Network Analysis is NOT....

Your IEEE 802.3 X.25 ISDN switched-packet data stream is running at 147 MBPS with a BER of $1.523 \times 10^{-9}$.
## What Types of Devices are Tested?

<table>
<thead>
<tr>
<th>Device type</th>
<th>Active</th>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RFICs</td>
<td>Dielectrics</td>
</tr>
<tr>
<td></td>
<td>MMICs</td>
<td>R, L, C's</td>
</tr>
<tr>
<td></td>
<td>T/R modules</td>
<td>/transmitters</td>
</tr>
<tr>
<td></td>
<td>Transceivers</td>
<td>Antennas</td>
</tr>
<tr>
<td></td>
<td>Receivers</td>
<td>Switches</td>
</tr>
<tr>
<td></td>
<td>Tuners</td>
<td>Multiplexers</td>
</tr>
<tr>
<td></td>
<td>Converters</td>
<td>Mixers</td>
</tr>
<tr>
<td></td>
<td>VCAs</td>
<td>Samplers</td>
</tr>
<tr>
<td></td>
<td>Amplifiers</td>
<td>Multipliers</td>
</tr>
</tbody>
</table>

### Device Integration

- High
- Low

### Device Placement

- Duplexers
- Diplexers
- Filters
- Couplers
- Bridges
- Splitters, dividers
- Combiners
- Isolators
- Circulators
- Attenuators
- Adapters
- Open, shorts, loads
- Delay lines
- Cables
- Transmission lines
- Waveguide
- Resonators
- Dielectrics
- Amplifiers
- VCOs
- VTFs
- Oscillators
- Modulators
- VCA transmitters
- Transistors

---

*Network Analyzer Basics*
Lightwave Analogy to RF Energy

- Incident
- Reflected
- Transmitted

DUT

RF
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, AM-to-PM conversion
- 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

---

Network Analyzer Basics

Agilent Technologies
Agenda

- **What measurements do we make?**
  - Transmission-line basics
  - Reflection and transmission parameters
  - S-parameter definition

- **Network analyzer hardware**
  - Signal separation devices
  - Detection types
  - Dynamic range
  - T/R versus S-parameter test sets

- **Error models and calibration**
  - Types of measurement error
  - One- and two-port models
  - Error-correction choices
  - Basic uncertainty calculations

- **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 $\approx$ 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 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)

![Diagram of Transmission Line Types and Impedance Chart](image)
Power Transfer Efficiency

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

Maximum power is transferred when $RL = RS$
Transmission Line Terminated with Zo

For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line.

Zs = Zo

Zo = characteristic impedance of transmission line

V_{inc} \rightarrow \text{Vrefl = 0! (all the incident power is absorbed in the load)}

V_{refl} = 0! (all the incident power is absorbed in the load)
Transmission Line Terminated with Short, Open

For reflection, a transmission line terminated in a short or open reflects all power back to source

\[ Z_s = Z_0 \]

\[ V_{\text{inc}} \rightarrow \rightarrow \rightarrow \rightarrow V_{\text{refl}} \]

In-phase (0°) for open, out-of-phase (180°) for short

Network Analyzer Basics

Agilent Technologies
Transmission Line Terminated with 25 Ω

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

**Reflection**

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

- SWR
- S-Parameters \( S_{11}, S_{22} \)
- Reflection Coefficient \( \Gamma, \rho \)
- Return Loss
- Impedance, Admittance \( R + jX, G + jB \)

**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

Network Analyzer Basics

Agilent Technologies
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

$$\rho = |\Gamma|$$

Return loss = -20 log(\rho),

$$VSWR = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 \cdot \rho}$$

No reflection

\((Z_L = Z_0)\)

| \(|\rho|\) | 0 dB |
|---------|------|
| 0       | 1    |

Full reflection

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

| \(|\rho|\) | 0 dB |
|---------|------|
| 0       | ∞    |

Network Analyzer Basics

Agilent Technologies
Smith Chart Review

Smith Chart maps rectilinear impedance plane onto polar plane

Rectilinear impedance plane

Polar plane

Smith chart
Transmission Parameters

Transmission Coefficient

\[ T = \frac{V_{\text{Transmitted}}}{V_{\text{Incident}}} = \tau \angle \phi \]

