Network Analysis

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Keysight Technologies

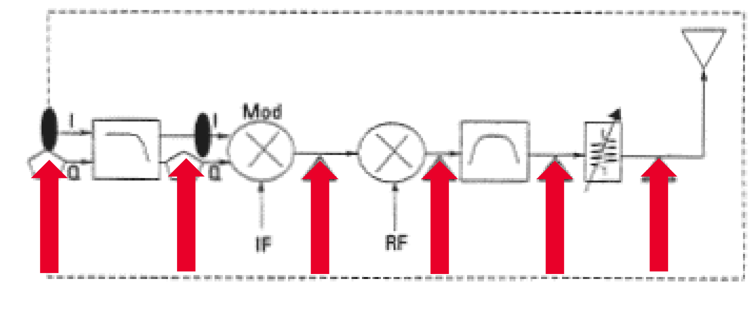
KEYSIGHT TECHNOLOGIES

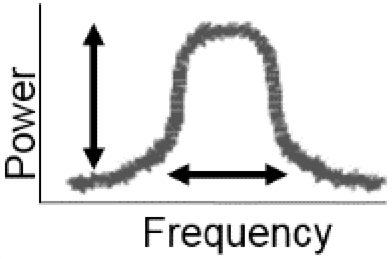
Agenda

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

Transmit Receive Design Challenges

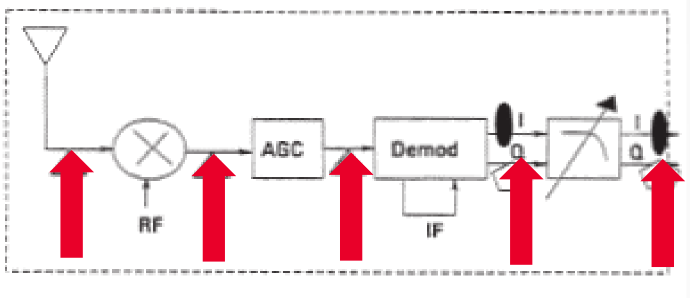
TRANSMIT





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

RECEIVE

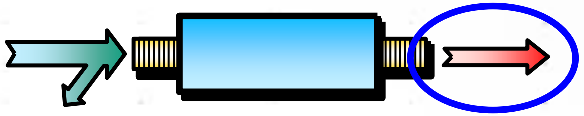


- Sensitivity
- Adjacent Channel Selectivity
- Operating Frequency
- Environment/Interference
- Noise
- Dynamic Range

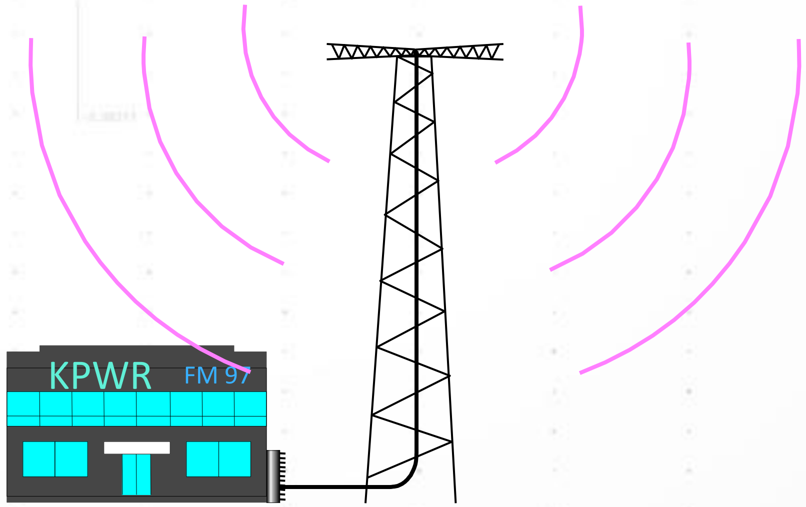
End goal: maximize link budget, fidelity & efficiency

Why Do We Need to Test Components?

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

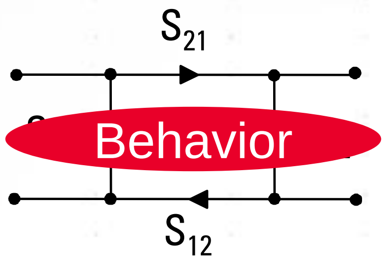


- Ensure distortionless transmission of communications signals
  - Linear: constant amplitude, linear phase / constant group delay
  - Nonlinear: harmonics, intermodulation, compression, X-parameters
- Ensure good match when absorbing power (e.g., an antenna)

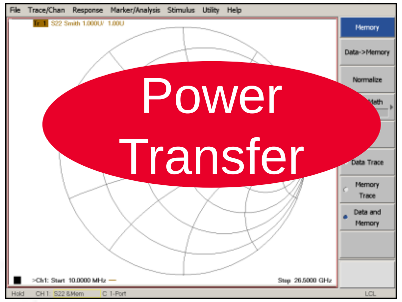


The Need for Both Magnitude and Phase

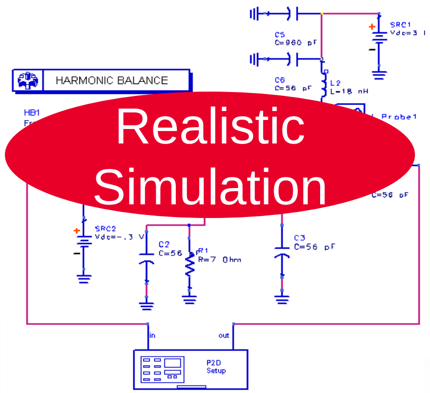
1. Complete characterization of linear networks



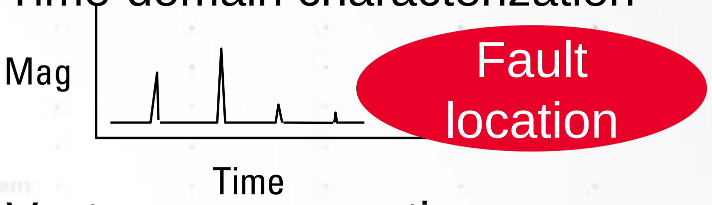
2. Complex impedance needed to design matching circuits



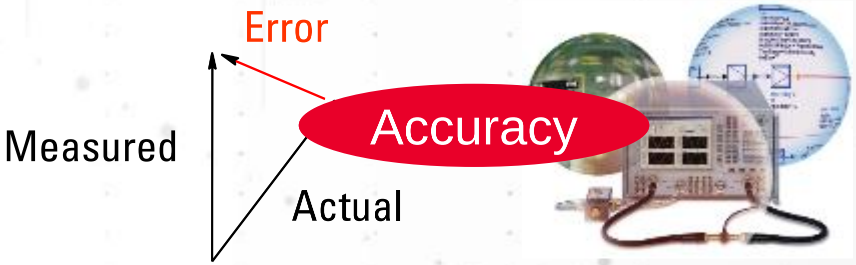
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction



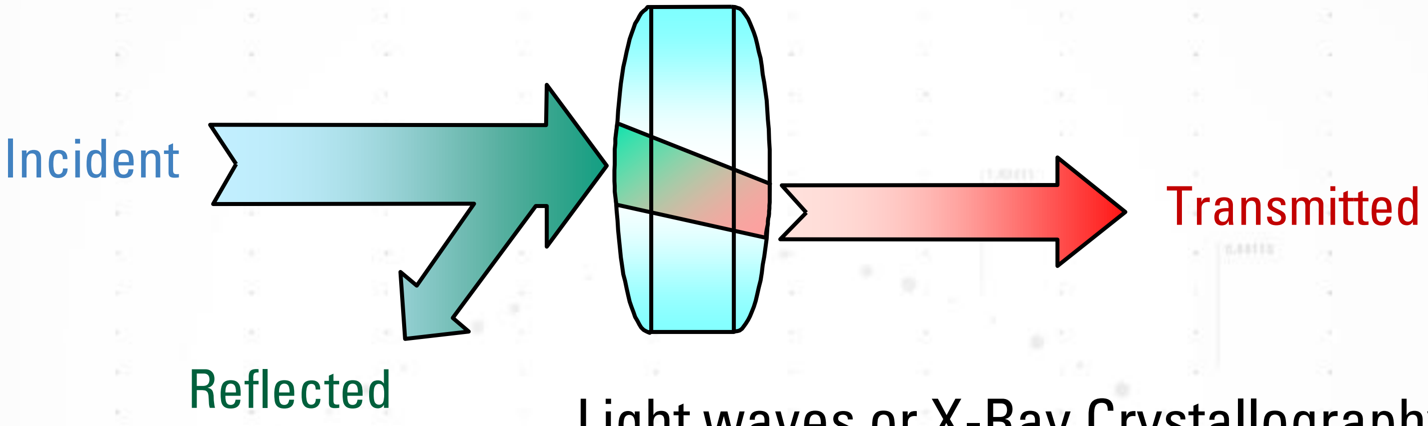
6. X-parameter (nonlinear) characterization

Pre-distortion

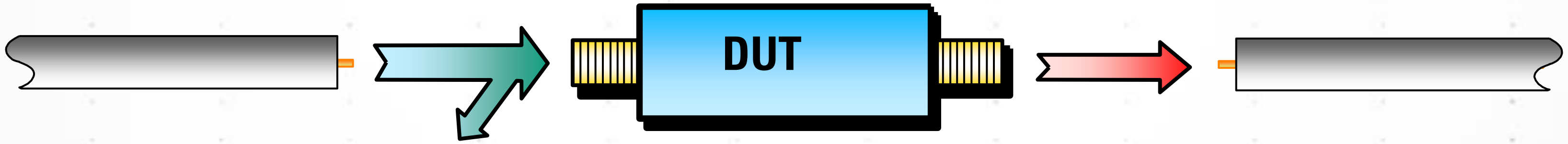
Agenda

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

RF Energy Transmission



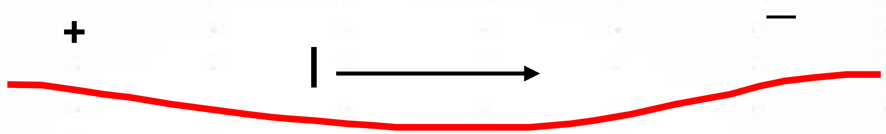
Light waves or X-Ray Crystallography and X-Ray Scattering

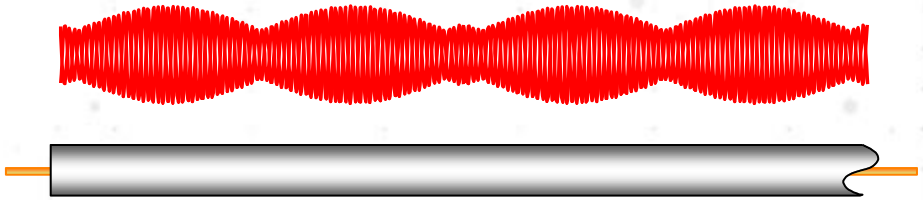


RF Scattering

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

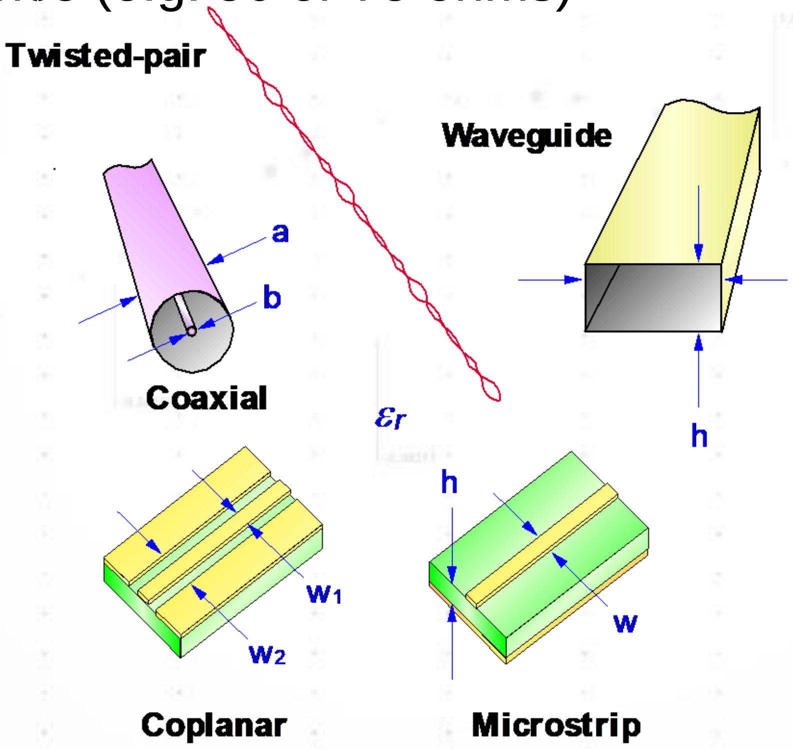




- High Frequencies
  - Wavelength ~ or << length of transmission medium
  - Need transmission lines for efficient power transmission
  - Matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer
  - Measured envelope voltage dependent on position along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

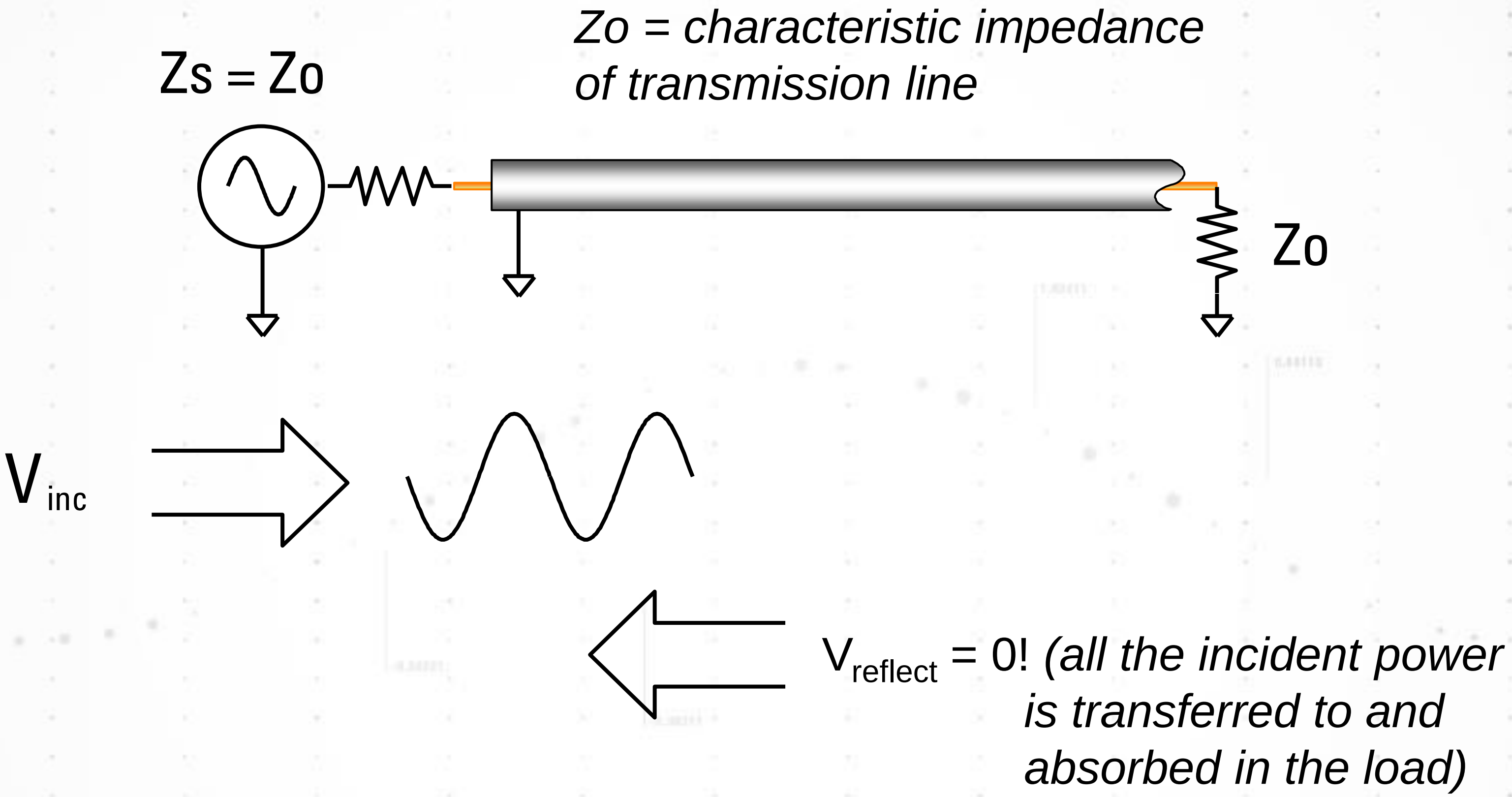
Transmission line Z_o

- 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)



