Application Note

ACCURATE TEST FIXTURE CHARACTERIZATION AND DE-EMBEDDING

Products:

► R&S® ZNA

► R&S® ZNB

► R&S® ZNBT

► R&S® ZND

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For measurements of non-connectorized devices, test fixtures, probes or other structures are used to adapt from the coaxial interface of the test setup to the device under test (DUT). For accurate measurements of the DUT, these lead-ins and lead-outs need to be characterized, so that their effects can be mathematically removed, i.e. de-embedded from the measurement results.

This application note provides practical hints to accurately characterize and de-embed these lead-in and lead-out structures with R&S Vector Network Analyzers ZNA, ZNB, ZNBT and ZND. As de-embedding is also essential in other test equipment like oscilloscopes, etc., this guide also describes, how lead-ins and lead-outs can be accurately characterized with a VNA and then exported as an S-Parameter file to be used by other test instruments.

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1.1 Test fixture characterization for VNA measurements

1.1.1 Coaxial calibration and de-embedding

For maximum accuracy, Vector Network Analyzers (VNAs) use system error correction. The VNA setup including cabling is typically calibrated up to a coaxial calibration plane using an automatic calibration unit or a manual calibration kit. The VNA then applies its system error correction, eliminating the systematic, reproducible errors up to the calibration planes.

In the most common setup, the instrument is connected through a set of coaxial cables to a coaxial Device under Test (DUT). After the calibration the calibration planes are located in this case directly at the coaxial connectors of the DUT (left setup in Figure 1).

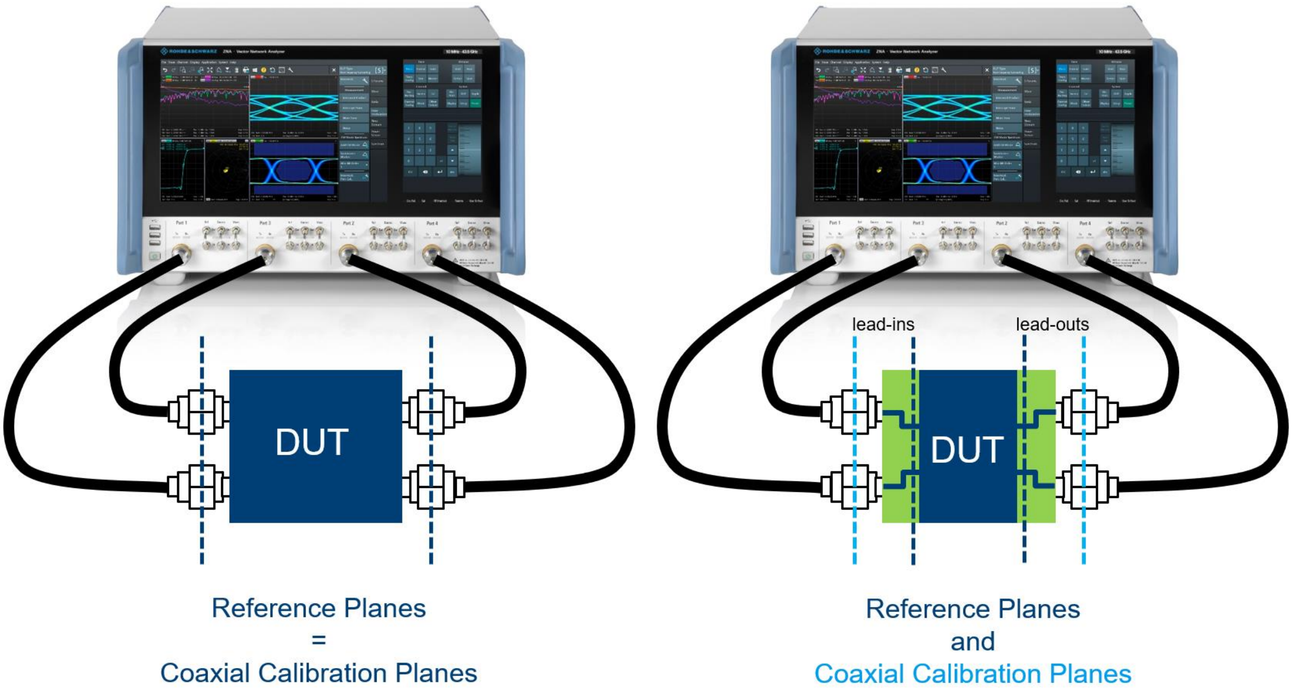

Figure 1 - VNA setups including coaxial calibration planes and reference planes for DUTs with and without coaxial connectors.

In many cases however, the DUT does not have coaxial connectors and the calibration of the VNA cannot be made directly to the ports of the DUT (right setup in Figure 1). This is e.g. the case for measurements of PCB signal structures, non-coaxial connectors or cables and all non-connectorized components. In these cases, test fixtures, probes or other structures are used to adapt from the coaxial interface to the device under test. The corresponding lead-ins and lead-outs between coaxial calibration plane and the reference plane at the DUT need to be modelled, i.e. characterized via their S-Parameters, so that they can be de-embedded (mathematically removed) from the measurement results. For these devices, a 2-step approach is required:

Step 1:
Calibration with an automatic calibration unit or a manual calibration kit at the coaxial interface of the lead-ins and lead-outs.

Step 2:
Characterization of the lead-ins and lead-outs to de-embed them from the measurement results and to move the reference plane from the coaxial interface directly to the DUT ports.

Figure 2 shows an example for the measurement of a PCIe 5.0 CEM connector with R&S®ZNB26. The setup is calibrated to the end of the coaxial cables. In this example, cables with a 2.92 mm connector and a 2.92 mm automatic calibration unit are used. Baseboard and Add-in Card have a 2.4 mm connector. The lead-in to the CEM connector reference plane on the baseboard therefore includes the 2.92 mm to 2.4 mm adapters as well as the signal traces on the baseboard to the CEM connector reference plane. Likewise, the lead-out to the CEM connector reference plane on the Add-in Card also includes the corresponding 2.92 mm to 2.4 mm adapters as well as the signal traces to the CEM connector reference plane on the Add-in Card. Lead-in and lead-out are modelled and de-embedded to extract the performance of the tested PCIe 5.0 CEM connector.

Figure 2 - Measurement of a PCIe 5.0 CEM connector with R&S®ZNB26

Figure 3 shows another example, measuring a MultiGBASE-T1 Automotive Ethernet inline connector, using R&S®ZNB8. Calibration is again done at the end of the coaxial cable. Here, lead-in and lead-out to the reference plane at the inline connector include the corresponding adapter and the section of the Automotive Ethernet cable up to the reference plane of the inline connector. Lead-in and lead-out are modeled and de-embedded to show the performance of the tested inline connector.

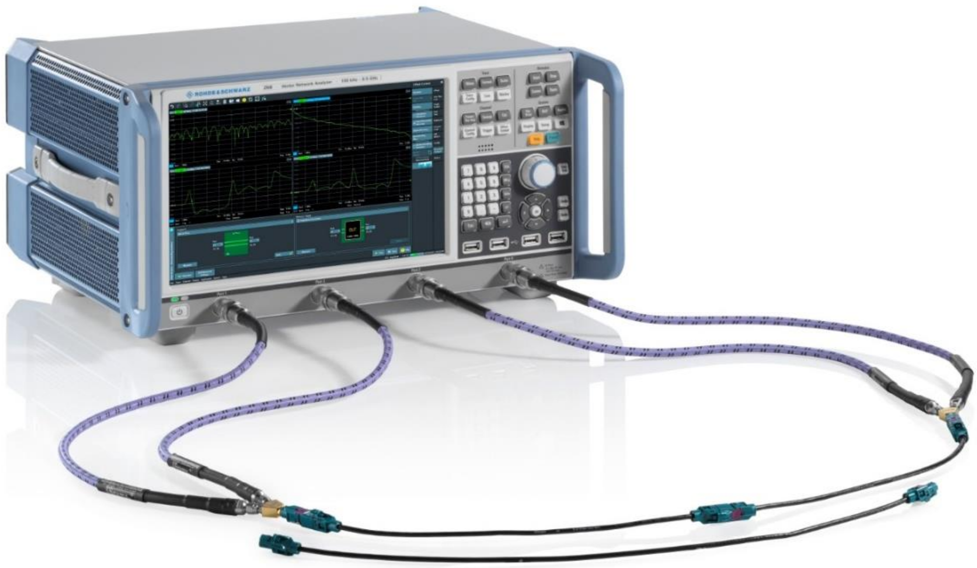

Figure 3 - Measurement of a MultiGBASE-T1 Automotive Ethernet inline connector with R&S®ZNB8 with a corresponding 2x-Thru cable

1.1.2 Limits of TRL calibration and benefits of de-embedding

For lead-in and lead-out structures on PCBs, TRL calibration is often considered as an alternative to de-embedding. In this case the calibration structures include replicas of the lead-in / lead-out structures as well as the required TRL reference standards (Thru, Reflect and Line). The structures can be implemented on the same PCB as the actual lead-ins and lead-outs to the DUT. With that, a calibration can be done directly to the ports of the DUT.

