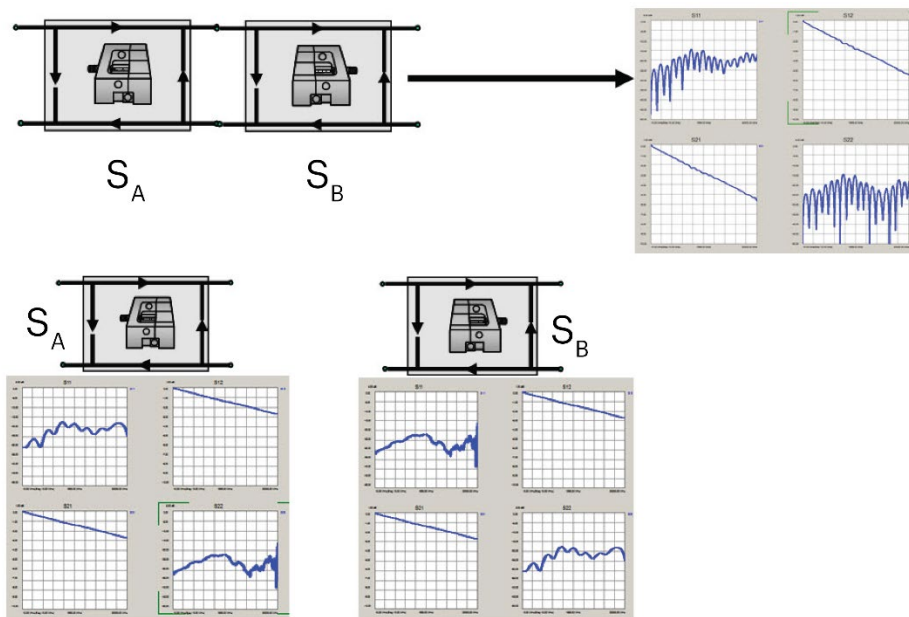


Figure 7. Step 3: From the measured, composite, total S-parameters of the 2x thru reference fixture, the measured S11A and S22B elements from the time gated S11 values, and using a little matrix algebra and network theory, each unique value of the A and B fixture S-parameters can be uniquely calculated. The result is the S_A and S_B S-parameters.

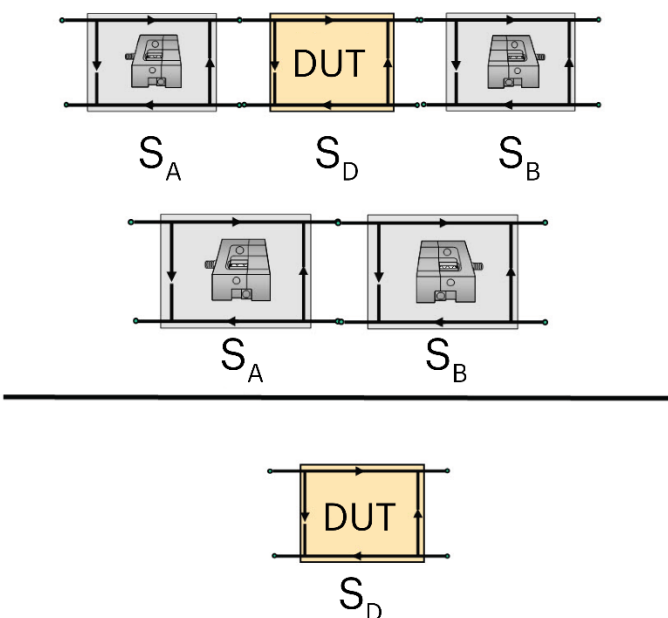


Figure 8. Step 4 (final step): Using the measurements of the Fixture + DUT and the 2x thru reference fixture, from which the fixture S-parameters are extracted, the DUT S-parameters are de-embedded.

