Objectives

- Review RF basics (transmission lines, etc.)
- Understand what types of measurements are made with vector network analyzers (VNAs)
- Examine architectures of modern VNAs
- Provide insight into nonlinear characterization of amplifiers, mixers, and converters using a VNA
- Understand associated calibrations
- Application: Amplifiers test and Fixture Simulator
- Automation VBA example
Network Analysis is NOT…

Your IEEE 802.37 X.25 ASDN switched-packet data stream is running at 547 MBPS with a BER of $1.523 \times 10^{-9}$.
What Are Vector Network Analyzers?

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?

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<td>Transistors</td>
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Device Test Measurement Model

- RFIC Testers
- Ded. Testers
- VSA
- SA
- VNA
- TG/SA
- SNA
- NF Mtr.
- Imped. An.
- Param. An.
- Power Mtr.
- Det/Scope

- Simple
- Complex

- Measurement plane
- NF
- Intermodulation Distortion
- Intermodulation Distortion
- Harm. Dist.
- LO stability
- Image Rej.
- Gain/flat.
- Compr’n
- Phase/GD
- AM-PM
- Isolation
- Mixers
- Rtn loss
- Balance
- Impedance
- S-parameters
- NF
- NF

- Stimulus type
- Simple
- Complex

- DC
- CW
- Swept freq
- Swept power
- Noise
- 2-tone
- Multi-tone
- Complex modulation
- Pulsed-RF
- Protocol

- Full call sequence
- Pulsed S-parm.
- Pulse profiling
- BER
- EVM
- ACP
- Regrowth
- Constell.
- Eye
- Intermodulation Distortion
- NF
- Measurement plane
- Agilent Technologies
Lightwave Analogy to RF Energy

Incident → Lightwave → Reflected

Transmitted
Why Do We Need to Test Components?

Verify specifications of “building blocks” for more complex RF systems

Ensure distortionless transmission of communications signals

- Linear: constant amplitude, linear phase / constant group delay
- Nonlinear: harmonics, intermodulation, compression, X-parameters

Ensure good match when absorbing power (e.g., an antenna)
The Need for Both Magnitude and Phase

1. Complete characterization of linear networks

2. Complex impedance needed to design matching circuits

3. Complex values needed for device modeling

4. Time-domain characterization

5. Vector-error correction

6. X-parameter (nonlinear) characterization
Agenda

- What measurements do we make?
  - Network analyzer hardware
  - Error models and calibration
  - Applications
  - Automation
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 ($Z_0$) is very important for low reflection and maximum power transfer
- Measured envelope voltage dependent on position along line
Transmission line $Z_0$

$Z_0$ determines relationship between voltage and current waves

$Z_0$ is a function of physical dimensions and $\varepsilon_r$

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

Twisted-pair

Coaxial

Waveguide

Coplanar

Microstrip

Characteristic impedance for coaxial airlines (ohms)
For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match).

Maximum power is transferred when $R_L = R_S$. 
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.

\[ Z_s = Z_0 \]

For in-phase \( (0^\circ) \) for open, out-of-phase \( (180^\circ) \) for short.
Transmission Line Terminated with 25 Ohms

Standing wave pattern does not go to zero as with short or open.
High-Frequency Device Characterization

**REFLECTION**

\[
\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}
\]

- VSWR
- S-Parameters \(S_{11}, S_{22}\)
- Reflection Coefficient \(\Gamma, \rho\)
- Return Loss

**TRANSMISSION**

\[
\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}
\]

- Gain / Loss
- S-Parameters \(S_{21}, S_{12}\)
- Transmission Coefficient \(T, \tau\)
- Insertion Phase
- Group Delay
Reflection Parameters

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

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

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

No reflection
\((Z_L = Z_o)\)

Full reflection
\((Z_L = \text{open, short})\)

<table>
<thead>
<tr>
<th>(Z_L = Z_o)</th>
<th>(Z_L = \text{open, short})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>1 dB</td>
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<tr>
<td>1 dB</td>
<td>0 dB</td>
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</tbody>
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Agilent Technologies
Smith Chart Review

Rectilinear impedance plane

Smith Chart maps rectilinear impedance plane onto polar plane

Polar plane

Smith chart

- \( Z_L = Z_0 \)
- \( \Gamma = 0 \)
- \( Z_L = 0 \) (short)
- \( \Gamma = 1 \angle 180^\circ \)
- \( Z_L = \infty \) (open)
- \( \Gamma = 1 \angle 0^\circ \)
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

Frequency

Magnitude

Phase

Frequency
Magnitude Variation with Frequency

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

\[ F(t) = \sin wt + \frac{1}{3} \sin 3wt + \frac{1}{5} \sin 5wt \]
Deviation from Linear Phase

Use electrical delay to remove linear portion of phase response

Linear electrical length added

(Electrical delay function)

Deviation from linear phase

Low resolution

High resolution
Group Delay

Group Delay ($t_g$)

$$\frac{-d \phi}{d \omega} = \frac{-1}{360^\circ} \cdot \frac{d \phi}{d f}$$

- $\phi$ in radians
- $\omega$ in radians/sec
- $\phi$ in degrees
- $f$ in Hertz ($\omega = 2 \pi f$)

- Group-delay ripple indicates phase distortion
- Average delay indicates electrical length of DUT
- Aperture ($\Delta \omega$) of measurement is very important
Why Measure Group Delay?