A drawback however is that, depending on the required frequency range, typically several Line standards are required in TRL. Also, to avoid ultra-long Line standards, TRL is typically combined with TRM (Thru - Reflect - Match) in the lower frequency range. Due to the many calibration standards required in TRL / TRM, this calibration method is quite cumbersome for DUTs, that need to be measured in a wide frequency range. In contrast to that, de-embedding often only requires a single reference structure (e.g. a 2x-Thru) and is therefore by far easier in handling.

Besides this, TRL / TRM calibration assumes that the lead-in / lead-out replicas to the Thru, Reflect, Line and Match standards are identical to the actual lead-in and lead-out structures to the DUT. Even when implementing them on the same PCB as the 'Fixture - DUT - Fixture' structure and applying best impedance control, this is impossible. These standards will always be at a different position on the PCB, take a different path along the PCB's fiber weave structure and therefore will have different impedance profiles over the length of their trace, compared to the lead-ins and lead-outs to the DUT itself. These differences are particularly critical for longer lead-ins and lead-outs and at higher signal bandwidths and strongly reduce measurement accuracy with TRL / TRM calibration. Impedance corrected de-embedding (see section 2.3) provides a major advantage here, as it accurately models the actual DUT lead-ins / lead-outs with their own impedance profiles, which are often different from the impedance profiles of the lead-in / lead-out replicas in the used TRL / TRM calibration standards.

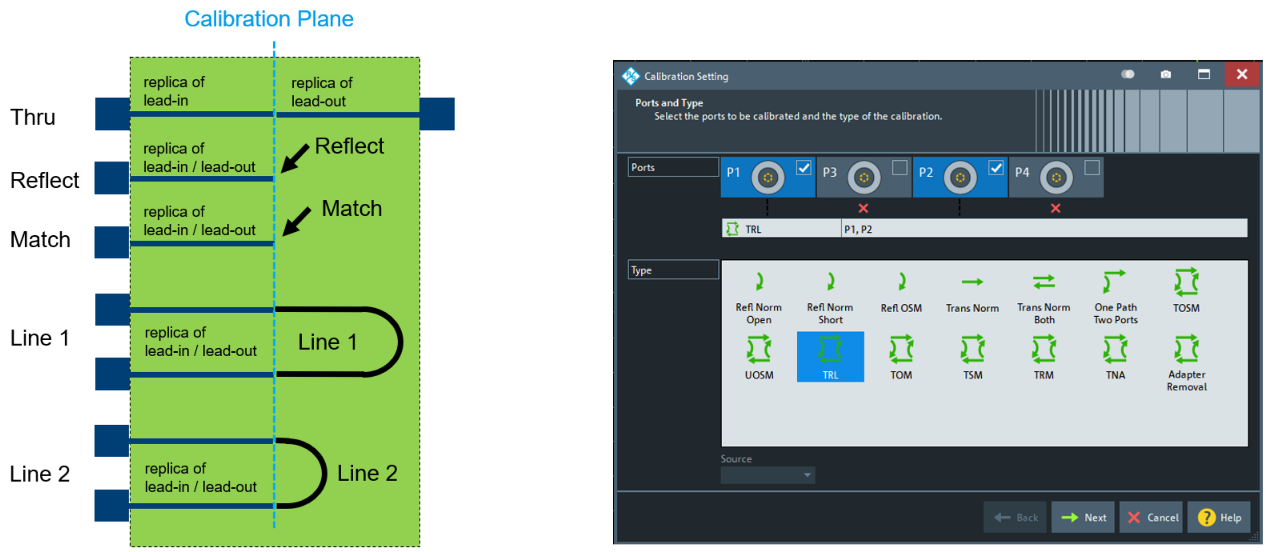

Figure 4 - TRL calibration standards for a single-ended measurement and selection of TRL calibration in R&S®ZNA, R&S®ZNB, R&S®ZNBT and R&S®ZND

1.2 Test fixture characterization for oscilloscope measurements

Measurements with oscilloscopes or other test instruments often have lead-in and lead-out structures between the test equipment and the Device under Test, which need to be de-embedded to have the reference plane right at the DUT. For best accuracy, the characterization of the lead-ins and lead-outs is typically done with a Vector Network Analyzer.

Figure 5 shows a typical setup for a System on Chip (SoC) on a test board. The SoC typically needs to be measured at its balls, where it is soldered onto the PCB. Sometimes, even measurements up to the bumps of the die are of interest. In both cases, the signal path between the test equipment (e.g. oscilloscope or arbitrary waveform generator) and the desired reference plane is best characterized with a VNA. The resulting S-Parameters are then exported from the VNA to the scope or AWG and used by these instruments to move the reference plane to the package or even up to the die.

An additional challenge here is the fact that oscilloscopes and AWGs do require S-Parameter files for de-embedding down to DC (0 Hz), however measurements with a Vector Network Analyzer cannot be done down to DC. Due to that, an accurate and complete lead-in measurement with the VNA also needs to include a sophisticated DC extrapolation, accurately modeling the signal path at low frequencies and calculating the S-Parameters down to the DC point.

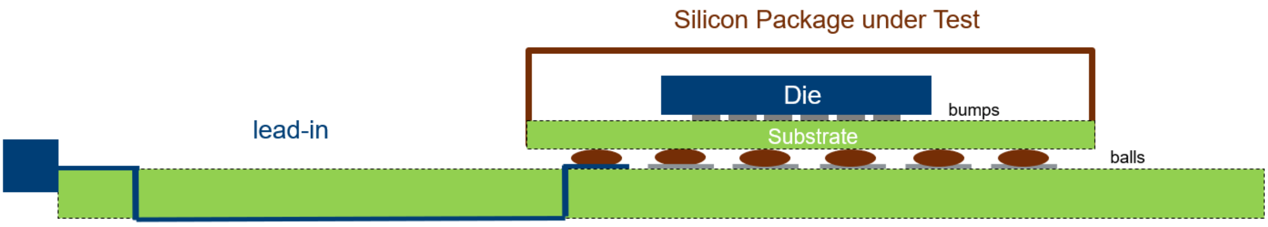

Figure 5 – SoC measurement with an oscilloscope. For accurate de-embedding the lead-in is typically measured with a VNA.

The measurement of the signal trace to the SoC is often made with a PCB probe in absence of the SoC. The probe is connected to the solder pads underneath the SoC and the S-Parameters of the trace between probes and coaxial connectors are measured with a VNA. Depending on the availability of related ground pads, typically probes with GSSG (Ground-Signal-Signal-Ground) or SS (Signal-Signal) footprints are used. Figure 6 shows an example, using an SS-probe. In this example, the probe is characterized, using a 1x-Open (probe pins open) and a 1x-Short (probe pins shorted). The probe is then de-embedded from the measurement, initially resulting in a reference plane position right at the probe tips. Using the parameter "Scaling for flight time" in the advanced settings of the R&S de-embedding solution (see Figure 7), the reference plane can be slightly pushed forward or pulled back. For good de-embedding results, it is recommended to slightly push the reference plane forward into the lead-in. This establishes some distance between the reference plane and the discontinuity at probe tips and solder pads and improves the accuracy of the measurement results. Another challenge is the effect of a varying contact resistance between probe tips and pads. The probe contact resistance will have different values when connecting to the de-embedding reference structures (here 1x-Open and 1x-Short) and to the solder pads at the actual lead-in to the DUT. This causes different impedance profiles in the signal paths of the probe to the used de-embedding reference structures and the actual lead-in and affects the accuracy of traditional de-embedding. This can be overcome with impedance corrected de-embedding (see section 2.3).

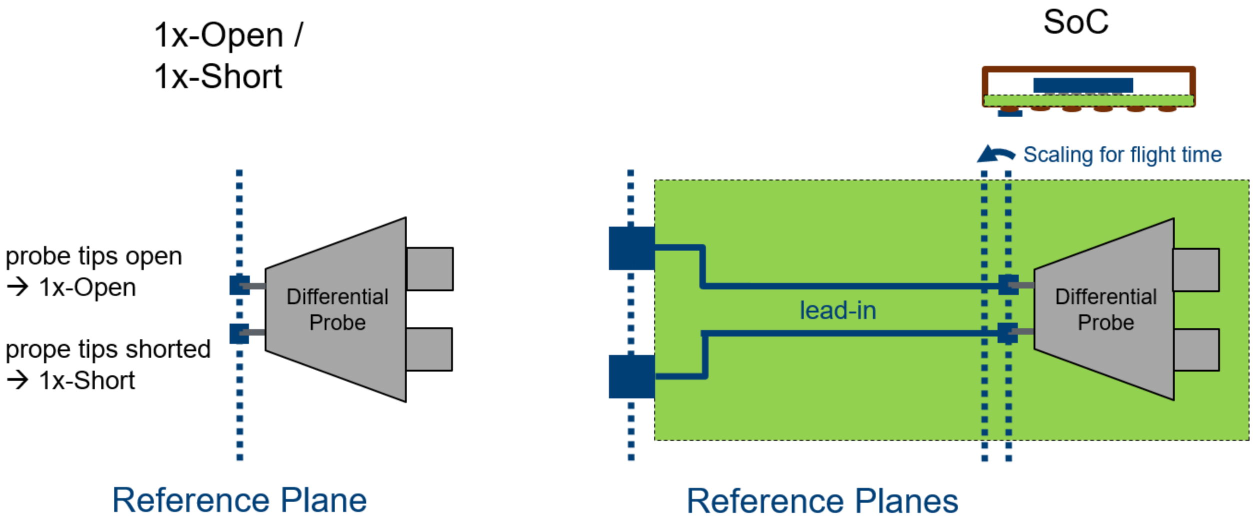

Figure 6 – Measurement of the lead-in to an SoC with an SS probe. The probe is characterized, using a 1x-Open and a 1x-Short reference structure. For best de-embedding results, the reference plane is slightly pushed into the lead-in and away from the probe tips.

