Vector network analysis
Calibration and advanced measurements
Application examples (I)

Production-line testing

On-wafer testing
Application examples (II)

RCS measurement

Pulsed measurements
Wave quantities and S-parameters – 2 ports

**Wave quantities:**
- Incident wave: $a_i$
- Reflected/Transmitted wave: $b_i$

**S-parameters:**

**Forward meas.:** $a_2 = 0$
- $S_{11}$: reflection coef. ($b_1 / a_1$)
- $S_{21}$: fwd transmission coef. ($b_2 / a_1$)

**Reverse meas.:** $a_1 = 0$
- $S_{22}$: reflection coef. ($b_2 / a_2$)
- $S_{12}$: rev transmission coef. ($b_1 / a_2$)
Why do we measure S-parameters?

- At DC and low frequencies, voltages and currents are typically measured using capacitive probes.

- This technique doesn’t apply to radio frequencies ... it creates short or open circuits depending on the frequency.

- S-parameters relate incoming and reflected waves in the defined reference plane. [S] stands for scattering.

- S-parameters are complex values (amplitude and phase).

- Ideal for RF measurements because measurements can be performed in a matched and practical state (usually 50 Ω) using wave quantities.

- When components are cascaded, it is easy to compute the overall performance by multiplying the S-parameters matrices.
Relationship between S-parameters and voltage/current

\[
\begin{pmatrix}
V_1 \\
V_2 \\
\vdots \\
V_N
\end{pmatrix}
= 
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1N} \\
Z_{21} & \ddots & & \vdots \\
\vdots & & \ddots & \vdots \\
Z_{N1} & \cdots & \cdots & Z_{NN}
\end{bmatrix}
\begin{pmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{pmatrix}
\]

\[
S = \begin{pmatrix}
S_{11} \\
S_{12} \\
S_{21} \\
S_{22}
\end{pmatrix}
\]

\[
Z = \begin{pmatrix}
\Delta Z \\
\Delta Z
\end{pmatrix}
\]

\[
\Delta Z = (Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}
\]
How do we separate the waves at the source level from the ones at the receiver level? => using a directional element

Receivers and detectors required to measure the level of the wave quantities

Heterodyne concept used to process data in intermediate frequency (IF) => LO generator to convert the RF frequency to IF
Types of directional elements

Depending on the frequency range of a VNA, different kind of directional elements are used:

VSWR Bridge

Directional Coupler (above 20 GHz)
Agenda

- Calibration of the vector network analyzer
  - What is the purpose of calibration
  - Calibration methods
  - Measurement error
  - Dynamic range
  - Measurement Accuracy
- Group delay measurement
- Amplifier measurement
  - Linear parameters
  - Non-linear parameters
- Time domain
  - Modes
  - Gating and filtering in time domain
  - Applications
Agenda

- **Calibration of the vector network analyzer**
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- **Amplifier measurement**
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  - Non-linear parameters

- **Time domain**
  - Modes
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Calibration vs. system error correction

**Calibration:**
- Instrument has to be calibrated once a year by an appropriate service to check its raw performance.

**System error correction (SEC):** performed before a measurement to take into account the testing setup:
- Reference impedance environment (e.g. 50 Ω)
- Test cables(s) / adaptors
- Transmission line type (coaxial, wave guide, microstrip, etc)
- Calibration kit
- Calibration technique
Main purpose of SEC

- Set the reference plane to properly measure device under test (at the port of VNA by default) => critical for phase / delay
- Take into account imperfections of VNA
Setup: importance of test cables

- Connector type should be selected depending on frequency range
- Cables are the “weak link” in your setup
- Connector type of the test cable should match with the one of the used cal. kit
- Phase stable cables are required for accurate measurements
System error correction (I)

Error sources occurring during VNA measurement

- Stochastic errors
- Systematic errors

<table>
<thead>
<tr>
<th>No possible correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability of instrument (thermal drift)</td>
</tr>
<tr>
<td>Stability of test setup (connection repeatability, cable position)</td>
</tr>
<tr>
<td>Noise (sources and receivers)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error sources corrected by “system error correction“:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source mismatch</td>
</tr>
<tr>
<td>Port mismatch</td>
</tr>
<tr>
<td>Coupler directivity</td>
</tr>
<tr>
<td>Frequency response</td>
</tr>
</tbody>
</table>
System error correction (II)