Same peak-peak phase ripple can result in different group delay
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

\[ \begin{align*}
H\text{-parameters} & \\
V_1 &= h_{11}I_1 + h_{12}V_2 \\
l_2 &= h_{21}I_1 + h_{22}V_2
\end{align*} \]

\[ \begin{align*}
Y\text{-parameters} & \\
l_1 &= y_{11}V_1 + y_{12}V_2 \\
l_2 &= y_{21}V_1 + y_{22}V_2
\end{align*} \]

\[ \begin{align*}
Z\text{-parameters} & \\
V_1 &= z_{11}I_1 + z_{12}l_2 \\
V_2 &= z_{21}I_1 + z_{22}l_2
\end{align*} \]

\[
h_{11} = \frac{V_1}{I_1} \bigg|_{V_2=0} \quad (\text{requires short circuit})
\]

\[
h_{12} = \frac{V_1}{V_2} \bigg|_{I_2=0} \quad (\text{requires open circuit})
\]
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 (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 **electronic-simulation** tools

![Diagram of S-parameters](image)

- \( b_1 = S_{11} a_1 + S_{12} a_2 \)
- \( b_2 = S_{21} a_1 + S_{22} a_2 \)
Measuring S-Parameters

\[ S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \mid a_2 = 0 \]

\[ S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1} \mid a_2 = 0 \]

\[ S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2} \mid a_1 = 0 \]

\[ S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2} \mid a_1 = 0 \]
Equating S-Parameters With Common Measurement Terms

\[ S_{11} = \text{forward reflection coefficient (input match)} \]
\[ S_{22} = \text{reverse reflection coefficient (output match)} \]
\[ S_{21} = \text{forward transmission coefficient (gain or loss)} \]
\[ S_{12} = \text{reverse transmission coefficient (isolation)} \]

Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format.
Measurements on Nonlinear Components

Nonlinear Networks

- Saturation, crossover, intermodulation, and other nonlinear effects can cause signal distortion.
- Effect on system depends on amount and type of distortion and system architecture.
Scattering Parameters – Power Dependence

An early attempt at providing some power-dependence was the P2D files used in ADS.

Unfortunately these files did not properly capture non-linear behavior except S11 and S21 compression, nor did they predict harmonics and IMD.
X-parameters come from the Poly-Harmonic Distortion (PHD) Framework

Port Index
Harmonic (or carrier) Index

\[ B_{1k} = F_{1k} (DC, A_{11}, A_{12}, ..., A_{21}, A_{22}, ...) \]
\[ B_{2k} = F_{2k} (DC, A_{11}, A_{12}, ..., A_{21}, A_{22}, ...) \]

Spectral map of complex large input phasors to large complex output phasors. Black-Box description holds for transistors, amplifiers, RF systems, etc.
X-parameters Reduce to S-parameters

\[ B_{21}(|A_{11}|) = X_{21}^{(F)}(|A_{11}|)P + X_{21,21}^{(S)}(|A_{11}|)A_{21} + X_{21,21}^{(T)}(|A_{11}|)P^2A_{21}^* \]

<table>
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<th>dB</th>
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\[ \frac{X_{21}^{(F)} / |A_{11}|}{A_{11}} \rightarrow S_{21} \]

\[ X_{21,21}^{(S)}(|A_{11}|) \rightarrow S_{22} \]

\[ X_{21,21}^{(T)}(|A_{11}|) \rightarrow 0 \]

Reduces to (linear) S-parameters in the appropriate limit.
Agenda

• What measurements do we make?
• Network analyzer hardware
• Error models and calibration
• Applications
• Automation
Generalized Network Analyzer Block Diagram (Forward Measurements Shown)
- Supplies stimulus for system
- Can sweep frequency or power
- Traditionally NAs had one signal source
- Modern NAs have the option for a second internal source and/or the ability to control external source.
  - Can control an external source as a local oscillator (LO) signal for mixers and converters
  - Useful for mixer measurements like conversion loss, group delay
Signal Separation

- Measure incident signal for reference
- Separate incident and reflected signals

**Diagram:**
- **splitter**
- **directional coupler**
- **bridge**
- **Detector**
- **Test Port**
**Directivity** is a measure of how well a directional coupler or bridge can separate signals moving in opposite directions.

\[
\text{Directivity} = \text{Isolation (I)} - \text{Fwd Coupling (C)} - \text{Main Arm Loss (L)}
\]

![Diagram showing the Directivity concept with a directional coupler and the separation of leakage and reflected signals.](Image)
Directional Bridge

