De-embedding with the WavePulser 40iX

TECHNICAL BRIEF

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Summary

The WavePulser 40iX offers many de-embedding methods. This technical brief explores these methods and helps the reader understand what he or she needs to provide to the instrument to obtain the best results.

Introduction

In signal integrity, when measuring the s-parameters of a device under test (DUT), it is a rare circumstance when the DUT has the same connectors as the measurement instrument. The connector type for the WavePulser 40iX high-speed interconnect analyzer is a 2.92 mm female coaxial connection at the end of the user-supplied cables, and while these connectors are quite popular in the microwave community, most devices that are tested for signal integrity would not have this connector type. For this reason, generally extra circuitry exists in between the WavePulser and the DUT which, at a minimum, provides the change from the standard microwave connectors to other types. If this extra circuitry were completely transparent, meaning it does not affect the measurement, then it could be ignored. Most often, this is not the case, and it is desirable to remove this extra circuitry from the measurement. This is where de-embedding comes in. Simply stated, de-embedding is the act of removing extra circuitry surrounding the DUT that is often present for the sole purpose of making the measurement.

De-embedding Types Supported

The WavePulser 40iX supports many different de-embedding methods. These methods fall into three broad categories:

- Calibration methods
- Time-domain methods
- Traditional frequency-domain methods

Calibration methods are methods by which various known standards are attached to a fixture and raw measurements are made. These measurements are called raw because they are measurements of the standards through the fixture. By comparing the measurements made in this way to the definitions of the standards, error terms can be generated which are used to calculate DUT measurements, thus de-embedding the fixture. Another calibration method is to take raw measurements of known standards through a section of trace to define the standard at the end of the trace. Usually, the trace is on the fixture itself, and each trace to the standard is carefully constructed to be as identical as possible to each other and to the actual connection to the DUT. Performing a calibration with the standard defined in this manner enables the de-embedding of the trace during the measurement of the DUT.

All the calibration methods can be applied directly or as a *second-tier calibration*. This is the subject of another technical brief. [1]

Time-domain methods include time-gating, also called port extension, and *peeling* methods using the information provided by the impedance trace. Armed with some knowledge or assumptions about the loss of a small

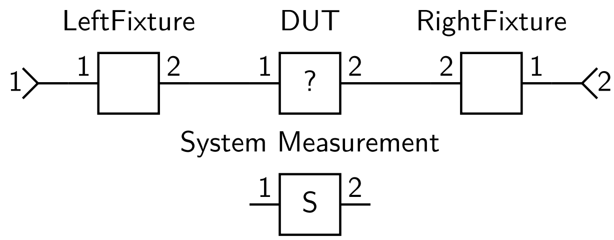


Figure 1: Simple adapter de-embedding

section of transmission line between the instrument ports and the DUT, an approximation of the line using small sections with the measured impedance allows for the development of a model of a de-embedding structure that can be de-embedded using the frequency-domain methods. This is also the subject of another technical brief. [2]

Frequency-domain methods are most commonly used for de-embedding. All the frequency domain methods solve a problem stated in a basic way:

> *Given a system known to consist of fixture elements, whose s-parameters are known and a DUT whose s-parameters are unknown, solve for the s-parameters of the DUT given a measurement made of the entire system.*

An example of a de-embedding problem posed in this manner is shown in figure 1. Here, a measurement has been made of a system consisting of a left fixture, a DUT and a right fixture. The fixture s-parameters are known, as are the s-parameters measured of the entire system. In fact, this an example of how all de-embedding problems are posed within the open-source SignalIntegrity software in [3]. While the open-source software treats all de-embedding problems in the same manner, mathematically, this is actually a special case called adapter de-embedding (see [4]). Most are used to solving this type of problem using transmission parameters, or T-parameters. The steps would be, for each frequency:

1. The s-parameters of the fixtures and system are converted to T-parameters, the two fixtures and the system.
2. The inverse of the fixture T-parameters are multiplied from the left and the right by the system T-parameters (keeping in mind the port orientation of the fixtures).
3. The result is converted back to s-parameters.

For most engineers, this is the easiest way to conceptualize the solution for most engineers. However, the adapter de-embedding method is the method used for this type of problem when you are fortunate enough to have the problem posed as two-port devices between the instrument ports and the DUT ports.

If a traditional frequency-domain de-embedding problem cannot be posed in the manner required for adapter de-embedding, then fixture de-embedding must be utilized. This method, which assumes one large fixture between all ports of the measurement instrument and all ports of the DUT, is capable of solving any traditional de-embedding problem, but some extra work might be required to generate the fixture. This will be discussed later in this document.

