APPLICATION NOTE

Overview

The calibration solution presented in this document is focused on calibration of InfinityQuad™ probes, where the probes are assumed in all four quadrants of the device under test (DUT), as shown in Figure 1. However, this solution can be applied to general single, dual, or multi-channel probes, as well as cases where the quadrants are not fully occupied. A hypothetical probe setup is shown in Figure 1. The blue tips are associated with channels that do not need calibration, i.e., grounds, logic, bypassed power, disconnected opened channels, as well as RF channels that do not need calibration. The red tips are those of the RF channels that need calibration. Table 1 shows the various types of RF channels available in InfinityQuad probes. In this document, they will all be referred to as "S" (Signal), unless stated otherwise.

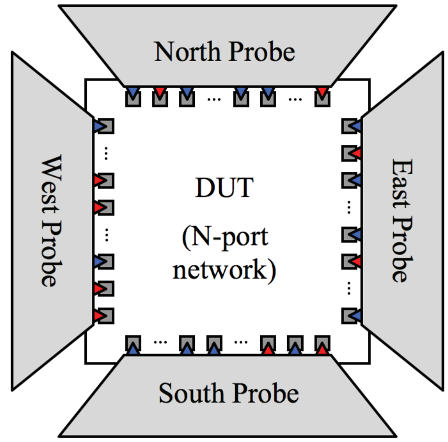


Figure 1. DUT with four quadrant probes. The red tips are those of the channels that need calibration.

Table 1. Various RF channels in InfinityQuad probe.

Label	Max Frequency	Connector Interface	Note
L	0.5 GHz	SMA or BNC	Uses reconnectable 1-meter cable assembly
S	20 GHz	2.92 mm	Uses permanently attached 5" cable assembly
K	40 GHz	2.92 mm	
Q	50 GHz	2.4 mm	
V	67 GHz	1.85 mm	
W	110 GHz	1 mm	

The S channels (red tips) can be adjacent to other types of channels (red or blue tips), forming various RF signal configurations, such as ground-signal (GS), signal-ground (SG), ground-signal-ground (GSG), ground-signal-signal (GSS), differential signal-signal pairs without grounds (SS). In some cases, the bypassed powers (P) are used in place of grounds (G) such as in PS, GSP. In this document, Ps used this way will be referred to as Gs unless stated otherwise. The network analyzer calibrates these variously configured channels, treating them individually as ports. If N is the total number of these ports, the network analyzer regards the DUT as an N-port network. Note that the differential SS configuration is counted as a single port, since the differential pair will be connected to a single port of the network analyzer through a balun outside the probe. The technique described in this application note is called the N+1 Port SOLT/SOLR calibration, where N is the number of ports in the test set-up that need to be calibrated and the N+1'th port is assigned to an additional RF channel for common thru pair measurements. However, this does not mean that one necessarily needs a VNA with N+1 ports, as described later in this application note.

Required Parts

Impedance Standard Substrate (ISS)

The recommended FormFactor ISSs for using InfinityQuad probes are listed in Table 2. Configurations or frequency ranges that are not shown in this table are not specified. However, for these configurations, one can proceed with the calibration by choosing a configuration from the table that closest fits the application. This can also cause resonances which can be examined by observing the open reflection measurements after calibration.

All the configurations in Table 2 can be treated as either as GSG, GS_, G_S, or _SS_, and their calibration coefficients are listed in Table 3. Note that the under-bar represents any channel except for G or P, or can represent the edges i.e., outside the first and last channels of the probe. When using other multi-channel probes or other calibration standards, their cal coefficients are usually provided with the probe, or found in published documents. If they are not, one can perform a Line-Reflect-Reflect-Match (LRRM) calibration and extract the cal-coefficients by remeasuring the standards.

Table 2. Recommended ISS for InfinityQuad probes.

