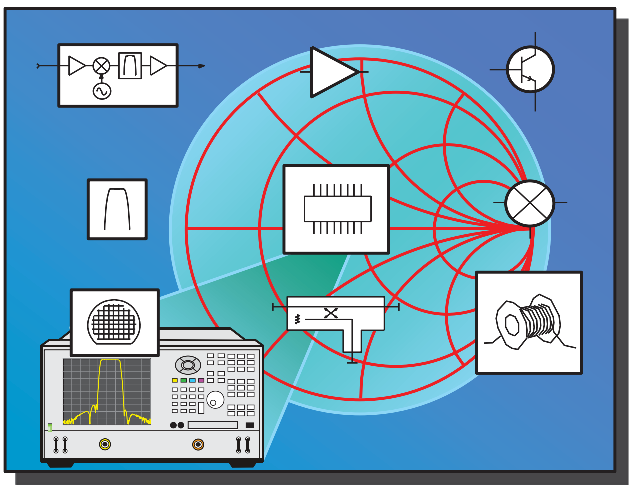
Network Analysis
Back to Basics

Objectives

Review RF basics

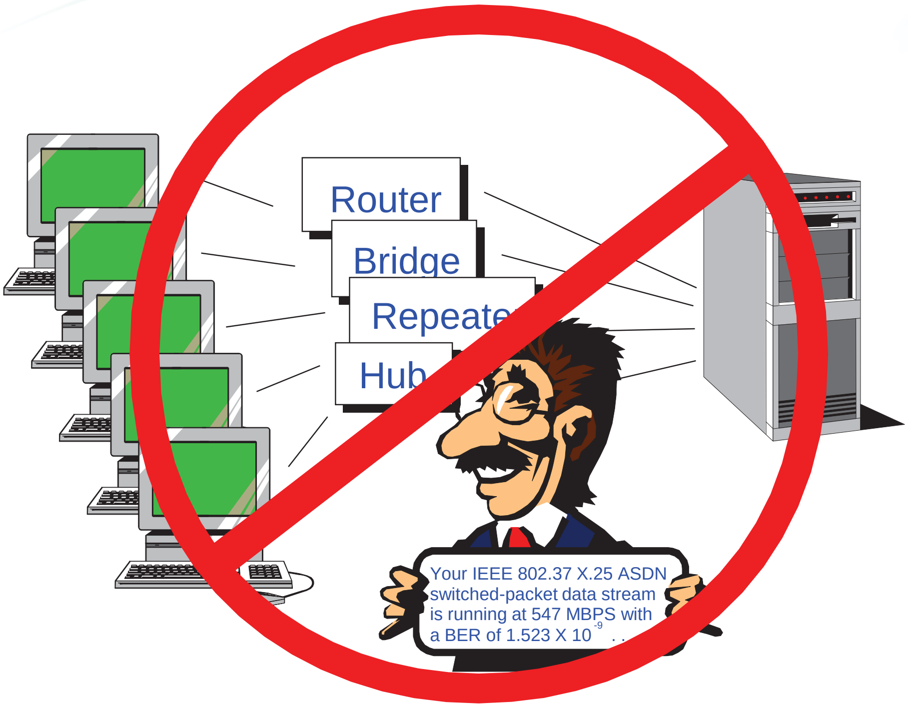
Understand fundamentals on S-parameter measurements

Examine architectures and calibrations of VNAs

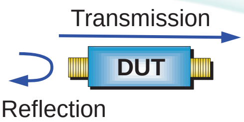


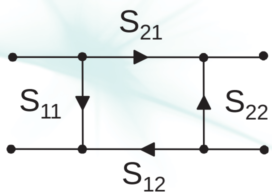
Anticipate ___Accelerate ___Achieve
Agilent Technologies
May 30, 2013

Network Analysis is NOT….



What Are Vector Network Analyzers?





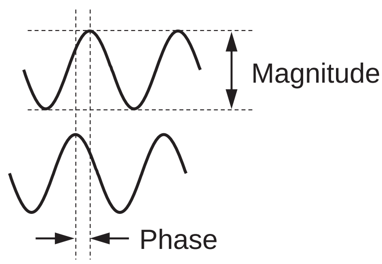
Are stimulus-response test systems

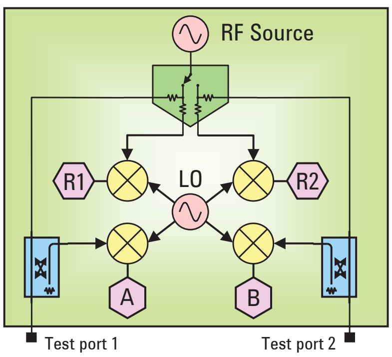
Characterize forward and reverse reflection and transmission responses (S-parameters) of RF and microwave components

Quantify linear magnitude and phase

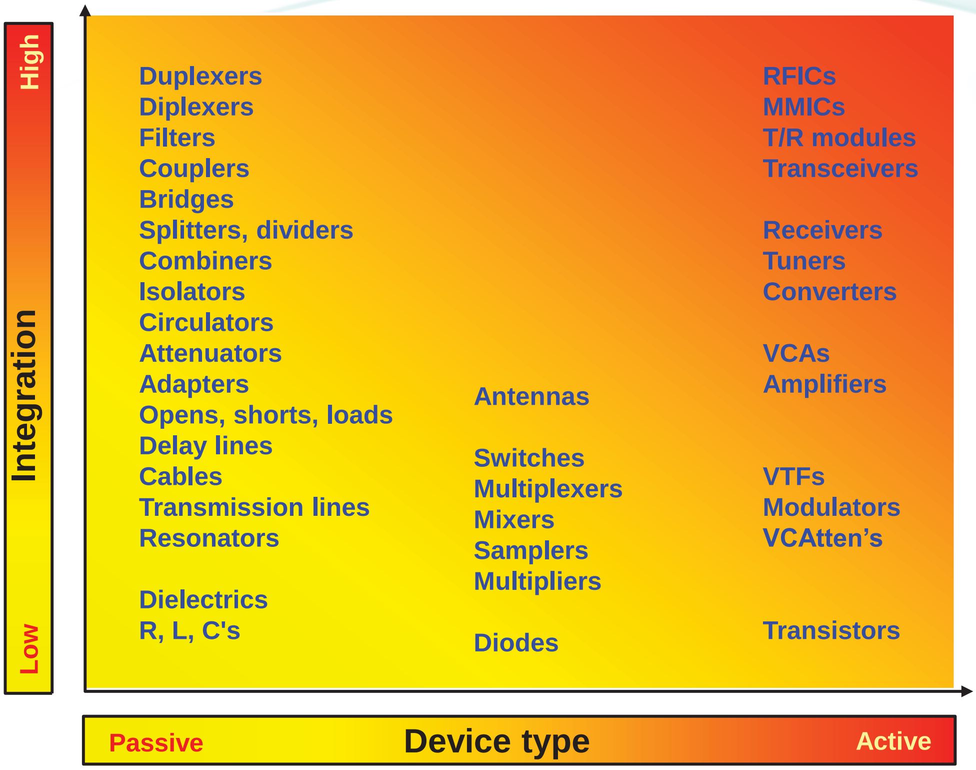
Are very fast for swept measurements

Provide the highest level of measurement accuracy

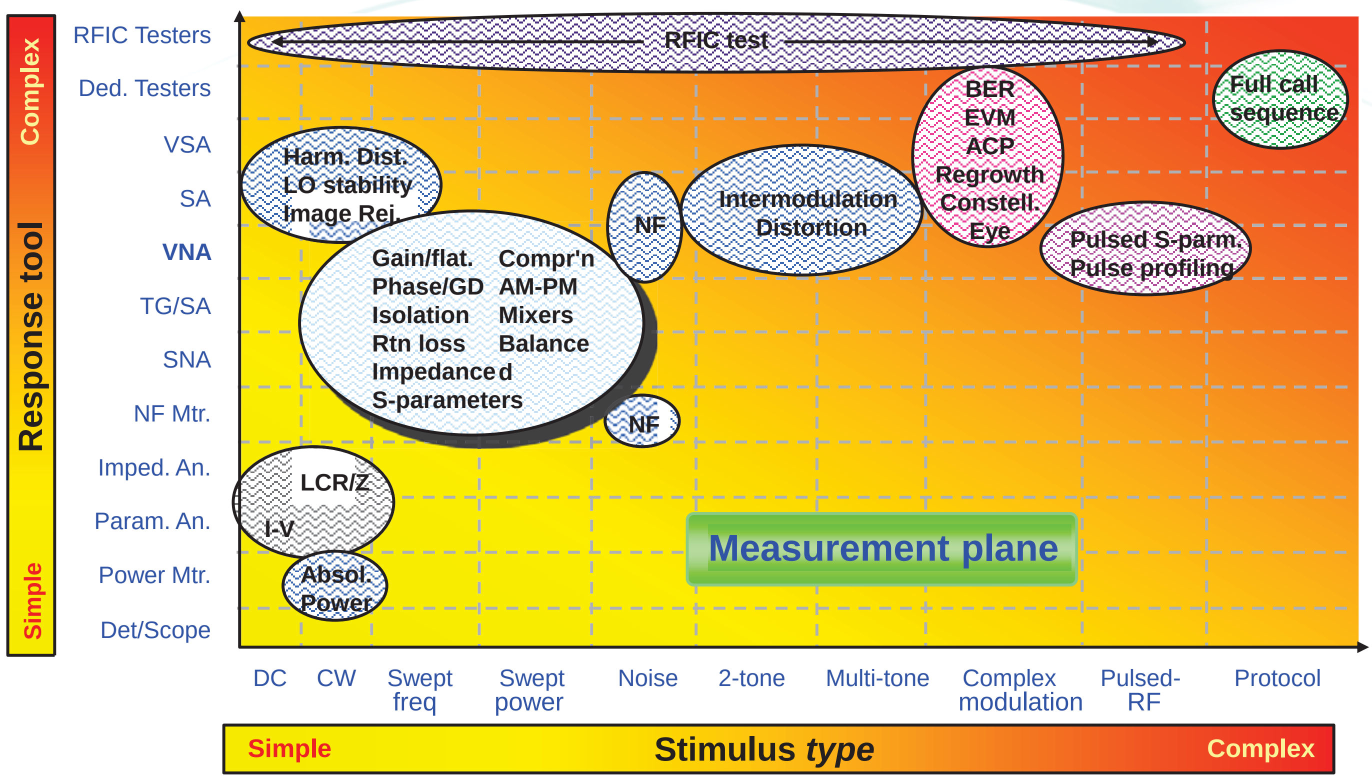




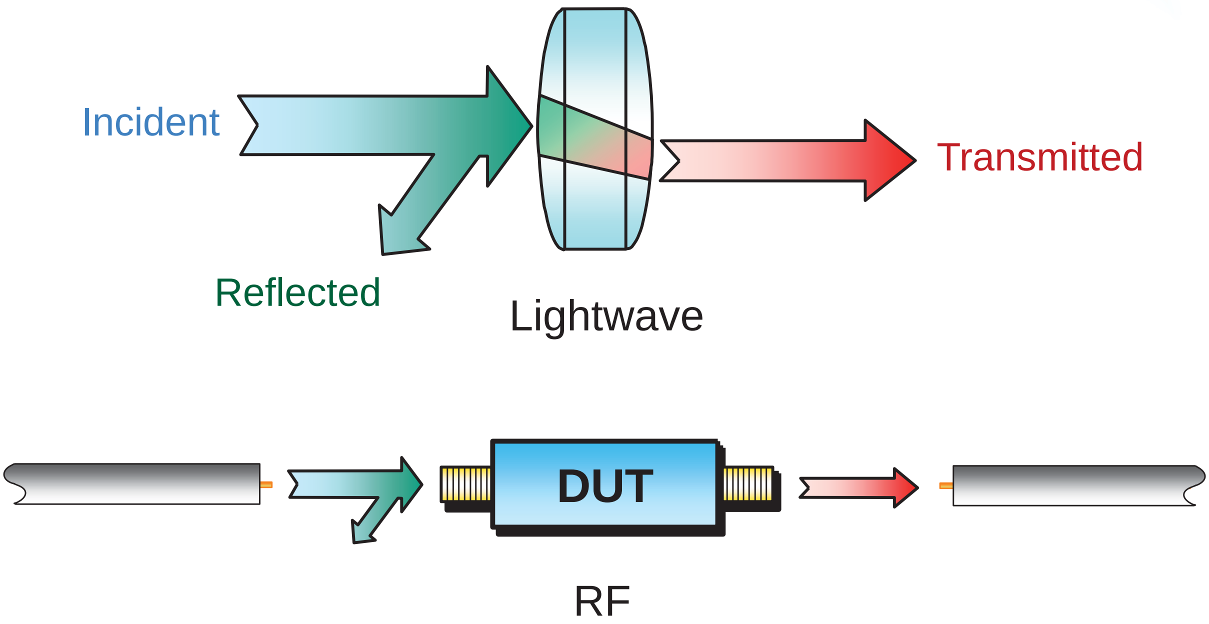
What Types of Devices are Tested?



Device Test Measurement Model



Lightwave Analogy to RF Energy



Why Do We Need to Test Components?

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

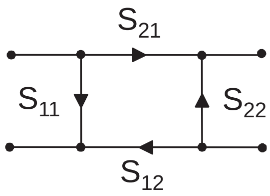
Ensure distortionless transmission of communications signals

- Linear: constant amplitude, linear phase / constant group delay
- Nonlinear: harmonics, intermodulation, compression, X-parameters

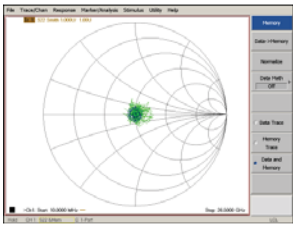
Ensure good match when absorbing power (e.g., an antenna)

The Need for Both Magnitude and Phase

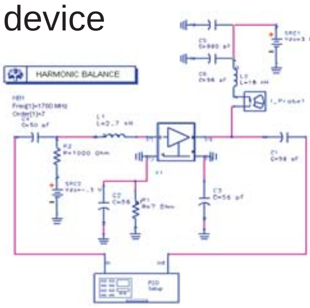
1. Complete characterization of linear networks



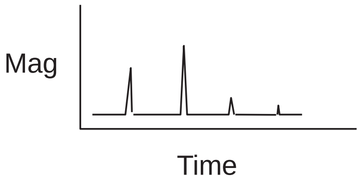
2. Complex impedance needed to design matching circuits



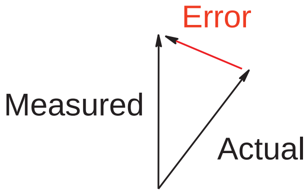
3. Complex values needed for device modeling



4. Time-domain characterization

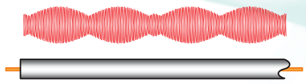


5. Vector-error correction

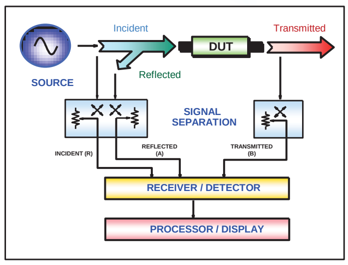


6. X-parameter (nonlinear) characterization

Agenda



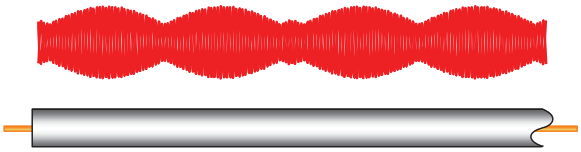
- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Advanced S-parameter measurements



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

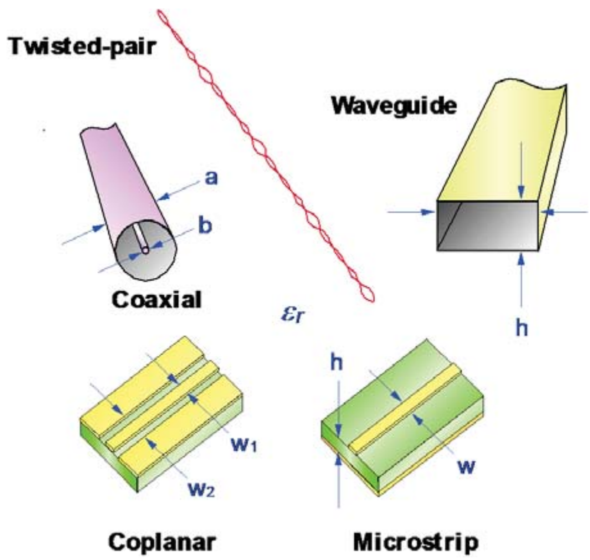
- Wavelength ≈ or << length of transmission medium
- Need transmission lines for efficient power transmission
- Matching to characteristic impedance (Z_o) is very important for low reflection and maximum power transfer
- Measured envelope voltage dependent on position along line

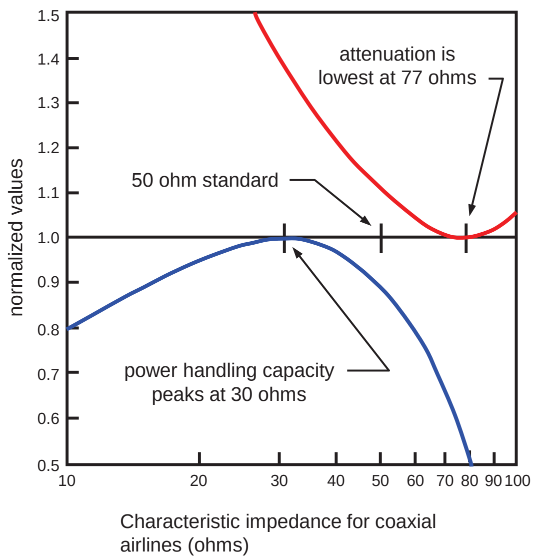
Transmission line Z_o

Z_o determines relationship between voltage and current waves

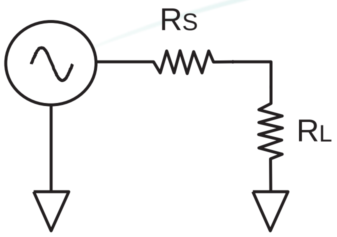
Z_o is a function of physical dimensions and ε_r