Good practices to reduce stochastic errors:

- Allow warm up time of the instrument (reduce thermal drift)
- Use suitable connectors and cables (torque properly), clean connectors, and try to minimize the movement of the test cables (repeatability)
- Use IF bandwidth as small as possible (minimize noise) => sweep time!!!
System error correction (III)

Effect of the IF filter bandwidth on dynamic range:

- If IFBW is increased by factor 10:
  1. Dynamic range drops by 10 dB
  2. Measurement speed is 10 times faster

Example of trace noise with IFBW = 1 MHz

0.1 dB
System error correction (IV)

- Amplitude and phase variations when a cable is bent:

Example of typical variation as a function of temperature

<table>
<thead>
<tr>
<th></th>
<th>10 MHz</th>
<th>1 GHz</th>
<th>3 GHz</th>
<th>4.5 GHz</th>
<th>6 GHz</th>
<th>8.5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag dB/°C</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.012</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>Phase  °/°C</td>
<td>-0.026</td>
<td>0.014</td>
<td>0.05</td>
<td>0.088</td>
<td>0.068</td>
<td>0.23</td>
</tr>
</tbody>
</table>
System error correction (V)

Reflection coefficient measurement:

The instrument measures $S_{11M}$, but the actual quantity is $S_{11A}$.
System error correction (VI)

1-port error model: 3 terms

To measure the actual $a_1$ and $b_1$, imperfections are modelized in the error terms formed by $E_{DF}$, $E_{SF}$ and $E_{RF}$.

$E_{DF} = \text{Directivity}$  
$E_{SF} = \text{Source match}$  
$E_{RF} = \text{Frequency response (reflection)}$
System error correction (VII)

Relationship between $S_{11A}$, $S_{11M}$, and the error terms:

$$S_{11M} = \frac{b_1}{a_1}$$

$$S_{11M} = E_{DF} + \frac{S_{11A} \cdot E_{RF}}{1 - S_{11A} \cdot E_{SF}}$$
System error correction (VIII)

2-port error model (One path two port): 5 terms

Compared to the 1-port model, the error terms $E_{TF}$ and $E_{XF}$ are added

- $E_{DF}$ = Directivity
- $E_{SF}$ = Source match
- $E_{RF}$ = Reflection tracking
- $E_{TF}$ = Transmission tracking
- $E_{XF}$ = Isolation

Port 1

Port 2

$S_{11M}$

$S_{11A}$

$S_{21A}$

$S_{21M}$
System error correction (IX)

Full 2-port error model: forward measurement (6 terms)

Measurement done in two steps (forward $a_2 = 0$ and reverse $a_1 = 0$)
Even if only $S_{11}$ is displayed, the forward and reverse meas. are performed

$E_{XF}$

$E_{DF} = \text{Directivity}$
$E_{SF} = \text{Source match}$
$E_{RF} = \text{Reflection tracking}$
$E_{TF} = \text{Transmission tracking}$
$E_{LF} = \text{Load match}$
$E_{XF} = \text{Isolation}$
System error correction (X)

Coaxial calibration standards:

**Open:**
\[ C = C_0 + C_1 f + C_2 f^2 + C_3 f^3 \]
Parameters: Electrical length, Capacitance, Loss

**Short:**
Parameters: Electrical length, Inductance, Loss

**Match:** Charge (50 Ω)
System error correction (XI)
System error correction (XII)

Two major classes of error correction techniques:

- **Scalar calibration (Normalization or Response calibration):**
  - Compensates frequency response only
  - Does not require measurement of phase during calibration
  - Measure one standard only
  - Response = Data / MEM_{Standard}

- **Vector calibration:**
  - Requires measurement of phase during calibration
  - Compensates all major sources of systematic errors
  - Requires at least 3 calibration standards
  - Various techniques available based on the application contraints
System error correction (XIII)

Different types of system error correction are available for VNAs:

- **Standard calibration** (use of well defined calibration standards such as open, short or match). Possibility to calibrate 1 port only.
  - OSM (O=Open, S=Short, M=Match)
  - TOSM (T=Thru)

