**Network Analyzer Basics**

**What Types of Devices are Tested?**

<table>
<thead>
<tr>
<th>Device type</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas</td>
<td>NF</td>
</tr>
<tr>
<td>Switches</td>
<td>Gain</td>
</tr>
<tr>
<td>Mixers</td>
<td>Flatness</td>
</tr>
<tr>
<td>Samplers</td>
<td>Phase</td>
</tr>
<tr>
<td>Multipliers</td>
<td>Isolation</td>
</tr>
<tr>
<td>Diodes</td>
<td>Return</td>
</tr>
<tr>
<td>Transistors</td>
<td>Power</td>
</tr>
</tbody>
</table>

**Device Test Measurement Model**

- **NF Mtr.**
- **Imped. An.**
- **Power Mtr.**
- **SNA**
- **VNA**
- **SA**
- **VSA**
- **84000**
- **TG/SA**
- **Ded. Testers**

- **I-V**
- **Absol. Power**
- **Gain/Flatness**
- **LCR/Z**
- **Harm. Dist.**
- **LO stability**
- **Image Rej.**
- **Gain/Flat.**
- **Phase/GD**
- **Isolation**
- **Rtn Ls/VSWR**
- **Impedance**
- **S-parameters**
- **Compr'n**
- **AM-PM**

**Lightwave Analogy to RF Energy**

- **Incident**
- **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, AM-to-PM conversion
- Ensure good match when absorbing power (e.g., an antenna)
**Network Analyzer Basics**

**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

**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
- Availability

**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 (Zo) is very important for low reflection and maximum power transfer

**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)

**Power Transfer Efficiency**

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

Maximum power is transferred when \( R_L = R_S \)

For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line
Network Analyzer Basics

Transmission Line Terminated with Short, Open

\[ Z_s = Z_0 \]

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

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

Transmission Line Terminated with 25 \( \Omega \)

\[ Z_s = Z_0 \]

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

High-Frequency Device Characterization

Reflection Parameters

\[ R \rho \phi \]

\[ \Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_l - Z_0}{Z_l + Z_0} \]

Return loss \( = -20 \log(\rho) \), \( \rho = |\Gamma| \)

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

No reflection (\( Z_s = Z_0 \))

<table>
<thead>
<tr>
<th>( \rho )</th>
<th>Return Loss (dB)</th>
<th>Full reflection (( Z_s = \text{open, short} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 dB</td>
<td>0 dB</td>
</tr>
<tr>
<td>( \infty )</td>
<td>RL</td>
<td>Full reflection</td>
</tr>
<tr>
<td>1</td>
<td>VSWR</td>
<td>1</td>
</tr>
</tbody>
</table>

Transmission Parameters

\[ \frac{V_{\text{incident}}}{V_{\text{transmitted}}} \]

Transmission Coefficient \( \tau \)

\[ \tau = \frac{V_{\text{transmitted}}}{V_{\text{incident}}} = \epsilon \angle \phi \]

Insertion Loss (dB)

\[ = -20 \log \left( \frac{V_{\text{transmitted}}}{V_{\text{incident}}} \right) \]

Gain (dB)

\[ = 20 \log \left( \frac{V_{\text{transmitted}}}{V_{\text{incident}}} \right) \]

Smith Chart Review

Smith Chart maps rectilinear impedance plane onto polar plane.
**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**

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

**Phase Variation with Frequency**

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

**Deviation from Linear Phase**

- **Group Delay**
  - 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

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

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

Y-parameters

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

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

Z-parameters

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

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

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 if desired
- can easily import and use S-parameters in our electronic-simulation tools

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
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 from two or more

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)

Agenda

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

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
Network Analyzer Basics

Directivity

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

![Diagram of Directivity](image)

Interaction of Directivity with the DUT (Without Error Correction)

![Graph of Interaction](image)

Detector Types

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

- **Tuned Receiver**
  - Scalar broadband
  - (no phase information)

- **Vector**
  - (magnitude and phase)

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

Comparison of Receiver Techniques

- **Broadband (diode) detection**
  - Higher noise floor
  - False responses

- **Narrowband (tuned-receiver) detection**
  - High dynamic range
  - Harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor
Network Analyzer Basics

Dynamic Range and Accuracy

Error Due to Interfering Signal

Dynamic range is very important for measurement accuracy!

