

Keysight Technologies

# Characterization of PCB Insertion Loss with a New Calibration Method

Application Note

## Abstract

There are several existing techniques like Direct Loss Subtraction, THRU-Reflection-Line (TRL) calibration and Automatic Fixture Removal (AFR) with 2X THRU fixtures for characterizing PCB unit length insertion loss. In this application note, two methods will be discussed. 1) A new method for characterizing PCB loss by using AFR with 1X Open fixtures is proposed. This new method has been proven to have similar accuracy with TRL and AFR with 2X THRU, but can save much more PCB area and measurement time; 2) based on measurements and simulations of transmission lines with different reference impedance, the measurement bandwidth, accuracy, efficiency and cost of these techniques are compared.



## Introduction

It is critical to determine the PCB unit length loss characteristics for 1) material electrical parameters extraction; 2) PCB electrical performance estimation; 3) evaluation of the passive channel design; 4) PCB material selection; and 5) evaluation of the PCB fabrication quality, etc.

To characterize the insertion loss of the transmission lines on the PCB, test fixtures of coaxial to microstrip / stripline transitions (launches) are necessary to connect the PCB transmission line to the coaxial ports of the measurement instrument, such as a VNA or TDR. The test fixtures are not electrically transparent and their effects need to be removed from the total measurement.

There are several existing techniques like Direct Loss Subtraction, THRU-Reflection-Line (TRL) as well as Automatic Fixture Removal (AFR) with 2X THRU fixtures that can be utilized to remove the effects of the test fixtures and characterize only the insertion loss of the PCB transmission lines. All of these methods have some assumptions and limitations in real application.

## Direct Loss Subtraction

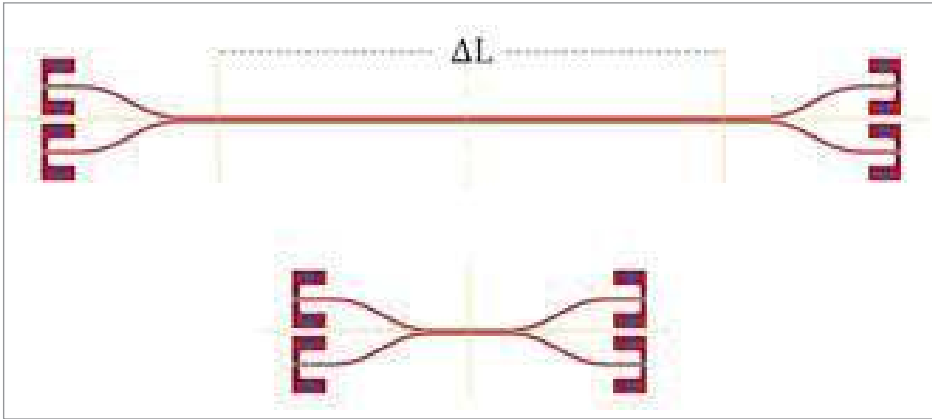


Figure 1. PCB insertion loss characterization with direct subtraction method

The concept of the direct loss subtraction is very simple and is shown in Figure 1. Fabricate two differential transmission lines on the PCB with different lengths. Mount coaxial connectors on the end of the transmission lines so that their S-parameters can be measured with the VNA directly using SOLT calibration, then the insertion loss of the short differential line is subtracted directly from the insertion loss of the longer line, resulting in the insertion loss of the PCB trace with length of  $\Delta L$ . This procedure is very similar to the response calibration in the VNA.

To use the direct loss subtraction method, two assumptions are made: the first is the launches in the short line is very consistent with that in the longer line; the second is the launch must have a very good match, otherwise, the mismatch of the transition parts will become residual error after subtraction and will be transferred to the insertion loss measurement of the PCB trace, causing ripples on the insertion loss characterization.

## TRL Calibration

TRL calibration is theoretically the most accurate method for in-fixture measurement calibration. It utilizes a set of calibration standards including a THRU, a Reflect and a delayed Line standard to calculate the error model. Several delayed Lines with different electrical lengths may be used to extend the calibration frequency. Sometimes a Match standard is used to cover the low frequency range because it is not practical to fabricate a very long Line standard.

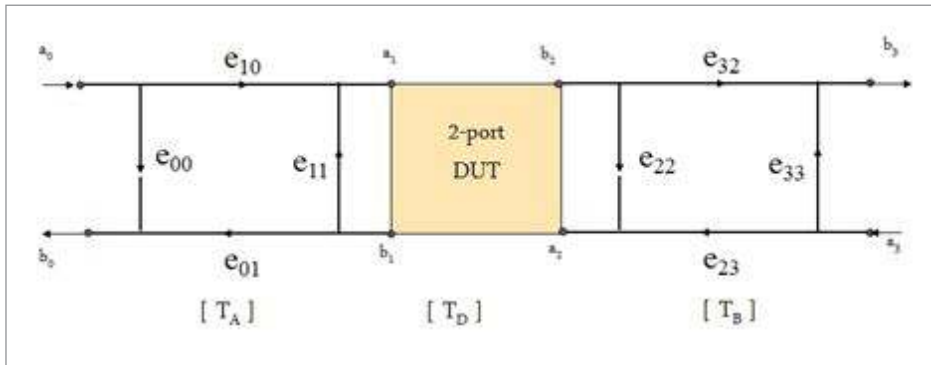


Figure 2. TRL calibration error model



Figure 3. A typical TRL calibration kit on PCB

Figure 2 shows the TRL calibration error model and Figure 3 shows a typical TRL calibration kit on a PCB. A total of 10 measurements are used to calculate the eight unknown error terms, four measurements are of the four S-parameters of the THRU standard, two measurements are of the Open standard on both ports, four measurements are of the four S-parameters of the delayed Line standard.