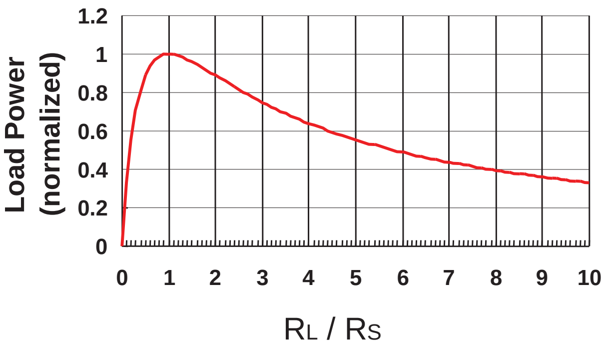
Z_o is usually a real impedance (e.g. 50 or 75 ohms)





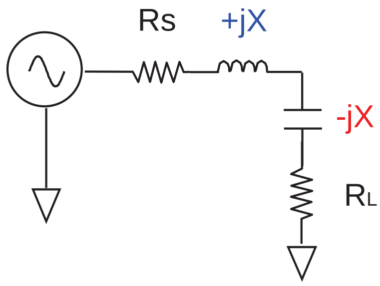
Power Transfer Efficiency





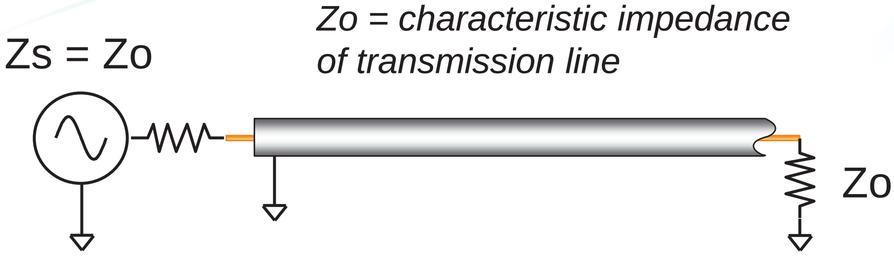
Maximum power is transferred when $R_L = R_S$

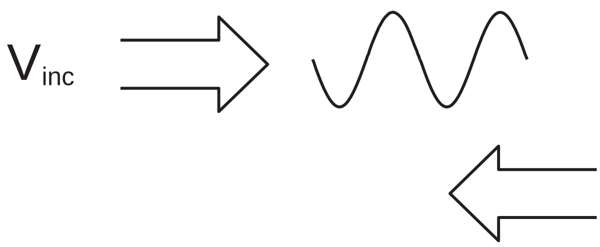
For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)



Transmission Line Terminated with Zo

Zo = characteristic impedance of transmission line

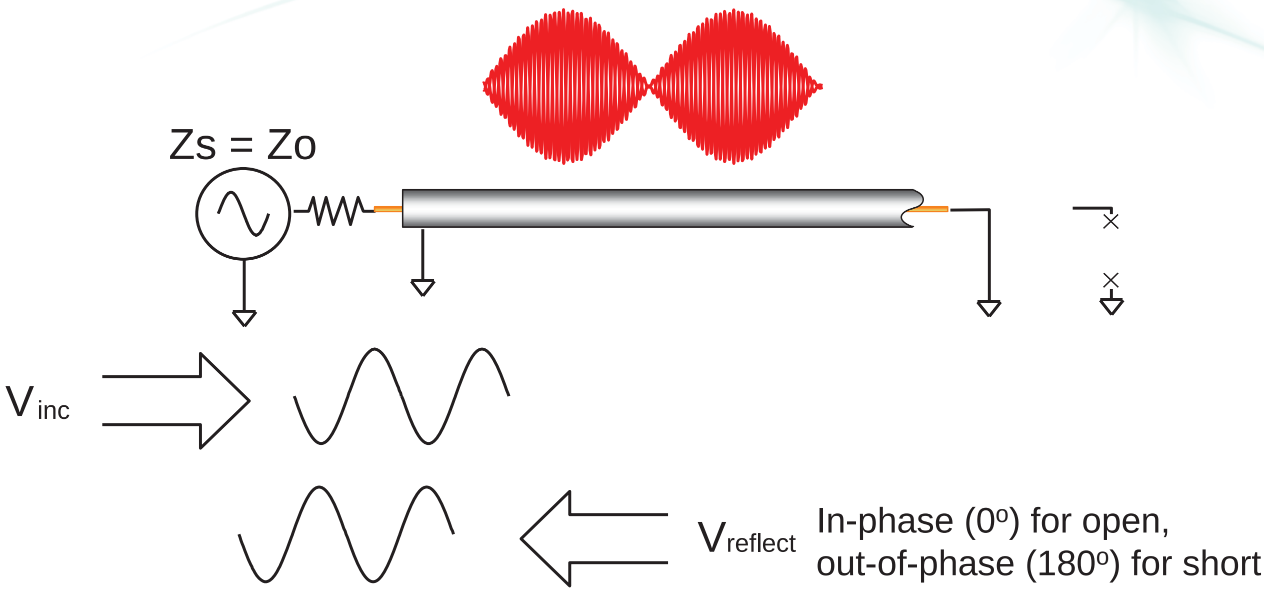




$V_{reflect}$ = 0! *(all the incident power is transferred to and absorbed in the load)*

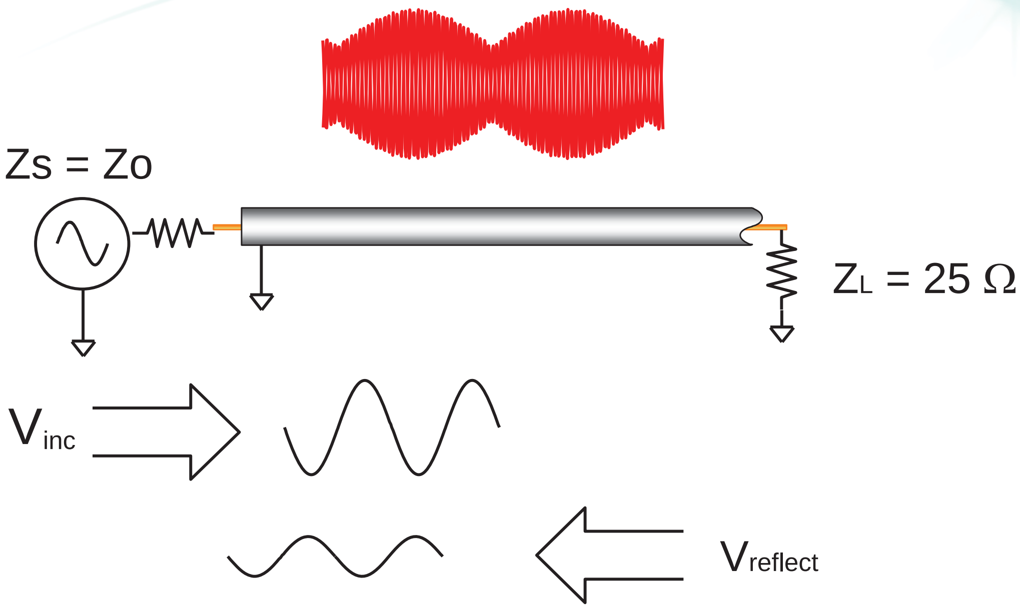
For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

Transmission Line Terminated with Short, Open



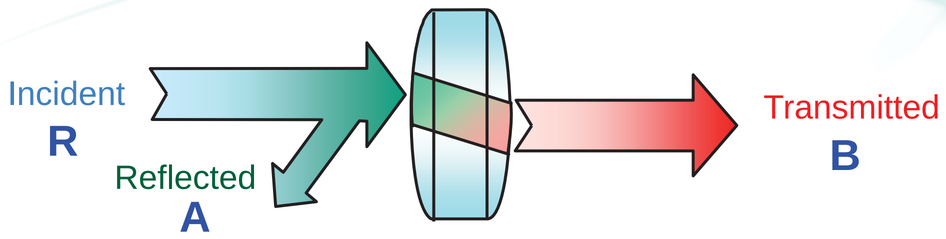
For reflection, a transmission line terminated in a short or open reflects all power back to source

Transmission Line Terminated with 25 Ohms



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

High-Frequency Device Characterization



REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

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

TRANSMISSION

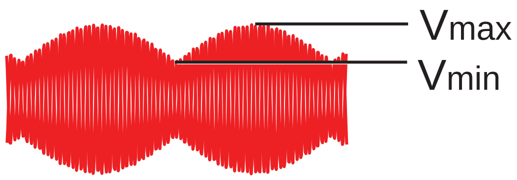
$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

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

Reflection Parameters

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

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

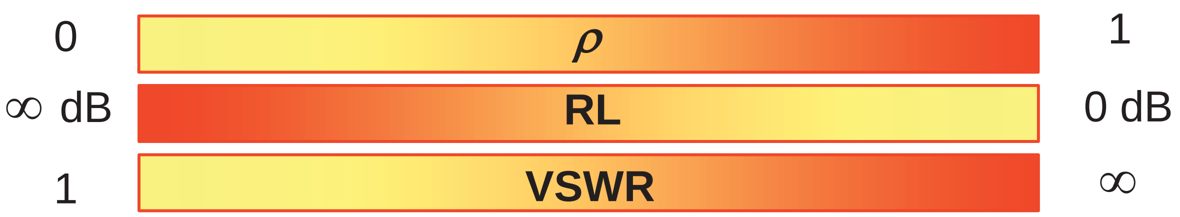


Voltage Standing Wave Ratio

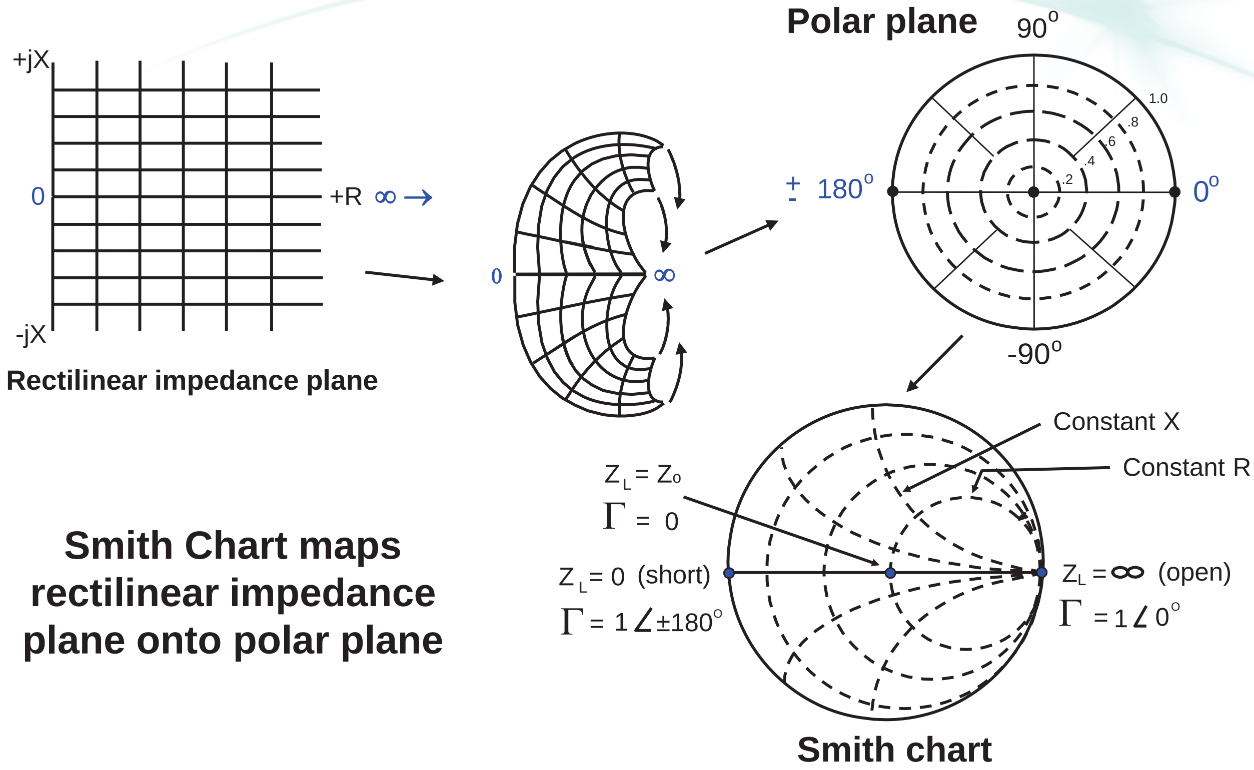
$$\textbf{VSWR} = \frac{V_{max}}{V_{min}} = \frac{1+\rho}{1-\rho}$$

No reflection
($Z_L = Z_o$)

Full reflection
(Z_L = open, short)



Smith Chart Review



Smith Chart maps rectilinear impedance plane onto polar plane

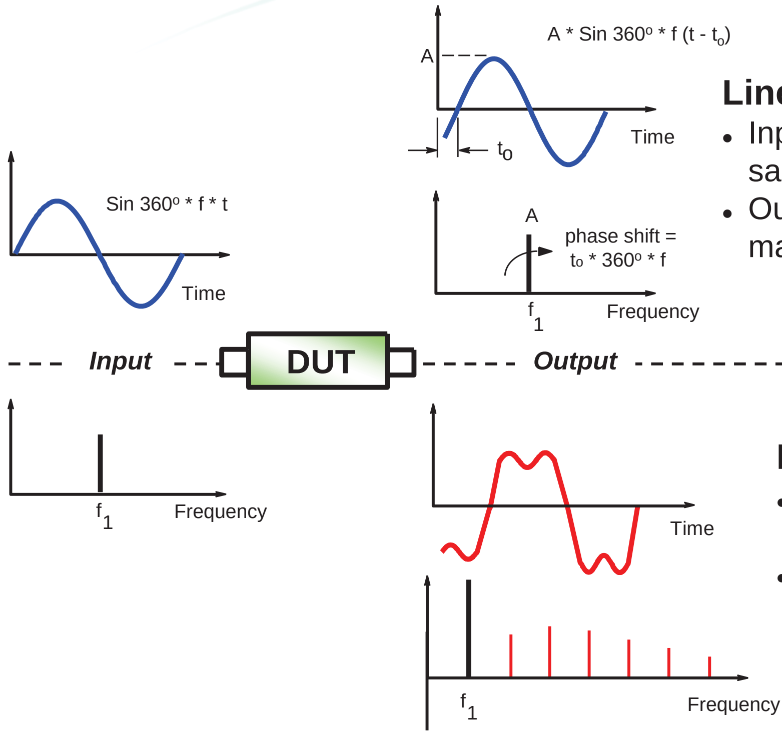
Transmission Parameters

$$\text{Transmission Coefficient} = T = \frac{V_{Transmitted}}{V_{Incident}} = \tau \angle \phi$$

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

$$\text{Gain (dB)} = 20 \text{ Log} \left| \frac{V_{Trans}}{V_{Inc}} \right| = 20 \text{ Log}(\tau)$$

Linear Versus Nonlinear Behavior



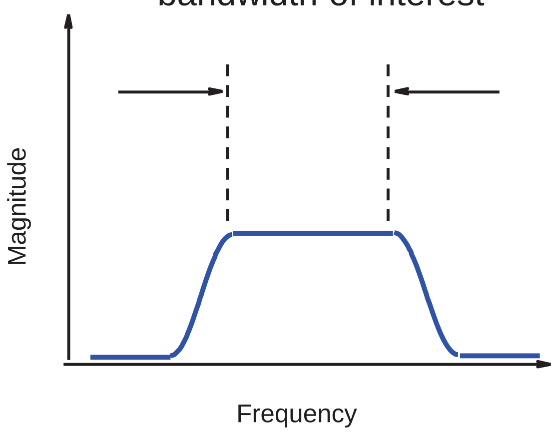
Linear behavior:
- Input and output frequencies are the same (no additional frequencies created)
- Output frequency only undergoes magnitude and phase change

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

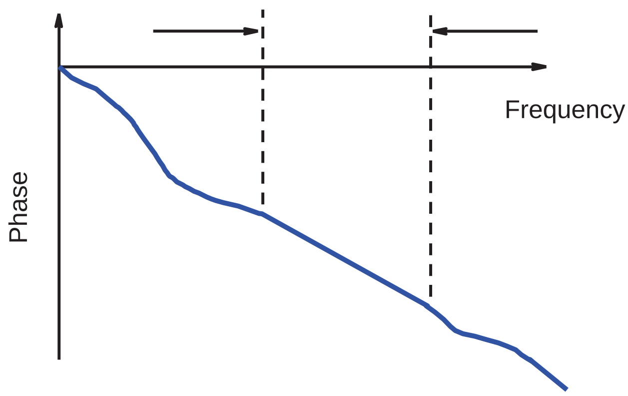
Criteria for Distortionless Transmission