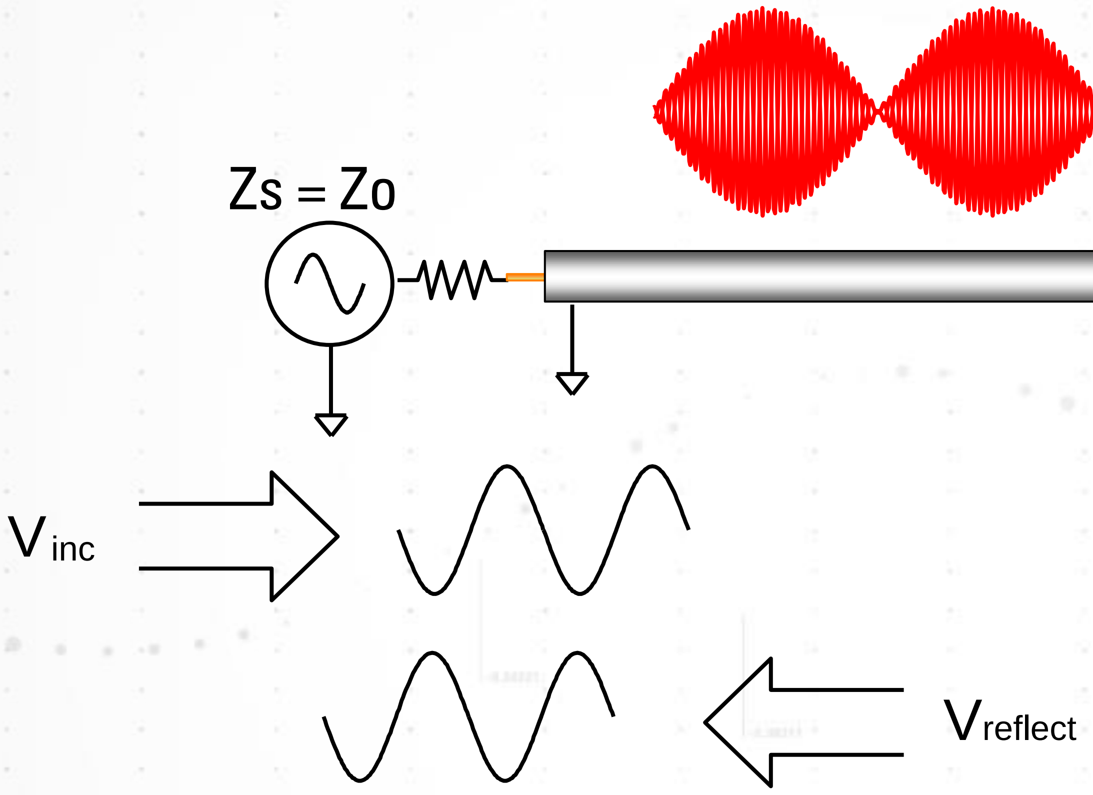
For more information on transmission line basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

Transmission Line Terminated with Zo



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

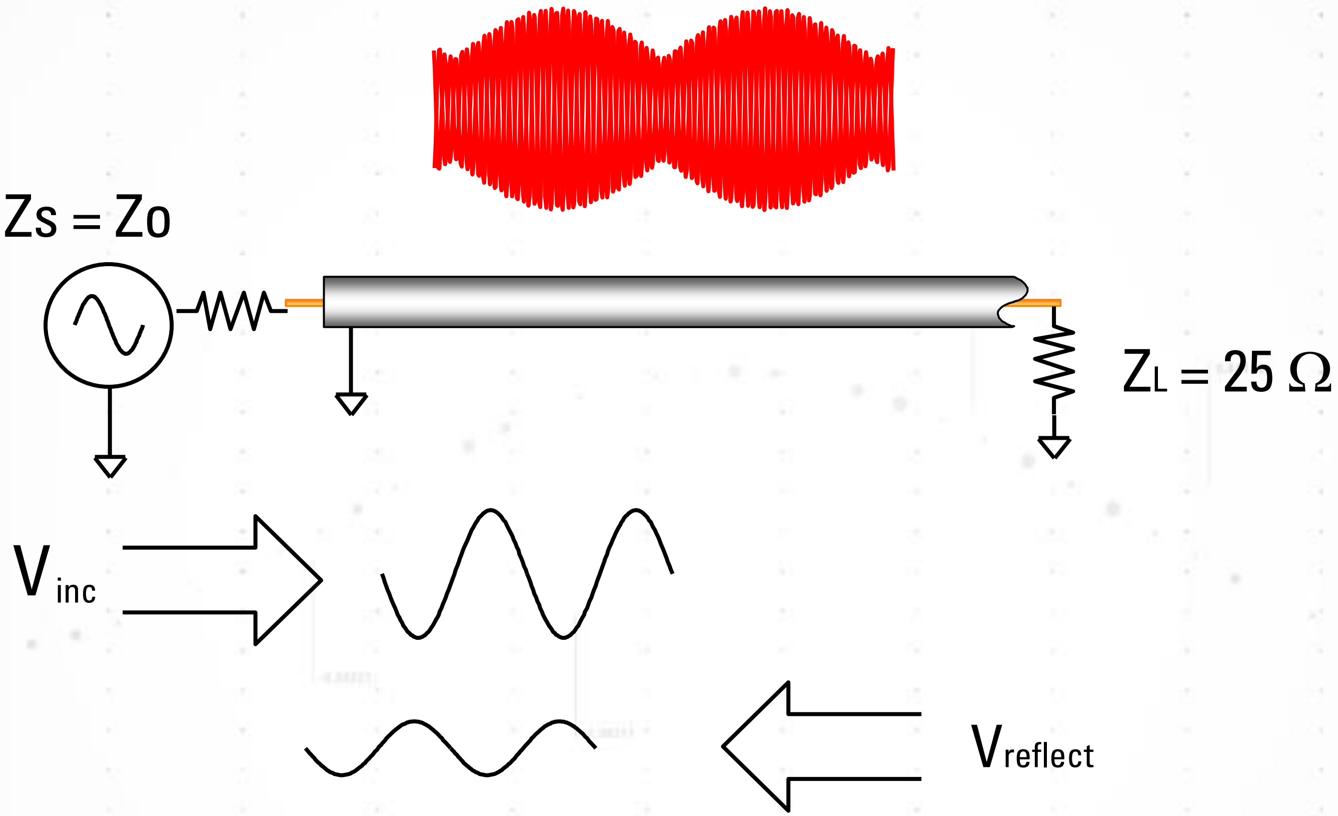
Transmission Line Terminated with Short, Open



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

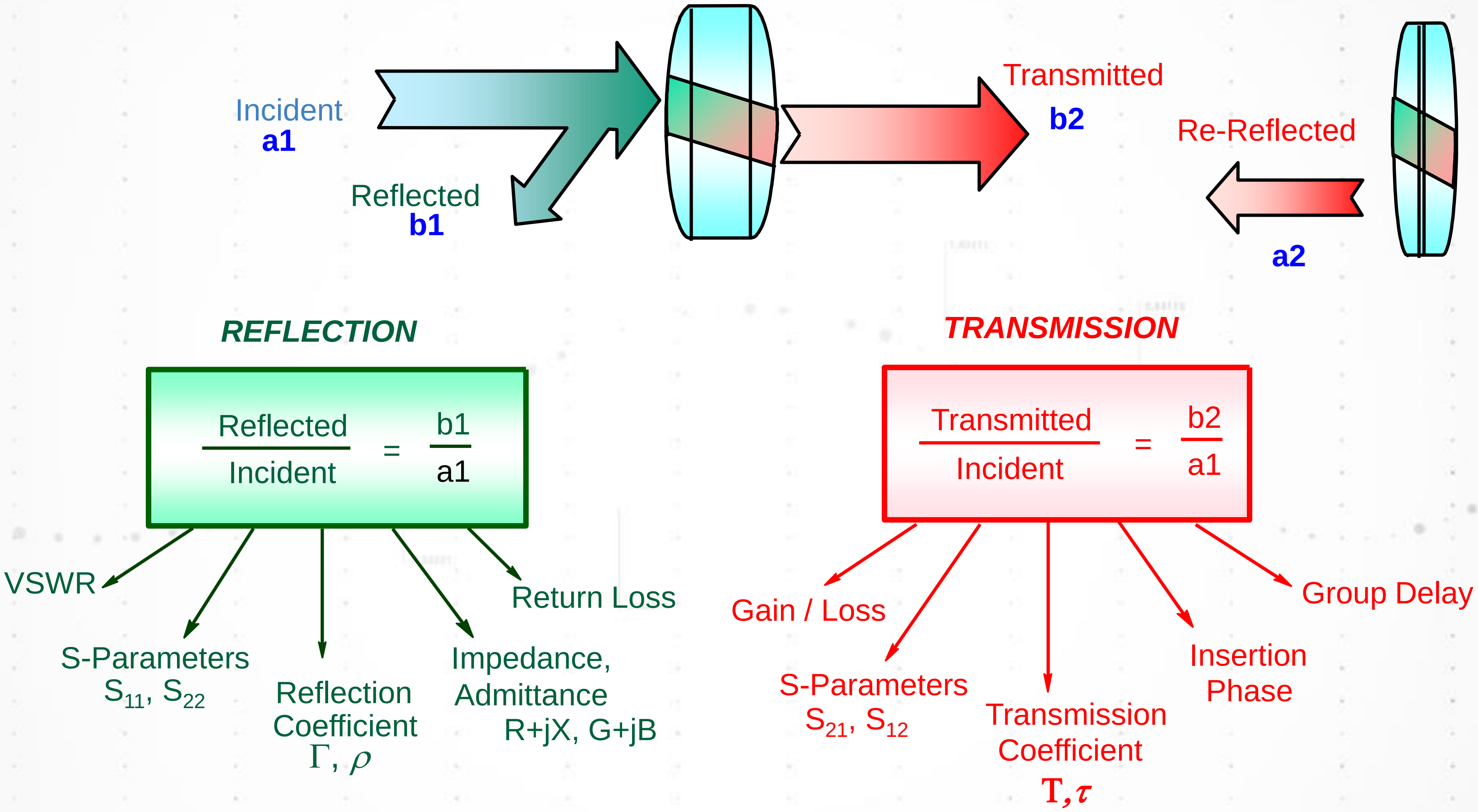
For reflection, a transmission line terminated in a short or open reflects all power back to source

Transmission Line Terminated with 25 ohms



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

High-frequency Device Characterization

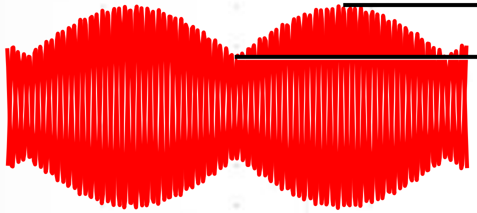


Reflection Parameters

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

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

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



Vmax

Vmin

Voltage Standing Wave Ratio

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

No reflection (ZL = Zo)

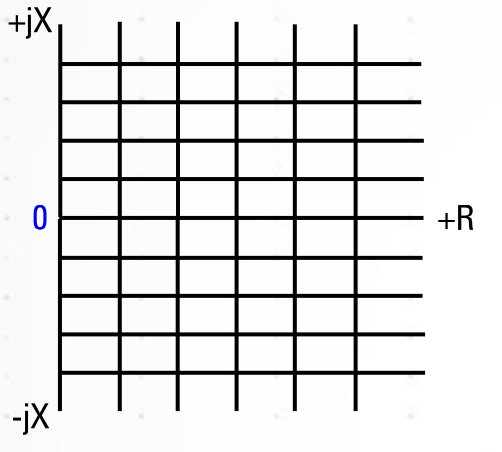
Full reflection (ZL = open, short)

0	ρ	1
$(-)\infty$ dB	**RL**	0 dB
1	**VSWR**	∞

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

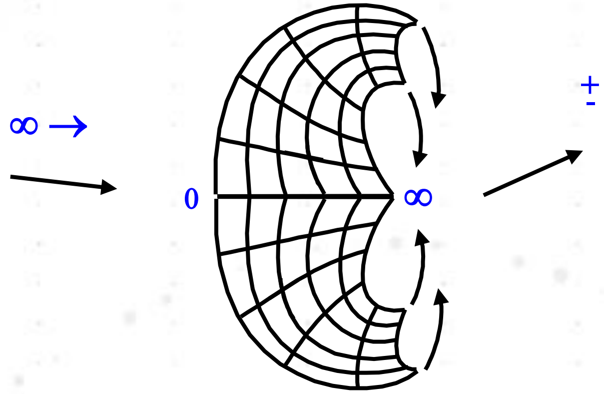
Smith Chart Review

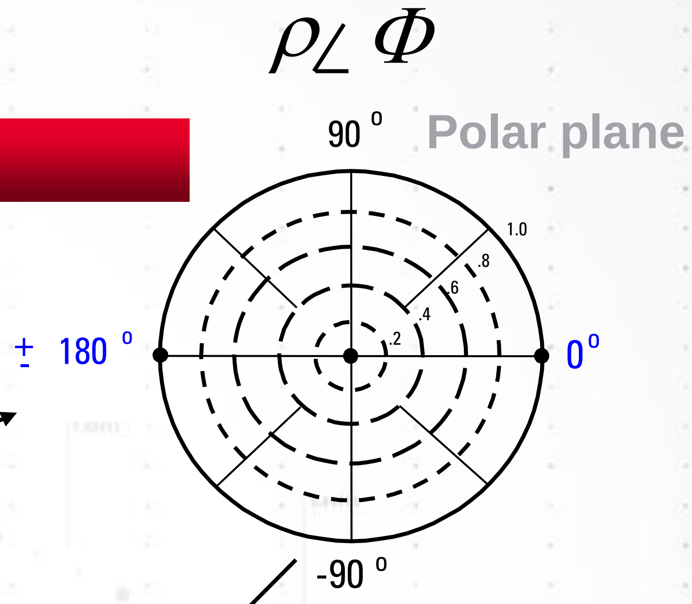
QUICKLY AND EASILY GET IMPEDANCE



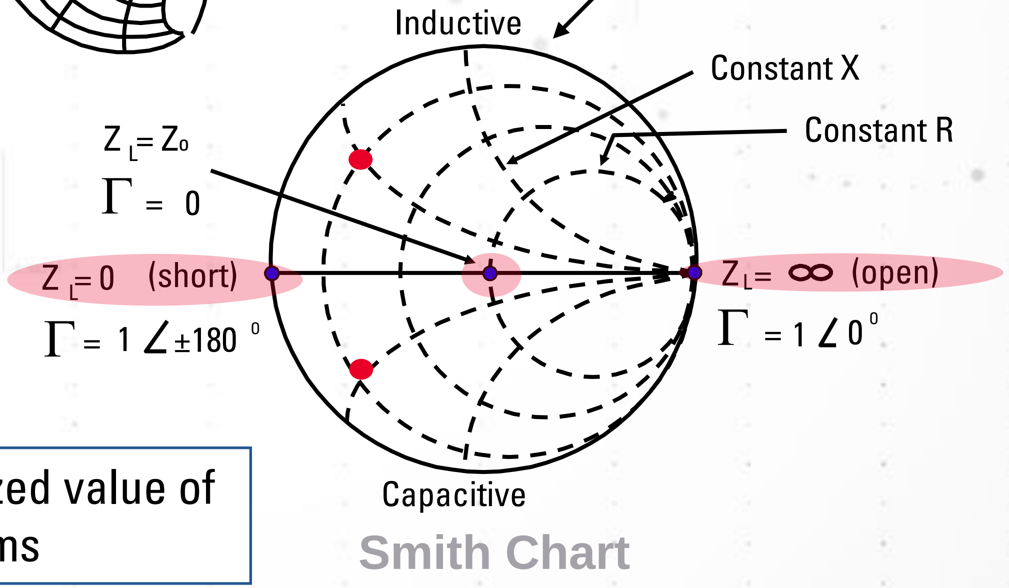
Rectilinear impedance plane

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

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

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

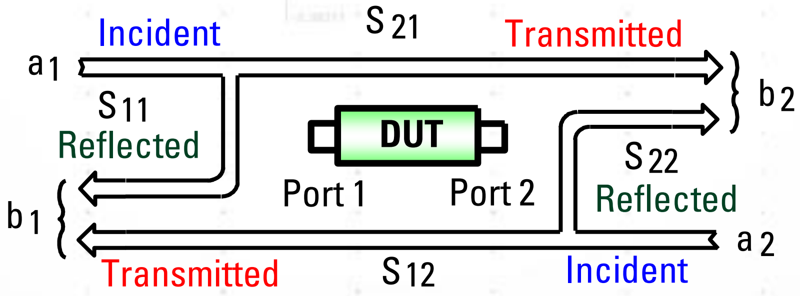
(Impedance)

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

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

Why Use Scattering, S-Parameters?

