Choosing a Test Network for the Forward-Reverse Method of VNA Standard Characterization

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Description

This report describes the method employed to choose a test network to use as central element in the Forward-Reverse (FR) method of characterizing VNA calibration standards. A full description of the FR method will be provided in future reports, but it suffices to say that it is better to use a single frequency. The method is more sensitive at higher frequencies, but the model of the standards is expected to be more accurate at lower frequencies. A good compromise is 1 GHz, and therefore the results presented here correspond to that frequency.

The selection method consists of identifying the S-parameters of the test network that maximize the effect of realistic errors in the parameters of the standards. This effect is quantified by the figure of merit:

$$FoM = |St_{11f} - St_{11r}| + |St_{12f}St_{21f} - St_{12r}St_{21r}| + |St_{22f} - St_{22r}|, \quad (1)$$

where *St* corresponds to the S-parameters of the test network, and *f* and *r* represent the Forward and Reverse directions.

Simulations are generated in which the standards are projected to the measurement plane through synthetic test networks in forward and reverse mode. Then, *St* is recovered assuming incorrect values for the standards. The errors in the standards are always the same: 20% error in the loss of the *short* and *load*, and 10-ps error in the delay of the *load*. The true value for the delay is 30 ps, different from the nominal 0 ps. It is necessary to use a value different from zero in the simulations in order for the FoM to be sensitive to changes in the loss of the *load*. The simulations also added noise at the measurement plane, at a level of 1e-5 for the real and imaginary parts. Different FoMs are obtained for errors in the loss of the *short*, loss of the *load*, and delay of the *load*. The selection of *St* has to maximize the return of the three FoMs.

With fixed errors in the standards, the value of the components of *St* are chosen by sweeping over their magnitude and phase and identifying those that maximize the FoMs under stable conditions. The sweeps of St_{11} and St_{22} are done in the range 0 to 1 (steps of 0.1) and -180° to 180° (steps of 36°) respectively. For the magnitude and phase of $S_{12}S_{21}$ the values tested are 1, 0.5, and -90°, 0°, 90°, 180° respectively. This resolution is sufficient for identifying the trends that allow optimizing the test network. A full multidimensional search would be very time-consuming and its return would be only marginally better.

Since the purpose of this study is to optimize *St*, the calculations are conducted assuming a perfectly calibrated VNA. Errors in this calibration have to be addressed during the stage of parameter estimation. The same applies to the impact of noise, and the quantification of covariance.

Figures 1 and 2

Figures 1 and 2 show the dependence of the FoMs on relevant combinations of St_{11} and St_{22}. The magnitude of St_{11} is 0.1 in figure 1 and 0.9 in figure 2. The phase of St_{11}, and the magnitude and phase of St_{22} sweep their entire range.

These results are obtained for $St_{12}St_{21}$ with a magnitude of 1 and a phase of 0°. The FoM for the loss of the *short* is plotted in black, for the loss of the *load* is plotted in cyan, and for the delay of the *load* is plotted in black. Higher values of FoM are better. The noise level is plotted in red and represents the output in the case of no errors in the assumption for the standards.

The conclusions are:

- At a given $|St_{11}|$, the FoMs increase with $|St_{22}|$.
- The FoMs are modulated by the phase of St_{22}, especially for high $|St_{11}|$.
- The FoM corresponding to the loss of the *short* is sensitive to the phase of St_{11} only at high $|St_{11}|$, in which case the highest value is obtained for a phase of 180°.

Therefore, it is better to choose a small $|St_{11}|$ and a large $|St_{22}|$ in order to have low sensitivity of their phases but high sensitivity to errors in the standards. Good values are 0.1 or lower for $|St_{11}|$, and 0.9 or higher for $|St_{22}|$, respectively.