Linear Networks

Constant amplitude over bandwidth of interest

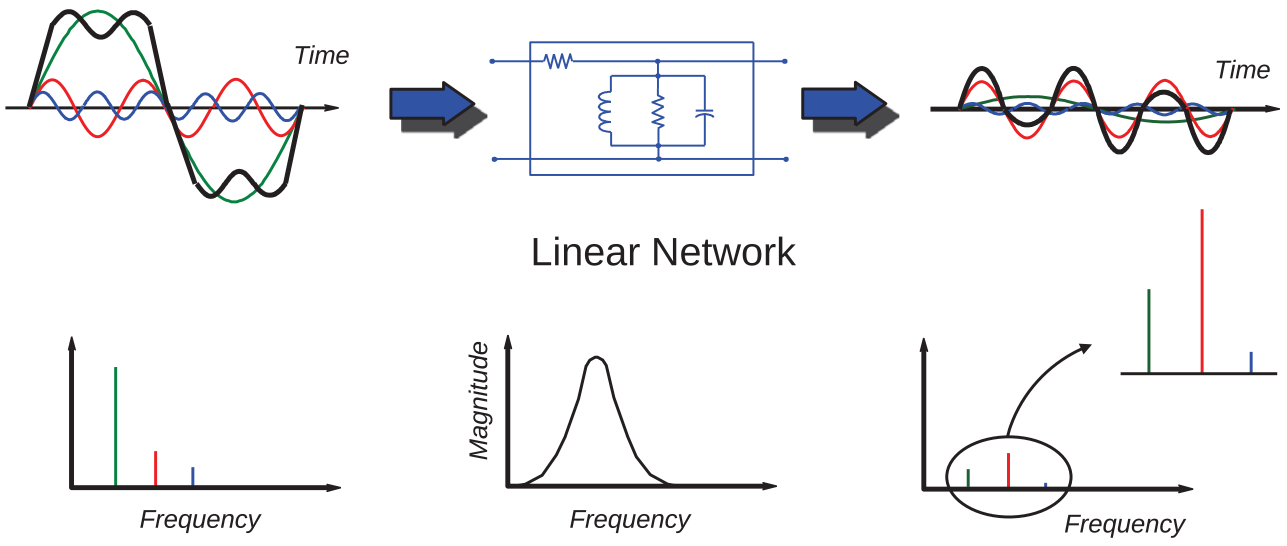


Linear phase over bandwidth of interest



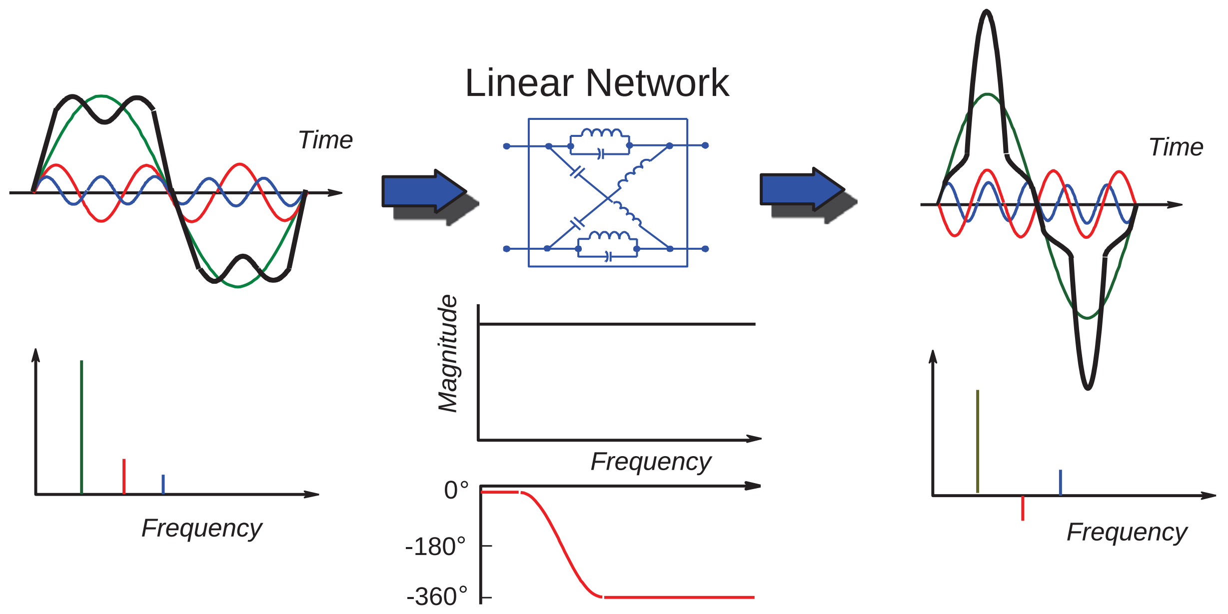
Magnitude Variation with Frequency

F(t) = sin wt + 1/3 sin 3wt + 1/5 sin 5wt



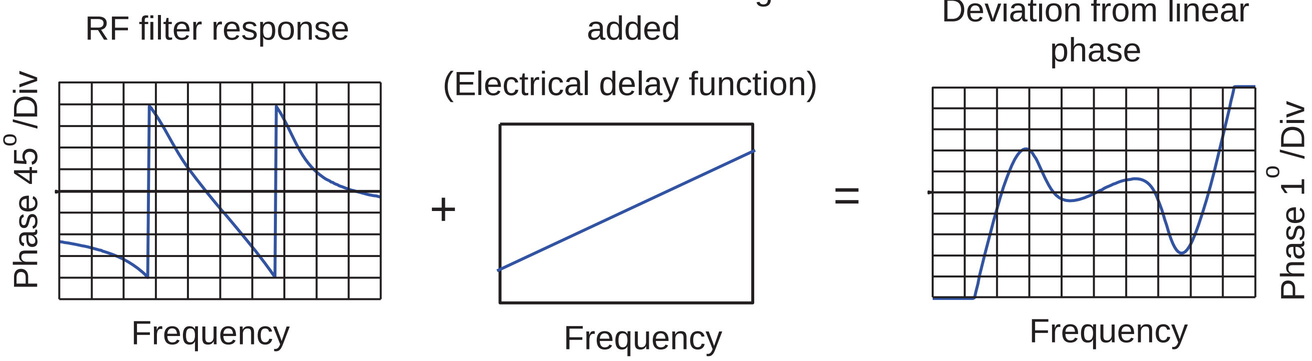
Phase Variation with Frequency

F(t) = sin wt + 1 /3 sin 3wt + 1 /5 sin 5wt



Deviation from Linear Phase

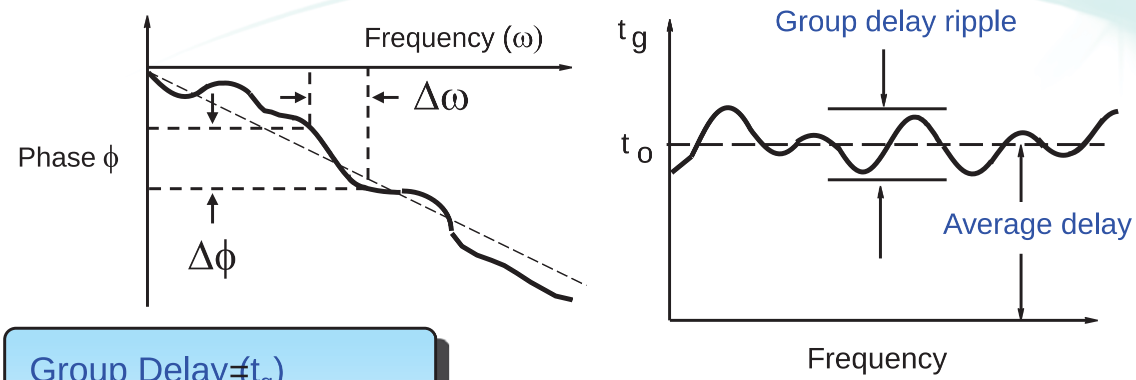
Use electrical delay to remove linear portion of phase response



Low resolution

High resolution

Group Delay



Group Delay (t_g)

$$\frac{-d\,\phi}{d\,\omega} = \frac{-1}{360^{o}} * \frac{d\,\phi}{d\,f}$$

ϕ in radians

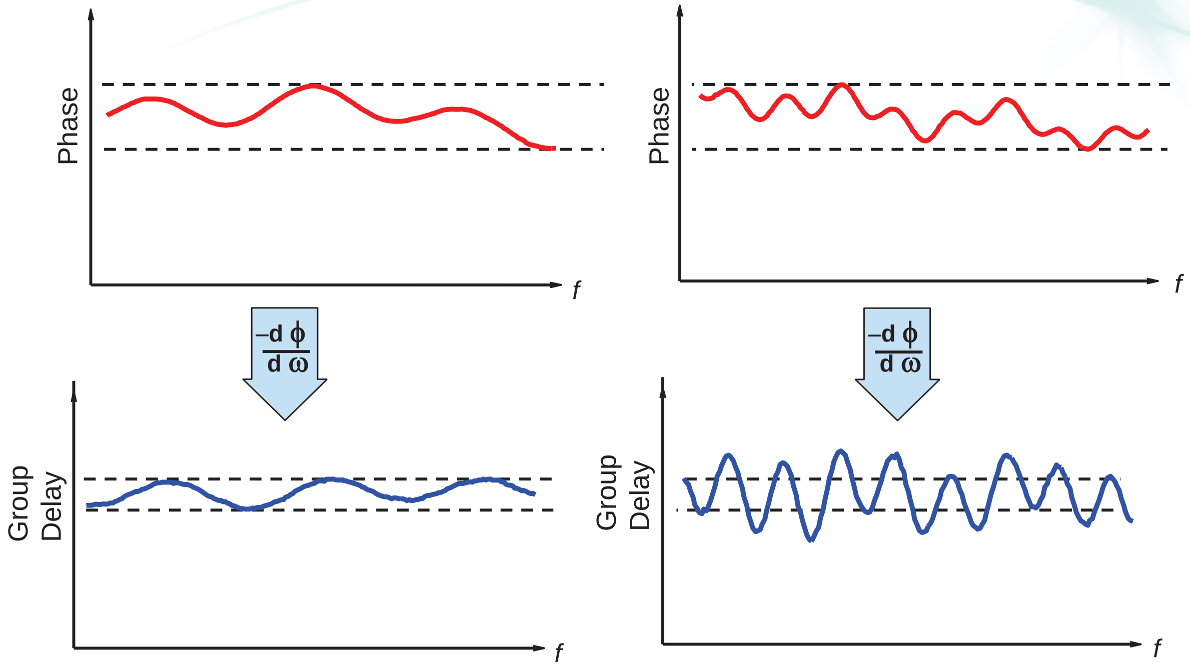
ω in radians/sec

ϕ in degrees

f in Hertz ($\omega = 2\,\pi\,f$)

- Group-delay ripple indicates phase distortion
- Average delay indicates electrical length of DUT
- Aperture ($\Delta\omega$) of measurement is very important

Why Measure Group Delay?



Same peak-peak phase ripple can result in different group delay

Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

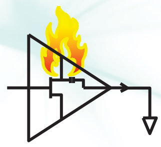
- Gives linear behavioral model of our device
- Measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- Compute device parameters from measured data
- Predict circuit performance under any source and load conditions

H-parameters	Y-parameters	Z-parameters
$V_1 = h_{11}I_1 + h_{12}V_2$	$I_1 = y_{11}V_1 + y_{12}V_2$	$V_1 = z_{11}I_1 + z_{12}I_2$
$I_2 = h_{21}I_1 + h_{22}V_2$	$I_2 = y_{21}V_1 + y_{22}V_2$	$V_2 = z_{21}I_1 + z_{22}I_2$

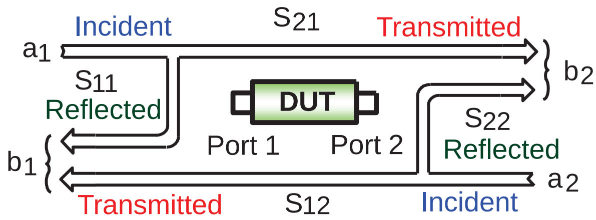
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit)***

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

Why Use S-Parameters?



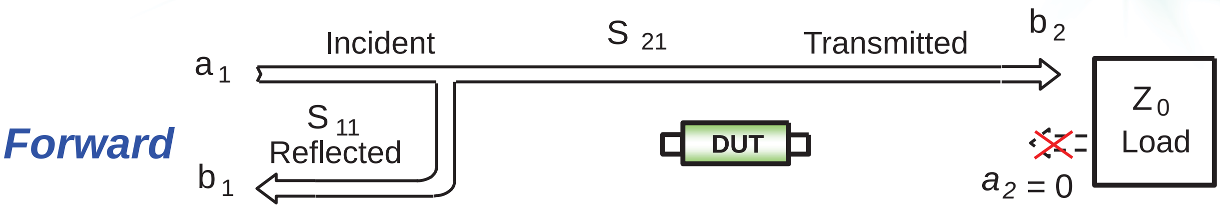
- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade**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

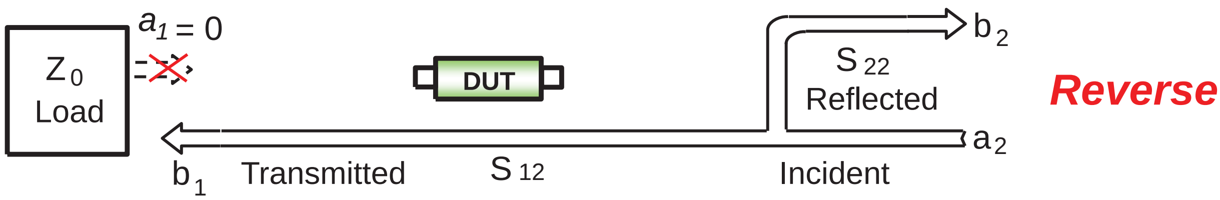


$$S_{11} = \frac{Reflected}{Incident} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

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

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

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



Equating S-Parameters With Common Measurement Terms

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

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

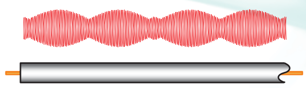
S_{21} = forward transmission coefficient ***(gain or loss)***

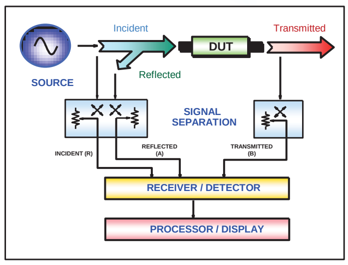
S_{12} = reverse transmission coefficient ***(isolation)***

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

Agenda

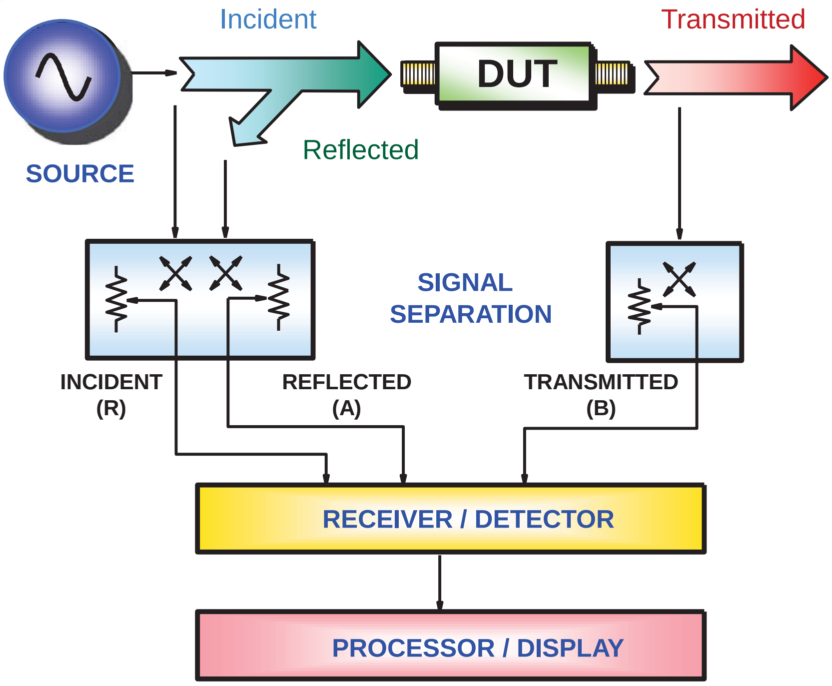
- What measurements do we make?
- ➡ Network analyzer hardware
- Error models and calibration
- Advanced S-parameter measurements



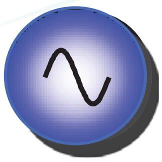


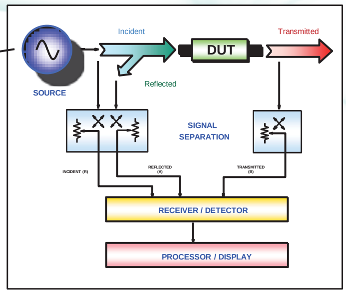
Anticipate __Accelerate __Achieve
Agilent Technologies
May 30, 2013

Generalized Network Analyzer Block Diagram (Forward Measurements Shown)



Source

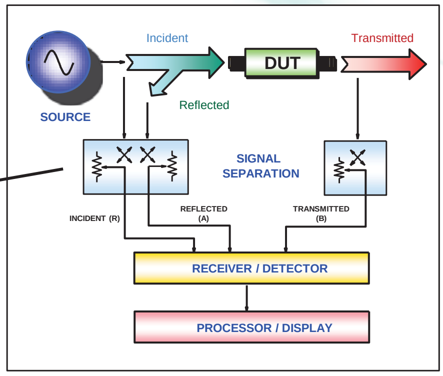


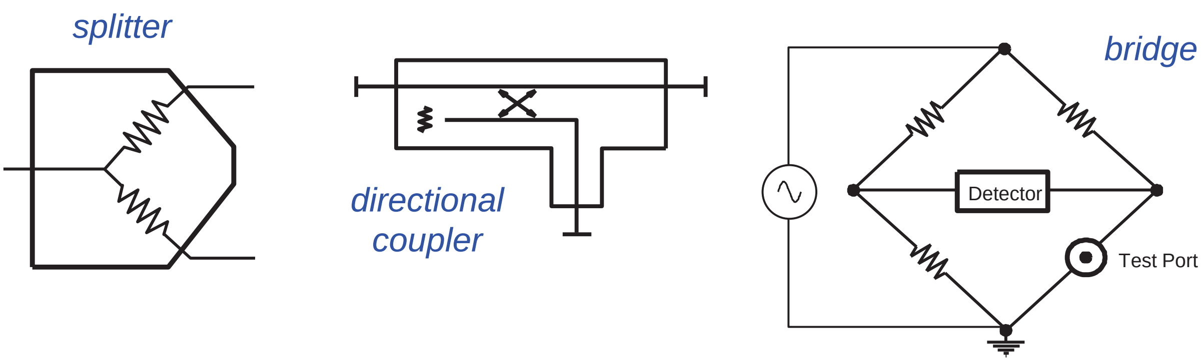


- Supplies stimulus for system
- Can sweep frequency or power
- Traditionally NAs had one signal source
- Modern NAs have the option for a second internal source and/or the ability to control external source.
  - Can control an external source as a local oscillator (LO) signal for mixers and converters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