- 50-ohm load at test port balances the bridge -- detector reads zero
- Non-50-ohm load imbalances bridge
- Measuring magnitude and phase of imbalance gives complex impedance
- "Directivity" is difference between maximum and minimum balance
- Advantage: less loss at low frequencies
- Disadvantages: more loss in main arm at high frequencies and less power-handling capability
Interaction of Directivity with the DUT (Without Error Correction)

DUT RL = 40 dB

Return Loss

Frequency

Directivity

Data max

Add in-phase

Device

Directivity

Data = vector sum

Data min

Add out-of-phase (cancellation)

Device

Directivity

Data = vector sum

Add in-phase

Device

Directivity

Data = vector sum

Add in-phase

Device

Directivity
Detector Types:
Narrowband Detection - Tuned Receiver

- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal rejection
- Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
- Trade off noise floor and measurement speed
Tuned Receiver Front Ends: Mixers Versus Samplers

It is cheaper and easier to make broadband front ends using samplers instead of mixers, but dynamic range is considerably less.
Dynamic Range and Accuracy

Error Due to Interfering Signal

Dynamic range is very important for measurement accuracy!
T/R Versus S-Parameter Test Sets

### Transmission/Reflection Test Set

- RF comes out port 1; port 2 is receiver
- Forward measurements only
- **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
Processor / Display

- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math
Achieving Measurement Flexibility

Channel
- Sweep type
- Frequencies
- Power level
- IF bandwidth
- Number of points
- Trigger state
- Averaging
- Calibration

Trace
- Parameter
- Format
- Scale
- Markers
- Trace math
- Electrical delay
- Phase offset
- Smoothing
- Limit tests
- Time-domain transform
Three Channel Example

- **Channel 1**
  - frequency sweep (narrow)
  - S11
  - S11
  - S21

- **Channel 2**
  - frequency sweep (broad)
  - S21

- **Channel 3**
  - power sweep
  - S21

[Diagram of channel examples with windows and data plots]
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Applications
- Automation
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)
- Generally, are largest sources or error

**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 caused by **temperature variation**

![Diagram of Measurement Error Modeling](image-url)
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
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
Using Known Standards to Correct for Systematic Errors

- **1-port calibration** (*reflection measurements*)
  - Only three systematic error terms measured
  - Directivity, source match, and reflection tracking

- **Full two-port calibration** (*reflection and transmission measurements*)
  - Twelve 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:

\[ S_{11M} = E_D + E_{RT} \left[ \frac{S_{11A}}{1 - E_S \cdot S_{11A}} \right] \]

- Assumes good termination at port two if testing two-port devices
- If using port two 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
Before and After A One-Port Calibration

Data before 1-port calibration

Data after 1-port calibration
Two-Port Error Correction

Forward model

Port 1

Port 2

$E_D$ = fwd directivity
$E_S$ = fwd source match
$E_{RT}$ = fwd reflection tracking
$E_L$ = fwd load match

$E_D'$ = rev directivity
$E_S'$ = rev source match
$E_{RT}'$ = rev reflection tracking
$E_L'$ = rev load match

- 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 a network analyzers!!!
Crosstalk: Signal Leakage Between Test Ports During Transmission

Can be a problem with:
- High-isolation devices (e.g., switch in open position)
- High-dynamic range devices (some filter stopbands)

Isolation calibration
- Adds noise to error model (measuring near noise floor of system)
- Only perform if really needed (use averaging if necessary)
- If crosstalk is independent of DUT match, use two terminations
- If dependent on DUT match, use two DUTs with termination on output
Errors and Calibration Standards

**UNCORRECTED FULL 2-PORT**
- Convenient
- Generally not accurate
- No errors removed

**RESPONSE**
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

**1-PORT**
- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

**ENHANCED-RESPONSE**
- Combines response and 1-port
- Corrects source match for transmission measurements

For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking
Calibration Summary

**Reflection**

*Test Set (cal type)*

- **T/R** (one-port)
- **S-parameter** (two-port)

- Reflection tracking ✔ ✔
- Directivity ✔ ✔
- Source match ✔ ✔
- Load match ✗ ✔

*error cannot be corrected*

*enhanced response cal corrects for source match during transmission measurements*

---

**Transmission**

*Test Set (cal type)*

- **T/R** (response, isolation)
- **S-parameter** (two-port)

- Transmission Tracking ✔ ✔
- Crosstalk ✔ ✔
- Source match ✔ ✗
- Load match ✗ ✔

*error can be corrected*

*error cannot be corrected*
Response versus Two-Port Calibration

Measuring filter insertion loss

After two-port calibration

After response calibration

Uncorrected
ECal: Electronic Calibration

- Variety of two- and four-port modules cover 300 kHz to 67 GHz
- Nine connector types available, 50 and 75 ohms
- Single-connection calibration
  - dramatically reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated characterized terminations provide excellent accuracy

Microwave modules use a transmission line shunted by PIN-diode switches in various combinations
1. Select adapters for the module to match the connector configuration of the DUT.