[Figure 7](#) shows a measurement example on a demo PCB. The probe is de-embedded from the measurement and the resulting S-Parameters of the signal trace are extrapolated down to DC. The screenshot on the right shows an example of the advanced settings in R&S®ZNx-K220 / ISD with “Scaling for flight time” and “DC extrapolation”.

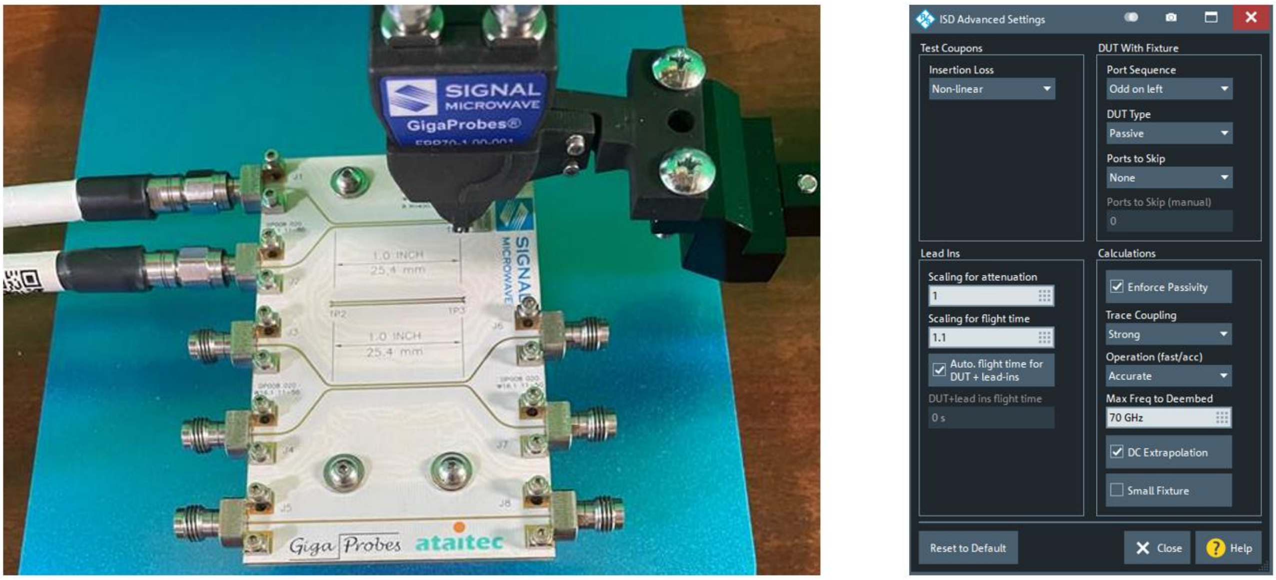

Figure 7 - Measurement of a PCB signal trace with a VNA. For an accurate measurement of the signal trace, the probe is characterized and de-embedded from the measurement.

1.3 Test fixture characterization and de-embedding in R&S VNAs

To simplify the process of test fixture characterization and de-embedding, R&S has integrated the de-embedding workflow into the Vector Network Analyzers R&S®ZNA, R&S®ZNB, R&S®ZNBT and R&S®ZND. The workflow implementation assists the user in the definition of the DUT, the characteristics of the test fixture and the selection of the used de-embedding structure(s) and guides the user through the steps of the whole de-embedding process.

Rohde & Schwarz has integrated the following industry-leading de-embedding tools. The algorithms have been intensively used during the development of the IEEE Std 370:

- R&S®ZNx-K210: Workflow integration of the Open Source De-embedding Algorithm, provided with the IEEE Std 370 (EZD – Easy De-embedding).
- R&S®ZNx-K220: Workflow integration of the Ataitec In-Situ De-embedding Algorithm (ISD).
- R&S®ZNx-K230: Workflow integration of the Clear Signal Solutions Smart Fixture De-embedding Algorithm (SFD).

2 Test Fixture Characterization and De-embedding: How it works and how to get best results

2.1 De-embedding structures

Test fixture modeling and characterization requires reference structures, often called de-embedding structures or de-embedding coupons, which need to be replicas of the lead-ins and lead-outs in the 'Fixture - DUT - Fixture' structure. Typically, the following de-embedding structures are being used, with the 2x-Thru coupon being the most common:

- 2x-Thru: reference structure, mirroring the lead-in / lead-out at the reference plane to the DUT

- 1x-Open: reference structure as replica of the lead-in / lead-out to the reference plane at the DUT, terminated by an open

- 1x-Short: reference structure as replica of the lead-in / lead-out to the reference plane at the DUT, terminated by a short

For a symmetric structure with lead-ins and lead-outs, the same de-embedding coupons can be used for the left side as well as for the right side. In case lead-ins and lead-outs are different, separate coupons have to be used, as shown in Figure 8.

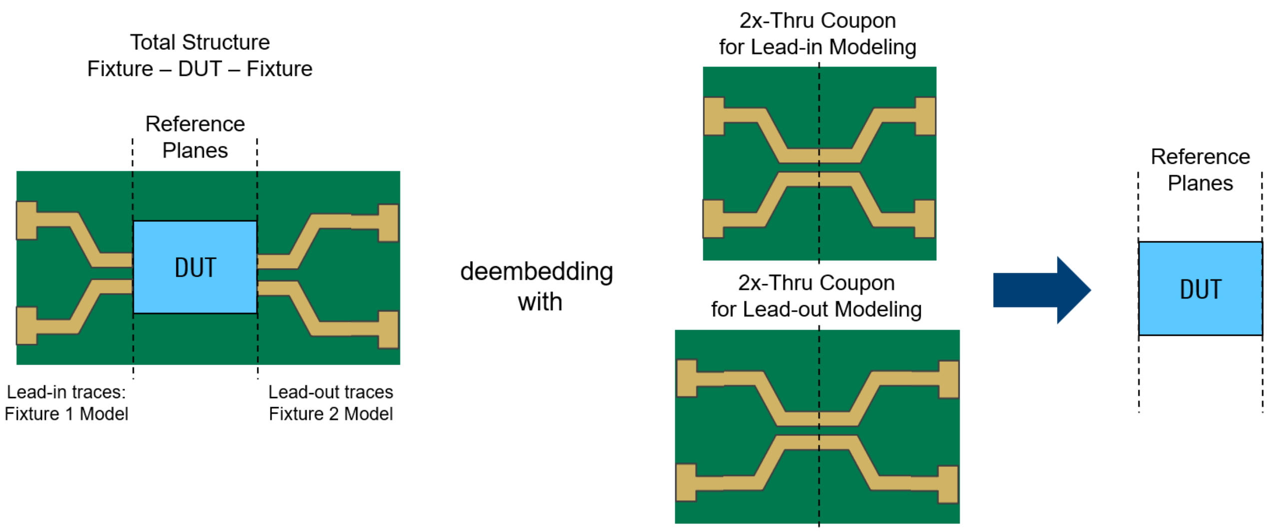

Figure 8 – Example for an asymmetric structure. 2x-Thru coupons are used for test fixture characterization and de-embedding. Lead-in and Lead-out traces are different and require separate coupons for de-embedding

2.2 De-embedding workflow

The De-embedding Assistant in R&S®ZNA, R&S®ZNB, R&S®ZNBT and R&S®ZND guides the user through the de-embedding workflow, first by letting the user configure the topology of the total 'Fixture - DUT - Fixture' structure. Here, both the type of the DUT as well as the characteristics of the test fixtures are defined. Figure 9 shows an example for a balanced DUT with a differential input and a differential output. Lead-ins and lead-outs are uncoupled, i.e. characterized with single-ended models for de-embedding, using s2p files. The total structure in this example is symmetrical, i.e. the same coupon is used for characterizing left-side (lead-in) and right-side (lead-out) fixture.

Figure 9 – Topology configuration of the 'Fixture - DUT - Fixture' structure.

