Vector Network Analyzers Fundamentals

Axel Hahn & Ansgar Lessmann

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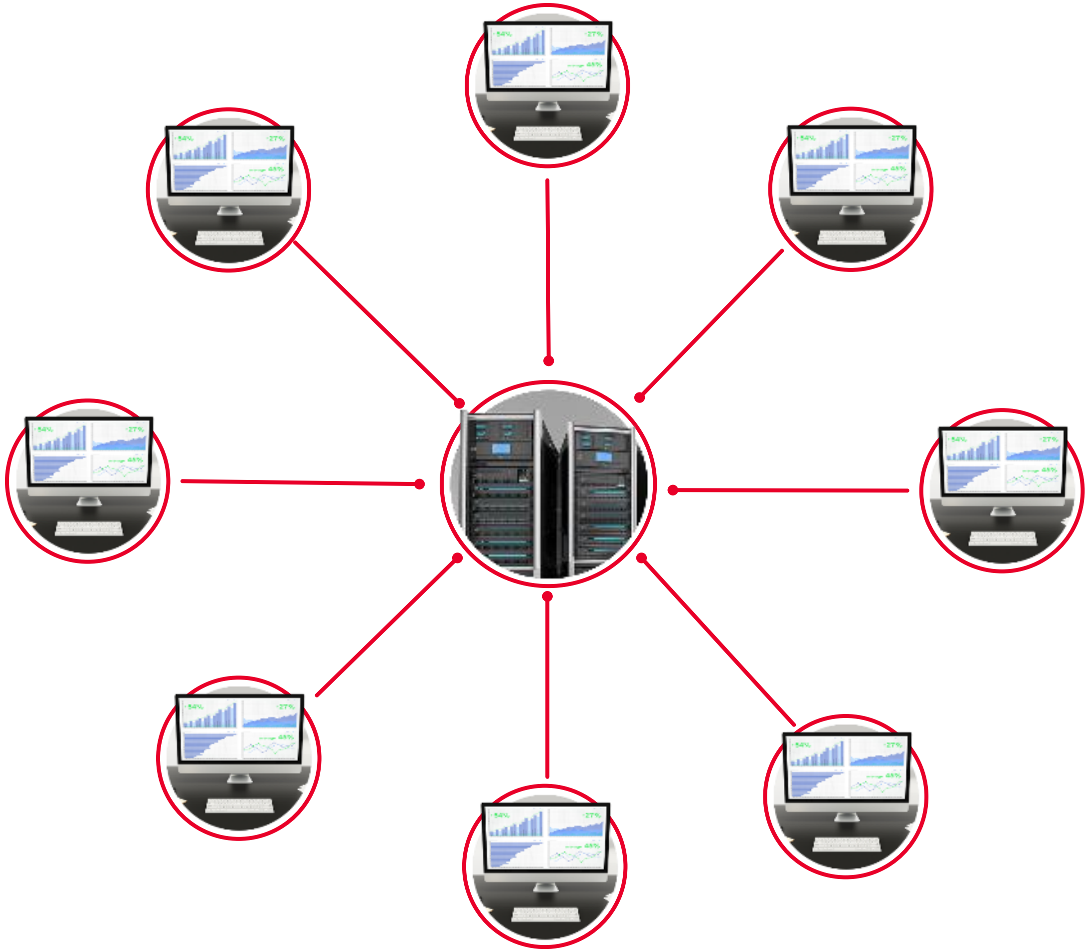
Solutions Engineering – Keysight Technologies

KEYSIGHT TECHNOLOGIES

Agenda

- What is a Network Analyzer?
- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

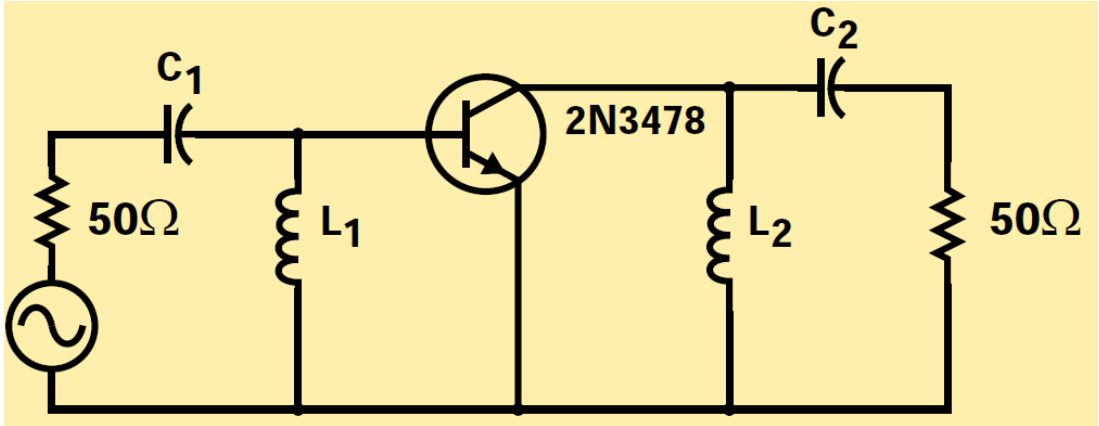
Network Analysis is NOT the analysis of…

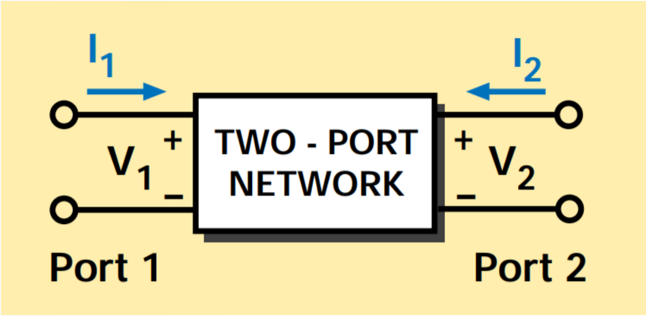


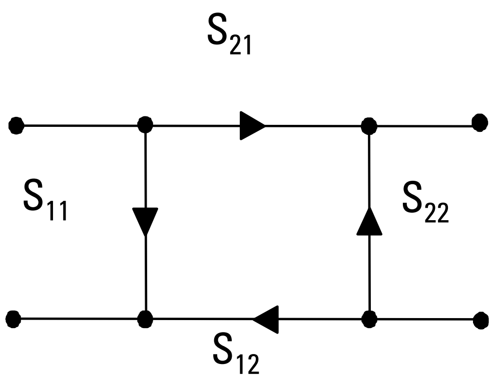
Computers, Network/protocol performance etc…

What is a Network Analyzer?

A *network analyzer* is an instrument that measures the network parameters of electrical networks.

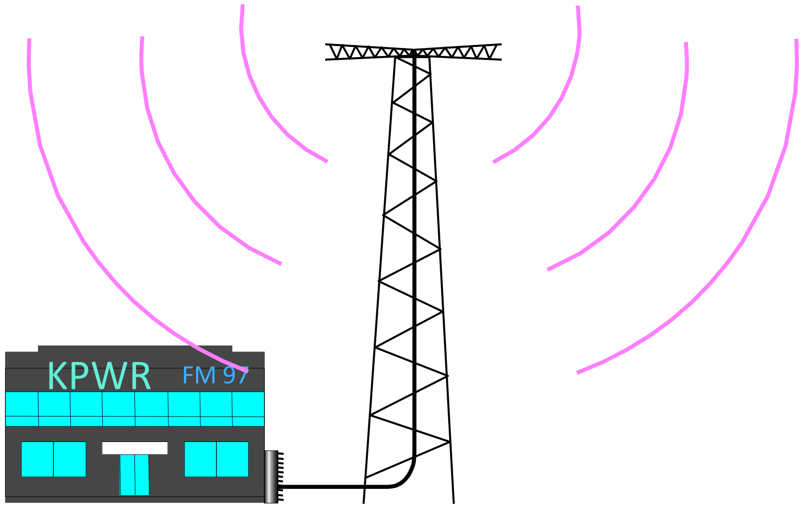






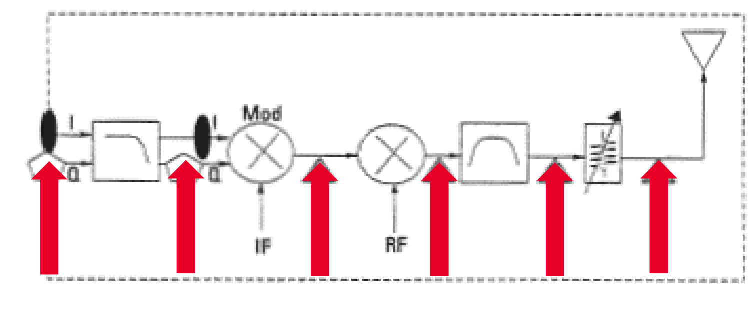
Why Do We Need to Test Components?

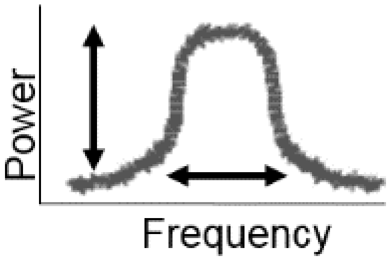
- Verify specifications of "building blocks" for more complex RF systems
- Ensure distortionless transmission of communications signals
  - Linear: constant amplitude, linear phase / constant group delay
  - Nonlinear: harmonics, intermodulation, compression, X-parameters
- Ensure good match when absorbing power (e.g., an antenna)



Transmit Receive Design Challenges

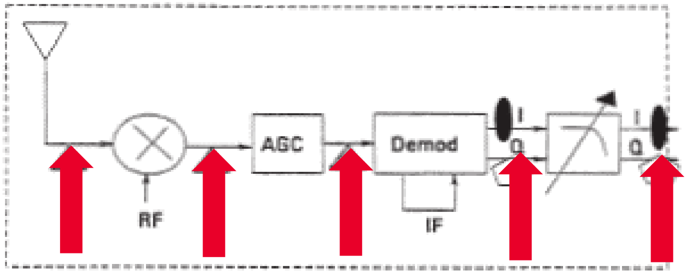
TRANSMIT





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

RECEIVE

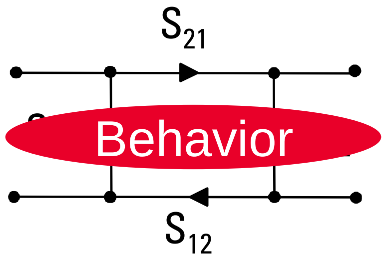


- Sensitivity
- Adjacent Channel Selectivity
- Operating Frequency
- Environment/Interference
- Noise
- Dynamic Range

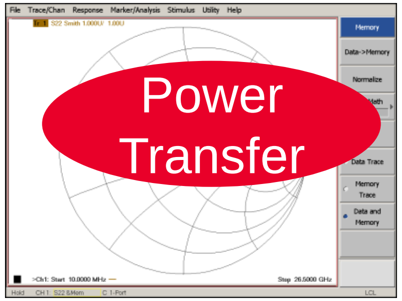
End goal: maximize link budget, fidelity & efficiency