- **Self calibration / partial** (use of lines or network elements). Calibration only on 2 ports or more).
  - Normalization and 1 path-2 ports
  - LRL, TRL, LRM (L=Line, R=Reflect)
  - TRM, TSM, TOM, TNA (N=Symmetrical Network, A=Attenuator)
  - Automatic calibration: UOSM (U=Unknown thru)
**System error correction (XIV)**

Comparison of calibration methods:

<table>
<thead>
<tr>
<th>CALIBRATION TECHNIQUE</th>
<th>OSM</th>
<th>TOM</th>
<th>TRM</th>
<th>TRL</th>
<th>TNA</th>
<th>UOSM</th>
<th>TOSM</th>
<th>TOM-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error model (terms)</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>12</td>
<td>15</td>
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<tr>
<td>Suitable for transmission measurements</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>No band limitation due to singularities</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Indirect plausibility check</td>
<td>•</td>
<td></td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Partially unknown standards</td>
<td></td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Consideration of DUT depended cross talk</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>•</td>
<td></td>
<td>•</td>
</tr>
<tr>
<td>Usage of standards with different gender</td>
<td>•</td>
<td>•1)</td>
<td>•1)</td>
<td>•1)</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Suitable for non-insertable DUTs</td>
<td>•</td>
<td></td>
<td></td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<td>Possible usage of sliding match</td>
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<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Well-suited for on-waver measurements</td>
<td>•</td>
<td></td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Effective directivity attained</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Minimum number of calibration standards</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Contacts 2) in two port VNA</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

1) Assuming the standards produce symmetrical reflections.
2) The number of “contacts” is used to assess the amount of work involved in the calibration procedure. By contact, we mean setting up an electrical connection. For example, mounting a one-port standard requires one contact. Mounting a two-port standard requires two contacts.
System error correction (XV)

- **Mechanical calibration kits:**

- **Calibration modules (uses a series of electronic switches):**
### System error correction (XVI)

**Effective system data for different kind of calibration kits**

Example between 10 MHz and 15 GHz (units in dB):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Economical (mech.)</th>
<th>Auto. module (El.)</th>
<th>High-quality (mech.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity</td>
<td>23 to 41</td>
<td>32 to 40</td>
<td>36 to 40</td>
</tr>
<tr>
<td>Source match</td>
<td>20 to 36</td>
<td>26 to 36</td>
<td>30 to 36</td>
</tr>
<tr>
<td>Reflection tracking</td>
<td>0.025 to 0.05</td>
<td>0.1 to 0.2</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>Load match</td>
<td>21 to 39</td>
<td>32 to 40</td>
<td>36 to 40</td>
</tr>
<tr>
<td>Transmission tracking</td>
<td>0.10 to 0.40</td>
<td>0.15 to 0.2</td>
<td>0.1 to 0.2</td>
</tr>
</tbody>
</table>
Measurement accuracy (I)

Because the directional coupler is not ideal, a leaky signal is transmitted directly to the reference receiver even if there is no reflection on the test port.

Directivity is a factor used to quantify the amplitude of the residual signal.
Measurement accuracy (II)

- After calibration, the **directivity** of the measurement system can be evaluated.

- An air line is inserted between the test port and a match to create ripples in the frequency range of interest.

- The measured ripple is used to evaluate the directivity.

![Diagram showing incident signal (es), residual signal (ed), measured signal (ex), and offset of the match (z_x)].

Es: incident signal
Ed: residual signal (Directivity)
Ex: measured signal

Measure of ripples

Test port

Offset of the match
Measurement accuracy (III)