TRL calibration in theory seems to be a very simple and straightforward method. In reality, the engineer requires extensive experience in the design, fabrication and verification of the TRL cal kit. There are many limitations that restrain the accuracy of the calibration results, such as the phase difference between the THRU and Lines must be within  $(20 \sim 160) + N * 180$  degrees in the frequency range used, in which N is an integer, measurement uncertainty is much higher if the phase difference is close to  $N * 180$  degrees. The consistency between the coaxial connectors of the calibration standards are critical to good calibration accuracy. As the calibration reference impedance is determined by the delay Line, the impedance variation should be as small as possible. After the TRL calibration kit has been created, you also need to characterize the cal kit model and create a cal kit definition on the VNA, after that you can use the cal kit for your calibration. These limitations make TRL calibration complicated to implement for design engineers.

## Automatic Fixture Removal (AFR) with 2X THRU

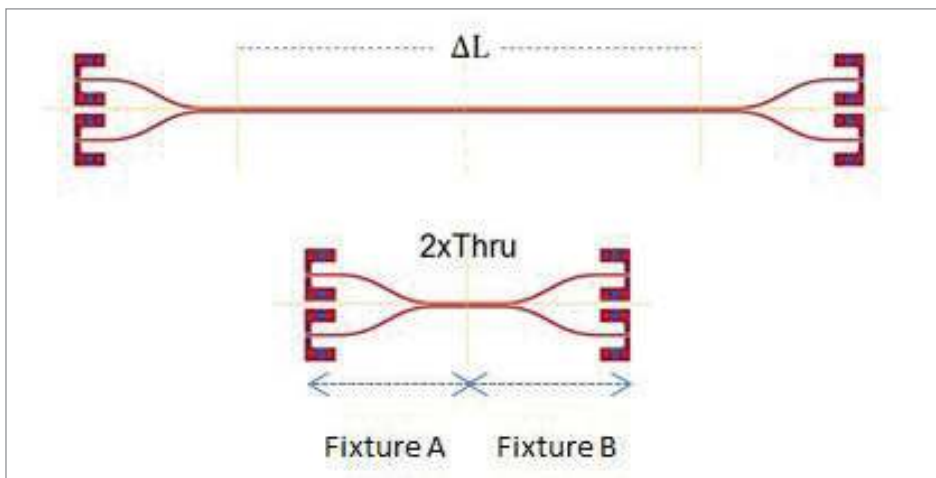


Figure 4. PCB loss characterization with 2X THRU AFR

The test structures used in 2X THRU AFR[1][2] (shown in Figure 4) for characterizing the PCB insertion loss is very similar to those used in the Direct Subtraction method, but 2X THRU is based on fixture model de-embedding[4] and is more accurate than the Direct Subtraction method. In 2X THRU AFR, the short line (or so called 2X THRU) can be mathematically separated to two parts – fixture A and fixture B based on time domain gating[3] and signal flow diagram calculations, then the extracted S-parameters of fixture A and fixture B can be de-embedded from the longer line measurement (so called DUT). The de-embedding result is the four S-parameters of the PCB trace with length of  $\Delta L$ .

The 2X THRU AFR also has some limitations. First, the launches of the shorter line must be consistent with that in the longer line, left to left, right to right respectively. Any inconsistency between the two will cause an error in the de-embedding model and error in the PCB insertion loss measurement. Second, the return loss and insertion loss of the 2X THRU must not cross each other in the frequency range concerned, often a 5 dB separation is required to make sure the fixture has wider bandwidth than the DUT. Otherwise, the de-embedding result may show some gain, which is not correct.

The 2X THRU AFR has been accepted by commercial companies like Huawei to replace TRL calibration in the PCB loss characterization process because it has been validated to have the similar accuracy with TRL calibration, but is much simpler.

## Characterization of PCB Insertion Loss with New 1X AFR

With the new method of 1X AFR using an Open standard which was introduced in early 2014, we can characterize the PCB loss with two Open fixtures of different lengths, shown in Figure 5. With this method, we can save half PCB areas than 2X THRU AFR. As the differential Open fixture requires a 2-port measurement rather than 4-port measurement of the 2X THRU, with 1X AFR we can save more calibration and measurement time.

The procedure of using 1X AFR in characterizing the PCB insertion loss is as follows:

1. Extract 4-port S-parameters of the Open fixtures from 2-port measurements

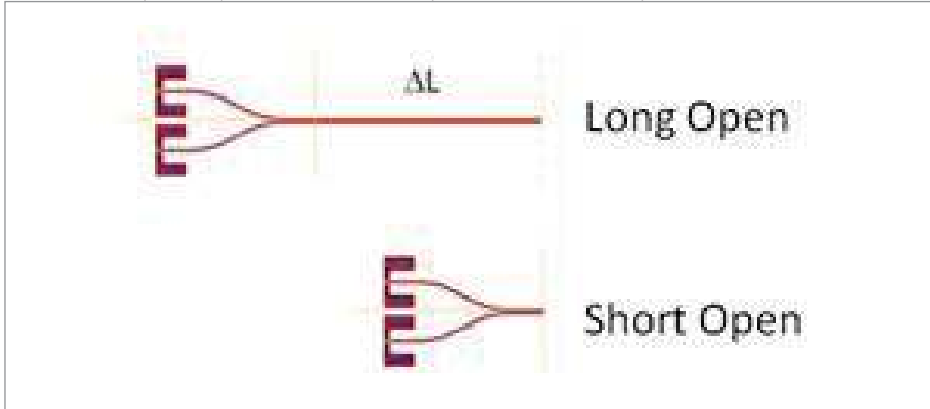


Figure 5. Two Open fixtures used for extracting PCB insertion loss with length of  $\Delta L$

With 1X AFR, the 4-port S-parameters of the two Open fixtures can be extracted from the 2-port Open measurements respectively. The characterization is also based on time domain gating and signal flow diagram, similar to the 2X THRU AFR.