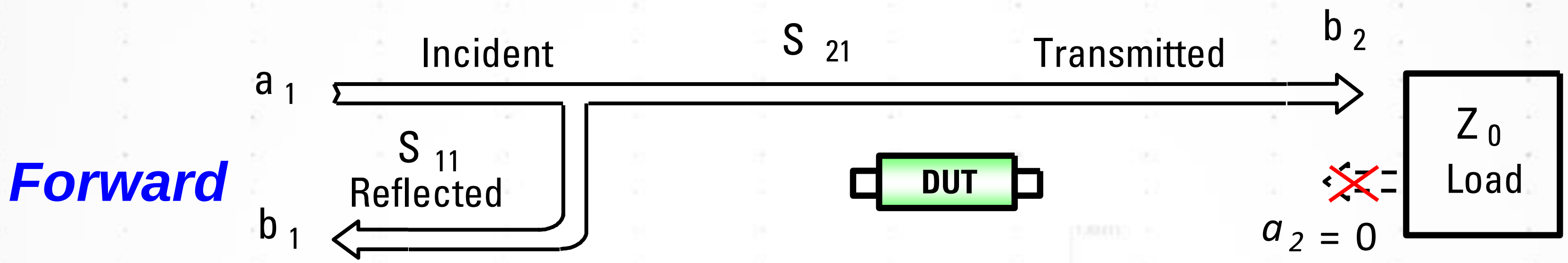
- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade**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

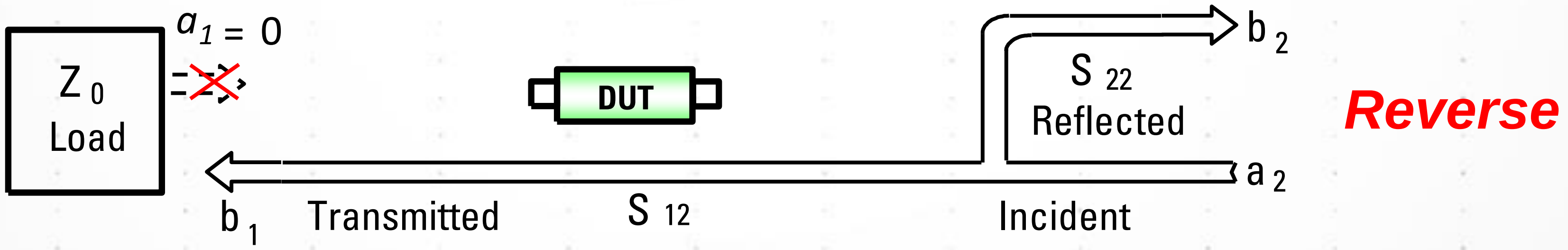


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left. \frac{b_1}{a_1} \right|_{a_2 = 0}$$

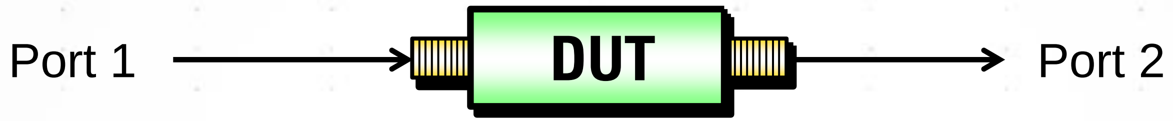
$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left. \frac{b_2}{a_1} \right|_{a_2 = 0}$$

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

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



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)***

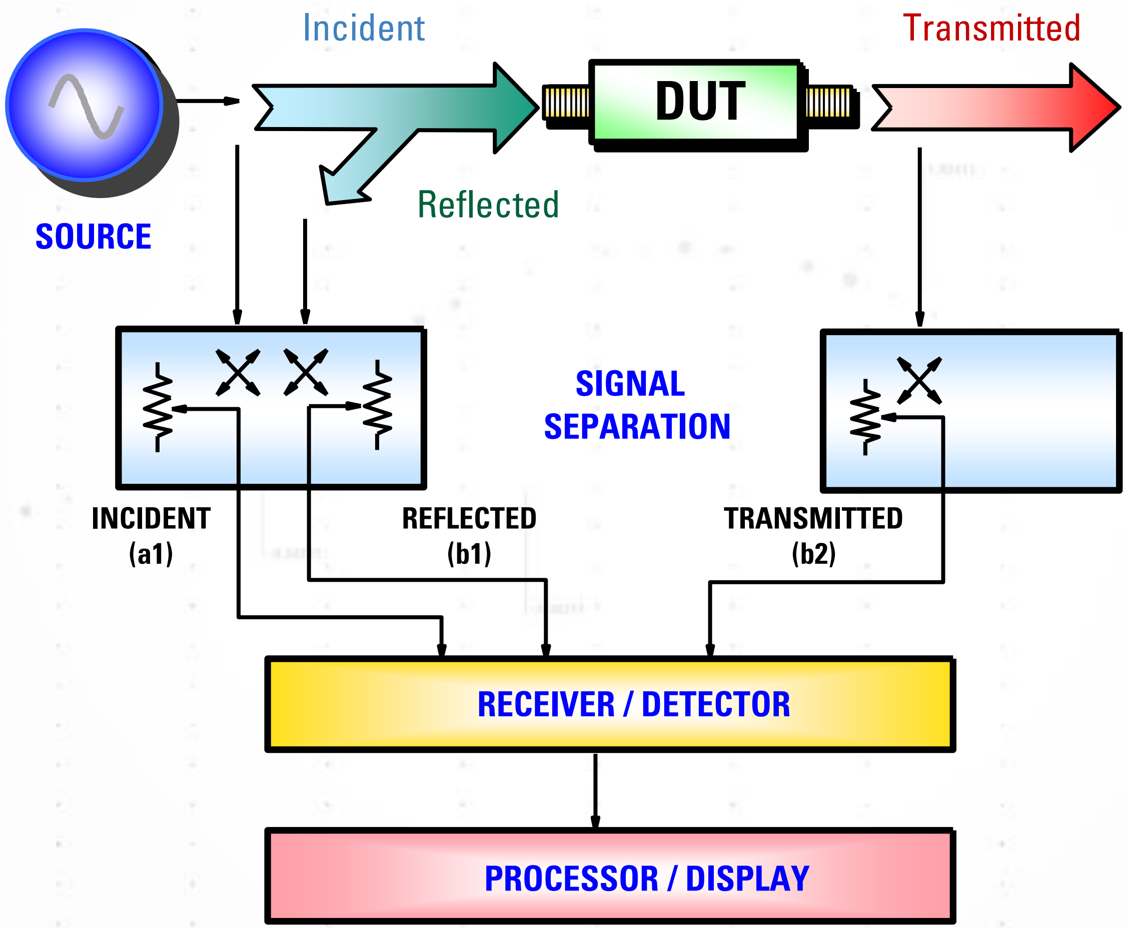
Remember S-parameters are inherently complex, linear quantities – however, we often express them in a log-magnitude format

Agenda

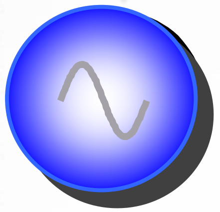
- RF/Microwave Design Challenges
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

Generalized Network Analyzer Block Diagram

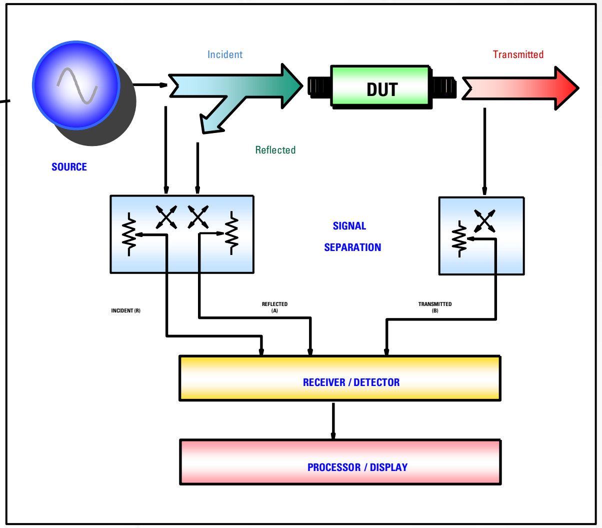
FORWARD MEASUREMENTS SHOWN



Source



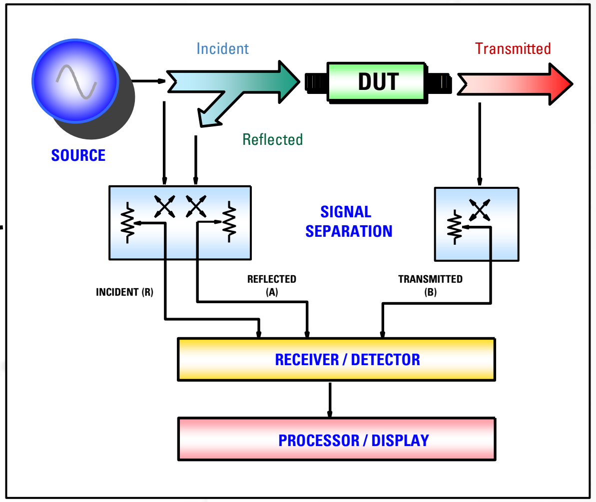
- Source stimulus can sweep frequency or power or phase
- Modern NAs may have the option for a second internal source and/or the ability to control external source
  - Used for driving differential devices
  - Can control an internal or external source as a local oscillator (LO) signal for mixers and converters
  - Useful for mixer measurements like conversion loss, group delay



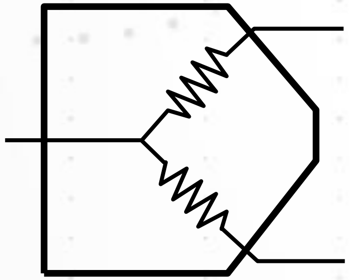
For more information on converter testing:
http://www.keysight.com/upload/cmc_upload/All/PNA_Advances_Converter_Testing.pdf

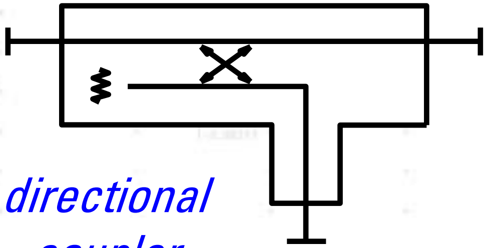
Signal Separation

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

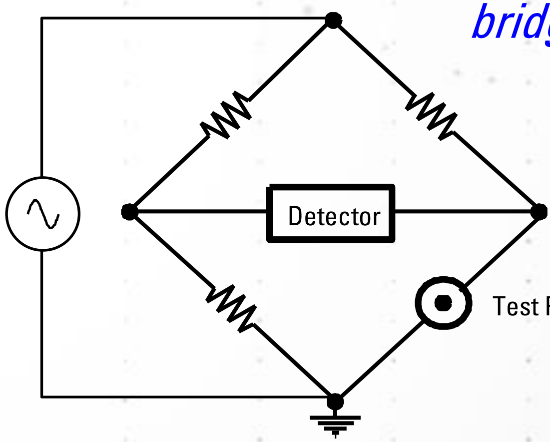


splitter



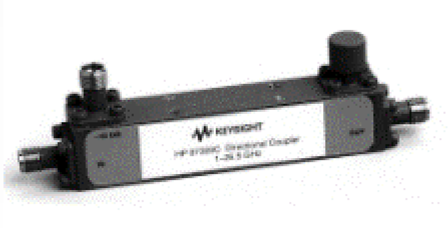


directional coupler

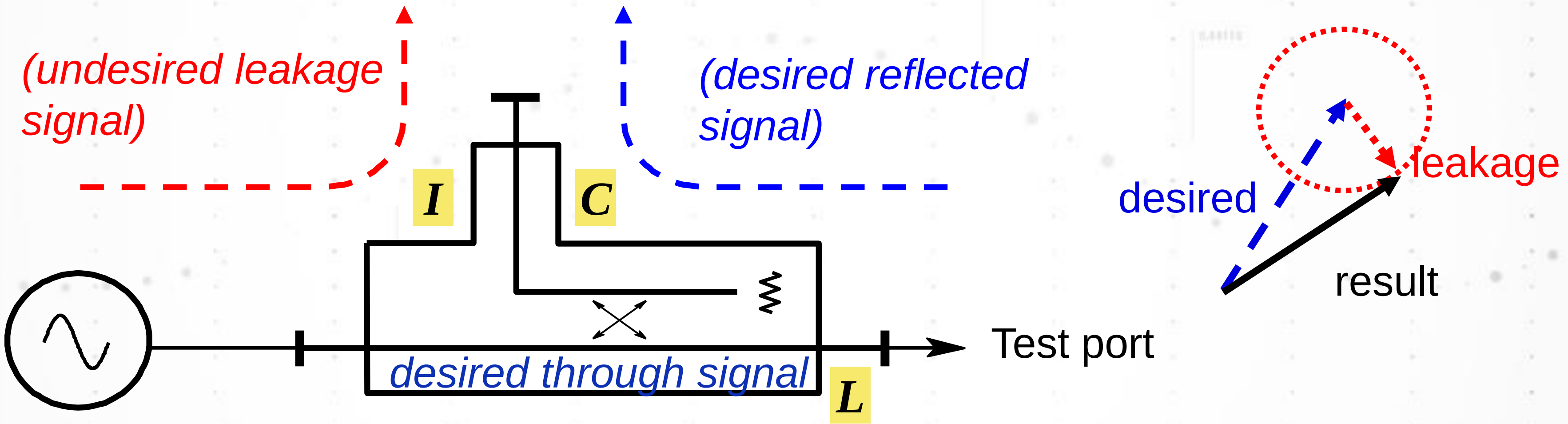


bridge

Directional Coupler & Directivity



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



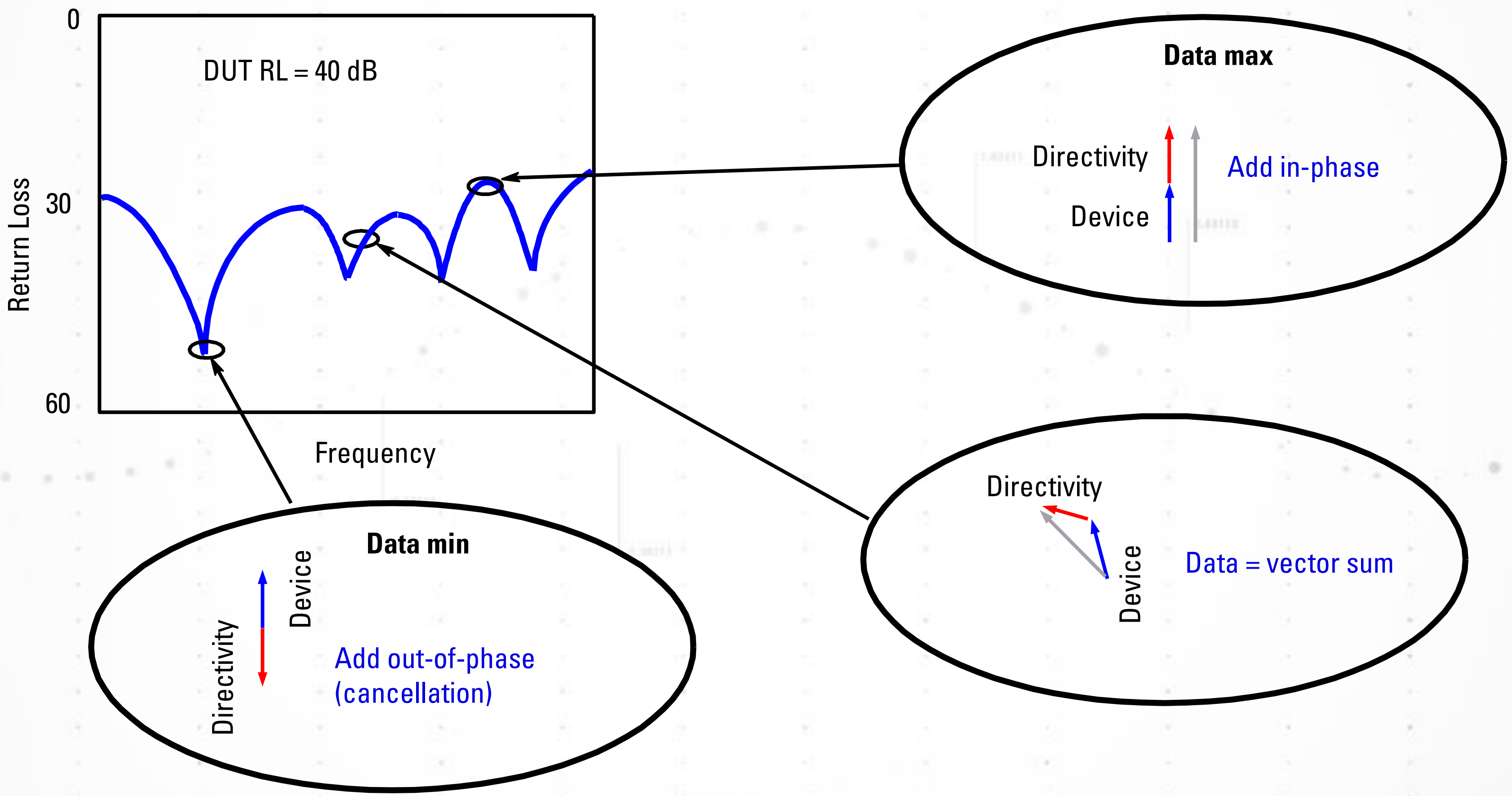
Directional Coupler

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

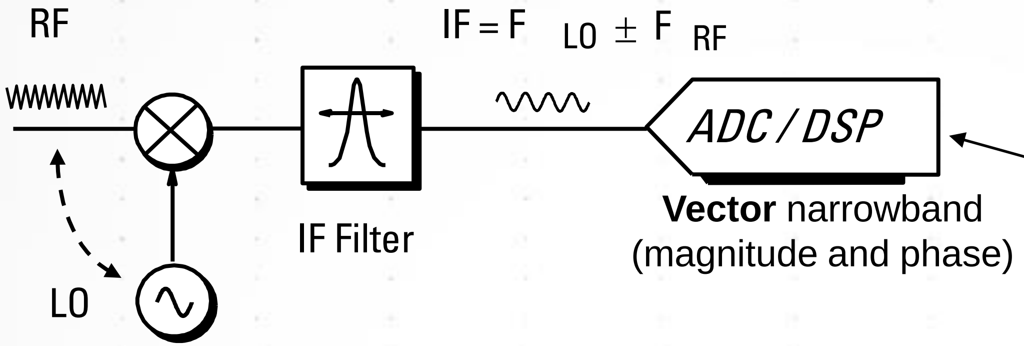
Directivity = 50 dB (I) – 20dB(C) – 1 dB(L) = 29 dB

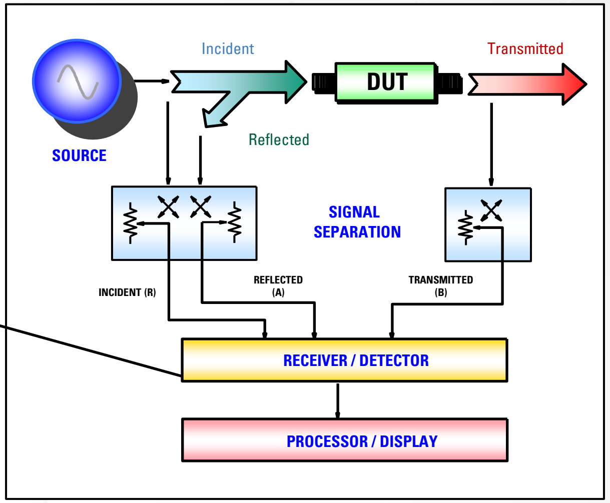
Interaction of Directivity with the DUT

(WITHOUT ERROR CORRECTION)

