Network Analyzer Basics
Network Analysis is NOT....
What is a Vector Network Analyzer?

Vector network analyzers (VNAs)…

- Are stimulus-response test systems
- Characterize forward and reverse reflection and transmission responses (S-parameters) of RF and microwave components
- Quantify linear magnitude and phase
- Are very fast for swept measurements
- Provide the highest level of measurement accuracy
### What Types of Devices are Tested?

<table>
<thead>
<tr>
<th>Passive</th>
<th>Device type</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Duplexers</td>
<td>RFICs</td>
</tr>
<tr>
<td></td>
<td>Diplexers</td>
<td>MMICs</td>
</tr>
<tr>
<td></td>
<td>Filters</td>
<td>T/R modules</td>
</tr>
<tr>
<td></td>
<td>Couplers</td>
<td>Transceivers</td>
</tr>
<tr>
<td></td>
<td>Bridges</td>
<td>Receivers</td>
</tr>
<tr>
<td></td>
<td>Splitters, dividers</td>
<td>Tuners</td>
</tr>
<tr>
<td></td>
<td>Combiners</td>
<td>Converters</td>
</tr>
<tr>
<td></td>
<td>Isolators</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Circulators</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Attenuators</td>
<td>VCAs</td>
</tr>
<tr>
<td></td>
<td>Adapters</td>
<td>Amplifiers</td>
</tr>
<tr>
<td></td>
<td>Opens, shorts, loads</td>
<td>VCOs</td>
</tr>
<tr>
<td></td>
<td>Delay lines</td>
<td>VTFs</td>
</tr>
<tr>
<td></td>
<td>Cables</td>
<td>Oscillators</td>
</tr>
<tr>
<td></td>
<td>Transmission lines</td>
<td>Modulators</td>
</tr>
<tr>
<td></td>
<td>Waveguide</td>
<td>VCAAtten’s</td>
</tr>
<tr>
<td></td>
<td>Resonators</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dielectrics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R, L, C’s</td>
<td>Diodes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transistors</td>
</tr>
<tr>
<td>Low</td>
<td>Antennas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiplexers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Samplers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multipliers</td>
<td></td>
</tr>
</tbody>
</table>

Integration scale from Low to High.
Lightwave Analogy to RF Energy

- **Incident**
- **Reflected**
- **Transmitted**

**Lightwave**

**DUT**

**RF**
Agenda

- What measurements do we make?
  - Transmission-line basics
  - Reflection and transmission parameters
  - S-parameter definition
- Network analyzer hardware
- Error models and calibration
- Agilent’s Solutions
- Example measurements
- Appendix
Transmission Line Basics

Low frequencies
- wavelengths >> wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

High frequencies
- wavelength » or << length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line
Equivalent network to determine the Characteristic Impedance
Transmission line Zo

Zo determines relationship between voltage and current waves

Zo is a function of physical dimensions and $\varepsilon_r$

Zo is usually a real impedance (e.g. 50 or 75 ohms)
Characteristic Impedance $Z_0$

\[ Z_0 = \sqrt{R + j\omega L} \div \sqrt{G + j\omega C} \]

\[ Z_0 = \sqrt{\frac{L}{C}} \]

At high frequencies $\omega L >> R$ and $\omega C >> G$
Power Transfer Efficiency

For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)

Maximum power is transferred when $R_L = R_S$
Transmission Line Terminated with Zo

\[ Z_s = Z_0 \]

\( Z_0 = \text{characteristic impedance of transmission line} \)

\[ V_{\text{inc}} \rightarrow \text{wave} \rightarrow Z_0 \]

\[ V_{\text{refl}} = 0! \text{ (all the incident power is absorbed in the load)} \]

For reflection, a transmission line terminated in \( Z_0 \) behaves like an infinitely long transmission line.
Transmission Line Terminated with Short, Open

For reflection, a transmission line terminated in a short or open reflects all power back to source.
Transmission Line Terminated with 25 Ω

