ENGINEERS
NEVER STOP LEARNING

Network Analysis

是德科技專案經理

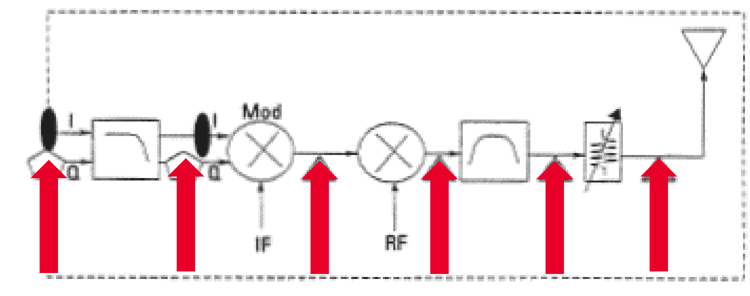
Keven Chang

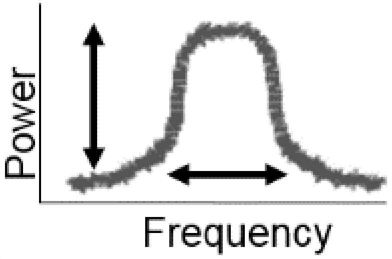
Agenda

- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

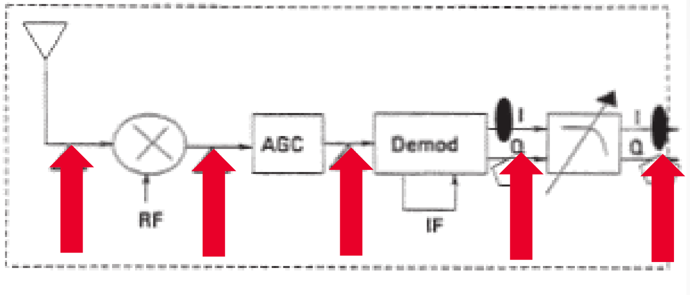
Transmit Receive Design Challenges

TRANSMIT





RECEIVE



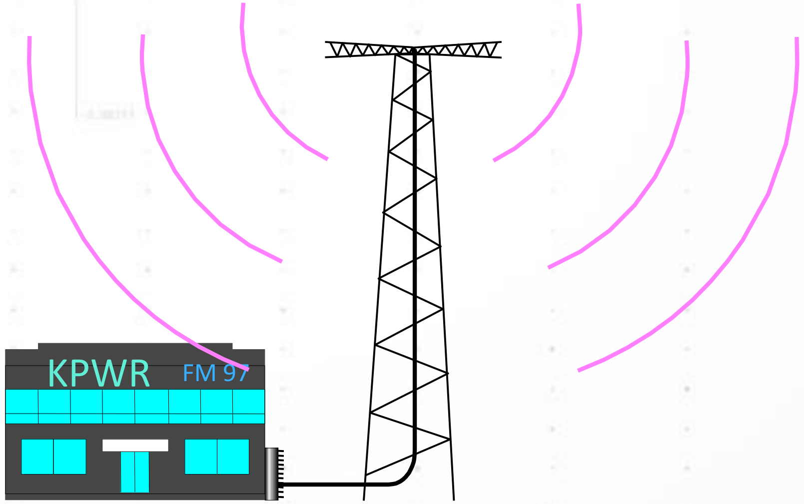
- Output Power
- Operating Frequency
- Environment/Interference
- Noise

- Sensitivity
- Adjacent Channel Selectivity
- Operating Frequency
- Environment/Interference
- Noise
- Dynamic Range

End goal: maximize link budget, fidelity & efficiency

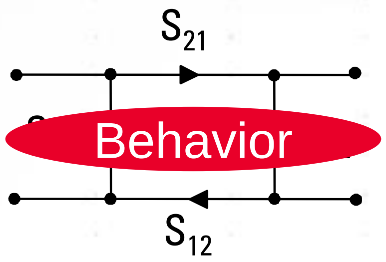
Why Do We Need to Test Components?

- Verify specifications of “building blocks” for more complex RF systems
- Ensure distortion less 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)

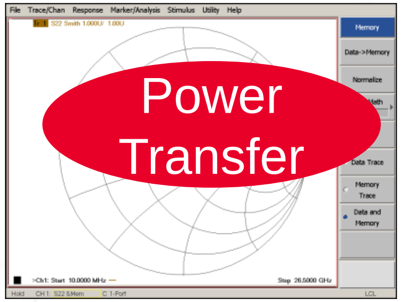


The Need for Both Magnitude and Phase

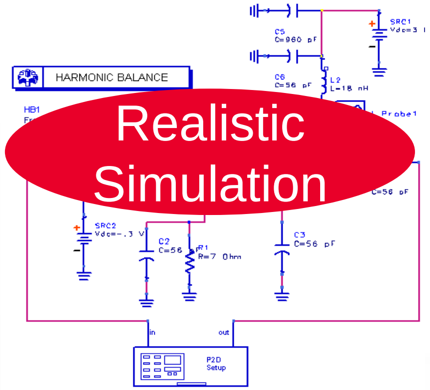
1. Complete characterization of linear networks



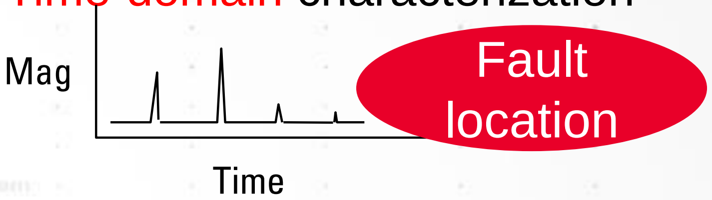
2. Complex impedance needed to design matching circuits



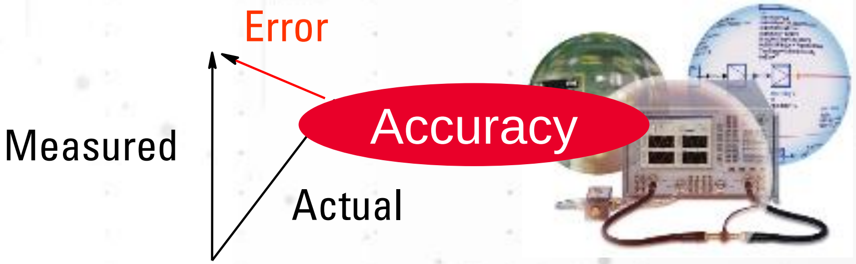
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction

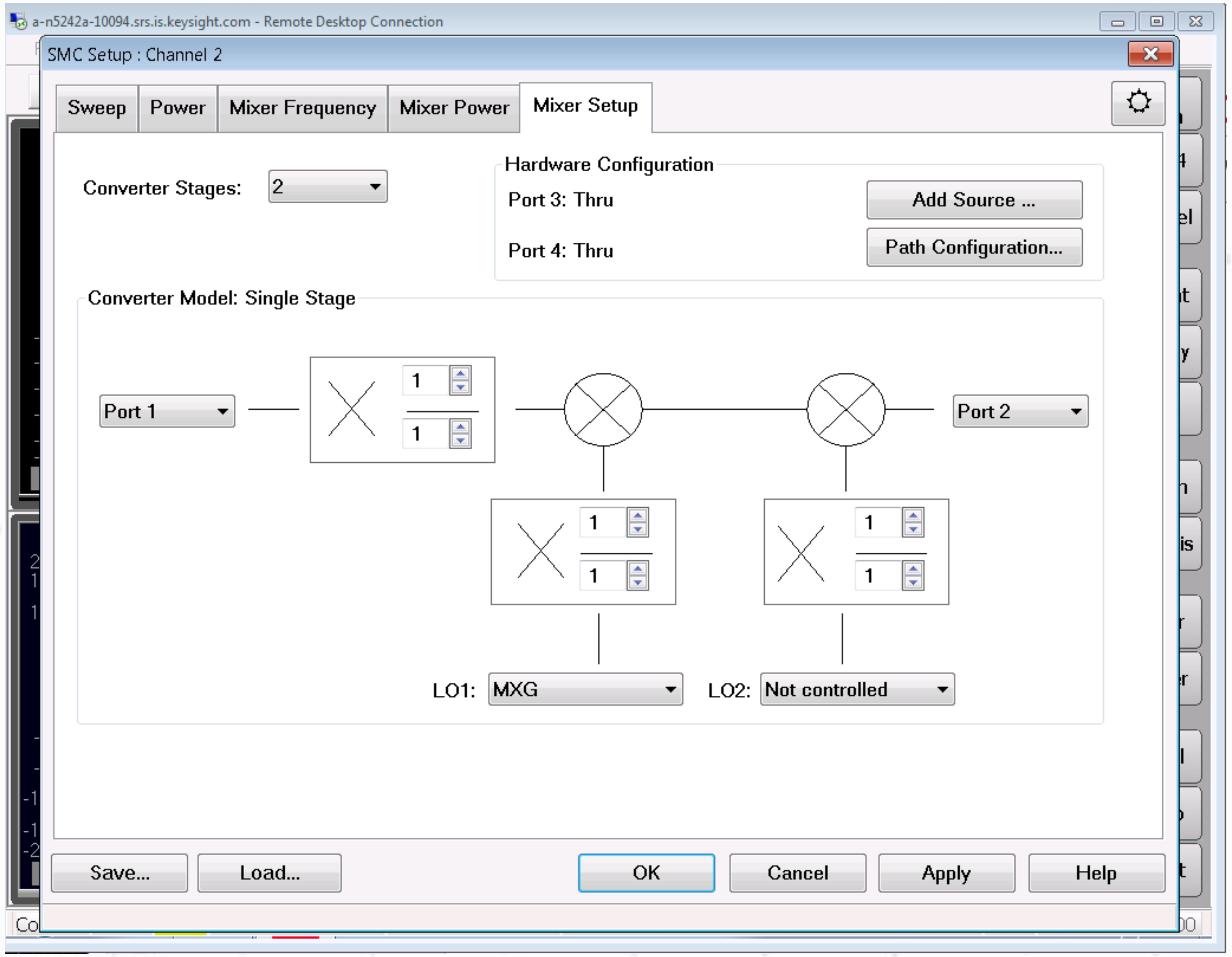


6. X-parameter (nonlinear) characterization

Pre-distortion

Mixer Measurement is simplified with UI

SUPPORTS SINGLE AND DUAL STAGE CONVERTERS.



a-n5242a-10094.srs.is.keysight.com - Remote Desktop Connection

SMC Setup : Channel 2

Converter Stages: 2

Hardware Configuration
Port 3: Thru
Port 4: Thru

Converter Model: Single Stage

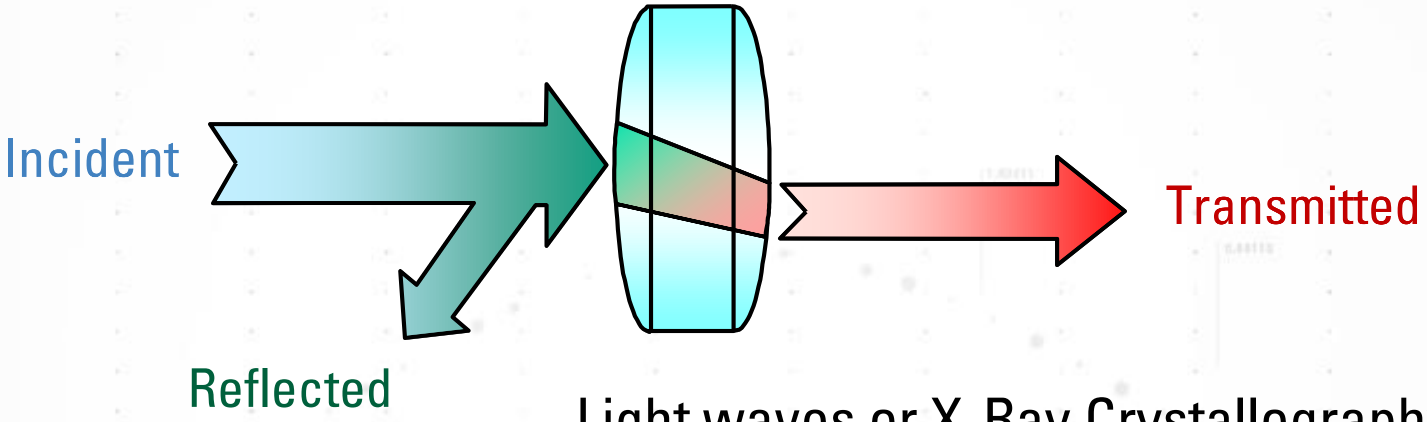
Port 1
Port 2

LO1: MXG
LO2: Not controlled

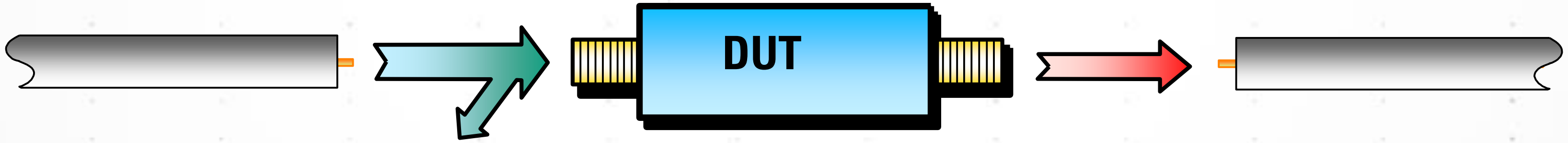
Agenda

- RF/Microwave Design Challenges
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