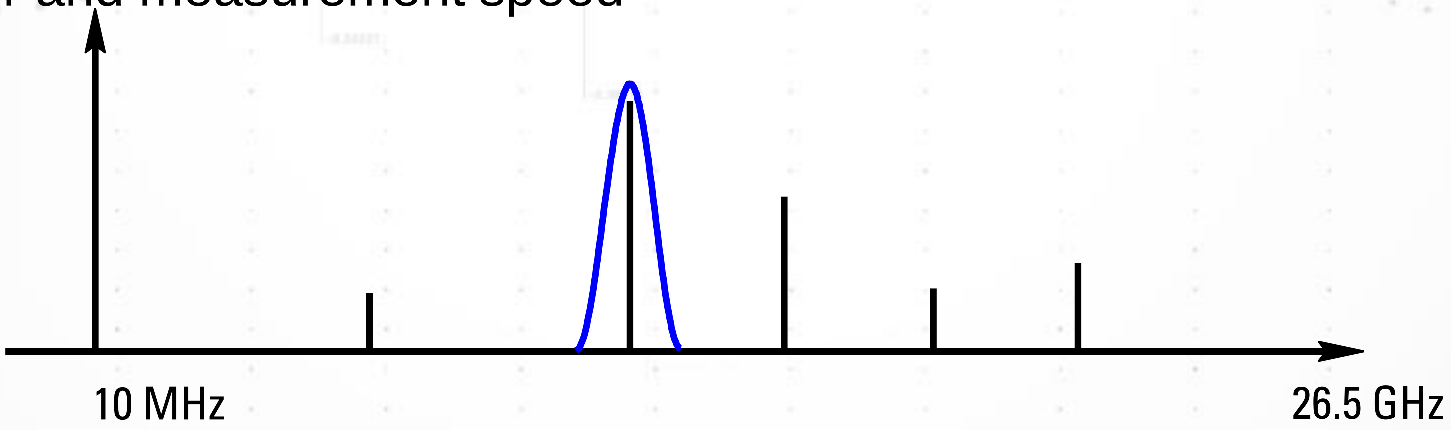


Narrowband Detection - Tuned Receiver



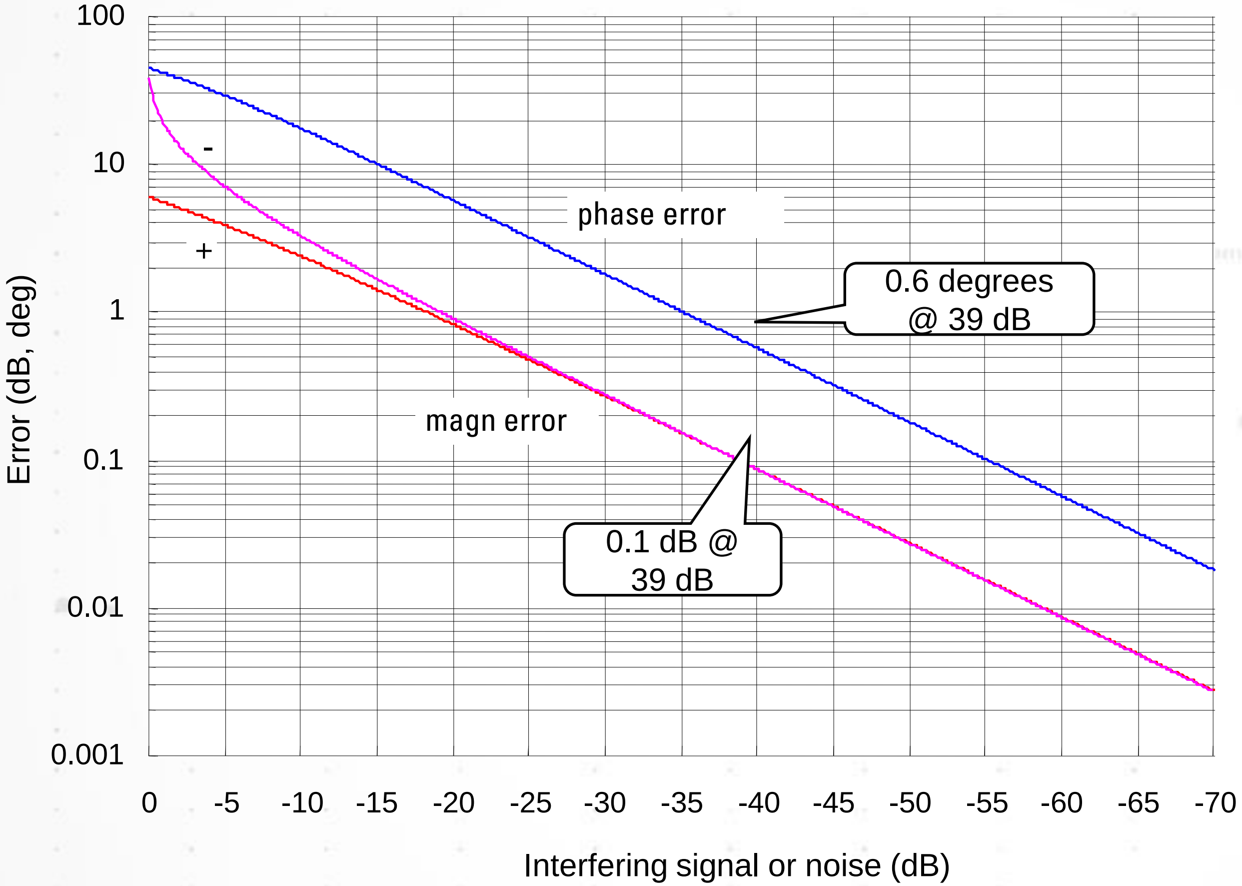


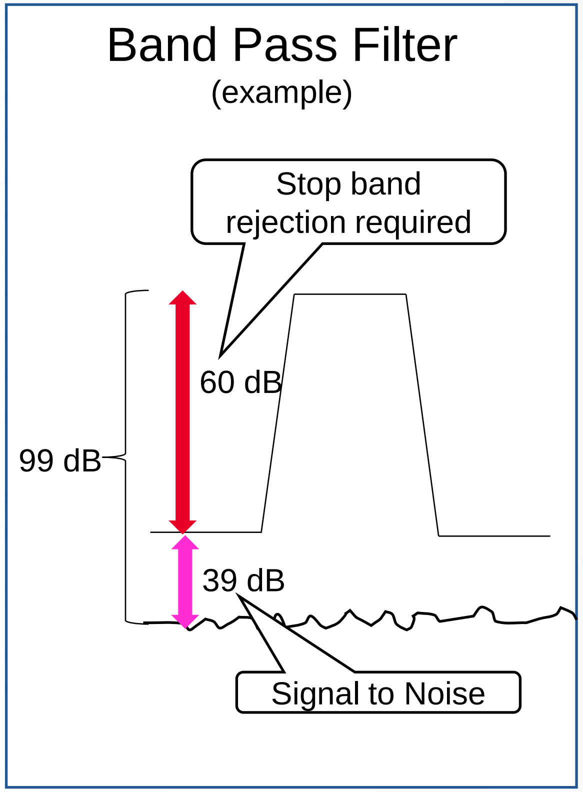
- Best sensitivity / dynamic range
- Provides harmonic / spurious signal rejection
- Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
- Trade off noise floor and measurement speed



Dynamic Range and Accuracy

ERROR DUE TO INTERFERING SIGNAL



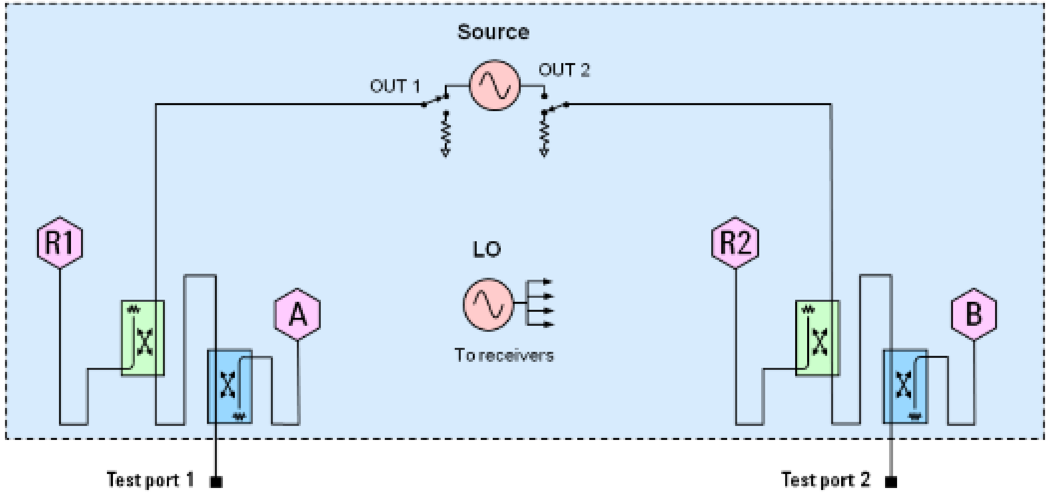


Dynamic range for 0.1 dB accuracy = 60 dB (rejection) + 39 dB (SNR) = 99 dB

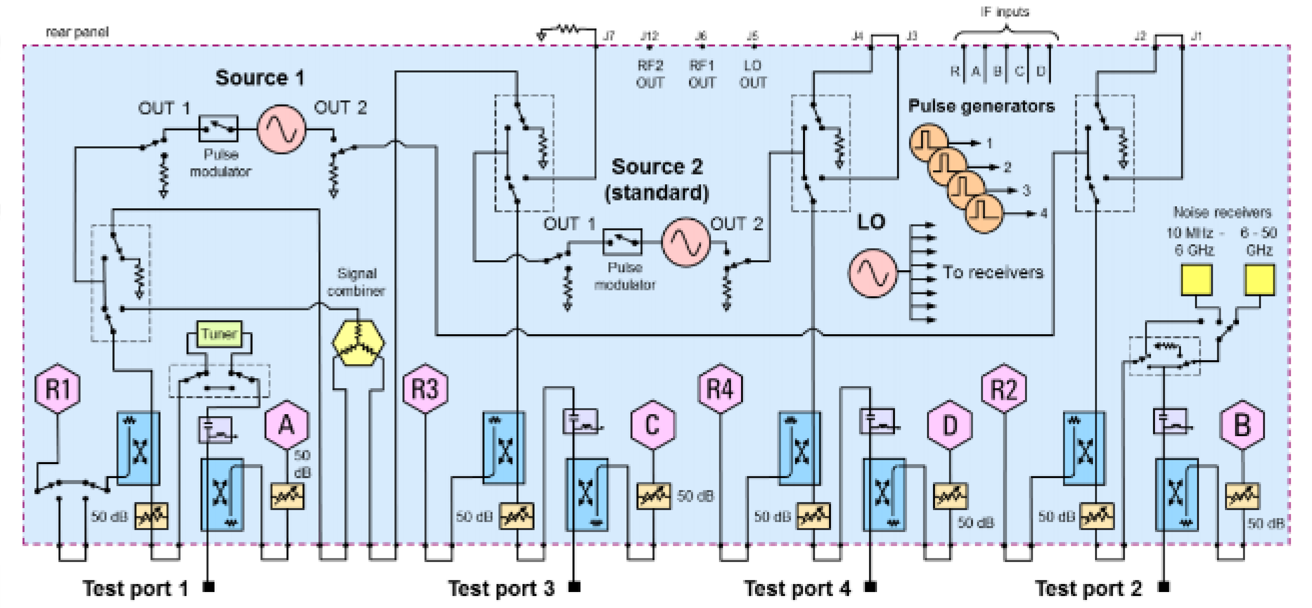
Dynamic range is very important for measurement accuracy!

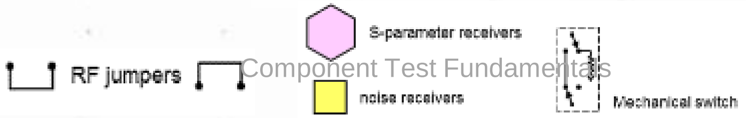
VNA Block Diagram Examples

- **Basic 2 Port**

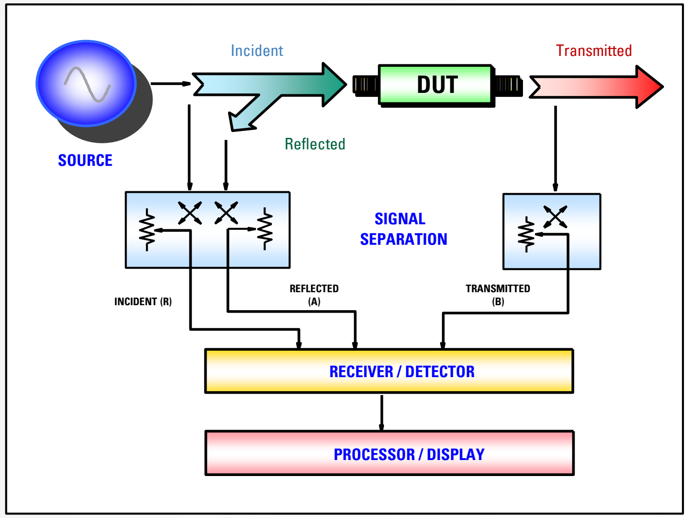


- **Performance 4 Port**
  - Access loops & switches
  - Two sources & combiner
  - Pulse modulation
  - Noise tuner & LNA receiver
  - Attenuators
  - Bias-T's





Processor / Display

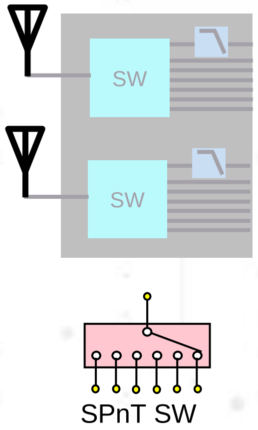


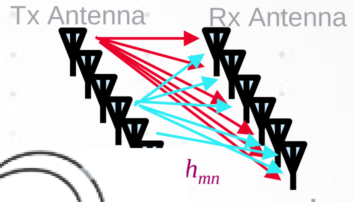
- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math

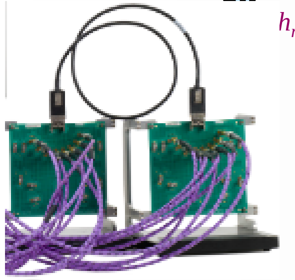
Multiport Measurement Architectures

Application Examples

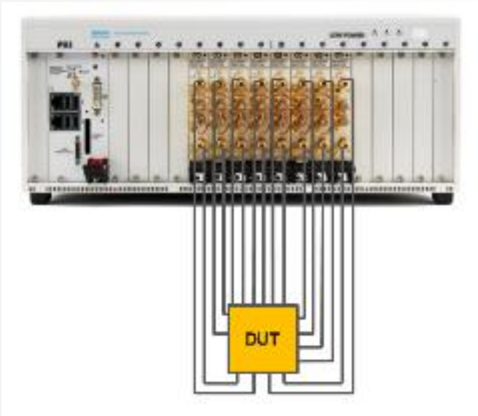
- RF front end modules / antenna switch modules
- Channel measurements of MIMO antennas
- Interconnects (ex. cables, connectors)
- General-purpose multiport devices