The Need for Both Magnitude and Phase

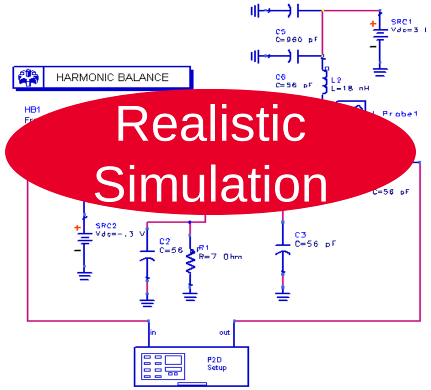
1. Complete characterization of linear networks



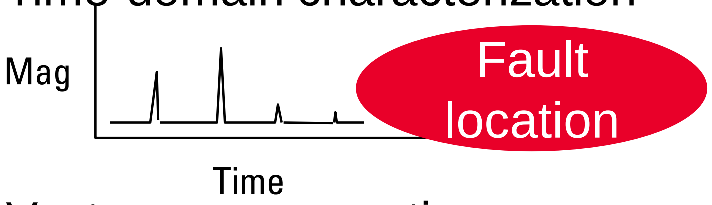
2. Complex impedance needed to design matching circuits



3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction

6. X-parameter (nonlinear) characterization

Pre-distortion

Agenda

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- Transmission Lines and S-Parameters
- Network Analyzer Block Diagram
- Network Analysis Measurements
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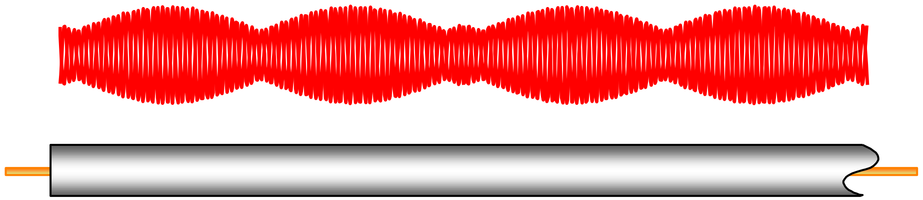
Transmission Line Basics

- Low Frequencies

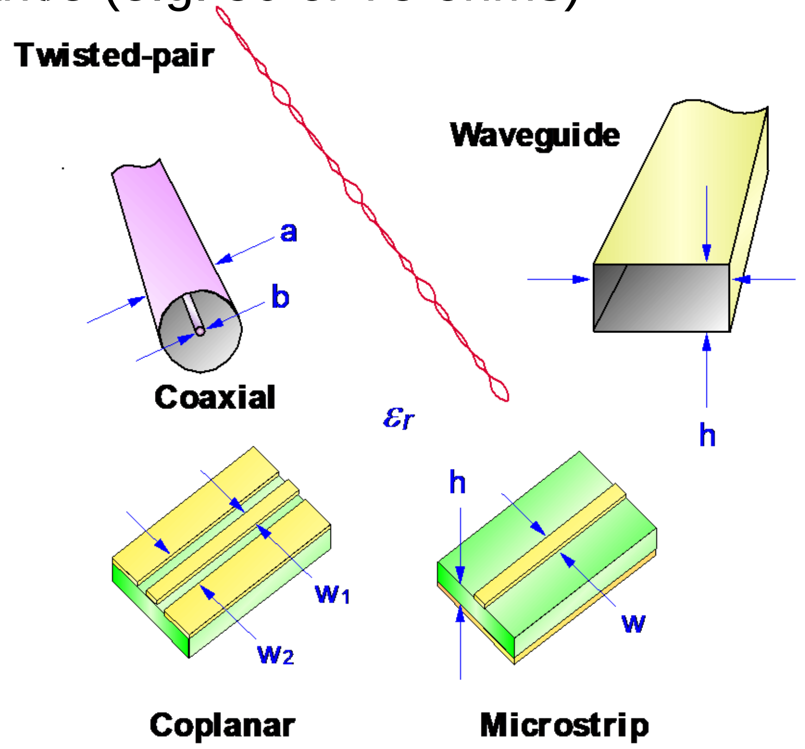
  - Wavelengths >> wire length
  - Current (I) travels down wires easily for efficient power transmission
  - Measured voltage and current not dependent on position along wire



- 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

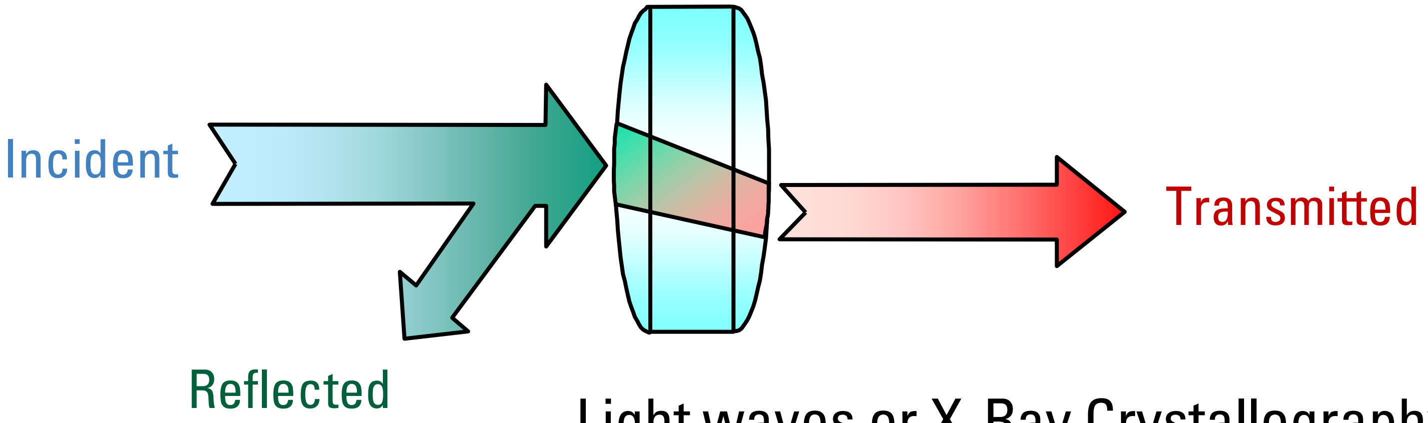
Transmission line Z_o

- 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)

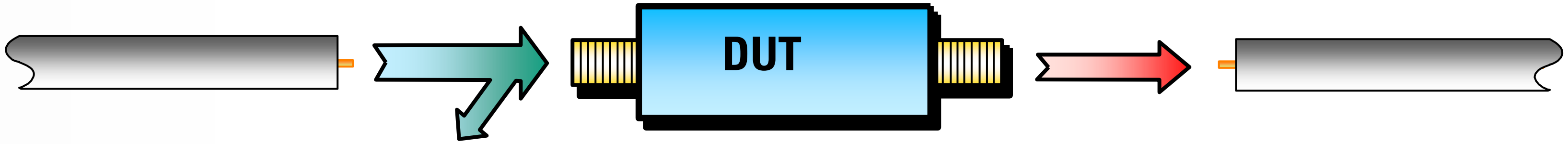


For more information on transmission line basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

RF Energy Transmission

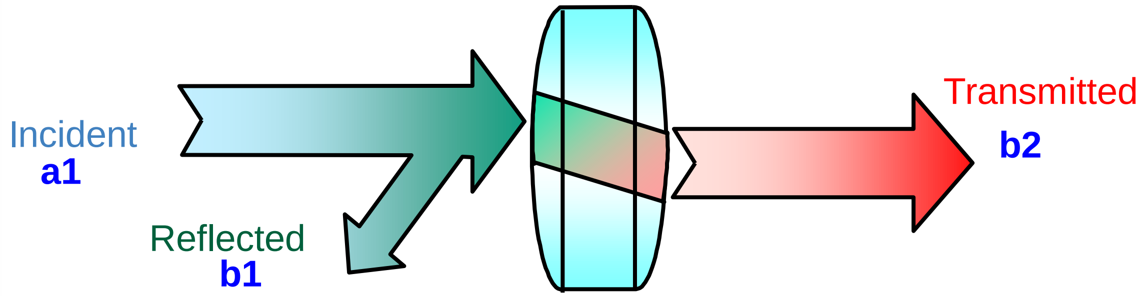


Light waves or X-Ray Crystallography
and X-Ray Scattering



RF Scattering

High-frequency Device Characterization



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

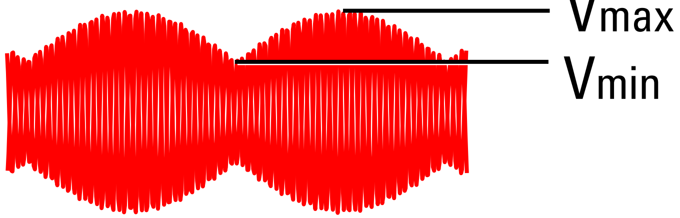
Reflection Coefficient $= \Gamma = \dfrac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \dfrac{Z_L - Z_o}{Z_L + Z_o}$

$\rho = |\Gamma|$

Return loss $= -20 \log(\rho)$

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

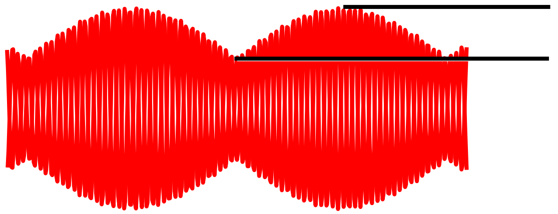
Voltage Standing Wave Ratio $= \dfrac{1 + \rho}{1 - \rho}$



Reflection Parameters

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

Voltage Standing Wave Ratio $= \dfrac{1 + \rho}{1 - \rho}$



No reflection (ZL = Zo)

Full reflection (ZL = open, short)

No reflection	Parameter	Full reflection
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

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

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

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

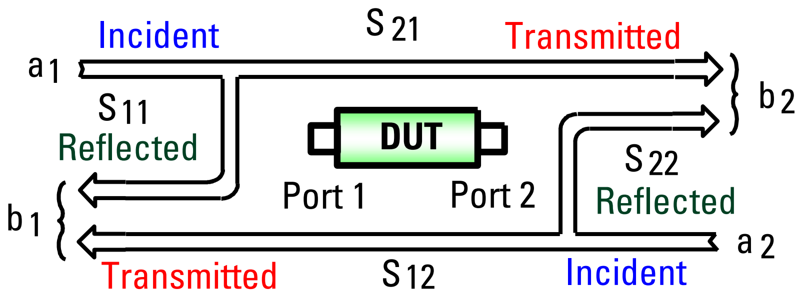
(Impedance)

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

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

Why Use Scattering, S-Parameters?