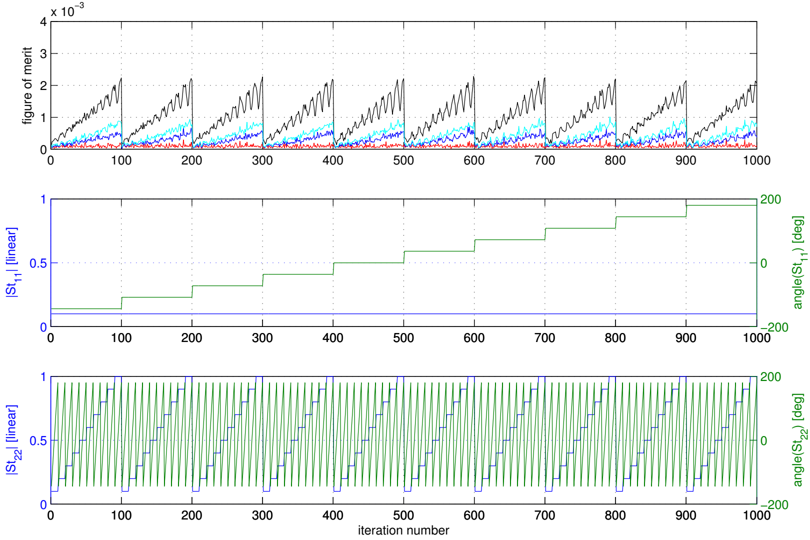
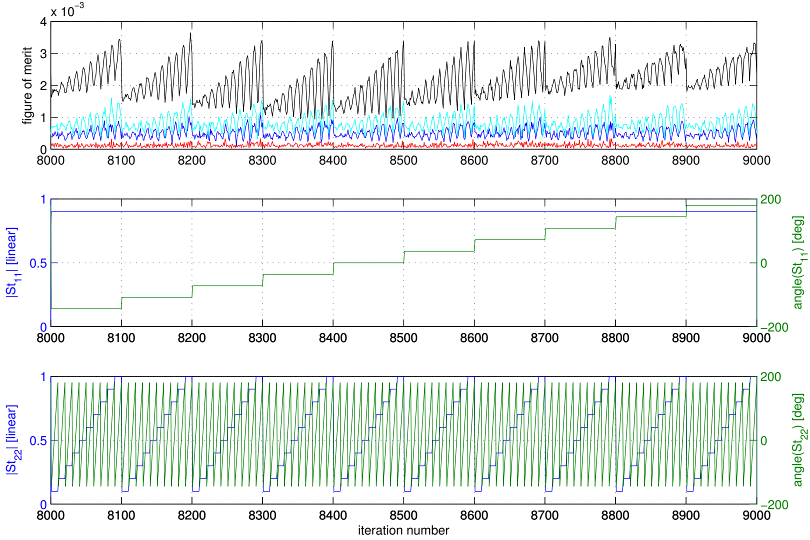

x 10^-3
figure of merit
|St11| [linear]
angle(St11) [deg]
|St22| [linear]
angle(St22) [deg]
iteration number

Figure : (1)



x 10^−3
figure of merit
|St11| [linear]
angle(St11) [deg]
|St22| [linear]
angle(St22) [deg]
iteration number

Figure : (2)

Figure 3

From figures 1 and 2 it was concluded that optimal values for $|St_{11}|$ and $|St_{22}|$ are $\leq$ 0.1 and $\geq$ 0.9 respectively. This was done for $St_{12}St_{21}$ with magnitude 1 and phase 0.

Figure 3 presents the results for $St_{12}St_{21}$ with phases of 90°, 180°, and 270°, for $|St_{11}|$=0.1 and $|St_{22}|$=0.9. The phases of St_{11} and St_{22} are not critical in these comparisons, and values 0° and 180° were used, respectively.

Figure 3 clearly shows that as the phase of $St_{12}St_{21}$ increases toward 180°, the FoMs increase dramatically from their values at 0° ($\leq$ 2e-3, seen as a single dot in the figure) while the noise remains stable between 90° and 270°. Thus, the phase of $St_{12}St_{21}$ that produces the highest sensitivity under these conditions is 180°.

Simulations were run in which the magnitude of $St_{12}St_{21}$ was lowered from 1 down to 0.5, and the effect on the FoMs was minimal, within the noise. Therefore, this is not a critical parameter in the optimization of *St*, and these results are not shown in figure 3.

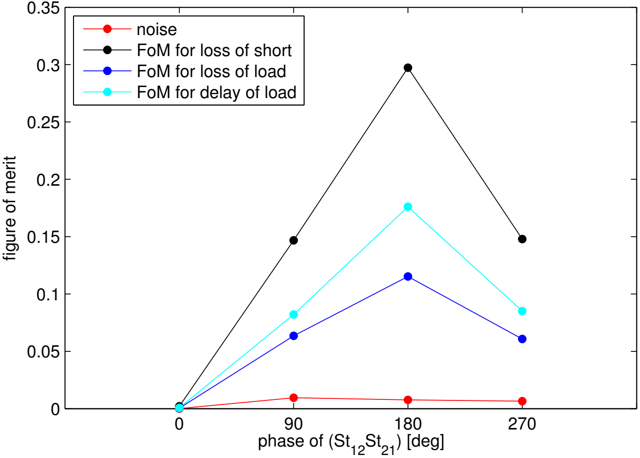

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
figure of merit
noise
FoM for loss of short
FoM for loss of load
FoM for delay of load
0
90
180
270
phase of (St12St21) [deg]

Figure : (3)

Conclusion

- The highest sensitivity to errors in the standards (loss of *short*, loss of *load*, delay of *load*) under the FR method at 1 GHz is obtained using a test network with $|St_{11}| \leq 0.1$, $|St_{22}| \geq 0.9$, and phase of $St_{12}St_{21}$ equal to 180°. The phases of St_{11} and St_{22} are not restricted to any value, and the magnitude of $St_{12}St_{21}$ can lay anywhere between 0.5 and 1 while still keeping the test network practically optimal.