RF Energy Transmission

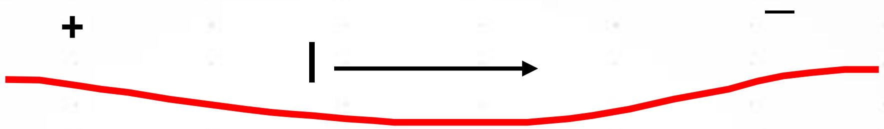


Light waves or X-Ray Crystallography and X-Ray Scattering

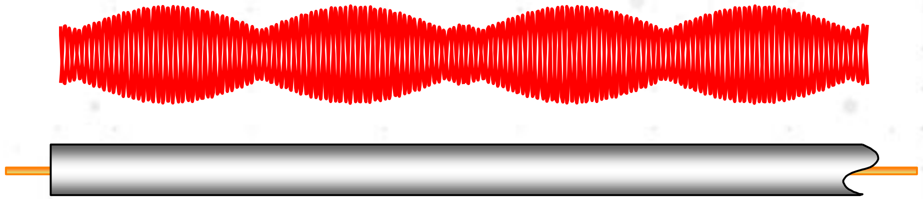


RF Scattering

Transmission Line Basics



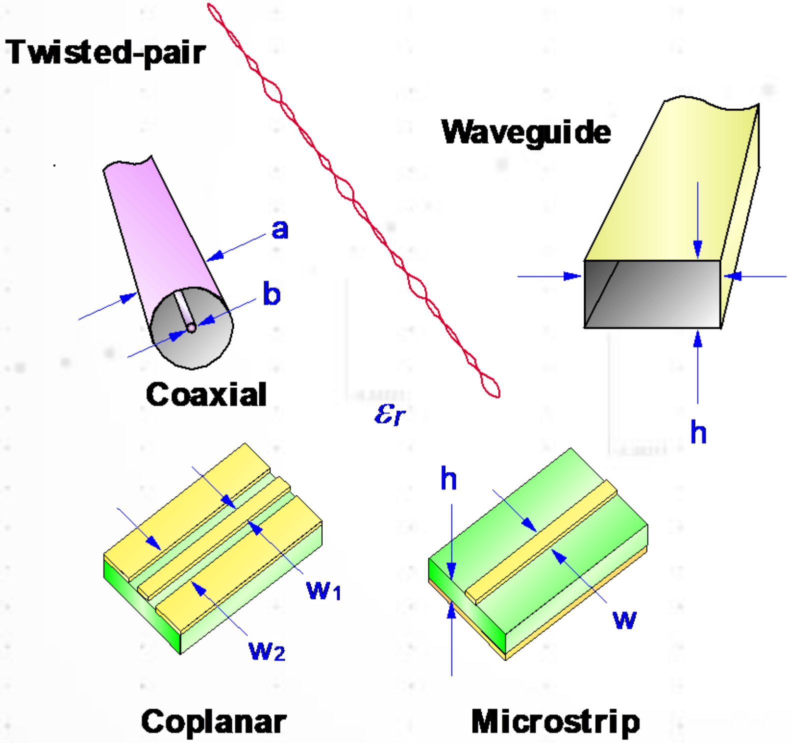
- Low Frequencies
  - Wavelengths >> wire length
  - Current (I) travels down wires easily for efficient power transmission
  - Measured voltage and current not dependent on position along wire

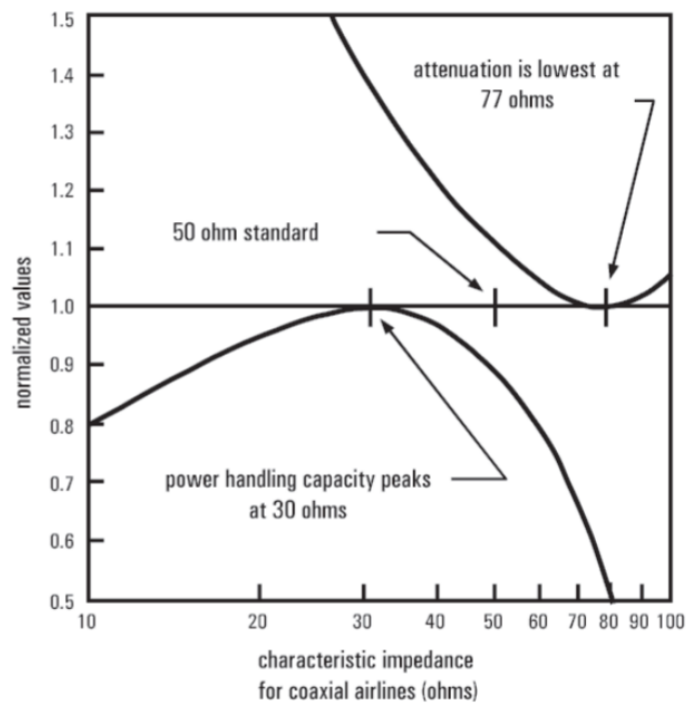


- High Frequencies
  - Wavelength ~ or << length of transmission medium
  - Need transmission lines for efficient power transmission
  - Matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer
  - Measured envelope voltage dependent on position along line

Transmission line Z_o

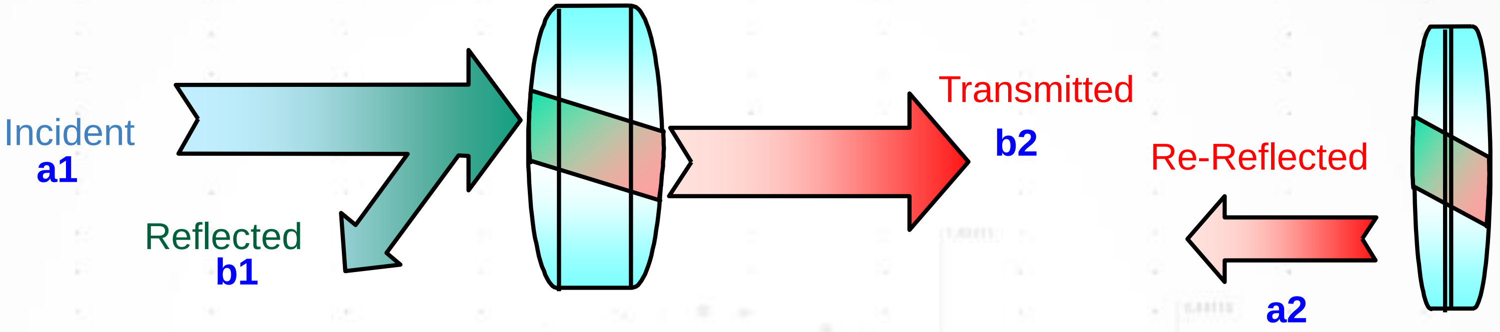
- Z_o determines relationship between voltage and current waves
- Z_o is a function of physical dimensions and ε_r
- Z_o is usually a real impedance (e.g. 50 or 75 ohms)





For more information on transmission line basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

High-frequency Device Characterization


Incident
a1
Reflected
b1
Transmitted
b2
Re-Reflected
a2

REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{b1}{a1}$$

- VSWR
- S-Parameters S_{11}, S_{22}
- Reflection Coefficient Γ, ρ
- Impedance, Admittance R+jX, G+jB
- Return Loss

TRANSMISSION

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{b2}{a1}$$

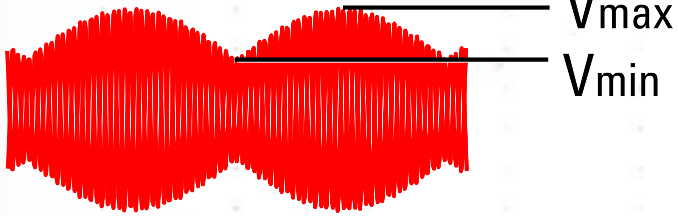
- Gain / Loss
- S-Parameters S_{21}, S_{12}
- Transmission Coefficient T, τ
- Insertion Phase
- Group Delay

Reflection Parameters

Reflection Coefficient [S11] $= \Gamma = \frac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \frac{Z_L - Z_o}{Z_L + Z_o}$

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

Colloquially: Return loss = $20 \log(\rho)$,

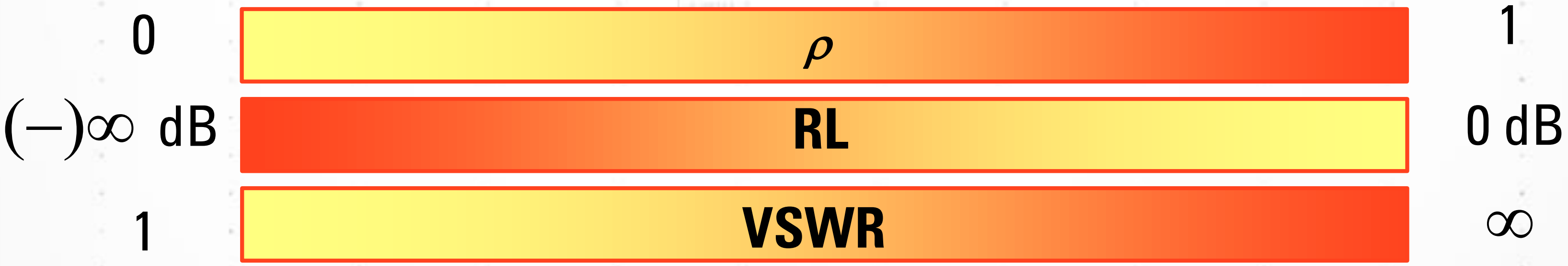


Voltage Standing Wave Ratio

$$\textbf{VSWR} = \frac{V_{max}}{V_{min}} = \frac{1 + \rho}{1 - \rho}$$

No reflection
(ZL = Zo)

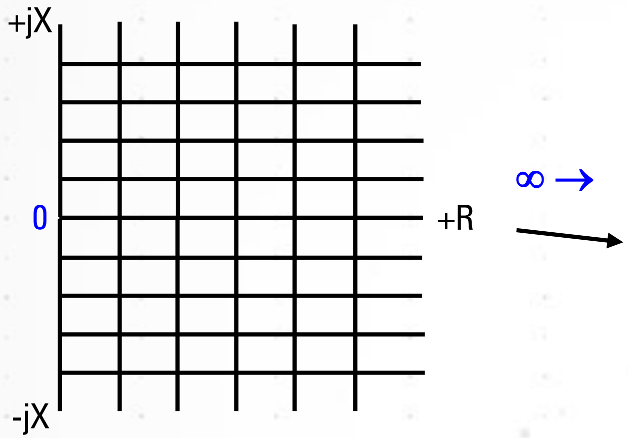
Full reflection
(ZL = open, short)



For more information on reflection/transmission parameter basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

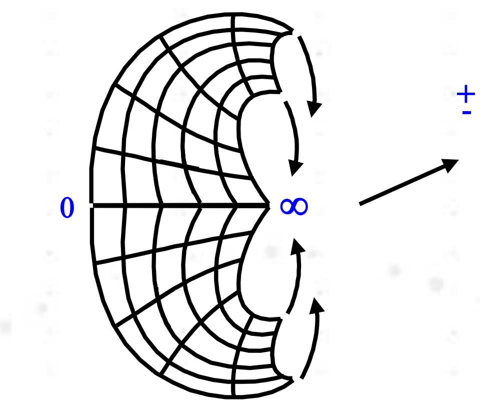
Smith Chart Review

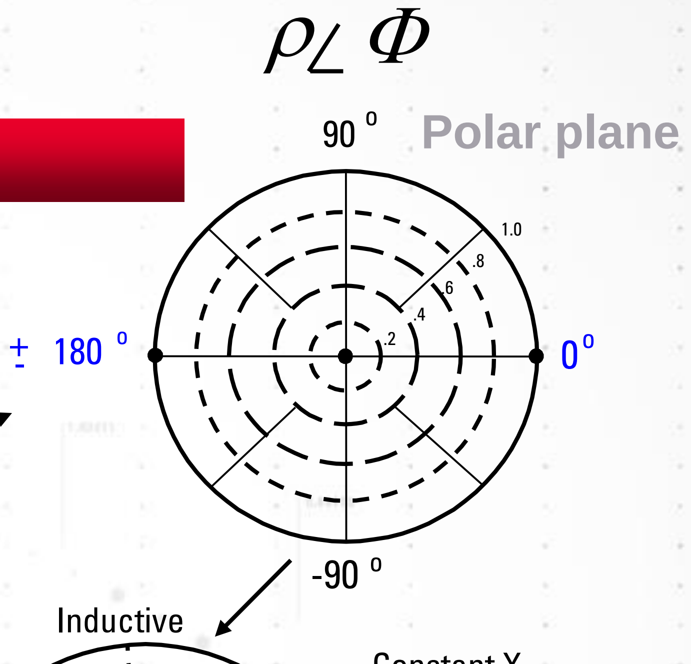
QUICKLY AND EASILY GET IMPEDANCE

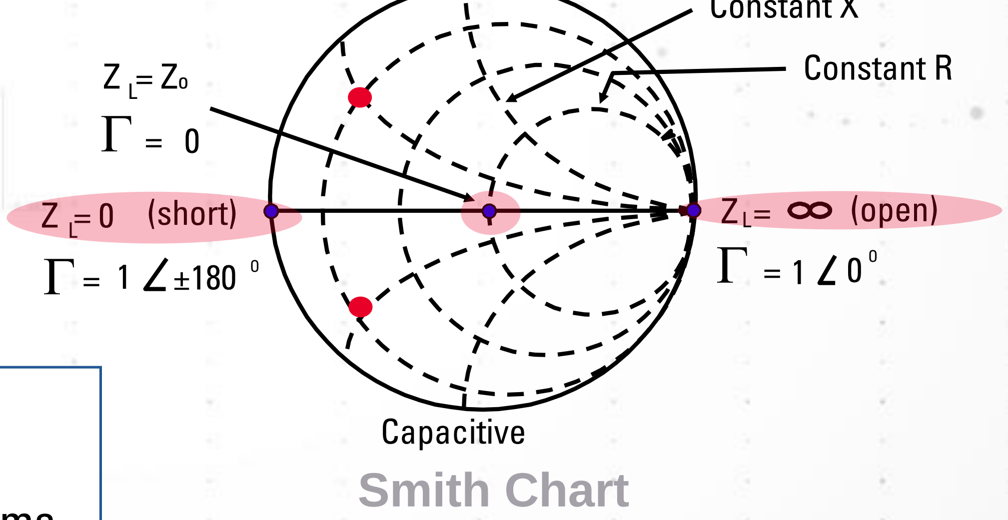


Rectilinear impedance plane

i.e: R+jX,







Smith Chart maps rectilinear impedance plane onto polar plane

Example: in a 50-ohm system,
a normalized value of 0.3 - j0.15
becomes 15 - j7.5 ohms