Accuracy: conversion table

- X dB below Ref
- Uncertainty of +xB/-xB around the measured value

<table>
<thead>
<tr>
<th>XdB</th>
<th>(Ref+X)</th>
<th>Ref-X</th>
<th>Ref+/-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>-0.02</td>
<td>0.02</td>
<td>0.04</td>
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<tr>
<td>3</td>
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<td>0.05</td>
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<td>0.06</td>
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<td>0.14</td>
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<td>0.08</td>
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<td>9</td>
<td>-0.09</td>
<td>0.09</td>
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<tr>
<td>10</td>
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<td>0.20</td>
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<td>11</td>
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<td>0.21</td>
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<tr>
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<td>0.22</td>
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<td>0.46</td>
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<td>0.48</td>
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<td>0.66</td>
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<td>34</td>
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<td>0.34</td>
<td>0.68</td>
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<td>35</td>
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<td>0.35</td>
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<td>-0.36</td>
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<td>0.72</td>
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<td>37</td>
<td>-0.37</td>
<td>0.37</td>
<td>0.74</td>
</tr>
<tr>
<td>38</td>
<td>-0.38</td>
<td>0.38</td>
<td>0.76</td>
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<tr>
<td>39</td>
<td>-0.39</td>
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<td>0.78</td>
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<td>-0.40</td>
<td>0.40</td>
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<td>41</td>
<td>-0.41</td>
<td>0.41</td>
<td>0.82</td>
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<td>42</td>
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<td>0.42</td>
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<td>43</td>
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<td>0.44</td>
<td>0.88</td>
</tr>
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<td>0.45</td>
<td>0.90</td>
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<td>-0.46</td>
<td>0.46</td>
<td>0.92</td>
</tr>
<tr>
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<td>-0.47</td>
<td>0.47</td>
<td>0.94</td>
</tr>
<tr>
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<td>-0.48</td>
<td>0.48</td>
<td>0.96</td>
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<td>49</td>
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<td>0.98</td>
</tr>
<tr>
<td>50</td>
<td>-0.50</td>
<td>0.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Measurement accuracy (IV)

1.4 dB ripple at 1.65 GHz

1.4 dB around a RL of -20.5 dB

Directivity $= 22 + 20.5 \text{ dB} = 42.5 \text{ dB}$
Measurement accuracy (V)

- Example: VSWR of $Z_x = 1.29$ => $RL = 18$ dB
- Directivity $Ed = 40$ dB
- The conversion table provides the error caused by directivity on a VSWR of 1.29

Es: incident signal

Ed: residual signal (Directivity)

Ex: measured signal

Test port

Directional coupler

Non ideal match
Partial reflection

Uncertainty 1.38 dB

18.72 dB
17.34 dB
Measurement accuracy (VI)

- Similarly, the **source match** (or port match) can be measured.

- In this case, an air line is inserted between the test port and a short.

![Diagram showing measurement accuracy](image)

- **Es**: incident signal
- **Ex**: measured signal
- **Ea**: reflected signal
- **Zx**: Short circuit

Measure of ripples

Ed

Ex
Values given by the manufacturer for accuracy in reflection
Measurement accuracy (VIII)

Measurement accuracy in transmission

1. Transmission losses
2. Reflections between DUT/Port 1
3. Reflections between DUT/Port 2
4. Reflections between the ports
5. Isolation
Values given by the manufacturer for accuracy in transmission
Measurement accuracy (X)

Uncertainty in dB

S21 Transmission Coefficient in dB*)

\[ |S'_{21}|^2 = \left| \frac{1 - \Gamma_1 \Gamma_2}{(1 - \Gamma_1 S_{11})(1 - \Gamma_2 S_{22}) - S_{12} S_{21} \Gamma_1 \Gamma_2} \right|^2 \cdot |S_{21}|^2 \]
Measurement accuracy (XI)

Receiver linearity: measurement and calibration for $a_1 = -10$ dBm and $a_1 = +10$ dBm
Measurement accuracy (XII)

Example of the error caused by an adaptor mounted on the test port and not taken into account during calibration:

Directivity of 40 dB
- DUT has a RL of 18 dB
- Directivity - RL = 22 dB
- Error + 0.66, - 0.72 dB
- RL comprised between 17.34 and 18.72 dB

Directivity of 32 dB
- DUT has a RL of 18 dB
- Directivity - RL = 14 dB
- Error + 1.6, - 1.9 dB
- RL comprised between 16.4 and 19.9 dB

Directivity with adaptor
- Coupler 40 dB
- Adaptor: ROS 1.03
- New directivity = 32 dB

Adaptor: ROS 1.03
Measurement accuracy (XIII)

- A possibility to take into account the adaptor on port 1 is to use de-embedding (specifications of the imperfections of the adaptor)
- Works well for low losses
- Limitations:
  - Measurements of a RL of 20 dB through a cable, 3-dB and 10-dB attenuators