From the user's perspective, a measurement of the DUT + Fixture is performed, and a measurement of the 2x thru reference fixture is performed. From the AFR pull down screen in PLTS, the two files are identified and the execute button is clicked. Everything else is performed automatically and the de-embedded DUT's S-parameters are displayed and then available for storage.

Evaluating the Accuracy of the AFR Technique

It is difficult to evaluate the accuracy of any calibration technique in the absence of well characterized reference standards. There are no good reference standards for fixtures and DUTs.

However, since the AFR technique is a new way of processing S-parameter files, the technique and how accurately it is implemented in PLTS can be evaluated using simulated S-parameters files. In this case, we know exactly what the DUT is and compare how well the AFR technique in PLTS extracts an accurate value of the DUT.

The only reason we use simulated S-parameters to evaluate the accuracy of the AFR process is because we know exactly what the answer is supposed to be, with no hidden assumptions. In addition, once we evaluate the accuracy of the calculations performance by PLTS, we can add non-ideal measurement features to explore the impact on the accuracy of the extracted DUT based on real world effects.

As a test case, the model for a typical structure was created. This was a small via structure, embedded in a uniform transmission line with a small launch discontinuity. The model, implemented in ADS, is shown in Figure 9.

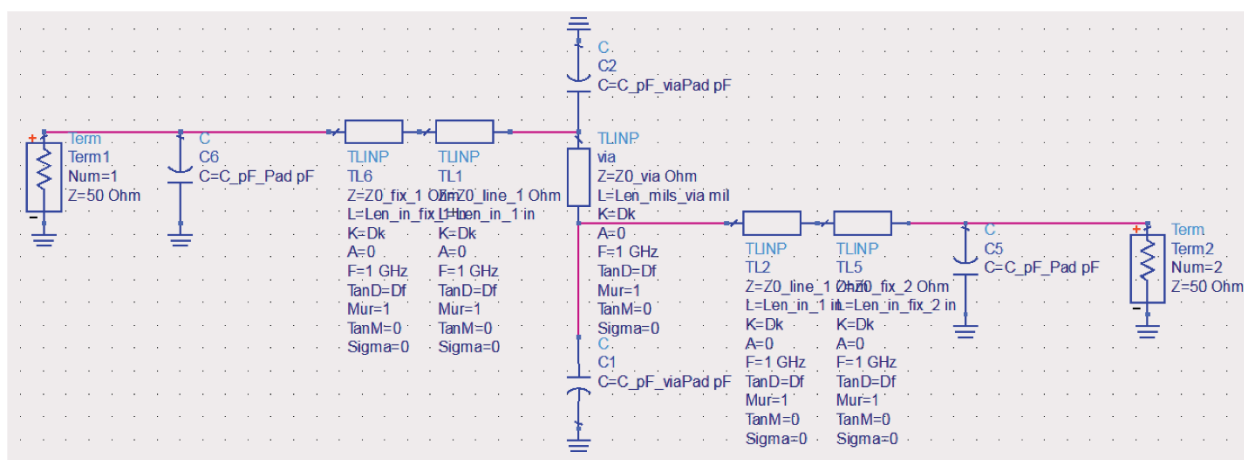


Figure 9. ADS model of the DUT + fixture for this accuracy test

The initial capacitor at the beginning of the circuit represents the via pad stack at the launch. The first uniform lossy transmission line segment is the length of trace from the launch to near the via field. The second short, lossy transmission line is a $\frac{1}{4}$ inch length of trace feeding the via discontinuity. This is part of what we consider to be the DUT.

The via structure is modeled as a thru section of transmission line, as the via goes from the trace on the top of the board to the trace on the bottom of the board. Small capacitors are added to the ends of this thru transmission line to represent the excess capacitance of the capture pads of the via.

The other half of the test circuit is the other fixture, a mirror image of the fixture circuit on the left side.

This circuit is the composite of the DUT + fixture on both ends. In addition, we built a circuit that includes just the 2x thru reference fixture by combining the launches and transmission line segments of the two fixture ends. This circuit is shown in Figure 10.