Signal Separation

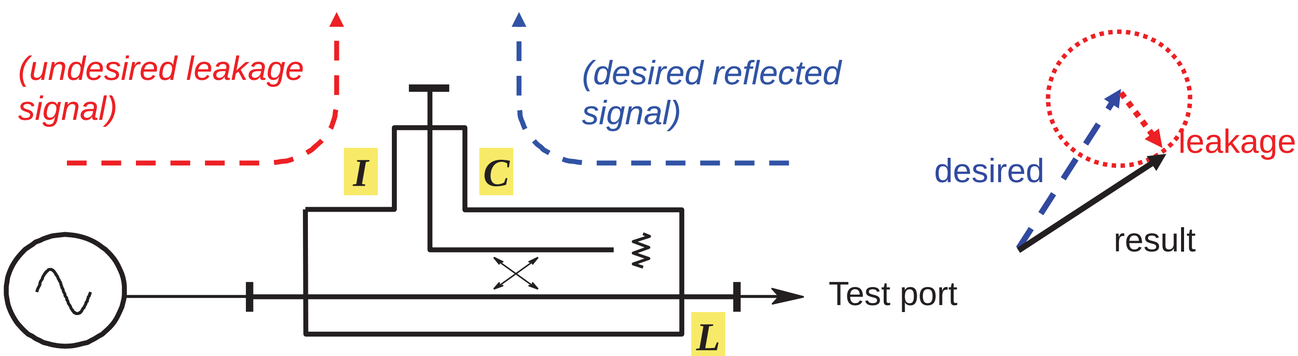
- Measure incident signal for reference
- Separate incident and reflected signals





Directivity

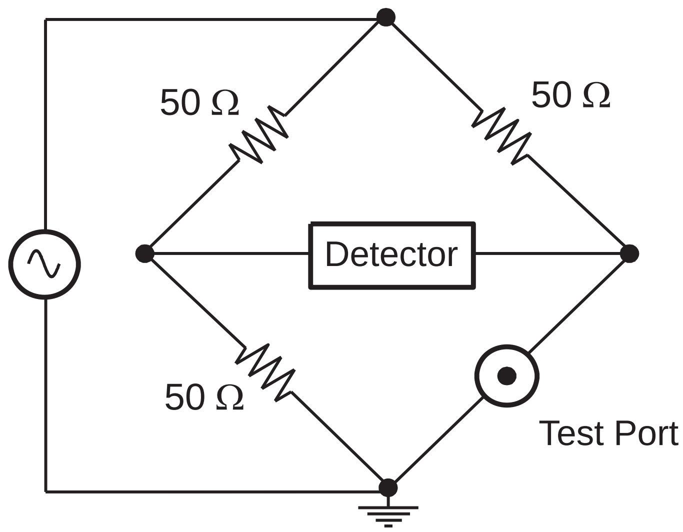
Directivity is a measure of how well a directional coupler or bridge can separate signals moving in opposite directions



Directional Coupler

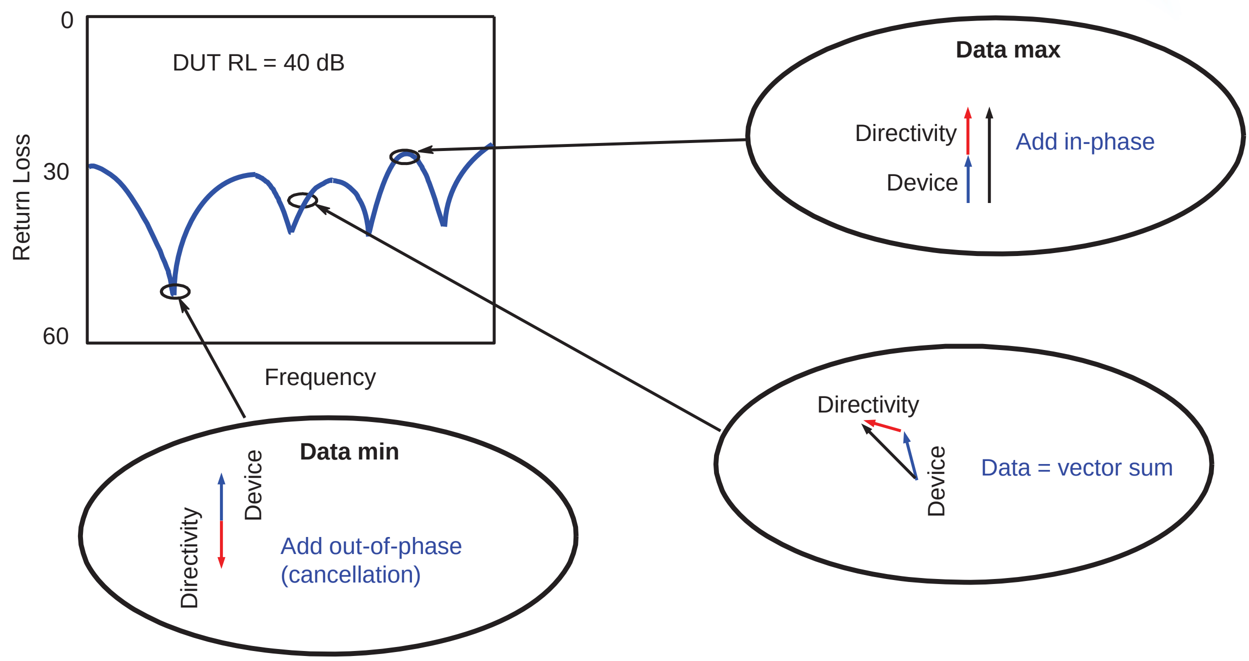
Directivity = Isolation (I) - Fwd Coupling (C) - Main Arm Loss (L)

Directional Bridge

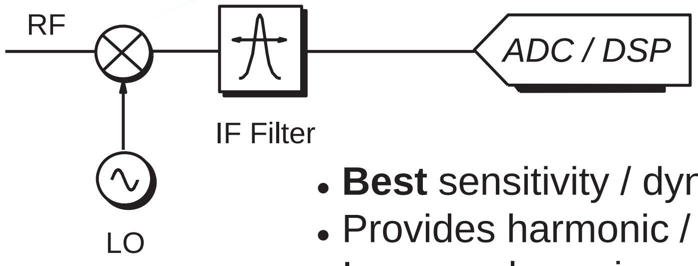


- 50-ohm load at test port balances the bridge -- detector reads zero
- Non-50-ohm load imbalances bridge
- Measuring magnitude and phase of imbalance gives complex impedance
- "Directivity" is difference between maximum and minimum balance
- Advantage: less loss at low frequencies
- Disadvantages: more loss in main arm at high frequencies and less power-handling capability

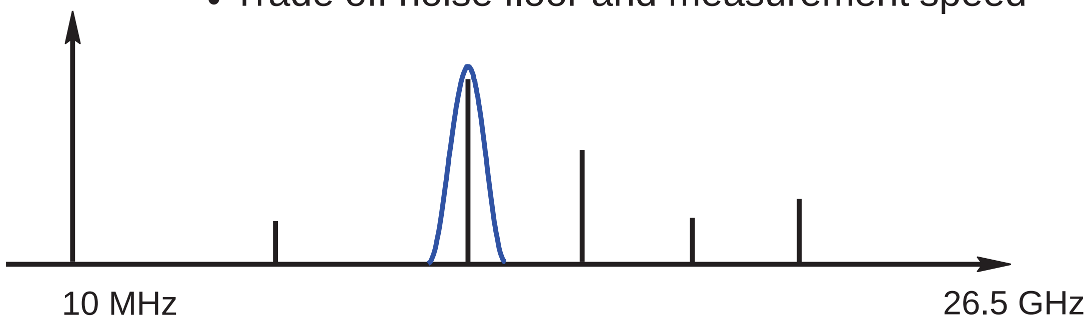
Interaction of Directivity with the DUT (Without Error Correction)



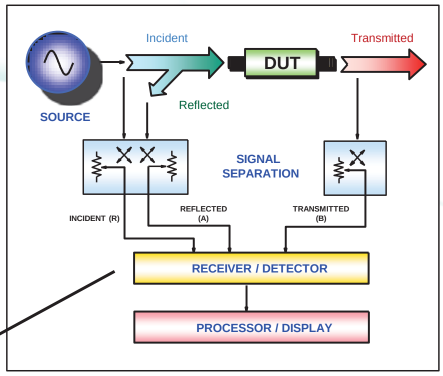
Detector Types:
Narrowband Detection - Tuned Receiver

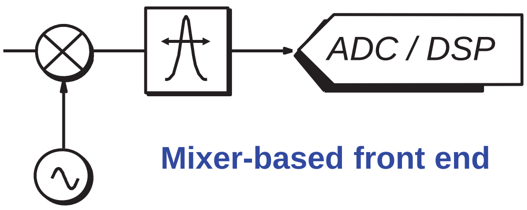


- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**, decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed



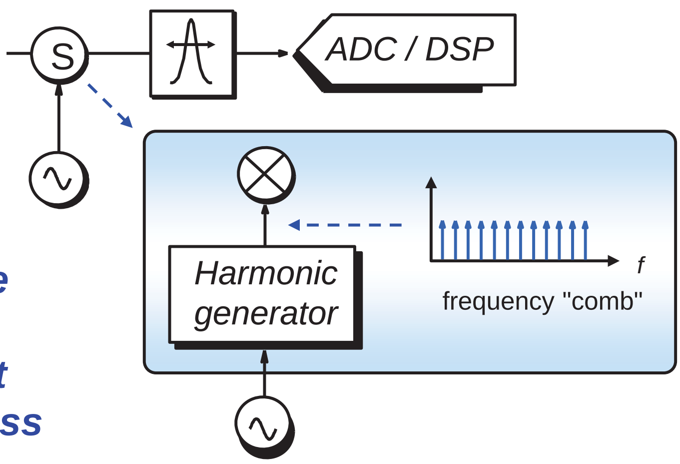
Tuned Receiver Front Ends:
Mixers Versus Samplers





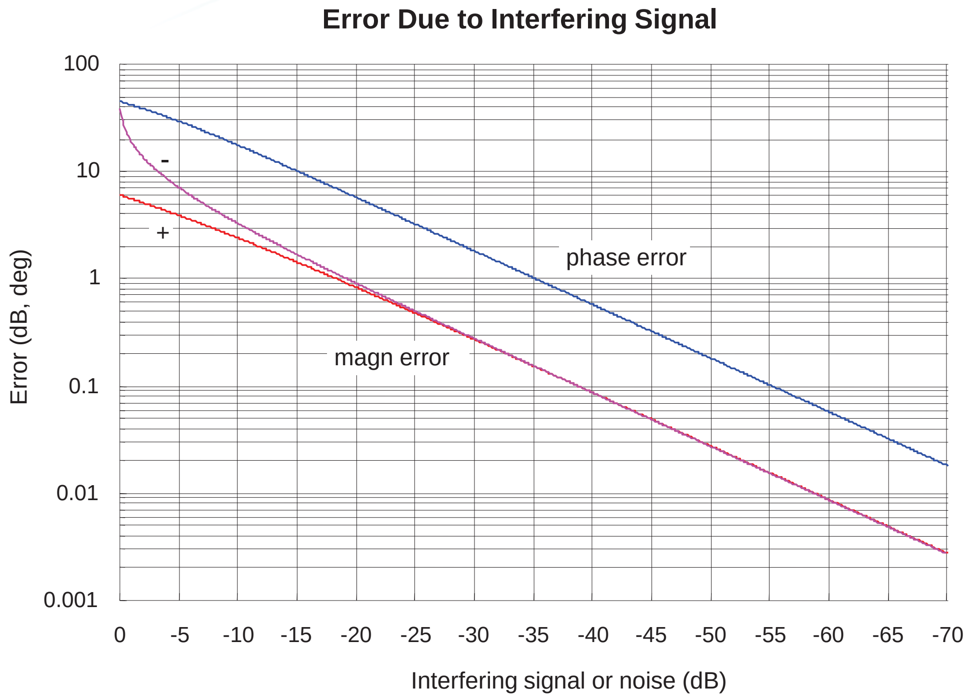
Mixer-based front end

Sampler-based front end



It is cheaper and easier to make broadband front ends using samplers instead of mixers, but dynamic range is considerably less

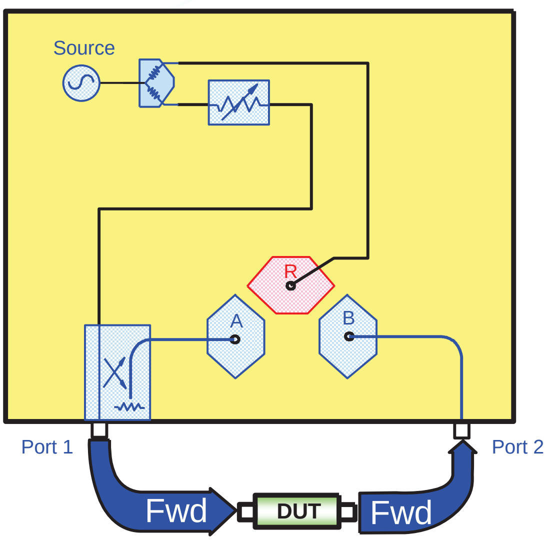
Dynamic Range and Accuracy



Dynamic range is very important for measurement accuracy!

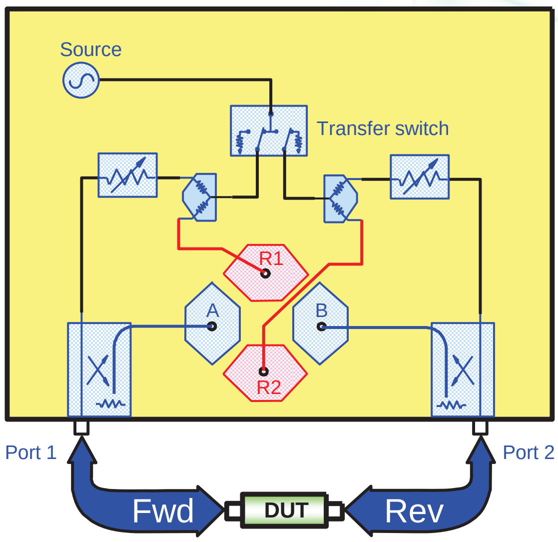
T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



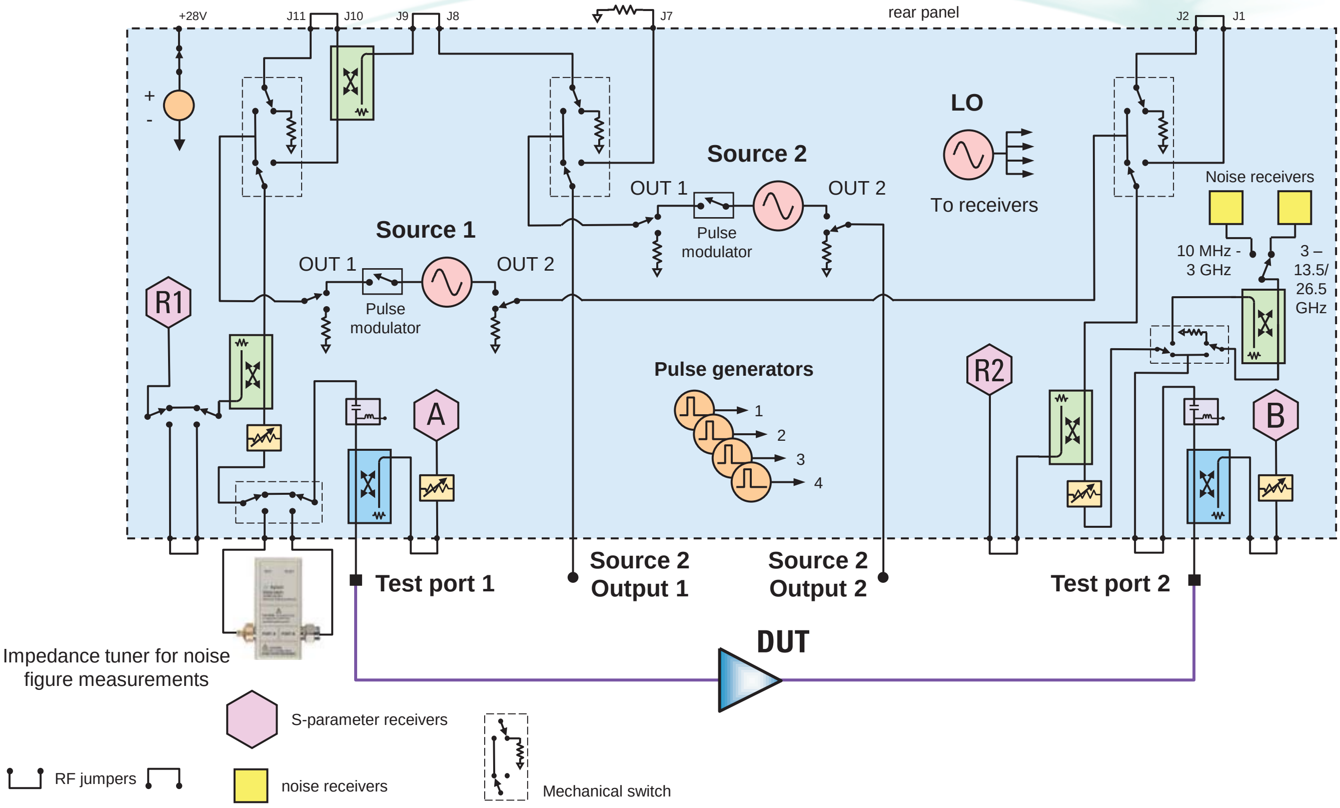
- RF comes out port 1; port 2 is receiver
- Forward measurements only
- **Response**, **one-port** cal available