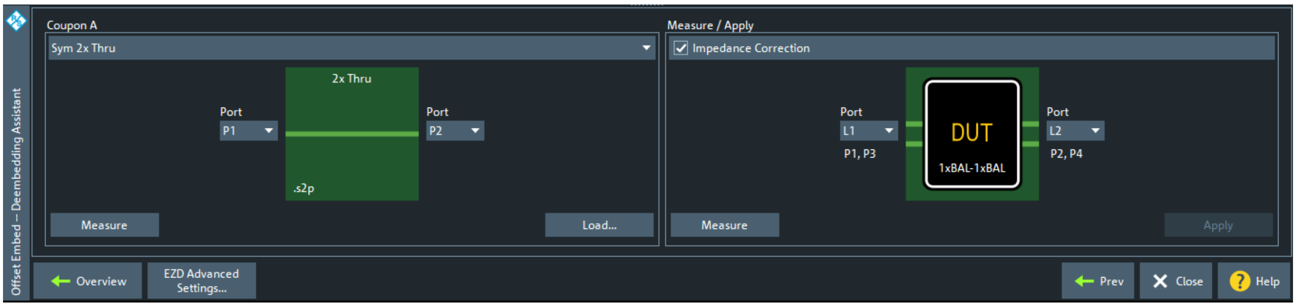

Figure 10 – De-embedding workflow for impedance-corrected de-embedding, following the topology configuration in Figure 9.

Based on this topology, the de-embedding workflow in Figure 10 guides the user through the following 3 steps. For impedance corrected de-embedding all 3-steps are required, for traditional de-embedding without impedance correction, step 2 is skipped:

1.) Selection and measurement of the de-embedding structures:

The 2x-Thru coupon, mirroring the lead-in and lead-out, is typically easy to implement and provides an accurate and well-defined de-embedding structure. It provides the best results in fixture modelling and is therefore the first choice in de-embedding.

Where a 2x-Thru coupon is not possible or not available, either a 1x-Open or a 1x-Short coupon is used. The 1x-Open coupon is also easy to implement. Due to its undefined fringe effects, it however delivers the least accurate de-embedding results and is mainly used, when neither a 2x-Thru nor a 1x-Short coupon is available. Better results can be obtained with a 1x-Short coupon. Using a combination of 1x-Open and 1x-Short can further increase the accuracy, in some cases even almost up to the level that is achieved with a 2x-Thru coupon.

2.) Measurement of the total structure:

For impedance-corrected de-embedding, a second step is required. The total ‘Fixture – DUT – Fixture’ structure is measured to derive the fixture model with the impedance profile of the actual lead-in and lead-out. In traditional de-embedding without impedance correction, this step is skipped, because the fixture model is only derived from the de-embedding structure (e.g. 2x-Thru coupon), and its impedance profile matches the one of the used de-embedding structure (e.g. the used 2x-Thru coupon) and not the impedance profile of the lead-in and lead-out really connected to the DUT. These profiles are typically quite different. Therefore, traditional de-embedding without impedance correction typically does not completely remove the lead-ins and lead-outs from the measurement, often creating phantom limbs in the de-embedding result (see section 2.3).

3.) Test fixture modeling and de-embedding:

When hitting the Apply button, the de-embedding tool calculates the models for lead-in and lead-out and its related S-Parameters, based on the measurements of de-embedding coupons and total 'Fixture - DUT - Fixture' structure. If selected in the advanced settings, also the extrapolation to the DC point is performed. The S-Parameters of the lead-in and lead-out models are then loaded into the VNA's de-embedding engine. In case they are required for de-embedding in an oscilloscope, AWG or other instrument, they can be exported from the VNA and imported into this other instrument.

2.3 De-embedding with and without impedance correction

Implementing de-embedding coupons that are identical replicas of the lead-ins and lead-outs to the DUT is practically impossible, both because of the general tolerances in the PCB production process and because the characteristics of PCB signal traces differ with location and routing on the PCB. The impedance profile over the length of a signal trace e.g. varies with its position and orientation relative to the fiber weave structure of the PCB and its routing through the layer and via structure of the board. Same applies for cables, where cable impedances are never identical, but always follow certain tolerances.

Traditional test fixture modeling without impedance correction assumes that the de-embedding coupons are an identical replica of the lead-ins and lead-outs in the 'Fixture - DUT - Fixture' structure, also having an identical impedance profile. The test fixture model therefore is only created from the de-embedding coupon itself.

Particularly at the higher bandwidths used in modern technologies, this assumption is no longer correct and significantly impacts the accuracy of the results. The quality of the de-embedding results highly increases with the accuracy of the fixture model and how well it represents the impedance profile of the actual lead-ins and lead-outs. Due to that, impedance corrected de-embedding has become a general recommendation in the industry. Modern de-embedding tools like R&S ZNx-K210 (EZD), ZNx-K220 (ISD) and ZNx-K230 (SFD) model the lead-ins and lead-outs of the 'Fixture - DUT - Fixture' structure as they are and with their real impedance profiles and deliver highly accurate results. To do so, impedance corrected de-embedding not only requires the measurement of the de-embedding coupon, but also the measurement of the total structure, to derive the corresponding test fixture model.

Only in cases where coupon and fixture are identical structures, it is not required to use impedance correction. An example is a test board, where the DUT is placed in a test socket or directly on the board and can be removed during the coupon measurement and loaded for the measurement of the full ‘Fixture – DUT – Fixture’ structure. Aside from possible variation of contact resistance between test socket and DUT, de-embedding without impedance correction might be sufficient. It however is strongly recommended to still compare the results with impedance corrected de-embedding to evaluate potential effects of varying contact resistance.

The test of a MultiGBase-T1 Automotive Ethernet inline connector in Figure 3, is typical example for the need of impedance corrected de-embedding. As shown in Figure 11, the cable impedances of lead-in (98 Ω), lead-out (102 Ω) and 2x-Thru (100 Ω) are not identical. Traditional de-embedding without impedance correction erroneously models the lead-in and lead-out with the 100 Ω cable impedance of the used 2x-Thru cable, producing phantom limbs in the de-embedding result (Figure 12). With impedance-corrected de-embedding, the lead-in and lead-out are correctly modeled with their real impedance profiles (98 Ω for the lead-in and 102 Ω for the lead-out). The de-embedding result shows the true behavior of the inline connector without any phantom limbs (Figure 13).

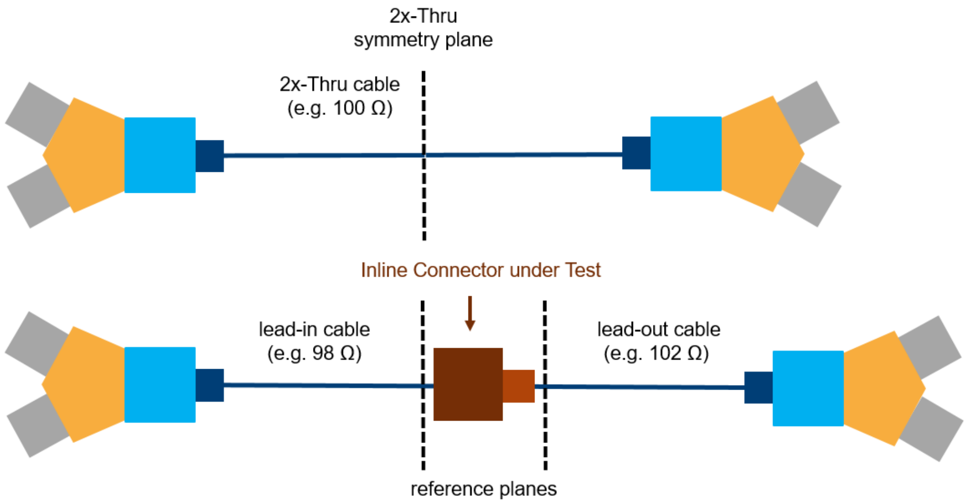

Figure 11 - Measurement example (Figure 3) of an inline connector for MultiGBASE-T1 Automotive Ethernet, comparing de-embedding results with and without impedance correction. For accurate test fixture modelling, the reference planes are placed with some distance to the discontinuities of the inline connector. De-embedding results therefore include a short section of cable on either side of the connector. The 2x-Thru cable is derived by mirroring lead-in / lead-out cable at the reference plane.