Adapter and Fixture De-embedding Selection

The basic setup menu is shown in figure 2. This menu provides the bare minimum information required to perform a measurement. Advanced setup is accessed by clicking on any of the small plus signs scattered

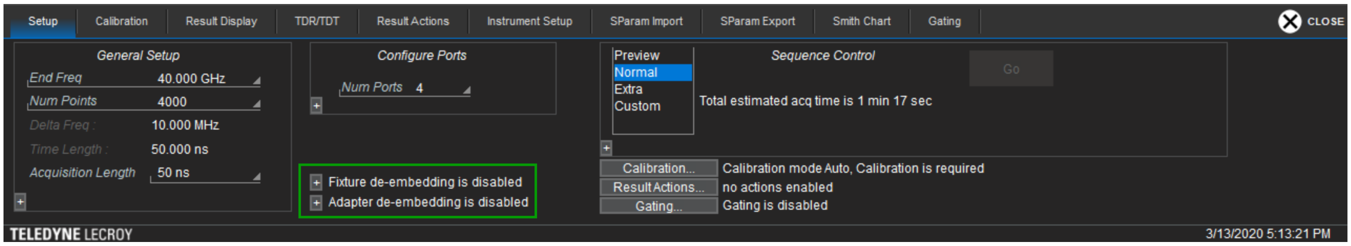


Figure 2: WavePulser 40iX basic setup menu

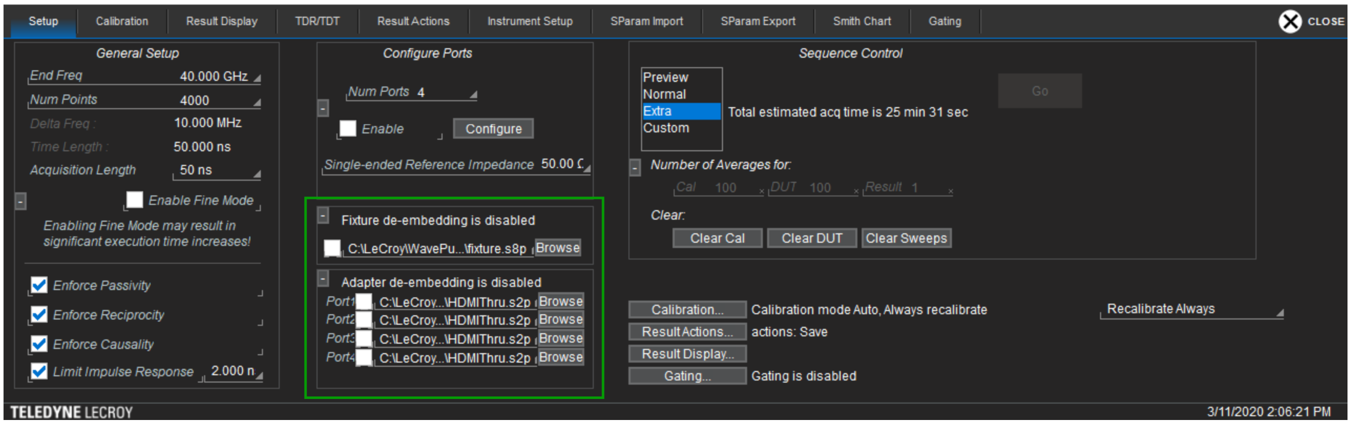


Figure 3: WavePulser 40iX advanced setup menu

throughout the setup, which indicates advanced setup possibilities when expanded. Although the advanced setup controls are hidden, nearby text on the menu indicates the configuration status.

For example, the status of the hidden fixture and adapter de-embedding settings is shown to be "disabled" by the text inside the green box in figure 2.

If any plus sign is clicked, the setup menu expands, as shown in figure 3. Here, one can see that, among other advanced settings, the fixture and adapter de-embedding sections are expanded. The adapter de-embedding area shows a list for each physical port of the WavePulser. For each port, a checkbox is provided that enables the de-embedding of an adapter on the specified port, and shows the name of the two-port s-parameter file containing the s-parameters to de-embed. For adapter de-embedding, the assumption is always a two-port, single-ended device with port 1 of the adapter connected to the physical WavePulser port and port 2 connected to the DUT.

Fixture de-embedding operates in a similar manner, but in this case, the assumption is a fixture with twice the number of single-ended ports as the DUT where, for P DUT ports, ports 1 to P are connected to the physical WavePulser ports and ports $P + 1$ to $2 \cdot P$ are connected to ports 1 to P of the DUT.

This is shown schematically in figure 4, which shows it is possible to utilize both adapter and fixture de-embedding at the same time, provided one keep in mind the de-embedding schematic that is assumed.