Notice: The fixture extraction procedure above has been integrated in Keysight PLTS software and PNA firmware.

2. After the 4-port S-parameters of the two Open fixtures have all been acquired, the 4-port data of the short Open fixture can be de-embedded from the 4-port data of the long Open fixture, resulting in the 4-port S-parameters of PCB with length of  $\Delta L$ , from which the differential insertion loss can be determined.

The 1X AFR also has some limitations. First, similar to 2X THRU AFR, the launches of the two Opens must be consistent. Any inconsistency between the two will cause error in the de-embedding model and error in the PCB insertion loss measurement. Second, the impedance variations of the PCB traces must be as small as possible, especially when getting close to the Open end. As bandpass time domain gating is used to extract the fixture insertion loss from the Open measurement in 1X AFR, the mismatch close to the Open response may still be included after gating and may cause ripples on the extracted insertion loss. This effect will be discussed in more detail.

## Comparisons of Different Methods in Characterizing PCB Insertion Loss with Simulations

To validate the performance of the new 1X AFR and compare the results of all the above methods, ADS simulations were used to create the test structures of the PCB trace without launch, the two 2X THRU and the two Open fixtures with different lengths. S-parameter simulations can be done to acquire all the S-parameters of these structures. After that, Direct Loss Subtraction, 2X THRU AFR and 1X AFR are used to characterize the insertion loss of the PCB trace and compared to the actual data. The lengths of all the structures are shown in the table below.

Dielectric Constant: 3.85

	Line length (mil)
PCB trace length without launches	11000
Launch	150
2X THRU AFR Longer line (Direct Subtraction longer line)	11300
2X THRU AFR Shorter line (Direct Subtraction shorter line)	1300
1X AFR Longer Open	11150
1X AFR Shorter Open	1150

Reference impedance of 100 ohm and 90 ohm are validated respectively. Two cascaded short transmission lines with impedance of 104 ohm and 92 ohm are used to emulate the impedance variations on coaxial connectors.

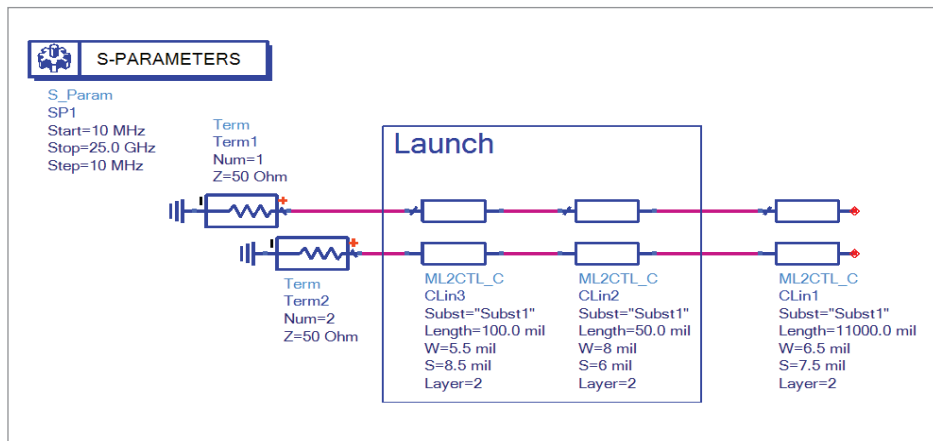


Figure 6. Schematic for simulating the s2p of the longer Open fixture

The S-parameters of the longer Open standard can be simulated with the schematic shown in Figure 6. Similarly, the schematic can be modified to simulate the S-parameters of the shorter Open, the long 2X THRU and the short 2X THRU.

## Comparisons of Different Methods in Characterizing PCB Insertion Loss with Simulations *continued*

In the comparisons below, the actual data of the PCB trace is taken as the reference, the results of Direct Loss Subtraction, 2X THRU AFR and 1X AFR are compared to the actual data independently and the differences are calculated, the maximum error compared to actual data can be used as the index of the performance of that method.

The intended measurement bandwidth is 20 GHz, but the AFR result may have some gating effects[5] that cause errors at the high end of the frequency range (as shown in Figure 7). The general solution to this issue is to measure 20% higher than the intended bandwidth, so all the simulations are done up to 25 GHz and the comparisons are done up to 20 GHz.