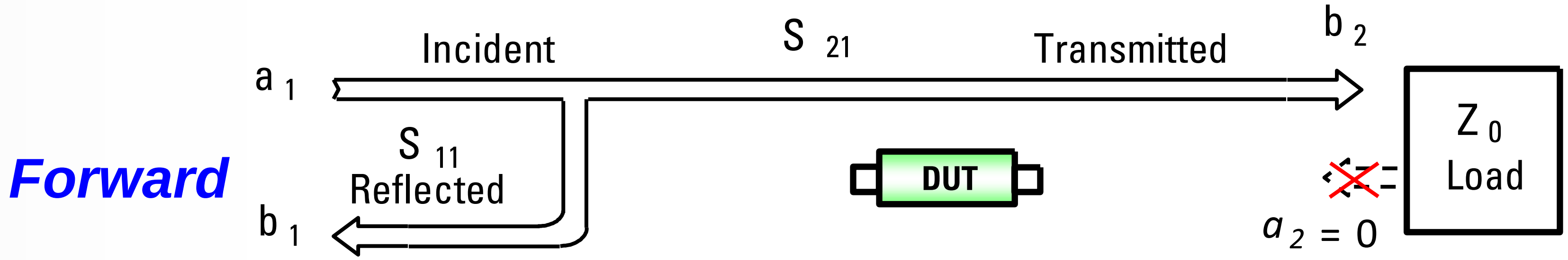
- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade**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

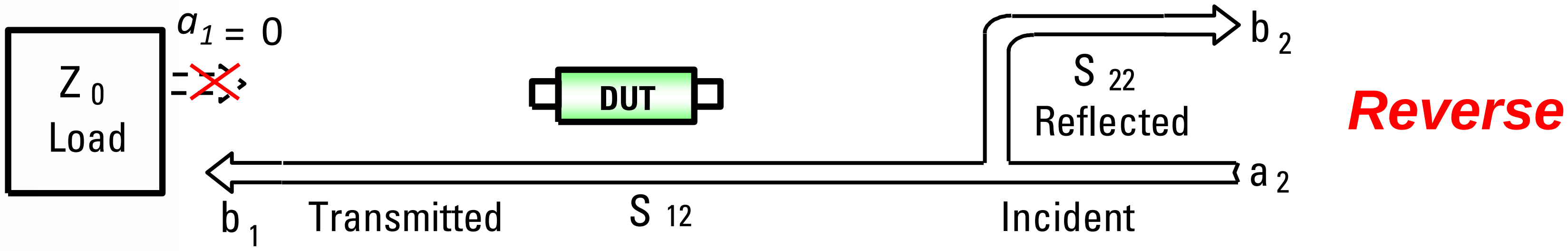


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

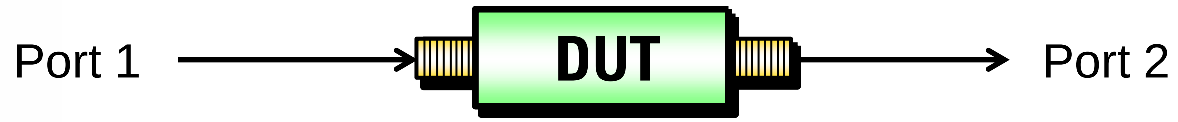
$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

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

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



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)***

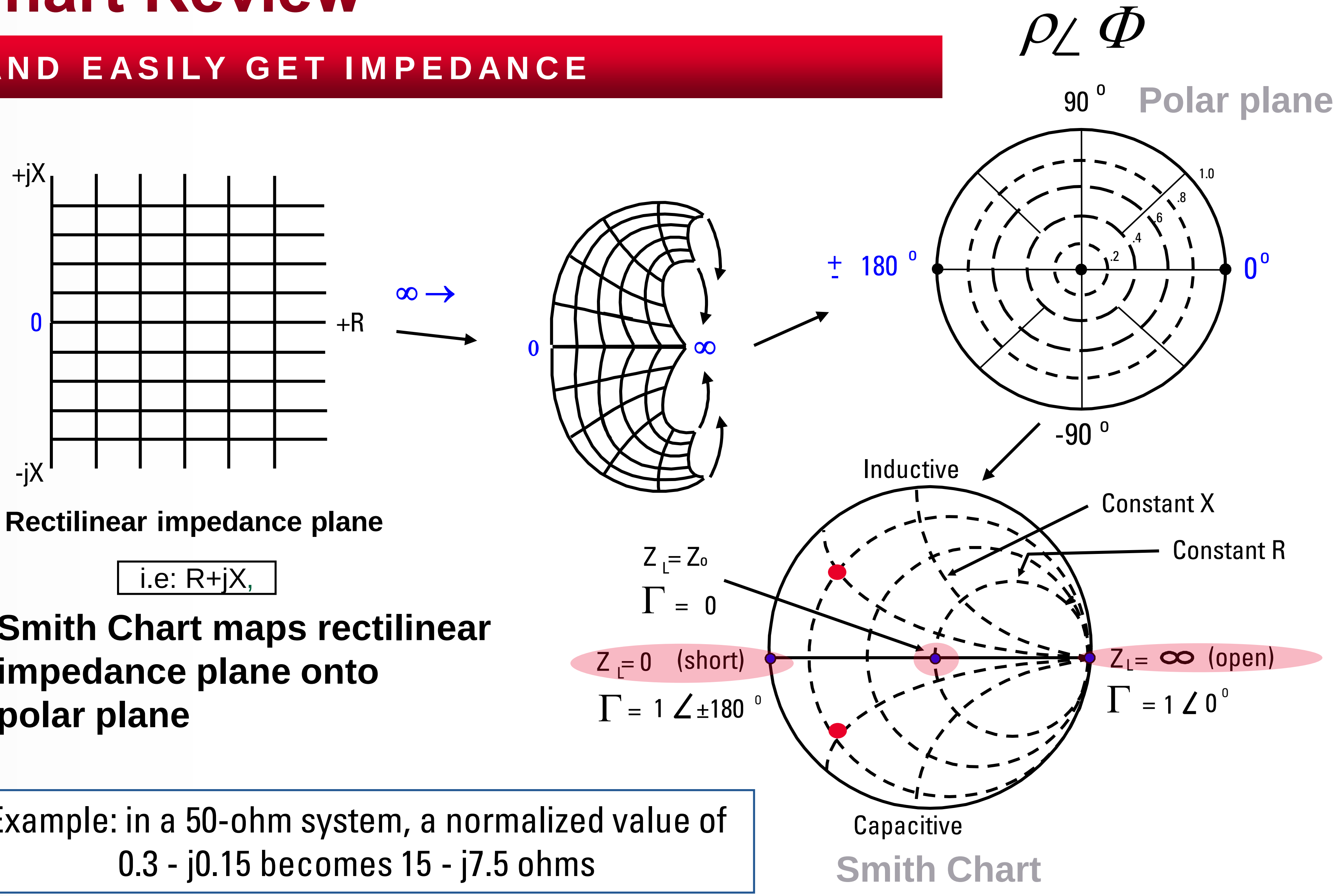
S_{12} = reverse transmission coefficient ***(isolation)***

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

KEYSIGHT TECHNOLOGIES

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

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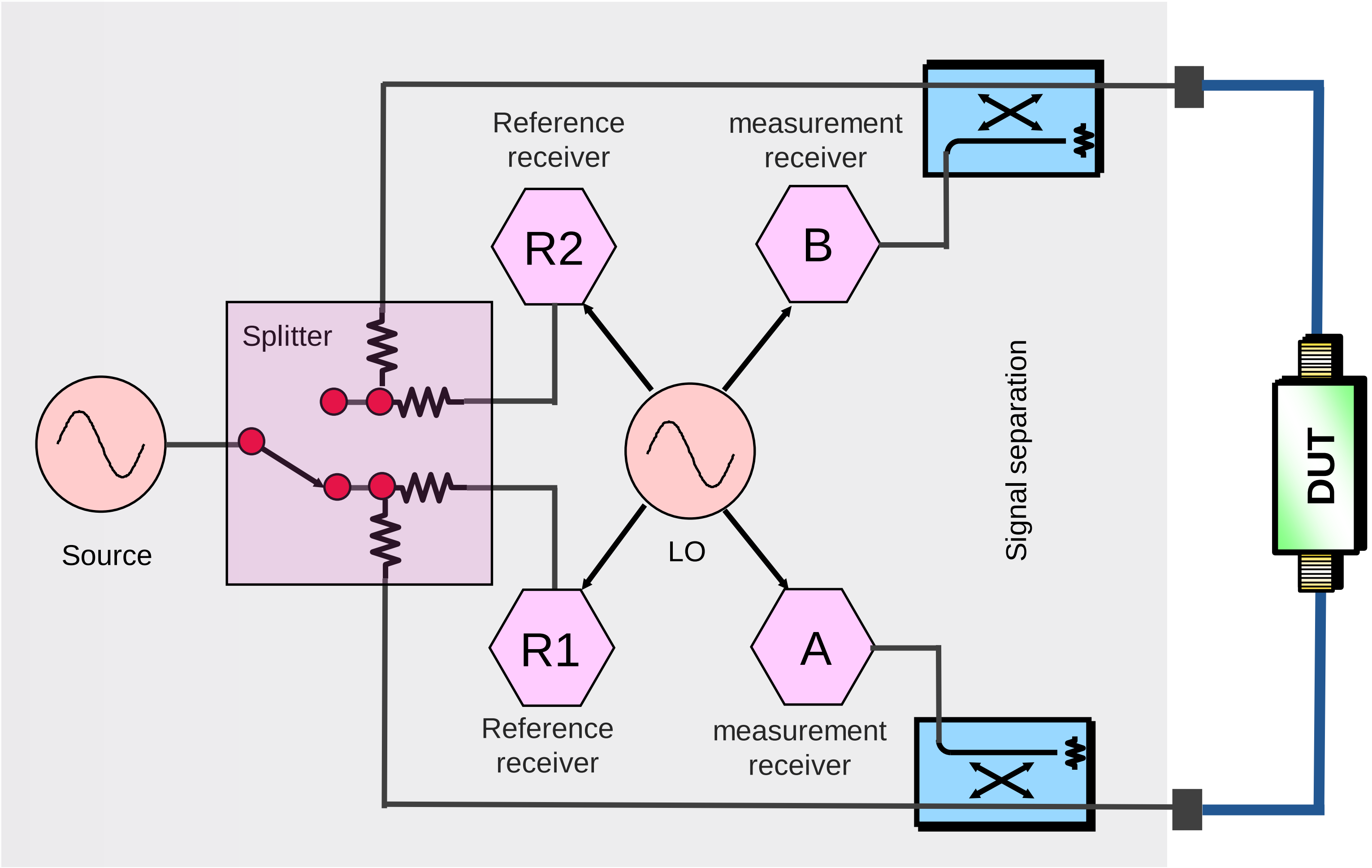
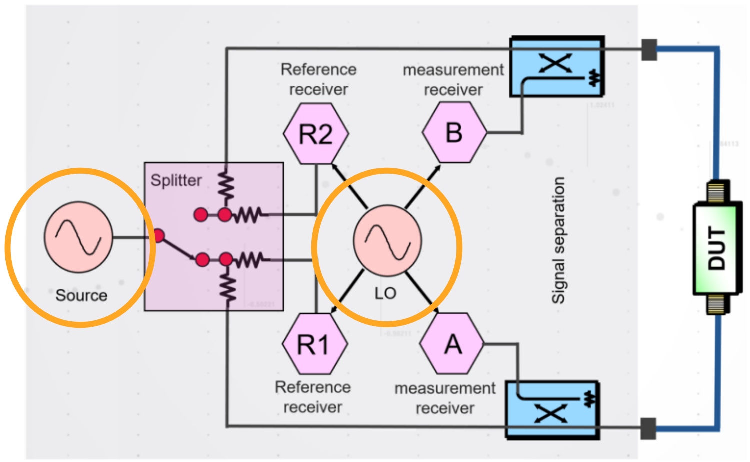
Generalized Network Analyzer Block Diagram