<table>
<thead>
<tr>
<th>Cable / adaptor</th>
<th>3 dB att.</th>
<th>10 dB att.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td>Port 1</td>
<td>Port 1</td>
</tr>
<tr>
<td>20 dB load</td>
<td>20 dB load</td>
<td>20 dB load</td>
</tr>
</tbody>
</table>

![Graphs showing measurement accuracy](image-url)
Measurement accuracy (XIV)

Accuracy as a function of the system error correction:

**Green:** Full two port (TOSM)
- Corrects source- and load mismatch

**Red:** 1-path 2-port cal
- Corrects source port mismatch only

**Blue:** Normalization
- No correction for source or load mismatch

Normalization and 1-path 2-port cal:
- Deviation 0.05 dB
- Half the measurement time
Types of measurements

<table>
<thead>
<tr>
<th>4 principal categories:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear measurements (S-parameters, group delay, balanced DUT, stability, switching time, …)</td>
</tr>
<tr>
<td>Nonlinear measurements (n dB compression point, harmonics, …)</td>
</tr>
<tr>
<td>Time-domain measurements (distance to fault, transmission line impedance, …)</td>
</tr>
<tr>
<td>Frequency conversion measurements (mixers, frequency multipliers,…)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Important parameters for a measurement:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
</tr>
<tr>
<td>IF filter bandwidth =&gt; speed vs. dynamic range</td>
</tr>
<tr>
<td>Power level at the input of the DUT (-20 dBm for active devices, 0 dBm for passive ones)</td>
</tr>
<tr>
<td>Observed result (S, Z, Y, ratios, wave quantities …)</td>
</tr>
</tbody>
</table>
Agenda

- Calibration of the vector network analyzer
  - What is the purpose of calibration
  - Calibration methods
  - Measurement error
  - Dynamic range
  - Measurement Accuracy

- Group delay measurement

- Amplifier measurement
  - Linear parameters
  - Non-linear parameters

- Time domain
  - Modes
  - Gating and filtering in time domain
  - Applications
Group delay measurement (I)

Reference plane

Ideal transmission line

$\phi_{ref} = 0^\circ$

$f_1$

$f_2$

$f_3$

$f_4$

$f_5$

$f_6$

$f_7$

$\phi_1$

$t$

$\phi_7$

$\phi$

$-180^\circ$

$-360^\circ$
Group delay measurement (II)

- Group delay helps to evaluate the distortion of devices

- Definition: the group delay corresponds to the slope of the phase of S21 compared to a linear variation
  \[ \tau = - \frac{1}{360^\circ} \frac{d}{df} \text{Arg}(S21) \]

- Because discrete frequency points are defined on the VNA, a discrete differentiation (aperture) is used to compute the group delay
Group delay measurement (III)

- The total delay corresponds to the propagation time.
- Deviation from a constant group delay indicates distortion.
- The aperture defines the number of frequency points used to compute the group delay.
Group delay measurement (IV)

Example 1: cable

Aperture = 1

Aperture = 10
Group delay measurement (V)

Example 2: filter

- **Regular**
- **SAW**
Influence of the variation of the phase in a linear network

\[ F(t) = \sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t \]
Agenda

I Calibration of the vector network analyzer
   I What is the purpose of calibration
   I Calibration methods
   I Measurement error
   I Dynamic range
   I Measurement Accuracy
I Group delay measurement
I Amplifier measurement
   I Linear parameters
   I Non-linear parameters
I Time domain
   I Modes
   I Gating and filtering in time domain
   I Applications
Amplifier measurement (I)

- Linear device: parameters only vary as a function of frequency

- Non-linear device: parameters vary as a function of frequency and amplitude level at its input

- A device can be linear and non-linear alternatively
Amplifier measurement (II)

S-parameters
Amplifier measurement (III)

- VNAs can provide gain statistics: gives insight on values of maximum gain, slope and flatness (deviation from straight line)
Amplifier measurement (IV)

- Modern VNA capabilities for non-linear measurements:
  - High output power (easy measurement setup)
  - Optimized power sweep to maximize the dynamic range
  - High power compression point of the receivers
  - Segmented sweep with different power level
  - Possibility to measure all S-parameters at once
  - Power added efficiency (PAE) test set

Pout = 28 dBm
n dB gain compression point measurement carried out to assess the power range where a non-linear component is linear.

Typically, b2 / a1 is displayed as a function of the input power.