Fixture De-embedding Details

When the de-embedding cannot be accomplished through adapter de-embedding, fixture de-embedding can be utilized to solve any de-embedding problem. This is not obvious to some because, for example, figure 4 is not shown in the manner that most people visualize their de-embedding problem. It can be seen though that as the fixture connects all WavePulser ports to all DUT ports, any arbitrary circuit can be placed inside the fixture to

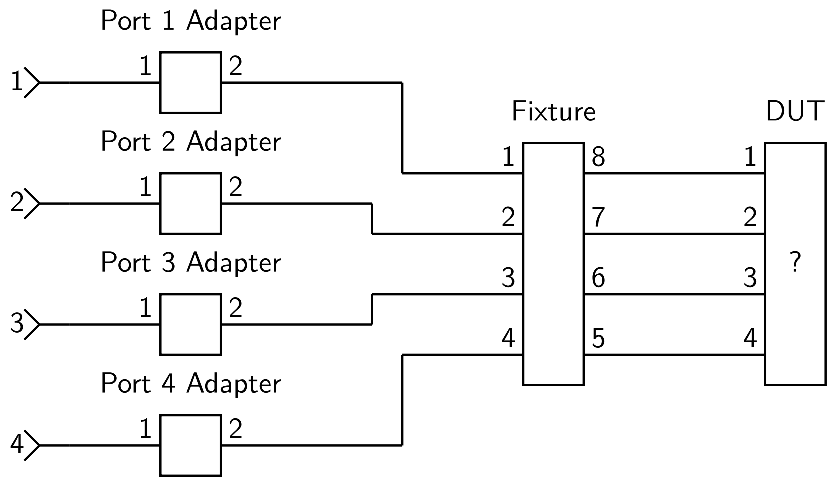


Figure 4: Fixture and adapter de-embedding circuit

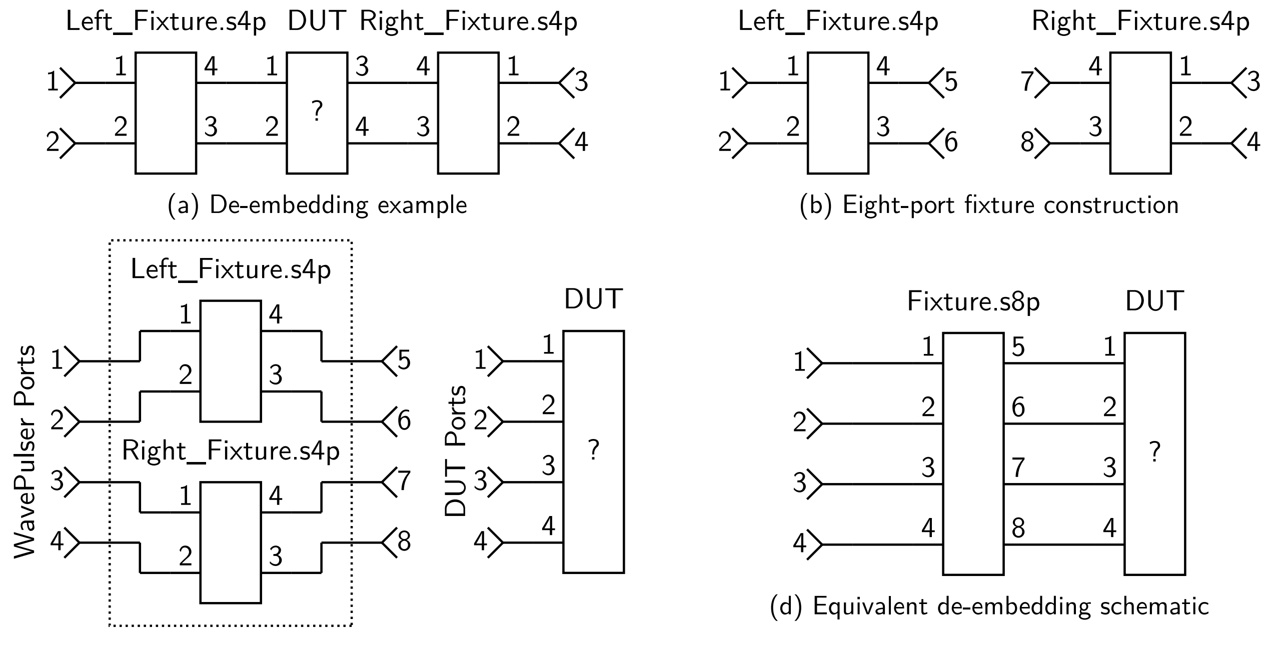
solve any problem posed. That being said, sometimes the devices to be de-embedded need to be manipulated into the form of a fixture for use. This manipulation can be performed with the free open-source software called *SignalIntegrity* offered by Teledyne LeCroy (see [3] for the download location).