S-Parameter Test Set

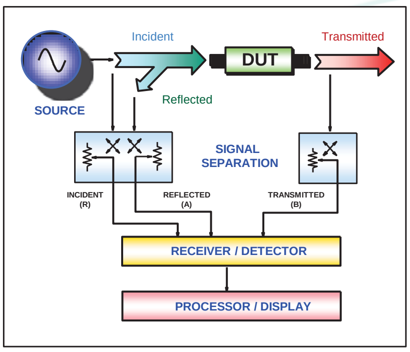


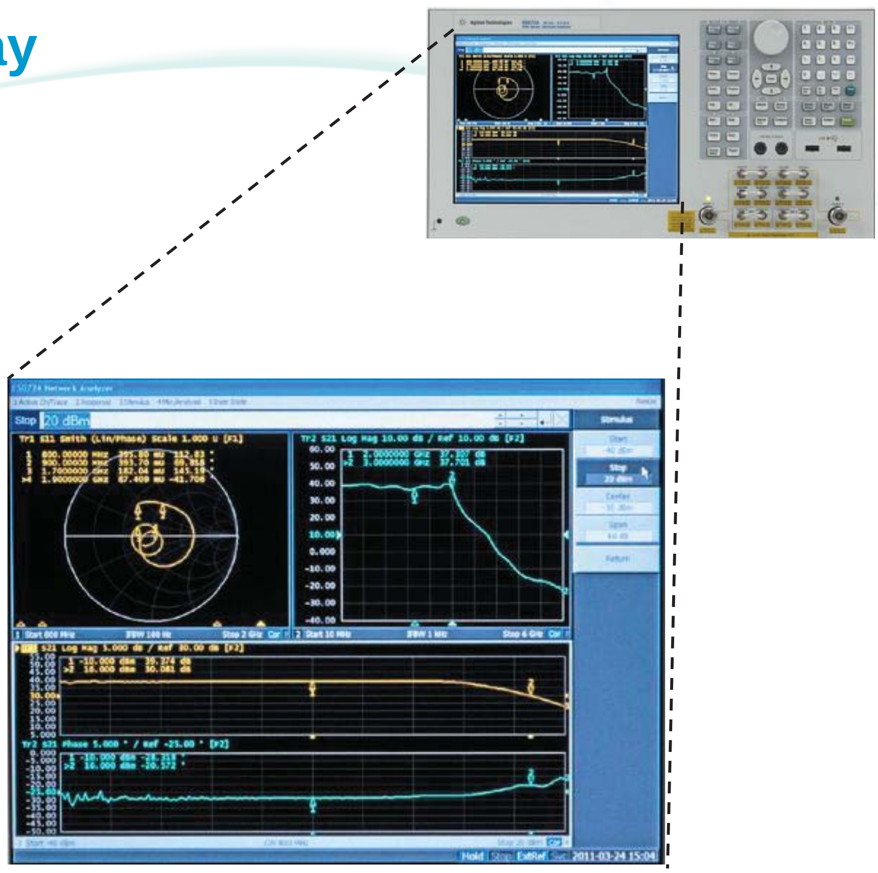
- RF comes out port 1 or port 2
- Forward and reverse measurements
- **Two-port** calibration possible

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



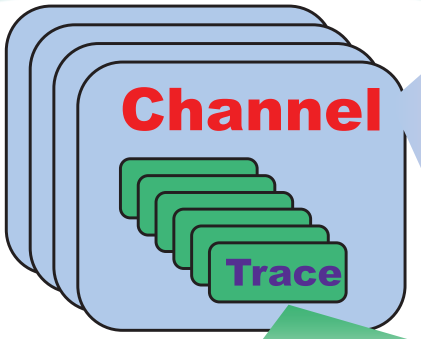
Processor / Display



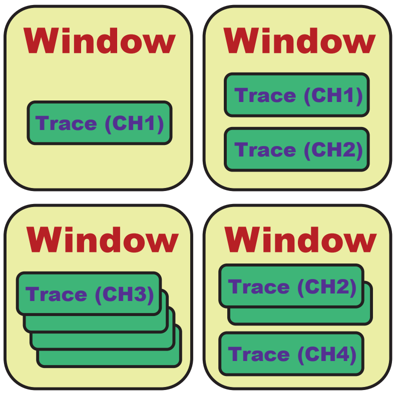


- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math

Achieving Measurement Flexibility

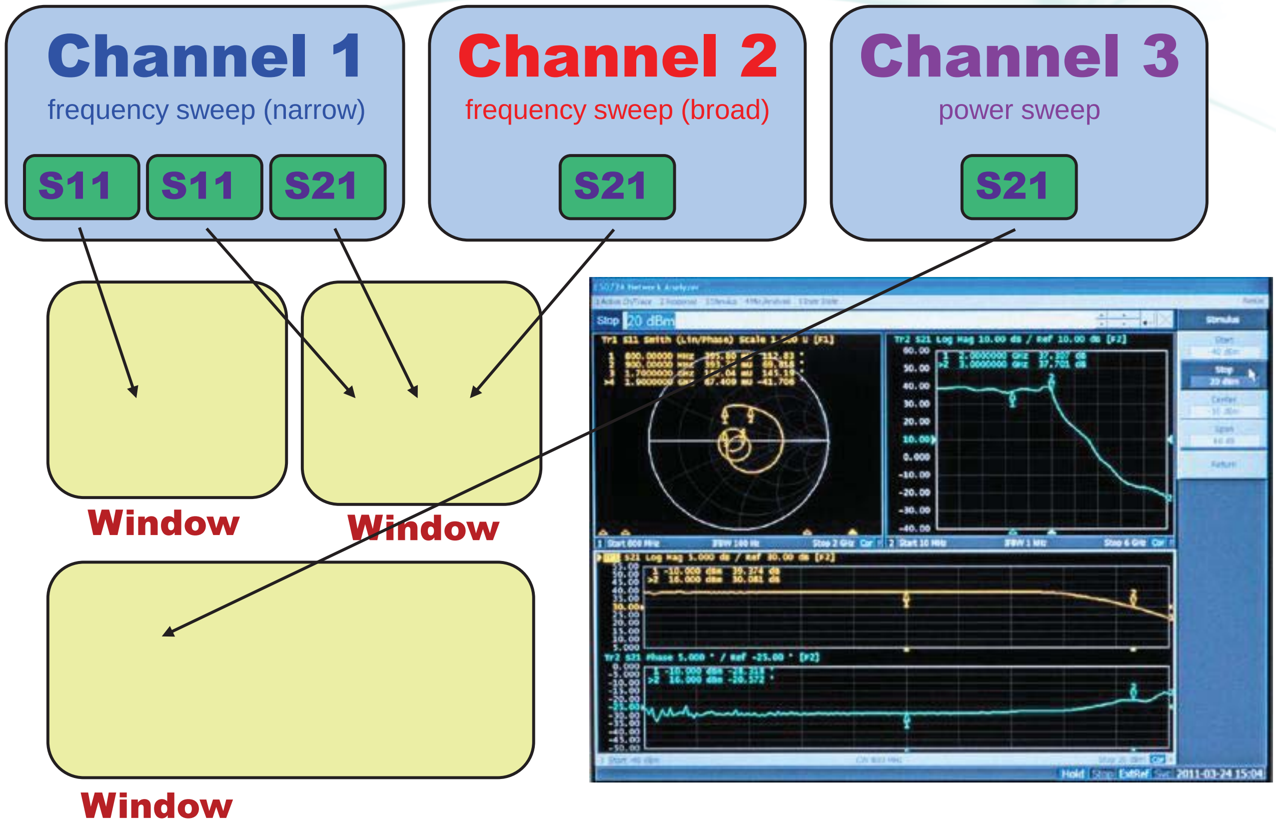


Channel
- Sweep type
- Frequencies
- Power level
- IF bandwidth
- Number of points
- Trigger state
- Averaging
- Calibration



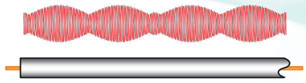
Trace
- Parameter
- Format
- Scale
- Markers
- Trace math
- Electrical delay
- Phase offset
- Smoothing
- Limit tests
- Time-domain transform

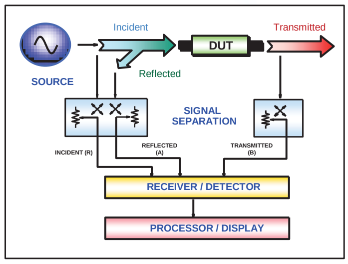
Three Channel Example



Agenda

- What measurements do we make?
- Network analyzer hardware
- ➡ Error models and calibration
- Advanced S-parameter measurements





The Need For Calibration

Why do we have to calibrate?

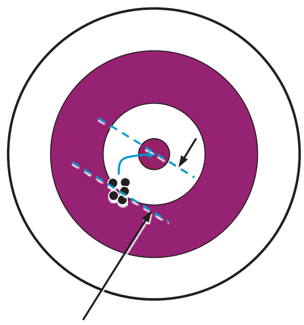
- It is impossible to make perfect hardware
- It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

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



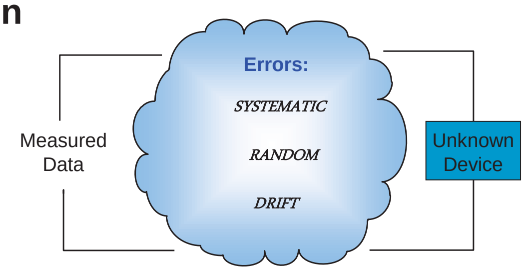
Systematic error

Measurement Error Modeling

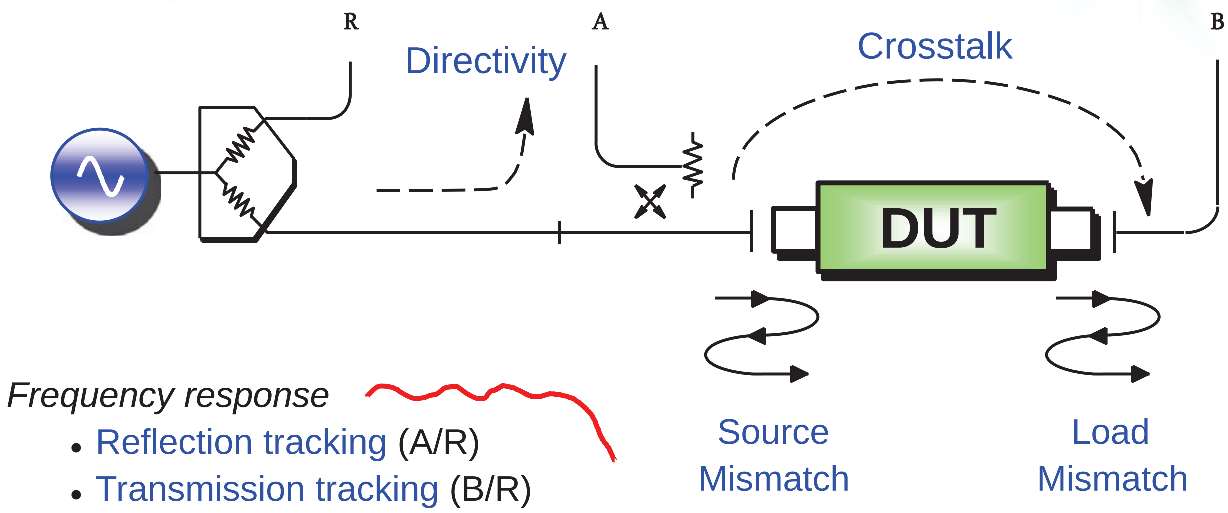
Systematic errors
- Due to **imperfections** in the analyzer and test setup
- Assumed to be **time invariant** (predictable)
- Generally, are largest sources or error

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**

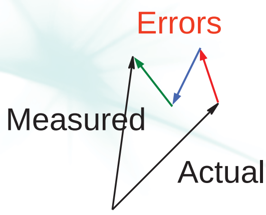


Systematic Measurement Errors



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

What is Vector-Error Correction?



Vector-error correction…

- Is a process for characterizing systematic error terms
- Measures known electrical standards
- Removes effects of error terms from subsequent measurements

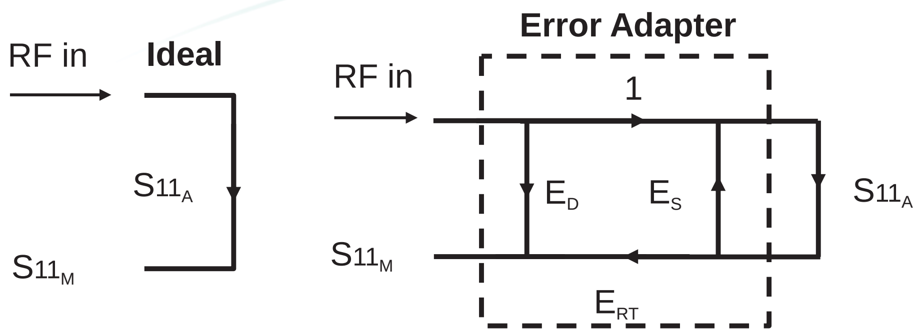
Electrical standards…

- Can be mechanical or electronic
- Are often an open, short, load, and thru, but can be arbitrary impedances as well

Using Known Standards to Correct for Systematic Errors

- **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
  - Usually requires 12 measurements on four known standards (SOLT)
- Standards defined in **cal kit definition** file
  - Network analyzer contains standard cal kit definitions
  - CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!
  - User-built standards must be characterized and entered into user cal-kit

Reflection: One-Port Model



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

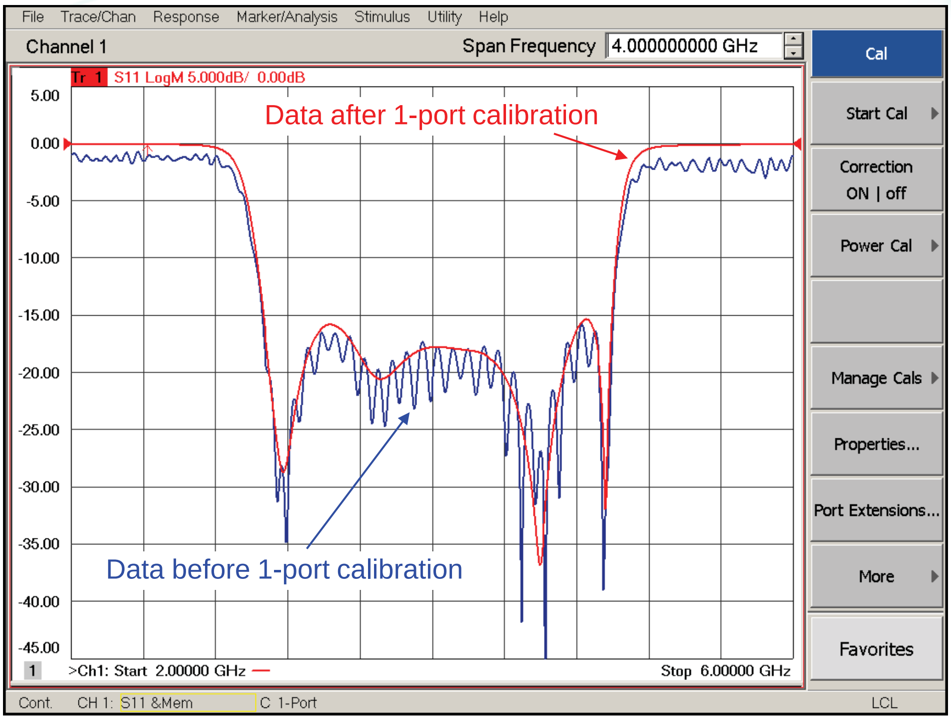
$S11_A$ = Actual

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

$$S11_M = E_D + E_{RT}\left[\frac{S11_A}{1 - E_S\, S11_A}\right]$$

- 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

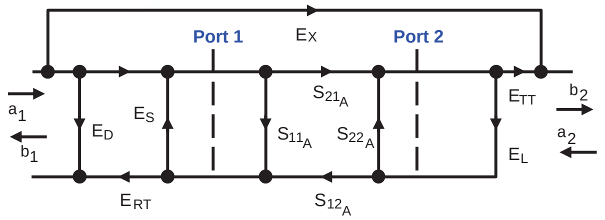
Before and After A One-Port Calibration



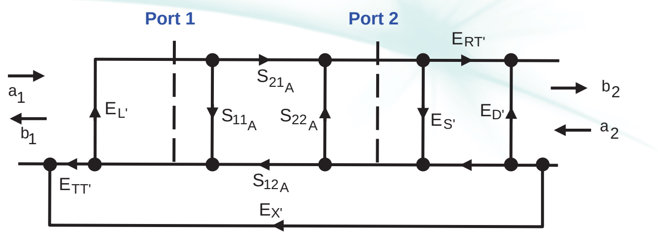
Anticipate __Accelerate __Achieve
Agilent Technologies
May 30, 2013

Two-Port Error Correction

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 analyzers!!!