$Z_s = Z_0$

$Z_L = 25 \Omega$

Standing wave pattern does not go to zero as with short or open
Reflection Parameters

Reflection Coefficient
\[ \Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \rho \angle \Phi = \frac{Z_L - Z_0}{Z_L + Z_0} \]

Return loss
\[ \text{Return loss} = -20 \log(\rho), \quad \rho = |\Gamma| \]

Voltage Standing Wave Ratio
\[ \text{VSWR} = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho} \]

- No reflection (\(Z_L = Z_0\))
  - 0 dB
  - 1

- Full reflection (\(Z_L = \text{open, short}\))
  - ∞ dB
  - 0 dB
  - ∞
Smith Chart Review

Smith Chart maps rectilinear impedance plane onto polar plane

Rectilinear impedance plane

Polar plane

Smith chart

Z_L = Z_o
Γ = 0

Z_L = 0 (short)
Γ = 1 ∠ 0°

Z_L = ∞ (open)
Γ = 1 ∠ 0°

Constant X

Constant R
Transmission Parameters

Transmission Coefficient \( T = \frac{V_{\text{Transmitted}}}{V_{\text{Incident}}} = \tau \angle \phi \)

Insertion Loss (dB) \( = -20 \log \left( \frac{V_{\text{Trans}}}{{V_{\text{Inc}}}} \right) = -20 \log \tau \)

Gain (dB) \( = 20 \log \left( \frac{V_{\text{Trans}}}{{V_{\text{Inc}}}} \right) = 20 \log \tau \)
Linear Versus Nonlinear Behavior

Linear behavior:
- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

Nonlinear behavior:
- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)
Criteria for Distortionless Transmission

Linear Networks

Constant amplitude over bandwidth of interest

Linear phase over bandwidth of interest

Magnitude

Frequency

Phase

Frequency
Magnitude Variation with Frequency

\[ F(t) = \sin wt + \frac{1}{3} \sin 3wt + \frac{1}{5} \sin 5wt \]
Phase Variation with Frequency

\[ F(t) = \sin wt + \frac{1}{3} \sin 3wt + \frac{1}{5} \sin 5wt \]
Why Use S-Parameters?

- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools

\[
\begin{align*}
b_1 &= S_{11} a_1 + S_{12} a_2 \\
b_2 &= S_{21} a_1 + S_{22} a_2
\end{align*}
\]
Equating S-Parameters with Common Measurement Terms

S11 = forward reflection coefficient (*input match*)
S22 = reverse reflection coefficient (*output match*)
S21 = forward transmission coefficient (*gain or loss*)
S12 = reverse transmission coefficient (*isolation*)

*Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format*
Agenda

- What measurements do we make?
- Network analyzer hardware
  - T/R versus S-parameter test sets
  - Configurable Test set
- Error models and calibration
- Agilent’s Solutions
- Example measurements
- Appendix
Generalized Network Analyzer Block Diagram

SOURCE

Incident

DUT

TRANSMITTED (B)

Relected

REFLECTED (A)

SIGNAL SEPARATION

INCIDENT (R)

RECEIVER / DETECTOR

PROCESSOR / DISPLAY
### T/R Versus S-Parameter Test Sets

#### Transmission/Reflection Test Set

- RF always comes out port 1
- port 2 is always receiver
- **response**, **one-port** cal available

#### S-Parameter Test Set

- RF comes out port 1 or port 2
- forward and reverse measurements
- **two-port** calibration possible
Configurable Test set

Easy access to internal source and receivers
- Direct access to the signal paths between the internal source, receivers, bridges, and the analyzer’s test ports on the front panel.
- Enables to improve instrument sensitivity or to add components or peripherals for a wide variety of applications.

Front panel

Block Diagram
Configurable Test set (Examples)

Direct receiver access for accurate high-power measurements

- A booster amplifier can be added on source path for even higher power input to DUT. Direct receiver access with external couplers to pick up signals enables to eliminate temperature drift and effect of high reverse isolation of a booster amplifier.