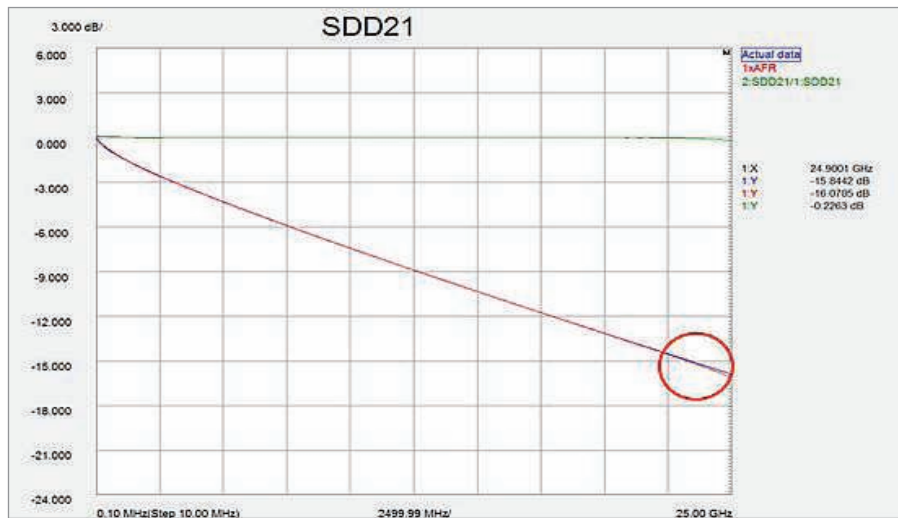


Figure 7. Gating effects at high frequency

### A. Comparisons of methods with 100 ohm reference impedance

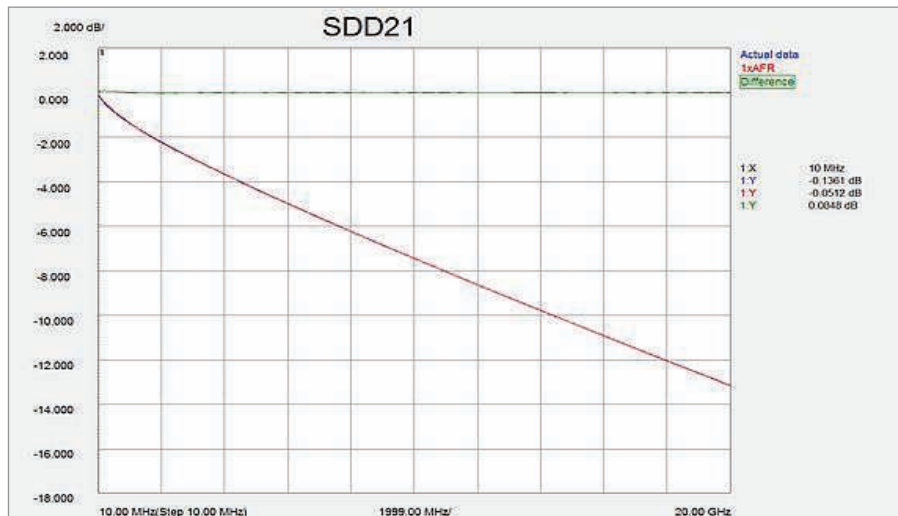


Figure 8. Actual data vs 1X AFR

The maximum difference between actual data and 1X AFR is 0.0848 dB at 10 MHz ( $\Delta L = 11$  inches), shown in Figure 8.



## Comparisons of Different Methods in Characterizing PCB Insertion Loss with Simulations *continued*



Figure 9. Gating effects at high frequency

The maximum difference between actual data and 2X THRU AFR is 0.0012 dB at 810 MHz ( $\Delta L = 11$  inches), shown in Figure 9.

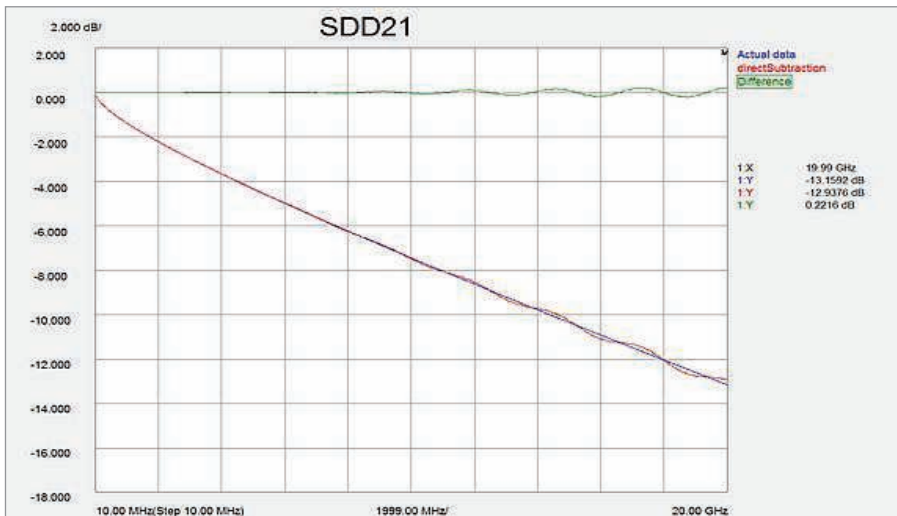


Figure 10. Actual data vs Direct Subtraction

The maximum difference between actual data and Direct Loss Subtraction is 0.2216 dB at 19.99 GHz ( $\Delta L = 11$  inches), shown in Figure 10.

From the comparisons above, we can see for the same PCB length of 11 inches, the Direct Loss Subtraction method is pretty good below 5 GHz, but at higher frequencies the ripples due to mismatch is bigger and the maximum error of insertion loss compared to the actual data is about 0.2216 dB, or 0.022 dB/inch. For the simulation data, the 2X THRU AFR is the most accurate and shows only 0.0001 dB/inch error; the 1X AFR is not as accurate as 2X THRU AFR due to gating effect at low frequency, but is still very accurate - 0.008 dB/inch maximum error.

## Comparisons of Different Methods in Characterizing PCB Insertion Loss with Simulations *continued*

### B. Comparisons of methods with 90 ohm reference impedance



Figure 11. Actual data vs 1X AFR

The maximum difference between actual data and 1X AFR is 0.08 dB at 10 MHz ( $\Delta L = 11$  inches), shown in Figure 11.