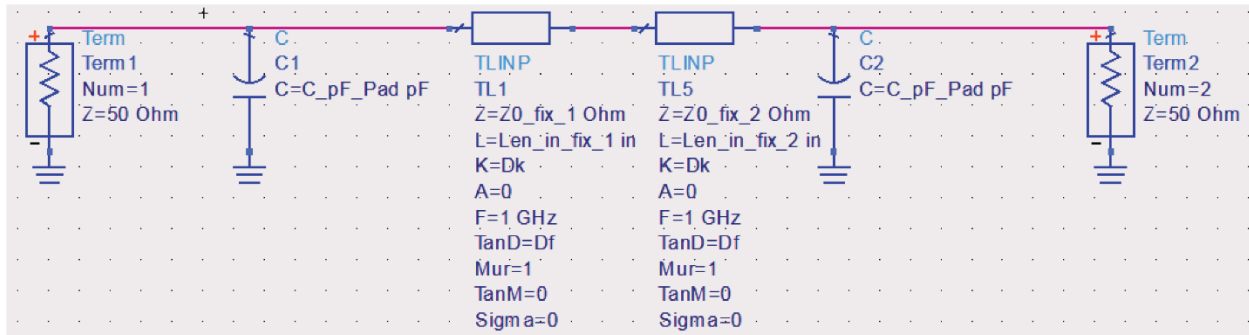


Figure 10. ADS circuit of just the 2x thru reference fixture

The S-parameters of these two circuits were simulated and used to emulate what actual measurements would represent. These 2-port S-parameter files were imported into PLTS and treated exactly like measured data sets.

As an example, the T11 of the composite of the DUT + fixture circuit, as displayed in PLTS, is shown in Figure 11.

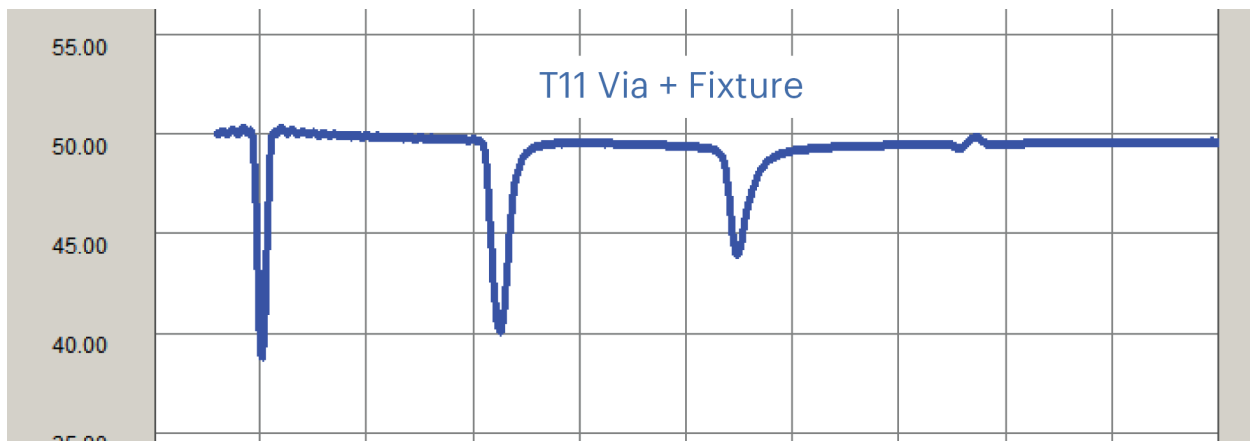


Figure 11. T11 of the composite circuit of the DUT + fixture, generated by the ADS simulation and brought into PLTS and displayed by PLTS. Note the impedance drop at the launch and the via structure. This simulated response is very similar to the measured response from a real via embedded in the middle of the test fixture, as shown in Figure 1.

The AFR technique was applied to the two simulated data sets of the DUT + fixture and the 2x thru reference fixture. The DUT only S-parameter model was extracted in PLTS using AFR.