Example DUTs:
- Power Amps (Handset, BTS, A/D, general-purpose)
- Passive components connected to PA (Filters/duplexer, coupler, antenna, etc)
Configurable Test set (Examples)

Improved forward measurement receiver sensitivity

- An alternative configuration to bypass the loss associated with internal bridge.
- Combining with segment sweep, dynamic range can be extended up to 150 dB.
- Faster throughput for high-attenuation DUT because of wider IFBW to achieve the same trace noise.

Example DUTs:
BTS filters, attenuators, isolation of RF switches.

Block Diagram

Wider dynamic range with the alternative configuration.

Two jumpers are connected differently with this configuration.
Agenda

• What measurements do we make?
• Network analyzer hardware
• Error models and calibration
  – measurement errors
  – what is vector error correction?
  – calibration types
  – accuracy examples
  – calibration considerations
• Example measurements
• Agilent’s Solutions
• Appendix
The Need For Calibration

Why do we have to calibrate?

- It is impossible to make perfect hardware
- It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

How do we get accuracy?

- With vector-error-corrected calibration
- Not the same as the yearly instrument calibration

What does calibration do for us?

- Removes the largest contributor to measurement uncertainty: systematic errors
- Provides best picture of true performance of DUT
Measurement Error Modeling

**Systematic errors**
- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

**Random errors**
- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise**, switch and connector **repeatability**

**Drift errors**
- due to system performance changing **after** a calibration has been done
- primarily cause by **temperature variation**

Errors:
- **SYSTEMATIC**
- **RANDOM**
- **DRIFT**

Measured Data

Unknown Device
Systematic Measurement Errors

Frequency response
- reflection tracking (A/R)
- transmission tracking (B/R)

Six forward and six reverse error terms yields 12 error terms for two-port devices
Types of Error Correction

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error

\[ S_{11a} \quad \rightarrow \quad \text{thru} \quad \rightarrow \quad S_{11m} \]
What is Vector-Error Correction?

Vector-error correction...

• Is a process for characterizing systematic error terms
• Measures known electrical standards
• Removes effects of error terms from subsequent measurements

Electrical standards...

• Can be mechanical or electronic
• Are often an open, short, load, and thru, but can be arbitrary impedances as well
Calibration
Using Known Standards to Correct for Systematic Errors

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements
- **1-port calibration** *(reflection measurements)*
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit
Reflection: One-Port Model

To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns:

\[ S_{11M} = E_D + E_{RT} \]

- Assumes good termination at port two if testing two-port devices
- If using port 2 of NA and DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results
Two-Port Error Correction

- Each actual S-parameter is a function of all four measured S-parameters.
- Analyzer must make forward and reverse sweep to update any one S-parameter.
- Luckily, you don't need to know these equations to *use* network analyzers!!!
Response versus Two-Port Calibration

Measuring filter insertion loss

After response calibration
After two-port calibration
Uncorrected

START 2 000.000 MHz
STOP 6 000.000 MHz
ECal: Electronic Calibration

30 kHz to 26.5 GHz module
10 MHz to 67 GHz module
Control ECal directly from the PNA or ENA Network Analyzers via USB
Nine connector types available
Ideal calibration technique for manufacturing
Mixed-connectors available
- Type-N 50 ohm, 3.5 mm and 7-16
  N4690 Series, 2-port Microwave ECal
85090 Series, 2-port RF ECal
N4431B, 4-port RF ECal
Adapter Considerations

**Coupler directivity** = 40 dB

\[ \rho_{\text{measured}} = \text{Directivity} + \rho_{\text{adapter}} + \rho_{\text{DUT}} \]

**Worst-case System Directivity**

- **28 dB**
  - APC-7 to SMA (m)
  - SWR: 1.06

- **17 dB**
  - APC-7 to N (f) + N (m) to SMA (m)
  - SWR: 1.05, 1.25

- **14 dB**
  - APC-7 to N (m) + N (f) to SMA (f) + SMA (m) to (m)
  - SWR: 1.05, 1.25, 1.15