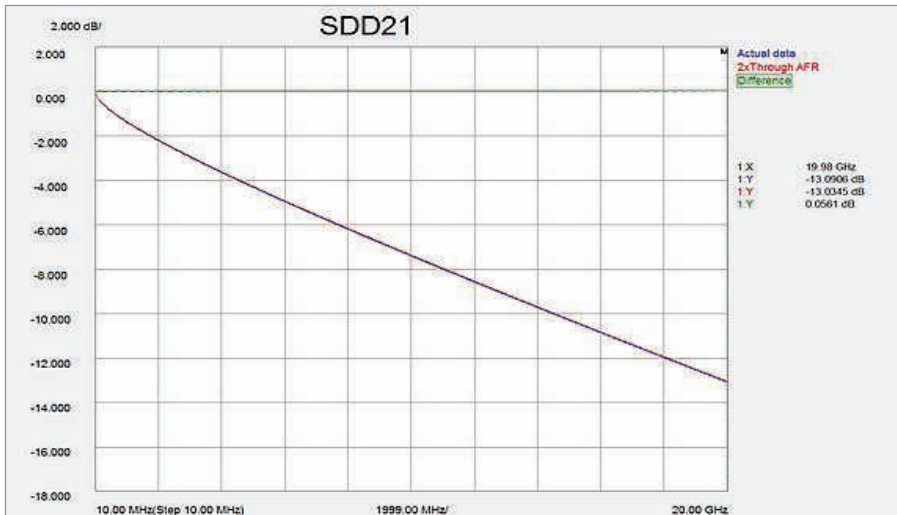


Figure 12. Actual data vs 2X THRU AFR

The maximum difference between actual data and 2X THRU AFR is 0.0561 dB at 19.98 GHz ( $\Delta L = 11$  inches), shown in Figure 12.

## Comparisons of Different Methods in Characterizing PCB Insertion Loss with Simulations *continued*

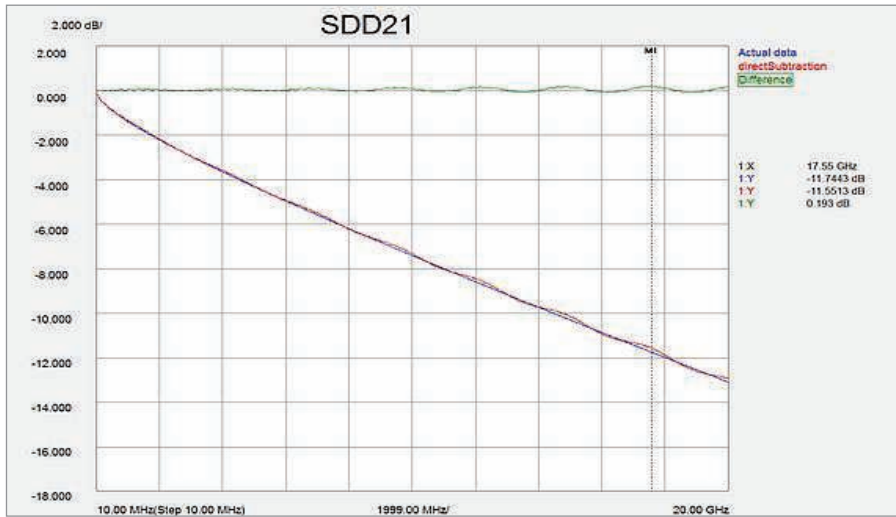


Figure 13. Actual data vs Direct Subtraction

The maximum difference between actual data and Direct Loss Subtraction is 0.193 dB at 17.55 GHz ( $\Delta L = 11$  inches), shown in Figure 13.

The 90 ohm validation shows that the 1X AFR and 2X THRU AFR show very close result to the actual data (less than 0.005 dB/inch error). The Direct Loss Subtraction method shows ripples due to mismatch and the maximum error of about 0.02 dB/inch.

## Comparisons of Different Methods with Measurements

To validate the performance of the new 1X AFR and compare the results of all the above methods in real applications, two PCBs with all the test structures for the above methods have been fabricated (shown in Figure 14 and Figure 15), with two reference impedances (100 ohm and 90 ohm respectively). The length of the transmission line on the PCB after removing the fixtures have the same length, so the insertion loss characterized with different methods can be compared directly. Below are the PCB parameters, layout, and a photo of the fabricated board.

Dielectric Constant: 3.9 at 5 GHz

	Line length (mil)
PCB trace length without launches	10000
TRL Open	500
TRL thru	1000
TRL Line1	3480
TRL Line2	1496
TRL Line3	1099
TRL DUT	11000
2X AFR Longer line (Direct Subtraction longer line)	12327
2X AFR Shorter line (Direct Subtraction shorter line)	2327
1X AFR Longer Open	11400
1X AFR Shorter Open	1400

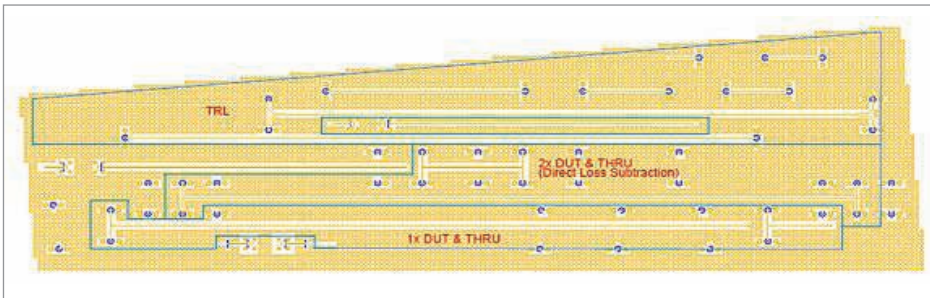


Figure 14. PCB layout with all the structures used for comparison of the loss characterization methods

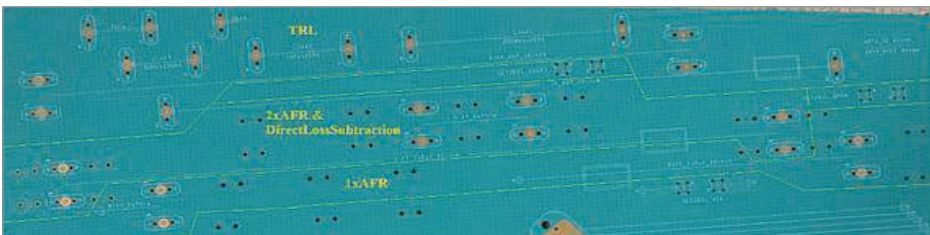


Figure 15. Snapshot of the fabricated PCB (coaxial connectors not mounted)

The PCB was designed to work up to 20 GHz, but there is a fabrication defect on the PCB that causes a resonance dip at 18.2 GHz, so all the comparisons are done below 17 GHz. In the comparisons below, the TRL calibration method is presumed to be the most accurate method, so the PCB insertion loss with TRL calibration is taken as the reference, the result of Direct Loss Subtraction, 2X THRU AFR and 1X AFR are compared to TRL result independently and the differences are calculated, the maximum error compared to TRL can be used as the index of the performance of that method.