To illustrate the creation of a fixture, suitable for use in the WavePulser, an example is provided in figure 5. A common example is the measurement of a four-port DUT whereby two four-port fixtures are used on each end, as shown in figure 5a. This example was created in the *SignalIntegrity* software. If system s-parameters (the measured s-parameters of this four-port system) were provided, the application would be able to perform the de-embedding operation and recover the s-parameters of the DUT. In this example, however, we will concern ourselves with the creation of the fixture file required for use in the WavePulser application. Since the DUT has four ports, the fixture file has eight, as explained previously. The easiest way to design a proper fixture file is to construct exactly the schematic as in figure 5a, then move the DUT element away and connect ports to the newly unconnected fixture locations, making sure that, for a P-port DUT, the new ports are numbered $P+1$ for DUT port 1, $P+2$ for DUT port 2, etc., up to $2 \cdot P$ for DUT port P. Then, delete the DUT element that moved away (but was retained to check the port numbering) and compute the s-parameters of the resulting schematic that is shown in figure 5b. The *SignalIntegrity* application allows the specification of the number of frequency points and end frequency, thus determining the frequency resolution of the fixture. This must be chosen properly for your application and should, at a minimum, contain the expected number of frequency points and end frequency that are planned to be used for the de-embedded DUT calculation.

It is easy to become disoriented with the fixture de-embedding situation, so figure 5c is provided, which shows the fixture constructed from figure 5b, but in the same orientation as the fixture shown in figure 4. The fixture calculated can be solved with the *SignalIntegrity* software using the schematic shown in figure 5d, given four-port s-parameter measurements of the entire system. Of course, here the goal is to create the fixture file for the WavePulser, as shown in figure 3 where the file `Fixture.s8p` is provided for fixture de-embedding.

De-embedding Math

The complete description of the mathematics used for de-embedding is provided in [4, 5]. Here, the equations for de-embedding a $2 \cdot P$-port fixture with s-parameters $\mathbf{F}$ from a P-port unknown DUT with s-parameters $\mathbf{S}$ are provided without justification. Given known system s-parameters $\mathbf{S_m}$ for a fixture de-embedding arrangement



(a) De-embedding example

(b) Eight-port fixture construction

(c) Eight-port fixture alignment

(d) Equivalent de-embedding schematic

Figure 5: Fixture de-embedding example

as shown in figure 5d, the fixture s-parameters are partitioned in the block matrices:

$$\underset{2\cdot P\times 2\cdot P}{\mathbf{F}} = \begin{pmatrix} \underset{P\times P}{\mathbf{F}_{11}} & \underset{P\times P}{\mathbf{F}_{12}} \\ \underset{P\times P}{\mathbf{F}_{21}} & \underset{P\times P}{\mathbf{F}_{22}} \end{pmatrix}.$$

Solving for the unknown DUT s-parameters using the solution established in [4] results in

$$\mathbf{B} = \mathbf{F}_{12}{}^{-1} \cdot (\mathbf{S_m} - \mathbf{F}_{11}),$$

$$\mathbf{A} = \mathbf{F}_{21} + \mathbf{F}_{22} \cdot \mathbf{B},$$

$$\mathbf{S} = \mathbf{B} \cdot \mathbf{A}^{-1}.$$

This fixture de-embedding equation is very adaptable, and in fact, becomes the adapter de-embedding solution when the block matrices $\mathbf{F}_{11}$, $\mathbf{F}_{12}$, $\mathbf{F}_{21}$, and $\mathbf{F}_{22}$ are constructed as diagonal matrices with the adapter s-parameters placed on the diagonal in port order. In other words, with adapter s-parameters of $\mathbf{A_p}$ for each port (with $\mathbf{A_p} = \left(\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix}\right)$ used as the s-parameters when an adapter is not present), the block matrices are formed as

$$\mathbf{F_{rc}}_{pp} = \mathbf{A_p}_{rc},$$

where both $r \in 1,2$ and $c \in 1,2$.

Conclusion

The WavePulser 40iX contains a multitude of de-embedding methods not typically found in other instruments including calibration, time-domain and frequency-domain methods. Often, the problem is a simple two-port adapter de-embedding problem. When it is not, fixture de-embedding can be used to solve any frequency-domain de-embedding problem, albeit with the construction of fixture s-parameters, which are easily performed using the open-source *SignalIntegrity* software.

References

[1] P. J. Pupalaikis, "WavePulser 40iX Second-Tier Calibration," Teledyne LeCroy Technical Brief, Mar. 2020.

[2] P. J. Pupalaikis, "Time-Domain Techniques for De-embedding and Impedance Peeling," Teledyne LeCroy Technical Brief, Mar. 2020.

[3] The *SignalIntegrity* project, `https://pypi.org/project/SignalIntegrity/` and `https://github.com/TeledyneLeCroy/SignalIntegrity/`.

[4] P. J. Pupalaikis, *S-Parameters for Signal Integrity*. Cambridge: Cambridge University Press, 2020, pp. 287–290.

[5] P. J. Pupalaikis and K. Doshi, "Method for de-embedding device measurements," U.S. Patent 8 566 058, Oct. 22, 2013.