We know exactly what the behavior of the DUT only should be because we simulated just the DUT in a separate circuit, shown in Figure 12. This simulated S-parameter file is the “answer”, to compare what the AFR technique extracts.

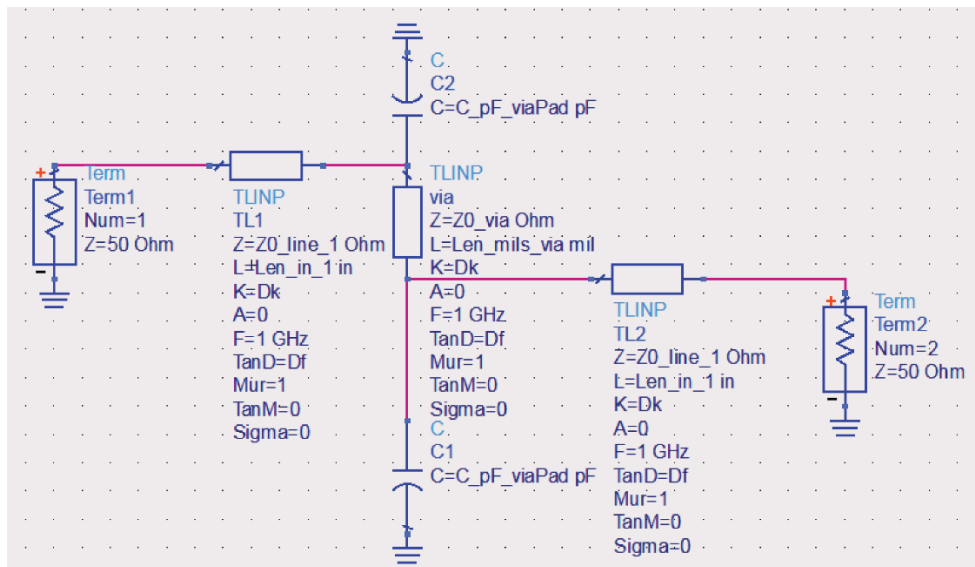


Figure 12. The ADS circuit model of just the via structure. The S-parameters simulated from this circuit are the “answer” that is compared to the extracted DUT S-parameters by the AFR technique in PLTS.

The S11 and S21 of the DUT, as simulated directly from the ADS circuit, and as extracted by the AFR technique in PLTS, are shown in Figure 13.

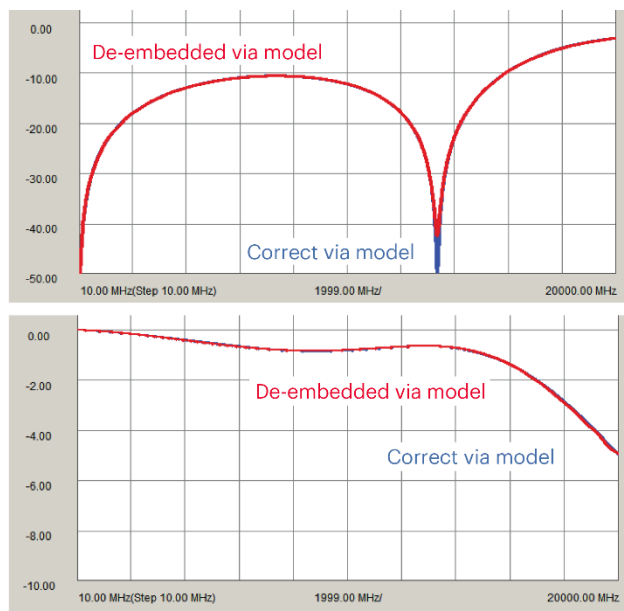


Figure 13. Comparing the correct answer for the S11 (top) and S21 (bottom) values with the de-embedded values using PLTS

The agreement between the de-embedded S-parameters from PLTS and the actual DUT, as simulated by ADS, is seen to be excellent all the way up to the 20 GHz bandwidth of the simulation. This suggests that the AFR algorithm implemented in PLTS can be a very accurate process to de-embed a DUT from a symmetrical fixture.