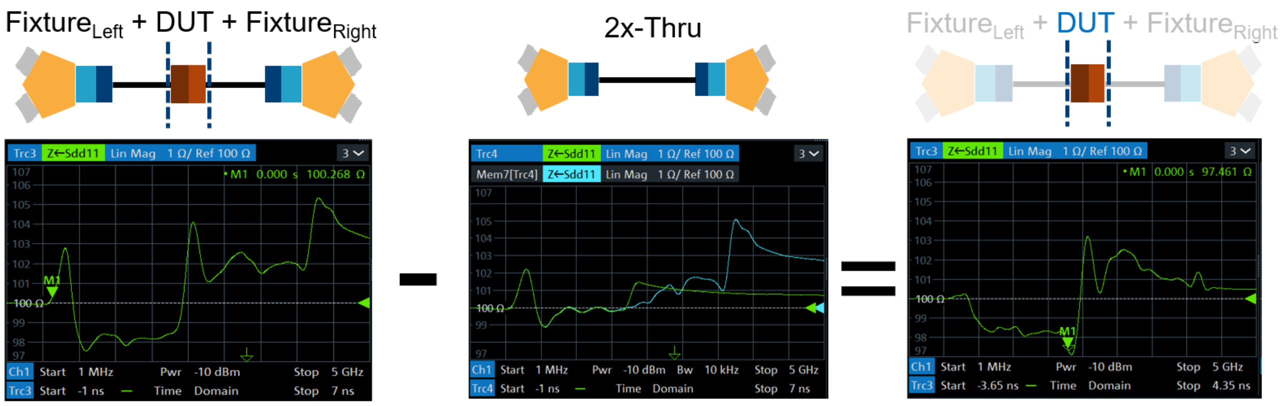

Figure 12 – Traditional de-embedding without impedance correction: The diagram on the left shows the impedance profile of the total structure with the 98 Ω impedance profile of the lead-in and the 102 Ω impedance profile for the lead-out as well as the inline connector in the middle. The model for the left fixture (diagram in the middle: green trace) is directly generated from the 2x-Thru cable, matching its 100 Ω impedance profile (diagram in the middle: blue trace). The lead-in is not correctly modeled, same applies to the lead-out. The diagram on the right shows that lead-in and lead-out are not properly removed, leaving phantom limbs in the de-embedding result.

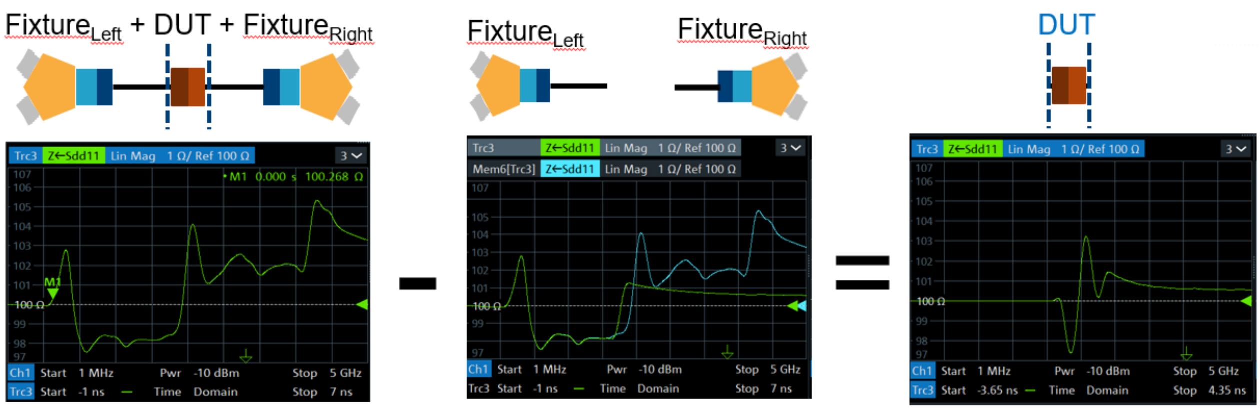

Figure 13 - De-embedding with impedance correction: The diagram on the left again shows the impedance profile of the total structure with the 98 Ω impedance profile of the lead-in and the 102 Ω impedance profile for the lead-out as well as the inline connector in the middle. The model for the left fixture (diagram in the middle: green trace) is properly generated, matching the 98 Ω impedance profile of the lead-in (diagram in the middle: blue trace). The same applies to the lead-out. The diagram on the right shows that lead-in and lead-out are completely removed, leaving no phantom limbs in the de-embedding result. It shows the true characteristics of the inline connector with a short section of cable on either side of the connector.

2.4 Test fixture performance criteria

To achieve good de-embedding results, both a good test fixture and a good de-embedding tool with accurate impedance correction is required.

In the ideal case, the test fixture in the total 'Fixture - DUT - Fixture' structure would have ideal lead-ins and lead-outs (low insertion loss, high return loss, low crosstalk, low mode conversion, etc.) and the used de-embedding coupons would be an ideal replica of the lead-ins and lead-outs of the total structure, with the same impedance profiles over the length of their trace. The de-embedding coupons therefore should be implemented on the same PCB with their traces being oriented in the same direction, routed on the same PCB layers and using the same layer transitions and test point launches as in the total structure.

Even with the highest efforts in test fixture design, these ideal conditions can only be met to a certain extent. Besides the above test fixture design criteria, IEEE Std 370 therefore defines 3 different classes of test fixtures, Class A, B and C. Class A has the most stringent design requirements and Class C the least. For similar de-embedding results, Class A fixtures could be de-embedded with a less sophisticated de-embedding tool, whereas Class C fixtures need the most sophisticated tool. As test fixture characteristics also change with the frequency and test fixtures often are Class A or Class B for lower frequencies and Class B or Class C for higher frequencies, a more sophisticated de-embedding tool allows to use a given test fixture also up to higher frequencies.

Table 1 below shows the fixture performance characteristics according to the IEEE Std 370.

	Class A limit	Class B limit	Class C limit
Insertion loss of 2x-Thru	-10 dB	-15 dB	-15 dB
Return loss of 2x-Thru	-20 dB	-10 dB	-6 dB
Insertion loss minus return loss of 2x-Thru	5 dB	0 dB	0 dB
'Fixture - DUT - Fixture' crosstalk minus 'Fixture - Fixture' crosstalk (using dogleg / spiderleg structure)	6 dB	6 dB	6 dB
Impedance variation between 2x-Thru coupon and actual lead-ins / lead-outs	+/- 2.5%	+/-5%	+/-10%
Line to line or pair to pair skew between lead-ins / lead-outs / 2x-Thru halves	1 / (10 x fmax) for 50 GHz: 2 ps	1 / (10 x fmax) for 50 GHz: 2 ps	1 / (10 x fmax) for 50 GHz: 2 ps
Min length of 2x-Thru	3 wavelengths at highest frequency	3 wavelengths at highest frequency	3 wavelengths at highest frequency
Additional requirement for mixed mode de-embedding: Differential to common mode conversion loss minus insertion loss	- 15 dB	- 15 dB	-15 dB

Table 1 - Fixture electrical requirements (FER) according to IEEE Std 370

An example of a 2x-Thru measurement is shown in Figure 14 below. According to Table 1, the return loss (S11) is Class B over the entire frequency range since it is between -20 dB and -10 dB. The insertion loss (S21) never exceeds -10 dB, so it exhibits Class A performance for insertion loss. The insertion loss minus return loss exceeds 5 dB starting at around 35 GHz, thus it exhibits Class A performance below 35 GHz for this performance characteristic. Overall, due to return loss performance, it would be considered a Class B test fixture for the entire range from 10 MHz to 40 GHz.

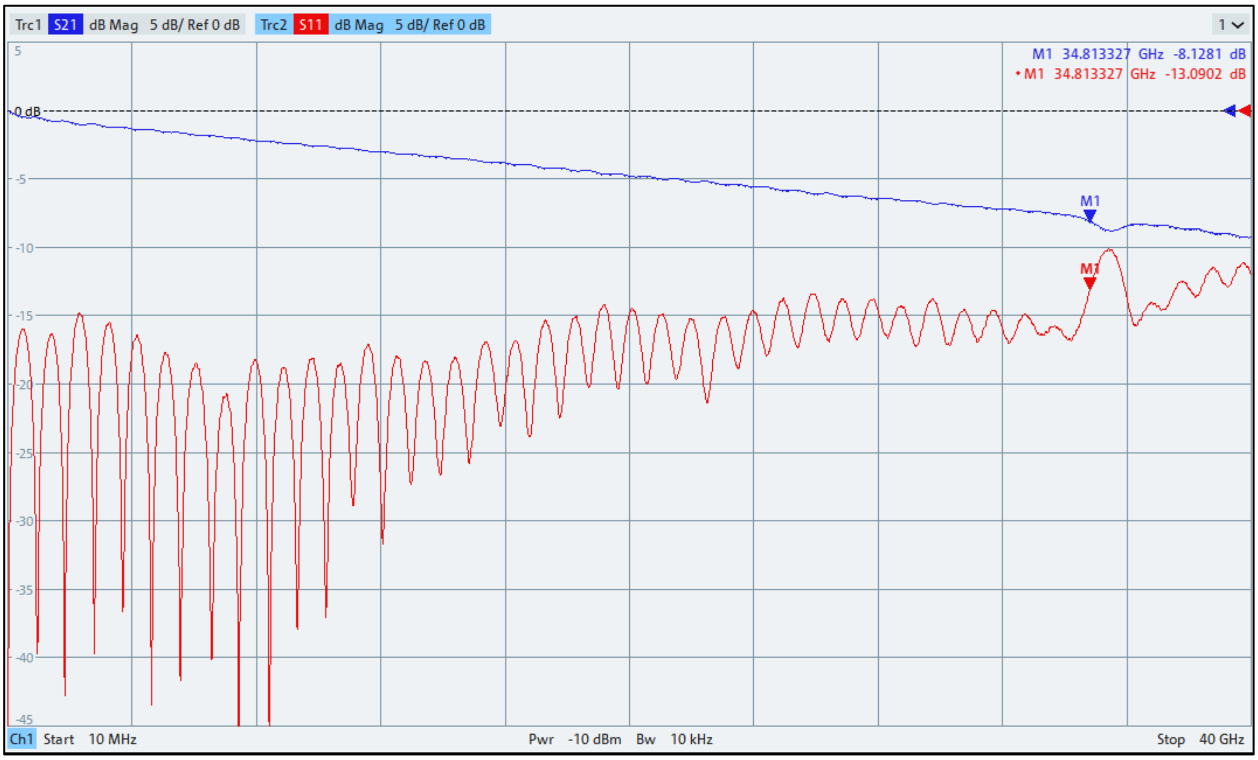

Figure 14 - Test fixture performance verification: measuring the 2x-Thru of a PCIe 5.0 CEM connector test fixture with R&S®ZNA43