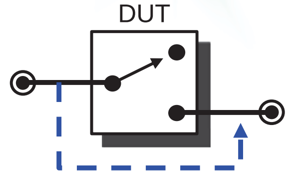
$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_{D'}}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

Crosstalk: Signal Leakage Between Test Ports During Transmission

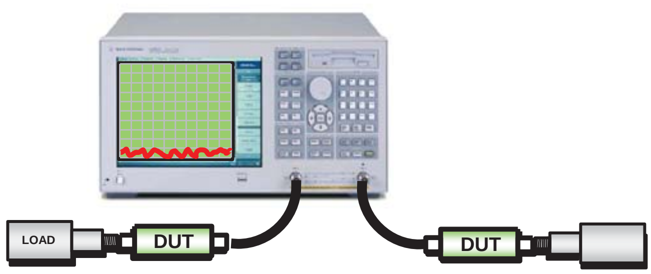


Can be a problem with:

- High-isolation devices (e.g., switch in open position)
- High-dynamic range devices (some filter stopbands)

Isolation calibration

- Adds noise to error model (measuring near noise floor of system)
- Only perform if really needed (use averaging if necessary)
- If crosstalk is **independent** of DUT match, use two terminations
- If **dependent** on DUT match, use two DUTs with termination on output

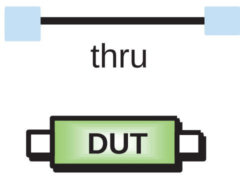


Errors and Calibration Standards

UNCORRECTED

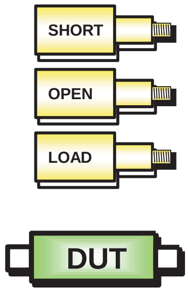
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



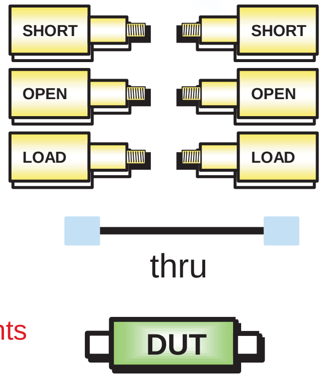
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



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

FULL 2-PORT

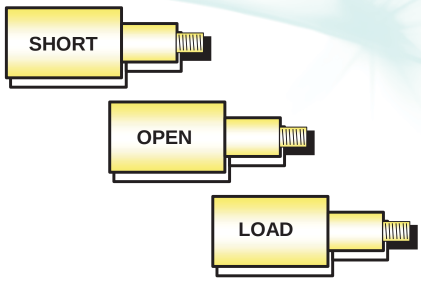


- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

ENHANCED-RESPONSE

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

Calibration Summary



Reflection	Test Set (cal type) T/R (one-port)	Test Set (cal type) S-parameter (two-port)
Reflection tracking	✓	✓
Directivity	✓	✓
Source match	✓	✓
Load match	✗	✓

Transmission	Test Set (cal type) T/R (response, isolation)	Test Set (cal type) S-parameter (two-port)
Transmission Tracking	✓	✓
Crosstalk	✓	✓
Source match	(✓*) ✗	✓
Load match	✗	✓

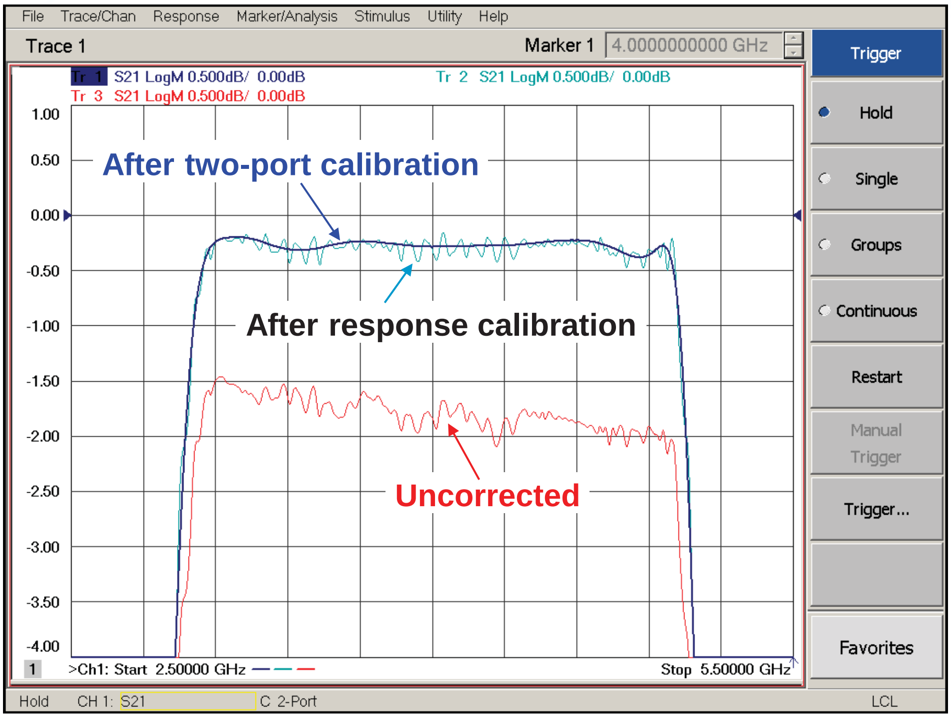
✓ *error can be corrected*

✗ *error cannot be corrected*

✓* *enhanced response cal* corrects for source match during transmission measurements

Response versus Two-Port Calibration

Measuring filter insertion loss



ECal: Electronic Calibration

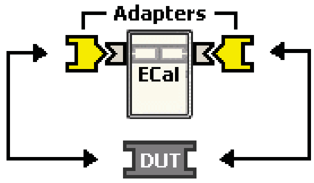
- Variety of two- and four-port modules cover 300 kHz to 67 GHz
- Nine connector types available, 50 and 75 ohms
- Single-connection calibration
  - dramatically reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated characterized terminations provide excellent accuracy

USB controlled

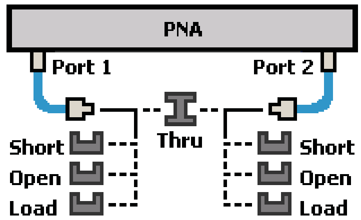
Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

ECAL User Characterizations

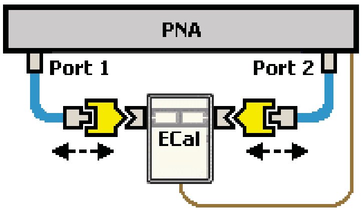
1. Select adapters for the module to match the connector configuration of the DUT.



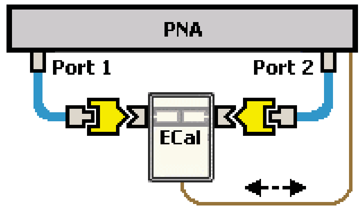
2. Perform a calibration using appropriate mechanical standards.



3. Measure the ECal module, including adapters, as though it were a DUT



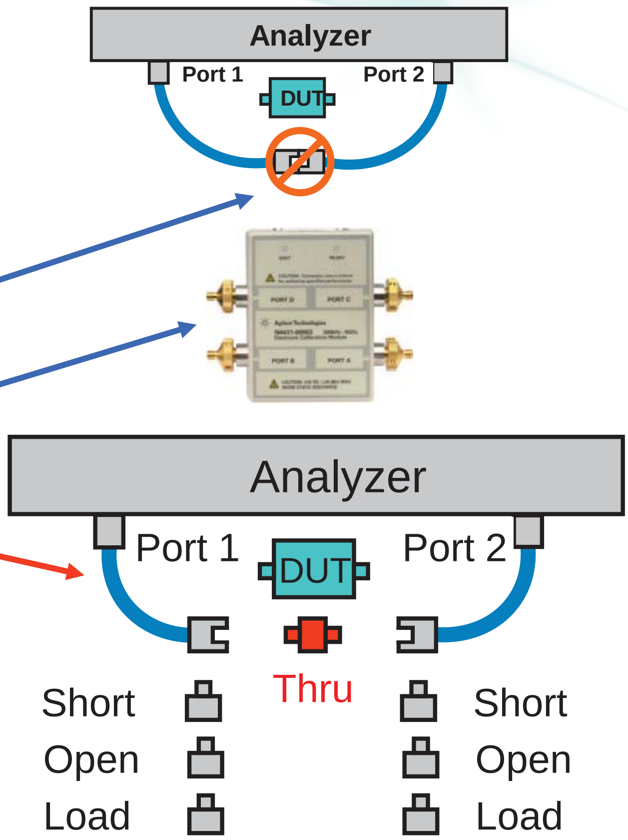
4. VNA stores resulting characterization data inside the module.



Unknown-Thru Calibration

Cal Methods are listed in order of ascending accuracy (least accurate first):

- *Uncharacterized Thru Adapter*
- *Electronic Calibrator (Ecal)*
- *Ecal with Unknown Thru*
- *Mechanical with Unknown Thru Cal*
- *Adapter Removal*

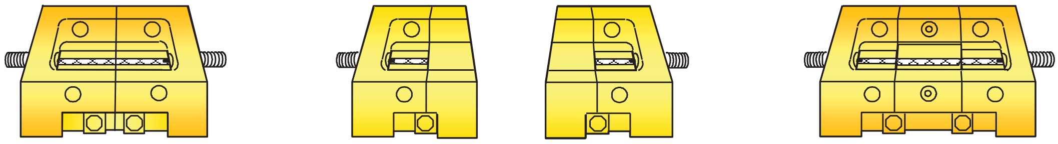


Thru-Reflect-Line (TRL) Calibration

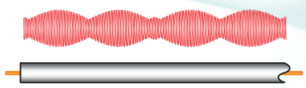
We know about Short-Open-Load-Thru (SOLT) calibration... What is TRL?

- A two-port calibration technique
- Good for non-coaxial environments (waveguide, fixtures, wafer probing)
- Characterizes same 12 systematic errors as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

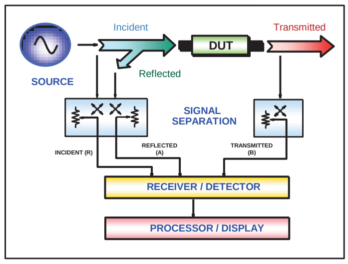
TRL was developed for **non-coaxial microwave** measurements



Agenda



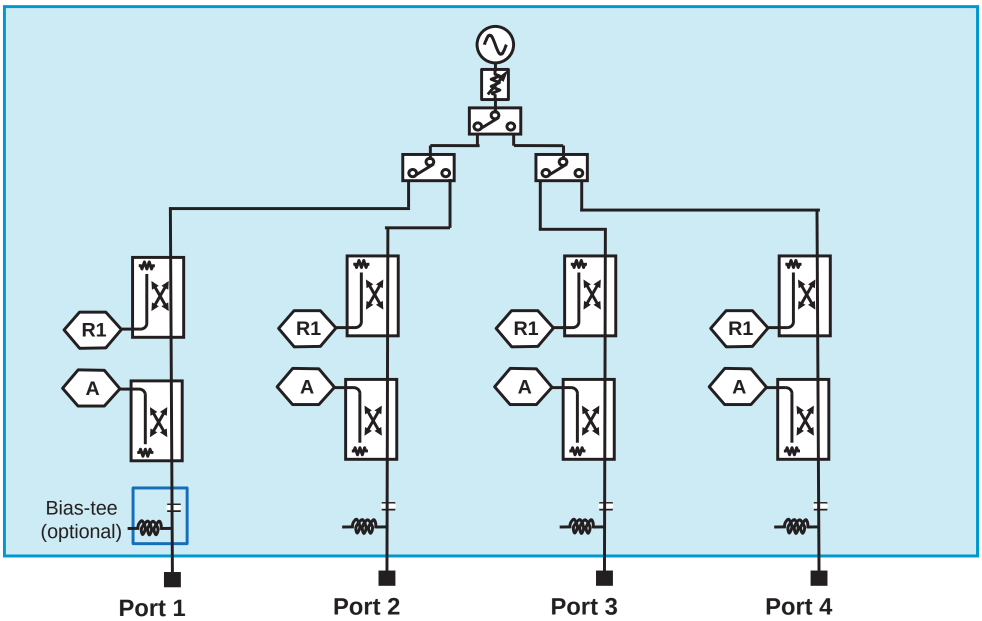
- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- ➡ Advanced S-parameter measurements



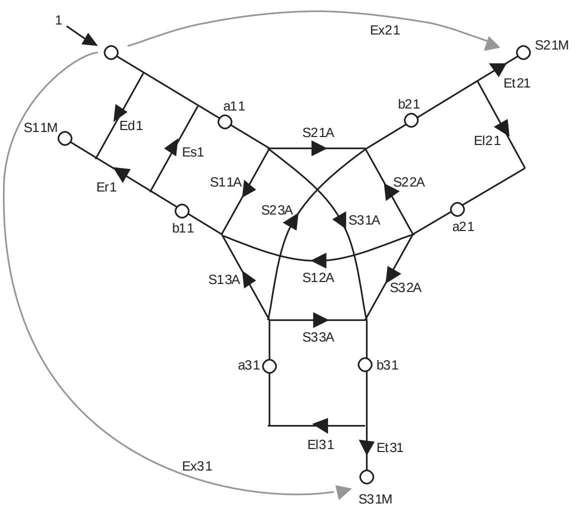
Advanced S-parameter measurements

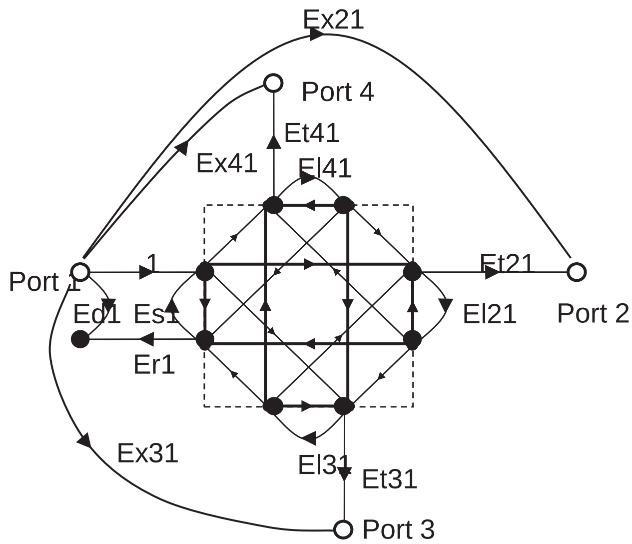
- – Multiport S-parameter measurement
- – Mixed-mode S-parameter measurement
- – Time domain analysis
- – Gain Compression

4-port VNA Block Diagram (E5071C)



Full 3 and 4-Port Error Correction





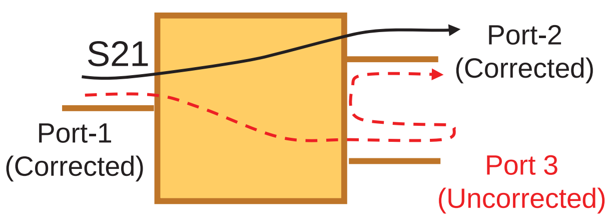
Total number of Error Terms:
3N+3N*(N-1) = 3N^2

2-port Error Terms :	3*2^2 = 12
3-port Error Terms :	3*3^2 = 27
4-port Error Terms :	3*4^2 = 48

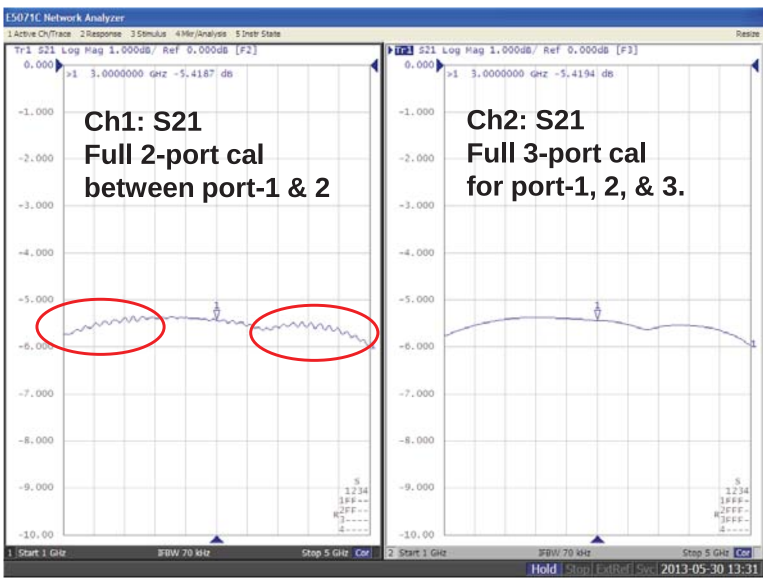
When full 3 and 4-port cal required?

- Reflection from uncorrected test port affects measurement.
- Measure mixed-mode S-parameters

Ex) 2-way power divider (isolation between output ports=13 dB)



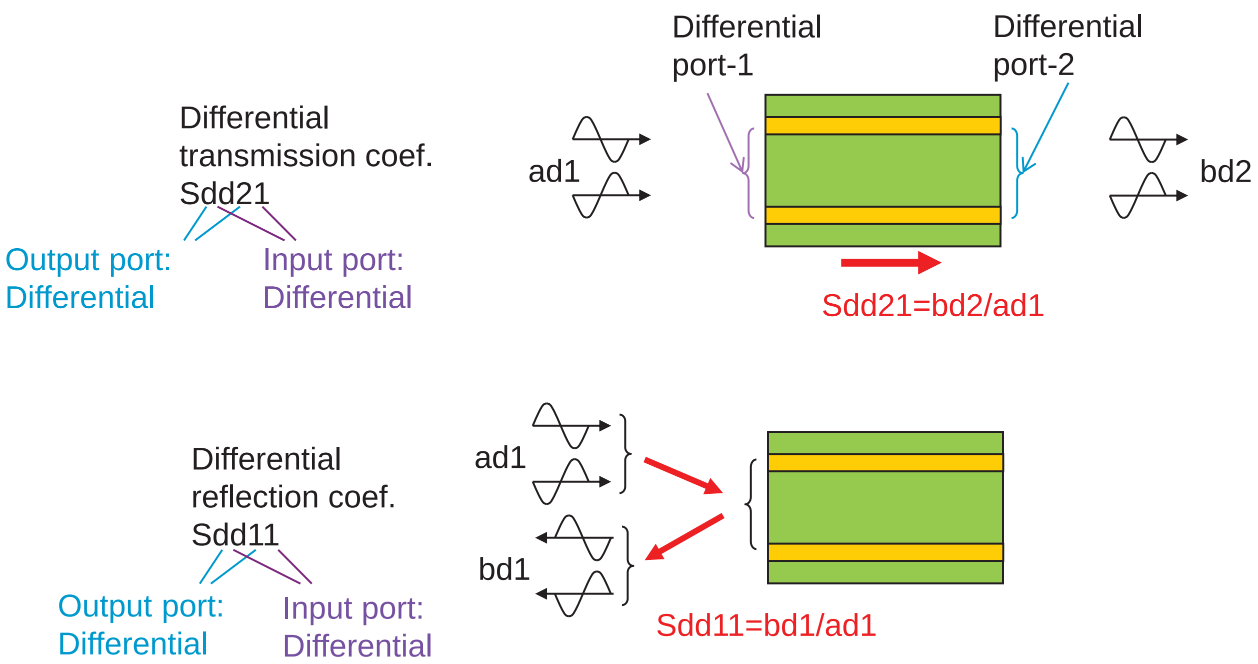
Reflection at uncorrected port-3
affect measurement at port-2.