Enter the Real World

The AFR technique, as with EVERY de-embedding technique, such as TRL and LRM, makes the fundamental assumption that the reference fixture structure used to generate the S-parameter files in the de-embedding process, are identical fixtures to those that connect to the DUT.

In the real world, this is never the case, and is the source of many of the artifacts such as non passive and non causal data often seen in VNA measurements.

In the real world, three important artifacts are often present which will affect the accuracy of EVERY de-embed process:

- All the fixtures to the DUT are not identical
- The fixture elements that are part of the reference fixture are not identical to the fixtures that are connected to the DUT
- The two ends of the fixture in the 2x thru reference fixture are not perfectly symmetrical

It is difficult to quantify how much of a variation between the reference and the fixture contributes to how much error in the extracted DUT. One way to explore this effect is by distorting the circuits used in the simulation example above, where the “correct” answer is known.

As one example, the fixture to the DUT was kept the same, but the 2x thru reference fixture was distorted. It was designed to be asymmetrical with impedance off from 50 Ohms. The comparison between the simulated TDR response of the DUT + fixture and the 2x thru reference fixture are shown in Figure 14.

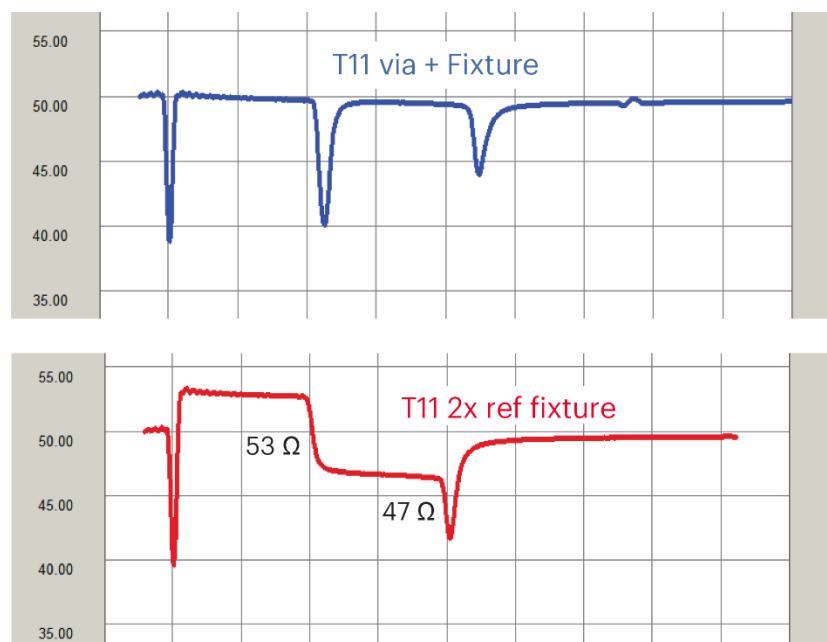


Figure 14. Simulated TDR response of the DUT and fixture and the 2x thru reference fixture, as input files to the AFR technique in PLTS.

This is one example of how the fixture used as the reference to build the de-embed files can be different from the fixture that connects the VNA to the DUT. The impact on using the incorrect fixture model is seen when we compare the actual DUT S-Parameters with what is extracted by the AFR technique. This is compared in Figure 15.