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

$V_1 = h_{11}I_1 + h_{12}V_2$

$I_2 = h_{21}I_1 + h_{22}V_2$

(Hybrid)

Y-parameters

$I_1 = y_{11}V_1 + y_{12}V_2$

$I_2 = y_{21}V_1 + y_{22}V_2$

(Admittance)

Z-parameters

$V_1 = z_{11}I_1 + z_{12}I_2$

$V_2 = z_{21}I_1 + z_{22}I_2$

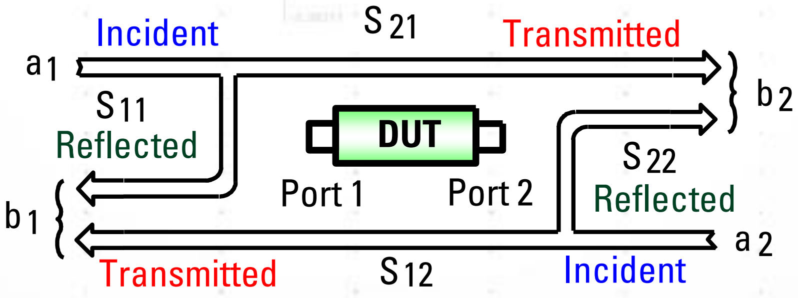
(Impedance)

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

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

Why Use Scattering, S-Parameters?

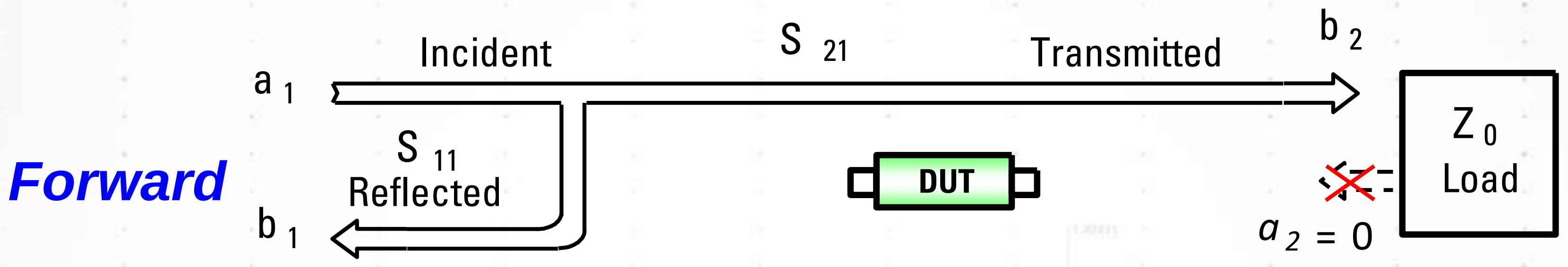
- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade** 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



$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

Measuring S-Parameters



Forward

Incident

S_{21}

Transmitted

a_1

b_2

S_{11}

Reflected

b_1

DUT

Z_0

Load

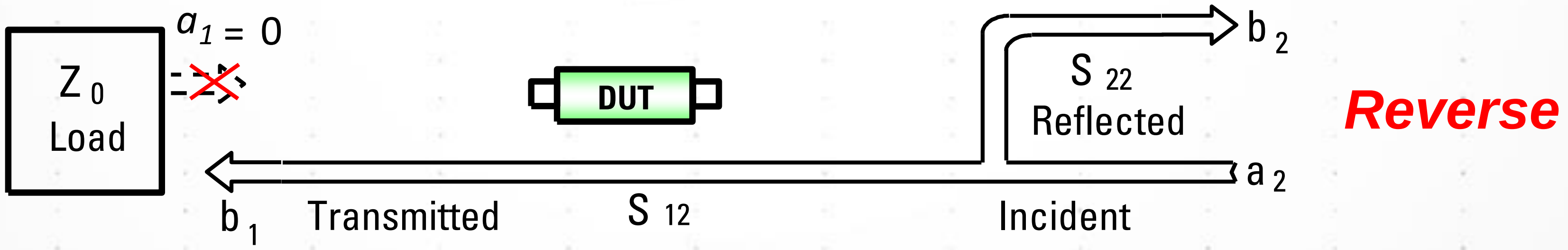
$a_2 = 0$

$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0}$$



$a_1 = 0$

Z_0

Load

DUT

b_2

S_{22}

Reflected

Reverse

a_2

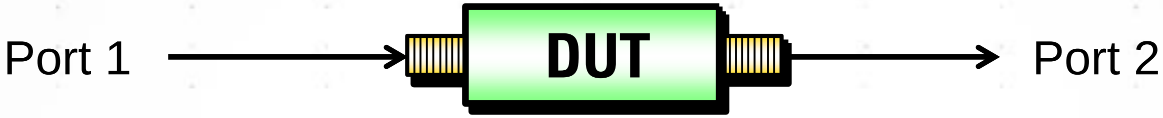
b_1

Transmitted

S_{12}

Incident

Equating S-Parameters With Common Measurement Terms



S_{11} = forward reflection coefficient ***(input match)***

S_{22} = reverse reflection coefficient ***(output match)***

S_{21} = forward transmission coefficient ***(gain or loss)***

S_{12} = reverse transmission coefficient ***(isolation)***

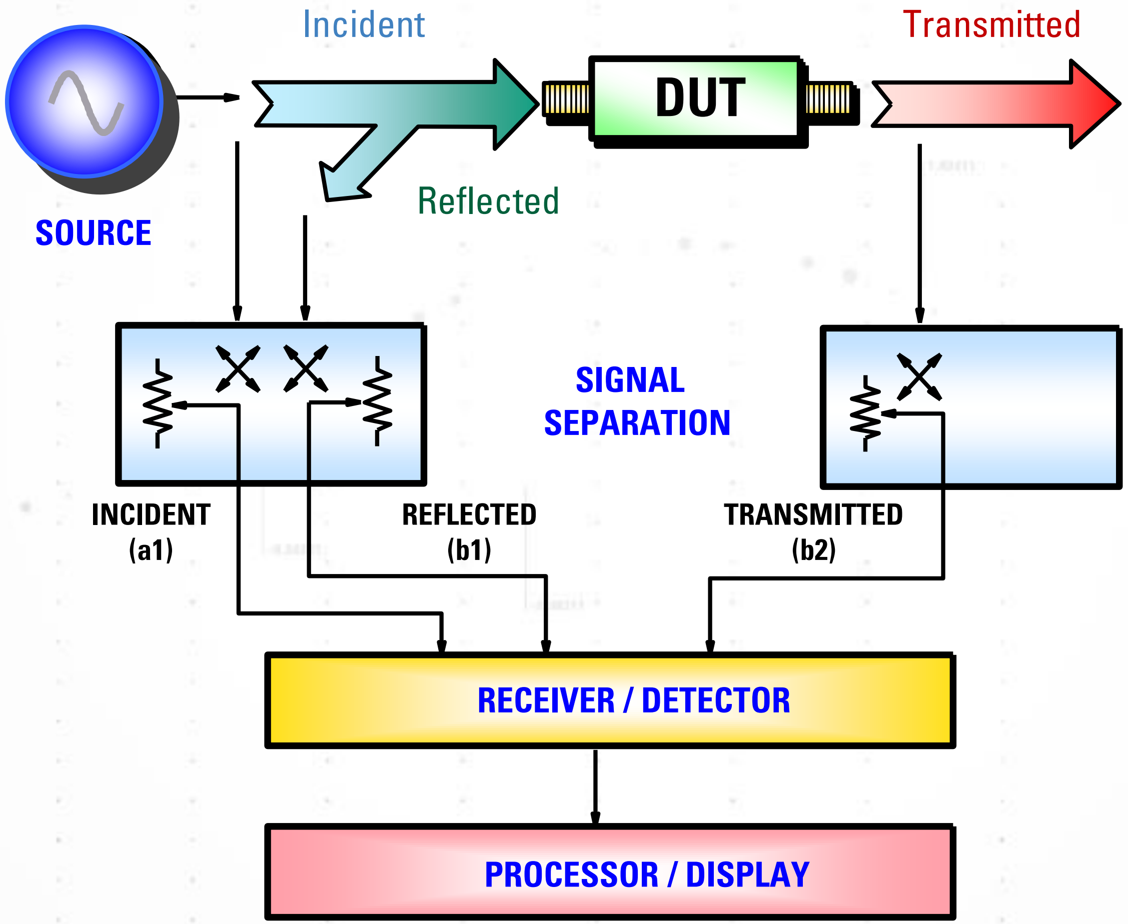
Remember S-parameters are inherently complex, linear quantities – however, we often express them in a log-magnitude format

Agenda

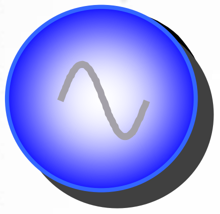
- RF/Microwave Design Challenges
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

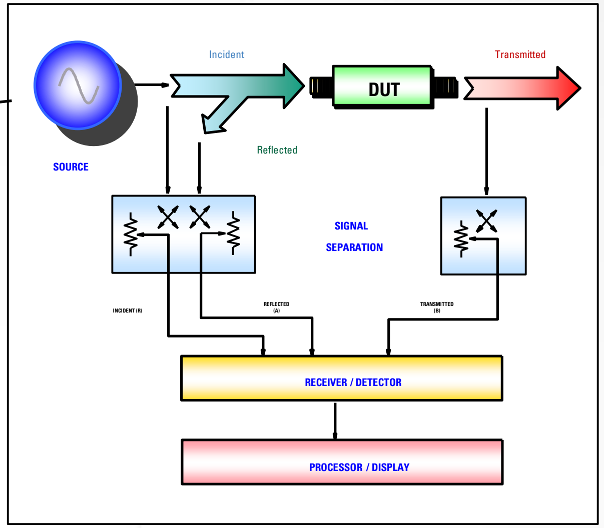
Generalized Network Analyzer Block Diagram

FORWARD MEASUREMENTS SHOWN



Source





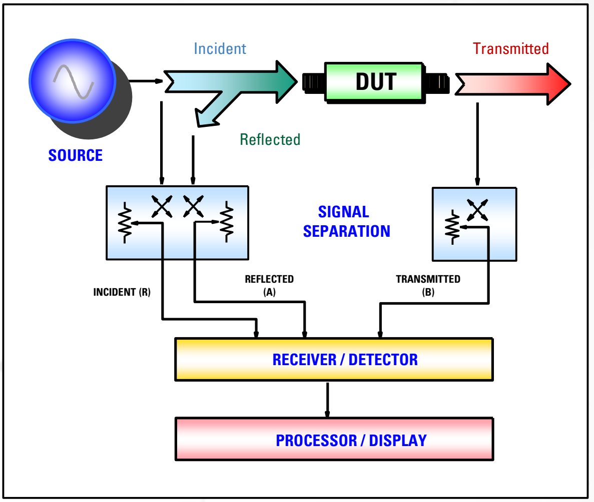
- Source stimulus can sweep frequency or power or phase
- Modern NAs may have the option for a second internal source and/or the ability to control external source

  Used for driving differential devices
  Can control an internal or external source
  as a local oscillator (LO) signal for mixers and converters
  Useful for mixer measurements
  like conversion loss, group delay