**APC-7 calibration done here**

DUT has SMA (f) connectors
Calibrating Non-Insertable Devices

When doing a through cal, normally test ports mate directly
- cables can be connected directly without an adapter
- result is a zero-length through

What is an insertable device?
- has same type of connector, but different sex on each port
- has same type of sexless connector on each port (e.g. APC-7)

What is a non-insertable device?
- one that cannot be inserted in place of a zero-length through
- has same connectors on each port (type and sex)
- has different type of connector on each port (e.g., waveguide on one port, coaxial on the other)

What calibration choices do I have for non-insertable devices?
- use an uncharacterized through adapter
- use a characterized through adapter (modify cal-kit definition)
- swap equal adapters
- adapter removal
- Un-known Thru
Thru-Reflect-Line (TRL) Calibration

We know about Short-Open-Load-Thru (SOLT) calibration...

What is TRL?
- A two-port calibration technique
- Good for noncoaxial environments (waveguide, fixtures, wafer probing)
- Uses the same 12-term error model as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- TRL (requires 4 receivers)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

TRL was developed for non-coaxial microwave measurements
In-Fixture Measurements

**Measurement problem:** coaxial calibration plane is not the same as the in-fixture measurement plane

Error correction with coaxial calibration
- Loss
- Phase shift
- Mismatch
Error Correction Choices

- **Port Extensions**
  - Direct Measurement: Easier, Lower Accuracy
  - Modeling: Harder, Higher Accuracy

- **De-embedding**
  - Full 2/3/4-port corrections (SOLT, TRL, LRM...)

- **New! Automatic Port Extensions**
Internal Measurement Automation

Simple: **recall states**

More powerful:

- **Test sequencing**
  - available on 8753
  - keystroke recording
  - some advanced functions

- **Windows-compatible programs**
  - available on PNA Series
  - Visual Basic, VEE, LabView, C++, ...

- **Visual Basic for Applications**
  - available on ENA Series

![Visual Basic for Applications on ENA](image)
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Agilent’s Solutions
  - RF/MW Vector Network Analyzer
  - LF/RF Vector Network Analyzer
  - Multi port Solutions
  - NVNA
- Example measurements
- Appendix
Agilent’s RF/MW Vector Network Analyzers

Test Accessories

Network Analyzer Basics

PNA-X, NVNA
Industry-leading performance
10 MHz to 13.5, 26.5, 43.5, 50, 67, & 110 GHz
Banded mm-wave to 2 THz

PNA
Performance VNA
10 MHz to 13.5, 26.5, 43.5, 50, 67, & 110 GHz
Banded mm-wave to 2 THz

PNA-L
World’s most capable value VNA
300 kHz to 6, 13.5, 20 GHz
10 MHz to 40, 50 GHz

PA-L
Low cost VNA
300 kHz to 4.5, 6.5, 8.5
300 kHz to 14, 20.0 GHz

ENA
World’s most popular economy VNA
100 kHz to 4.5, 6.5, 8.5
300 kHz to 14, 20.0 GHz

ENAL
Low cost VNA
300 kHz to 1.5/3.0 GHz
LF VNA 5 Hz to 3 GHz

FieldFox
RF Analyzer & RF VNA
5 Hz to 4/6 GHz

Mm-Wave Solutions
Up to 2 THz

PNA-X Receiver
8530A Antenna Replacement

Agilent Technologies
Sep. 2011
Agilent’s LF/RF Vector Network Analyzers

**Combination NA / SA**

4395A
- 500 MHz (4395A), 1.8 GHz (4396B)
- Impedance measurement
- Fast, FFT-based spectrum analysis
- Time-gated spectrum-analyzer option

**LF**

E5100A
- 300 MHz
- Economical
- Fast, small
- Target markets: resonators, filters
- Equivalent-circuit models
- Evaporation-monitor-function option