2.5 Recommended frequency range and sweep settings

The de-embedding algorithm transforms frequency domain measurements into the time domain to derive the model of the used test fixture. As a higher frequency range provides better time domain resolution, it also increases the accuracy of the fixture model. For best de-embedding results, it is therefore recommended to choose a sophisticated de-embedding tool and to model the fixture over the entire frequency range where it meets Class A, B or C limits, even if the DUT itself only needs to be measured up to a lower frequency. In the example of the PCIe 5.0 CEM connector in Figure 2 and Figure 14, the connector needs to be verified up to 24 GHz. Measuring the 2x-Thru and total 'Fixture - DUT - Fixture' structure up to 24 GHz already provides good test fixture models and good de-embedding results. Accuracy of the test fixture models and de-embedding results however can be further increased by characterizing the test fixture all the way up to 40 GHz.

The step size of the VNA's frequency sweep is another important parameter. It defines the unambiguous range of the time domain measurement and needs to be chosen according to the maximum expected flight time or electrical length of the structure. For good de-embedding results, the step size should be chosen low enough to have a sufficient number of points per 360º phase change in the transmission measurement. As a minimum, at least 8 points are required per 360º phase change, i.e. at least 8 points per the number of wavelengths in the structure for the highest frequency point. For example, a structure with a flight time of 2 ns, that is characterized up to 40 GHz has at this maximum frequency a length of 2 ns / (1 / 40 GHz) = 80 wavelength and needs to be measured with at least 8 x 80 = 640 points. For increased de-embedding accuracy however a higher number of sweep points is highly recommended.

To get the maximum time domain resolution for the useable frequency range of the test fixture, de-embedding algorithms typically apply the low pass mode to transform the frequency domain into the time domain. This requires the sweep to be defined in a harmonic grid, where the start frequency is an integer multiple of the step size of the VNA. With this, the low pass mode allows to extract the DC point and to mirror the negative frequencies, thereby doubling the effective TDR resolution and hence also the resolution of the fixture model.

Based on that, the recommended VNA sweep settings are:

Start frequency and step size:

Start frequency and step size are typically identical and chosen according to the maximum expected electrical length of the structure and the required granularity in the frequency domain. A very common value is 10 MHz.

Stop frequency

The stop frequency should be as high as possible, fully using the frequency range of the test fixture, where it meets Class A, B or C limits. It must be at least as high as the maximum frequency of the DUT, preferably even higher. Due to the required harmonic grid, the stop frequency needs to be an integer multiple of the step size.

In order to provide the minimum required time domain resolution for the de-embedding algorithm, the full span (f_stop - f_start) should be at least 4 GHz or larger.

3 Test Fixture Characterization and De-embedding: Consistency Checks

As the Device under Test is typically unknown, the quality of the fixture model and the resulting accuracy of the de-embedding process is often difficult to judge from the measurement results of the de-embedded DUT. Therefore, IEEE Std 370 lists certain tests that can be used to verify the consistency of the de-embedding process itself. The methods described below are marked as normative in IEEE Std 370 and are widely used in the industry.

Below example measurements are made with the 'Fixture – DUT 2A - Fixture' and 'Fixture – DUT 2B - Fixture' structures on the R&S de-embedding demo board, shown in Figure 15 and Figure 16. For the 'Fixture - DUT 2A - Fixture' structure, lead-ins and lead-outs are designed to match the impedance profile of the 2x-Thru. The lead-ins of the 'Fixture - DUT 2B - Fixture' structure are intentionally designed with 5% higher impedance, the lead-outs with 5% lower impedance than the 2x-Thru to show the effects of non-matching impedance profiles and to compare the de-embedding processes with and without impedance correction.

