Radiofrequency Measurements

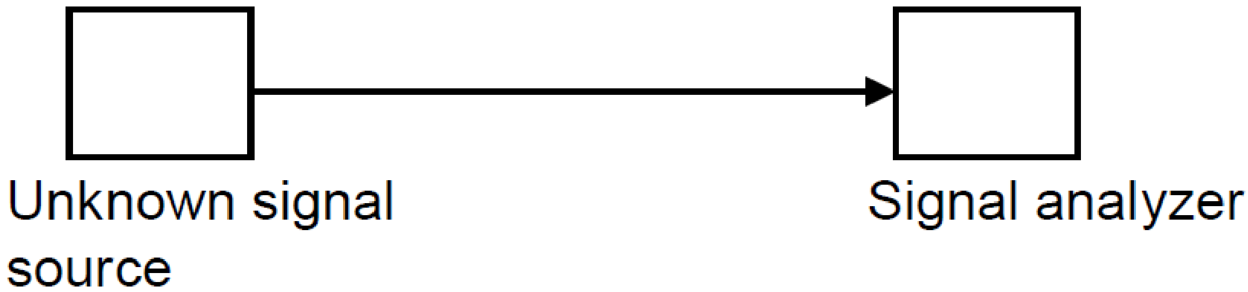
Network Analyzer

The next slides material is taken from AGILENT “Network Analyzer Basics”:

- BTB_Network_2005.pdf
- SLDPRE_BTB_2000Network.ppt
- 12-17-02-RF-network-analysis-Yates_791-1mb.pdf

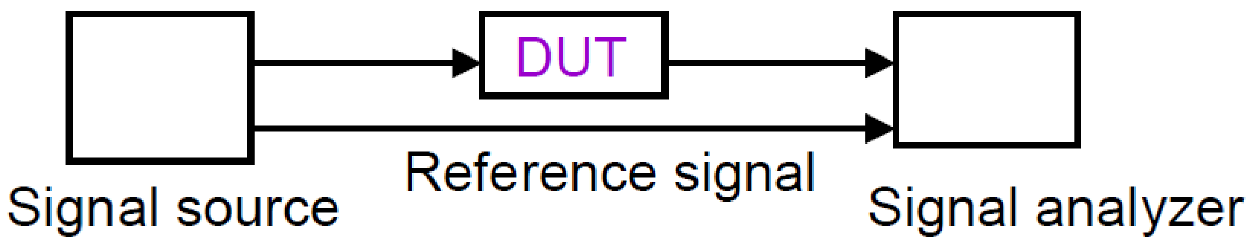
Network VS Signal Analysis

Signal Analysis Characterizes an Unknown Signal



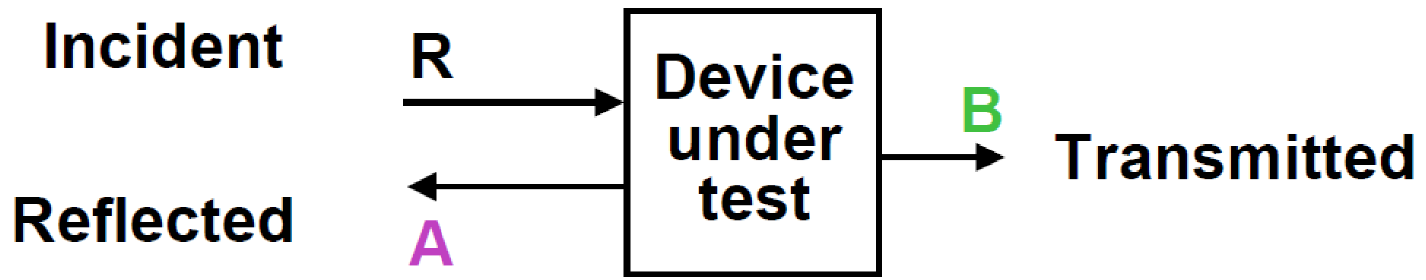
Network Analysis Characterizes an Unknown Circuit

(Device Under Test)



How do we characterize devices?

1 Utilize a stimulus/response test system.



Network analyzer receivers R, A, and B

Reverse tests: Move stimulus to other port

How do we characterize devices?