**4/6 GHz N9912A FieldFox**
- Cable and Antenna Analyzer, and Network Analyzer (Vector 1-port, Scalar 2-port)
- Lightweight (6 lbs) handheld instrument for field use
- QuickCal
- Spectrum Analysis
- Power Meter function with USB power sensor
- Vector Voltmeter function

**FieldFox N9923A**
- 2-port VNA
- S11, S21, S12, S22 / 4 & 6 GHz
- Full 2-port self & QuickCal
- Best handheld specs
- 100 dB system dynamic range (typical)
- Human tuning’ speed
- To feel ‘real-time’ for the human
- Vector voltmeter:
  - Dual channel ratio measurements
Agilent Multiport Solution Overview

• General purpose multiport components
  – Duplexer, Triplexer, power divider, LAN cable etc.
  – Multiple multiport device test

• Multiport components in Handset and WiLAN
  – Filter bank (multi SAW filter module)
  – Switch module in multi-band handset and Wireless LAN

• High-power device testing
  – Switch linearity of FEM for GSM handset
New E5092A is introduced
Up to 22-port, Up to 20GHz

- 87050E (8/12-port)
- U3042AE12 (16-port)
- Z5623AK66 (14-port)
- Z5623AK44 (8-port)
- Z5623AK64 (6-port)
- Z5623AK64 (8-port)
- Option 550 with N44xxB (4-port)
- PNA-L (4-port)
- High Power
- E5091A-009 (9-port)
- E5091A-016 (13/16-port)
- ENA (4-port)
- ENA-L
- PNA/PNA-X / PNA-L
- PNA-X

Freq
2.2G 4.5G 8.5G 20G 26.5/43.5/50/67G 500G
NVNA (Nonlinear Vector Network Analyzer)

To measure X-param, additional equipments are needed as shown above. This system enables measurements of the phase of harmonic signals and we call it “NVNA”.

- Signal generator (6GHz MXG)
- Power sensor (for amplitude CAL)
- E-CAL (for vector CAL)
- Phase reference 1 (to give stable phase)
- Phase reference 2 (for phase CAL)

N5241/2/4/5A: PNA-X
Agenda

• What measurements do we make?
• Network analyzer hardware
• Error models and calibration
• Agilent’s Solutions
• Example measurements
  Filter tests
  Gain compression
  AM to PM conversion
• Appendix
Frequency Sweep - Filter Test

- **Return loss**
  - CH1 S11
  - log MAG
  - 5 dB/
  - REF 0 dB

- **Insertion loss**
  - CH1 S21
  - log MAG
  - 0 dB/
  - REF 0 dB

- **Stopband rejection**
  - START 0.300 000 MHz
  - STOP 400.000 000 MHz
  - 69.1 dB

- **Return loss**
  - CENTER 200.000 MHz
  - SPAN 50.000 MHz

- **Insertion loss**
  - START 2 000.000 MHz
  - STOP 6 000.000 MHz
  - m1: 4.000 000 GHz - 0.16 dB
  - m2-ref: 2.145 234 GHz - 0.00 dB

Note: The diagrams illustrate the frequency sweep test results for different parameters such as return loss and insertion loss.
Optimize Filter Measurements with Swept-List or Segment Sweep Mode

Segment 3: 29 ms (108 points, -10 dBm, 6000 Hz)

Segment 1: 87 ms (25 points, +10 dBm, 300 Hz)

Segment 5: 129 ms (38 points, +10 dBm, 300 Hz)

Segments 2, 4: 52 ms (15 points, +10 dBm, 300 Hz)

Linear sweep: 676 ms (201 pts, 300 Hz, -10 dBm)

Swept-list sweep: 349 ms (201 pts, variable BW's & power)
Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

- gives linear behavioral model of our device
- measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- compute device parameters from measured data
- predict circuit performance under any source and load conditions

### H-parameters

\[ V_1 = h_{11} I_1 + h_{12} V_2 \]
\[ I_2 = h_{21} I_1 + h_{22} V_2 \]

### Y-parameters

\[ I_1 = y_{11} V_1 + y_{12} V_2 \]
\[ I_2 = y_{21} V_1 + y_{22} V_2 \]