2. Perform a calibration using appropriate mechanical standards.

3. Measure the ECal module, including adapters, as though it were a DUT.

4. VNA stores resulting characterization data inside the module.
Thru-Reflect-Line (TRL) Calibration

We know about Short-Open-Load-Thru (SOLT) calibration... What is TRL?

- A two-port calibration technique
- Good for non-coaxial environments (waveguide, fixtures, wafer probing)
- Characterizes same 12 systematic errors as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

TRL was developed for non-coaxial microwave measurements
Unknown-Thru Calibration

Cal Methods are listed in order of ascending accuracy (least accurate first):

- **Uncharacterized Thru Adapter**
- **Electronic Calibrator (Ecal)**
- **Ecal with Unknown Thru**
- **Mechanical with Unknown Thru Cal**
- **Adapter Removal**
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Applications
- Automation
VNA application examples

- RF amplifier test
- High-power measurement
RF amplifier test

Stability (K-factor)
Calculates stability (K-factor) from all S-parameters with equation editor

\[
K = 1 - \frac{|S_{11}|^2 - |S_{21}|^2 + |\Delta|^2}{2|S_{11}S_{21}|}
\]

where \( \Delta = S_{11}S_{22} + S_{12}S_{21} \)

Gain compression
Sweeps both frequency and input power level at PxDB

High-power test
Performs accurate tests with high-power input / output of DUT

Harmonic Distortion
Performs real-time harmonics test over frequency or input power

Pulsed-RF
Characterize pulsed performance of devices

Swept IMD
Performs IMD analysis over an entire range of frequencies

Efficiency (PAE)
Calculate power-added efficiency (PAE)

The modern VNA is a more suited solution for many parametric tests of RF amplifiers.
What is gain compression?

- Parameter to define the transition between the linear and nonlinear region of an active device.
- The compression point is observed as x dB drop in the gain with VNA’s power sweep.

![Graph showing gain compression](image)

- Linear region
- Compression (nonlinear) region
- Power is not high enough to compress DUT.
- Sufficient power level to drive DUT.

Enough margin of source power capability is needed for analyzers.
VNA Functions
Power sweep range

Ex.) RF amplifier - Gain compression point

• Power sweep range is limited within 25 dB (i.e. -15 to 10 dBm).
• VNA's output power is NOT high enough to see compression point of DUT.

• VNA can drive up to +20 dBm, enough to detect compression point.
• Wide power sweep range (>65 dB) enables linear and nonlinear test with a single sweep.
**VNA Functions**

**User Interface**

**Legacy VNA**
- Manual parameter setup only.
- Customers need to develop their own software for applications.

**Modern VNA**
- Measurement wizard is provided using the VNA’s built-in automated software environment (i.e. VBA; Visual Basic for Applications)
- Easy setup for calibration / measurement.
- No external system controller is necessary.
VNA Functions

Measurement Wizard

- Measurement wizard program speeds up measurements of RF amplifiers.
- Key parameters of amplifiers: S-parameters, harmonics distortion, gain compression (CW or Swept frequency), and swept-frequency IMD measurements.
- Can be downloaded from www.agilent.com/find/enavba
VNA application examples

– RF amplifier test
– High-power measurement
Why high-power measurements?

• Components used for transmitting data in wireless communications need to be tested with high-power signals **under conditions similar to actual operation**. (may be beyond the measurement capability of instruments!)

Diagram of RF interface in wireless communication
High-power Measurements

Temperature drift of a booster amp needs to be considered.

Configuration with a booster amp

---

Measurement Challenges:
- **Power leveling** - Eliminating short-term drift of a booster amplifier’s gain; variation of input power to DUT.

---

DUT’s actual input power (Pin)

When temperature changes after setup / calibration, input power levels are changed even **out of tolerance**!
High-power Measurements

Power leveling

DUT’s input power level should be within a specific target range - power leveling.

Configuration for input power leveling

DUT’s actual input power ($Pin$)

Measurement Challenges:

- Power leveling process takes very long time!
- Test configuration is complicated; necessary to lower overall cost of test systems.
VNA Function

Power leveling

VNA Function - Receiver leveling

- Adjusts the source power level using its receiver measurements.
- Replaces existing test systems for power leveling with reducing test complexity.

Leveling with rack & stack system

Receiver leveling offers fast and accurate leveling to compensate a booster amp’s drift with a simple connection.
High-power Measurements

Power leveling

Configuration of Power leveling

Leveled Input power (Pin)

Note: frequency sweep is performed to monitor Pin over frequency.