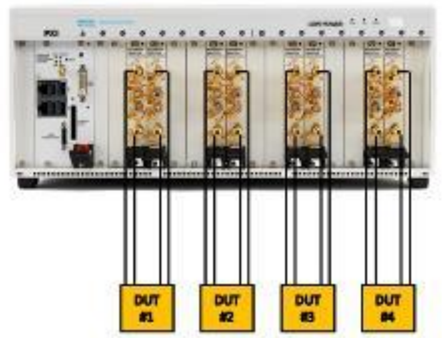




PXI Multiport VNA



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

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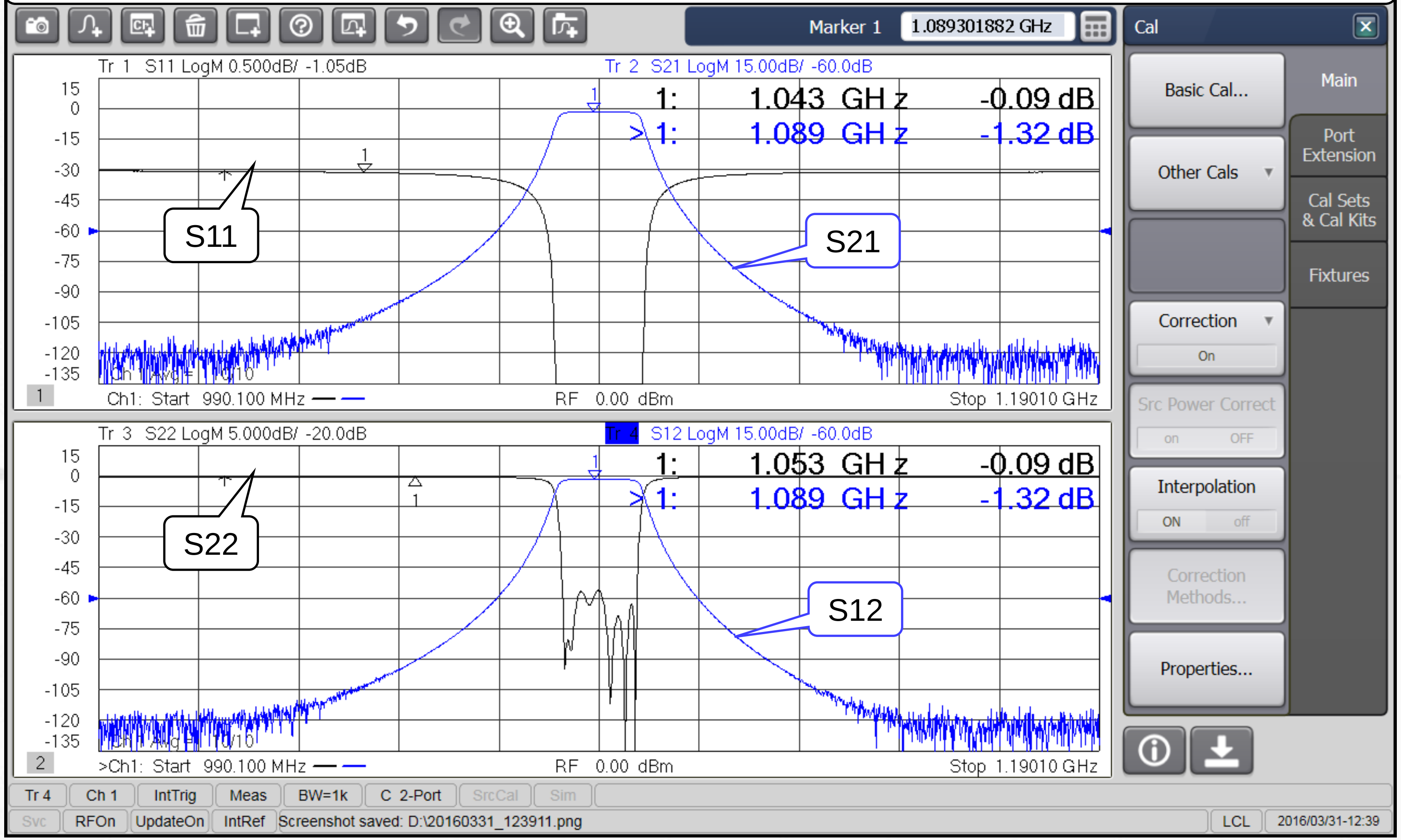
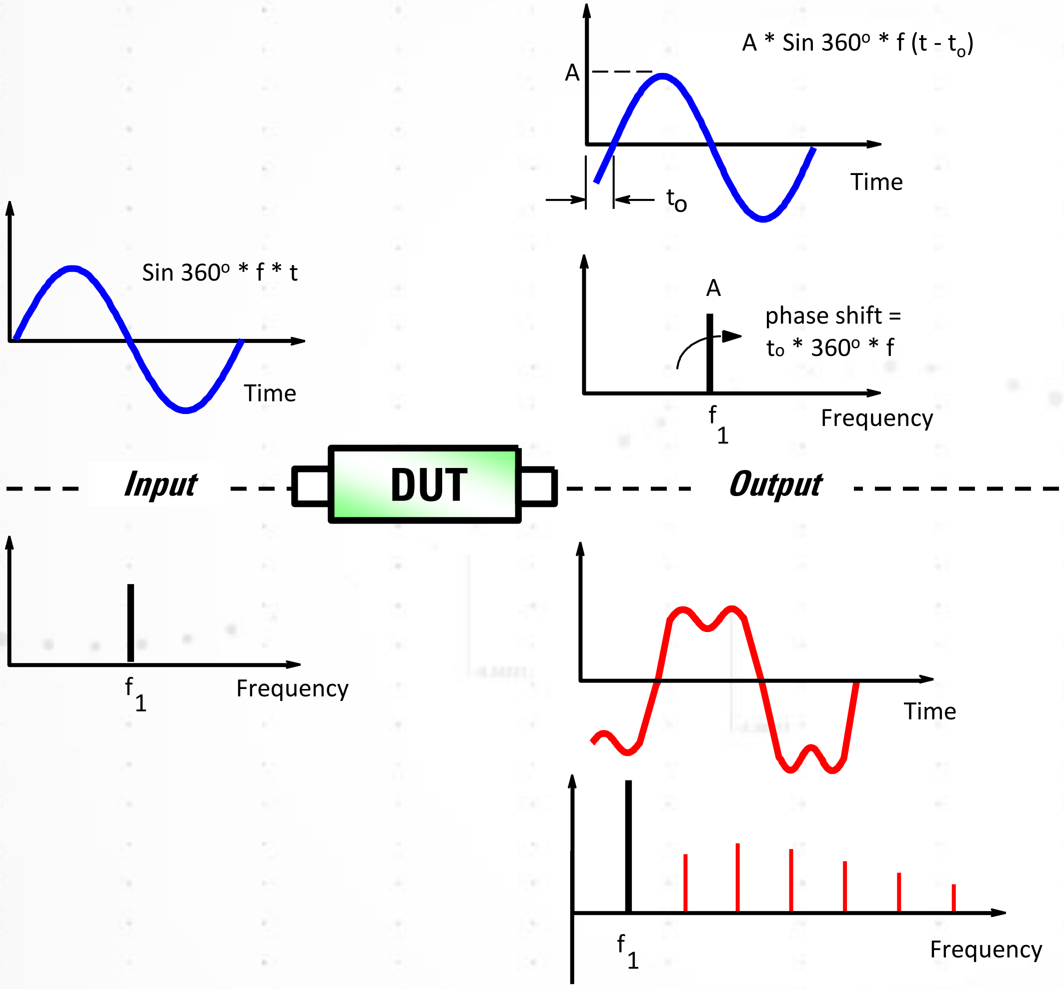
Bandpass Filter four S-Parameters

log magnitude plots of S11, S21, S22, S12



Linear Versus Nonlinear Behavior



Linear behavior:

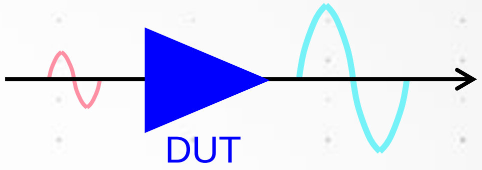
- Input and output frequencies are the same (no additional frequencies created)
- Output frequency only undergoes magnitude and phase change

Nonlinear behavior:

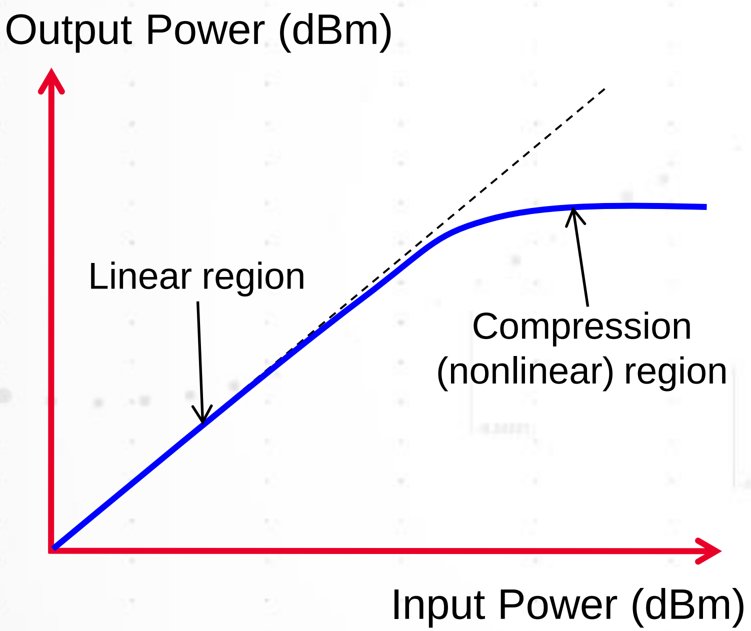
- Output frequency may undergo frequency shift (e.g. with mixers)
- Additional frequencies created (harmonics, intermodulation)

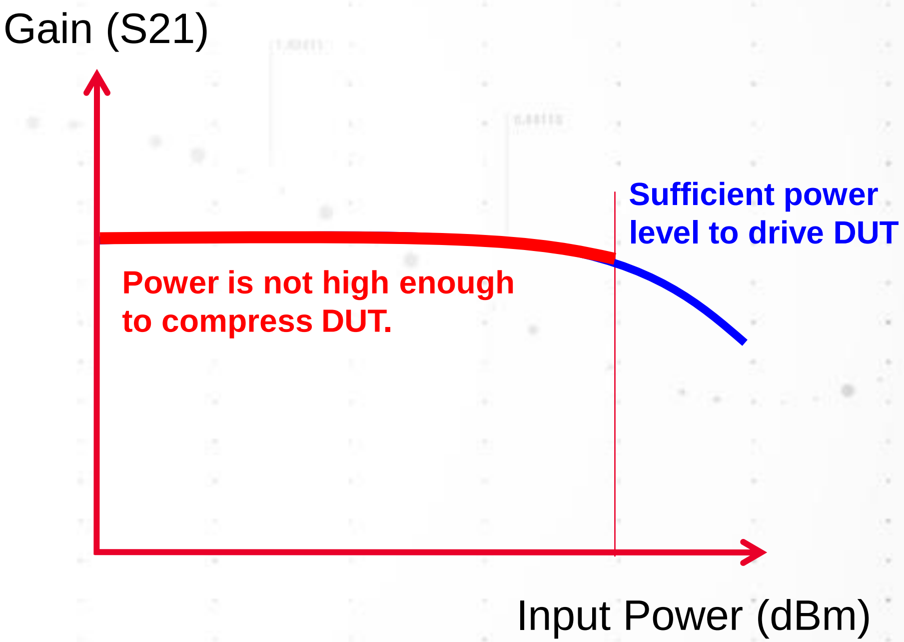
For more information on linear vs. non-linear basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

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.

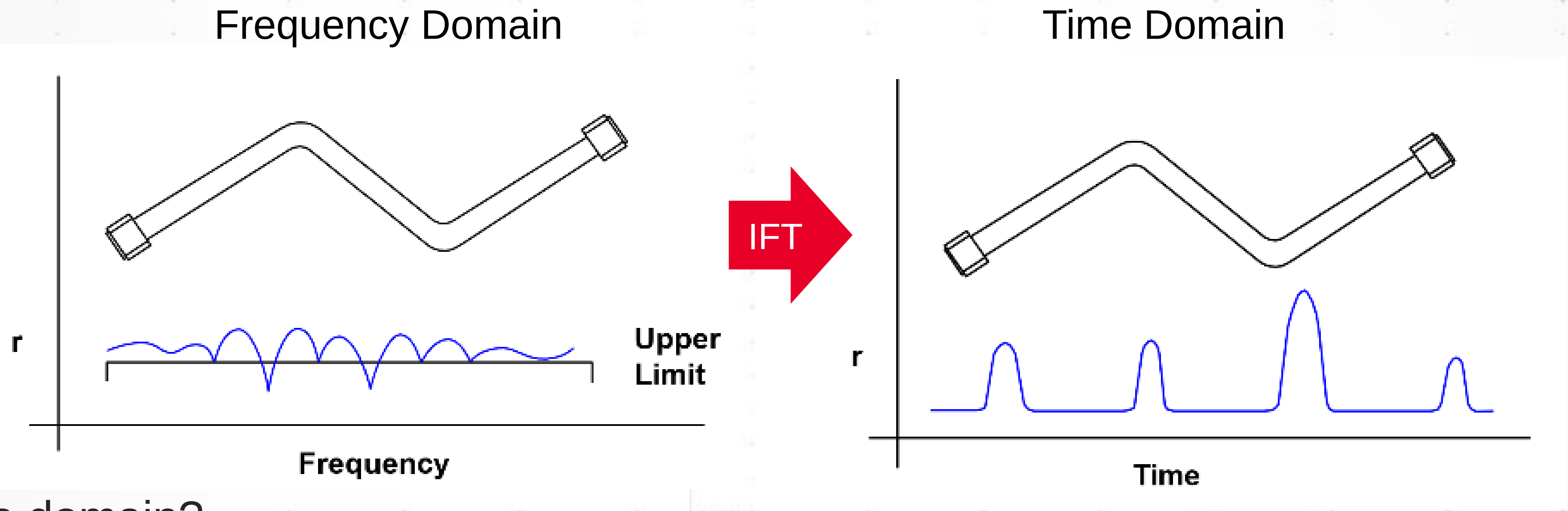




Enough margin of source power capability is needed for analyzers.

Time vs. Frequency Domain

S11 RESPONSE OF SEMIRIGID COAX CABLE



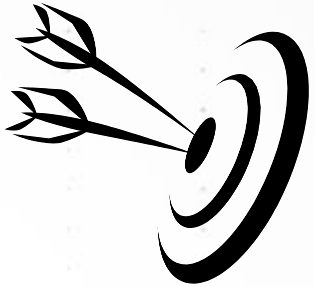
- Why time domain?
  - Locate faults
  - Identify passive or inductive circuit elements
  - Identify and remove unwanted fixture responses
  - And more…

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

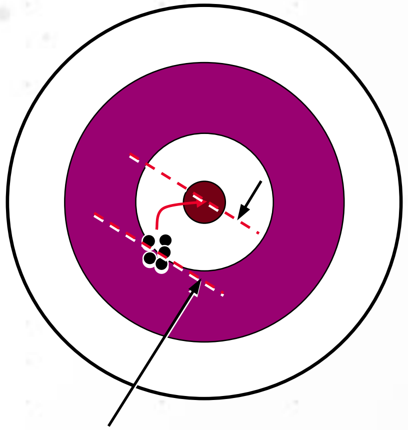
Agenda

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

The Need For Calibration

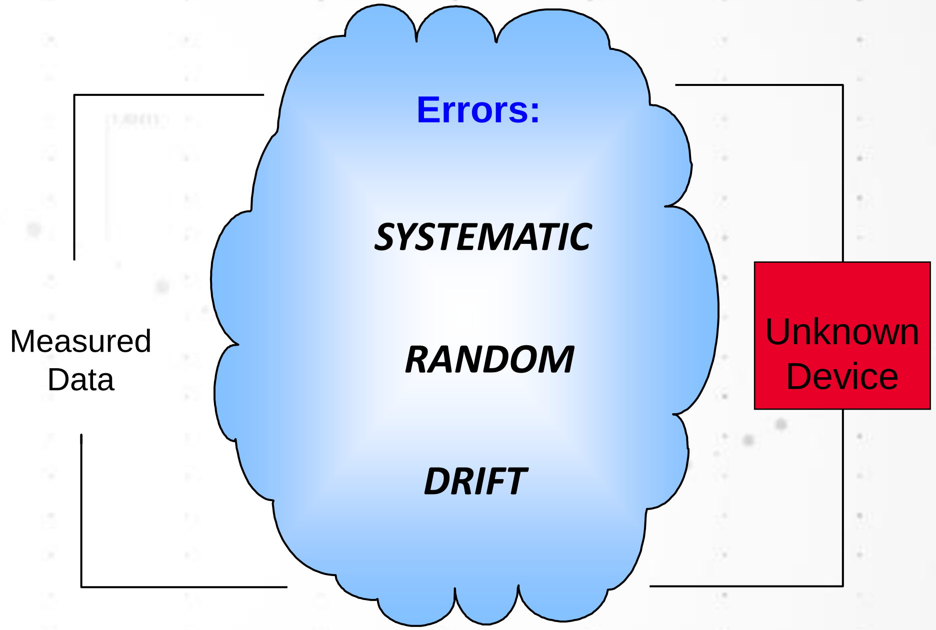


- **Why do we have to calibrate?**
  - It is impossible to make perfect hardware
  - It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction
- **How do we get accuracy?**
  - With vector-error-corrected calibration
  - Not the same 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

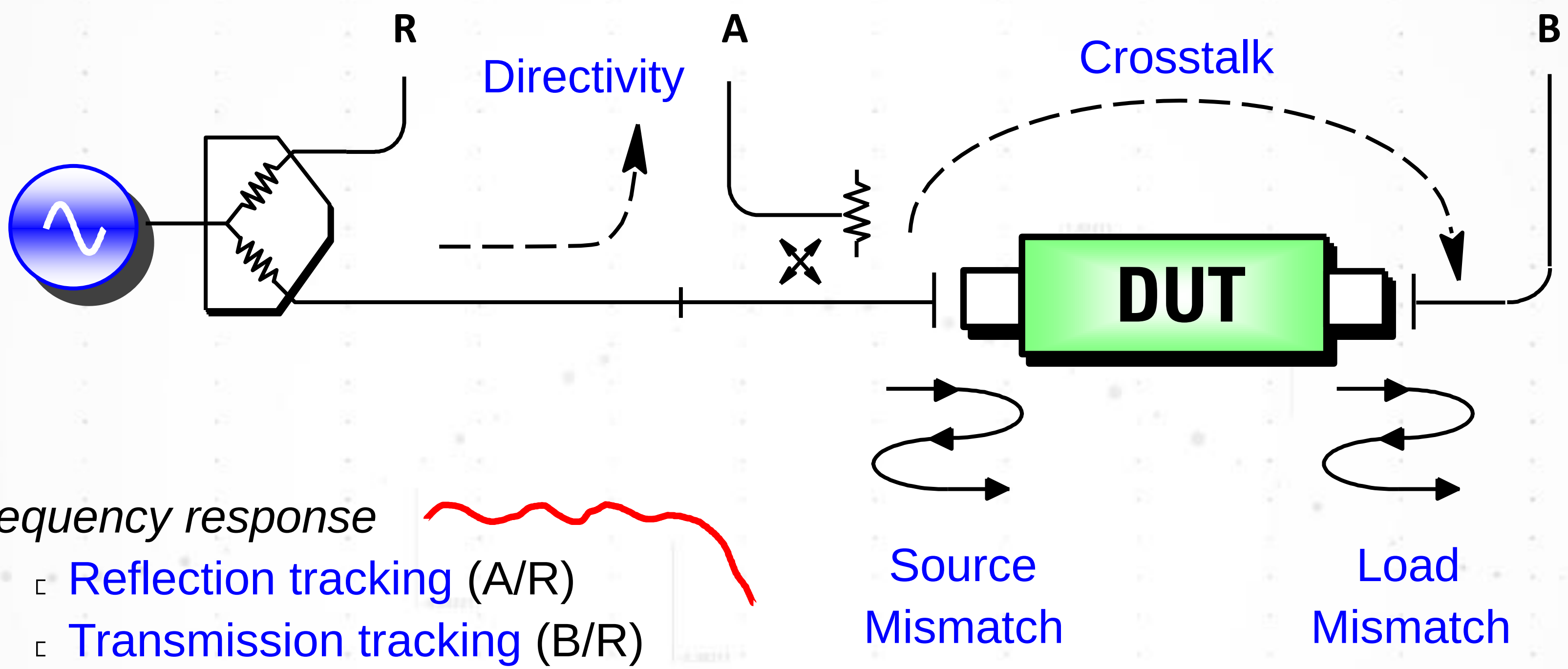


Measurement Error Modeling

- **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



Frequency response

- Reflection tracking (A/R)
- Transmission tracking (B/R)