### Z-parameters

\[ V_1 = z_{11} I_1 + z_{12} I_2 \]
\[ V_2 = z_{21} I_1 + z_{22} I_2 \]

\[ h_{11} = \left. \frac{V_1}{I_1} \right|_{V_2=0} \quad (requires \hspace{1mm} short \hspace{1mm} circuit) \]

\[ h_{12} = \left. \frac{V_1}{V_2} \right|_{I_1=0} \quad (requires \hspace{1mm} open \hspace{1mm} circuit) \]
Power Sweeps - Compression

Output Power (dBm)

Input Power (dBm)

Saturated output power

Compression region

Linear region
(slope = small-signal gain)
Power Sweep - Gain Compression

CH1 S21 log MAG 1 dB/ REF 32 dB 30.991 dB 12.3 dBm

1 dB compression: input power resulting in 1 dB drop in gain
**AM to PM Conversion**

**Measure of phase deviation caused by amplitude variations**

- AM can be undesired: supply ripple, fading, thermal
- AM can be desired: modulation (e.g. QAM)

**AM - PM Conversion**

\[
\text{AM - PM Conversion} = \frac{\text{Mag}(P_{m_{\text{out}}})}{\text{Mag}(A_{m_{\text{in}}})} \quad \text{(deg/db)}
\]
Measuring AM to PM Conversion

- Use transmission setup with a power sweep
- Display phase of S21
- AM - PM = 0.86 deg/dB
Characterizing Crystal Resonators/Filters

E5100A/B Network Analyzer

Example of crystal resonator measurement
Balanced Measurements

Now integrated in ENA and PNA FW

Data presented as mixed-mode S-parameters

Excellent dynamic range and accuracy

Many important features such as time domain, impedance re-normalization, user parameters...
VNA Applications

Amplifier test
Single connection:
Gain compression,
IMD, noise figure,
harmonics,
true differential,
PAE, hot $S_{22}$

Load-pull
Noise
parameters

T/R module
test

Satellite
payload test

Antenna
test

Lightwave
component
analysis

Mixer test
Scalar/vector Cal
absolute group delay
embedded LO

High Power
Devices &
Components

Non-linear
Modeling
Characterization
X-parameter* extraction
pulse envelope domain

High Power
Devices &
Components

Metrology
Primary standards/
calibration & repair

Millimeter &
Terahertz
research

Materials
measurements

Signal
integrity

Atomic
Force
Scanning
microscope

2 THz & beyond

500 GHz

110 GHz

67 GHz

50 GHz

43 GHz

26 GHz

13.5 GHz

6 GHz

300 kHz

PNA-X

PNA-L

PNA

2 THz & beyond

500 GHz

110 GHz

67 GHz

50 GHz

43 GHz

26 GHz

13.5 GHz

6 GHz

300 kHz

Plus medical, pharma,
agriculture, security, food etc.

*X-parameters is a trademark of Agilent Technologies.
Agenda

• What measurements do we make?
• Network analyzer hardware
• Error models and calibration
• Agilent’s Solutions
• Example measurements
• Appendix
  VNA Applications
  TDR
  Mixer/converter Measurement
  etc…….
Time-Domain Reflectometry (TDR)

- What is TDR?
  - time-domain reflectometry
  - analyze impedance versus time
  - distinguish between inductive and capacitive transitions
- With gating:
  - analyze transitions
  - analyzer standards

**Diagram:***
- Zo: impedance reference level
- Time-domain reflectometry graph showing:
  - Inductive transition
  - Capacitive transition
  - Non-Zo transmission line
TDR Basics Using a Network Analyzer

- start with broadband frequency sweep (often requires microwave VNA)
- use inverse-Fourier transform to compute time-domain
- resolution inversely proportionate to frequency span

Time Domain
- \( \int_0^t F(t) \, dt \):Integrate

TDR
- \( F^{-1} \)

Frequency Domain
- \( 1/s \cdot F(s) \)