2 Measure the amplitude and phase ratios over the device's frequency.

Forward and Reverse
Transmitted and Reflected

$$\left.\begin{array}{l} \dfrac{\text{Transmitted}}{\text{Incident}} = \dfrac{B}{R} \\[2ex] \dfrac{\text{Reflected}}{\text{Incident}} = \dfrac{A}{R} \end{array}\right\} \text{vs frequency}$$

How do we characterize devices?

3 Calculate application parameters from the ratio data.

Transmission Parameters

Transmission coefficient,
T and τ

Insertion gain and loss

S-parameters S21 and S12

Insertion phase

Group delay

Reflection Parameters

Reflection coefficient,
Γ and ρ

Return loss

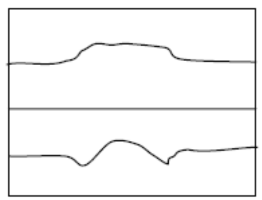
S-parameters S11, S22

Impedance, Z, R+jX
Admittance, A, G+jB

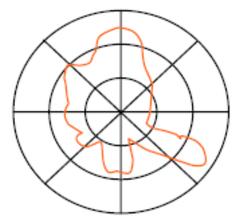
Standing wave ratio, SWR

How do we characterize devices?

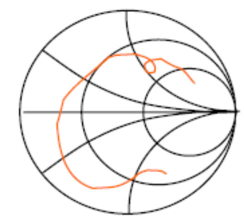
4 Present the results as numerical, graphical, or data objects.