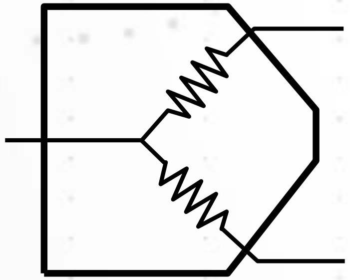
For more information on converter testing:
http://www.keysight.com/upload/cmc_upload/All/PNA_Advances_Converter_Testing.pdf

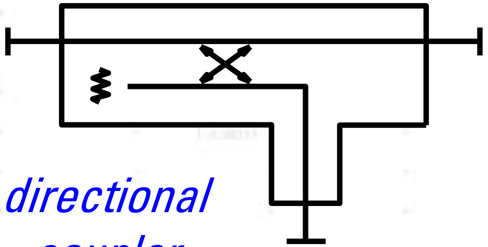
Signal Separation

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



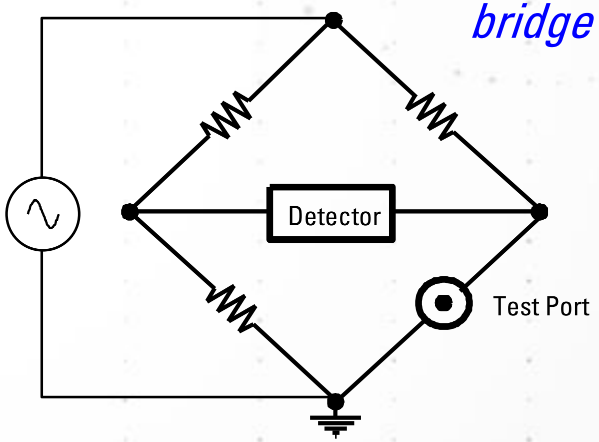
splitter



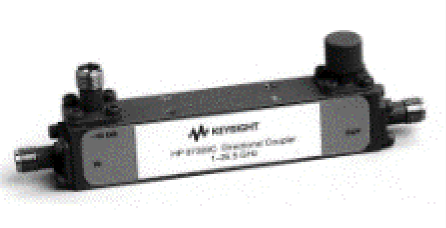


directional coupler

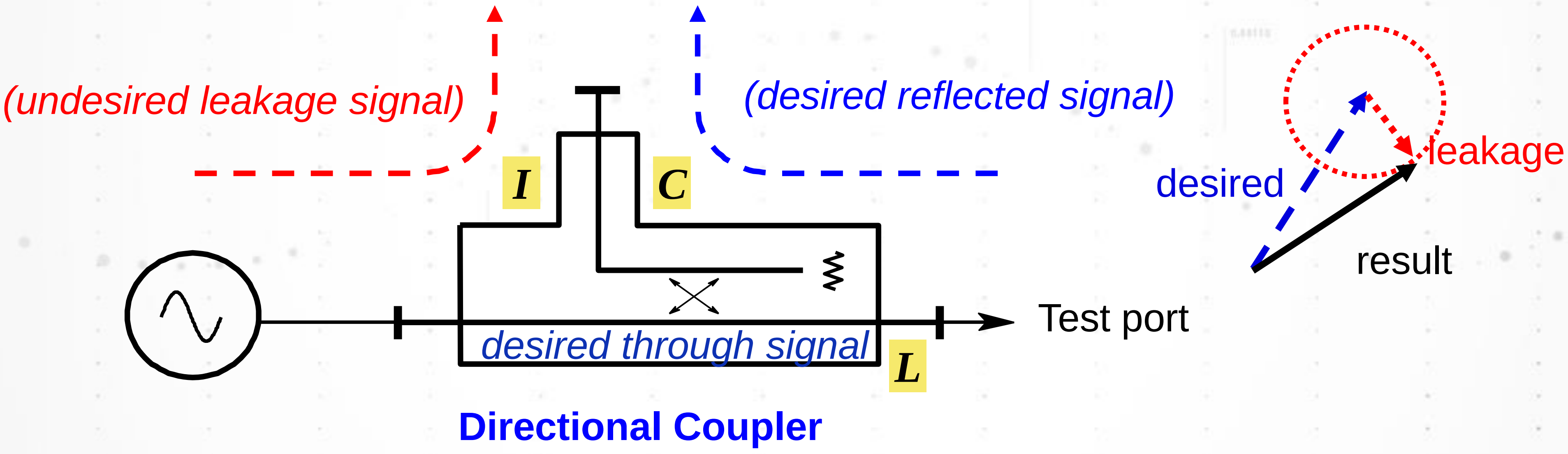
bridge



Directional Coupler & Directivity



- ***Directivity*** is a measure of how well a directional coupler or bridge can separate signals moving in opposite directions



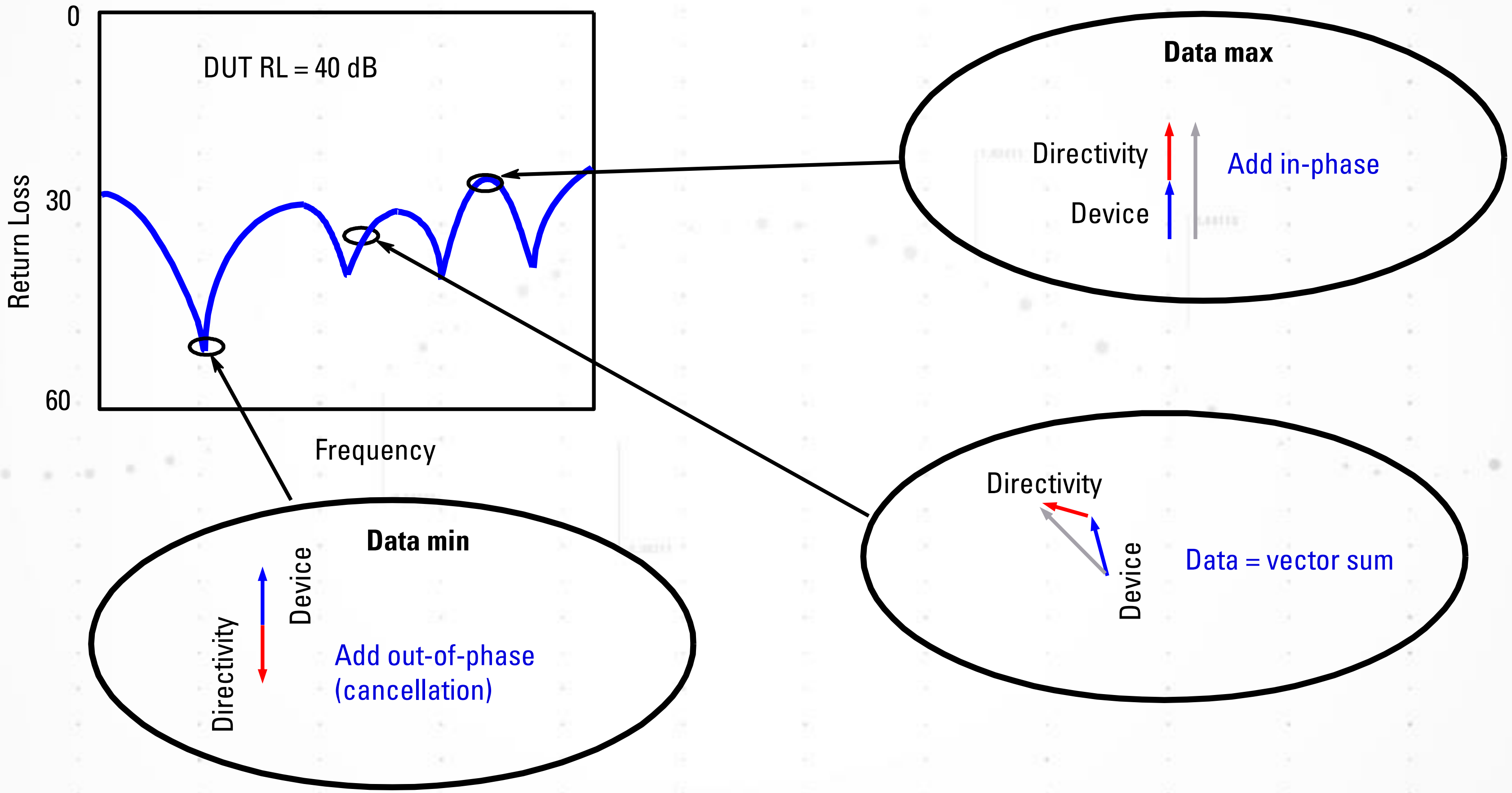
Directional Coupler

Directivity = Isolation (I) - Fwd Coupling (C) - Main Arm Loss (L)

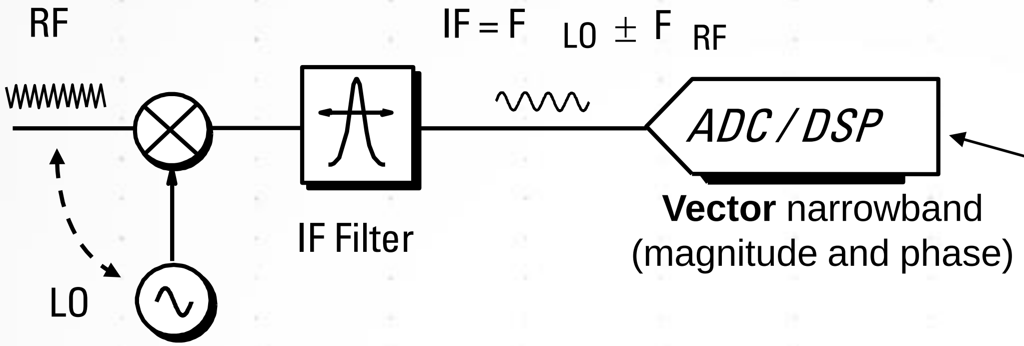
Directivity = 50 dB (I) – 20dB(C) – 1 dB(L) = 29 dB

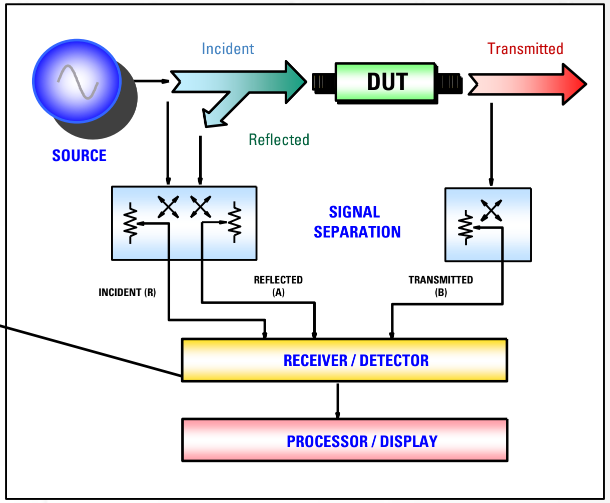
Interaction of Directivity with the DUT

(WITHOUT ERROR CORRECTION)