DUT’s Pin is accurately adjusted (i.e. within +0.1 dBm) at target power level of +43 dBm by using the VNA’s receiver leveling.
Fixture Simulator

- Balanced measurements (Mixed-mode S-parameters)
- (De-)Embedding / port matching
- Setup wizard of fixture simulator
- Port matching utility program
Fixture Simulator

Actual Calibration Plane

Data Process

Measured S-parameters → Port Extension → Network De-embedding → Port reference Z conversion → Port Matching → Unbalanced-Balanced Conversion → Differential Port Z conversion → Differential Matching circuit Embedding

Balanced (Mixed-mode) S-parameter → Single-ended S-parameter

Single-ended Balanced

Agilent Technologies
Built-in Balanced Measurement

Balanced component examples:

- **SAW Filters (Unbal-Bal)**
- **SAW Filters (Bal-Bal)**
- **Baluns**
- **Differential Amplifiers**
- **Cable**
Mixed-mode $S$-parameters

Measure Single-ended $S$-parameters

Simulate Hybrid Balun to extract differential and common

Obtain Mixed-mode $S$-parameters (Balanced and Common-mode $S$-parameters)

\[
\begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{pmatrix}
\]

\[
\begin{pmatrix}
V_{\text{diff}} \\
V_{\text{comm}}
\end{pmatrix} = \begin{pmatrix} A, B \\ C, D \end{pmatrix} \ast \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}
\]

\[
\begin{pmatrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{pmatrix}
\]
Examples of Mixed-mode S-Parameters

Mixed-mode $S_{21}$ for Bal-Bal

- $S_{dd21}$
- $S_{cd21}$
- $S_{dc21}$
- $S_{cc21}$

Mixed-mode $S_{21}$ for Single to Bal

- $S_{ds21}$
- $S_{cs21}$
- $S_{sc22}$
- $S_{cc22}$

Mixed-mode $S_{11}$

- $S_{dd11}$
- $S_{cd11}$
- $S_{dc11}$
- $S_{cc11}$

Balanced SAW filter measurement example
Embedding/De-embedding and Port Z Conversion

**Embedding**

Additional Network → DUT → Additional Network

- Measured S-parameter
- Embedded Response

**De-embedding**

DUT → Undesired Network

- Measured S-parameter
- De-embedded Response

**Complex Port Z Conversion**

**Measure**

DUT

- 50Ω

**Simulate**

DUT

- \( R+jX \)

- 50Ω
Embedding / De-embedding

(De-)Embedding of 2-port circuits

(De-)Embedding of 4-port circuits
De-embedding

*Accurate characterization of the DUT is achieved by de-embedding S-parameter (*.s2p) of a fixture.*

Calibrated system (cal plane at cable end)

Create an S2p file and de-embed
Embedding Virtual Networks

- Mathematically embed matching circuits on any ports as required.
- Predefined matching topologies or user defined S-parameters networks can be embedded.
Balanced SAW Filter Measurement Example

Single-ended (unbalanced) 9x9 S-parameters, S11 to S33

Balanced S-parameters (both differential and common modes)
Measurement Specifications

Connections

- Single-ended : Port 1
- Balanced : Port 2
- Balanced : Port 3

Setup

1. Preset : OK
2. Center : 942.5MHz
3. Span : 200MHz
4. Display :
   Number of Traces: 9
   Allocate Traces: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
5. Select parameter & format as shown on next page
6. Adjust Scale
Measure Single-ended S-parameters

Measurement parameters

S11  S12  S13
S21  S22  S23
S31  S32  S33

Measured S-parameter
Perform Full 3-port Calibration

Measured S-parameter (w/Full-3 Cal)
Apply Port Extension

Electrical length

Port 1: 180ps
Port 2: 280ps
Port 3: 280ps

Measured S-parameter (w/Full-3 Cal)
**Convert to Mixed-mode S-parameters**

**Measurement Parameters**

<table>
<thead>
<tr>
<th>Sss11</th>
<th>Ssd12</th>
<th>Ssc12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sds21</td>
<td>Sdd22</td>
<td>Sdc22</td>
</tr>
<tr>
<td>Scs21</td>
<td>Scd22</td>
<td>Scc22</td>
</tr>
</tbody>
</table>

---

**Diagram**

- Apply port extension
- Measured S-parameter (w/Full-3 Cal)
- Convert to mixed-mode S-parameter

---

**Agilent Technologies**
Modify Port Characteristic Impedance

Port characteristic impedance

Port 1: 50 ohms
Port 2: 100 ohms
Port 3: 100 ohms

Measured S-parameter (w/Full-3 Cal)

Apply port extension

Convert port characteristic impedance

Convert to mixed-mode S-parameter

* Differential & common impedance are automatically calculated from defined single-ended impedance.
Apply Port Matching

Matching specifications

Port 1: none
Port 2: Shunt L = 28nH
Port 3: Shunt L = 28nH

Apply port extension
Apply matching circuit
Convert port characteristic impedance*
Convert to mixed-mode S-parameter
Measured S-parameter (w/Full-3 Cal)