Advanced S-parameter measurements

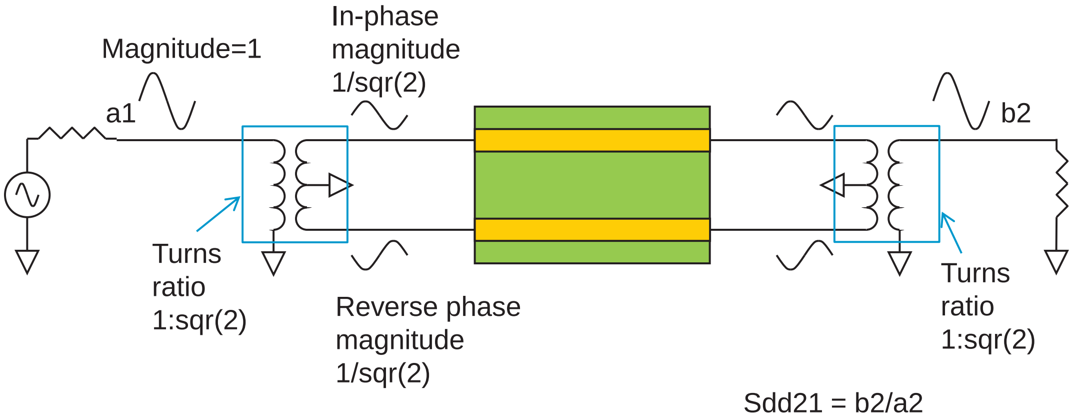
– Multiport S-parameter measurement
– Mixed-mode S-parameter measurement
– Time domain analysis
– Gain Compression

Differential S-parameter measurement

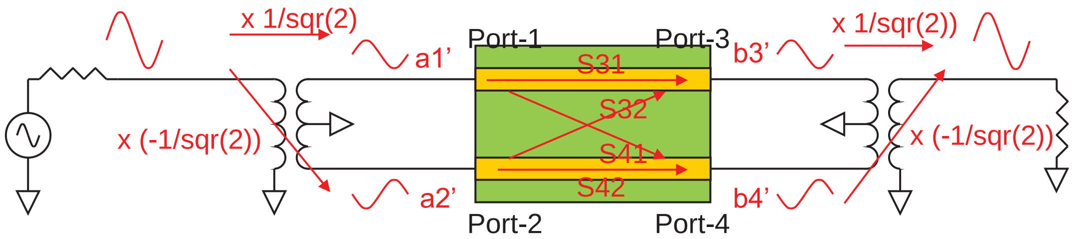


Differential S-parameter measurement

Sdd21 measurement using ideal balun transformers



Differential S-parameter measurement



We consider transmission characteristic of four signal paths;

S31 path: (1/sqr(2)) x S31 x (1/sqr(2)) = (1/2) x S31

S41 path: (1/sqr(2)) x S41 x (-1/sqr(2)) = (-1/2) x S41

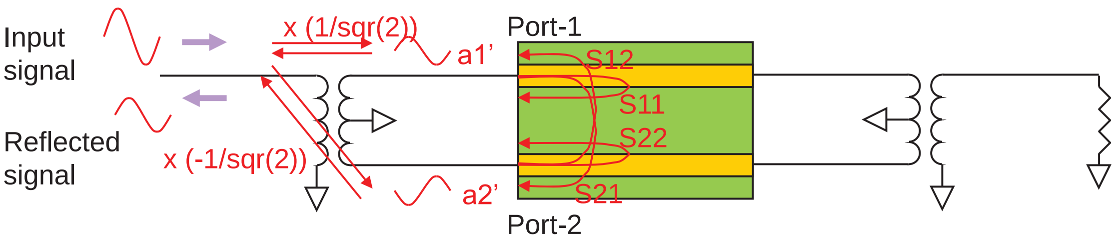
S32 path: (-1/sqr(2)) x S32 x (1/sqr(2)) = (-1/2) x S32

S42 path: (-1/sqr(2)) x S42 x (-1/sqr(2)) = (1/2) x S42

By superimposing above four equations, we can obtain Sdd21;

Sdd21 = (1/2)*(S31-S32-S41+S42)

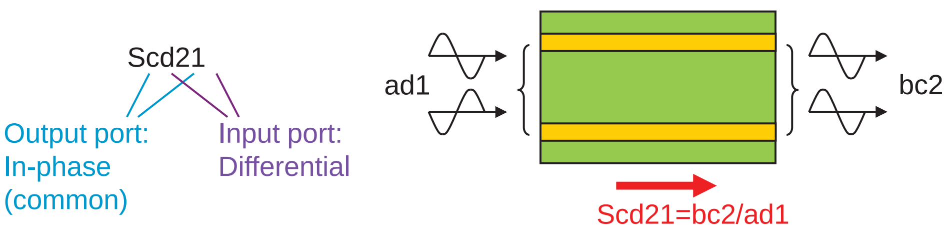
Differential S-parameter measurement

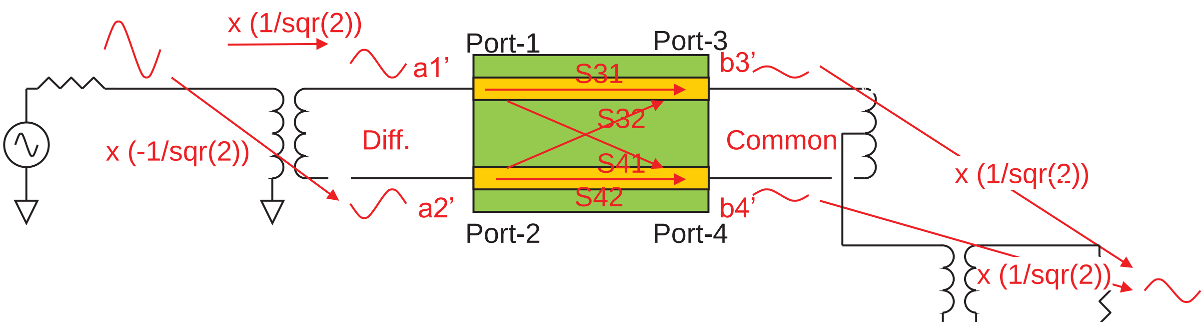


Sdd11 can be derived by superimposing transmission characteristics of S11, S12, S21, and S22 signal paths;

Sdd11 = (1/2)*(S11-S21-S12+S22)

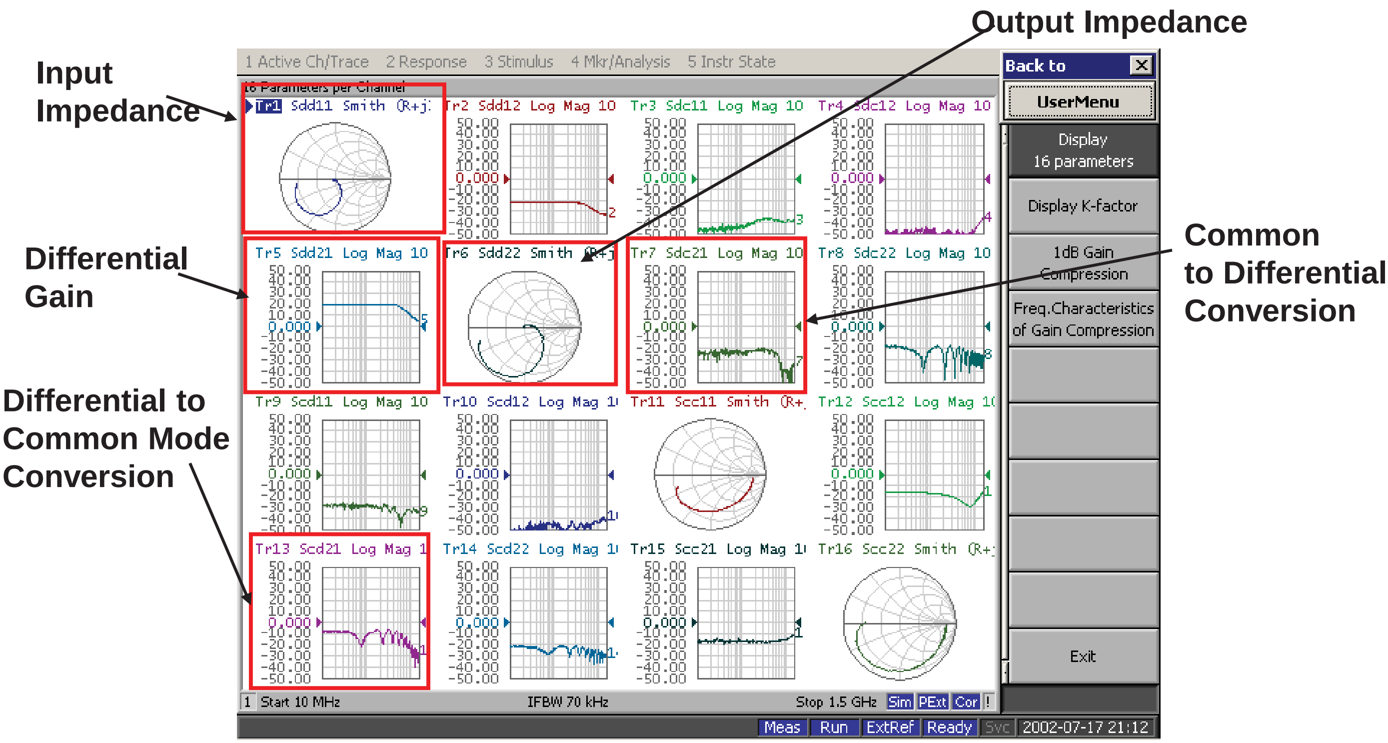
Differential-Common S-parameter measurement





Scd21=(1/2) x (S31-S32+S41-S42)