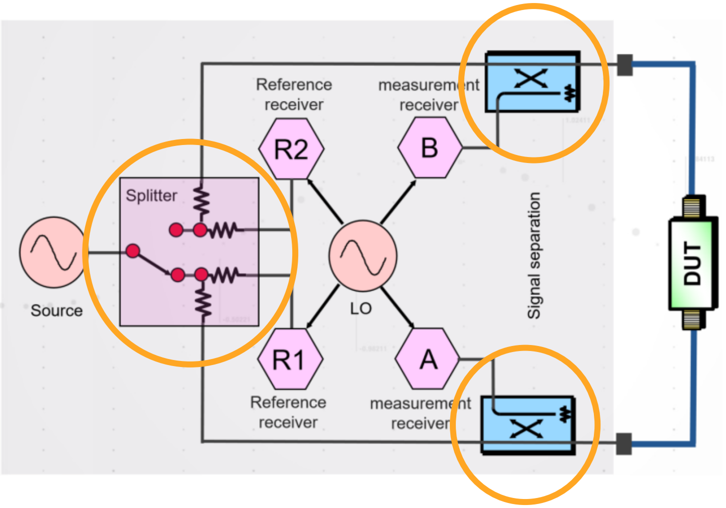
Source

- Supplies stimulus for system
- Can sweep frequency or power
- Traditionally NAs had one signal source
- Modern NAs have the option for a second internal source and/or the ability to control external source
  - Can control an external source as a local oscillator (LO) signal for mixers and converters
  - Useful for mixer measurements like conversion loss, group delay

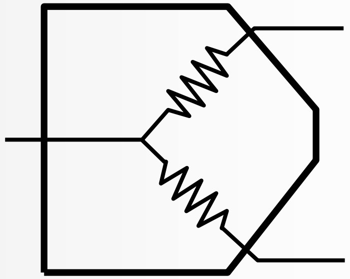


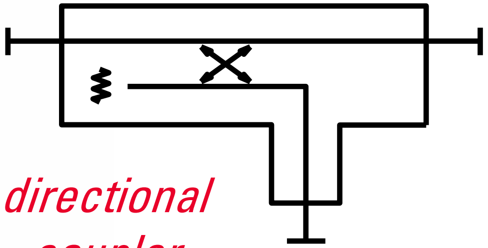
Signal Separation

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



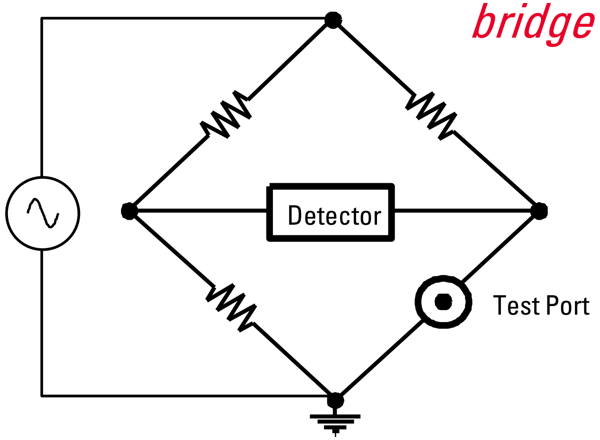
splitter





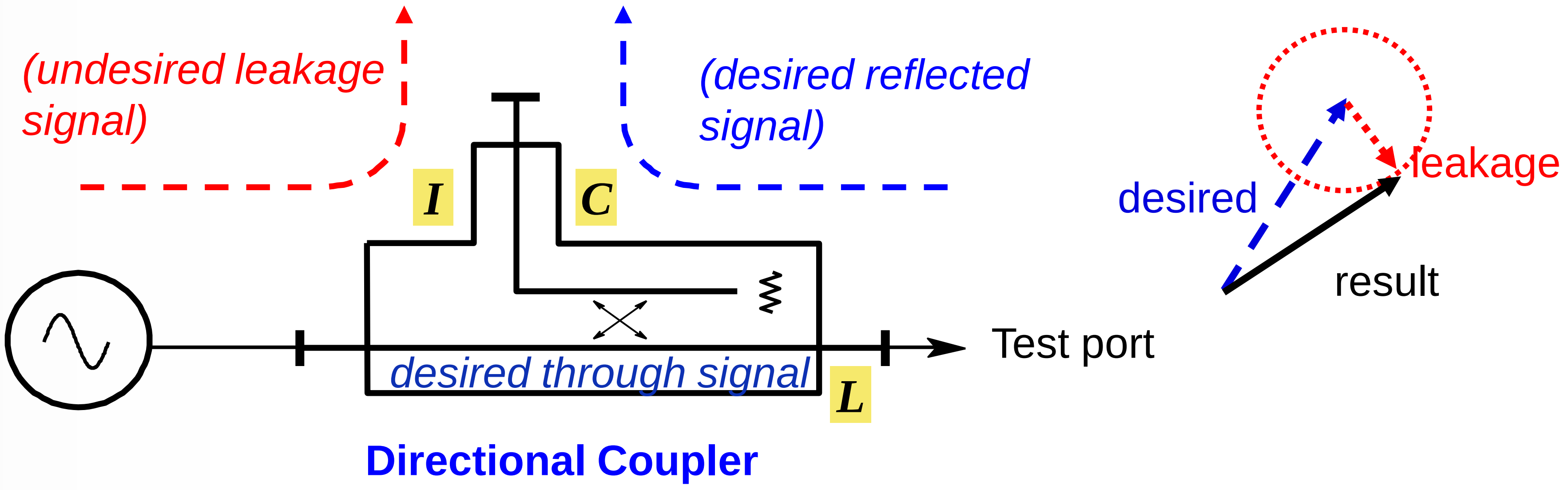
directional coupler

bridge



Directional Coupler & Directivity

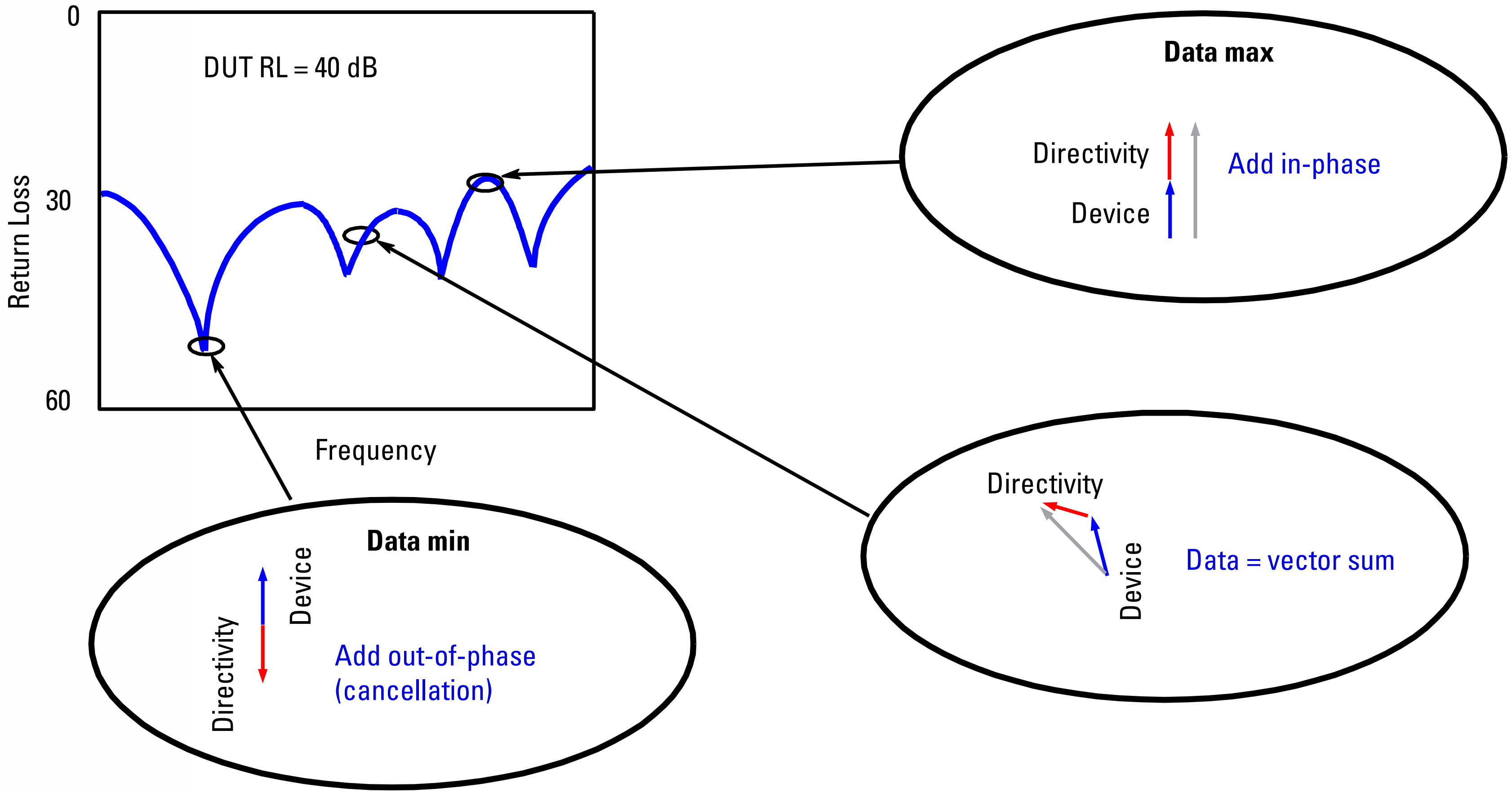
- ***Directivity*** is a measure of how well a directional coupler or bridge can separate signals moving in opposite directions



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

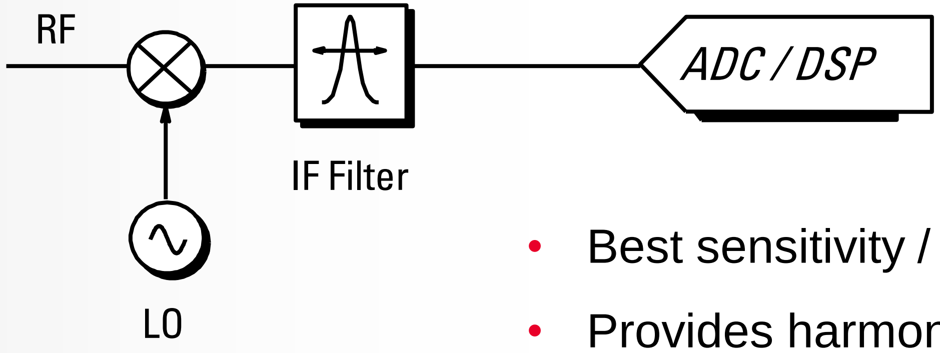
Interaction of Directivity with the DUT

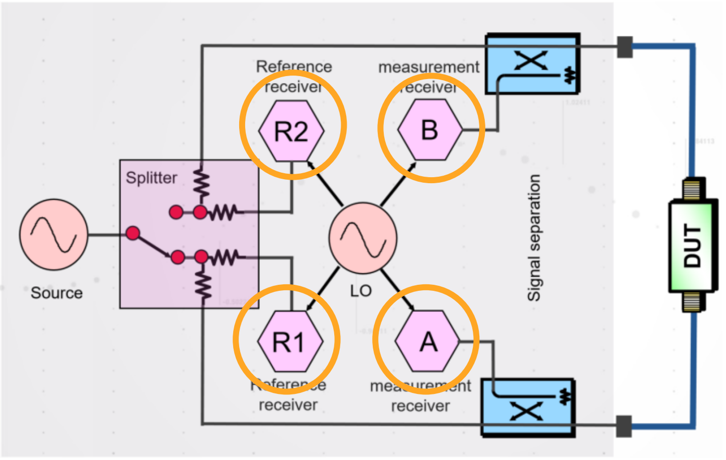
(WITHOUT ERROR CORRECTION)