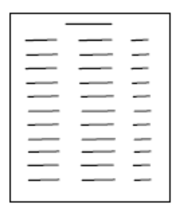
XY plot



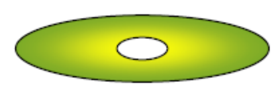
Polar plot



Smith chart

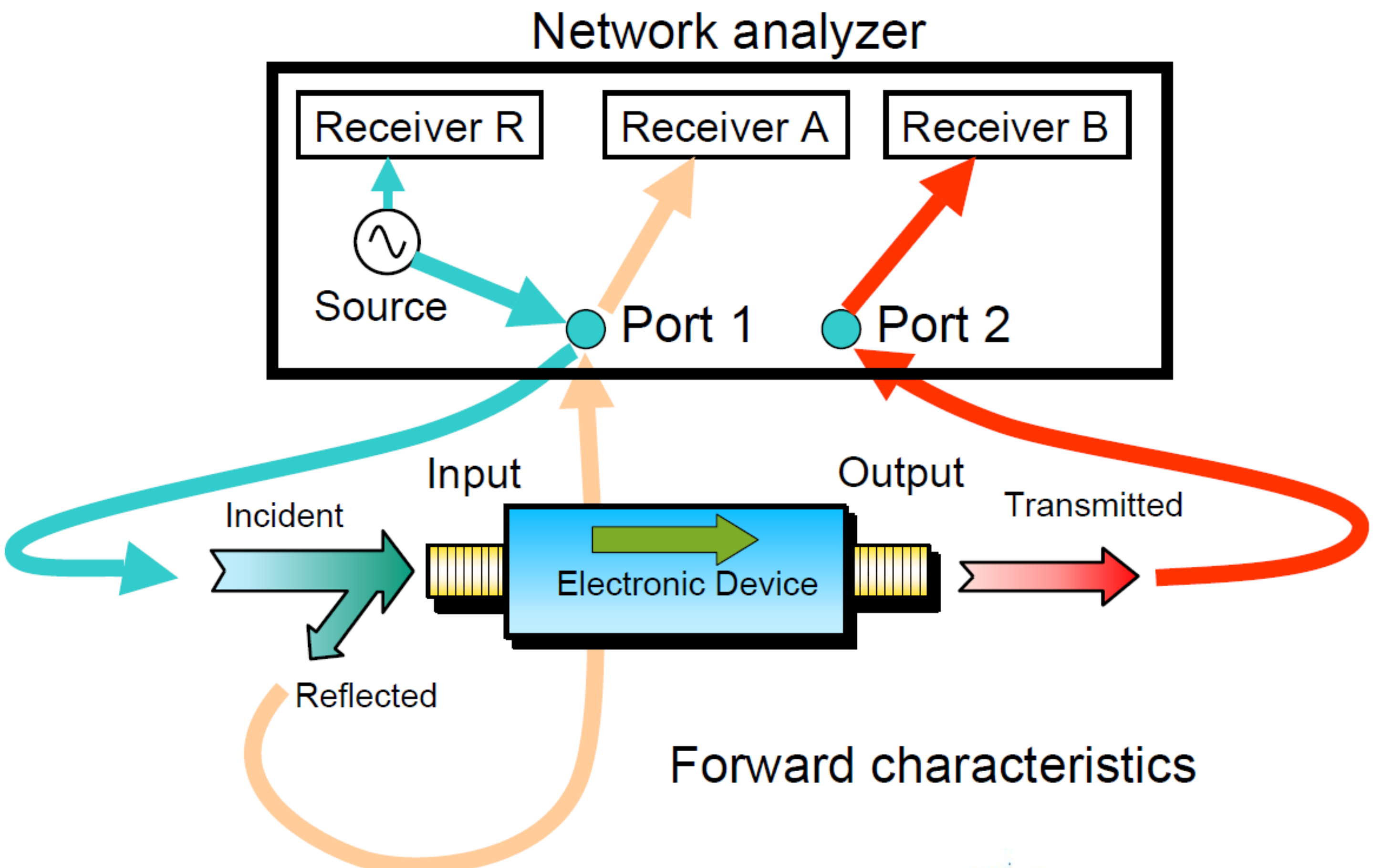


Printed table

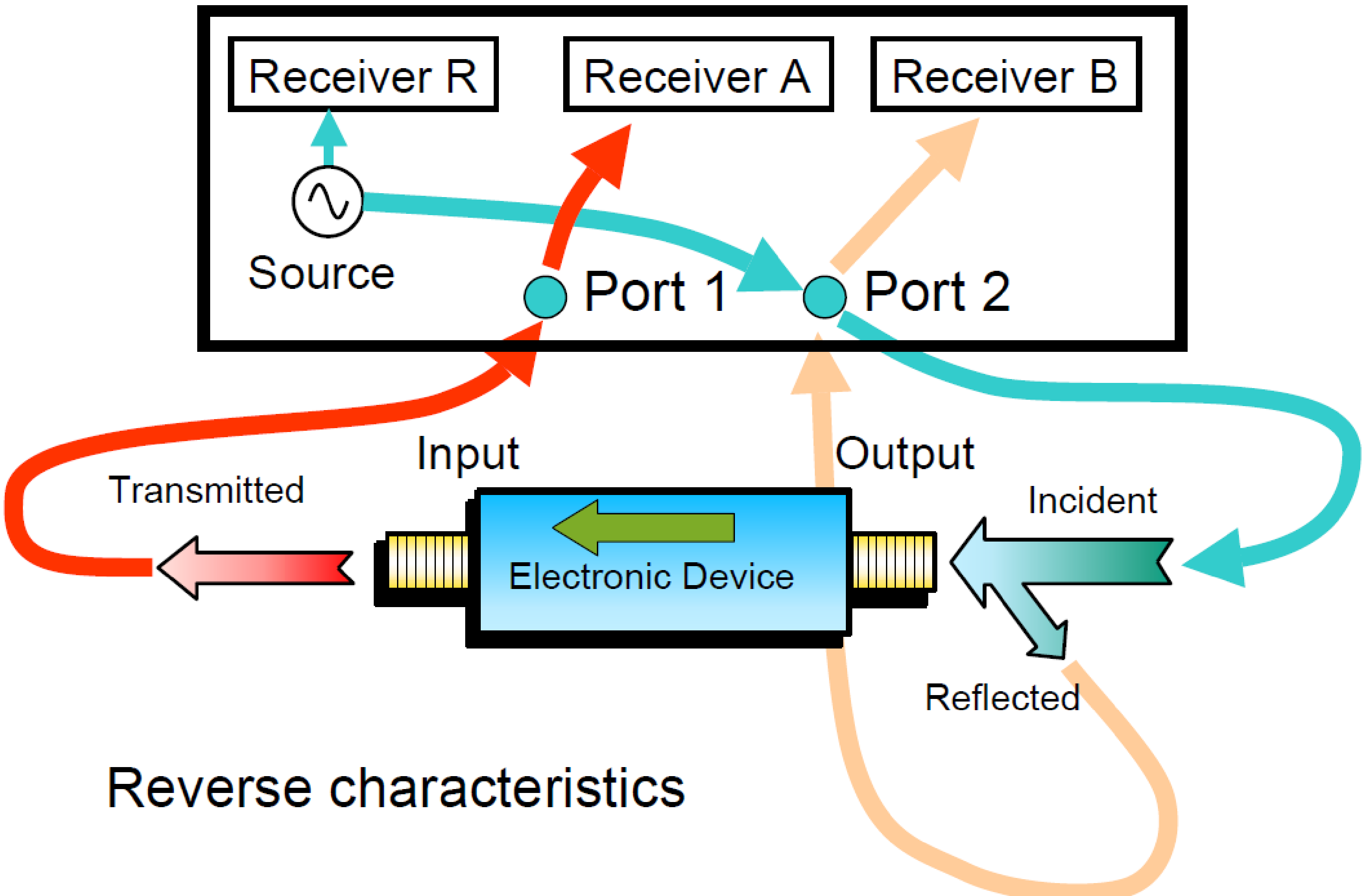


Data file

Network Analyzer Operation

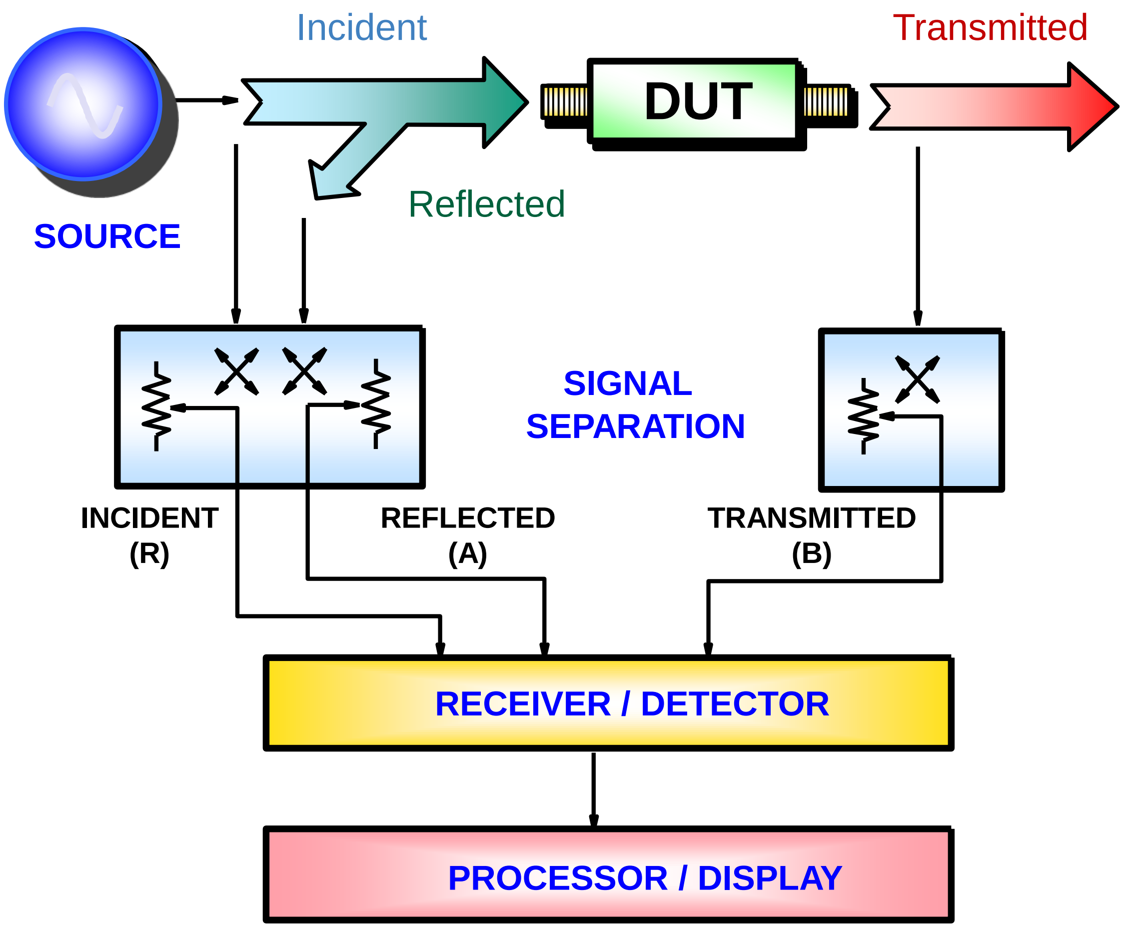