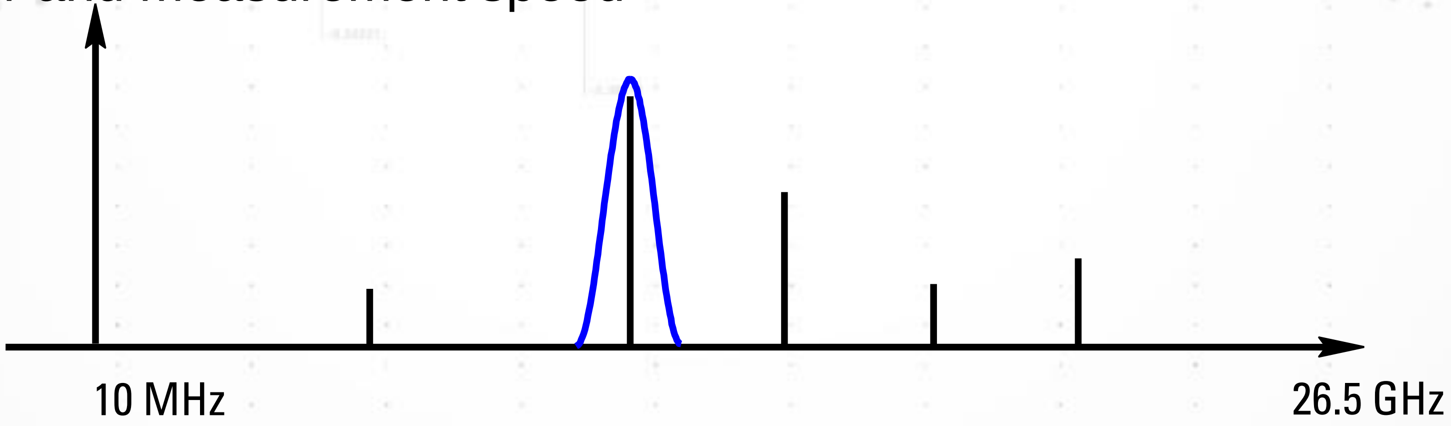


Narrowband Detection - Tuned Receiver



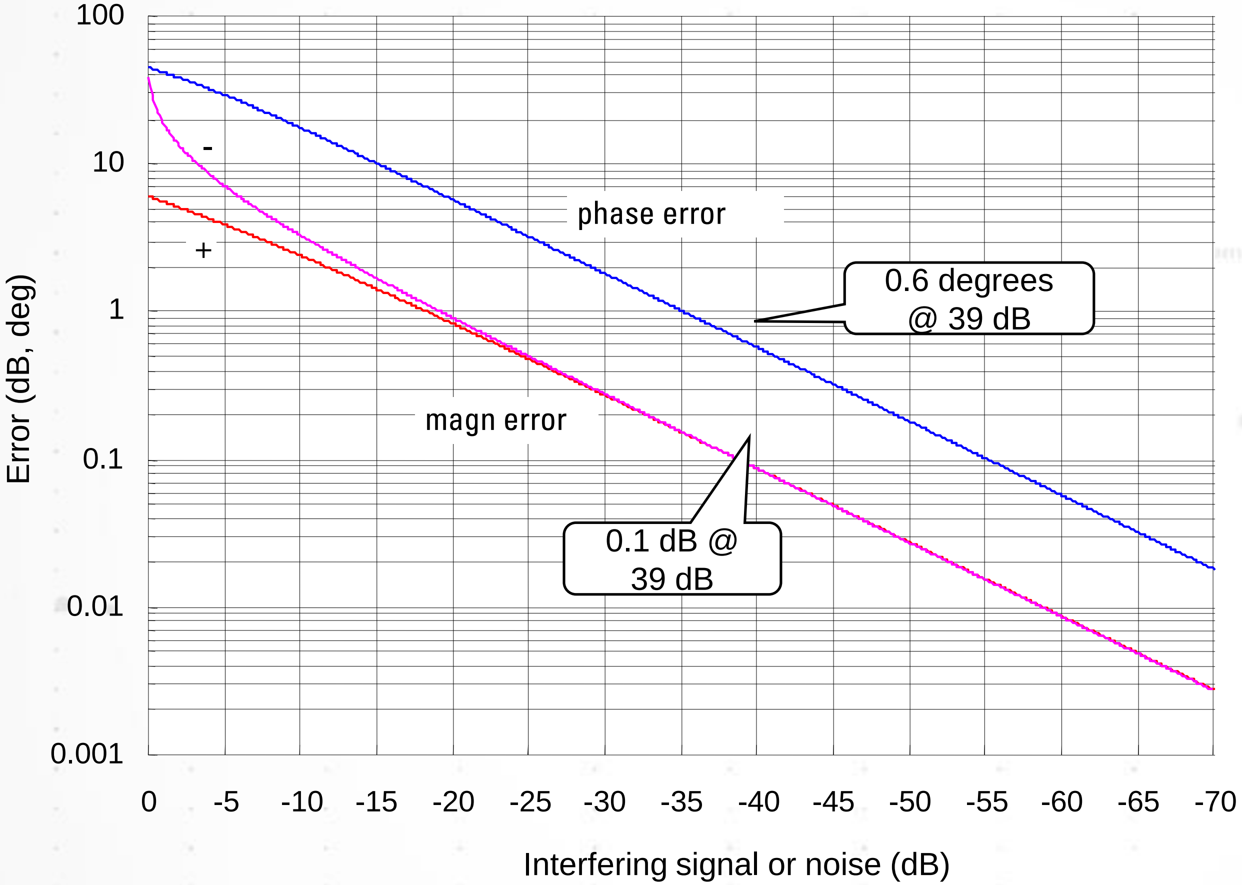


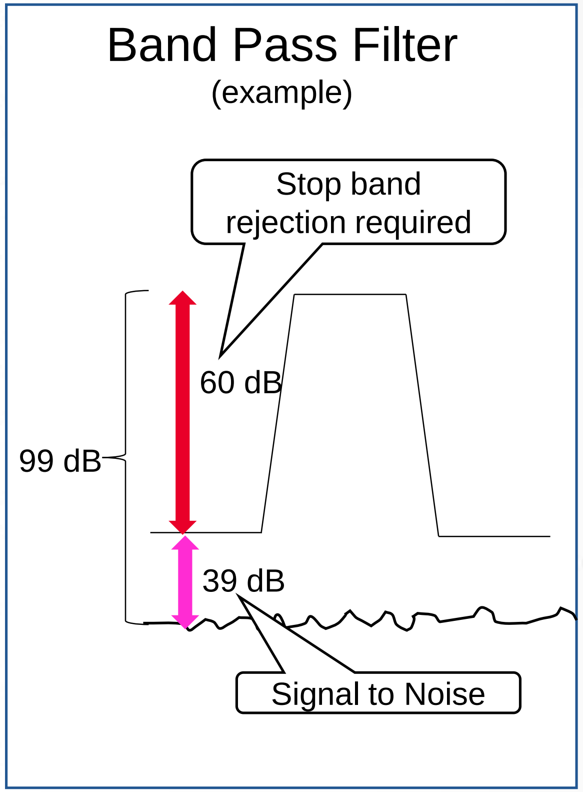
- Best sensitivity / dynamic range
- Provides harmonic / spurious signal rejection
- Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
- Trade off noise floor and measurement speed



Dynamic Range and Accuracy

ERROR DUE TO INTERFERING SIGNAL



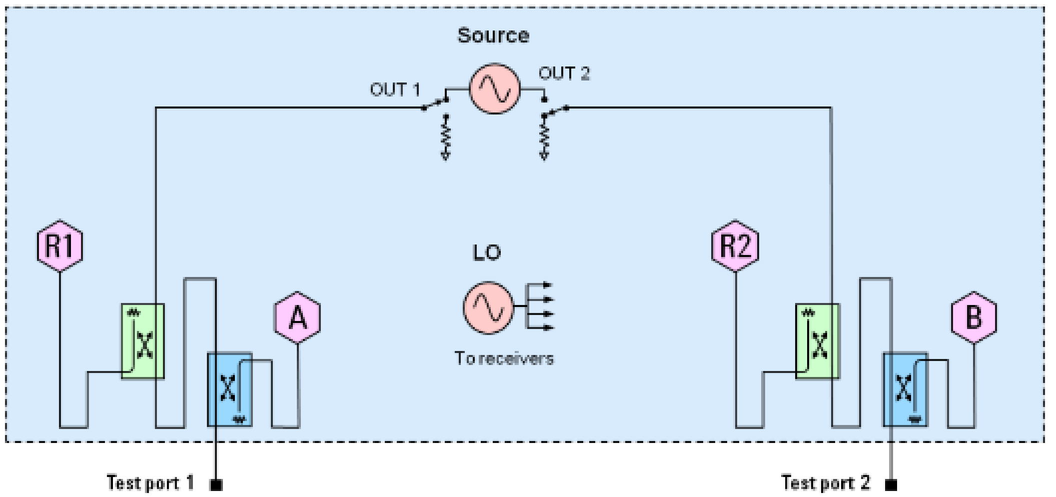


Dynamic range for 0.1 dB accuracy = 60 dB (rejection) + 39 dB (SNR) = 99 dB

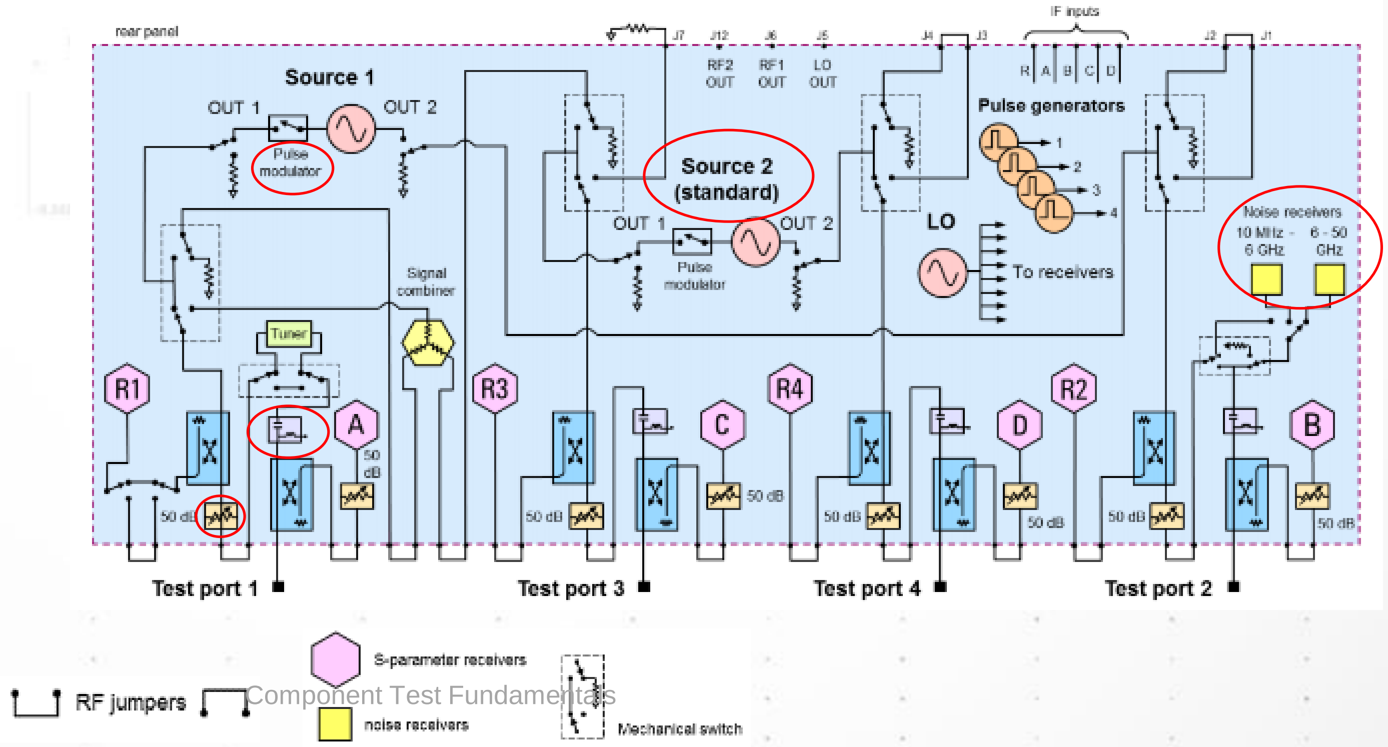
Dynamic range is very important for measurement accuracy!