Insertion Loss (dB)

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

Gain (dB)

\[ \text{Gain (dB)} = 20 \log \left| \frac{V_{\text{Trans}}}{V_{\text{Inc}}} \right| = 20 \log \tau \]
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 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

RF filter response

Linear electrical length added (Electrical delay function)

Yields

Deviation from linear phase

Low resolution

High resolution
Group Delay

Group Delay ($t_g$) = \[-\frac{d\phi}{d\omega}\]

- $\phi$ 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 of measurement is very important
Why Measure Group Delay?

Same p-p 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

**H-parameters**

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

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

\[h_{12} = \left. \frac{V_1}{V_2} \right|_{I_1=0} \text{ (requires open circuit)}\]

**Y-parameters**

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

**Z-parameters**

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

Network Analyzer Basics

Agilent Technologies
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

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

**Forward**

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

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

**Reverse**

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

\[ S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2} \mid a_1 = 0 \]
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*
Criteria for Distortionless Transmission

**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.
Measuring Nonlinear Behavior

Most common measurements:
- using a *network analyzer* and power sweeps
  - gain compression
  - AM to PM conversion
- using a *spectrum analyzer* + source(s)
  - harmonics, particularly second and third
  - intermodulation products resulting from two or more RF carriers
What is the Difference Between *Network* and *Spectrum* Analyzers?

**Network analyzers:**
- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase (frequency or power sweeps)
- offer advanced error correction

**Spectrum analyzers:**
- measure signal amplitude characteristics carrier level, sidebands, harmonics...)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (*no phase*) with tracking gen. or ext. source(s)

---

Network Analyzer Basics

Agilent Technologies
Network Analyzer Basics

Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix
Generalized Network Analyzer Block Diagram

SOURCE → Incident → DUT → Transmitted

- Incident
- Reflected

INCIDENT (R) → INCIDENT (R)
REFLECTED (A) → REFLECTED (A)
TRANSMITTED (B) → TRANSMITTED (B)

RECEIVER / DETECTOR

PROCESSOR / DISPLAY
Source

- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Agilent analyzers sold today have *integrated, synthesized* sources
Signal Separation

- measure incident signal for reference
- separate incident and reflected signals

![Diagram of signal separation](image)

**Diagram Elements:**
- **Splitter**
- **Directional Coupler**
- **Bridge**

**Diagram Descriptions:**
- Source
- Incident
- Reflected
- Transmitted
- Receiver/Detector
- Processor/Display

**Diagram Notations:**
- Incident (I)
- Reflected (R)
- Transmitted (T)

**Network Analyzer Basics**

![Agilent Technologies Logo](image)
Directivity

*Directivity* is a measure of how well a coupler can separate signals moving in opposite directions.

(undesired leakage signal) (desired reflected signal)

Directional Coupler

Test port
Interaction of Directivity with the DUT (Without Error Correction)

- Data Max
- Add in-phase
- DUT RL = 40 dB
- Data Min
- Add out-of-phase (cancellation)

Return Loss
Frequency

Agilent Technologies
Detector Types

**Diode**
Scalar broadband
(no phase information)

**Tuned Receiver**

Scalar broadband
(no phase information)

Vector
(magnitude and phase)

**Network Analyzer Basics**

---

Agilent Technologies
Broadband Diode Detection

- Easy to make **broadband**
- **Inexpensive** compared to tuned receiver
- Good for measuring frequency-translating devices
- Improve dynamic range by increasing power
- **Medium** sensitivity / dynamic range

10 MHz  26.5 GHz
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

Network Analyzer Basics

Agilent Technologies
Comparison of Receiver Techniques

**Broadband (diode) detection**

-60 dBm Sensitivity

- higher noise floor
- false responses

**Narrowband (tuned-receiver) detection**

< -100 dBm Sensitivity

- high dynamic range
- harmonic immunity

*Dynamic range = maximum receiver power - receiver noise floor*
Dynamic Range and Accuracy

Dynamic range is very important for measurement accuracy!
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
Processor / Display

- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts
Internal Measurement Automation