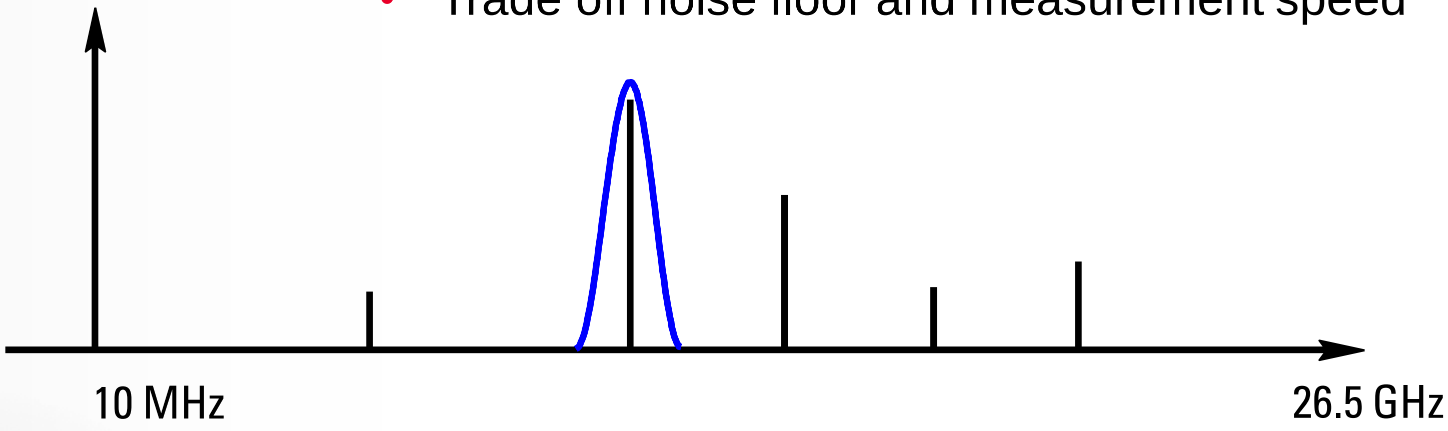
Receivers

NARROWBAND DETECTION - TUNED RECEIVER

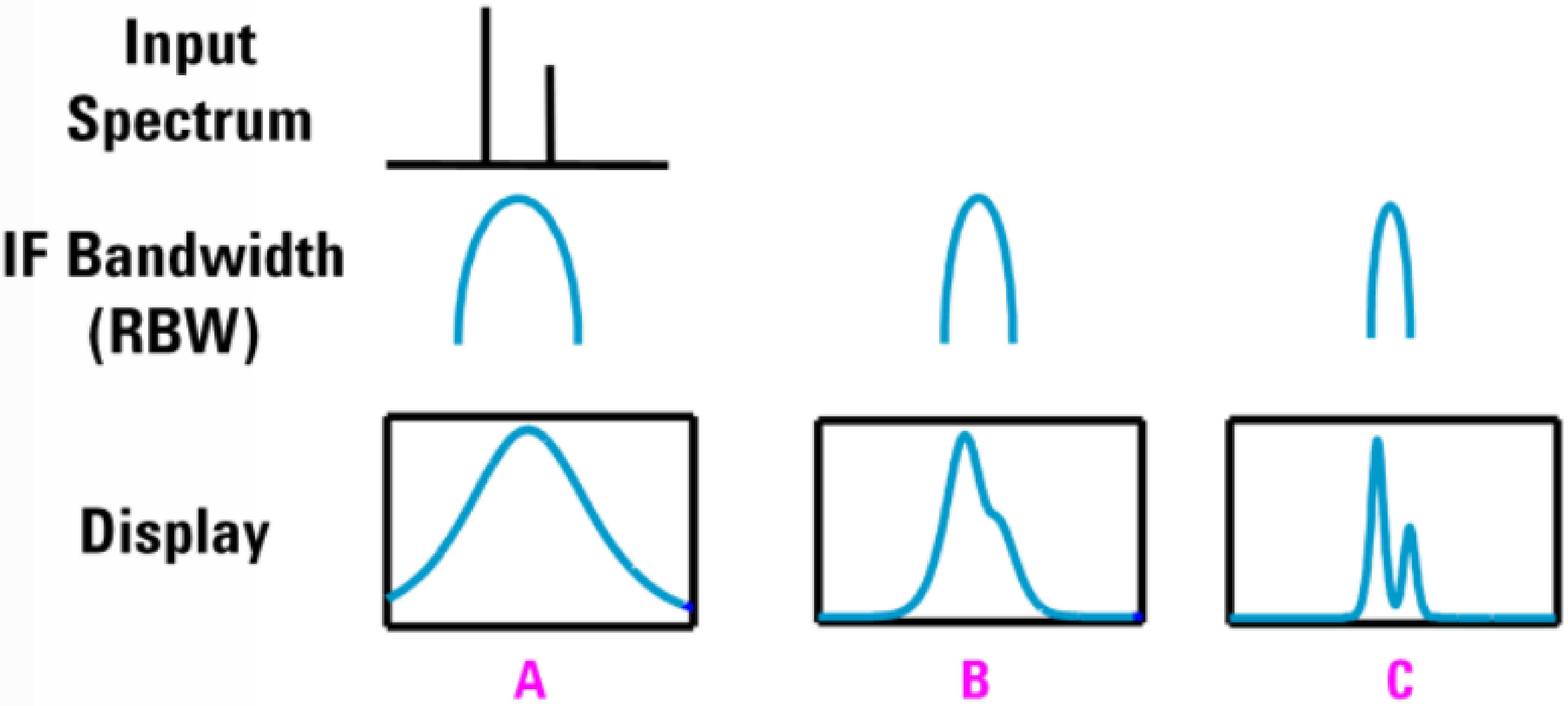




- Best sensitivity / dynamic range
- Provides harmonic / spurious signal rejection
- Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
- Trade off noise floor and measurement speed