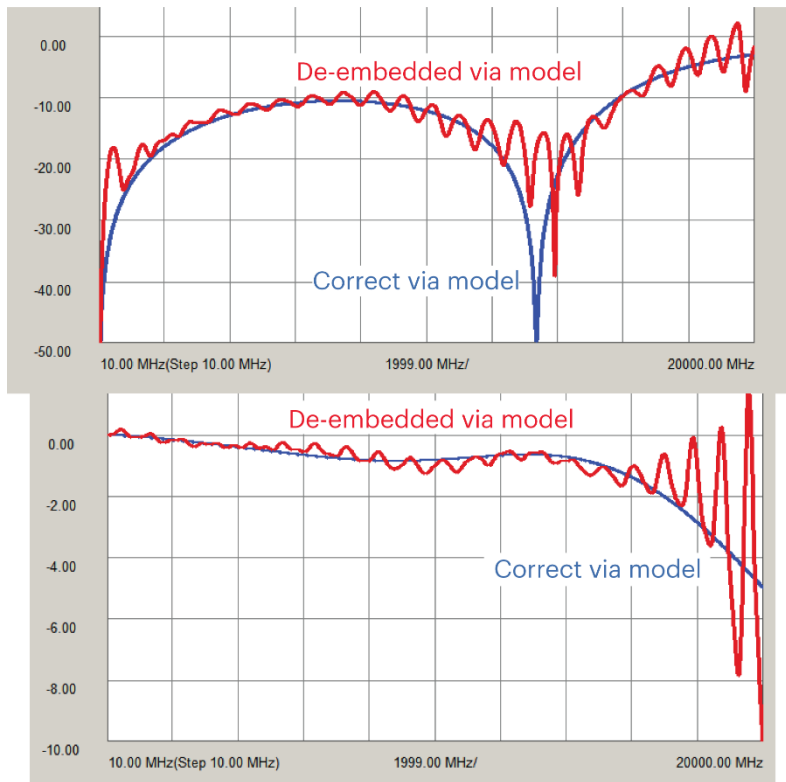


Figure 15. Comparing the return loss (top) and insertion loss (bottom) between the correct DUT model and the de-embedded DUT model, using a 2x thru reference fixture that is different from that attached to the DUT.

We see three important features in this comparison.

- The general features of the return and insertion loss are correctly de-embedded, even with the distorted 2x thru ref fixture
- There is increasingly poor agreement at higher frequency
- It is possible for the de-embedded S-parameter to have much lower insertion loss than the actual S-parameter, which can sometimes lead to non-passive behavior (insertion loss > 0dB). This is why a data integrity checker is an important feature in PLTS.

The exact features of the de-embedded S-parameters of the model, will, of course, depend on just how different the 2x thru reference fixture is different from the fixture elements to the DUT. We would expect a limited bandwidth to the extract model, and possibly some non passive behavior. In order to gain confidence in the accuracy of the de-embedded model, it is essential to compare the fixtures on each end with the 2x thru reference fixture to verify they are identical. If they are not, there is no hope to use ANY de-embedding technique to extract an accurate, high bandwidth model of the DUT.

This suggests that an important part of EVERY de-embed technique is good fixture design. The fixture should be as transparent as possible. It should be designed to be identical between the 2x thru reference fixture and the fixture to the DUT. Finally, some verification should be performed between the launches of the 2x thru reference fixture and the fixture to the DUT. This is most easily done by comparing the T11 responses. This comparison should be part of the general measurement routine.

A Real-World Differential Example

This same process can be applied to any DUT, single ended or differential, and for n-ports, not just to the 2-ports illustrated in the examples above. In the last example, a Samtec differential connector is used as the DUT. It is embedded in the middle of an evaluation board with a separate board having the 2x thru reference connector. The evaluation boards are shown in Figure 16.