Simple: recall states
More powerful:

- **Test sequencing**
  - available on 8753/8720 families
  - keystroke recording
  - some advanced functions
- **IBASIC**
  - available on 8712 family
  - sophisticated programs
  - custom user interfaces
- **Windows-compatible programs**
  - available on PNA Series
  - Visual Basic, VEE, LabView, C++, ...

```
1  ASSIGN @Hp8714 TO 800
2  OUTPUT @Hp8714;"SYST:PRES; *WAI"
3  OUTPUT @Hp8714;"ABOR;:INIT1:CONT OFF;:*WAI"
4  OUTPUT @Hp8714;"DISP:ANN:FREQ1:MODE SSTOP"
5  OUTPUT @Hp8714;"DISP:ANN:FREQ1:MODE CSPAN"
6  OUTPUT @Hp8714;"SENS1:FREQ:CENT 175000000 HZ;:*WAI"
7  OUTPUT @Hp8714;"ABOR;:INIT1:CONT OFF;:INIT1;:*WAI"
8  OUTPUT @Hp8714;"DISP:WIND1:TRAC:Y:AUTO ONCE"
9  OUTPUT @Hp8714;"CALC1:MARK1 0N"
10 OUTPUT @Hp8714;"CALC1:MARK:FUNC BWID"
11 OUTPUT @Hp8714;"SENS2:STAT ON; :WAI"
12 OUTPUT @Hp8714;"SENS2:FUNC 'XFR:POW:RAT 1,0';:DET NBAN; :WAI"
13 OUTPUT @Hp8714;"ABOR;:INIT1:CONT OFF;:INIT1;:*WAI"
14 OUTPUT @Hp8714;"DISP:WIND2:TRAC:Y:AUTO ONCE"
15 OUTPUT @Hp8714;"ABOR;:INIT1:CONT ON;:*WAI"
16 END
```
Agilent’s Series of HF Vector Analyzers

**Microwave**

8720/22 ET/ES series
- 13.5, 20, 40 GHz
- economical
- fast, small, integrated
- test mixers, high-power amps

8510C series
- 110 GHz in coax
- highest accuracy
- modular, flexible
- pulse systems

**RF**

8753ET/ES series
- 3, 6 GHz
- flexible hardware
- rich feature set
- offset and harmonic
- RF sweeps

PNA Series
- 3, 6, 9 GHz
- highest RF performance
- advanced connectivity
- internal automation, SCPI or COM/DCOM
Agilent’s LF/RF Vector Analyzers

**Combination NA / SA**

4395A/4396B
- 500 MHz (4395A), 1.8 GHz (4396B)
- impedance-measuring option
- fast, FFT-based spectrum analysis
- time-gated spectrum-analyzer option
- IBASIC
- standard test fixtures

**RF**

8712/14 ET/ES series
- 1.3, 3 GHz
- low cost
- narrowband and broadband detection
- IBASIC / LAN

**LF**

E5100A/B
- 180, 300 MHz
- economical
- fast, small
- target markets: crystals, resonators, filters
- equivalent-circuit models
- evaporation-monitor-function option
Key differences from network analyzer:

- **One channel** -- no ratioed or phase measurements
- More **expensive** than scalar NA (but better dynamic range)
- Only error correction available is **normalization** (and possibly open-short averaging)
- Less **accurate**
- Small **incremental cost** if SA is required for other measurements
Agenda

Why do we even need error-correction and calibration?
- It is impossible to make perfect hardware
- It would be extremely expensive to make hardware good enough to eliminate the need for error correction

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix
Calibration Topics

- 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
- Appendix
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 caused by temperature variation
Systematic Measurement Errors

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
What is Vector-Error Correction?

- 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.