VNA Block Diagram Examples

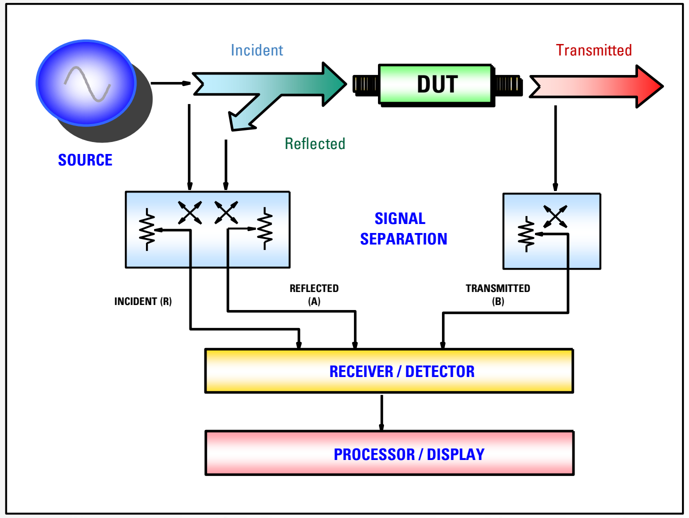
- **Basic 2 Port**



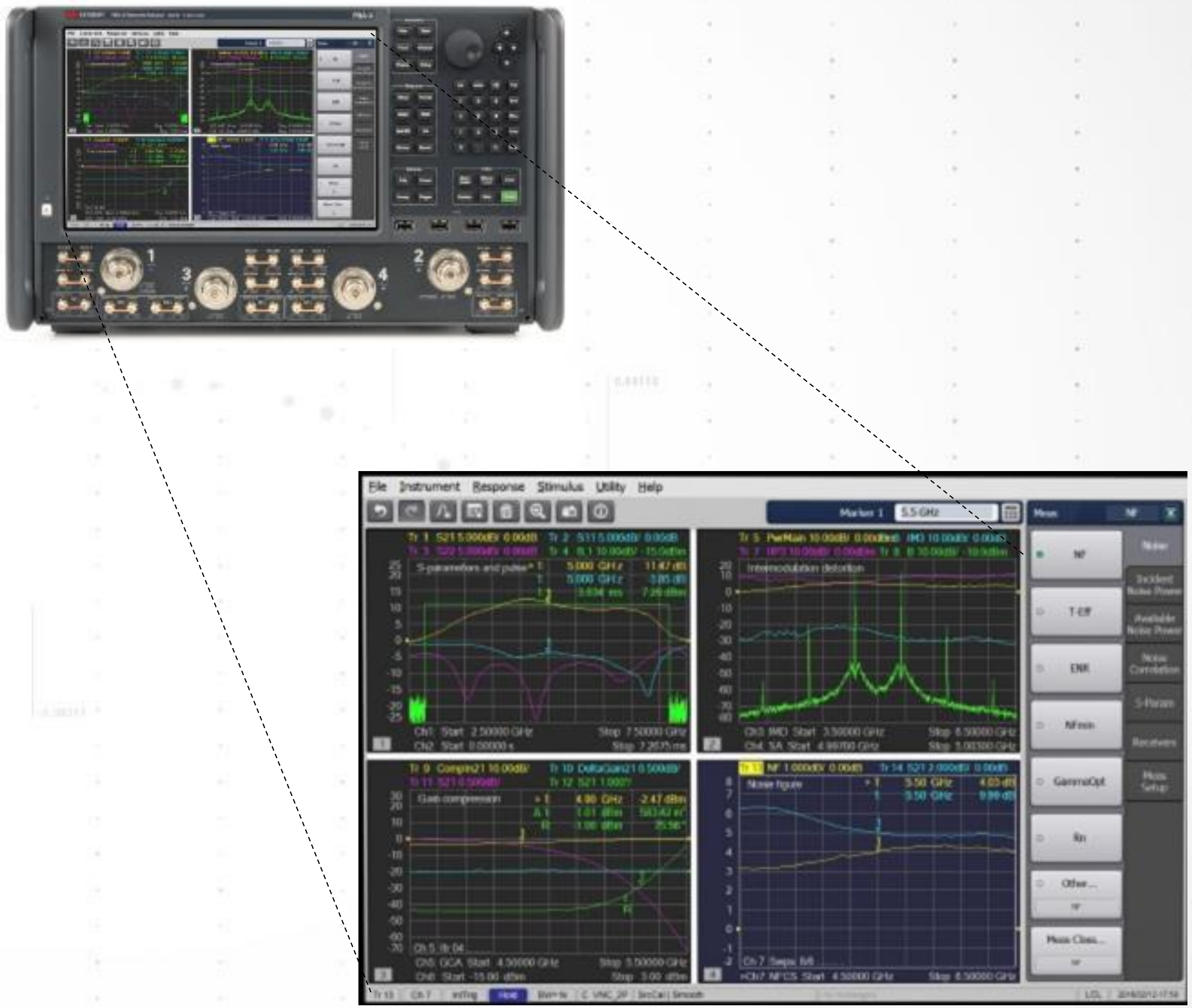
- **Performance 4 Port**
  - Access loops & switches
  - 2 sources & combiner
  - Pulse modulation
  - Noise tuner & LNA receiver
  - Attenuators
  - Bias-T’s



Processor / Display



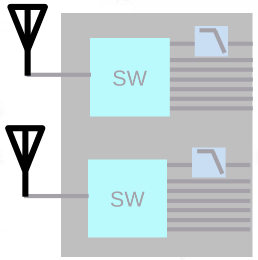
- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math

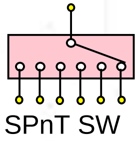


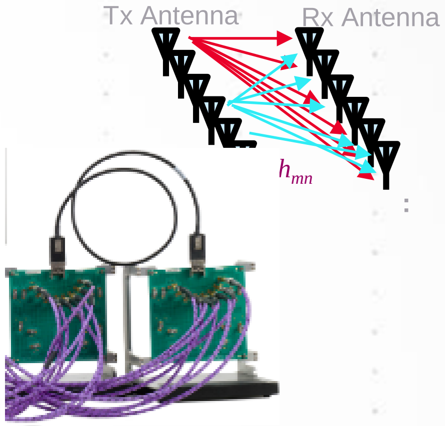
Multiport Measurement Architectures

Application Examples

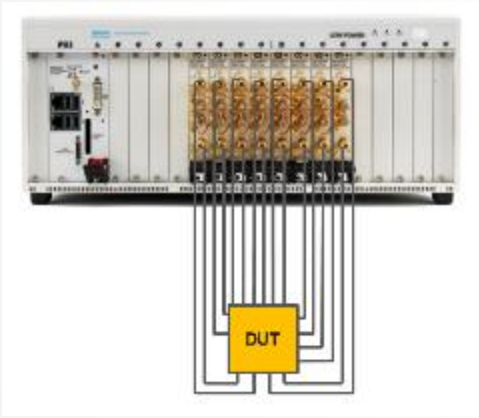
- RF front end modules / antenna switch modules
- Channel measurements of MIMO antennas
- Interconnects (ex. cables, connectors)
- General-purpose multiport devices



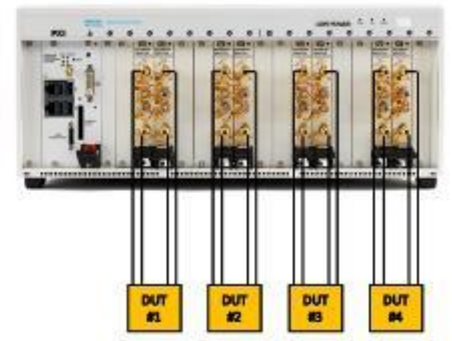




PXI Multiport VNA



PXI Multi-site VNA



Key Features

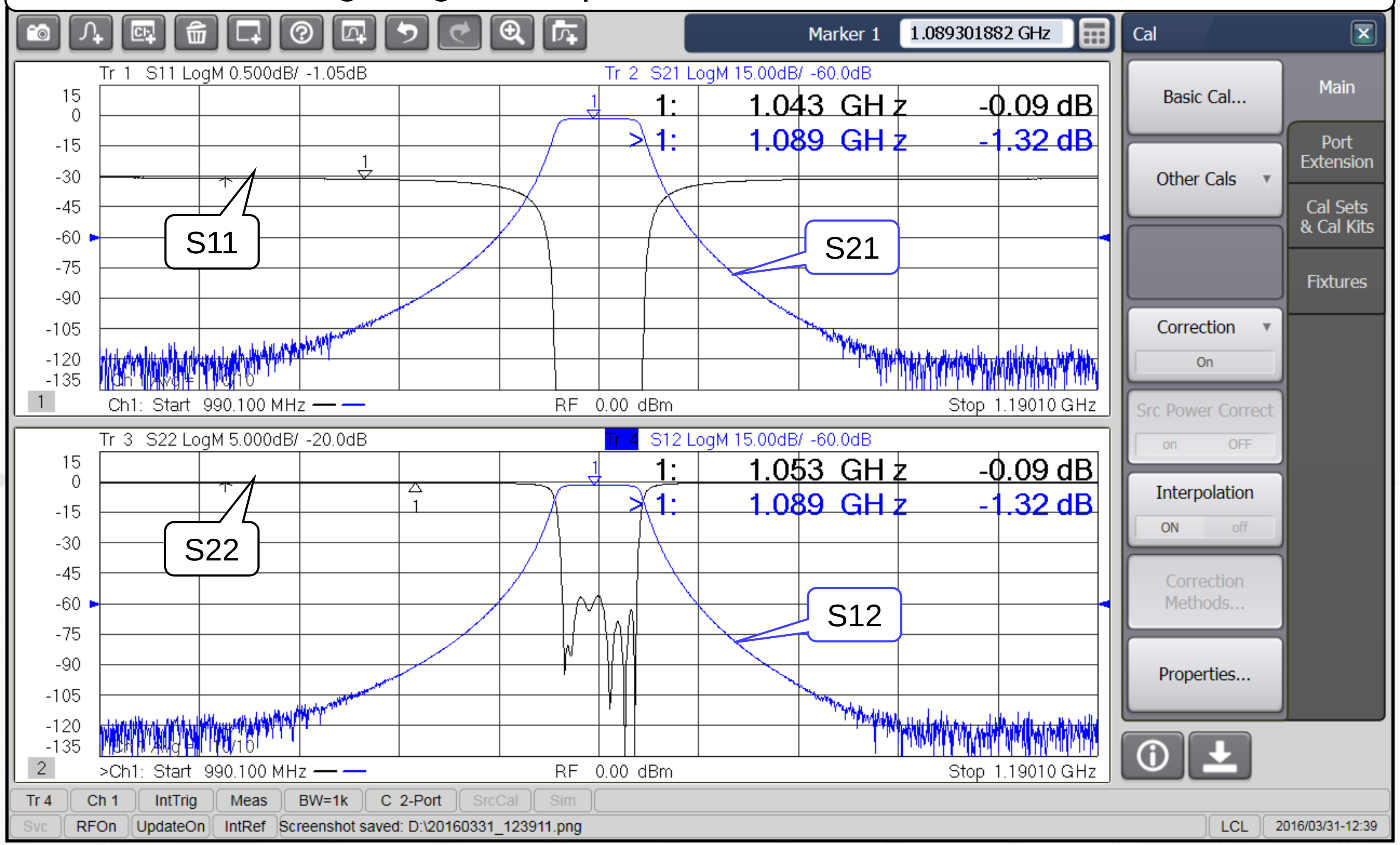
- True multiport VNA with independent modules
- Improved throughput
- High performance without external switches
- Full N-port correction
- Reconfigurable to multiport or multisite

Agenda

- RF/Microwave Design Challenges
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

Bandpass Filter four S-Parameters

log magnitude plots of S11, S21, S22, S12



Marker 1 1.089301882 GHz

Tr 1 S11 LogM 0.500dB/ -1.05dB

Tr 2 S21 LogM 15.00dB/ -60.0dB

1: 1.043 GHz -0.09 dB

>1: 1.089 GHz -1.32 dB

Ch1: Start 990.100 MHz RF 0.00 dBm Stop 1.19010 GHz

Tr 3 S22 LogM 5.000dB/ -20.0dB

Tr 4 S12 LogM 15.00dB/ -60.0dB

1: 1.053 GHz -0.09 dB

>1: 1.089 GHz -1.32 dB

>Ch1: Start 990.100 MHz RF 0.00 dBm Stop 1.19010 GHz

Correction On

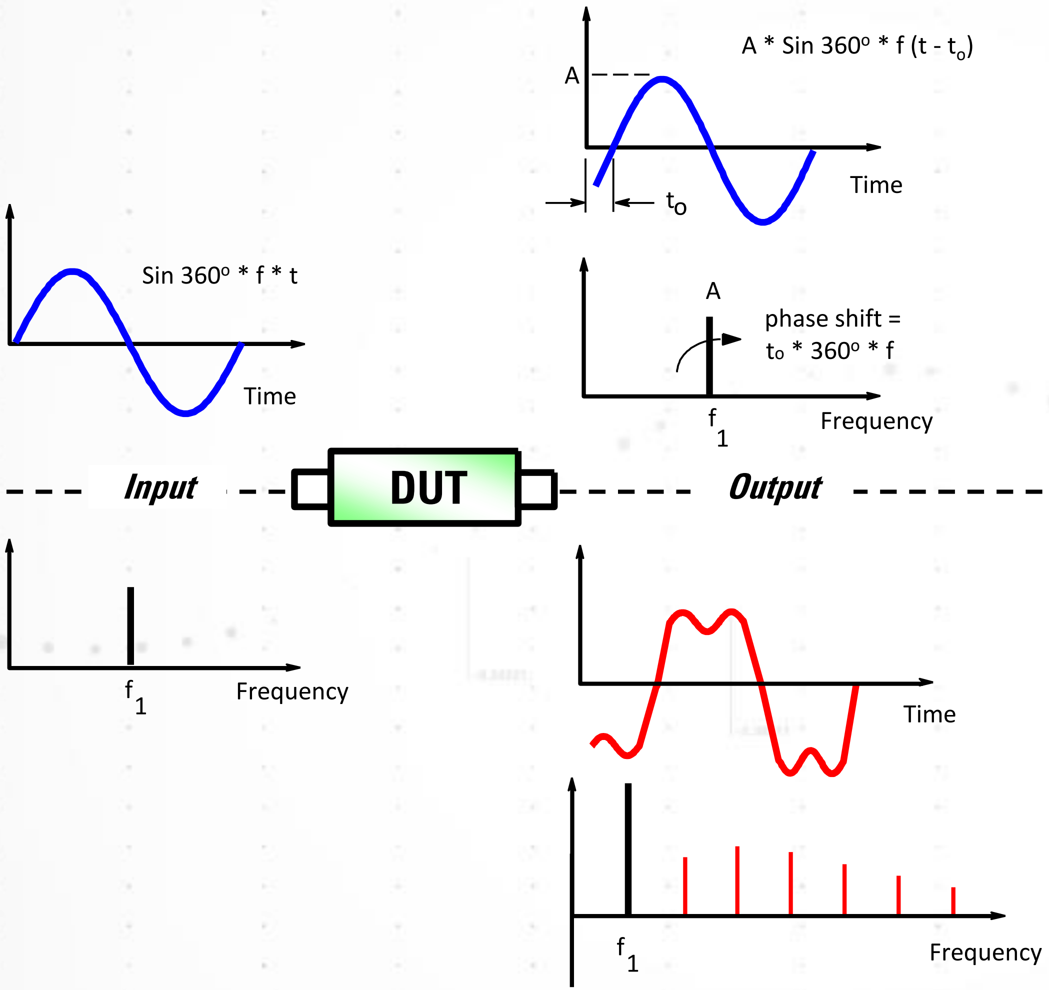
Src Power Correct on OFF

Interpolation ON off

Screenshot saved: D:\20160331_123911.png

2016/03/31-12:39

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

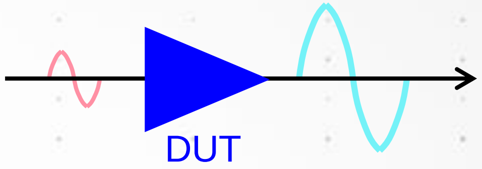
Nonlinear behavior:

Output frequency may undergo frequency shift (e.g. with mixers)

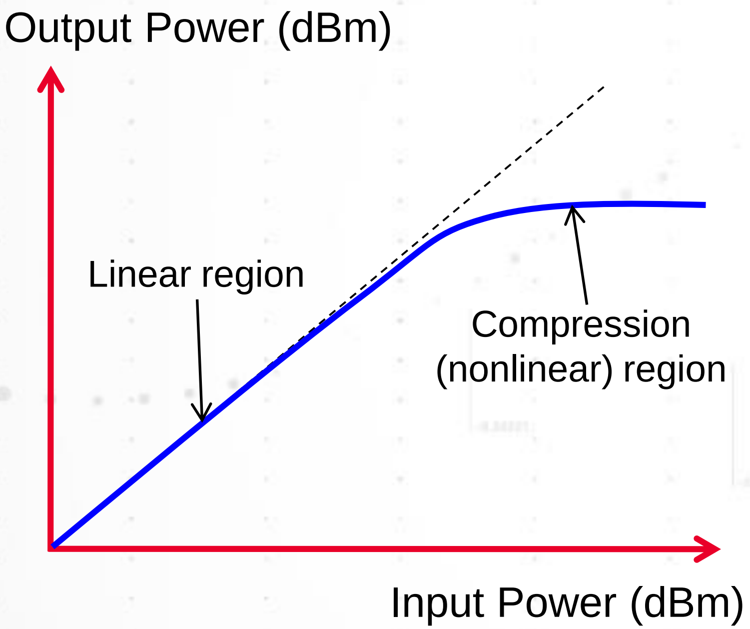
Additional frequencies created (harmonics, intermodulation)

For more information on linear vs. non-linear basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

Gain Compression

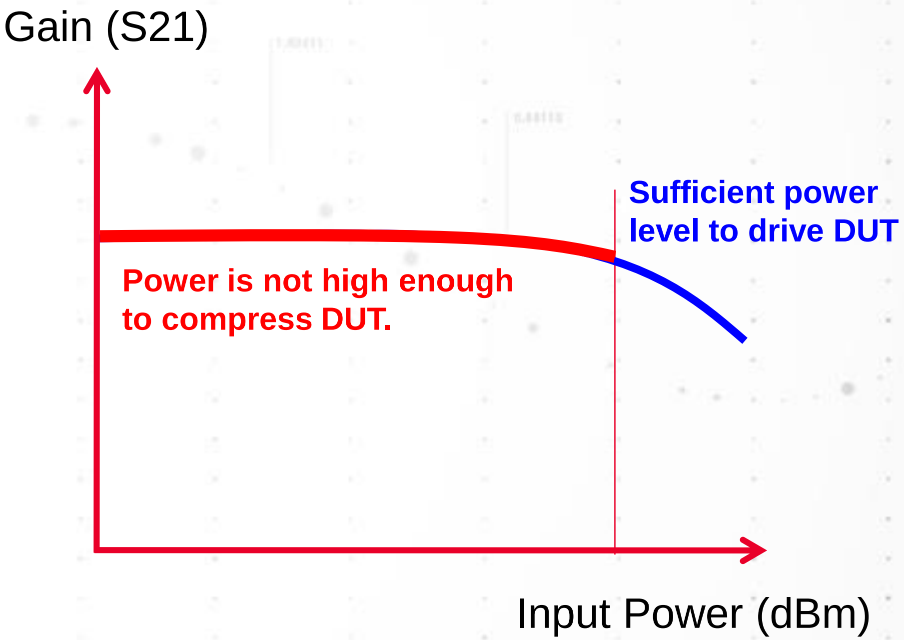


- Parameter to define the transition between the linear and nonlinear region of an active device.
- The compression point is observed as x dB drop in the gain with VNA’s power sweep.



Linear region

Compression (nonlinear) region



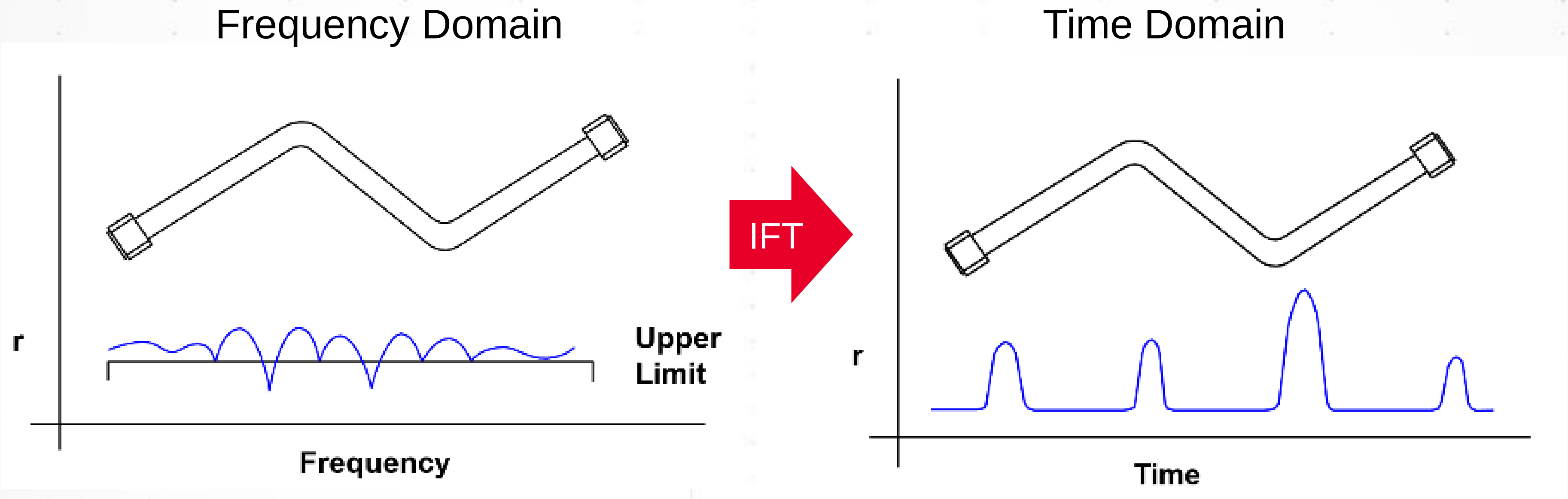
Sufficient power level to drive DUT

Power is not high enough to compress DUT.

Enough margin of source power capability is needed for analyzers.

Time vs. Frequency Domain

S11 RESPONSE OF SEMIRIGID COAX CABLE



- Why time domain?
  - Locate faults
  - Identify passive or inductive circuit elements
  - Identify and remove unwanted fixture responses
  - And more…

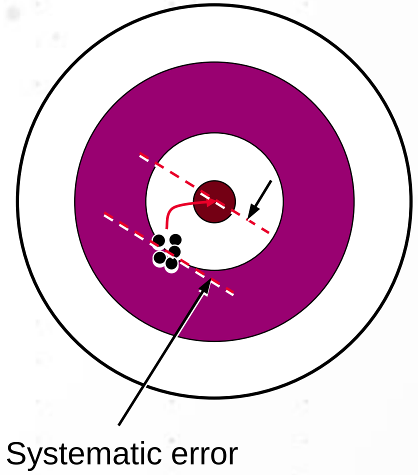
For more information on time domain basics:
http://literature.cdn.keysight.com/litweb/pdf/5989-5723EN.pdf?id=923465

Agenda

- RF/Microwave Design Challenges
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

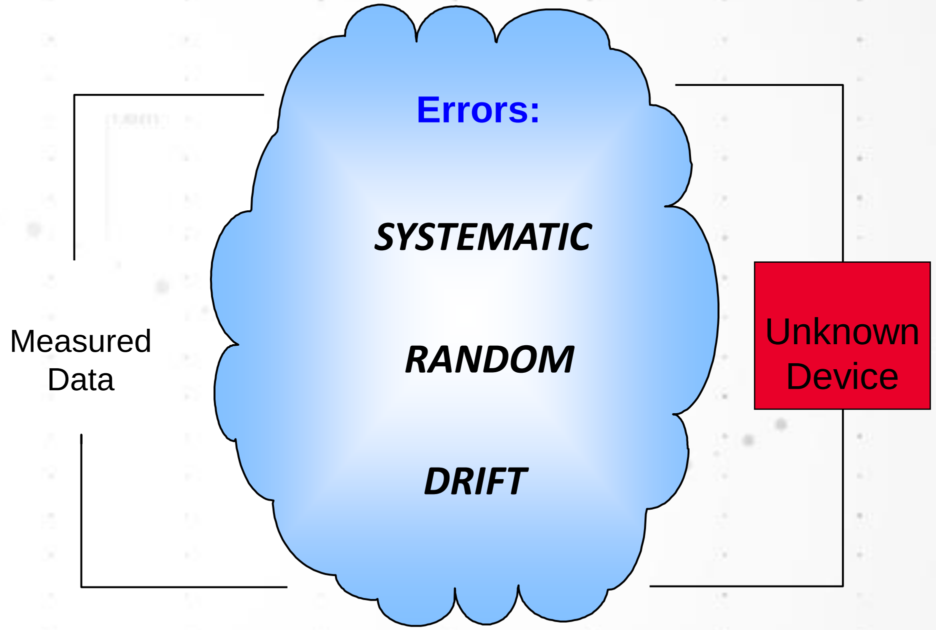
The Need For Calibration

- **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

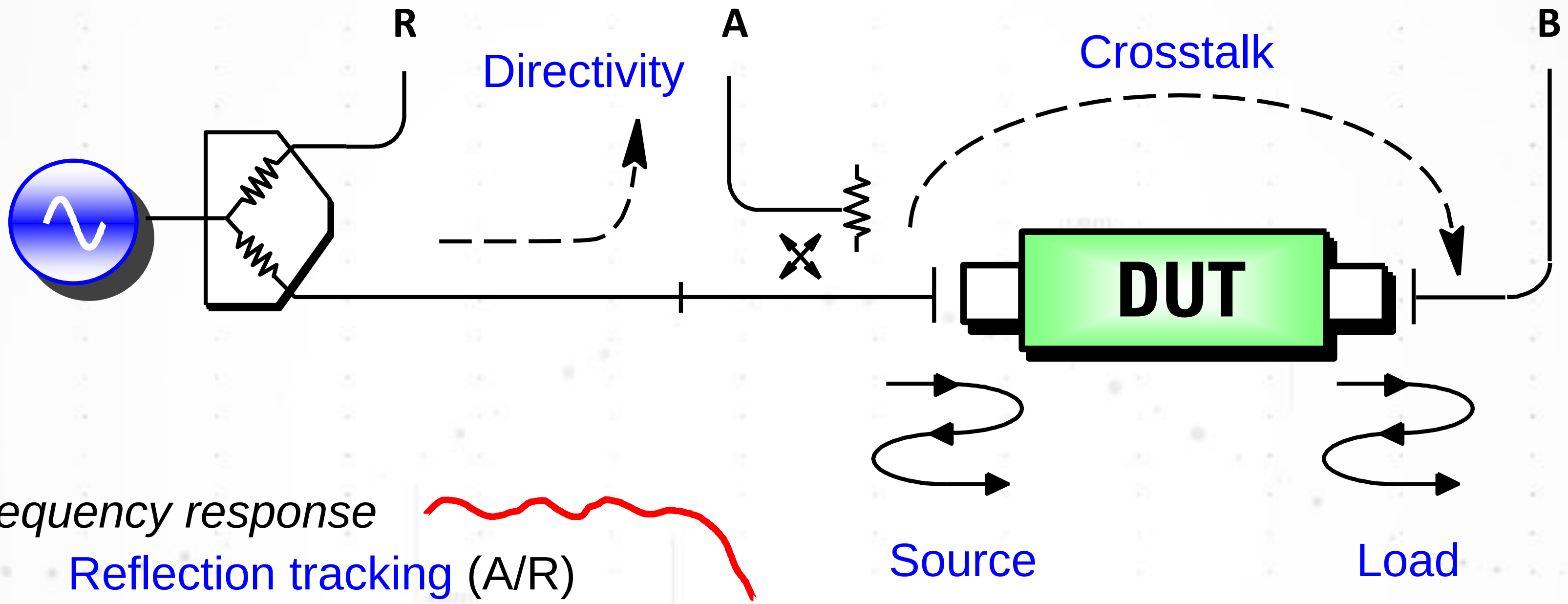


Measurement Error Modeling

- **Systematic Errors** ✓ CAL
  - 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** ✓ RE-CAL
  - Due to system performance changing ***after*** a calibration has been done
  - Primarily caused by **temperature variation**



Systematic Measurement Errors



Directivity

Crosstalk

Frequency response

Reflection tracking (A/R)

Transmission tracking (B/R)