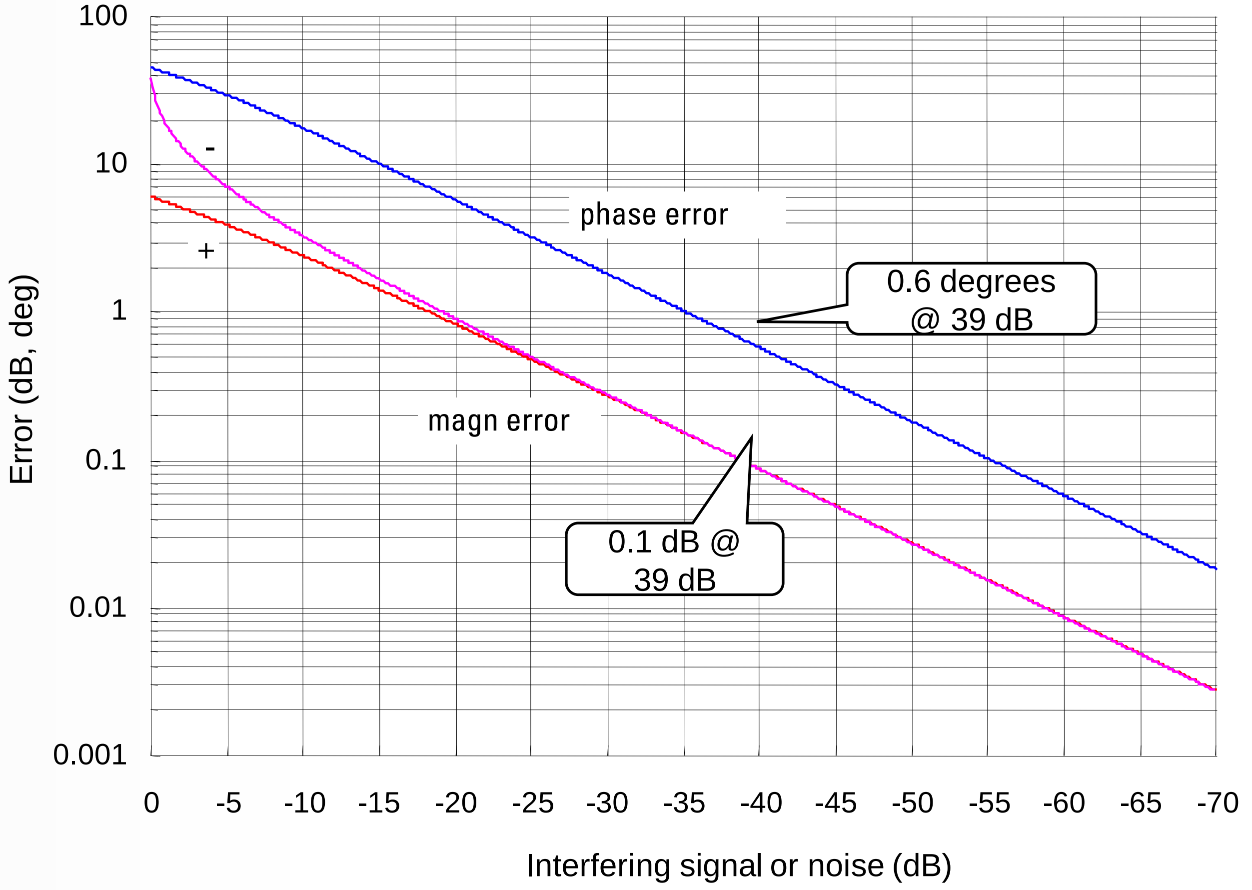


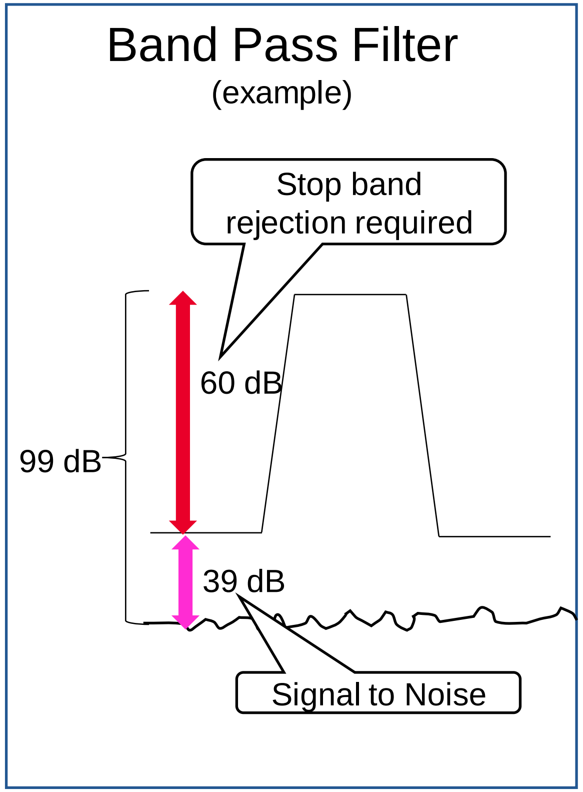
IF Bandwidth



Dynamic Range and Accuracy

ERROR DUE TO INTERFERING SIGNAL

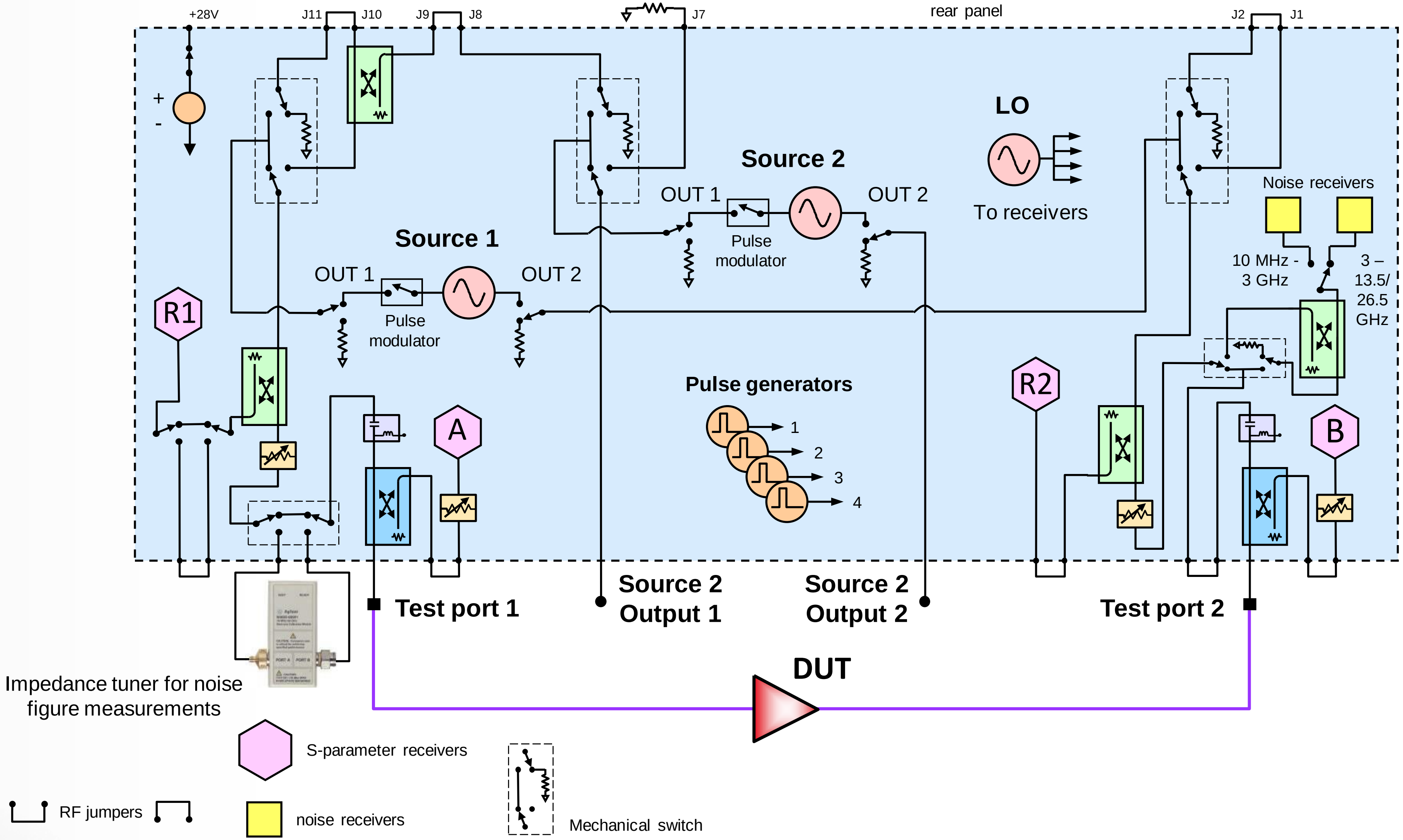




Dynamic range for 0.1 dB accuracy = 60 dB (rejection) + 39 dB (SNR) = 99 dB

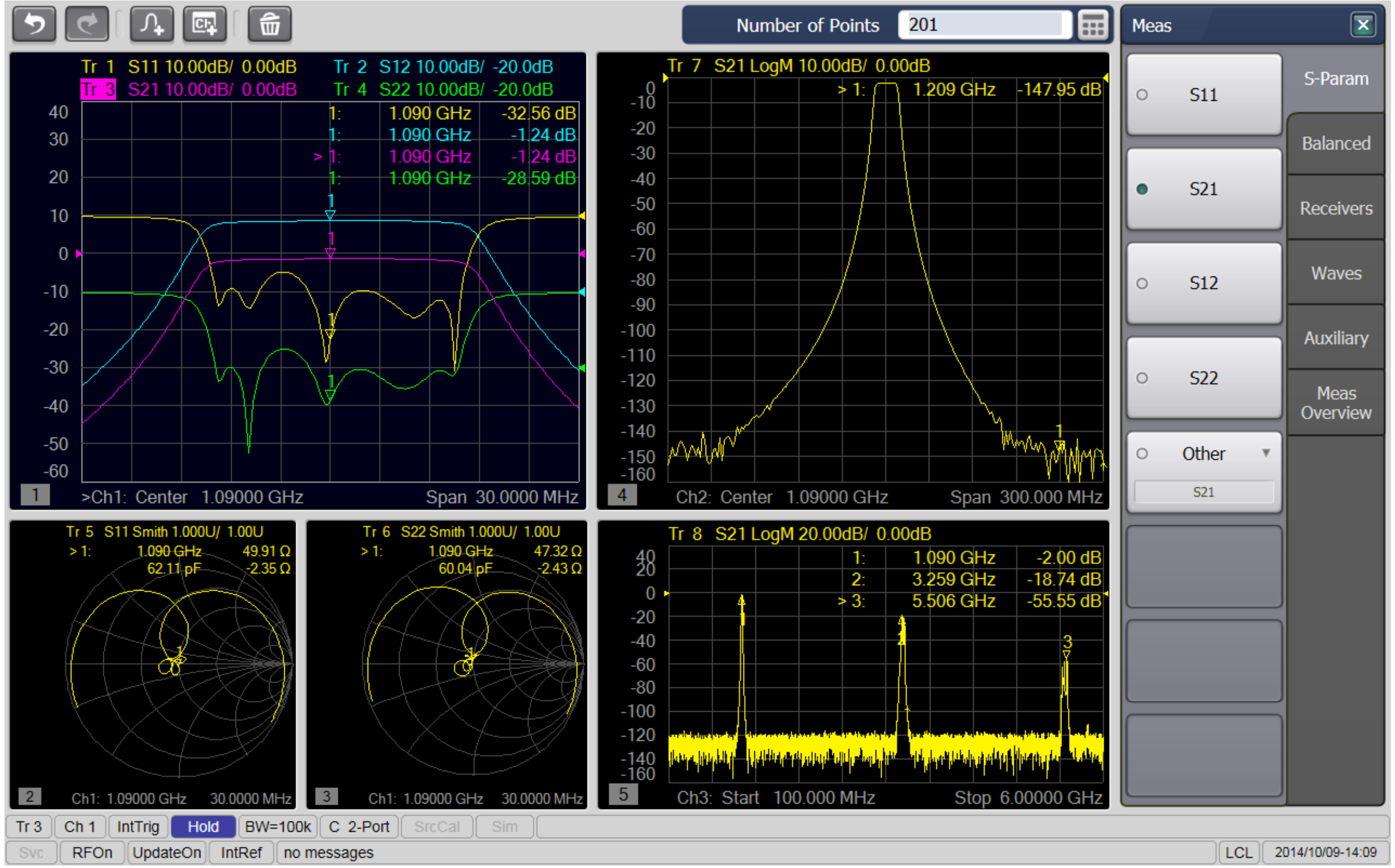
Dynamic range is very important for measurement accuracy!

Modern VNA Block Diagram (2-Port PNA-X)



Processor / Display

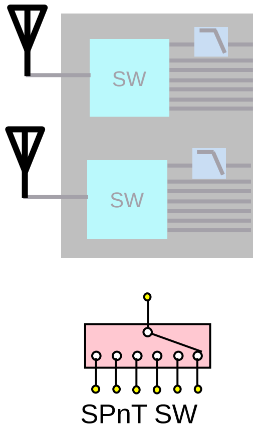
- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math

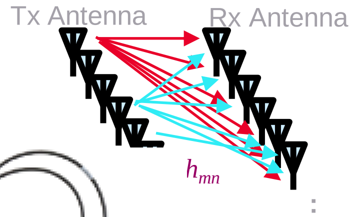


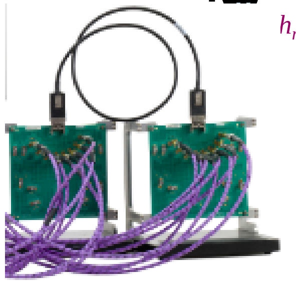
Multiport Measurement Architectures

Application Examples

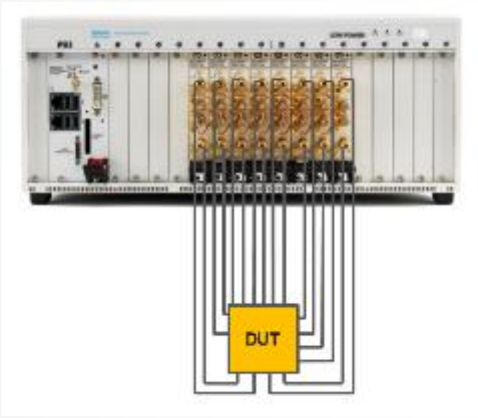
- RF front end modules / antenna switch modules
- Channel measurements of MIMO antennas
- Interconnects (ex. cables, connectors)
- General-purpose multiport devices