Pitch / Config.	75, 80 µm	100 µm	125, 150 µm	200, 250 µm
G**S**G	104-909 (G**S**G) DC - 20 GHz	101-190 (G**S**G) DC - 20 GHz		
G**K**G	104-909 (G**S**G) DC - 40 GHz	101-190 (G**S**G) DC - 40 GHz		
G**Q**G	104-909 (G**S**G) DC - 50 GHz	101-190 (G**S**G) DC - 50 GHz		
G**V**G	104-909 (G**S**G) DC - 67 GHz	101-190 (G**S**G) DC - 67 GHz		
G**W**G	104-783 (G**S**G) DC - 110 GHz			101-190 (G**S**G) DC - 67 GHz
G**S**_	104-909 (G**S**) DC - 20 GHz	103-726 (G**S**) DC - 20 GHz		
G**K**_	104-909 (G**S**) DC - 40 GHz	103-726 (G**S**) DC - 40 GHz		
G**Q**_	104-909 (G**S**) DC - 50 GHz	103-726 (G**S**) DC - 50 GHz		
G**V**_ G**W**_	104-909 (G**S**) DC - 67 GHz	103-726 (G**S**) DC - 67 GHz		103-726 (G**S**) DC - 50 GHz
G**S**P			103-726 (G**S**) DC - 20 GHz	
G**K**P			103-726 (G**S**) DC - 40 GHz	
G**Q**P G**V**P G**W**P			103-726 (G**S**) DC - 50 GHz	
G_**S**_ G_**K**_ G_**Q**_ G_**V**_ G_**W**_		129-246 (GS**S**G) DC - 20 GHz		129-247 (G**SS**G) DC - 20 GHz
_**SS**_		129-246 (G**SS**G) 2 - 18 GHz		129-247 (G**SS**G) 2 - 18 GHz

Note:
The signal lines that are to be calibrated are represented in bolded-black fonts.
The list only shows one representing both of the two mirrored cases, e.g., GSP also represents PSG.
The under-bar can be any channel except for G or P, or can represent the edges (outside the first and last channels of the probe).

Table 3. Calibration coefficients for InfinityQuad probes.

ISS P/N	Pitch / Cal Coeffs	75 µm	80 µm	100 µm	125 µm	150 µm	200 µm	250 µm
104-909 (GSG)	C-open-air (fF)	-6.2	-6.1					
	L-short (pH)	4.2	4.6					
	L-term (pH)	2.0	2.3					
104-909 (GS_)	C-open-air (fF)	-10.4	-10.4					
	L-short (pH)	26.2	27.0					
	L-term (pH)	43.5	43.8					
101-190 (GSG)	C-open-air (fF)			-8.6	-8.6	-8.5	-8.5	-8.4
	L-short (pH)			3.6	6.0	8.6	13.9	22.7
	L-term (pH)			1.7	4.1	6.6	12.7	24.8
104-783 (GSG)	C-open-air (fF)	-7.1	-7.1	-6.9	-6.6	-6.4		
	L-short (pH)	5.3	5.7	7.4	9.5	11.6		
	L-term (pH)	-1.5	-1.2	0.2	1.8	3.5		
103-726 (GS_, _SG)	C-open-air (fF)			-11.1	-11.3	-11.5	-11.9	-12.2
	L-short (pH)			26.1	36.3	46.5	66.9	87.3
	L-term (pH)			26.7	33.9	41.1	55.5	69.9
129-246* (_SS_)	C-open-sub (fF)			2.7	2.7	2.6		
	L-short (pH)			67.0	69.9	72.3		
	L-term (pH)			39.2	36.9	35.4		
129-247* (_SS_)	C-open-sub (fF)						5.4	5.3
	L-short (pH)						83.9	85.4
	L-term (pH)						52.8	52.6
129-246 (G_S, S_G)	C-open-sub (fF)			2.3	2.4	2.4		
	L-short (pH)			150.8	156.6	161.3		
	L-term (pH)			283.1	266.6	257.1		
129-247 (G_S, S_G)	C-open-sub (fF)						4.4	4.4
	L-short (pH)						246.3	269.0
	L-term (pH)						132.5	136.2

Note:
The under-bar can be any channel except for G or P, or can represent the edges (outside the first and last channels of the probe).
** The calibration coefficients are those used when the R-term and the reference impedances are defined as 50 Ω, and not 100 Ω.*