## Comparisons of Methods on PCB with 100 Ohm Reference Impedance

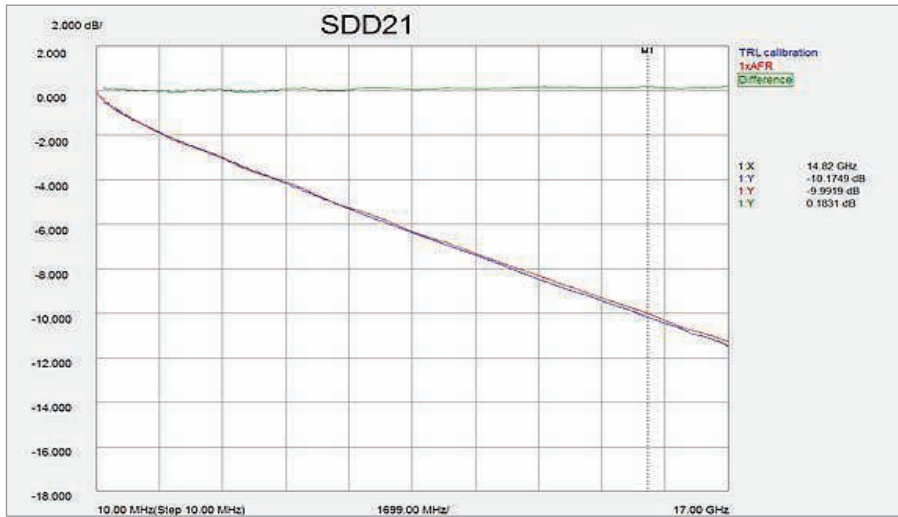


Figure 16. TRL calibration vs 1X AFR

The maximum difference between TRL calibration and 1X AFR is 0.1831 dB at 14.82 GHz ( $\Delta L = 10$  inches), shown in Figure 16.



Figure 17. TRL calibration vs 2X THRU AFR

The maximum difference between TRL calibration and 2X THRU AFR is 0.2118 dB at 14.66 GHz ( $\Delta L = 10$  inches), shown in Figure 17.

## Comparisons of Methods on PCB with 100 Ohm Reference Impedance *continued*



Figure 18. TRL calibration vs Direct Subtraction

The maximum difference between TRL calibration and Direct Loss Subtraction is 0.449 dB at 14.32 GHz ( $\Delta L = 10$  inches), shown in Figure 18.

From the comparisons above, we can see for the same PCB length of 10 inches, the Direct Loss Subtraction method is pretty good below 5 GHz, but at higher frequencies the ripples due to mismatch is bigger and the maximum error of insertion loss compared to TRL calibration method is about 0.45 dB, or 0.045 dB/inch. The characterized PCB losses with 1X AFR and 2X THRU AFR are both very close to the TRL calibration method –with around 0.02 dB / inch maximum error. Considering the fabrication precision and repeatability, this error is very small. This concludes that the new 1X AFR method for PCB loss characterization can result in similar performance to TRL calibration.

## Comparisons of Methods on PCB with 90 Ohm Reference Impedance

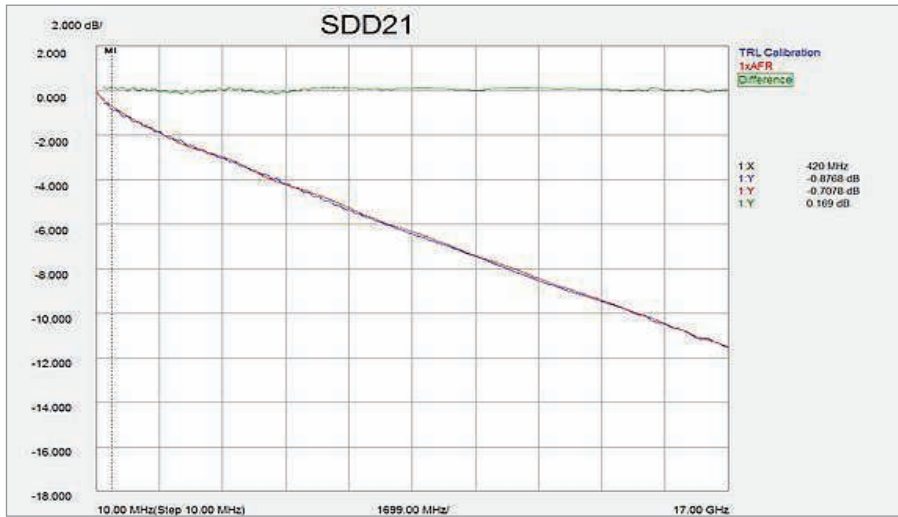


Figure 19. TRL calibration vs 1X AFR

The maximum difference between TRL calibration and 1X AFR is 0.169 dB at 420 MHz ( $\Delta L = 10$  inches), shown in Figure 19.



Figure 20. TRL calibration vs 2X THRU AFR

The maximum difference between TRL calibration and 2X THRU AFR is 0.2669 dB at 15.84 GHz ( $\Delta L = 10$  inches), shown in Figure 20.