Compression point is defined as the input or output power for which the gain drops by n dB (often 1 dB).
Amplifier measurement (VI)

- Simultaneous display of compression point for different frequencies

- Phase distortion around the compression point (AM/PM conversion)
Harmonics (2\(^{nd}\), 3\(^{rd}\), ... order) are generated by the non-linearity of a device (e.g., an amplifier).

Intercept points for 2\(^{nd}\) (IP2) and 3\(^{rd}\) (IP3) order are often used to evaluate the input power at which the fundamental frequency has an equal contribution to harmonics of 2\(^{nd}\) and 3\(^{rd}\) order (pure mathematical concept).

Often measured using a spectrum analyzer.
Amplifier measurement (VIII)

Intermodulation setup

example:
swept IP3+ measurement:

\[ f_{\text{IP3}^+} = 2 \cdot f_2 - f_1 \]
Amplifier measurement (IX)

- Intermodulation product

\[ IP_{ne} = \frac{a_{IMn}}{n-1} + L_m \]

- \( IP_{ne} \): n-th Intermodulation product
- \( a_{IMn} \): Intermodulation distance
- \( L_m \): input level
Agenda

- **Calibration of the vector network analyzer**
  - What is the purpose of calibration
  - Calibration methods
  - Measurement error
  - Dynamic range
  - Measurement Accuracy

- **Group delay measurement**

- **Amplifier measurement**
  - Linear parameters
  - Non-linear parameters

- **Time domain**
  - Modes
  - Gating and filtering in time domain
  - Applications
Time domain (I)

- Time domain reflectometry (TDR) often gives a clearer insight into the characteristics of the DUT

- A short rise time pulse is used at the input of the DUT, any impedance discontinuities will cause some of the incident signal to be sent back towards the source.

- Using a VNA, wave quantities results can be filtered and mathematically transformed in order to obtain the time domain representation (virtual pulse / step)

Applications:
- Distance-to-fault in connectors, transmission lines and circuit boards (telecoms, aviation wiring, etc);
- Semiconductor failure analysis (non-destructive method for the location of defects in semiconductor device packages)
- Moving the reference plane across unknown irregularities;
- Removal of unwanted signals in multipath propagation;
- Calibration optimization
Time domain (II)

Time domain vs. frequency domain:

- Time domain (II)
- FFT
- $\text{S}_{11} = f (\text{freq})$
- $\text{FFT}^{-1}$
- $\text{S}_{11} = f (\text{time})$

Port 1  cable 1  transition  cable 2  Match
Time domain (III)

To compute the time domain response, the analyzer uses the chirp z-transformation that is an extension of the (inverse) Fast Fourier Transform (FFT).

Compared to the FFT, the number of sweep points is arbitrary (not necessarily an integer power of 2).

The following properties of the Chirp z-transformation are relevant for the analyzer settings:

- The frequency points must be equidistant.
- The time domain response is repeated after a time interval which is equal to $\Delta t = 1/\Delta f$, where $\Delta f$ is the spacing between two consecutive sweep points in the frequency domain.
- $\Delta t$ is termed measurement range (in time domain) or ambiguity range.
The analyzer can emulate two different types of responses:
- The impulse response corresponds to the response of a DUT that is stimulated with a short pulse.
- The step response corresponds to the response of a DUT that is stimulated with a voltage waveform that transitions from zero to unity.

The two alternative responses are mathematically equivalent; the step response can be obtained by integrating the impulse response:

The step response is recommended for impedance measurements and for the analysis of discontinuities (especially inductive and capacitive discontinuities).

The impulse response has an unambiguous magnitude and is therefore recommended for most other applications.
Time domain (V)

I Impulse vs. step

stimulus

Reflection

Substrate
Trace (Micro strip line)
Via
In band pass mode, the time domain transform is based on the measurement results obtained in the sweep range between any set of positive start and stop values.

The sweep points must be equidistant.

No assumption is made about the measurement point at zero frequency (DC value).

The time domain result is complex with a generally undetermined phase depending on the delay of the signal.
Time domain (VII)

In low pass mode, the measurement results are extended towards $f = 0$ (DC value) and it is assumed that the negative frequency response is the complex conjugate of the positive.

Together with the DC value, the condition of equidistant sweep points implies that the frequency grid must be harmonic.