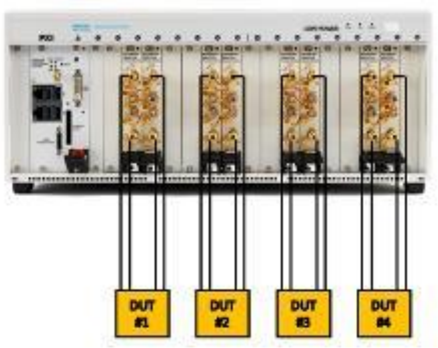




PXI Multiport VNA



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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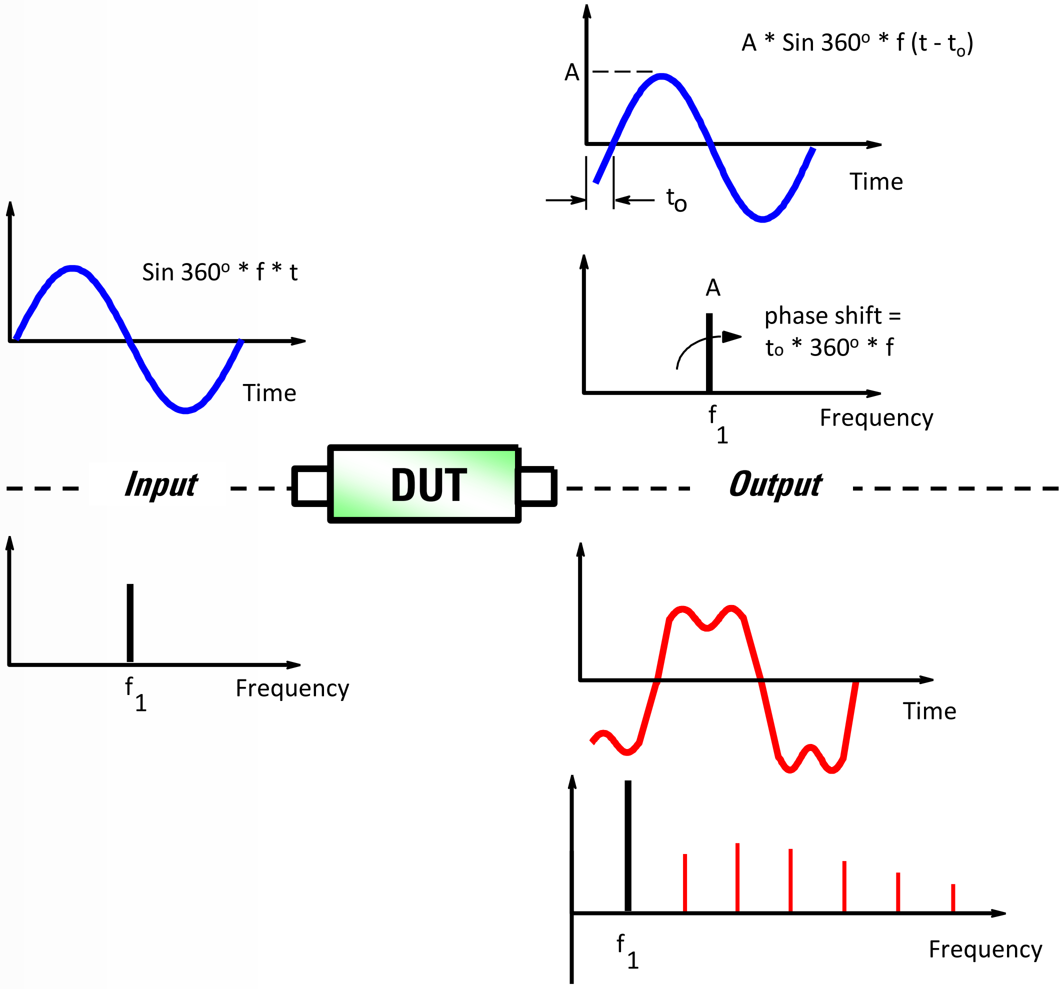
Linear Versus Nonlinear Behavior

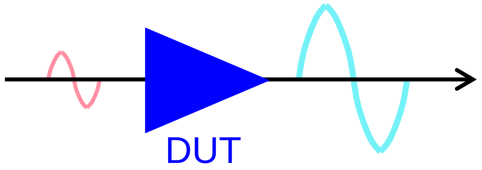


Linear behavior:
- Input and output frequencies are the same (no additional frequencies created)
- Output frequency only undergoes magnitude and phase change

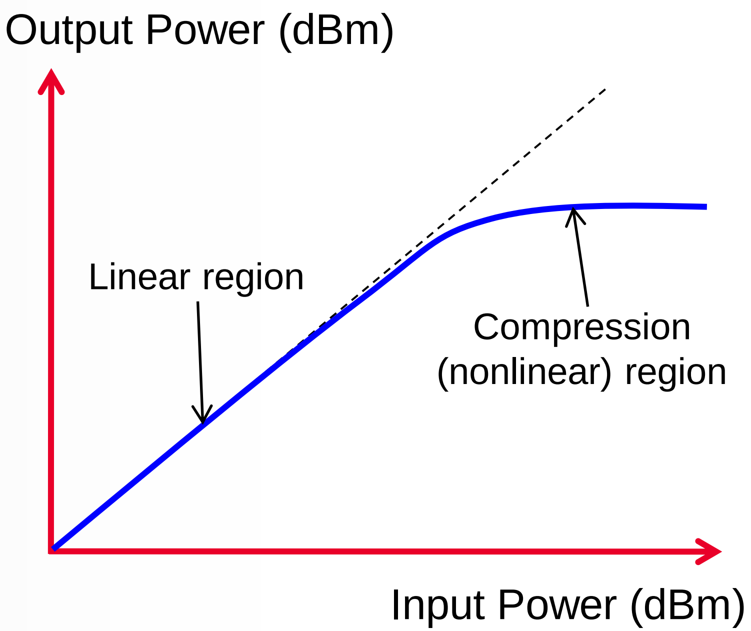
Nonlinear behavior:
- Output frequency may undergo frequency shift (e.g. with mixers)
- Additional frequencies created (harmonics, intermodulation)

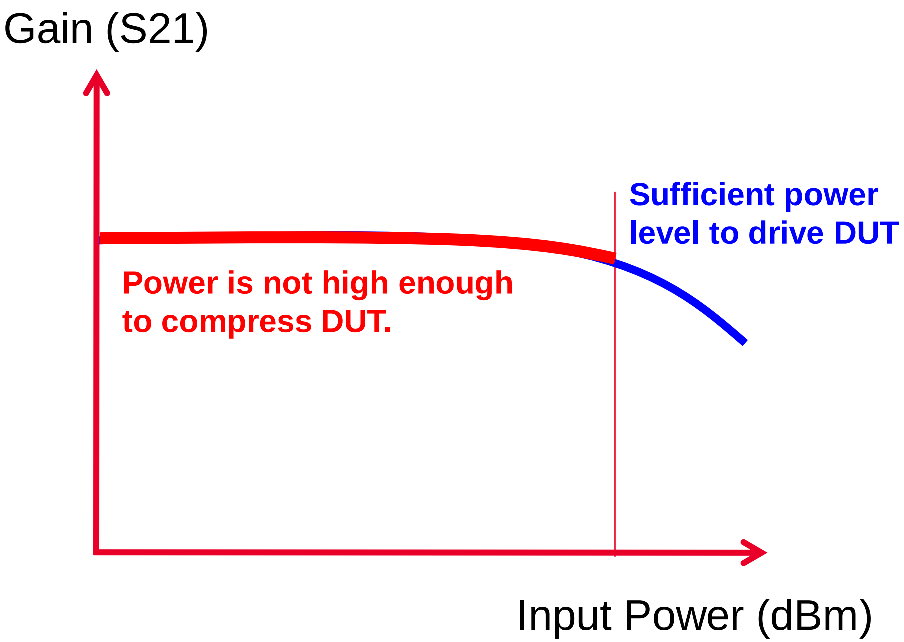
For more information on linear vs. non-linear basics:
http://literature.cdn.keysight.com/litweb/pdf/5965-7917E.pdf

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.





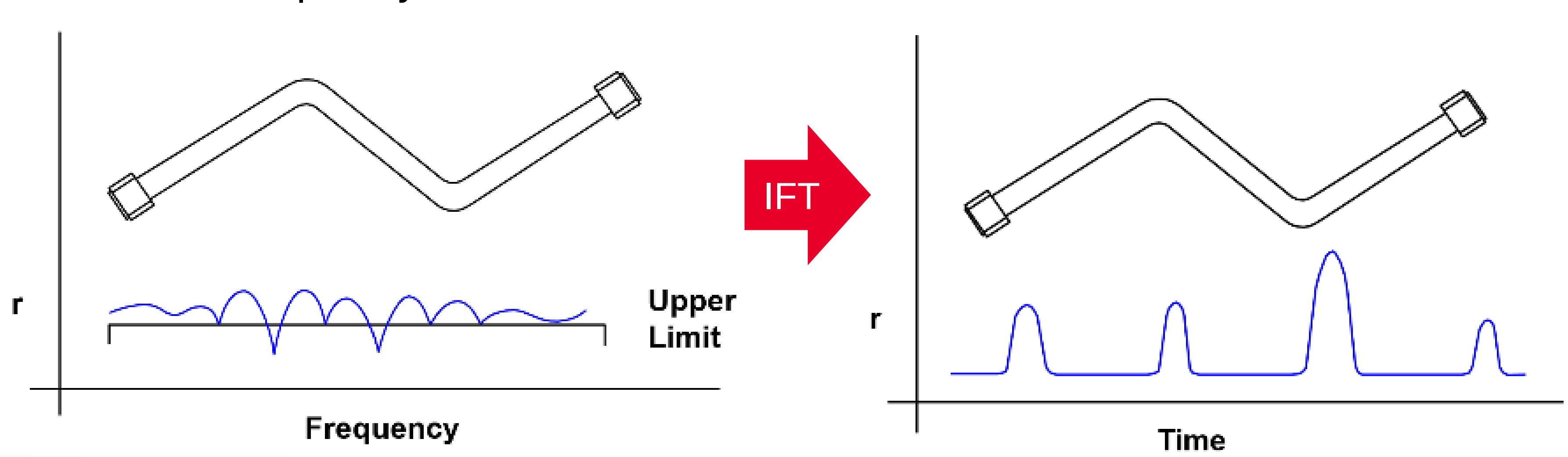
Enough margin of source power capability is needed for analyzers.

