A simplified method of VNA uncertainty estimation

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Outline

Problem

- Rigorous uncertainty propagation through VNA measurement model requires specification of basic uncertainty influences and use of software.
- Residual error method with ripple technique requires handling of beadless airlines and makes questionable assumptions in its current form.

Is it possible to estimate VNA uncertainty in a simpler way?

Possible Solution

Black Box approach that combines verification process with uncertainty estimation.

Credits:
Based on a method developed by Frederic Pythoud (EMC lab METAS).
The method is promoted by the Swiss Accreditation System for use in EMC labs.

Method is being refined and is at this point still preliminary.

Principle

- Previously characterized verification standards are measured
- The deviation needs to be within previously defined tolerance intervals
- The quoted uncertainty is based on the tolerance intervals and other contributions based on additional measurements.

Simple example: Measurement of matched load

Ingredients:

- Declared tolerance interval $T_{low-reflect}$
- Characterized OSL kit for VNA calibration
- Characterized verification load: $S_{11}^{load} \pm u\left(S_{11}^{load}\right)$

Steps:

- VNA is calibrated with OSL
- Verification load is measured: M_{11}^{load}
- Tolerance check: $\left|M_{11}^{load} - S_{11}^{load}\right| < T_{low-reflect}$
- DUT load measured: $S_{11}^{dut} \pm u_{rep}\left(S_{11}^{dut}\right)$
- $u\left(S_{11}^{dut}\right) = \sqrt{\left(u\left(S_{11}^{load}\right)\right)^2 + \left(\frac{T_{low-reflect}}{\sqrt{2}}\right)^2 + \left(u_{rep}\left(S_{11}^{dut}\right)\right)^2}$

Uncertainty influences

that need to be addressed:

- Noise
- Drift
- Linearity
- Cable
- Connector
- Calibration standards

Ingredients

- A set of traceably characterized calibration standards
  - Open, Short, Load
- A set of traceably characterized stable verification standards
  - High reflects: Open, Short
  - Load
  - Something with $S_{11} \simeq 0.5$, e.g. T-checker
  - Attenuators
  - Transparent device: Beaded airline or adapter

Verification process

- Characterized verification standards: S_{xx}^{ver}, $u\left(S_{xx}^{ver}\right)$
- Previously defined Tolerance intervals/regions (ev. f dependent): T_{ver}
- Verification measurements: M_{xx}^{ver}
- Verify that $\left|M_{xx}^{ver} - S_{xx}^{ver}\right| < T_{ver}$

Assign basic uncertainties:

Low reflect: $u_{lr} = \sqrt{\left(u\left(S_{11}^{load}\right)\right)^2 + \left(\frac{T_{lr}}{\sqrt{2}}\right)^2}$

High reflect: $u_{hr} = \sqrt{\left(\max\left(u\left(S_{11}^{open}\right), u\left(S_{11}^{short}\right)\right)\right)^2 + \left(\frac{T_{hr}}{\sqrt{2}}\right)^2}$

Linearity ($S_{11} \simeq 0.5$): $u_{l} = \sqrt{\left(u\left(S_{11}^{Tcheck}\right)\right)^2 + \left(\frac{T_{lin}}{\sqrt{2}}\right)^2}$

Calibration Standards: One Port

PRELIMINARY:

DUT S_{11}: Uncertainty contribution to S_{11} due to one port standards

$$u_{1p}\left(S_{11}^{dut}\right) = u_{lr} + \left|S_{11}^{dut}\right| \left(u_{lr} + u_{hr}\right)$$

for $u_r = \max\left(u_{lr}, u_{hr}\right)$:

$$u_{1p}\left(S_{11}^{dut}\right) = \left(1 + 2\left|S_{11}^{dut}\right|\right) u_r$$

Calibration Standards: Two Port Reflection

PRELIMINARY:

SOLT:
DUT S_{11}: Uncertainty contribution to S_{11} due to one port standards:

$$u_{1p}\left(S_{11}^{dut}\right) = u_{lr} + \left|S_{11}^{dut}\right|\left(u_{lr} + u_{hr}\right) + \left|S_{21}^{dut}\right| u_{lr}$$

for $u_r = \max\left(u_{lr}, u_{hr}\right)$:

$$u_{1p}\left(S_{11}^{dut}\right) = \left(1 + 2\left|S_{11}^{dut}\right| + \left|S_{21}^{dut}\right|\right) u_r$$

Unknown Thru: Not yet done.