Due to the symmetry of the trace in the frequency domain, the time domain result is harmonic.
Time domain (VIII)

Harmonic grid:
- All frequencies must be an integer multiples of the frequency step $\Delta f$
- The first frequency is $f = 0$
- The second frequency is $f_1 = \Delta f$
- A set of $K$ frequencies is required between $f = 0$ and the minimum frequency of the VNA $f_{\text{min}}$ (determined through interpolation)

$$f_i = f_1 + (i-1) \Delta f$$

Time resolution:

- Band pass mode: $\Delta t = \frac{1}{f_{\text{stop}} - f_{\text{start}} + \Delta f} \approx \frac{1}{f_{\text{stop}} - f_{\text{start}}}$
- Low pass mode: $\Delta t = \frac{1}{2 \cdot f_{\text{stop}} + \Delta f} \approx \frac{1}{2 \cdot f_{\text{stop}}}$

<table>
<thead>
<tr>
<th>DUT</th>
<th>DC value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open or capacitance</td>
<td>$\Gamma(0) = 1$</td>
</tr>
<tr>
<td>Short or inductance</td>
<td>$\Gamma(0) = -1$</td>
</tr>
<tr>
<td>Resistor $R$ or resistor $R$ with parallel capacitor or resistor $R$ with series inductance</td>
<td>$\Gamma(0) = \frac{R - Z_0}{R + Z_0}$</td>
</tr>
</tbody>
</table>
## Pass band vs. low pass modes:

<table>
<thead>
<tr>
<th>Transform type</th>
<th>Band pass</th>
<th>Low pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Easiest to use: works with any set of equidistant sweep points</td>
<td>Higher response resolution (doubled) Includes information about DC value Real result Impulse and step response</td>
</tr>
<tr>
<td>Restrictions</td>
<td>No step response Undetermined phase</td>
<td>Needs harmonic grid</td>
</tr>
<tr>
<td>Use for...</td>
<td>Scalar measurements where the phase is not needed DUT's that don't operate down to f = 0 (e.g. pass band or high pass filters)</td>
<td>Scalar measurements where the sign is of interest DUT's with known DC value</td>
</tr>
</tbody>
</table>
Time domain (X)

- Example: measurement of a short circuit

![Graph showing time domain analysis]

- Band pass
- Low pass
Time domain (XI)

- Real scale:
  - Short
  - Open
Time domain (XII)

Natural limitations:

Frequency domain

1

DC

\( f \)

Time domain

\( FFT^{-1} \)

Pulse response

\( x = \pi t / f_{\text{span}} \)

\( \sin x / x \)
Time domain (XIII)

- Finite bandwidth of the VNA limits the resolution in time domain
- Side lobes reduce the dynamic range

Optimization of the time domain response:
- Use of windowing
- Trade-off between dynamic and resolution
Time domain (XIV)

I Effect of windowing
Time domain (XV)

**Aliasing:**

Sampling in the frequency range causes aliasing in the time domain

\[ \Delta t = \frac{1}{\Delta f} = \frac{\text{No. of freq. points} - 1}{F} \]

Ambiguity range = \( \frac{1}{\Delta f} \cdot 3e8 \)
Time domain (XVI)

- The resolution enhancement factor improves the resolution without increasing the upper frequency.

- The frequency performance (max frequency) of the connectors, cables and PCB will be not affected.
Time domain (XVII)

- VNA: 8.5 GHz stop frequency
- Window: Rectangle

![Graphs showing time domain analysis with VNA settings.](image-url)
Time domain (XVIII)

- DUT: PCB Board with micro strip line at different impedances, $Er \sim 3$, SMA Connector and FarEnd SMA Connector terminated

- Schematic of the DUT:
Time domain (XIX)

ZVA: Start: 10 MHz - 20 GHz
ZNB: Start 10 MHz - 8 GHz, REF: 2.5, fstep: 10 MHz

Time [ns]

Reflection Factor [U]
Time domain (XX)

- Gating functionality can be used to suppress unwanted reflections

- Gating will be applied to time domain mode whereas Windowing will be applied to frequency domain

- Two different types of gating are available:
  - Band pass mode
  - Notch mode

- Gated time domain measurements can be re transformed into frequency domain
Time domain (XXI)

1 Example: gating

e.g. Damaged connector