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

Understanding the Error Terms

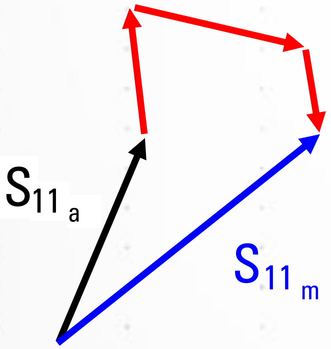
- **Tracking**
  - **Loss in the path**
- **Match**
  - **Input or Output Reflections**
- **Leakage**
  - **Crosstalk or Directivity**

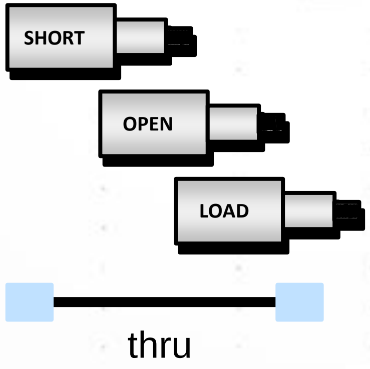
Measurement\Error	Tracking Response	Mismatch	Leakage
Input Reflection	ERF	ESF	EDF
Forward Transmission	ETF	ELF	EXF
Reverse Transmission	ETR	ELR	EXR
Output Reflection	ERR	ESR	EDF

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

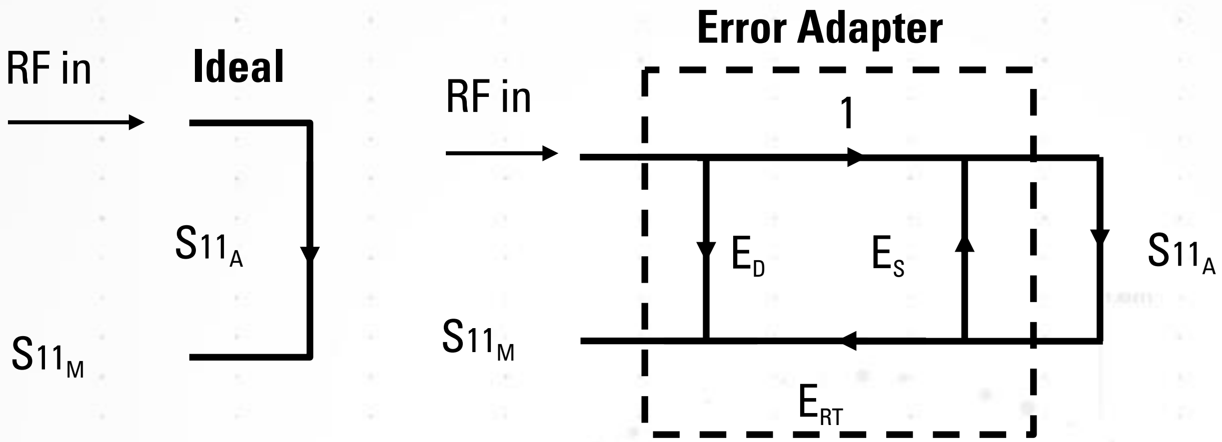
- **Vector**
  - Requires more calibration standards
  - Requires an analyzer that can measure phase
  - Accounts for all major sources of systematic error





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

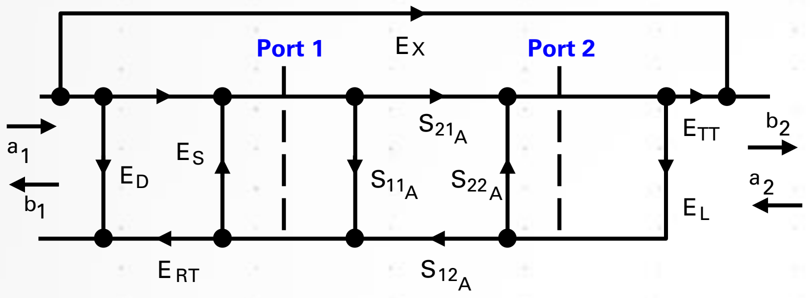
- To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

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

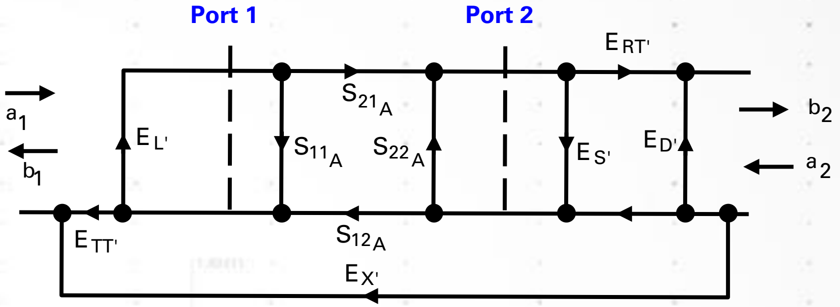
  - Assumes good termination at port two if testing two-port devices
  - If using port two of NA *and* DUT reverse isolation is low (e.g., filter passband):
    - Assumption of good termination is not valid
    - Two-port error correction yields better results

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

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

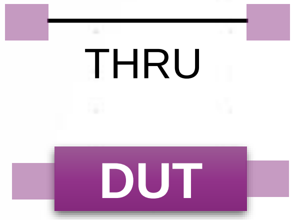
Significance of Calibration

TYPES OF CALIBRATION

UNCORRECTED

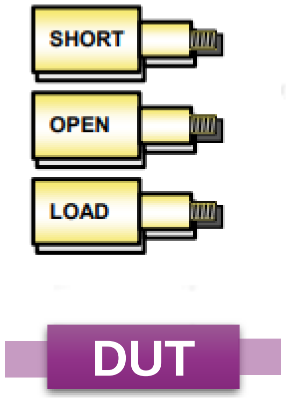
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



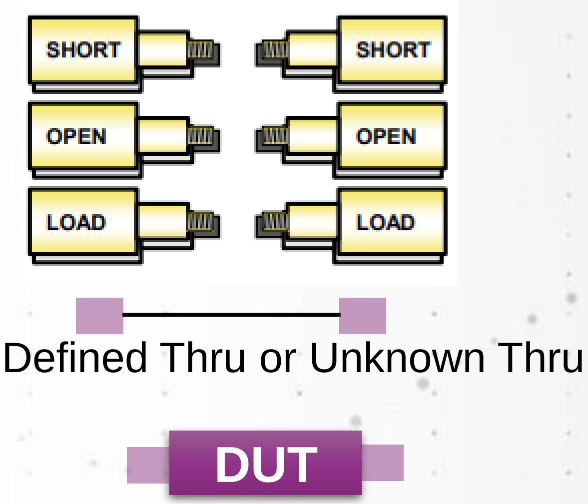
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

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



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

ENHANCED RESPONSE

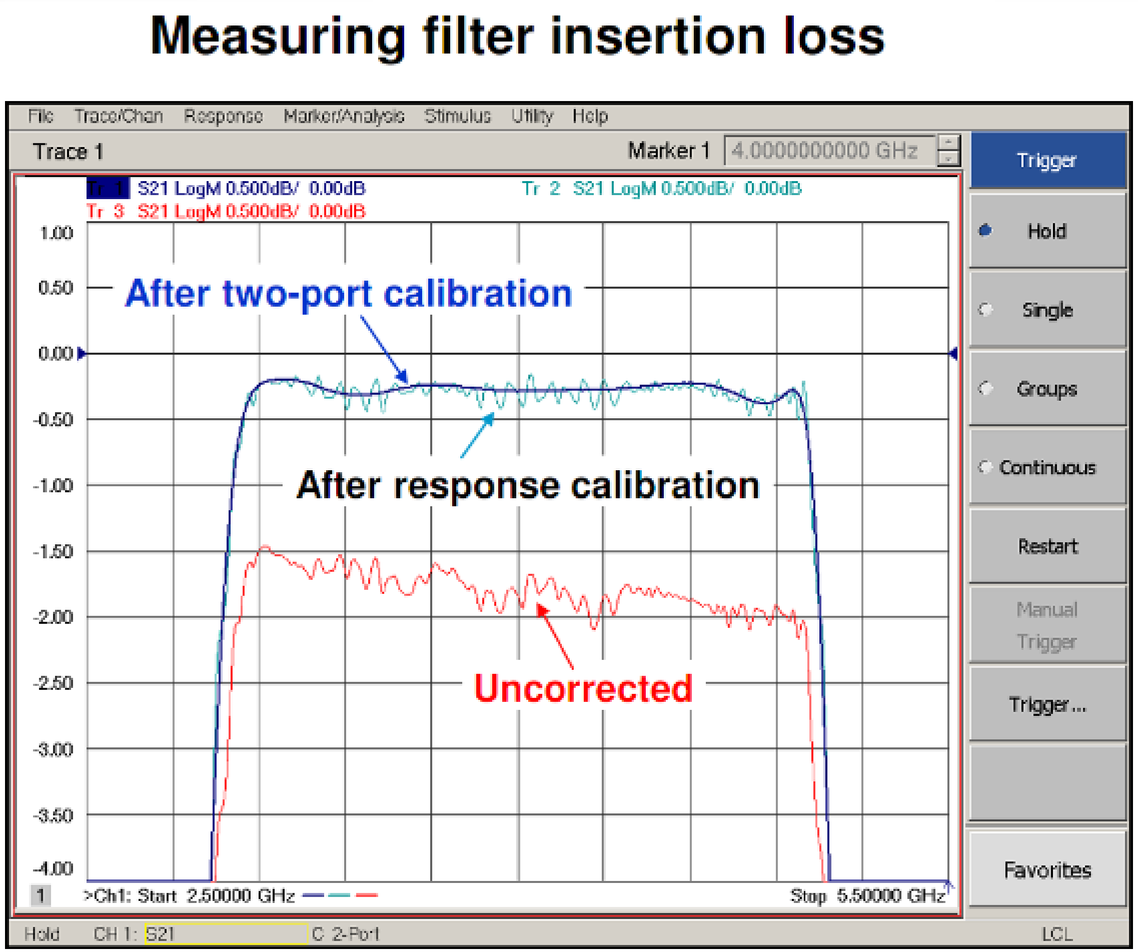
- Combines response and 1-port
- Corrects source match for transmission measurements

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



Agenda

- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction
- **Bonus Topic: Software Defined Instruments and Active Device Measurements**

What is a Software Defined Instrument (SDI)?

- **Flexible RF Hardware**
  - Multiple Broadband Sources
    - High Power, Low Harmonics
    - Phase Controlled
    - Internally Combined
  - **Multiple, Wideband, High Dynamic Range Receivers**
    - Coherent conversion between channels
    - Highly Linear response.
  - **Hardware can be Reconfigured for Optimum RF Performance**
    - Internally Switched Combiner
    - Switched Rear-Panel Access to RF Ports
    - RF “Loops” to Support High-Power or Low Noise

What SDI was introduced: Summer, 2007?

AND WHO INTRODUCED IT?

PNA-X: Summer, 2007

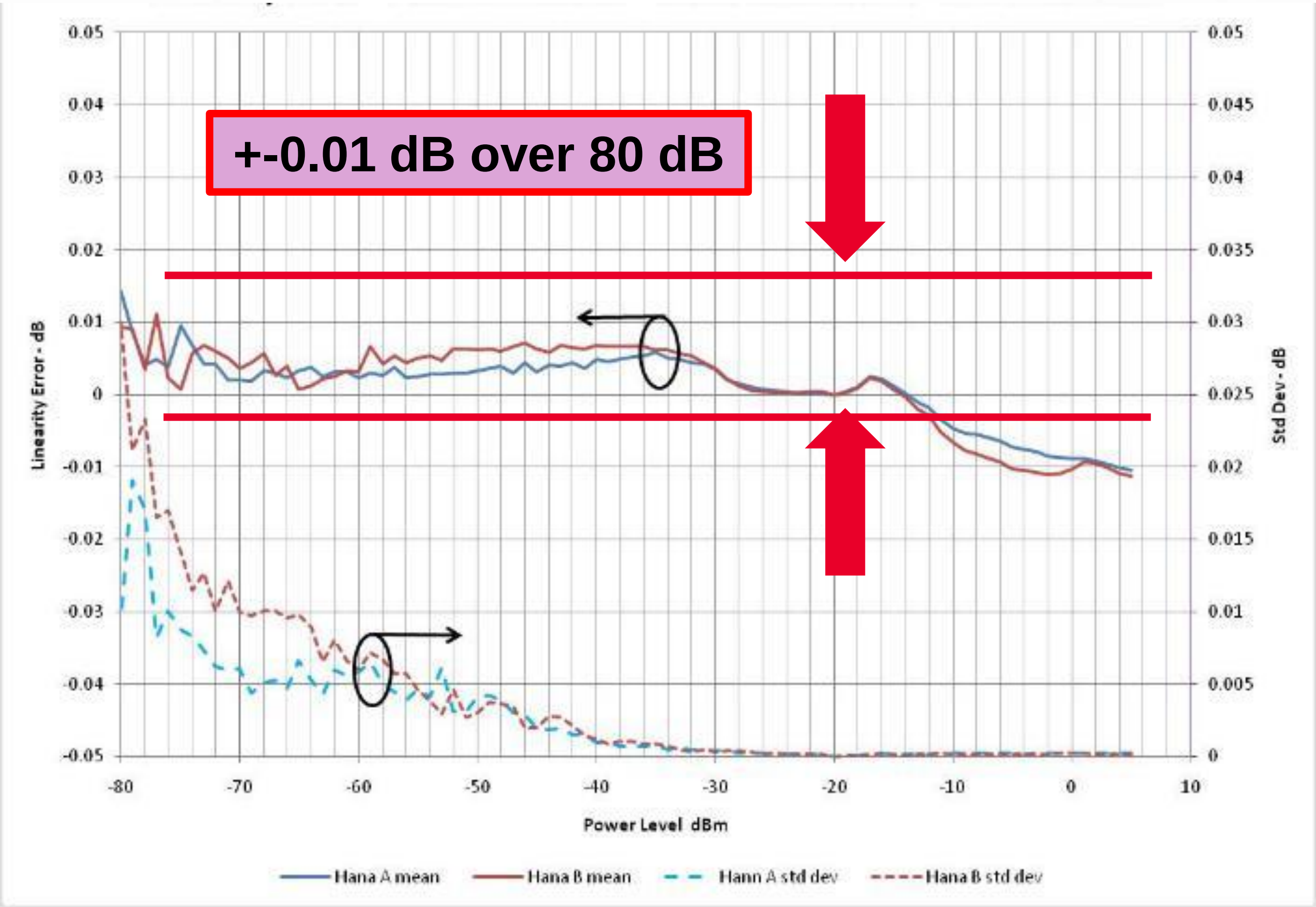
Iphone: June 29, 2007

What is a Software Defined Instrument?

- Flexible IF capability
  - Fully Digital IF with flexible IF path configurations
    - Wideband and Narrowband Detection
    - Optimized Analog Gain and Bandwidth
    - Fully Calibrated IF Response (Gain and Phase)
- Flexible Signal Processing
  - Allow linking customer data process blocks
    - Matlab compiled dll
- Flexible User Interface
  - Modify the UI elements to make sense for the applications

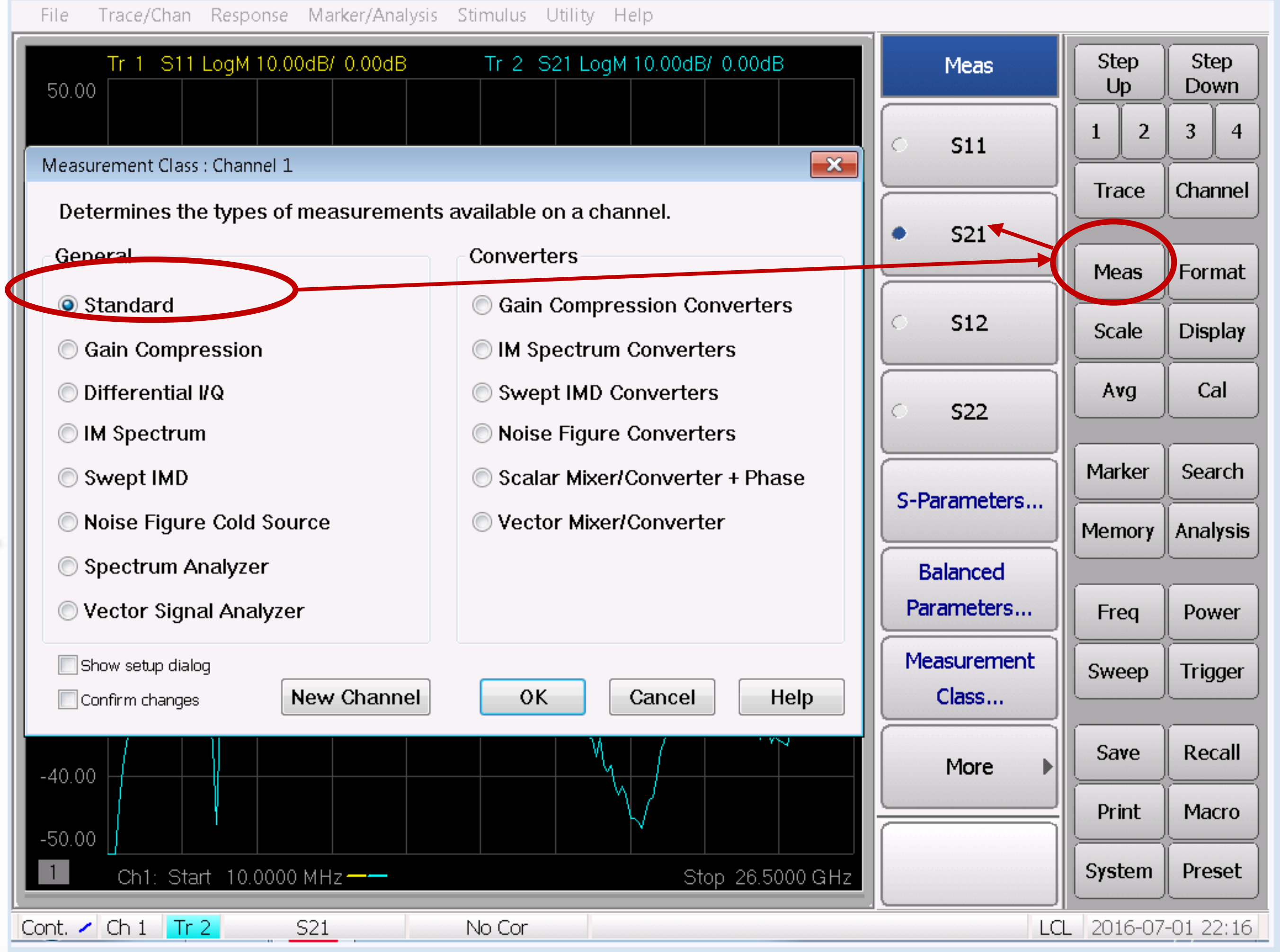
PNA-X receiver linearity: Most accurate receiver in the world!