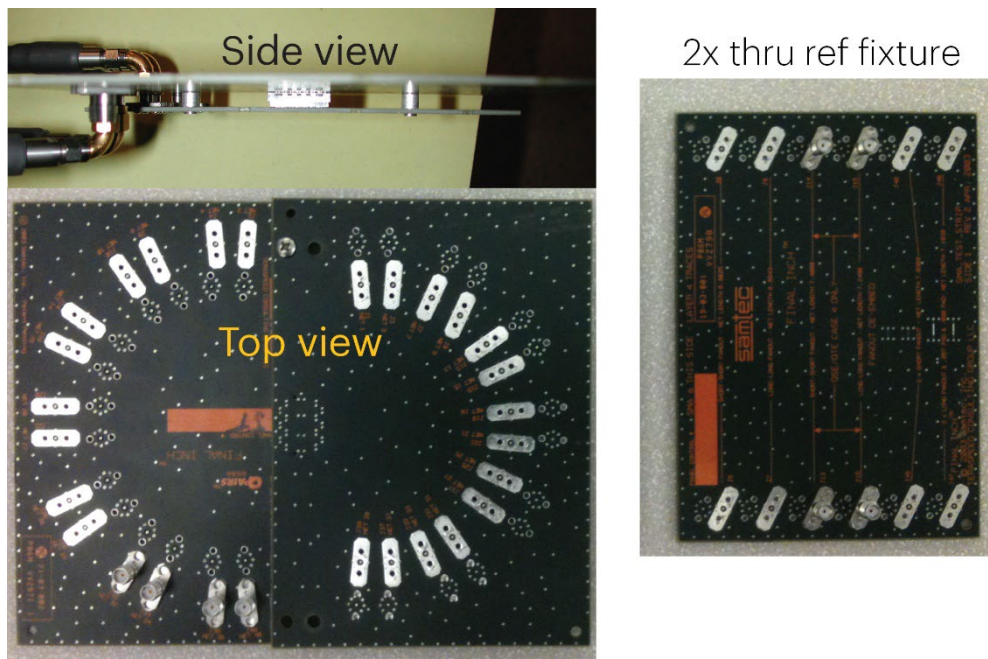


Figure 16. Samtec evaluation board for a board to board connector and associated 2x thru reference fixture

A differential channel on the eval board composed of Fixture A + DUT + Fixture B was measured on the eval board and a differential pair on the 2x thru reference fixture board were measured up to 20 GHz. The two different 4-port S-parameter files for these two samples are shown in Figure 17.