Source
Mismatch

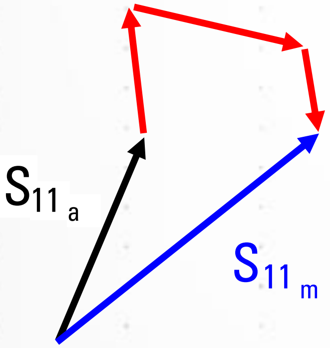
Load
Mismatch

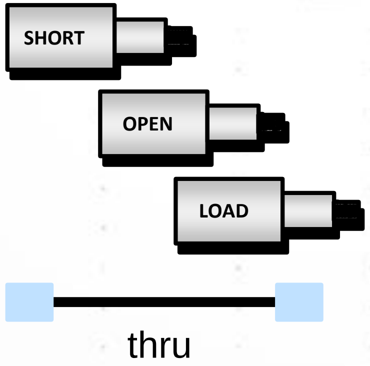
Six forward and six reverse error terms yields 12 error terms for two-port devices

Types of Error Correction

- **Response (normalization)**
  - Simple to perform
  - Only corrects for tracking (frequency response) errors
  - Stores reference trace in memory, then does data divided by memory

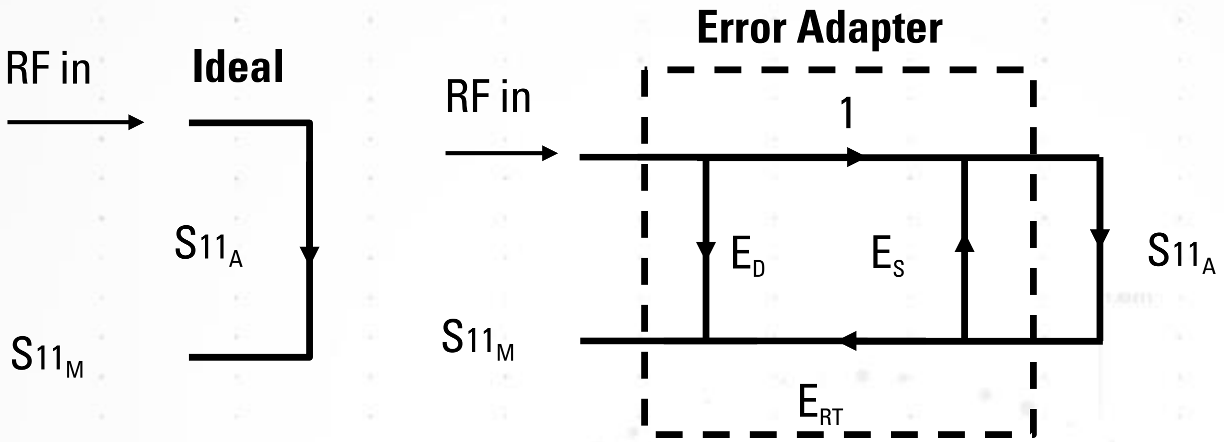
- **Vector**
  - Requires more calibration standards
  - Requires an analyzer that can measure phase
  - Accounts for all major sources of systematic error





Available Standards	
	Mechanical short, open, load, thru (SOLT)
	Electronically switched arbitrary know impedances

Reflection: One-Port Vector Error Model



E_D = Directivity
E_{RT} = Reflection tracking
E_S = Source Match
$S11_M$ = Measured
$S11_A$ = Actual

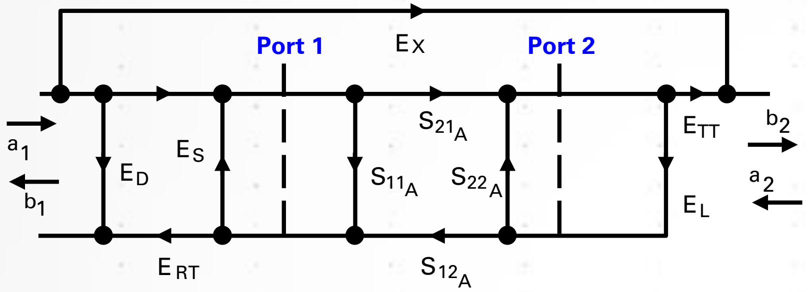
- To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

$$S11M = ED + ERT \left[\frac{S11A}{1 - ES\ S11A} \right]$$

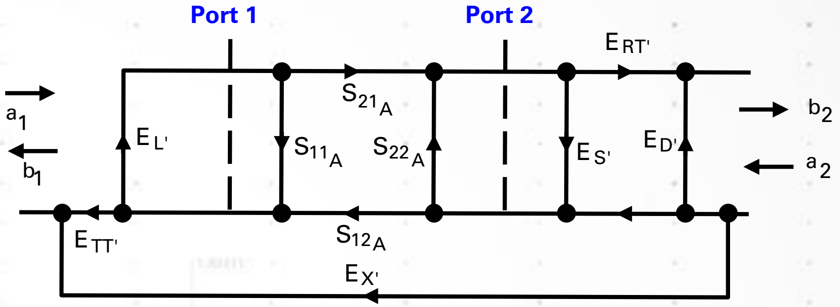
  - Assumes good termination at port two if testing two-port devices
  - If using port two of NA *and* DUT reverse isolation is low (e.g., filter passband):
    - Assumption of good termination is not valid
    - Two-port error correction yields better results

Two Port 12-term Error Model

Forward model



Reverse model



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

$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation

$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- 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 analyzer
- Crosstalk term, in most cases is not used

$$S_{11A} = \frac{S_{11N} \cdot (1 + S_{22N} \cdot ESR) - ELF \cdot S_{21N} \cdot S_{12N}}{(1 + S_{11N} \cdot ESF)(1 + S_{22N} \cdot ESR) - ELF \cdot ELR \cdot S_{21N} \cdot S_{12N}}$$

$$S_{21A} = \frac{S_{21N} \cdot (1 + S_{22N} \cdot [ESR - ELF])}{(1 + S_{11N} \cdot ESF)(1 + S_{22N} \cdot ESR) - ELF \cdot ELR \cdot S_{21N} \cdot S_{12N}}$$

$$S_{12A} = \frac{S_{12N} \cdot (1 + S_{11N} \cdot [ESF - ELR])}{(1 + S_{11N} \cdot ESF)(1 + S_{22N} \cdot ESR) - ELF \cdot ELR \cdot S_{21N} \cdot S_{12N}}$$

$$S_{22A} = \frac{S_{22N} \cdot (1 + S_{11N} \cdot ESF) - ELR \cdot S_{21N} \cdot S_{12N}}{(1 + S_{11N} \cdot ESF)(1 + S_{22N} \cdot ESR) - ELF \cdot ELR \cdot S_{21N} \cdot S_{12N}}$$

where a normalized S-parameter is defined as

$$S_{11N} = \frac{S_{11M} - EDF}{ERF}, \quad S_{21N} = \frac{S_{21M} - EXF}{ETF}, \quad S_{12N} = \frac{S_{12M} - EXR}{ETR}, \quad S_{22N} = \frac{S_{22M} - EDR}{ERR}$$

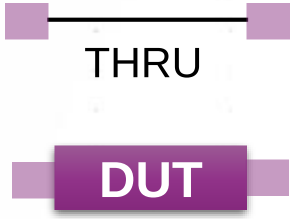
Significance of Calibration

TYPES OF CALIBRATION

UNCORRECTED

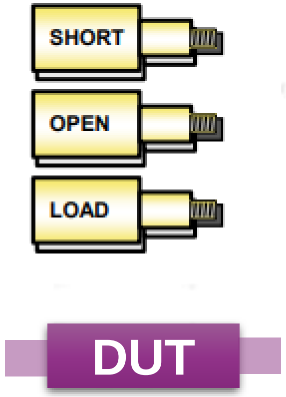
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



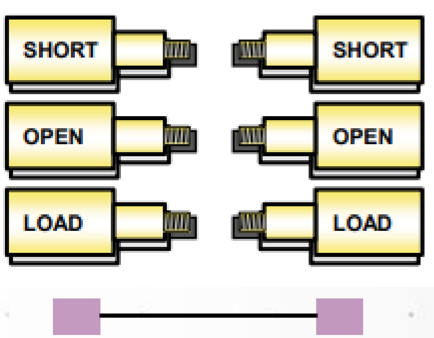
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with 2-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



Defined Thru or Unknown Thru

- Highest accuracy
- Removes these errors:
  - Directivity
  - Source/load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk (limited by noise)

ENHANCED RESPONSE

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

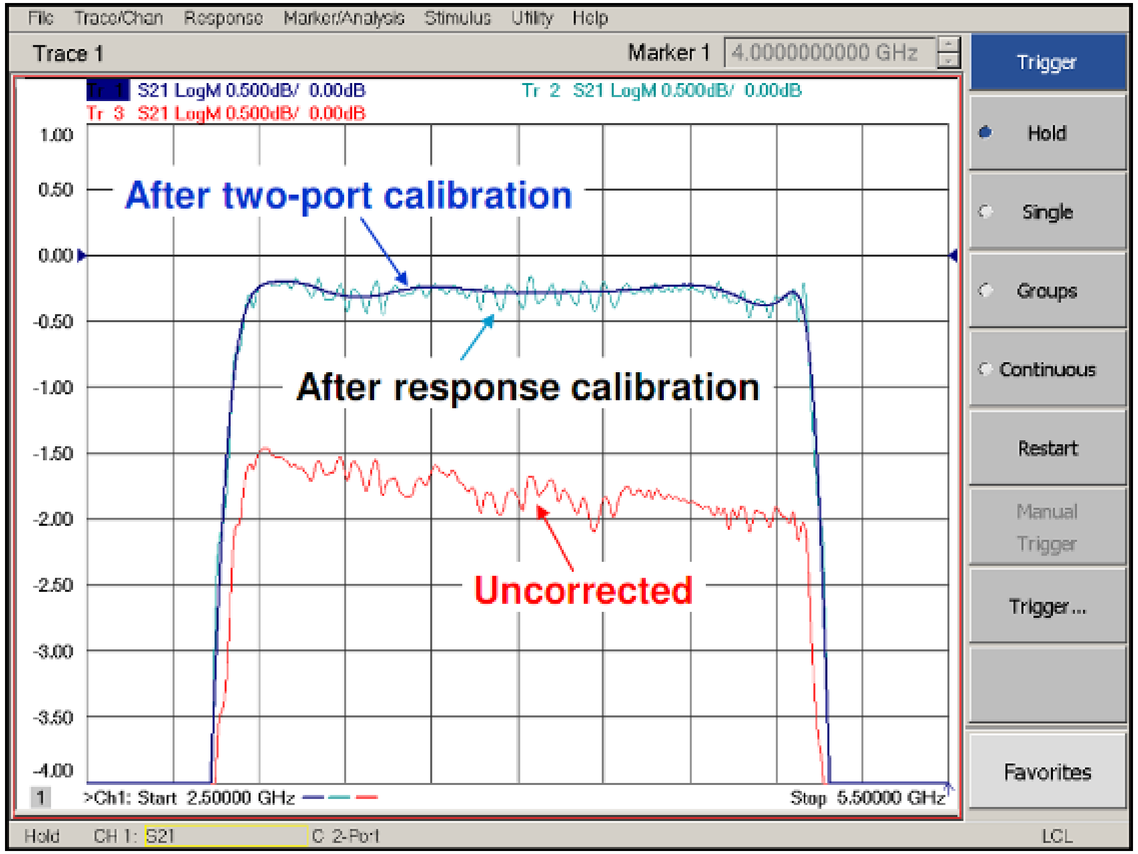
Using Known Standards to Correct for Systematic Errors

- **Response calibration (normalization)**
  - Only one systematic error term measured
  - Reflection tracking
- **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
  - 10 measurements on four known standards (SOLT)
  - 7 measurements using Unknown Thru; 4 measurements using QSOLT
- **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

VNA showing Band Pass Filter

UNCALIBRATED, RESPONSE CAL AND FULL 2 PORT CAL

Measuring filter insertion loss



After two-port calibration

After response calibration

Uncorrected

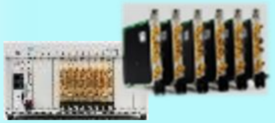
Vector Network Analyzers Product Portfolio

Handheld VNA

FieldFox
Carry precision with you
30 k to 50 GHz

Modular VNA

PXI Performance VNA (M9485A)
High-performance PXI VNA
Up to 9 GHz, max 24-ports



One-slot PXI VNA (M937xA)
Drive down the cost of size
Up to 26.5 GHz, max 32-ports

Benchtop VNA

PNA
Reach for unrivaled excellence
300 k to 1.5 THz

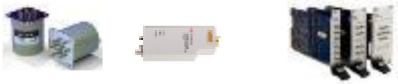
ENA
Drive down the cost of test
5 Hz to 20 GHz

Industry Broadest Price / Performance Choices

Accessories

Cal kits (Mech., E-Cal)
Up to 120 GHz

Accessories- Attenuator, Switch, Coupler, Splitter, etc.



Power meter / sensor

Software Applications

Ease-of-use, fundamental/advanced applications
Common VNA software platform
Flexibility in license types

Network Analyzer Measurement Resources

- Keysight RF and Digital Monthly Webcast Series www.keysight.com/find/webcastseries
  - Live and On Demand Viewing
  - Register for Future Webcasts
- Keysight RF Learning Center www.keysight.com/find/klcrf
  - Webcast Recordings
  - Application Notes
    - Understanding the Fundamentals of Network Analysis

KEYSIGHT
TECHNOLOGIES