Calibration Standards: Two Port Transmission

PRELIMINARY:

SOLT:
DUT S_{21}: Uncertainty contribution to S_{21} due to one port standards:

$$u_{1p}\left(S_{21}^{dut}\right) = 2\left|S_{11}^{dut}\right|\left|S_{21}^{dut}\right|\sqrt{u_{lr}^2 + u_{lr}u_{hr}}$$

for $u_r = \max\left(u_{lr}, u_{hr}\right)$:

$$u_{1p}\left(S_{21}^{dut}\right) = 2\sqrt{2}\left|S_{11}^{dut}\right|\left|S_{21}^{dut}\right| u_r$$

Unknown Thru: Not yet done.

Drift

Repeat verification procedure after DUT measurement again and recheck that deviations are still within tolerances.

Noise and Connector

Measurements of DUT are repeated at n $(n \geq 4)$ different connector orientations:

$$u_{rep}\left(S_{xx}\right) = \max\left\{s\left(\mathrm{Re}\left[S_{xx}\right]\right), s\left(\mathrm{Im}\left[S_{xx}\right]\right)\right\}$$

Standard deviation:

$$s\left(x\right) = \sqrt{2\sum_{i=1}^{n}\frac{\left(x_i - \hat{x}\right)^2}{n-1}}$$

Cable

One port measurements: Keep cable fixed

Two port measurements:

If possible use Unknown Thru calibration to avoid cable movements

For any cable movements:

1. Calibrate VNA.
2. Connect DUT.
3. Repeat movement of cable during 1. or 2. with DUT connected and record change in S-parameters.
4. Take maximum difference in S-parameters as an additional uncertainty contribution:
   $u_{cable}\left(S_{xx}\right) = \max\left(\left|\Delta S_{xx}\right|\right)$

Linearity

Reflection:

$$u_{lin}\left(S_{11}^{dut}\right) = 2u_l$$

Transmission: in work

Combined uncertainty

Reflection:

$$\begin{aligned}\left(u\left(S_{11}^{dut}\right)\right)^2 &= \left(u_{1p}\left(S_{11}^{dut}\right)\right)^2 + \left(u_{lin}\left(S_{11}^{dut}\right)\right)^2 + \\ &\quad \left(u_{cable}\left(S_{11}^{dut}\right)\right)^2 + \left(u_{rep}\left(S_{11}^{dut}\right)\right)^2\end{aligned}$$

Transmission: in work

Advantages

- Simple cookbook type procedure, clear pass/fail criteria.
- No handling of beadless airlines
- No software for uncertainty propagation needed.
- No previous characterization of VNA needed.
- The connector effect is taken care of.
- Not limited in frequency.
- The method combines verification and uncertainty evaluation.

Disadvantages

- The method is not strictly GUM. Uncertainties are not propagated through a measurement model.
- The method does not calculate uncertainty intervals with a defined coverage (e.g. 95%). The coverage is $> 95\%$.
- No detailed uncertainty budget and therefore no deeper understanding where the uncertainties are coming from.

Conclusion

- The method is correct in the sense that VNA uncertainties are not underestimated.
- The method is suitable for labs with low accuracy requirements.
- The method is suitable for labs where S-parameters are just secondary quantities.
- The efforts of implementation are manageable.
- An assessor can relatively easy verify if a lab fullfills the requirements.

We recommend to put it in cg-12!

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