\( F^{-1} \)

CH1 S\(_{22} \) Re 50 mU/ REF 0 U
Cor 20 GHz 6 GHz
CH1 START 0 s STOP 1.5 ns
Time-Domain Gating

- TDR and gating can remove undesired reflections (a form of error correction)
- Only useful for broadband devices (a load or thru for example)
- Define gate to only include DUT
- Use two-port calibration

![Graphs showing Thru in time and frequency domains with and without gating.](image)
Time-Domain Transmission

- RF Input
- RF Output
- Main Wave
- Triple Travel
- Leakage
- RF Output

CH1 S21 log MAG 15 dB/ REF 0 dB

- Gate on
- Gate off

START -1 us
STOP 6 us

Surface Wave
Triple Travel
RF Leakage

Cor

Agilent Technologies
Time-Domain Filter Tuning

Deterministic method used for tuning cavity-resonator filters

Traditional frequency-domain tuning is very difficult:
- lots of training needed
- may take 20 to 90 minutes to tune a single filter

Need VNA with fast sweep speeds and fast time-domain processing
Filter Reflection in Time Domain

Set analyzer’s center frequency = center frequency of the filter

Measure $S_{11}$ or $S_{22}$ in the time domain

Nulls in the time-domain response correspond to individual resonators in filter
Tuning Resonator #3

Easier to identify mistuned resonator in time-domain: null #3 is missing

Hard to tell which resonator is mistuned from frequency-domain response

Adjust resonators by minimizing null

Adjust coupling apertures using the peaks in-between the dips
The E5071C Option TDR application is a software embedded on the ENA, which provides…

- Simple and Intuitive
- Fast and Accurate
- Robustness

… one-box solution for high speed serial interconnect analysis
Mixers and Converters

Basic Mixer

- Up converter: $f_3 > f_1$
- Down converter: $f_3 < f_1$
- Upper mixing product: $f_3 = f_1 + f_2$
- Lower mixing product: $f_3 = f_1 - f_2$

Converter

- Up converter: $f_3 > f_1$
- Down converter: $f_3 < f_1$
- Upper mixing product: $f_3 = f_1 + f_2$
- Lower mixing product: $f_3 = f_1 - f_2$
Mixer Measurement Parameters

Conversion loss
Conversion compression
Conversion phase
Group delay
Isolation/SWR
Two tone third-order intermodulation distortion
Conversion Loss

Conversion loss (dB) = 10 \log \frac{\text{RF power (mW)}}{\text{IF power (mW)}}

Function of LO power
Conversion Loss

Swept IF

Conversion Loss

Fixed IF

Conversion Loss

Fixed RF

Conversion Loss
Conversion Compression

![Diagram showing Conversion Compression with axes: RF Input Power [dBm], IF Output Power [dBm], Conversion Loss (dB), 1-dB Compression Point, IF Power (dB) and Compression Region]
Conversion Phase

- Phase is a relative measurement.
- Must be made on two signals with the same frequency.

**Remember:**
- Phase is a relative measurement.
- Must be made on two signals with the same frequency.

\[
\Delta \phi = 90^\circ - 45^\circ = 45^\circ \\
\Delta \phi = 0^\circ - 45^\circ = 45^\circ
\]
Group Delay

- Customers who measure phase are typically interested in the group delay ripple
- Mathematical derivative of phase measurement
## PNA & ENA Network Analyzers Mixer Calibration Techniques

<table>
<thead>
<tr>
<th>Vector-Mixer Calibration</th>
<th>Scalar-Mixer Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Most accurate measurements of phase and absolute group delay</strong></td>
<td>Highly accurate conversion-loss measurements with simple setup and calibration</td>
</tr>
<tr>
<td>Removes magnitude and phase errors for transmission and reflection measurements</td>
<td>Removes mismatch errors during calibration and measurements by combining 2-port and power-meter calibrations</td>
</tr>
</tbody>
</table>