KEY TO S-PARAMETERS, IMD, SPURIOUS, NPR …



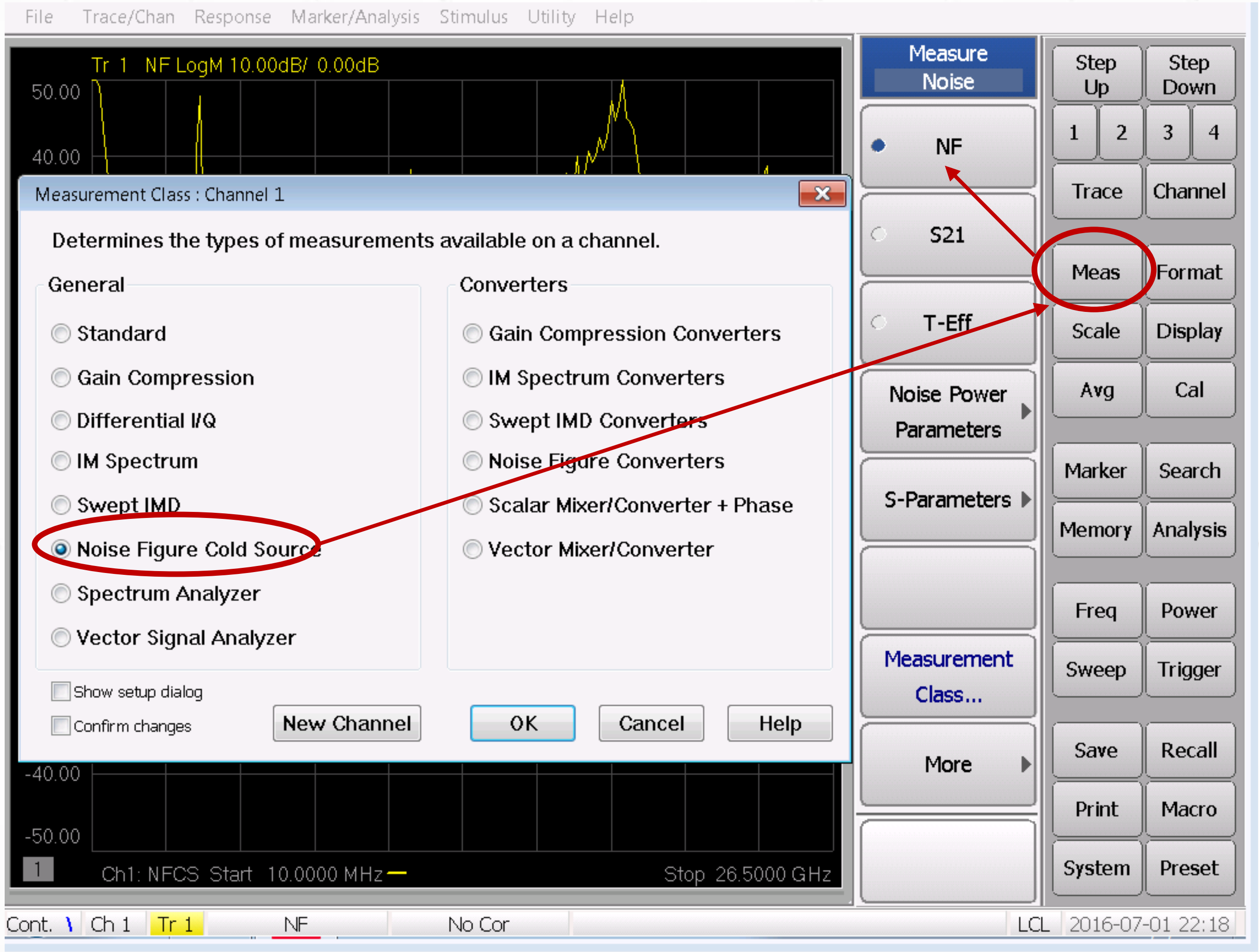
User Interface Changes:

FOR A STANDARD, THE MEASUREMENTS ARE "S-PARAMETER"



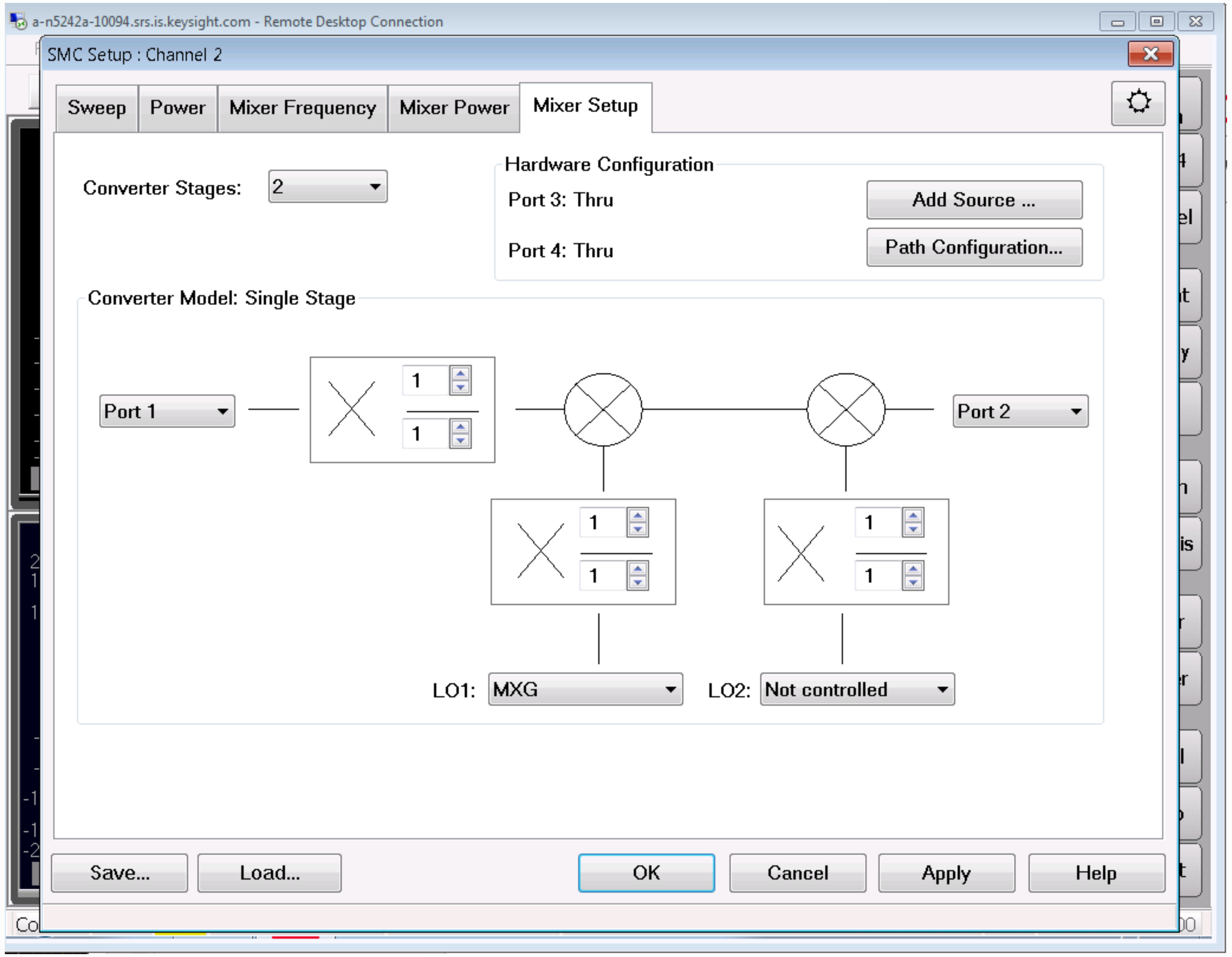
User Interface Changes:

FOR NOISE FIGURE ANALYZER, SHOW NF, NOISE PARAMETERS



Mixer Measurement is simplified with UI

SUPPORTS SINGLE AND DUAL STAGE CONVERTERS.



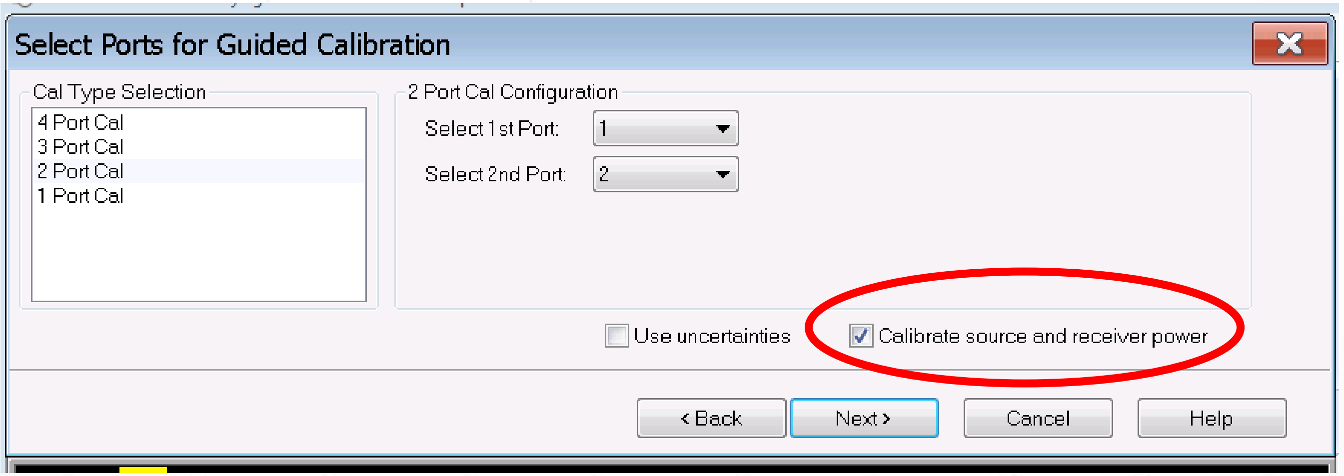
Synergy --

TOTAL IS GREATER THAN THE SUM OF THE PARTS

- Combine a VNA with a Power Meter
  - Match Corrected Source Power
    - better than a stand-alone Signal Generator
- Two Sources with Multi-Channel VNA
  - Swept Frequency, Swept Power IMD
  - Automatic Power Correction and Leveling at Input or Output
- Noise Figure Analyzer with VNA
  - Vector Corrected Noise Figure Measurements
  - Automatic Generation of Noise Parameters

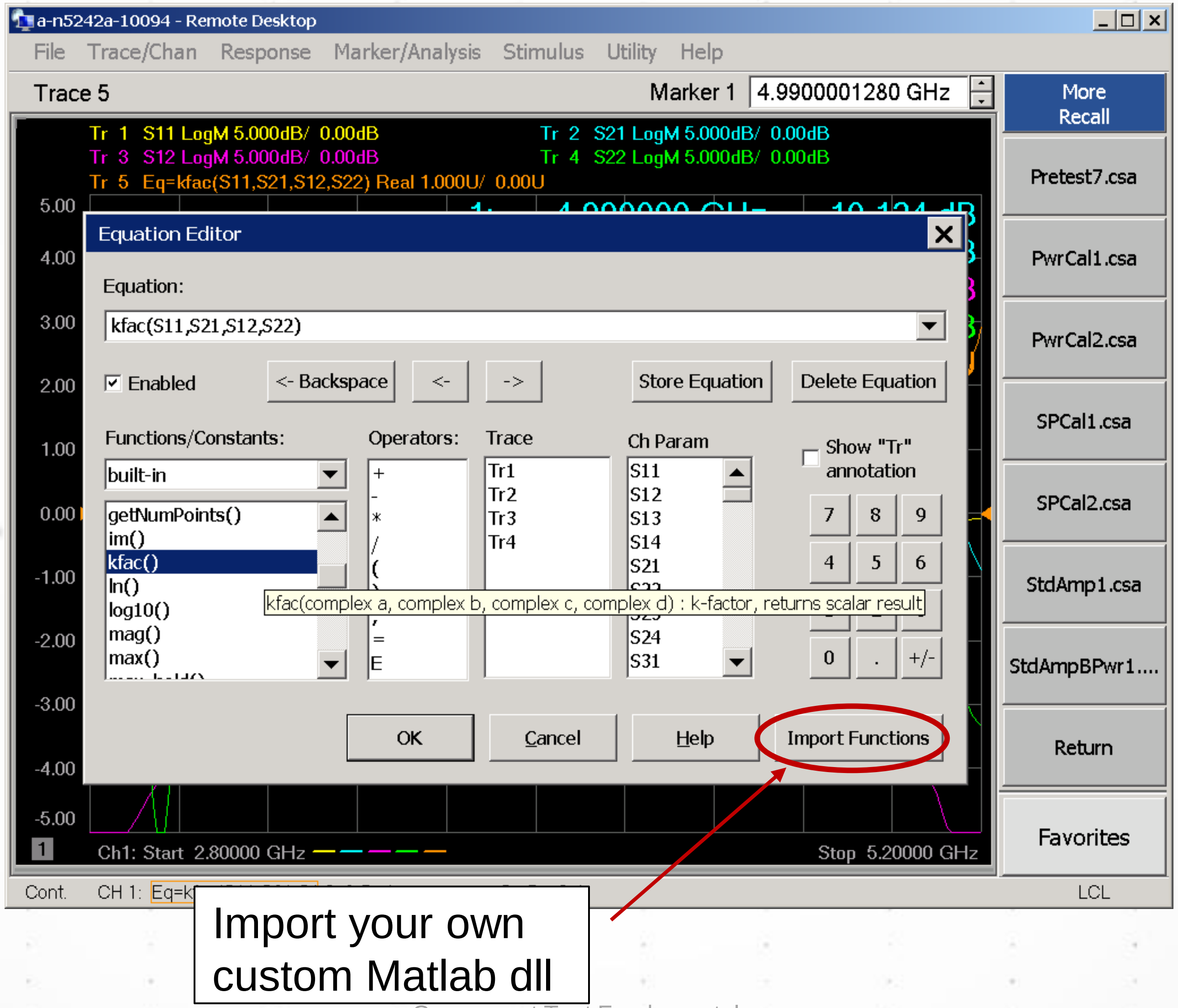
Modern firmware creates the first ever combination power and S-parameter cal

- Power calibration integrated with the S-parameter calibration wizard
- Full compensation for mismatch of the power sensor
- Only requires the power sensor on ***ONE*** port for complete power calibration of all sources on all S-parameter measurements
- Fully removes any adapter effect between the test port and the power sensor
- Allows for complete calibration of power for on-wafer or in-fixture meas.