## Comparisons of Methods on PCB with 90 Ohm Reference Impedance *continued*

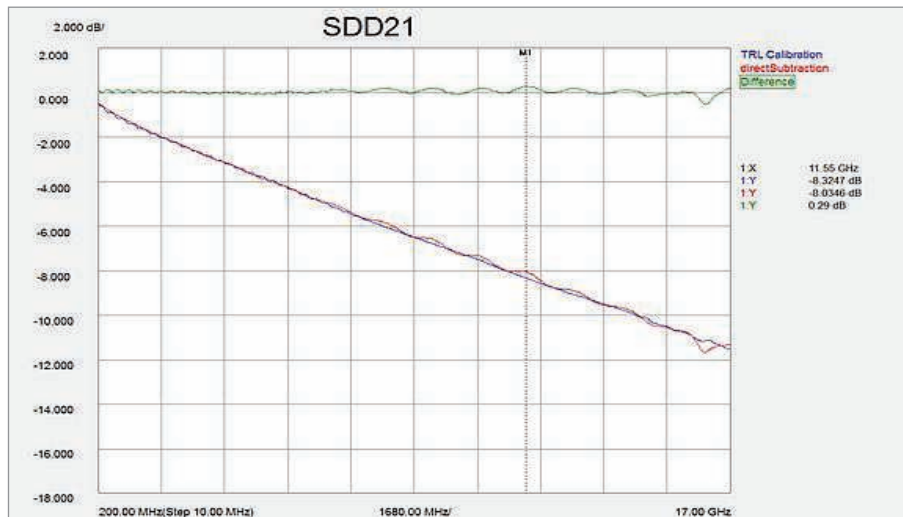


Figure 21. TRL calibration vs Direct Subtraction

The maximum difference between TRL calibration and Direct Loss Subtraction is 0.29 dB at 11.55 GHz ( $\Delta L = 10$  inches), shown in Figure 21.

The 90 ohm validation shows a similar result as the 100 ohm validation that the 1X AFR and 2X THRU AFR shows a very close result to the TRL calibration result (around 0.02 dB / inch maximum error in 17 GHz). The Direct Loss Subtraction method is pretty good below 5 GHz, but at higher frequencies the ripple due to mismatch is bigger and results in maximum error of about 0.03 dB / inch.



## Considerations on the Gating Range of 1X AFR Method

In the 1X AFR method, bandpass time domain gating is used for the extraction of the fixture insertion loss from the Open standard. The gating range has impacts on the accuracy of the extracted fixture insertion loss and the optimum gating range is the compromise of two aspects: if the gating range is too narrow to the Open response, part of the Open response may be gated off and causes the extracted insertion loss to have some ripples; if the gating range is too wide, although the complete Open response will be maintained, some mismatch effects caused by the impedance variations of the PCB trace will also be included after gating and introduce some ripples to the extracted insertion loss.

Figure 22 shows the gating range of 4x system rise time using the longer Open standard of 100 ohm.

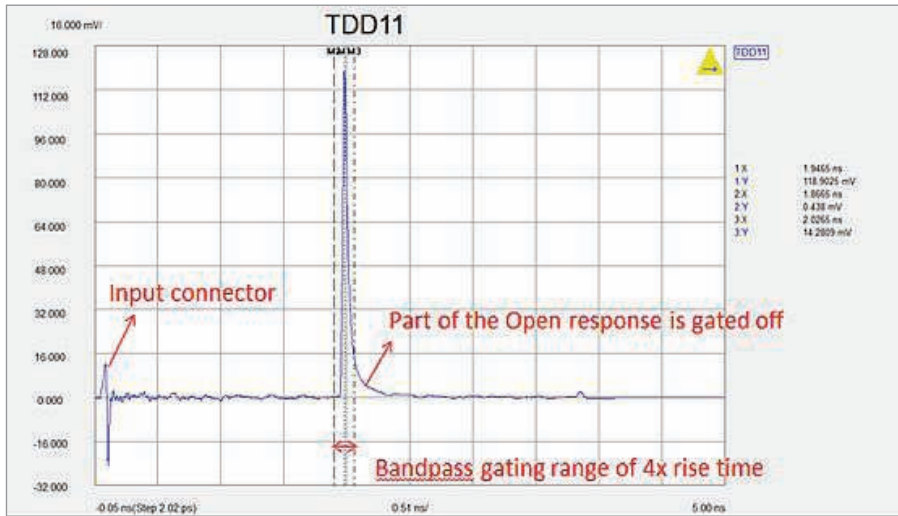


Figure 22. TDD11 Time domain impulse response of the differential Open standard. If the gating range is too narrow, part of the Open response will be gated off.

Figure 23 shows the gating range of 20x system rise time using the same Open standard.

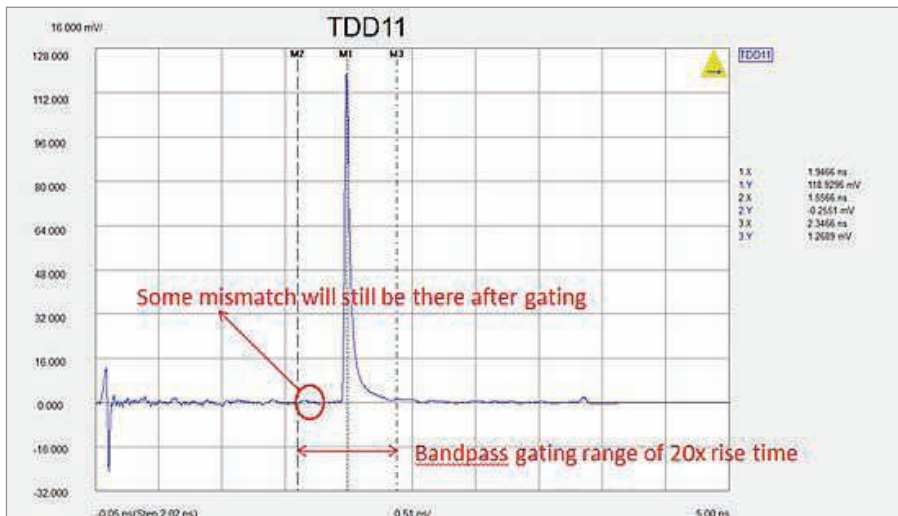


Figure 23. TDD11 Time domain impulse response of the differential Open standard. If the gating range is too wide, some mismatch will be included in the extracted insertion loss.