- 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

\[
S_{11M} = E_D + E_{RT} \\
\left[ \frac{S_{11A}}{1 - E_S} \right]
\]
Before and After One-Port Calibration

- **Return Loss (dB):**
  - Data before 1-port calibration
  - Data after 1-port calibration

- **VSWR:**
  - 1.00 to 2.00

- **MHz:**
  - 6000 to 12000

Network Analyzer Basics

Agilent Technologies
Network Analyzer Basics

**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!!!
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 DUT with termination on output
Errors and Calibration Standards

**UNCORRECTED**
- Convenient
- Generally not accurate
- No errors removed

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

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

**FULL 2-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

Network Analyzer Basics
### Calibration Summary

#### Reflection

<table>
<thead>
<tr>
<th>Test Set (cal type)</th>
<th>T/R (one-port)</th>
<th>S-parameter (two-port)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection tracking</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Directivity</td>
<td></td>
<td>✔️</td>
</tr>
<tr>
<td>Source match</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>Load match</td>
<td>✗</td>
<td></td>
</tr>
</tbody>
</table>

#### Transmission

<table>
<thead>
<tr>
<th>Test Set (cal type)</th>
<th>T/R (response, isolation)</th>
<th>S-parameter (two-port)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Tracking</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Source match</td>
<td>(✔️)</td>
<td>(✗)</td>
</tr>
<tr>
<td>Load match</td>
<td>(✗)</td>
<td></td>
</tr>
</tbody>
</table>

*error can be corrected*

*error cannot be corrected*

*enhanced response cal corrects for source match during transmission measurements*
Reflection Example Using a One-Port Cal

DUT
- 16 dB RL (.158)
- 1 dB loss (.891)
- Load match: 18 dB (.126)

Directivity: 40 dB (.010)

1.58

(.891)(.126)(.891) = .100

Measurement uncertainty:
-20 * log (.158 + .100 + .010) = 11.4 dB (-4.6 dB)
-20 * log (.158 - .100 - .010) = 26.4 dB (+10.4 dB)

Remember: convert all dB values to linear for uncertainty calculations!

\[
\rho \text{ or loss}_{\text{linear}} = 10 \left(\frac{-\text{dB}}{20}\right)
\]
Low-loss bi-directional devices generally require two-port calibration for low measurement uncertainty.
Transmission Example Using Response Cal

Thru calibration (normalization) builds error into measurement due to source and load match interaction.

\[
\text{Calibration Uncertainty} = (1 \pm \rho_s \rho_l) \\
= (1 \pm (.200)(.126)) \\
= \pm 0.22 \text{ dB}
\]
Filter Measurement with Response Cal

Source match = 14 dB (.200)

DUT
1 dB loss (.891)
16 dB RL (.158)

Load match = 18 dB (.126)

Total measurement uncertainty:
+0.60 + 0.22 = + 0.82 dB
-0.65 - 0.22 = - 0.87 dB

Measurement uncertainty
= 1 ± (.020 + .020 + .032)
= 1 ± .072
= + 0.60 dB
- 0.65 dB
Measuring Amplifiers with a Response Cal

Source match = 14 dB (.200)
DUT
16 dB RL (.158)
Load match = 18 dB (.126)

Measurement uncertainty
= 1 ± (.020 + .032)
= 1 ± .052
= + 0.44 dB
= - 0.46 dB

Total measurement uncertainty:
+0.44 + 0.22 = + 0.66 dB
-0.46 - 0.22 = - 0.68 dB
Filter Measurements using the Enhanced Response Calibration

Effective source match = 35 dB!

Source match = 35 dB (.0178)

DUT
1 dB loss (.891)
16 dB RL (.158)

Load match = 18 dB (.126)

Calibration Uncertainty
= (1 ± ρ_s ρ_L)
= (1 ± (.0178)(.126))
= ± .02 dB

Measurement uncertainty
= 1 ± (.020 + .0018 + .0028)
= 1 ± .0246
= ± .211 dB
- .216 dB

Total measurement uncertainty:
0.22 + .02 = ± 0.24 dB
Using the **Enhanced Response** Calibration Plus an Attenuator

- 10 dB attenuator (.316)
- SWR = 1.05 (.024 linear or 32.4 dB)
- Analyzer load match = 18 dB (.126)

**Calibration Uncertainty**

\[
(1 \pm \rho_s \rho_l) = (1 \pm 0.0178)(0.366) = \pm 0.01 \text{ dB}
\]

Source match = 35 dB (.0178)
- 1 dB loss (.891)
- 16 dB RL (.158)

**DUT**

- Effective load match = (.316)(.316)(.126) + .024 = .0366 (28.7 dB)