Additional GSG Probe and Related ISS for Through (Thru) Measurements

Prepare an additional GSG probe whose frequency range is equal to or greater than that of any of the N ports. The pitch of this additional GSG probe should be chosen so that the probe can be connected to any of the N ports via the thru standard in the ISSs at hand. Otherwise additional ISSs should be obtained to enable this. As shown in Figure 2, the 1 ps thru standard in ISS P/N 101-190 can cover most configurations of the InfinityQuad probe - GSG, GS_, _SS_ at any pitch between 75 - 250 µm. This thru standard can also can be used in the G_S, however, its pitch has to be between 75 - 125 µm to ensure that the G lands on one of the ground strips. For G_S with pitches between 150 - 250 µm, the 4 ps thru standard in ISS P/N 106-682 is recommended. Note that for the _SS_ one of the Ss lands on the ground strip in the thru standard as if it is a G.

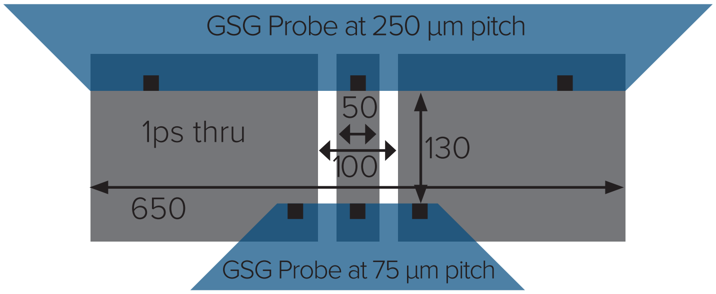


Figure 2. Dimensions of the 1 ps thru standard in ISS P/N 101-190 (units in µm).

Network Analyzer Settings

Port and Calibration Settings

Set-up the network analyzer for N+1-port calibration using Short-Open-Load-Thru (SOLT) or Short-Open-Load-Reciprocal Thru (SOLR) calibration. Assign the additionally prepared GSG probe to the N+1'th port. Define all ports' reference impedances as 50 Ω even the differential SS configuration. If the calibration coefficients for the SS configuration are defined for 100 Ω, they need to be scaled by a factor of two; multiplied by two for C_open; divided by 2 for R_term, L_term, L_short.

Select Thru Pairs

Select thru pairs so that each port, 1 through N, are paired with the N+1'th port as follows.

Port 1 & Port N+1, Port 2 & Port N+1, Port 3 & Port N+1, ..., Port N & Port N+1.

This can be done in Agilent's Calibration Wizard in their PNA and ENA. However, if the firmware in the network analyzer does not allow such manual selection and forces selection of thru pairs among the ports 1 through N (e.g., Port 4 & Port 5), one must manually input the S-parameters which can be calculated from the measurements of the previously mentioned thru pairs (e.g., Port 4 & Port N+1 and Port 5 & Port N+1) by multiplying the T-parameter matrices and converting back to S-parameters. Note that SOLT requires the correct delay values, while SOLR only requires their rough estimate. When using ISS P/N 101-190, the 1 ps delay is valid for most configurations in the InfinityQuad probe - GSG, GS_, _SS_ at 75 - 250 µm pitch, as well as and G_S configuration at 75 - 125 µm pitch. As shown in Table 4, the different configurations only cause ± 0.1 fs of delay which is equivalent to ± 0.1 µm tip placement error. This is far less than actual tip placement repeatability. Other longer delays listed in Table 1 are those from right-angle thru standards from ISS P/N 106-686 which will be mentioned again later in this document.

Table 4. Delay changes when using GS on GSG Thru standard.

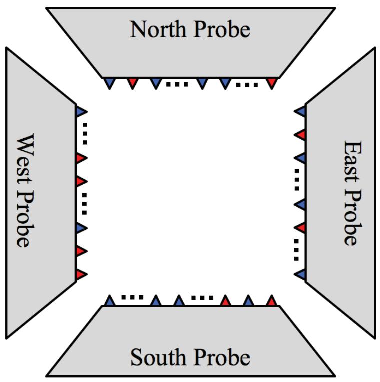
Thru length between tip-to-tip (µm)	Thru delay when using GSG (ps)	Reduced time delay when using GS (ps)	Equivalent reduced length when using GS (µm)
130	1.0	0.0001	0.01
2250	17.4	0.0063	0.82
12710	98.3	0.3316	42.86

Note:
Data shown for 250 µm pitched probes which can be considered as worst case for inconstant time delays between GSG and GS. The 1 ps thru standard is from ISS P/N 101-190 and other thru standards are from ISS P/N 106-686.