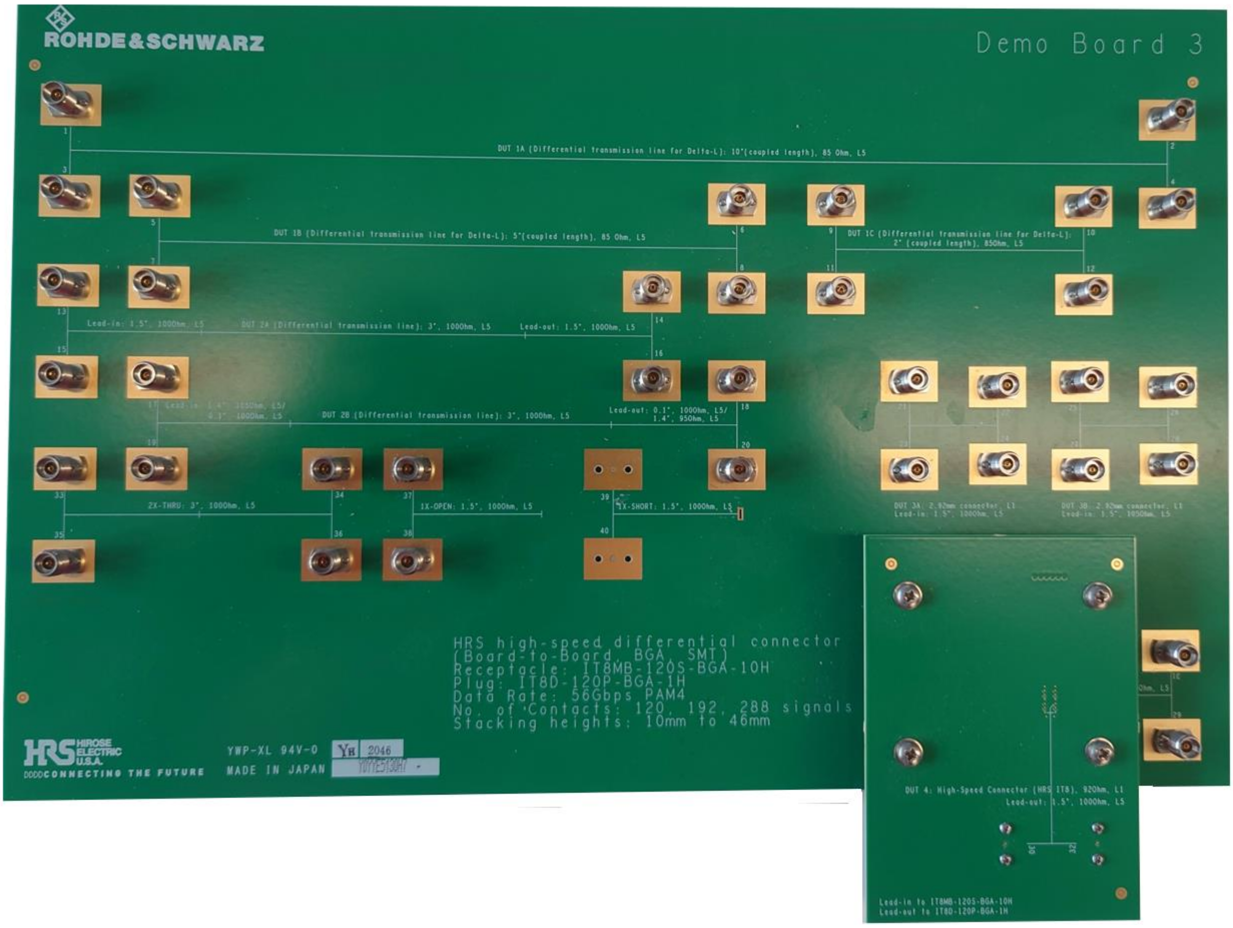

Figure 15 - R&S de-embedding demo board with differential signal structures

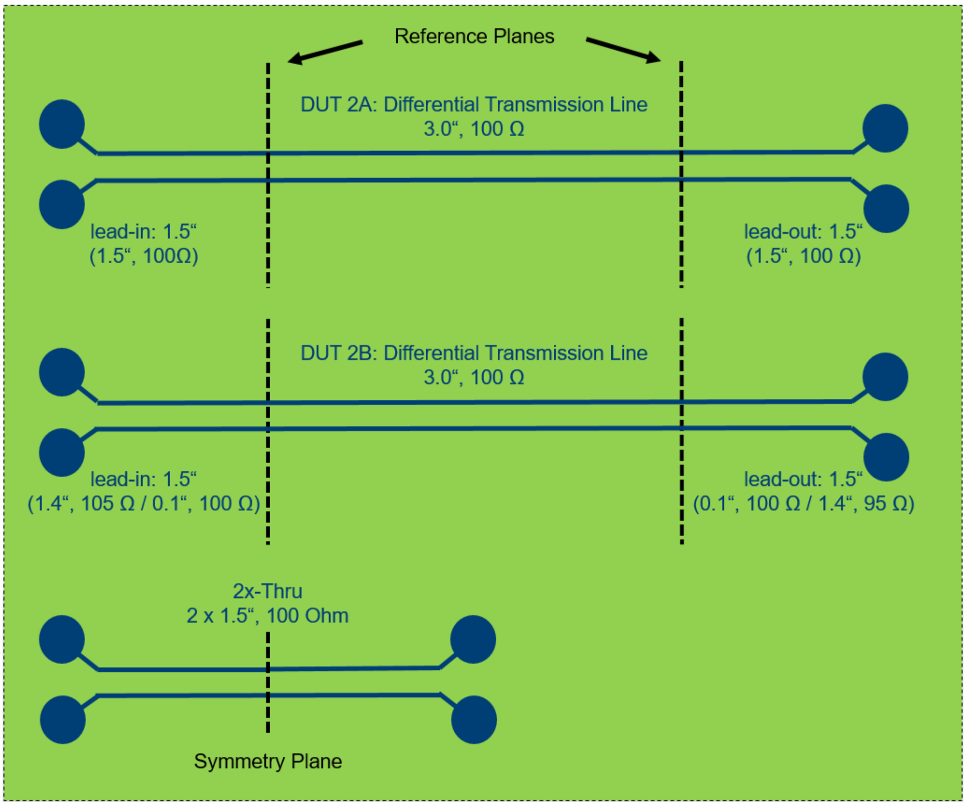

Figure 16 - R&S de-embedding demo board: Schematics of 'Fixture – DUT 2A - Fixture' and 'Fixture – DUT 2B - Fixture' structures as well as the used 2x-Thru coupon. All impedances are nominal values with a tolerance of ± 10%.

3.1 Comparing TDR impedance of fixture model and 'Fixture - DUT - Fixture' structure

For good de-embedding results, the de-embedding tool should accurately model the lead-ins and lead-outs in the 'Fixture - DUT - Fixture' structure, also correctly representing their actual impedance profile. The better they match, the better the quality of the model and the better the accuracy of the de-embedding results. A very useful consistency test therefore is to compare the TDR impedance of the derived fixture models on the left ('Fixture 1' model for the lead-in) and right side ('Fixture 2' model for the lead-out) with the TDR impedance of the actual lead-ins and lead-outs of the 'Fixture - DUT - Fixture' structure by displaying:

- TDR impedance of 'Fixture 1' model and 'Fixture - DUT - Fixture' structure
- TDR impedance of 'Fixture 2' model and reversed 'Fixture - DUT - Fixture' structure

For a comparison with the used 2x-Thru, it also can be helpful to display the TDR impedance of the used 2x-Thru coupon(s) together with the TDR impedance of the 'Fixture - DUT - Fixture' structure. This shows the difference in the impedance profiles between the used 2x-Thru(s) and the actual lead-ins and lead-outs in the total structure and the performance of the impedance correction in the fixture modelling.

Example 1: 'Fixture – DUT 2A - Fixture' structure on R&S de-embedding demo board

Figure 17 displays the impedance profiles (Z←Sdd11) seen from the left (lead-in) side, showing 'Fixture – DUT 2A - Fixture' structure (red trace) and the used 2x-Thru structure (blue trace). The fixture models are derived with impedance correction. The left fixture model (green trace) accurately follows the lead-in part of the 'Fixture – DUT 2A - Fixture' structure. Figure 18 displays the impedance profiles (Z←Sdd22) seen from the right (lead-out) side, showing the reversed 'Fixture – DUT 2A - Fixture' structure (red trace) and the reversed 2x-Thru structure (blue trace). The right fixture model (green trace) also accurately follows the lead-out part of the reversed 'Fixture – DUT 2A - Fixture' structure.

Figure 17 - Impedance corrected de-embedding with R&S®ZNA43: Consistency check, comparing the derived left fixture model (green trace) with the 'Fixture – DUT 2A - Fixture' structure (red trace) and the used 2x-Thru (blue trace).

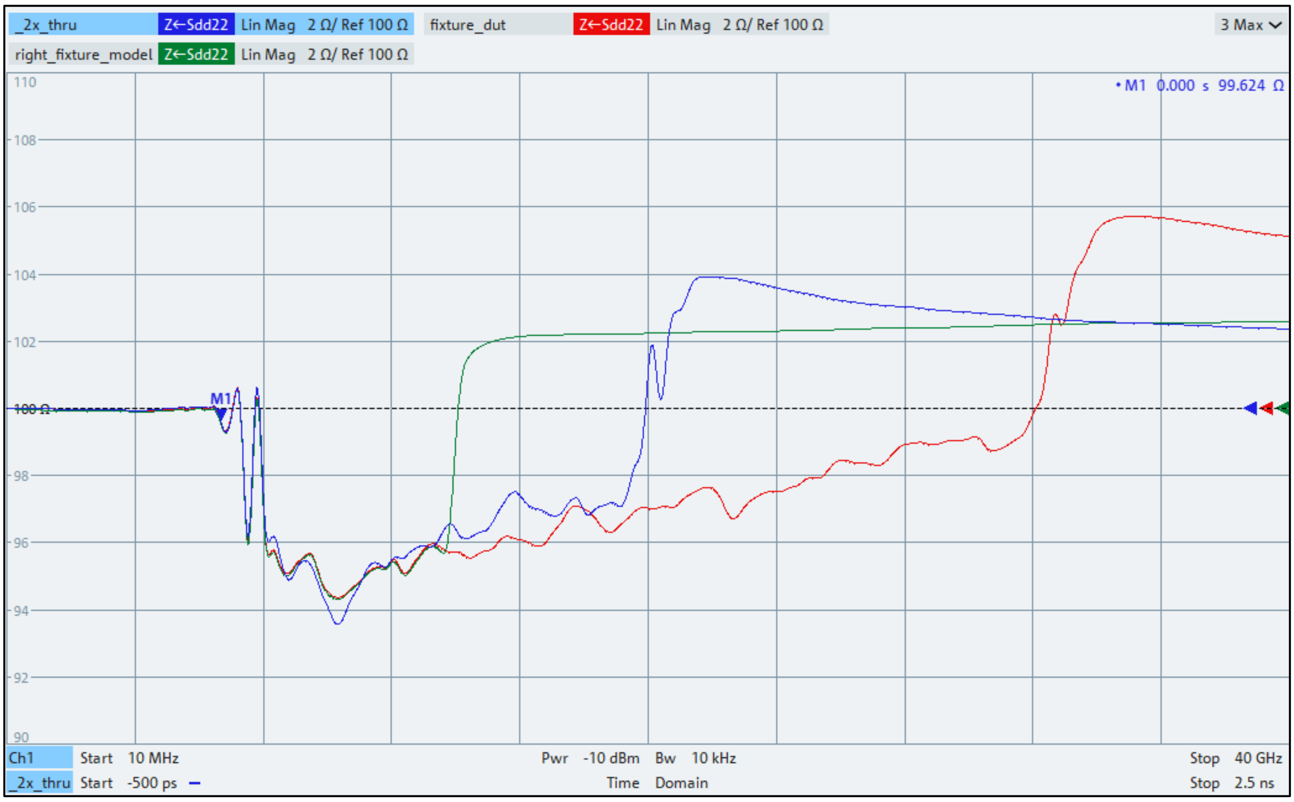

Figure 18 – Impedance corrected de-embedding with R&S®ZNA43: Consistency check, comparing the derived right fixture model (green trace) with the reversed 'Fixture – DUT 2A - Fixture' structure (red trace) and the reversed 2x-Thru (blue trace).

Example 2: 'Fixture – DUT 2B - Fixture' structure on R&S de-embedding demo board

In the same way, Figure 19 and Figure 20 respectively display the impedance profiles seen from the left (Z🡐Sdd11) and right (Z🡐Sdd22) side for the 'Fixture – DUT 2B - Fixture' structure. Thanks to the used impedance correction, the fixture models (green traces) again accurately follow the impedance profiles of the actual lead-in and lead-out, which in this example significantly differ from the 2x-Thru.

This consistency check provides excellent insights into the accuracy of the fixture models and how accurately they follow the actual lead-ins and lead-outs. It also provides a direct comparison to the used 2x-Thru. It is the method of choice to judge the quality of impedance corrected de-embedding.