Measurement uncertainty

\[
1 \pm (.006 + .0005 + .0028) = 1 \pm .0093 = \pm .08 \text{ dB}
\]

**Total measurement uncertainty:**

\[
0.01 + 0.08 = \pm 0.09 \text{ dB}
\]
Calculating Measurement Uncertainty After a Two-Port Calibration

**Corrected error terms:**

(8753ES 1.3-3 GHz Type-N)

- Directivity = 47 dB
- Source match = 36 dB
- Load match = 47 dB
- Refl. tracking = 0.019 dB
- Trans. tracking = 0.026 dB
- Isolation = 100 dB

**Reflection uncertainty**

\[
\text{Transmission uncertainty} = 0.158 \pm 0.0088 = 16 \text{ dB} \pm 0.53 \text{ dB, -0.44 dB (worst-case)}
\]

\[
\text{Reflection uncertainty} = 0.158 \pm 0.0088 = 16 \text{ dB} \pm 0.53 \text{ dB, -0.44 dB (worst-case)}
\]

DUT

1 dB loss (.891)
16 dB RL (.158)
Comparison of Measurement Examples

**Reflection**

<table>
<thead>
<tr>
<th>Calibration type</th>
<th>Measurement uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-port</td>
<td>-4.6/ 10.4 dB</td>
</tr>
<tr>
<td>One-port + attenuator</td>
<td>-1.9/ 2.5 dB</td>
</tr>
<tr>
<td>Two-port</td>
<td>-0.44/ 0.53 dB</td>
</tr>
</tbody>
</table>

**Transmission**

<table>
<thead>
<tr>
<th>Calibration type</th>
<th>Calibration uncertainty</th>
<th>Measurement uncertainty</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response</td>
<td>±0.22 dB</td>
<td>0.60/ -0.65 dB</td>
<td>±0.24</td>
</tr>
<tr>
<td>Enhanced response</td>
<td>±0.22 dB</td>
<td>±0.65 dB</td>
<td>±0.24</td>
</tr>
<tr>
<td>Enh. response + attenuator</td>
<td>±0.01 dB</td>
<td>±0.08 dB</td>
<td>±0.09</td>
</tr>
<tr>
<td>Two port</td>
<td>—</td>
<td>—</td>
<td>±0.05</td>
</tr>
</tbody>
</table>
Response versus Two-Port Calibration

Measuring filter insertion loss

After response calibration

After two-port calibration

Uncorrected
ECal: Electronic Calibration (85060/90 series)

- Variety of modules cover 30 kHz to 26.5 GHz
- Six connector types available (50 Ω and 75 Ω)
- Single-connection
  - reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated terminations provide excellent accuracy

Microwave modules use a transmission line shunted by PIN-diode switches in various combinations
Adapter Considerations

Coupler directivity = 40 dB

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

Worst-case System Directivity

Adapting from APC-7 to SMA (m)

- 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
  - SWR: 1.25

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

DUT has SMA (f) connectors

APC-7 calibration done here
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
Swap Equal Adapters Method

Accuracy depends on how well the adapters are matched - loss, electrical length, match and impedance should all be equal

1. Transmission cal using adapter A.

2. Reflection cal using adapter B.

3. Measure DUT using adapter B.
Adapter Removal Calibration

- Calibration is very accurate and traceable
- In firmware of 8753, 8720 and 8510 series
- Also accomplished with ECal modules (85060/90)
- Uses adapter with same connectors as DUT
- Must specify electrical length of adapter to within 1/4 wavelength of highest frequency (to avoid phase ambiguity)

1. Perform 2-port cal with adapter on port 2.  
   Save in cal set 1.
2. Perform 2-port cal with adapter on port 1.  
   Save in cal set 2.
3. Use ADAPTER REMOVAL  
   to generate new cal set.
4. Measure DUT without cal adapter.
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
- Two variations: TRL (requires 4 receivers) and TRL* (only three receivers needed)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

TRL was developed for non-coaxial microwave measurements.
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix
Frequency Sweep - Filter Test