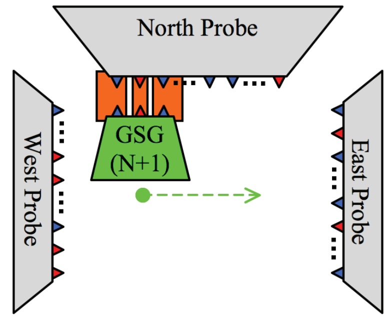
Measurement Sequence

Figure 3 shows the measurement sequence of the SOLT/SOLR calibration standards, ordered from Figure 3(a) to Figure 3(f). Note that the North and East probes are remounted after completing their thru measurements, which can cause variation in the electrical delays in the attached cables. The amount of such variation is described later in this document. However, one must try to minimize such variation by maintaining similar bending/routing of the cables as well as using a torque wrench when re-attaching the connectors.

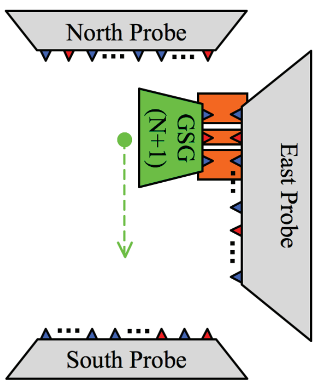
Furthermore, one can order the measurement sequence such that, out of the two probes facing each other (North and South or East and West), the probe that has the higher maximum frequency is measured last. For example, if the North probe's maximum frequency is 110 GHz and that of the South probe is 67 GHz, measuring the thru pairs in the North probe after those in the South probe will allow one to avoid remounting North probe (up the 110 GHz) which is more error-prone than remounting the South probe (up the 67 GHz).



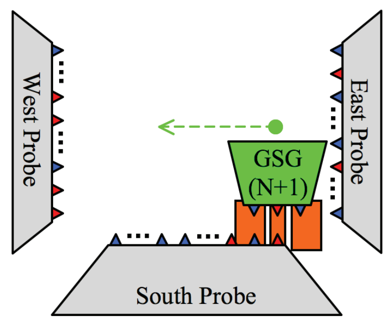
(a) Start



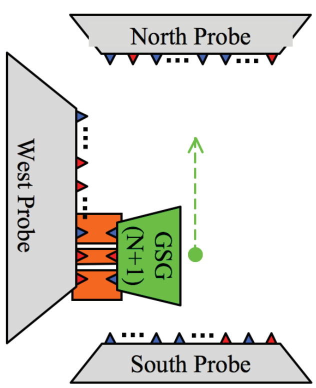
(b) Replace South probe with the N+1'th GSG probe and measure its SOL and all thru pairs with the ports in North Probe. Remount South probe afterwards.



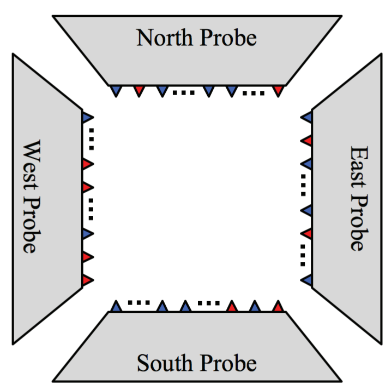
(c) Replace West probe with the N+1'th GSG probe and measure all thru pairs with ports in East Probe. Remount West probe afterwards.



(d) Replace North probe with the N+1'th GSG probe and measure all thru pairs with ports in South Probe. Remount North probe afterwards.



(e) Replace East probe with the N+1'th GSG probe and measure all thru pairs with ports in West Probe. Remount East probe afterwards.