Save “State & Cal”
Measurement Specifications

Setup

1. Preset : OK
2. Center : 942.5MHz
3. Span : 200MHz

Electrical length

Port 1 : 180ps
Port 2 : 280ps
Port 3 : 280ps

Port characteristic impedance

Port 1 : 50 ohms
Port 2 : 100 ohms
Port 3 : 100 ohms

Matching specifications

Port 1 : none
Port 2 : Shunt L = 28nH
Port 3 : Shunt L = 28nH
Setup Wizard of Fixture Simulator

Fast and easy measurements with setup wizard

Available at Agilent website at http://www.agilent.com/find/enavba
Agenda

• What measurements do we make?
• Network analyzer hardware
• Error models and calibration
• Applications
  Automation
Agilent IO Libraries Suite 16 provides one tool for fast start-up

**Agilent Connection Expert**

- **Instrument I/O on this PC**
  - COM1 (RS-232)
  - COM2 (RS-232)
  - COM3 (RS-232)
  - COM4 (RS-232)
  - USB (USB 1.0)
  - GPIB (GPIB 1)
  - LAN (TCP/IP)
- **LAN Instrument - myModelName**
  - VISA address: TCP/IP:192.168.1.15
  - IDN string:
    - Manufacturer: Agilent
    - Model: myModelName
    - Serial number: unknownSerialNumber
    - Firmware: unknownFirmwareRevision
  - I/O Interface: GPIB
  - Address check: Yes
  - Auto-identify: Yes

**System set-up in < 15 minutes**

- Identify and set up LAN, USB, GPIB, and converter interfaces
- Identify and communicate with instruments
- Change addresses and set interface aliases
- Works with NI-488 software and NI VISA I/O library
LAN eXtension for Instrumentation

LXI devices serve a web page

IP Address

Manufacturer
Model #
Serial #
Firmware rev.
IP Address
Domain name
etc.

Ability to change the IP address

Using standard web browser
LXI Possibilities

Long distance operations

Expert Troubleshooting

Parallel operations

Smart instruments

Reduce programming

Higher throughput

No trigger wires

Flexible triggering

Eliminate latency

Timestamp all data

Asset Management

Internal network
Software Integration

Agilent SystemVue

Integrated VBA Programming

Agilent ADS
Quick Demo Guide

ENA Series Network Analyzer - VBA Programming (UserMenu)

Procedure overview
1. Connect DUT to ENA
2. Launch VBA editor, and code VBA program
3. Run VBA Macro
4. Add bandwidth search module
5. Apply VBA macro to UserMenu buttons

In this demo...
- Code simple VBA macro for bandpass filter measurement
- Apply VBA macro to UserMenu buttons

Required Instrument and fixture
ENA series network analyzer (E5071C or E5061B)

N-Type Cable
Band pass filter (BPF)

1. Connect DUT to ENA

2. Launch VBA editor, and code VBA program
   a. Press [Macro setup] hard key then press VBA Editor soft key
   b. Create module and code procedure
      Click Insert in the menu bar then click Module
      Code as shown below in Module1

```vba
Sub main()
    Call Setup
End Sub
Sub Setup()
    SCPI.SYSTem.PRESet
    SCPI.SENSe.FREQuency.CENTer = "1.09E9"
    SCPI.SENSe.FREQuency.SPAN = "200E6"
    SCPI.CALCulate.PARameter.Count = 2
    SCPI.DISPlay.WINDow.Split = "D12"
    SCPI.CALCulate.PARameter(2).DEFine = "S21"
    SCPI.SENSe.BANDwidth.RESolution = 1000
    MsgBox "Setup done"
    SCPI.DISPlay.WINDow.TRACe(1).Y.SCALe.AUTO
    SCPI.DISPlay.WINDow.TRACe(2).Y.SCALe.AUTO
End Sub
```

3. Run VBA macro
   The ENA calls main() procedure, and this VBA program will set up the measurement parameters as shown below.

In this demo, we will use BPF (Center frequency = 1.09 GHz) but you can use another filter. Prepare appropriate cable and adapter to connect between ENA and DUT.

Figure1. DUT connection
Quick Demo Guide

4. Add Bandwidth Search Module

a. Open VBA Editor
b. Modify Sub() procedure of Module1 as below code

```vba
Sub Main()
    Call Setup
    Call Bandwidth
End Sub
```

c. Add below procedure on Module1

```vba
Sub Bandwidth()
    SCPI.CALCulate.PARameter(2).SELection.State = True
    .FUNCtion.TYPE = "MAX"
    .FUNCtion.EXECute
    BWIDth.State = True
End With
End Sub
```

d. Save VBA program and run

Click icon, then icon of the VBA editor
This code sets the measurement parameter, then make bandwidth search function as below.