CH1 S11 log MAG 5 dB/ REF 0 dB
CENTER 200.000 MHz SPAN 50.000 MHz

Return loss

CH1 S21 log MAG 10 dB/ REF 0 dB
START .300 000 MHz STOP 400.000 000 MHz

Stopband rejection

Insertion loss

Agilent Technologies
Optimize Filter Measurements with Swept-List Mode

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

Start: 525.000000 MHz
Stop: 1275.000000 MHz

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

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

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

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

Segment 5: 129 ms
(38 points, +10 dBm, 300 Hz)
Power Sweeps - Compression

- **Output Power (dBm)**
- **Input Power (dBm)**

- **Compression region**
- **Linear region**
  - (slope = small-signal gain)

- **Saturated output power**
Power Sweep - Gain Compression

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)

\[
\text{AM - PM Conversion} = \frac{\text{Mag}(\text{Pm}_{\text{out}})}{\text{Mag}(\text{Am}_{\text{in}})} \quad \text{(deg/dB)}
\]

- AM to PM conversion can cause bit errors

---

Network Analyzer Basics
Measuring AM to PM Conversion

- Use transmission setup with a power sweep
- Display phase of S21
- AM - PM = 0.86 deg/dB
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- **Appendix**
  - Advanced Topics
    - time domain
    - frequency-translating devices
    - high-power amplifiers
    - extended dynamic range
    - multiport devices
    - in-fixture measurements
    - crystal resonators
    - balanced measurements
  - Inside the network analyzer
  - Challenge quiz!
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

![Graph showing impedance versus time with inductive and capacitive transitions.](image)
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 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
Ten Steps for Performing TDR

1. Set up desired frequency range (need wide span for good spatial resolution)
2. Under SYSTEM, transform menu, press "set freq low pass"
3. Perform one- or two-port calibration
4. Select S11 measurement
5. Turn on transform (low pass step)
6. Set format to real
7. Adjust transform window to trade off rise time with ringing and overshoot
8. Adjust start and stop times if desired
9. For gating:
   - set start and stop frequencies for gate
   - turn gating on
   - adjust gate shape to trade off resolution with ripple
10. To display gated response in frequency domain
    - turn transform off (leave gating on)
    - change format to log-magnitude

* If using two channels (even if coupled), these parameters must be set independently for second channel
Time-Domain Transmission

Network Analyzer Basics

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
Frequency-Translating Devices

Medium-dynamic range measurements (35 dB)

High-dynamic range measurements (100 dB)
High-Power Amplifiers

+43 dBm max input (20 watts!)

85118A High-Power Amplifier Test System
High-Dynamic Range Measurements

Take advantage of extended dynamic range with direct-receiver access.
Multiport Device Test

Multiport analyzers and test sets:
- improve **throughput** by reducing the number of connections to DUTs with more than two ports
- allow **simultaneous** viewing of two paths (good for tuning duplexers)
- include **mechanical** or **solid-state** switches, 50 or 75 ohms
- degrade raw performance so **calibration** is a **must** (use two-port cals whenever possible)
- Agilent offers a variety of standard and custom multiport analyzers and test sets
87050E/87075C Standard Multiport Test Sets

- For use with 8712E family
- 50 Ω: 3 MHz to 2.2 GHz, 4, 8, or 12 ports
- 75 Ω: 3 MHz to 1.3 GHz, 6 or 12 ports
- Test Set Cal and SelfCal dramatically improve calibration times
- Systems offer fully-specified performance at test ports

*Once a month:* perform a Test Set Cal with external standards to remove systematic errors in the analyzer, test set, cables, and fixture

*Once an hour:* automatically perform a SelfCal using internal standards to remove systematic errors in the analyzer and test set
Test Set Cal Eliminates Redundant Connections of Calibration Standards

Reflection Connections

Through Connections

- 12-port
- 8-port
- 4-port

Test Set Cal

Traditional VNA Calibration

Network Analyzer Basics

Agilent Technologies
PNA Series plus External Test Set

- Test set controlled via GPIB and Agilent-supplied Visual Basic program executed from PNA Series analyzer
- Two port error correction available
- Z5623A H03
  - 3 port external test set
  - Solid-state switching for fast, repeatable measurements
- Z5623A H08
  - 8 port external test set
  - Mechanical switching for best RF performance
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
Characterizing Crystal Resonators/Filters