**Scalar-Mixer Calibration**
- Highly accurate conversion-loss measurements with simple setup and calibration
- Removes mismatch errors during calibration and measurements by combining 2-port and power-meter calibrations
Balanced Mixer Measurements

Vector-mixer characterization VBA macro offers Agilent patented balanced mixer characterization

Balanced mixer measurements require two calibration mixer/filter

Both mixer/filters are characterized with VBA macro
High Power Amplifier Setup Diagram – Based on PNA Network Analyzers

Example: PNA output power NOT enough to drive amplifier. Need to add pre-amplifier to boost power levels.
High-Dynamic Range Measurements

Take advantage of extended dynamic range with direct-receiver access.
PNA/PNA-X Option 086
Gain Compression Application (GCA)

GCA provides amplifier or converter gain compression data fast and accurately, at multiple frequencies, with a simple setup

✓ Measure this key device specification many times faster than current methods with GCA’s SMART sweep

✓ Achieve the highest measurement accuracy of any solution in the market by using mismatch correction
PNA-X Option 087 IMD Application

Achieves **fast and accurate IMD measurements** that are easy to set up and calibrate. Features a **simple user interface** that takes advantage of PNA-X’s **internal combiner and two internal sources** with high power and low harmonics, further solidifying PNA-X as the **best solution for active-device test**.

- Measures tone powers, IMD products (dBm or dBC), and intercept points of order 2, 3, 5, 7, or 9
- Sweep Fc, tone spacing, tone power, or LO power
- Spectrum measurements eliminate need for SA
- Works on 2- or 4-port PNA-X models
Noise Figure Measurement Options 028, 029, H29

Measure key amplifier parameters up to 50 GHz with a **single connection** (e.g. S-parameters, noise figure, compression, IMD, harmonics)

Achieve the **highest measurement accuracy** of any solution on the market

Typically 4 to 10 times **faster** than the NFA

ECal module used as an impedance tuner to remove the effects of imperfect system source match
S-Parameters:

**Linear Measurement, Modeling, and Simulation**

- Easy to measure at high frequencies
  - measure voltage traveling waves with a (linear) vector network analyzer (VNA)
  - don't need shorts/opens which can cause devices to oscillate or self-destruct
- Relate to familiar measurements (gain, loss, reflection coefficient ...)
- Can cascade S-parameters of multiple devices to predict system performance
- Can import and use S-parameter files in electronic-simulation tools (e.g. ADS)
- BUT: No harmonics, No distortion, No nonlinearities, ...
  Invalid for nonlinear devices excited by large signals, despite *ad hoc* attempts

### Linear Simulation:
Matrix multiplication

$S$-parameters

\[
\begin{align*}
  b_1 &= S_{11}a_1 + S_{12}a_2 \\
  b_2 &= S_{21}a_1 + S_{22}a_2
\end{align*}
\]

### Measure with linear VNA:
Small amplitude sinusoids

Model Parameters:
Simple algebra

\[
S_{ij} = \frac{b_i}{a_j} \bigg|_{a_k=0}^{k \neq j}
\]
X-Parameters are the Nonlinear Paradigm

X-parameters have the potential to revolutionize the characterization, design, and modeling of nonlinear components and systems.

X-parameters are the mathematically correct extension of S-parameters to large-signal conditions.

- Measurement based, device independent, identifiable from a simple set of automated NVNA measurements
- Fully nonlinear (magnitude and phase of distortion)
- Cascadable (correct behavior in even highly mismatched environment)
- Extremely accurate for high-frequency, distributed nonlinear devices

**NVNA:** Measure device X-parameters

**X-parameter model:** Simulate using X-parameters

**ADS:** Design using X-parameters
X-Parameters Come from the Poly-Harmonic Distortion (PHD) Framework

Data and model formulation in frequency (envelope) domain magnitude and phase enables complete time-domain input-output waveforms.
Noise Parameters with the PNA-X

PNA-X-based solution using Maury automated tuners

- Easy setup
- Fast calibration
- Fast measurement
- Higher accuracy

73 frequencies, 224x faster!
Thank You