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

Agilent’s Series of HF Vector Analyzers

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

RF
- 8712ET series
  - 1.3, 3 GHz
  - line cost
  - narrowband and broadband detection
  - IBASIC / LAN

8510C series
- 110 GHz in coax
- highest accuracy
- modular, flexible
- pulse systems
- Tx/Rx module test

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

E5100A/B
- 180, 300 MHz
- economical
- fast, small
- target markets: crystals, resonators, filters
- equivalent-circuit models
- evaporation-monitor-function option
Network Analyzer Basics

**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

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

**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

**Systematic Measurement Errors**

- Directivity
- Crosstalk
- Source Mismatch
- Load Mismatch

**Spectrum Analyzer / Tracking Generator**

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)
- Poorer accuracy
- Small incremental cost if SA is required for other measurements

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

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

**Appendix**
**Network Analyzer Basics**

**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**
- **Error Adapter**
- **Ideal**
  - RF in
  - \( E \)
- **Measured**
  - S11m = Ed + Ent
- **Actual**
  - S11a
- **Error Terms**
  - Ed = Diractivity
  - Er = Source Match
  - Sm = Measured
  - Sa = Actual

**Reflection Tracking**
- Combines response and 1-port
- Corrects source match for transmission measurements
- Removes these errors: Directivity, Source match, Reflection tracking

**Source Match**
- Removes these errors: Source match, Reflection tracking

**Directivity**
- Removes these errors: Directivity, Source match

**Transmission Tracking**
- Removes these errors: Reflection tracking

**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 Full 2-Port**
  - Convenient
  - Generally not accurate
  - No errors removed
- **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
- **Response**
  - Convenient
  - Generally not accurate
  - No errors removed
  - For reflection measurements
  - Need good termination for high accuracy with two-port devices
  - Removes these errors: Directivity, Source match, Reflection tracking
- **1-Port**
  - Convenient
  - Generally not accurate
  - No errors removed
  - For reflection measurements
  - Need good termination for high accuracy with two-port devices
  - Removes these errors: Directivity, Source match, Reflection tracking
  - Crosstalk

**Before and After One-Port Calibration**
- Data before 1-port calibration
- Data after 1-port calibration

**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!!!
Network Analyzer Basics

Reflection Example Using a One-Port Cal

Transmission Example Using Response Cal

Using a One-Port Cal + Attenuator

Filter Measurement with Response Cal

Measuring Amplifiers with a Response Cal

Calibration Summary

Transmission

Test Set (cal type)

T/R

S-parameter

(response, isolation, two-port)

Transmission Tracking

Source match

Load match

<table>
<thead>
<tr>
<th>Reflection</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/R</td>
<td>S-parameter</td>
</tr>
<tr>
<td>response</td>
<td>isolation</td>
</tr>
<tr>
<td>(two-port)</td>
<td>(two-port)</td>
</tr>
</tbody>
</table>

Transmission Tracking

Crosstalk

Source match

Load match

S-parameter

T/R

Transmission Test Set (cal type)

Reflection Example Using a One-Port Cal

Using a One-Port Cal + Attenuator

Filter Measurement with Response Cal

Measuring Amplifiers with a Response Cal

Measurement uncertainty:

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

Calibration Uncertainty

= (1 ± A, A)

= (1 ± (.200), .126)

= ± 0.22 dB

Transmission Example Using Response Cal

RL = 14 dB (.200)

DUT

16 dB RL (.158)

1 dB loss (.891)

Measurement uncertainty:

= -20 * log (.158 + .100 + .019)

= 11.4 dB (-4.6 dB)

= -20 * log (.158 - .039)

= 18.5 dB (+2.5 dB)

Network Analyzer Basics
Filter Measurements using the **Enhanced Response** Calibration

Effective source match = 35 dB!

**Calibration Uncertainty**

\[ \text{Measurement uncertainty} = 1 \pm (\text{Source} + \text{Load} + \text{Ref. tracking} + \text{Trans. tracking} + \text{Isolation}) \]

\[ = 1 \pm (0.0178 + 0.0018 + 0.0028) \]

\[ = 1 \pm 0.0246 \]

\[ = +0.211 \text{ dB} \]

\[ -0.216 \text{ dB} \]

**Total measurement uncertainty:**

\[ 0.22 + 0.02 = \pm 0.24 \text{ dB} \]

**Using the Enhanced Response Calibration Plus an Attenuator**

**Calibration Uncertainty**

\[ \text{Measurement uncertainty} = 1 \pm (\text{Source} + \text{Load} + \text{Ref. tracking} + \text{Trans. tracking} + \text{Isolation}) \]

\[ = 1 \pm (0.0178 + 0.0018 + 0.0028) \]

\[ = 1 \pm 0.0093 \]

\[ = \pm 0.08 \text{ dB} \]

**Total measurement uncertainty:**

\[ 0.01 + 0.08 = \pm 0.09 \text{ dB} \]