(f) Measure reflection standards SOL for ports 1 through N in the four quadrant probes. Afterwards, hit compute and complete calibration.

Figure 3. Calibration standard measurement for N+1-port SOLT/SOLR calibration; ordered from (a) to (f).

Calibration Using N Port VNA

If the VNA does not have an additional port, one can achieve the same effect by manually inputting the calculated measurements of the thru pair amongst ports 1 ~ N. For example, the thru pair measurement between Port i & Port j ($i \neq j$ are any numbers between 1 ~ N) can be calculated from the thru pair measurements of Port i with the added GSG probe and the thru pair measurements of Port j with the added GSG probe, by multiplying their T-parameter matrices and converting back to S-parameters.

Choosing Alternate Thru Pairs

Considering the available calibration substrates, probes, and Network Analyzer the user has on hand, it can be beneficial to choose alternate thru pairs to improve the calibration consistency. One can choose some thru pairs among the N ports in the quadrant probes and not necessarily pair them with the N+1'th port (the added GSG probe). This may include using the right-angle thru standards when one of the thru pairs is from the North or South probe and the other is from the East or West probe. As shown in Figure 5, the various right-angle thru standards in ISS P/N 106-686 can be used for most configurations in the InfinityQuad Probe - GSG, GS_, _SS_ at 75 - 250 µm pitch, as well as the G_S configuration at 75 - 125 µm pitch. These right-angle thru standards are often too long so that the difference in the configurations causes significant delay variation, as previously shown in Table 4. Therefore, when using these long thru standards at high frequencies, SOLR instead of SOLT is recommend so that the calibration repeatability becomes immune to the delay variation. When choosing alternate thru pairs, either straight or right-angled, there are three requirements that need to be satisfied.