Mixed-mode S-parameter Measurement Example - Differential amplifier



Advanced S-parameter measurements

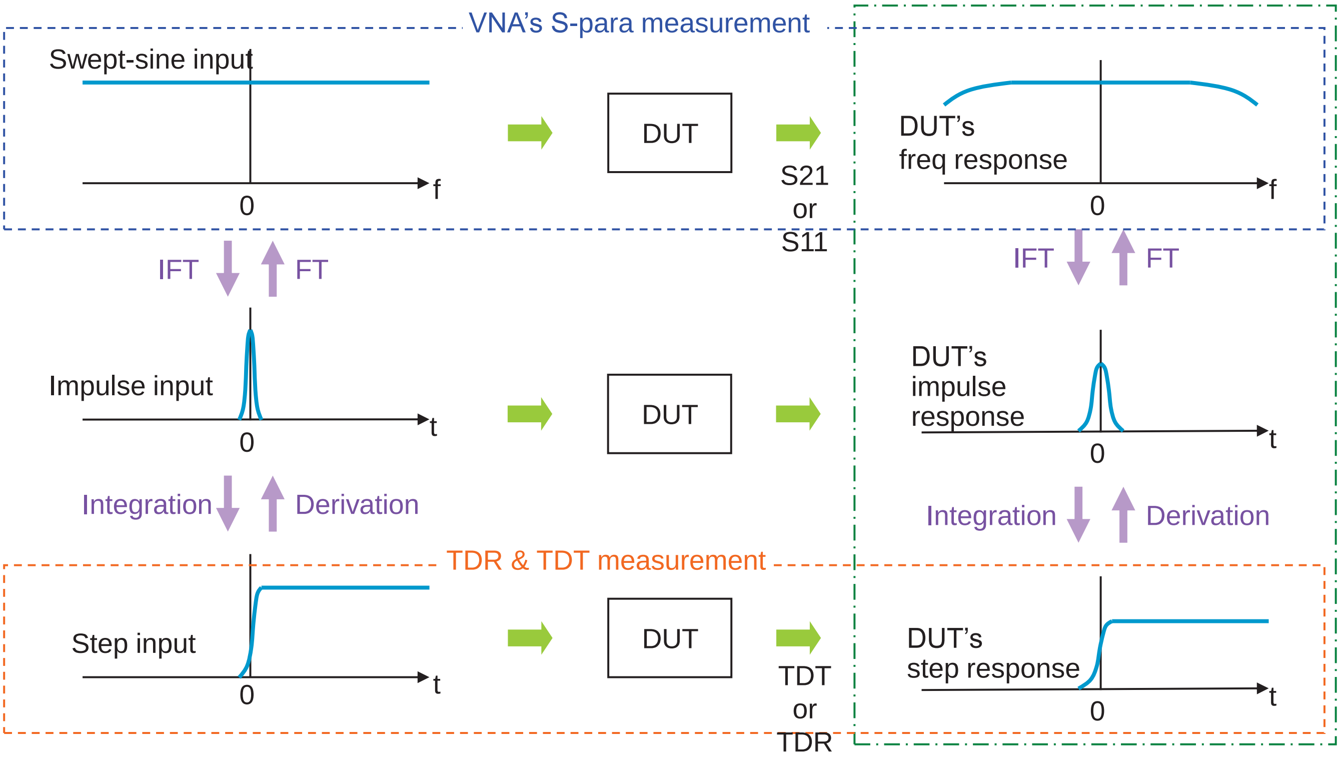
– Multiport S-parameter measurement

– Mixed-mode S-parameter measurement

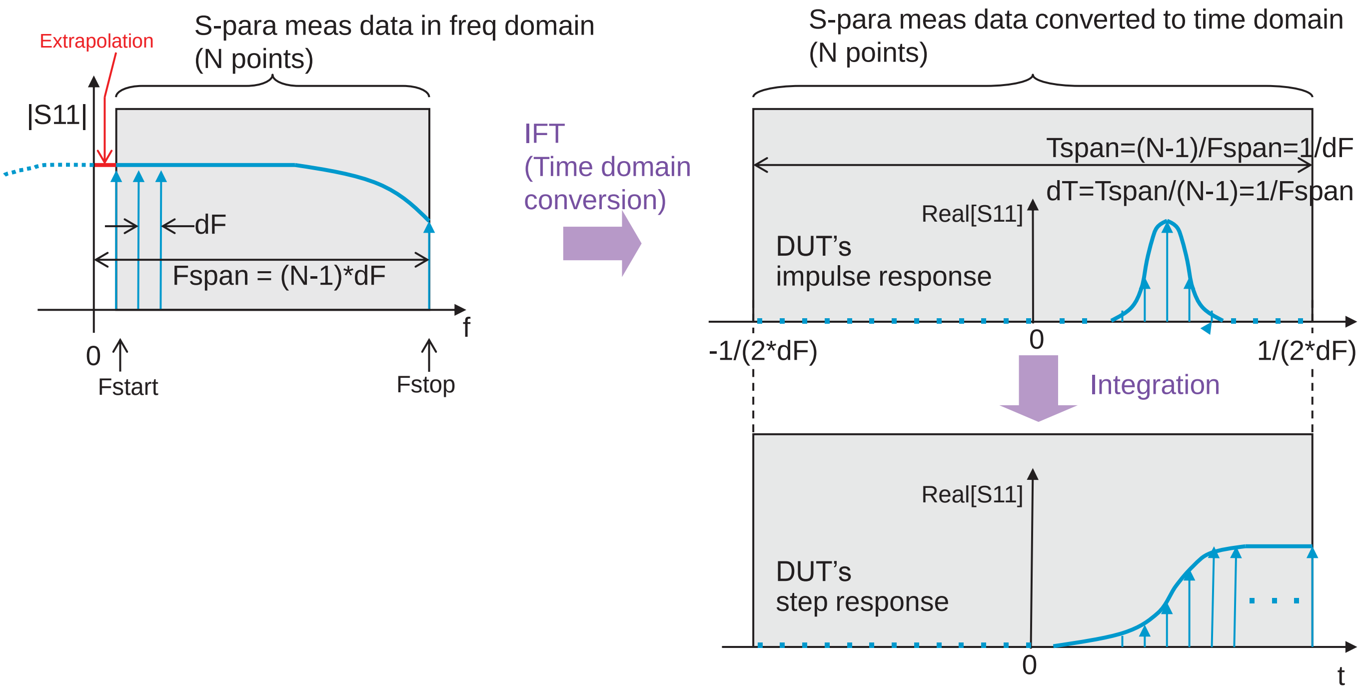
➡ – Time domain analysis

– Gain Compression

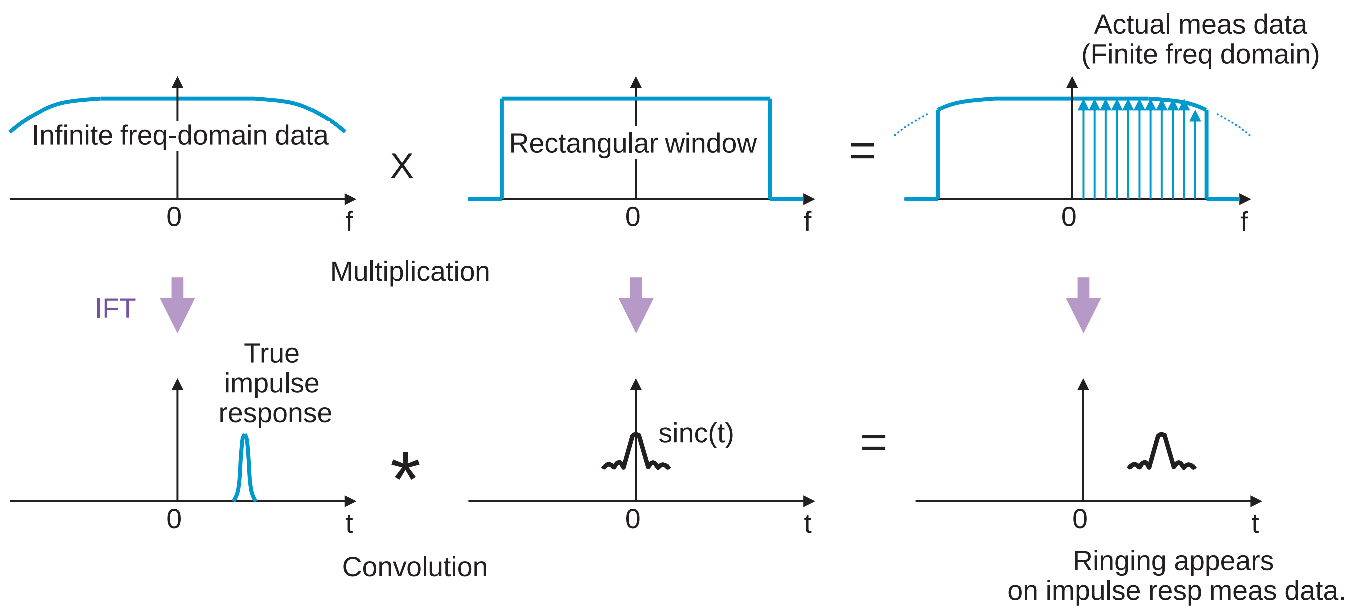
In the linear system



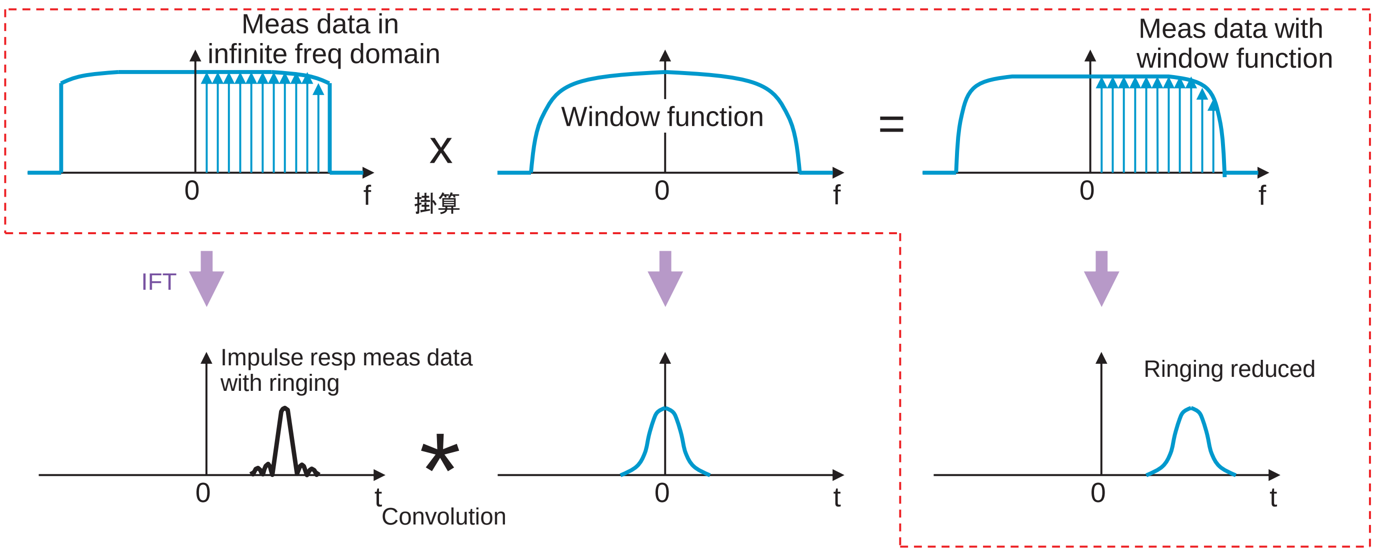
VNA's time domain conversion (case of low-pass modes)



Window function



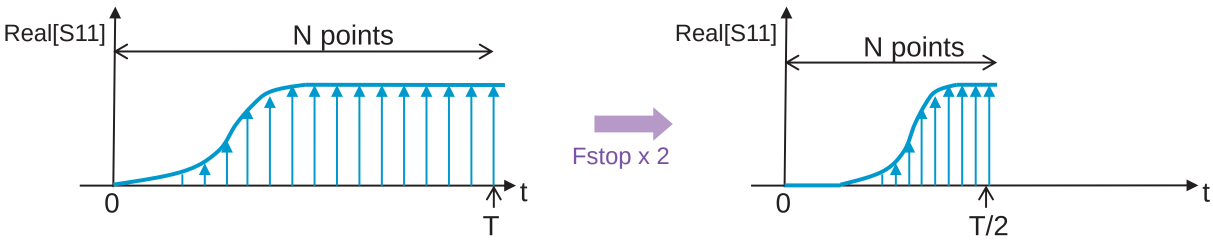
Window function

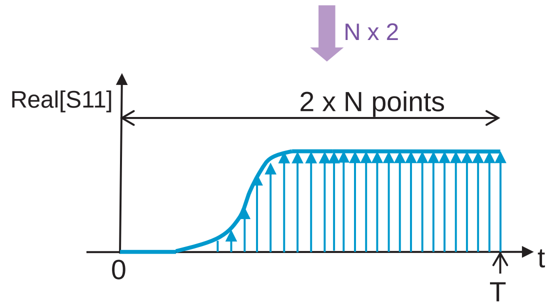


Time resolution

Higher Fstop → Higher time resolution.

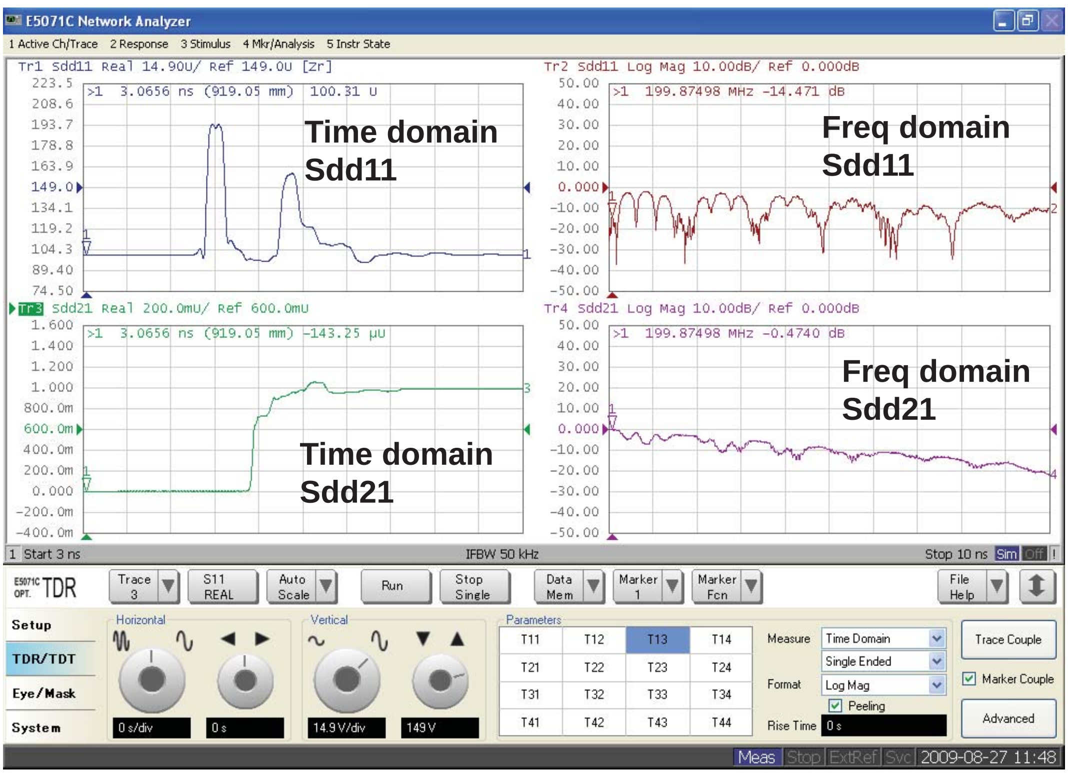
Ex) 2-times higher Fstop with same NOP → Time resolution is 2-times higher (but time span is ½).





Original time span can be obtained
by increasing NOP x 2

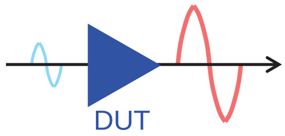
Example of VNA-based time domain analysis (E5071C)



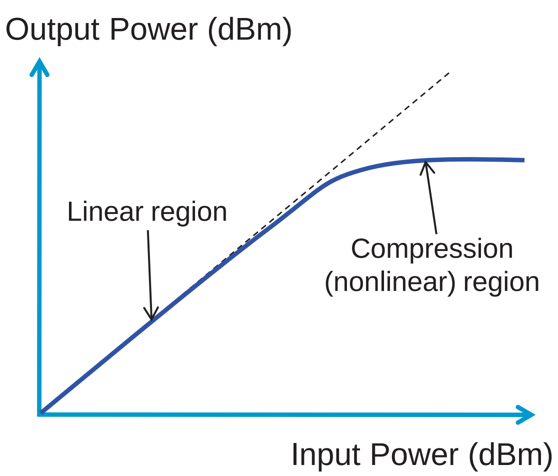
Advanced S-parameter measurements

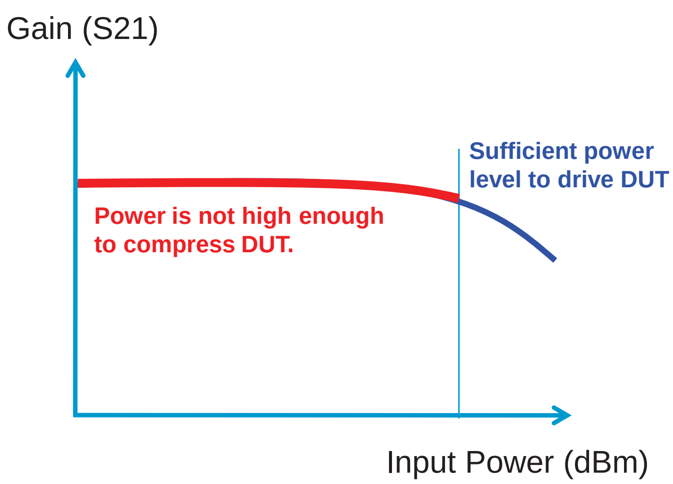
– Multiport S-parameter measurement
– Mixed-mode S-parameter measurement
– Time domain analysis
➡ – Gain Compression

What is gain compression?



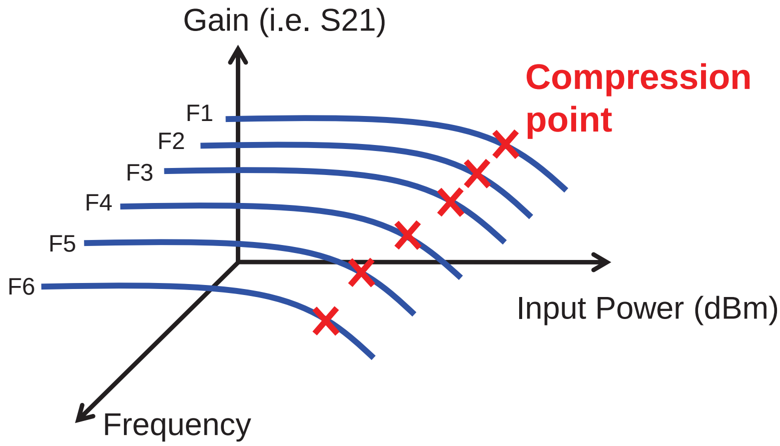
•Parameter to define the transition between the linear and nonlinear region of an active device.
•The compression point is observed as x dB drop in the gain with VNA's power sweep.

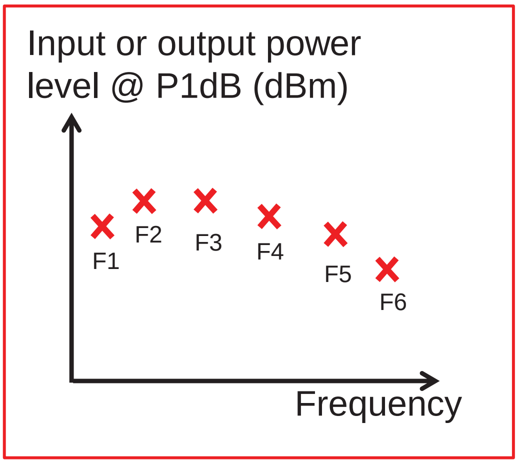




Enough margin of source power capability is needed for analyzers.

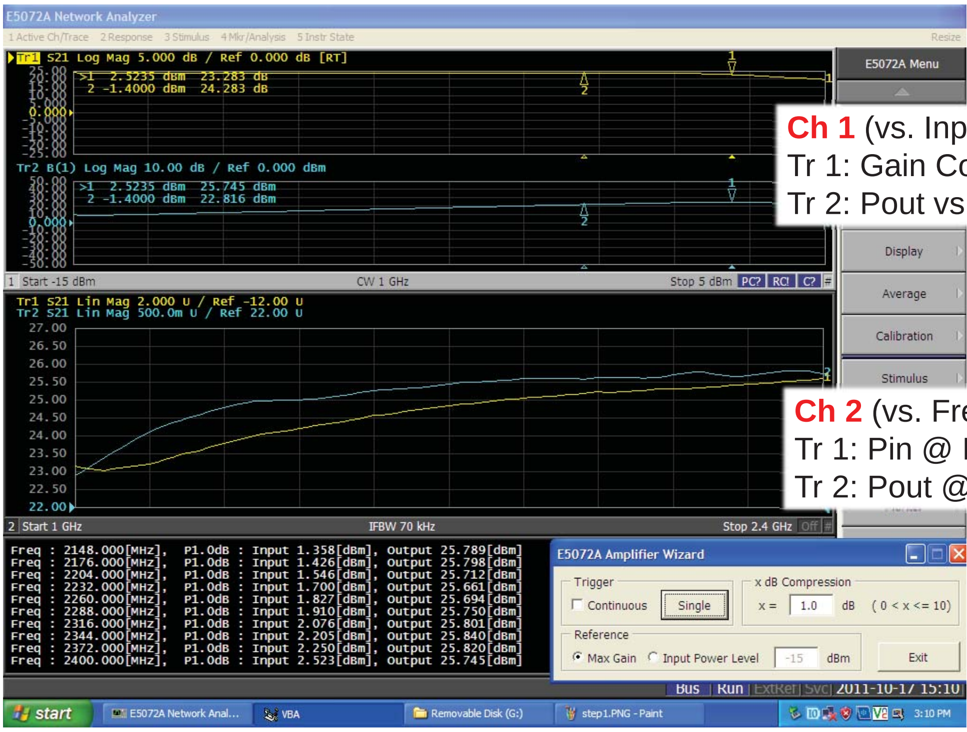
Gain compression over frequency





Gain compression over frequency

Gain compression measurement example



Ch 1 (vs. Input power):
Tr 1: Gain Compresssion vs. Pin
Tr 2: Pout vs. Pin

Ch 2 (vs. Frequency):
Tr 1: Pin @ P1dB vs. Freq
Tr 2: Pout @ P1dB vs. Freq

RF amplifier test

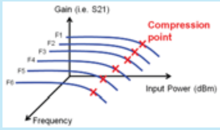
Stability (K-factor)
Calculates stability (K-factor) from all S-parameters with equation editor

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

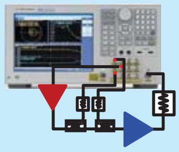
where

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

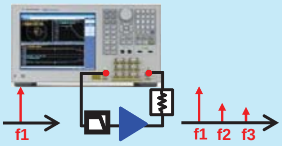
Gain compression
Sweeps both frequency and input power level at PxdB



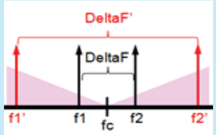
High-power test
Performs accurate tests with high-power input / output of DUT



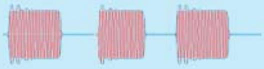
Harmonic Distortion
Performs real-time harmonics test over frequency or input power



Swept IMD
Performs IMD analysis over an entire range of frequencies



Pulsed-RF
Characterize pulsed performance of devices



Efficiency (PAE)
Calculate power-added efficiency (PAE)

The modern VNA is a more suited solution for many parametric tests of RF amplifiers.

Agilent Vector Network Analyzer Portfolio

Industry's Broadest Price/Performance Choices

PNA-X, NVNA
Most advanced and flexible microwave

PNA
High performance microwave

PNA-L
Economy microwave

Reach for unrivaled excellence

E5071C / E5072A
High performance RF NA

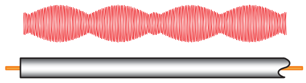
E5061B
- Low-cost simple RF NA
- LF-RF NA

Drive down the cost of test

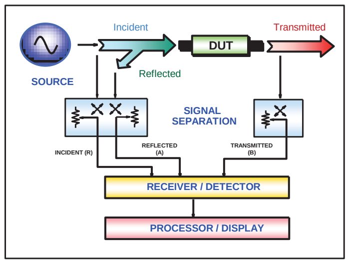
FieldFox
Portable RF/MW Analyzer

Carry Precision with you

Network Analysis Back to Basics



- ✓What measurements do we make?
- ✓Network analyzer hardware
- ✓Error models and calibration
- ✓Advanced S-parameter measurements



The End

THANK YOU!