5. Apply VBA procedure to UserMenu buttons

a. Open VBA Editor
b. Modify Sub() procedure of Module1 as below code

```vba
Sub Main()
    UserMenu.Item(1).enabled = True
    UserMenu.Item(2).enabled = True
    UserMenu.Item(1).Caption = "Setup"
    UserMenu.Item(2).Caption = "Bandwidth"
    UserMenu.Show
End Sub
```

c. Create UserMenu module

Click E5061B_Objects then Double-Click UserMenu
In the object box in the code window, select UserMenu as shown below.

```vba
Private Sub UserMenu_OnPress(ByVal ID As Long)
    If ID = 1 Then Module1.Setup
    If ID = 2 Then Module1.Bandwidth
    UserMenu.Show
End Sub
```

d. Code below procedure on UserMenu module

```vba
Private Sub UserMenu_OnPress(ByVal ID As Long)
    If ID = 1 Then Module1.Setup
    If ID = 2 Then Module1.Bandwidth
    UserMenu.Show
End Sub
```

e. Save program and run

Click icon, then icon of the VBA Editor

6. Use UserMenu Buttons

a. Press "Setup" button to run Setup procedure
b. Press "Bandwidth" button to run Bandwidth_Search procedure

Tips: Command finder
Using command finder chapter of the help file, you can easily find appropriate command for each button. To open help, press [Help] hard key, then click Programing > Command Reference > Command Finder.

www.agilent.com/find/ena_vba
## Useful Sample VBA Libraries for ENA Series Network Analyzers

Take a look and download useful free sample VBA wizards!

All of these sample programs are not password protected, so you can refer to the source code in order to develop and customize programs for your own applications.

<table>
<thead>
<tr>
<th>Sample VBA title</th>
<th>Revision</th>
<th>Release Date</th>
<th>E5071C Supported Firmware</th>
<th>E5070B/71B Supported Firmware</th>
<th>E5070A/71A Supported Firmware</th>
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<tr>
<td>ENA Setup Wizard VBA</td>
<td>Rev 01.30</td>
<td>2011/1/21</td>
<td>Rev 8.00 or later</td>
<td>Rev 6.50 or later</td>
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<tr>
<td>ENA Amplifier Measurement Wizard VBA</td>
<td>Rev 01.40</td>
<td>2011/1/21</td>
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<td>Rev 6.50 or later (VBA rev up to 01.11)</td>
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<td>ENA Mixer Measurement Wizard VBA</td>
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<td>2010/7/20</td>
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<td>Rev 6.50 or later (VBA rev up to 01.10)</td>
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<td>Rev 9.10 or later</td>
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<tr>
<td>Error Term Viewer Sample VBA</td>
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<td>8753 Keyboard Function Key Emulation Sample VBA</td>
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<td>Rev 8.00 or later</td>
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<td>USB 3.0 Connectors and Cable Assemblies Compliance Tests</td>
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<td>2009/12/18</td>
<td>Rev 9.10 or later</td>
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<td>2010/3/24</td>
<td>Rev 9.30 or later</td>
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<tr>
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<td>2011/2/28</td>
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<td>Not Supported</td>
<td>Not Supported</td>
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<tr>
<td>E5061B Data Transfer Program</td>
<td>Rev 01.00</td>
<td>2011/2/28</td>
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<td>Not Supported</td>
<td>Not Supported</td>
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<tr>
<td>E5061B Impedance Measurement Assistant VBA</td>
<td>Rev 01.10</td>
<td>2011/4/11</td>
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<td>Not Supported</td>
<td>Not Supported</td>
</tr>
</tbody>
</table>
**Agilent VNA Solutions**

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

**PNA**
- Performance VNA
- 10 MHz to 20, 40, 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

**ENA**
- World’s most popular economy VNA
- 9 kHz to 4.5, 8.5 GHz
- 300 kHz to 20.0 GHz

**ENA-L**
- Low cost VNA
- 300 kHz to 1.5/3.0 GHz

**FieldFox**
- RF Analyzer
- 5 Hz to 4/6 GHz

**Mm-wave solutions**
- Up to 2 THz

**PNA-X receiver**
- 8530A replacement

---

**Test Accessories**
ENA Series Network Analyzers

**E5072A**

- 2-port
- **Wide output power range**
- Configurable test set
- **150 dB dynamic range**

**E5071C**

- 2-port & 4-port
- Balanced meas.
- Up to 20 GHz
- Option TDR

**E5061B-3L5, LF-RF option**

- **5 Hz to 3 GHz**

**E5061B-115 to 237, RF options**

- **100 kHz to 1.5 / 3 GHz**
- Low-freq coverage
- Z-analysis function
- Low-cost simple RF NA
- 50 Ω & 75 Ω

**E5061B**

- 2-port
- **30 kHz to 4.5 / 8.5 GHz**

**E5072A**

- **9 / 100 kHz to 4.5 / 6.5 / 8.5 GHz**
- **300 kHz to 14 / 20 GHz**

**New!**
Accurate Handheld VNA N9923A (4/6 GHz)

- Full 2 port vector network Analyzer
- CalReady at each test port
- Full 2 port QuickCal
- 0.01 dB/deg C Stability Spec
- 100 dB dynamic range
- Power meter
- Vector Voltmeter (1 – and 2-channel)
- Distance to Fault
- LAN, USB, mini SD

Quad display  CAT  Vector volt Meter  Power Meter
APPENDIX
VNA application examples

- RF amplifier test
- High-power measurement
- Swept IMD measurement
- High-gain amp measurement
What is intermodulation distortion (IMD)?