Figure 19 - Impedance corrected de-embedding with R&S®ZNA43: Consistency check, comparing the derived left fixture model (green trace) with the 'Fixture – DUT 2B - Fixture' structure (red trace) and the used 2x-Thru (blue trace).

Figure 20 - Impedance corrected de-embedding with R&S®ZNA43: Consistency check, comparing the derived right fixture model (green trace) with the reversed 'Fixture – DUT 2B - Fixture' structure (red trace) and the reversed 2x-Thru (blue trace).

3.2 Self De-embedding of the used 2x-Thru

The self de-embedding method uses the fixture models, created from the 2x-Thru to de-embed the used 2x-Thru from itself. Using traditional de-embedding without impedance correction, the fixture model is just derived from the 2x-Thru. With impedance corrected de-embedding, the fixture model is derived from the 2x-Thru and the used 'Fixture – DUT - Fixture' structure, which is again the used 2x-Thru. The result in self de-embedding always is an electrically transparent interconnect with no loss and no phase shift, i.e. no residuals. IEEE Std 370 hereby defines the limits by a residual magnitude response (< 0.1 dB) and a residual phase response (< 1°).

For cases, where impedance corrected de-embedding is required, this method however has a major flaw. It does not include the measurement of the real 'Fixture – DUT - Fixture' structure with its actual lead-in and lead-out and cannot provide any information, how accurately they are modelled. This consistency check is a good indicator for the stability of the measurement, but only shows the quality of the de-embedding process in this self de-embedding scenario, where no impedance correction is required. It however cannot provide any insights into the de-embedding performance for the actual 'Fixture – DUT - Fixture' structure and how well the fixture models match the characteristics of the actual lead-ins and lead-outs. It produces good results, no matter if the fixture models match the lead-ins and lead-outs or not. In the example of the MultiGBASE-T1 Automotive Ethernet connector used in section 2.3, self de-embedding also shows good results for traditional de-embedding without impedance corrections and gives no indication about the risk of phantom limbs in the de-embedding results. This consistency check is very easy, but its results can be highly misleading and need to be used very carefully. It only describes the performance for a scenario, where traditional de-embedding without impedance correction is sufficient. In cases, where impedance-corrected de-embedding is required, the only meaningful consistency check is the comparison of the TDR impedances, described in section 3.1.

Figure 21 shows an example of this self de-embedding consistency test, using the 2x-Thru structure on the R&S de-embedding demo board with results for residual magnitude response and residual phase response.

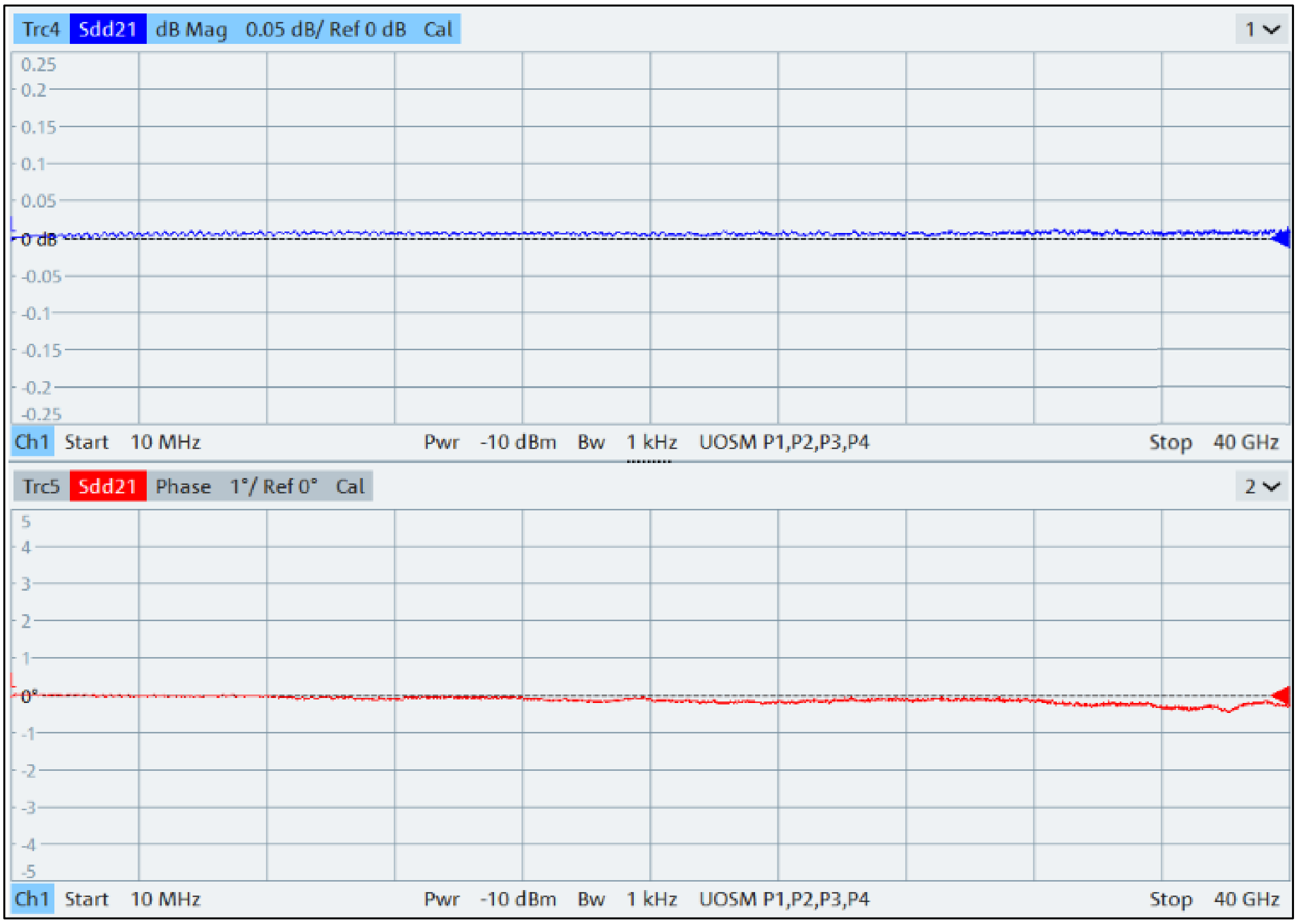

Figure 21 - De-embedding with R&S®ZNA43: Consistency check, self de-embedding the used 2x-Thru

4 Literature

[1] IEEE, "IEEE 370-2020 - IEEE Standard for Electrical Characterization of Printed Circuit Board and Related Interconnects at Frequencies up to 50 GHz," [Online]. Available: https://standards.ieee.org/standard/370-2020.html.

5 Ordering Information

For R&S ZNA Vector Network Analyzers:

Designation	Type	Order No.
Eazy De-embedding (EZD) for R&S®ZNA, meeting the requirements of IEEE Std 370	R&S®ZNA-K210	1339.3897.02
In-Situ De-embedding (ISD) for R&S®ZNA, meeting the requirements of IEEE Std 370	R&S®ZNA-K220	1339.3900.02
Smart Fixture De-embedding (SFD) for R&S®ZNA, meeting the requirements of IEEE Std 370	R&S®ZNA-K230	1339.3916.02

For R&S ZNB Vector Network Analyzers:

Designation	Type	Order No.
Eazy De-embedding (EZD) for R&S®ZNB, meeting the requirements of IEEE Std 370	R&S®ZNB-K210	1328.8592.02
In-Situ De-embedding (ISD) for R&S®ZNB, meeting the requirements of IEEE Std 370	R&S®ZNB-K220	1328.8605.02
Smart Fixture De-embedding (SFD) for R&S®ZNB, meeting the requirements of IEEE Std 370	R&S®ZNB-K230	1328.8611.02

For R&S ZNBT Vector Network Analyzers:

Designation	Type	Order No.
Eazy De-embedding (EZD) for R&S®ZNBT, meeting the requirements of IEEE Std 370	R&S®ZNBT-K210	1328.8634.02
In-Situ De-embedding (ISD) for R&S®ZNBT, meeting the requirements of IEEE Std 370	R&S®ZNBT-K220	1328.8640.02
Smart Fixture De-embedding (SFD) for R&S®ZNBT, meeting the requirements of IEEE Std 370	R&S®ZNBT-K230	1328.8657.02

For R&S ZND Vector Network Analyzers:

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Eazy De-embedding (EZD) for R&S®ZND, meeting the requirements of IEEE Std 370	R&S®ZND-K210	1328.8670.02
In-Situ De-embedding (ISD) for R&S®ZND, meeting the requirements of IEEE Std 370	R&S®ZND-K220	1328.8686.02
Smart Fixture De-embedding (SFD) for R&S®ZND, meeting the requirements of IEEE Std 370	R&S®ZND-K230	1328.8692.02

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Application Note | Accurate Test Fixture Characterization and De-embedding
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