Time vs. Frequency Domain

S11 RESPONSE OF SEMIRIGID COAX CABLE

Frequency Domain

Time Domain



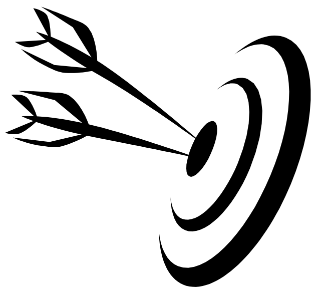
- Why time domain?
  - Locate faults
  - Identify passive or inductive circuit elements
  - Identify and remove unwanted fixture responses
  - And more…

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

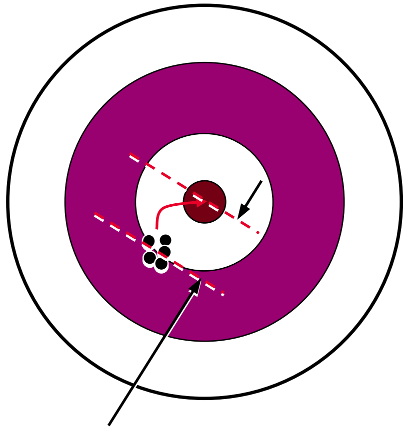
Agenda

- What is a Network Analyzer?
- 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



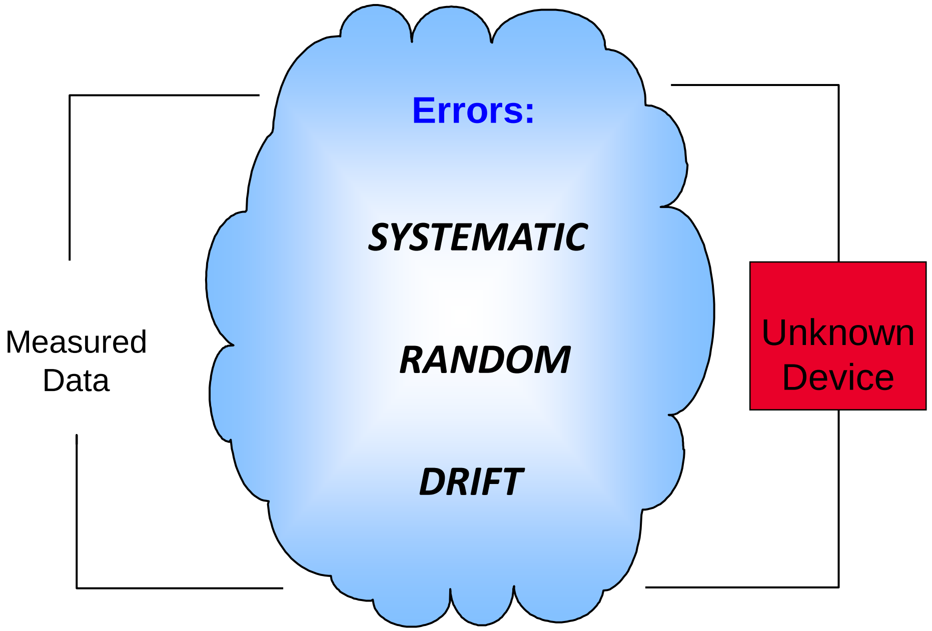
Measurement Error Modeling

- **Systematic Errors**

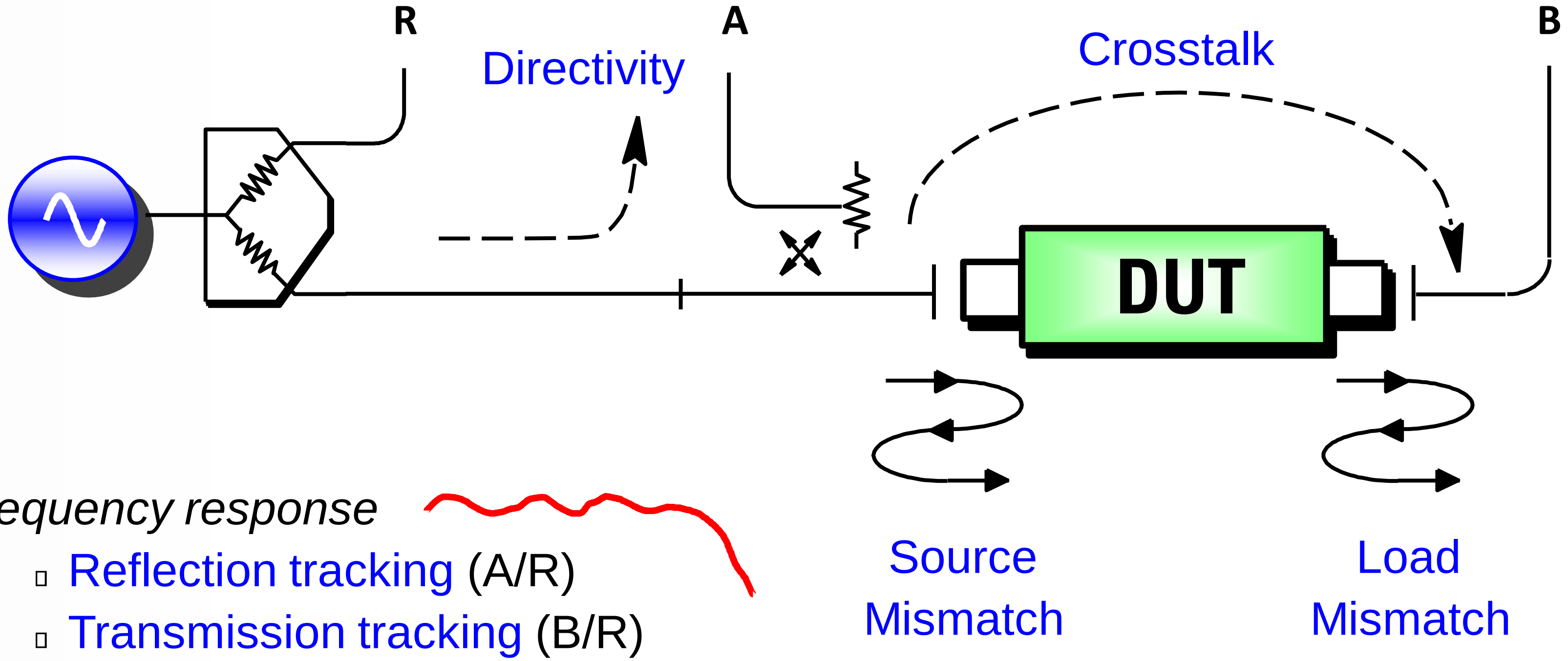
  - Due to imperfections in the analyzer and test setup
  - Assumed to be time invariant (predictable)
  - Generally, are largest sources or error
- **Random Errors**

  - Vary with time in random fashion (unpredictable)
  - Main contributors: instrument noise, switch and connector repeatability
- **Drift Errors**

  - Due to system performance changing ***after*** a calibration has been done
  - Primarily caused by **temperature variation**



Systematic Measurement Errors



Frequency response

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

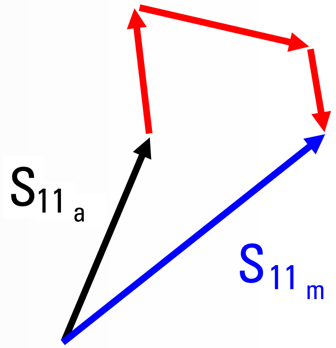
Six forward and six reverse error terms yields 12 error terms for two-port devices

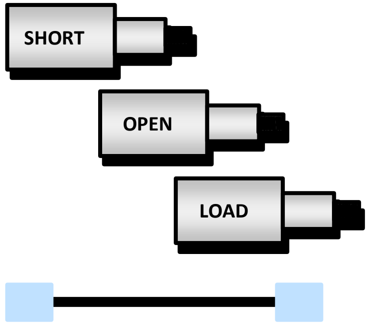
Types of Error Correction

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


thru

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





thru

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

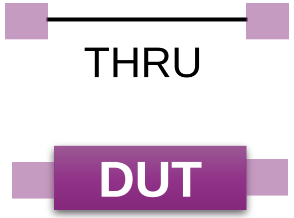
Significance of Calibration

TYPES OF CALIBRATION

UNCORRECTED

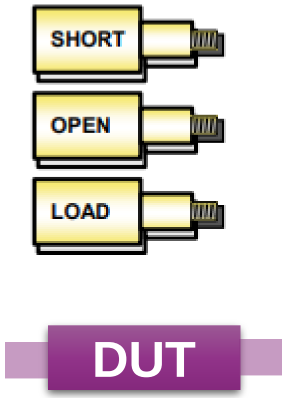
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



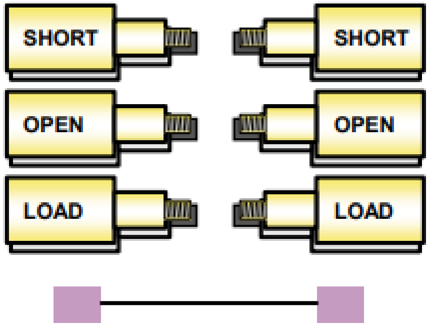
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

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

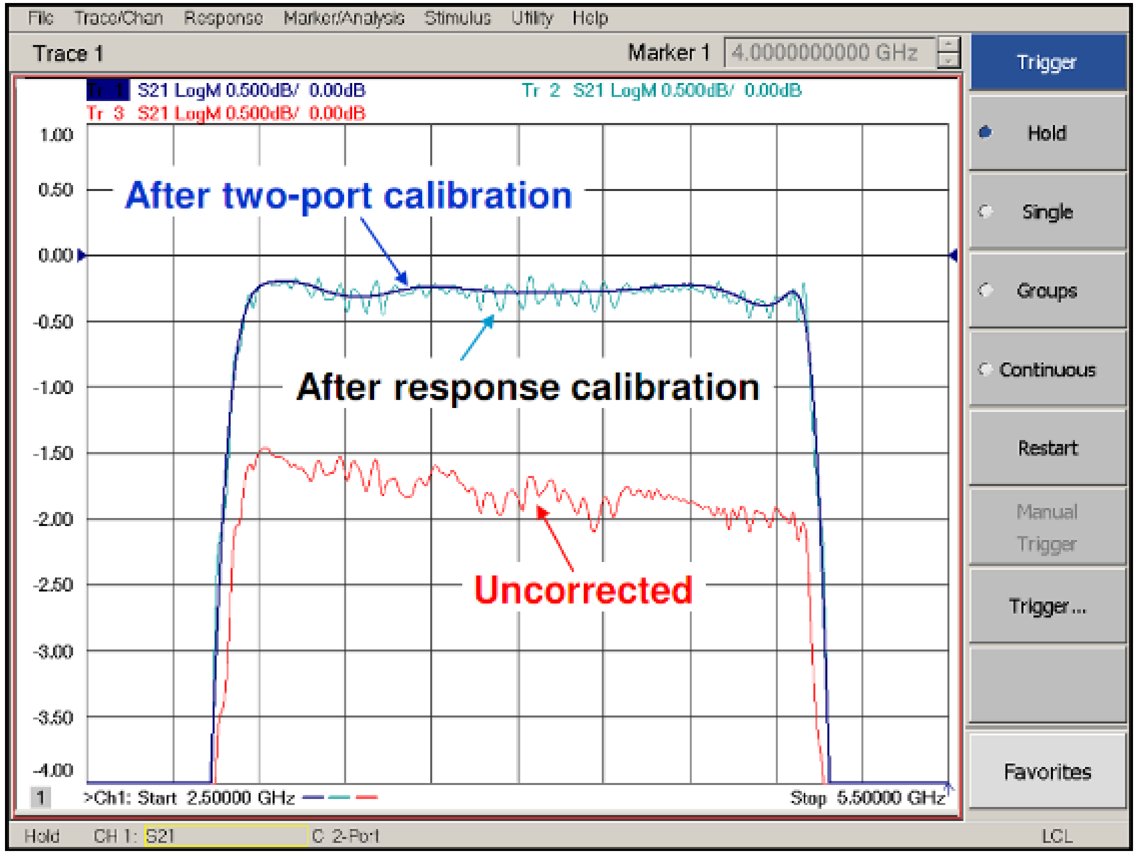
- **Full two-port calibration** *(reflection and transmission measurements)*
  - Twelve systematic error terms measured
  - 10 measurements on four known standards (SOLT)
  - 7 measurements using Unknown Thru; 4 measurements using QSOLT

- **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



KEYSIGHT
TECHNOLOGIES

KEYSIGHT
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