E5100A/B Network Analyzer

Example of crystal resonator measurement

<table>
<thead>
<tr>
<th>SEG</th>
<th>START</th>
<th>STOP</th>
<th>POINTS</th>
<th>POWER</th>
<th>IFBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.995 MHz</td>
<td>32.052 MHz</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 2</td>
<td>32.052 MHz</td>
<td>32.058 MHz</td>
<td>200</td>
<td>0 dBm</td>
<td>200Hz</td>
</tr>
</tbody>
</table>

0 dBm
What are Balanced Devices?

Ideally, respond to differential and reject common-mode signals

Differential-mode signal

Common-mode signal (EMI or ground noise)

Gain = 1

Balanced to single-ended

Differential-mode signal

Common-mode signal (EMI or ground noise)

Gain = 1

Fully balanced

Network Analyzer Basics

Agilent Technologies
What about Non-Ideal Devices?

Mode conversions occur...

Differential to common-mode conversion

Generates EMI

Susceptible to EMI

Common-mode to differential conversion

Network Analyzer Basics

Agilent Technologies
So What?

RF and digital designers need to characterize:

- Differential to differential mode (desired operation)
- Mode conversions (undesired operation)
- Operation in non-50-ohm environments
- Other differential parameters:
  - common-mode rejection ratio
  - K-factor
  - phase/amplitude balance
  - conjugate matches
Agilent Solution for Balanced Measurements

- Data presented as mixed-mode S-parameters
- Excellent dynamic range and accuracy
- Many important features such as time domain, impedance re-normalization, user parameters...

**Definitions:**
- D = differential mode
- C = common mode

Network Analyzer Basics

[Image of network analyzer measurements]
6 GHz Solution based on the PNA Series

**Network Analyzer**
- option 015 (allows standard VNA use)
- signal source
- receiver

**Test Set**
- adds 2 ports to VNA
- includes switches, 2 couplers

**Software**
- instrument control
- calibration routines
- error correction
- measurement routines
- “user” features
- time domain

**Optional 4-port ECAl module**
Target Markets

• **Wireless Communications**
  - Balanced topology less susceptible to EMI, noise
  - Less shielding required
  - RF grounding less critical
  - Better RF performance, smaller, lighter phones
  - LVDS extends battery life

• **Signal Integrity**
  - Verify waveform quality of high speed digital signals
  - Engineers primarily interested in time-domain analysis
Target Devices

RF/Microwave Components

- Balanced filters
- Differential/push-pull amplifiers
- Baluns
- Balanced transmission lines
- Cable connectors
- Couplers*, circulators*, splitters/combiners*

* single-ended devices that need 4-port error correction
Target Devices

**Digital Design**
- PCB backplanes
- PCB interconnects
- Sockets, packages
- High-speed serial interconnects (Ethernet, Firewire, Infiniband, USB ...)

Network Analyzer Basics

Agilent Technologies
Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements

Appendix
- Advanced Topics
  - time domain
  - frequency-translating devices
  - high-power amplifiers
  - extended dynamic range
  - multiport devices
  - in-fixture measurements
  - crystal resonators
  - balanced/differential
- Inside the network analyzer
- Challenge quiz!
Traditional Scalar Analyzer

Example: **8757D**
- requires external detectors, couplers, bridges, splitters
- good for low-cost microwave scalar applications
Directional Coupler Directivity

Directivity = Coupling Factor (fwd) \times Loss (through arm) \over Isolation (rev)

Directivity (dB) = Isolation (dB) \times Coupling Factor (dB) \times Loss (dB)

Examples:

Directivity = 50 \text{ dB} - 20 \text{ dB} = 30 \text{ dB}

Directivity = 50 \text{ dB} - 30 \text{ dB} - 10 \text{ dB} = 10 \text{ dB}

Directivity = 60 \text{ dB} - 20 \text{ dB} - 10 \text{ dB} = 30 \text{ dB}
One Method of Measuring Coupler Directivity

Assume perfect load (no reflection)