## Considerations on the Gating Range of 1X AFR Method *continued*

Ideally, the complete Open response should be included in the gating range. But we may need to compromise that to make it narrower to avoid including the mismatch effects, depending on the fabrication quality to control the PCB impedance variations. The optimum gating range for this Open standard is shown below. It includes most of the Open response but also avoids the mismatch caused by PCB impedance variations.

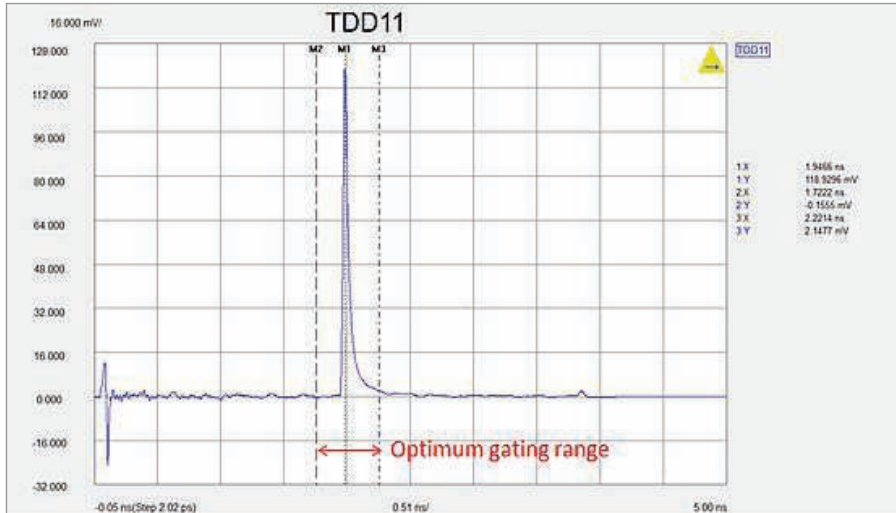


Figure 24. TDD11 Time domain impulse response of the differential Open standard. Optimum gating range.

Figure 24 shows the optimum gating range. It includes most of the Open response and also avoids including the input mismatch.

Figure 25 shows the effects of gating range on the extracted fixture insertion loss. If the gating range is too narrow, we would see some ripples at the 20% to approximately 30% of the frequency range, shown on the blue trace; if the gating range is too wide, we would see some ripples at higher frequencies caused by the mismatch effects, shown as the red trace. The green trace is the extracted insertion loss using the optimum gating range, it is very smooth at all frequency ranges and is very close to the TRL calibration result, which has been shown in the previous comparisons.

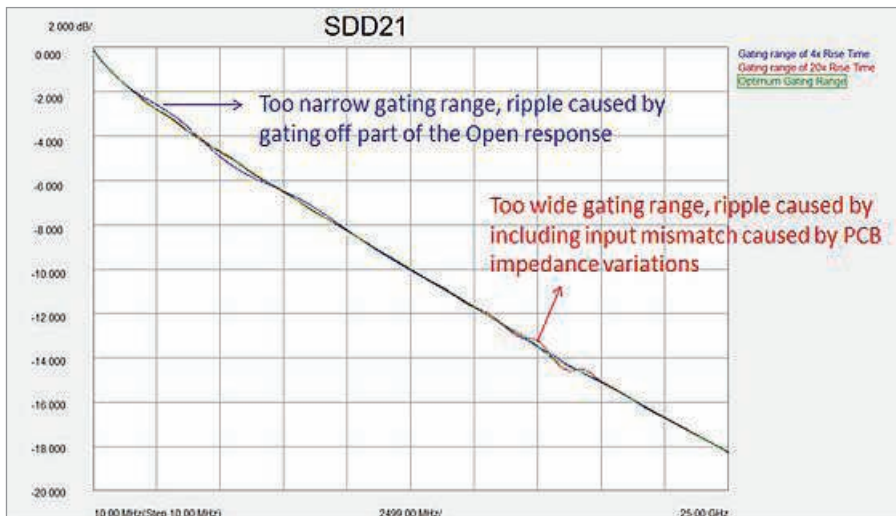


Figure 25. Extracted insertion loss with different gating range

In real applications, we should first optimize the fabrication quality to make sure the impedance variations are as small as possible, and then select the gating range carefully to optimize the extracted insertion loss if there are still some impedance variations.

## Conclusion

In this application note, we proposed using the new 1X AFR technique to characterize the PCB insertion loss. ADS simulations and real measurements on fabricated PCB structures have been done for the comparisons of extracted PCB insertion loss with different methods[6]. The new 1X AFR method is proven to have similar performance with the traditional TRL calibration and 2X THRU AFR methods, but it can save more PCB area, calibration and measurement time. When using 1X AFR method in this process, the Open standard should be optimized to have small impedance variations on the PCB trace, care needs to be taken in selecting the optimum gating range to achieve the best result.

The performance comparisons of all these methods are summarized in the table below:

	Direct Loss Subtraction	TRL calibration	2x THRU AFR	1X AFR
Complexity	Easy	Complicated	Easy	Easy
Accuracy	Low	High	High	High
Cost	Low	High	Low	Lowest
Measurement Bandwidth	Low	High	High	High

## References

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