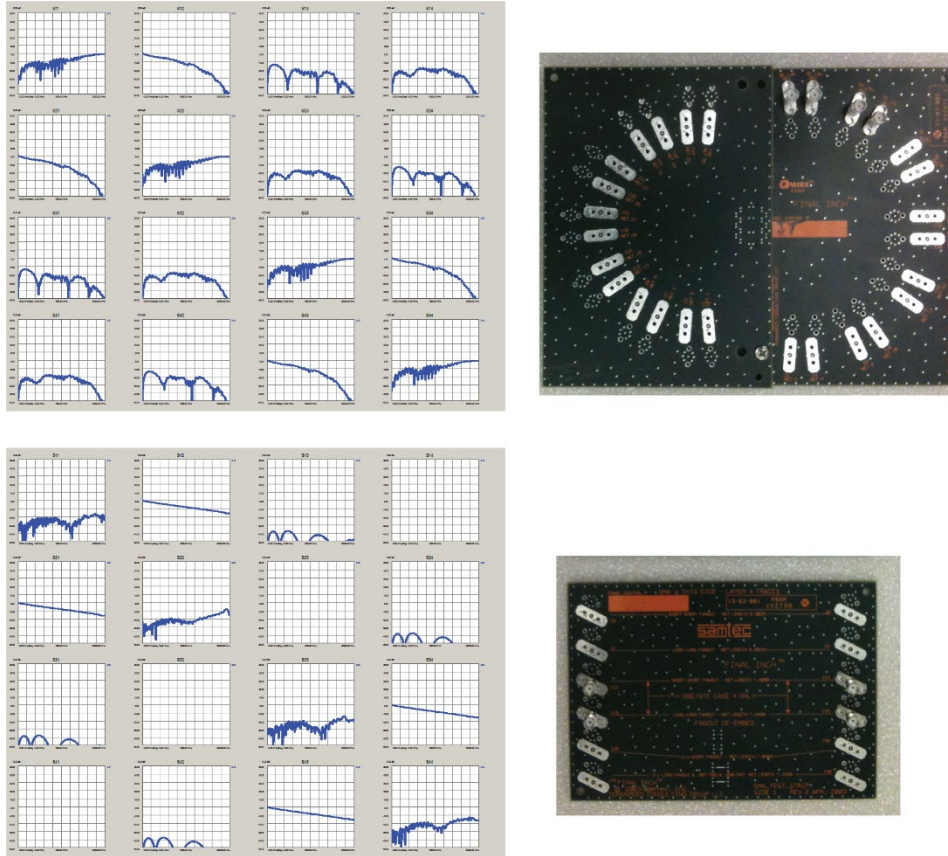


Figure 17. Measured 4-port S-parameters for the fixture + DUT and just the 2x thru reference fixture

The AFR technique was used to extract the S-parameters for just the DUT only. The S-Parameters of just the DUT are re-displayed in the time domain to compare the TDR response of the de-embedded connector with how it appears when embedded in the fixture. This is shown in Figure 18.

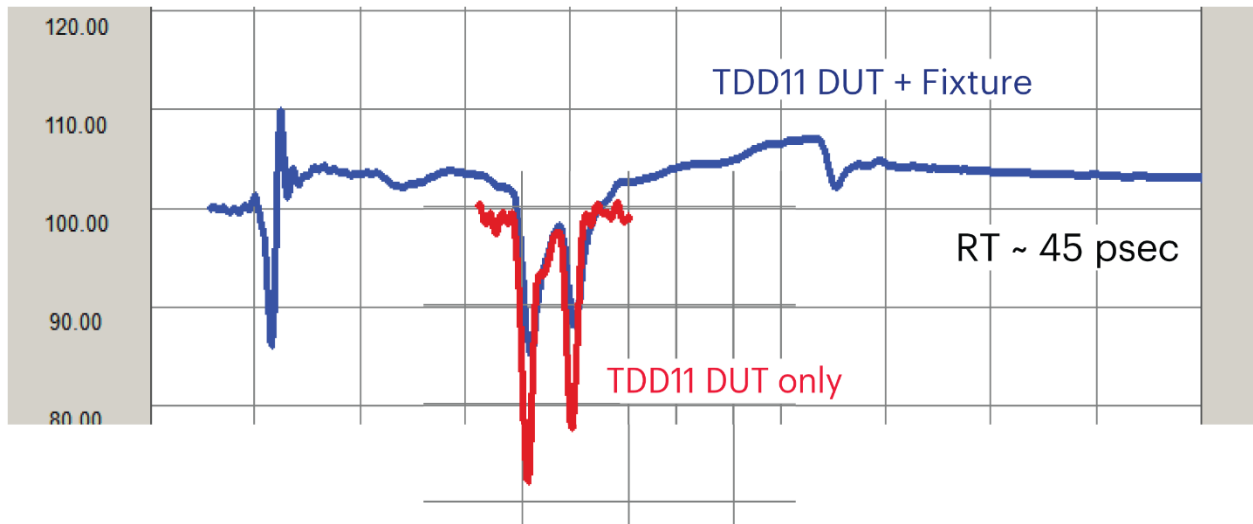


Figure 18. Comparison of the measured TDR response of the DUT in the middle of the fixture, and the TDR response of the DUT, de-embedded from the fixture.

This illustrates how much the fixture distorts the actual response of the connector. Without de-embedding, there would be no way of building a behavioral model of just the connector.

Conclusion

Measurements play a critical part in the design process for all high-speed digital products. But their value is only if they return accurate measurements on the interconnects that are important.

The traditional methods of removing fixture effects, while often times accurate, have been very complicated. This has limited them to use by the most expert engineers only.

With the introduction of the AFR technique, anyone can perform two simple measurements and with one mouse click, de-embed the DUT of interest. Of course, like all calibration techniques, it requires good fixture design.

The introduction of the AFR technique demonstrates that medicine does not have to taste bad to be good for you- de-embedding techniques do not have to be complicated to be accurate and of value.

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