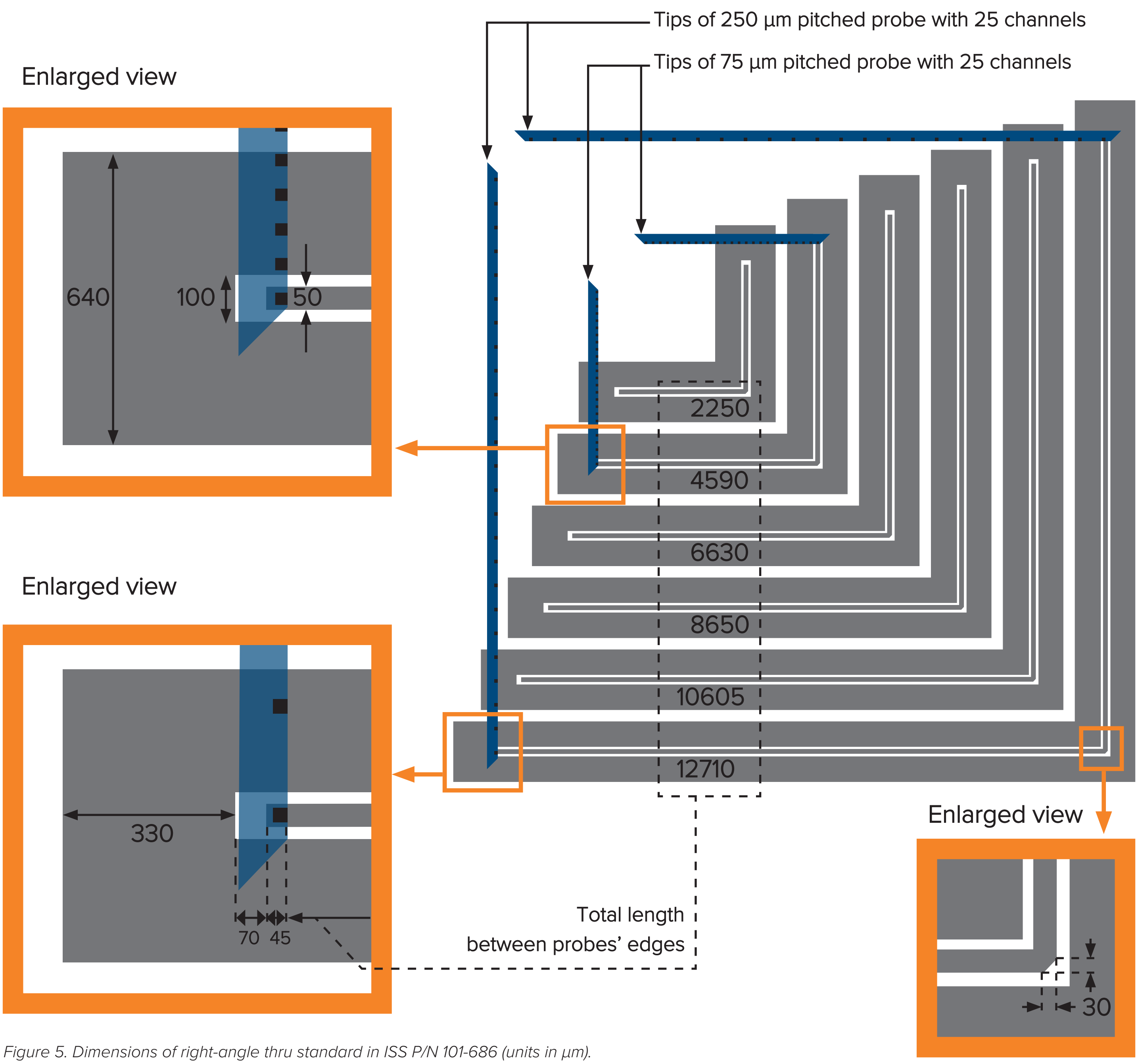


Figure 5. Dimensions of right-angle thru standard in ISS P/N 101-686 (units in µm).

Minimum Number of Thru Pairs

For N+1-port calibration one must choose at least N distinct thru pairs where each port has to be used at least once. For example, for a 4-port calibration where the ports are labeled as P1, P2, P3, P4, one can choose the following thru pairs as P1 & P2, P2 & P3, and P3 & P4.

- P1 & P2, P2 & P3, P3 & P4
- P1 & P2, P1 & P3, P2 & P4

However, it is invalid to choose following thru pairs because P4 had not been used.

- P1 & P2, P2 & P3, P3 & P1

Required Frequency Range

One must check to see if the chosen thru pairs will produce the required frequency range for each transmission term, i.e., Sij where $i \neq j$. For example, consider a 4-port case where each port has the maximum operating frequency limited by the connectors, as follows.

- P1: 40 GHz (2.54 mm K-connector)
- P2: 50 GHz (2.94 mm Q-connector)
- P3: 67 GHz (1.85 mm V-connector)
- P4: 110 GHz (1 mm W-connector)

Assume the chosen three thru pairs are as follows, all measured up to 110 GHz.

- P1 & P2, P1 & P3, P1 & P4

After calibration, the Network Analyzer calculates S34 from its raw measurement using the thru pair measurements of P1 & P3 and P1 & P4. However, since these are only valid up to 40 GHz due to the 2.94 mm connector at P1, the calculated S34 becomes only valid up to 40 GHz rather than the required 67 GHz. The same problem exists for S23 and S24 since they are all only valid up to 40 GHz rather than 50 GHz. In order to produce valid transmission terms up to their required maximum frequency, one correct way to choose the thru pairs is as follows.

- P1 & P4, P2 & P4, P3 & P4.

Ground Continuity

The chosen thru pairs will need to ensure that least one G (or P if it is used as a G, or one S from the SS) from each port is

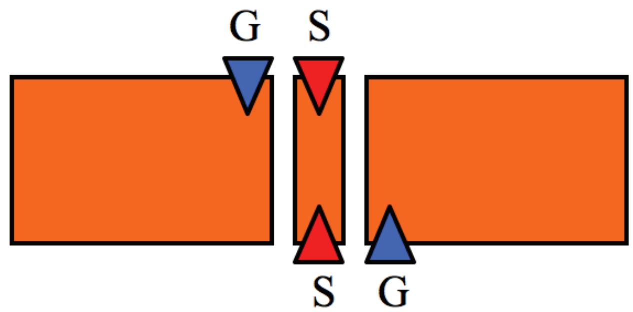


Figure 4. An example of invalid thru pair where the grounds are disconnected.

landing on the same ground strip in the thru standard. Figure 3 shows an example of what shouldn't be chosen because the GS configurations in both North and South probes are arranged in a way where the Gs are not connected.