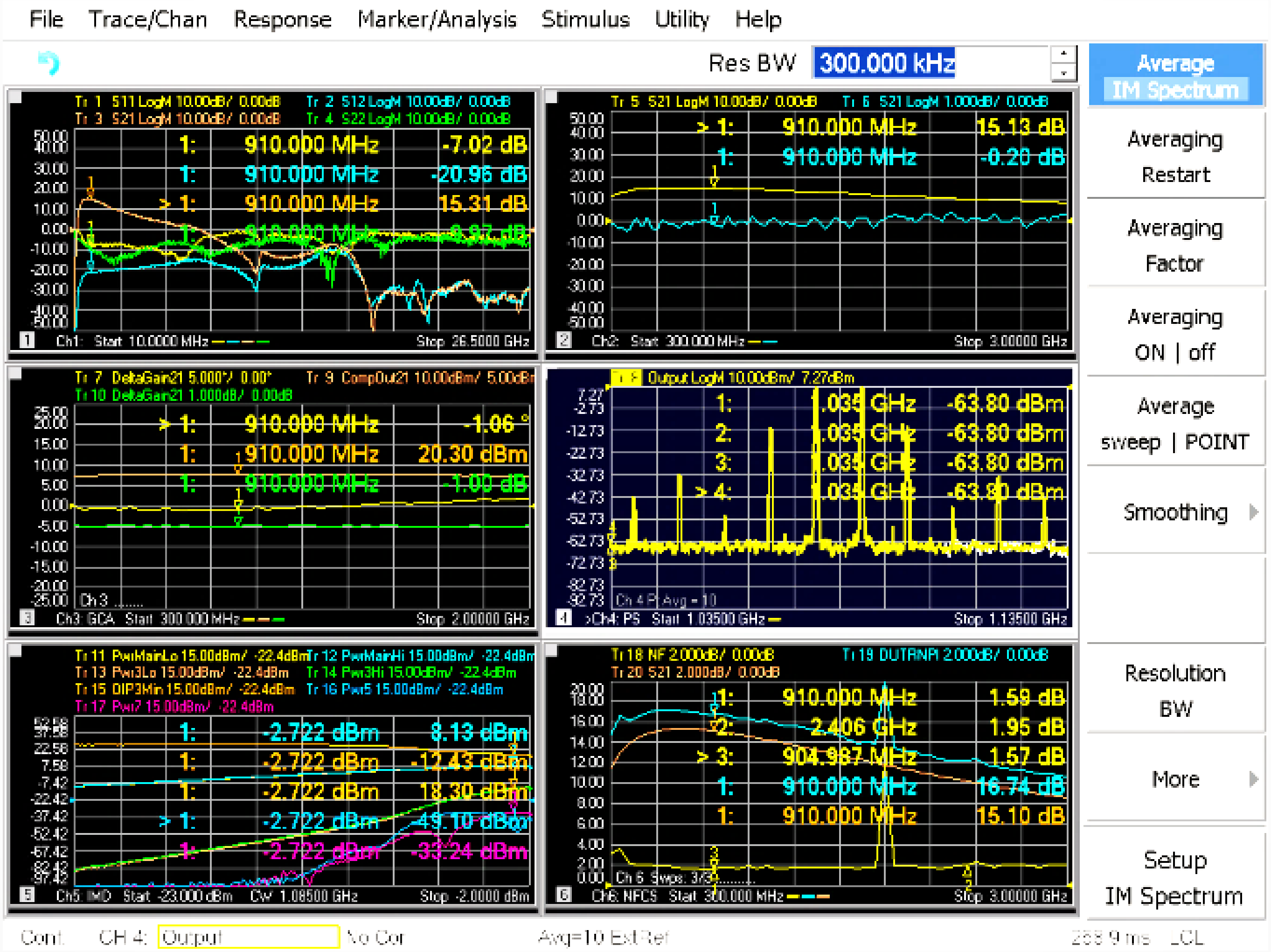
Measuring the Amplifier: Beyond S-parameters

SHOW STABILITY K-FACTOR USING THE EQUATION EDITOR FUNCTION



SDI VNA: More than just S-parameters

POWER, GAIN COMPRESSION, TWO TONE IMD, AND NOISE FIGURE



Combine VNA with DC Meters (SMU)

SOURCE MEASURE UNITS GIVE HIGH SPEED AND ACCURACY

- ✓ Complete control over all DC parameters
- ✓ PNA-X sweeps DC meters and SMUs
- ✓ Single user interface
- ✓ Repeatable, traceable measurements
- ✓ Open interface enables user customization

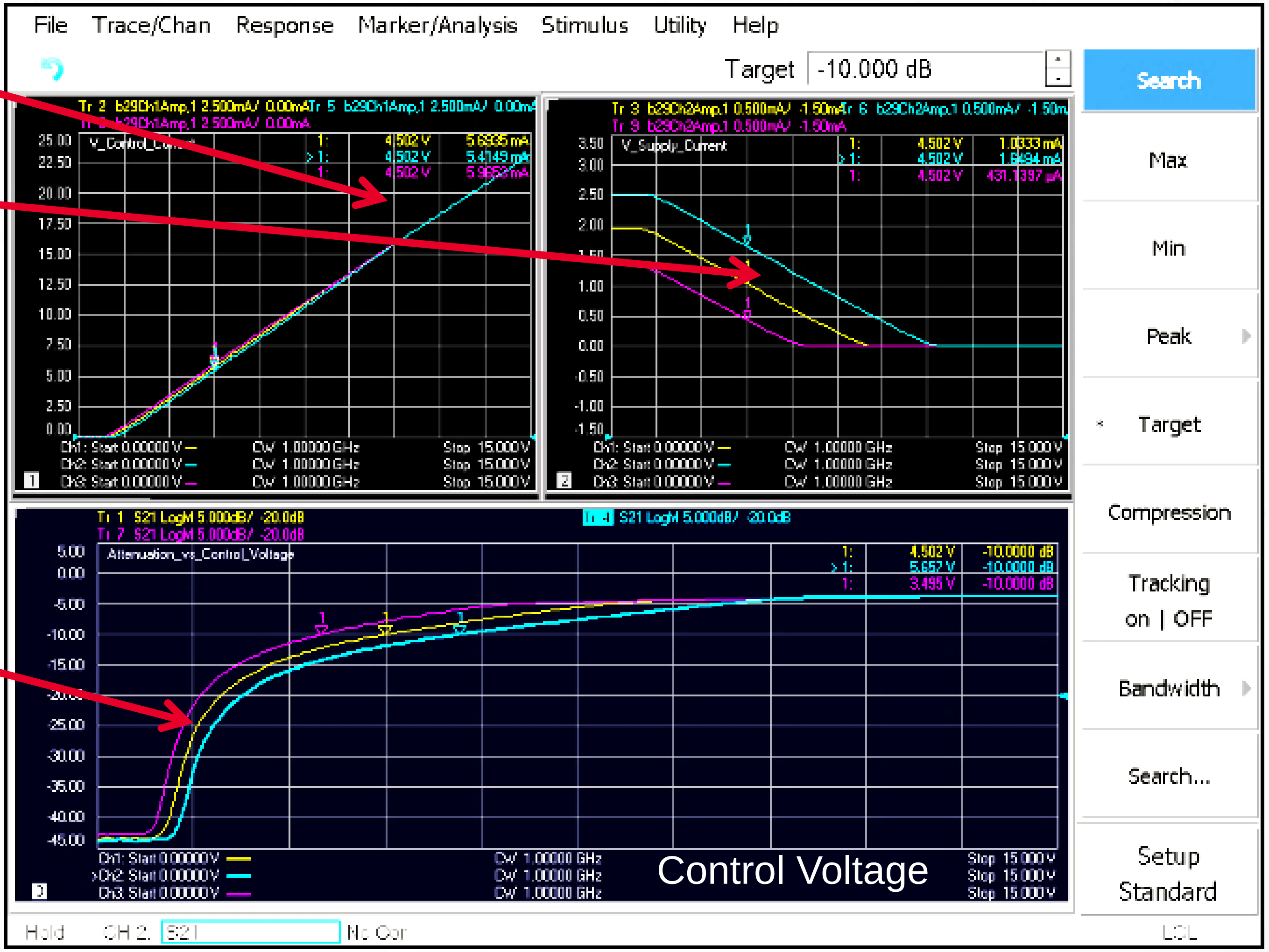
Measuring RF and DC response vs Voltage

VARIABLE GAIN ATTENUATOR: S21 VS. DC CONTROL VOLTAGE

Current of the Control Voltage

Current of the supply voltage

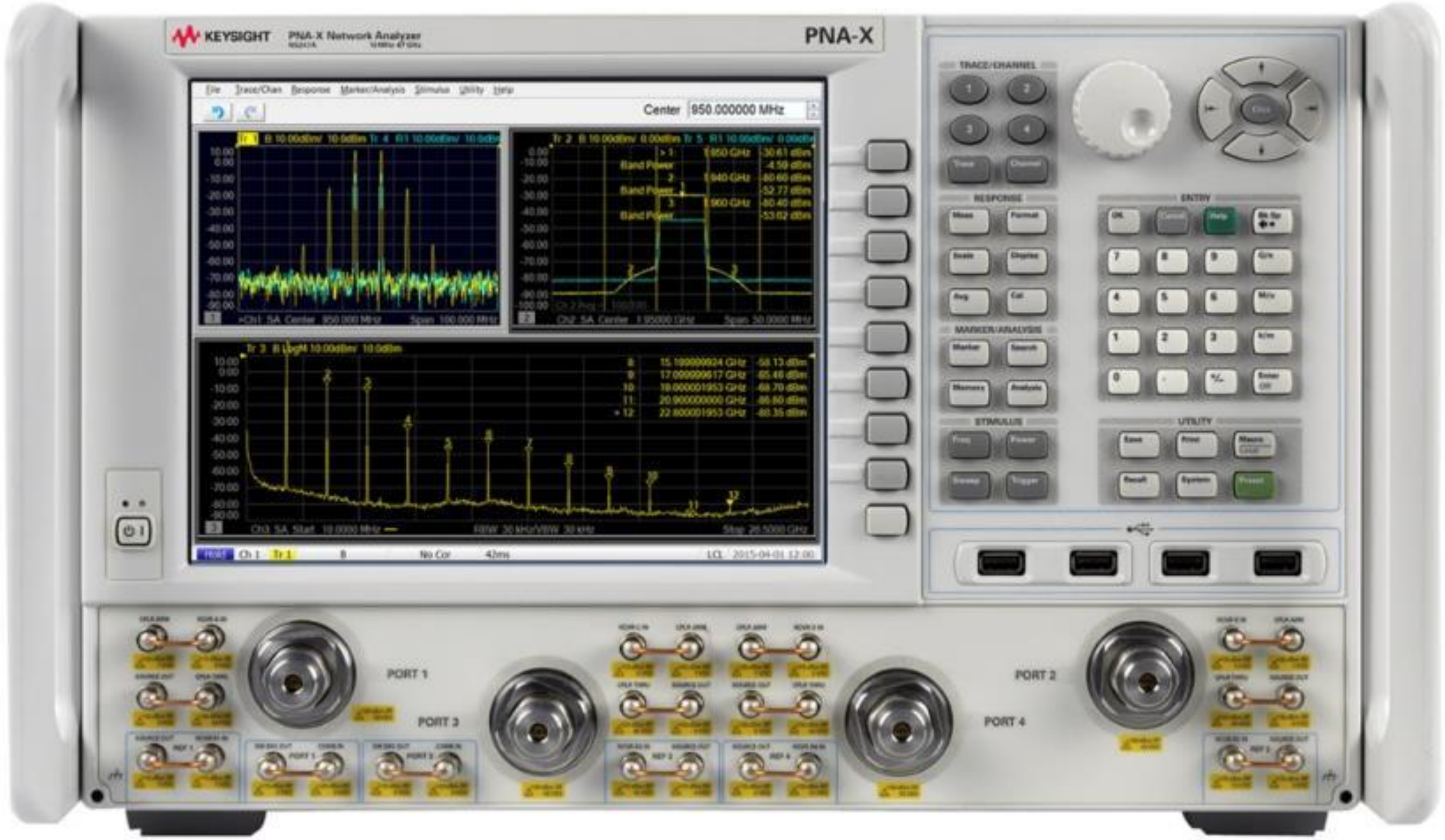
S21 (Y-Axis) vs Control Voltage (X-Axis) for 3 different supply voltages



PNA Microwave Vector Network Analyzer Becomes…

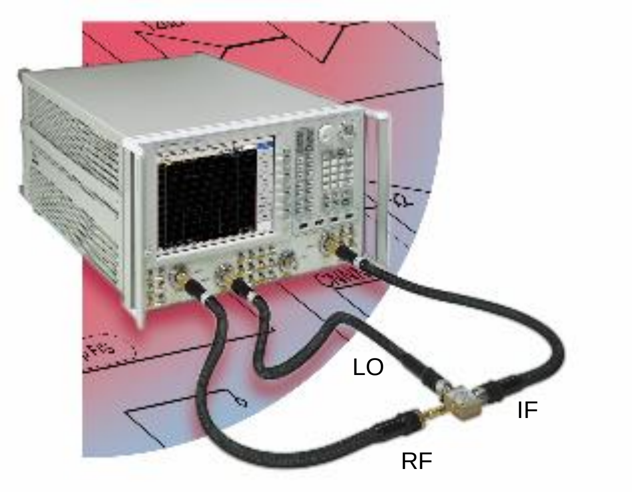
PNA - Spectrum Analyzer:

The ultimate case of Software Defined Instrument



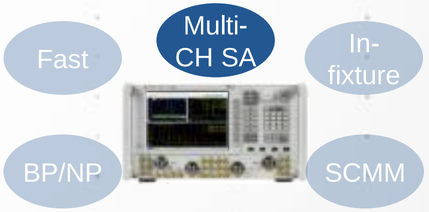
Newest Capability Multi-channel Spectrum Analyzer

WITH ALL TEST PORTS, A REFERENCE CHANNEL, SIMULTANEOUSLY



- RF input
- RF reflection
- RF feed-through
- RF harmonics
- LO reflection
- LO feed-though
- LO harmonics
- IF output
- High-/sub-order mixing spurs

Spectrum analysis on all ports of a mixer or converter provides unparalleled insight into device performance



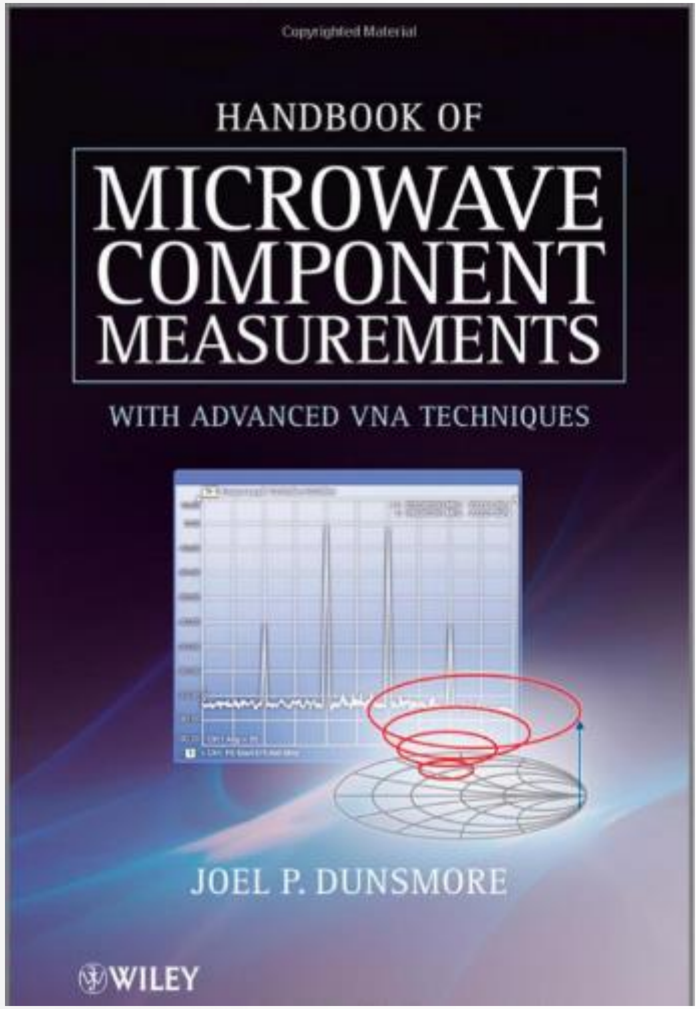
Synergy --

TOTAL IS GREATER THAN THE SUM OF THE PARTS

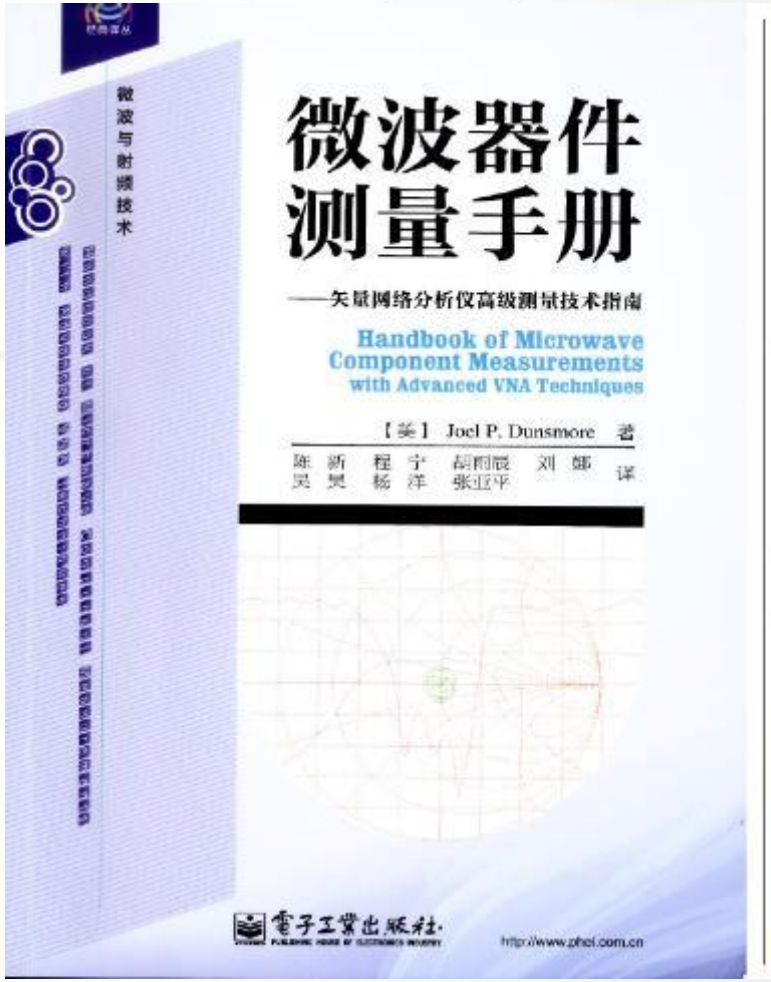
- Combine a VNA with DC meter and DC supply (SMU)
  - High Speed Multi-Dimension Power Added Efficiency (PAE)
- Spectrum Analyzer with a Multi-Channel VNA
  - Multiport and Synchronized (MIMO) SA
  - Worlds Most Accurate Spectrum Analyzer
  - Worlds Fastest Spectrum Analyzer for High Dynamic Range Spur Test
  - Worlds first Broadband 10 MHz-125 GHz mm-wave SA
  - Highest Frequency mm-wave Spectrum Analysis (1.5 THz)

For Reference Material on Advanced VNA Measurements:

HANDBOOK OF MICROWAVE COMPONENT MEASUREMENTS



Available in English or Mandarin



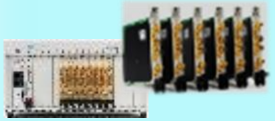
Vector Network Analyzers Product Portfolio

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

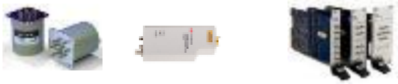
PNA
Reach for unrivaled excellence
300 k to 1.5 THz

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

Accessories

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

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



Power meter / sensor

Industry Broadest Price / Performance Choices

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