- A measure of nonlinearity of amplifiers.
- Two or more tones applied to an amplifier and produce additional intermodulation products.
- The DUT’s output will contain signals at the frequencies: \( n \cdot F_1 + m \cdot F_2 \).

\[
F_{\text{IMD}} = n \cdot F_1 + m \cdot F_2
\]

\[\text{ex.)}
\begin{align*}
\text{Lo } F_{\text{IM3}} &= 2 \cdot F_1 - F_2 \\
\text{Hi } F_{\text{IM3}} &= 2 \cdot F_2 - F_1 \\
\text{Lo } F_{\text{IM5}} &= 3 \cdot F_1 - 2 \cdot F_2 \\
\text{Hi } F_{\text{IM5}} &= 3 \cdot F_2 - 2 \cdot F_1 \\
\text{Lo } F_{\text{IM7}} &= 4 \cdot F_1 - 3 \cdot F_2 \\
\text{Hi } F_{\text{IM7}} &= 4 \cdot F_2 - 3 \cdot F_1
\end{align*}
\]
Third-order Intercept Point (IP3)

- The third-order intercept point (IP3) or the third-order intercept (TOI) are often used as figures of merit for IMD.

\[ IP3 \text{ (dBm)} = P(F1) + \frac{(P(F2) - P(2*F1-F2))}{2} \]

When high-side IM3 is used, the equation is:

\[ IP3 \text{ (dBm)} = P(F2) + \frac{(P(F1) - P(2*F2-F1))}{2} \]
• Using two SGs and a SA with CW signals.
• It requires a controller to synchronize instruments.
• If many frequencies must be tested, test time is increased dramatically.

• ENA with frequency-offset mode (FOM) option can set different frequencies at the source and receiver.
• Real-time swept frequency IMD measurements can be performed.
• Source power calibration and receiver calibration is available with VNA for accurate absolute power measurements.
VNA functions

Frequency Offset Mode

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

Normal Sweep

Source and receiver are tuned at the same frequency range. (i.e. S-parameter).

Frequency-offset Sweep

Source and receiver are tuned at the different frequency range (for harmonics, IMD test etc.)
IMD Measurement

Power levels of main tones and IM products in swept frequencies can be monitored with the VNA’s absolute measurements.

Configuration of IMD measurement with VNA

Measurement example (sweep delta)
IMD Measurement Wizard for the E5072A

Key Features:

• Measurement macro running on the E5072A with intuitive GUI
• Quick setup of two-tone IMD measurements
• Control all necessary equipments from E5072A
  – MXG (connected via GPIB/USB interface)
  – Power meter & sensor (connected via GPIB/USB interface)
  – USB power sensor (connected directly to the ENA’s USB port)
• Guided calibration wizard
• Various measurement sweep types
  – Fixed F1 and Swept F2
  – Sweep Fc
  – Sweep DeltaF
• Various IMD measurement parameters
  – Absolute power of fundamental tones (in dBm)
  – Power levels of IMD products (absolute in dBm), Low or High-side IM (3rd, 5th, 7th)
  – Calculated third-order intercept point (IP3)

Available at: www.agilent.com/find/enavba
VNA application examples

- RF amplifier test
- High-power measurement
- Swept IMD measurement
- High-gain amp measurement
VNA Functions
Uncoupled Power

Independent built-in source attenuators to uncouple power level
- Different output power level can be set for port 1 & 2 with independent source attenuators.
- Easy characterization of high-gain power amp without external attenuators on output port.
- More accurate reverse measurement (i.e. S12, S22) with wider dynamic range.

Example DUTs:
BTS repeaters, LNA, receivers.

![Diagram of high-gain amp with input power levels and attenuators](image-url)
High-gain amp measurement

DUT: High-gain (30 dB) RF Power amp

**Coupled power**
(Port 1 = Port 2 = -40 dBm)

**Uncoupled power**
(Port 1 = -40 dBm, Port 2 = 0 dBm)

More accurate S12 measurement with **uncoupled power** results in better trace of calculated K-factor.
Resources

- Configuration Guide (5990-8001EN)
- Data Sheet (5990-8002EN)
- Quick Fact Sheet (5990-8003EN)
- Technical Overview (5990-8004EN)
- Application Note
  - High-power measurement using the E5072A (5990-8005EN)

- ENA Series: www.agilent.com/find/ena
- E5072A Product page: www.agilent.com/find/e5072a
- Campaign page: www.agilent.com/find/e5072a_PR
- E5072A on YouTube: www.youtube.com/user/AgilentVNA#p/u/5/cA83A4qFEZU
THANK YOU!