Measurement Uncertainties Caused by Delay Variation

The SOLT/SOLR calibration algorithm relies on having consistent electrical delays in the error-network (the network describing the path from the network analyzer to the probe tips). Any variation in the delays may an increase the measurements' uncertainty after calibration. The delays can be kept relativity consistent when calibrating up to four ports using single- or dual-channel probes, since remounting the probes is not required. However, keeping consistent delays can become a bit challenging in the proposed N+1-port SOLT/SOLR calibration, since remounting the probes can change the bend of the cables or the torque of the connectors, as shown in Table 5. Furthermore, when using SOLT, any variation of the thru pairs caused by the various configurations (GSG, GS_, G_S, _SS_), as mentioned in Table 4, will manifest itself as delay variation in the error-network. This is because the SOLT algorithm considers the delay of the thru standard to be the value defined by the user, hence, any difference from the actual delay will be modeled into the error-network. The total delay variation can be expected to be the sum of all the mentioned variations in Table 4 and Table 5, since they will each make independent contributions. Fortunately, as shown in the next sub-section, these delay variations are likely to be small enough as to not cause significant measurement uncertainty, except at very high frequencies.

Table 5. Measured delay variation in common cable assemblies.

Cable Assembly			Delay Variations (Average)	
Vendor	Connectors	Cable	Reconnection	Bending cable 90° at 6 cm radius
SRC Cables	2.92 mm	0.047" conformable	0.05 ps	0.03 ps
W. L. Gore & Assoc.	2.4 mm	0.14" flexible	0.09 ps	0.10 ps
W. L. Gore & Assoc.	1 mm	0.167" flexible	0.04 ps	0.10 ps

Resulting Measurement Uncertainties

The proposed N+1-port SOLT/SOLR calibrations were applied to a 3-port case with the third probe at Port 3, which was used for measuring the thru pairs of Port 1 and Port 2 using the 1 ps thru standard. To illustrate the effects of having inconsistent delays, the cables were bent by 90° after remounting the probes, and the thru pairs were purposely defined to be 2 ps more from their correct values. Also, a conventional 2-port SOLR calibration was performed (using the correct delay values) which will be considered as the ideal case and compared to the proposed N+1-port SOLT/SOLR calibration. The comparison is done by the calibrated measurement of a lossy transmission line, as shown in Figure 6, where the S22 and the S12 were omitted due to their symmetry. In order to eliminate any additional measurement uncertainties caused by the probe-tips' placement variation, each calibration standard was measured only once and manually input to the calibration processes (N+1-port SOLT/SOLR and the 2-port SOLR) to create the plots in Figure 6.

The results show that the delay inconsistencies had almost no effect when using N+1-port SOLR calibration. This is because the defined delays of the thru pairs were still within in their valid range, where the transmission's phase at the lowest frequency is within ±90°of the actual values. The only delay variations were due to the reconnect of the connectors and bending the cables, all of which are 0.1 ps or less. When using N +1-port SOLT calibration, where the total delay variation was artificially increased by defining the thru pairs' delays to be off by 2 ps, the effects are still minimal except for the phase of S21. The change in the phase of S21 (~ 15 deg at 20 GHz) is directly caused by the total delay variation (~ 2 ps) as expressed as (1). This can be easily derived from the general cosine-wave equation where Δφ, Δt, and f are the change in phase, total delay variations, and frequency, respectively. Note that the phase differences in S11 near DC and 14 GHz are unimportant because their magnitudes are very low (< -40 dB).

$$\Delta \varphi |_{\text{in degrees}} = \Delta t \cdot f \cdot 360 \quad (1)$$

It is important to note that this example had defined the thru delays to be quite off from their actual values, to illustrate their effects. In most practical cases the delays will only be off due to the various configurations (GSG, GS_, G_S, _SS_) and remounting the probes which will be far less than 2 ps as listed in Table 4 and Table 5. Such small variations will not cause significant measurement uncertainties regardless of using the SOLT or SOLR version of the presented N+1-port calibration.