Directivity = 35 dB - 0 dB
= 35 dB
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
NA Hardware: Front Ends, Mixers Versus Samplers

It is cheaper and easier to make broadband front ends using samplers instead of mixers.
Mixers Versus Samplers: Time Domain

Single-balanced mixer (x1)

- Narrow pulse (easier to resolve noise)
- Wide pulse (tends to average noise)
Mixers Versus Samplers: Frequency Domain

Note: frequencies not to scale
Three Versus Four-Receiver Analyzers

3 receivers
- more economical
- TRL*, LRM* cals only
- includes:
  - 8753ES
  - 8720ES (standard)

4 receivers
- more expensive
- true TRL, LRM cals
- includes:
  - PNA Series
  - 8720ES (option 400)
  - 8510C
Why Are Four Receivers Better Than Three?

- **TRL**
  - four receivers are necessary to make the required measurements
  - TRL and TRL* use identical calibration standards

- **TRL**
  - assumes the source and load match of a test port are equal
    (port symmetry between forward and reverse measurements)
  - this is only a fair assumption for three-receiver network analyzers

- **TRL***
  - 8720ES Option 400 adds fourth sampler, allowing full TRL calibration
  - PNA Series has four receivers standard

In noncoaxial applications, TRL achieves better source and load match correction than TRL*

What about coaxial applications?
- SOLT is usually the preferred calibration method
- coaxial TRL can be more accurate than SOLT, but not commonly used
Challenge Quiz

1. Can filters cause distortion in communications systems?
   A. Yes, due to impairment of phase and magnitude response
   B. Yes, due to nonlinear components such as ferrite inductors
   C. No, only active devices can cause distortion
   D. No, filters only cause linear phase shifts
   E. Both A and B above

2. Which statement about transmission lines is false?
   A. Useful for efficient transmission of RF power
   B. Requires termination in characteristic impedance for low VSWR
   C. Envelope voltage of RF signal is independent of position along line
   D. Used when wavelength of signal is small compared to length of line
   E. Can be realized in a variety of forms such as coaxial, waveguide, microstrip

3. Which statement about narrowband detection is false?
   A. Is generally the cheapest way to detect microwave signals
   B. Provides much greater dynamic range than diode detection
   C. Uses variable-bandwidth IF filters to set analyzer noise floor
   D. Provides rejection of harmonic and spurious signals
   E. Uses mixers or samplers as downconverters
Challenge Quiz (continued)

4. Maximum dynamic range with narrowband detection is defined as:
   A. Maximum receiver input power minus the stopband of the device under test
   B. Maximum receiver input power minus the receiver’s noise floor
   C. Detector 1-dB-compression point minus the harmonic level of the source
   D. Receiver damage level plus the maximum source output power
   E. Maximum source output power minus the receiver's noise floor

5. With a T/R analyzer, the following error terms can be corrected:
   A. Source match, load match, transmission tracking
   B. Load match, reflection tracking, transmission tracking
   C. Source match, reflection tracking, transmission tracking
   D. Directivity, source match, load match
   E. Directivity, reflection tracking, load match

6. Calibration(s) can remove which of the following types of measurement error?
   A. Systematic and drift
   B. Systematic and random
   C. Random and drift
   D. Repeatability and systematic
   E. Repeatability and drift
Challenge Quiz (continued)

7. Which statement about TRL calibration is false?
   A. Is a type of two-port error correction
   B. Uses easily fabricated and characterized standards
   C. Most commonly used in noncoaxial environments
   D. Is not available on the 8720ES family of microwave network analyzers
   E. Has a special version for three-sampler network analyzers

8. For which component is it hardest to get accurate transmission and reflection measurements when using a T/R network analyzer?
   A. Amplifiers because output power causes receiver compression
   B. Cables because load match cannot be corrected
   C. Filter stopbands because of lack of dynamic range
   D. Mixers because of lack of broadband detectors
   E. Attenuators because source match cannot be corrected

9. Power sweeps are good for which measurements?
   A. Gain compression
   B. AM to PM conversion
   C. Saturated output power
   D. Power linearity
   E. All of the above
Answers to Challenge Quiz

1. E
2. C
3. A
4. B
5. C
6. A
7. D
8. B
9. E