**Calculating Measurement Uncertainty After a Two-Port Calibration**

**Corrected error terms:**

**Directivity = 47 dB**

**Source match = 36 dB**

**Load match = 47 dB**

**Ref. tracking = 0.019 dB**

**Trans. tracking = 0.025 dB**

**Isolation = 100 dB**

**Reflection uncertainty**

\[ S_{\text{ref}} = S_{\text{in}} + S_{\text{in}} E_L + S_{\text{in}} S_{\text{out}} E_F + S_{\text{out}} (1-E_F) \]

\[ = 0.091 \pm (0.0056 = 0.0056 + 0.0056 = 0.0112) \]

\[ = 0.091 \pm 0.0112 \text{ dB} \]

**Transmission uncertainty**

\[ S_{\text{trans}} = S_{\text{trans}} + S_{\text{trans}} E_L + S_{\text{trans}} S_{\text{out}} E_F + S_{\text{out}} (1-E_F) \]

\[ = 0.158 \pm (0.0056 = 0.0056 + 0.0056 = 0.0112) \]

\[ = 0.158 \pm 0.0112 \text{ dB} \]

**ECal: Electronic Calibration (85060/90 series)**

- Variety of modules cover 30 kHz to 26.5 GHz
- Six connector types available (50 \(\Omega\) and 75 \(\Omega\))
- 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

**Response versus Two-Port Calibration**

**Measuring filter insertion loss**

**Adapter Considerations**

**Coupler directivity = 40 dB**

**Adapter from APC-7 to SMA (m)**

**APC-7 calibration done here**

**Worst-case System Directivity**

<table>
<thead>
<tr>
<th>SWR (m)</th>
<th>SWR (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td></td>
</tr>
</tbody>
</table>

**DUT has SMA (f) connections**

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

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.
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

Frequency Sweep - Filter Test

Agenda

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Example measurements
- Appendix
Optimize Filter Measurements with Swept-List Mode

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

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

Power Sweeps - Compression

Linear region (slope = small-signal gain)

Segments 1, 4: 52 ms (15 points, +10 dBm, 300 Hz)

Segment 2: 29 ms (108 points, -10 dBm, 6000 Hz)

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

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

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

Power Sweeps - 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)

AM to PM conversion can cause bit errors

Agenda

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

- Impedance over time:
  - Zo
  - 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 proportional to frequency span

**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 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

**Time-Domain Transmission**

- RF input
- Gate Wave
- RF output

- leakage
- triple travel

**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
Network Analyzer Basics

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

High-Dynamic Range Measurements

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 duplexer)
  - 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

**Test Set Cal Eliminates Redundant Connections of Calibration Standards**

**In-Fixture Measurements**

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

**Characterizing Crystal Resonators/Filters**

**Balanced-Device Measurements**

- **ATN-4000 series (4-port test set + software)**
- measure tough singled-ended devices like couplers
- measure fully-balanced or single-ended-to-balanced DUTs
- characterize mode conversions (e.g. common-to-differential)
- incorporates 4-port error correction for exceptional accuracy
- works with 8753ES and 8720ES analyzers
- more info at www.atnmicrowave.com

**Traditional Scalar Analyzer**

- requires external detectors, bridges, splitters
- good for low-cost microwave scalar applications
**Network Analyzer Basics**

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**Directional Coupler Directivity**

\[
\text{Directivity} = \frac{\text{Isolation (rev)}}{1 + \text{Coupling Factor} \cdot \text{Loss (through arm)}}
\]

Examples:

- \( \text{Directivity} = 50 \text{ dB} - 20 \text{ dB} = 30 \text{ dB} \)
- \( \text{Directivity} = 50 \text{ dB} - 30 \text{ dB} - 10 \text{ dB} = 10 \text{ dB} \)
- \( \text{Directivity} = 60 \text{ dB} - 20 \text{ dB} - 10 \text{ dB} = 30 \text{ dB} \)

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**One Method of Measuring Coupler Directivity**

\[
\text{Directivity} = 35 \text{ dB} - 0 \text{ dB} = 35 \text{ dB}
\]

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**Directional Bridge**

- 50-ohm load at test port balances the bridge -- detector reads zero
- Non-50-ohm load imbalances the bridge
- Measuring magnitude and phase of imbalance gives complex impedance
- "Directivity" is difference between maximum and minimum balance

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**NA Hardware: Front Ends, Mixers Versus Samplers**

- It is cheaper and easier to make broadband front ends using samplers instead of mixers

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**Three Versus Four-Receiver Analyzers**

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

- 4 receivers:
  - more expensive
  - true TRL, LRM cal only
  - includes:
    - 8720ES (option 400)
    - 8510C

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**Why Are Four Receivers Better Than Three?**

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

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**8720ES Option 400 adds fourth sampler, allowing full TRL calibration**
Network Analyzer Basics

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, waveguides, 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

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

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 8700ES 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