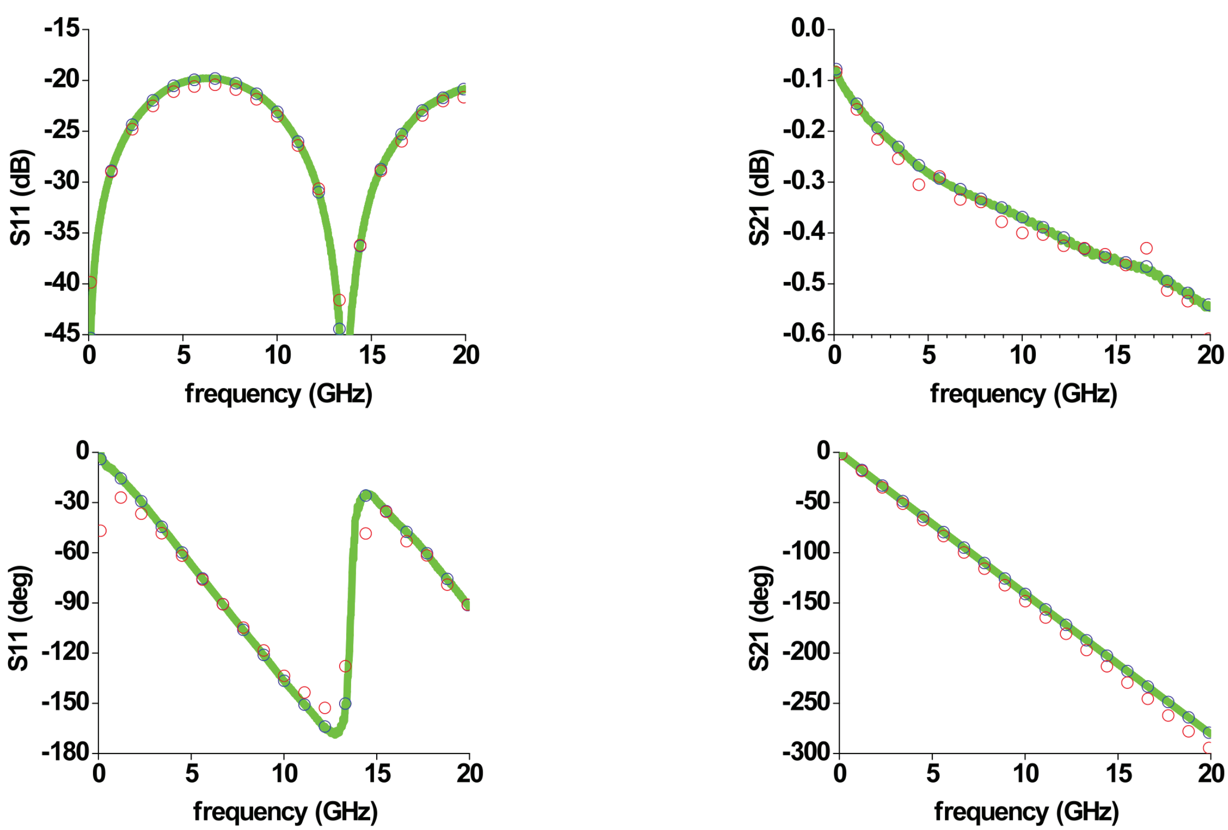


Fig. 6. Post-calibration measurements of a symmetric lossy transmission-line; using conventional 2-port SOLR calibration (thick green line) and using the presented N+1-port SOLT (red circle) / SOLR (blue circle) calibration.

Conclusion

It is shown that the proposed N+1-port SOLT/SOLR calibration can calibrate an N-port network of the InfinityQuad placed in four quadrants, using a standardized calibration procedure and standard calibration substrates that are commonly available. Although the inconsistency of the delay can cause measurement uncertainty, it is shown that their effects are likely to be minimal in most practical applications.

InfinityQuad-AN-0612