Network Analyzer Operation



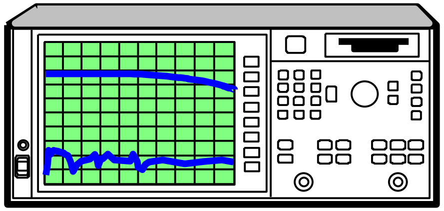
Reverse characteristics

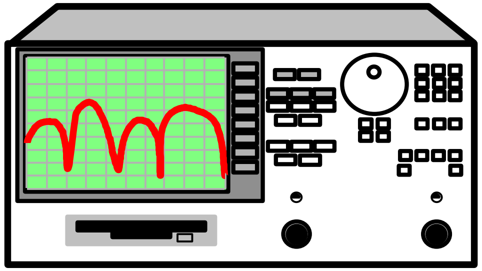
Generalized Network Analyzer Block Diagram



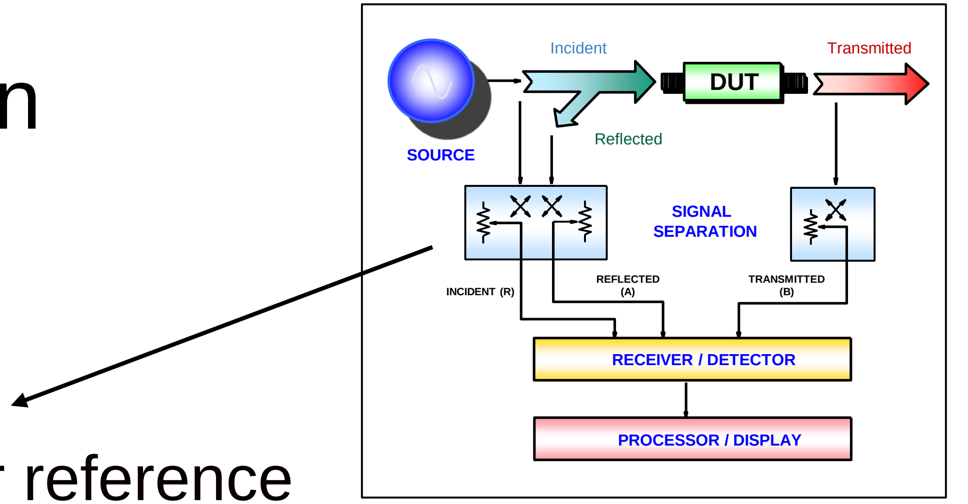
Source

- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Agilent analyzers sold today have ***integrated, synthesized*** sources



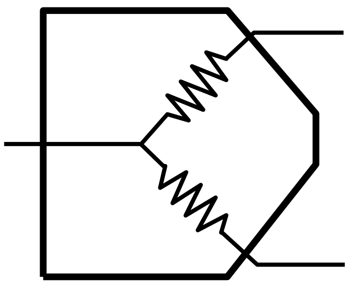


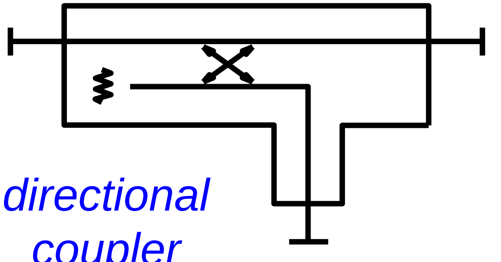
Signal Separation



- measure incident signal for reference
- separate incident and reflected signals

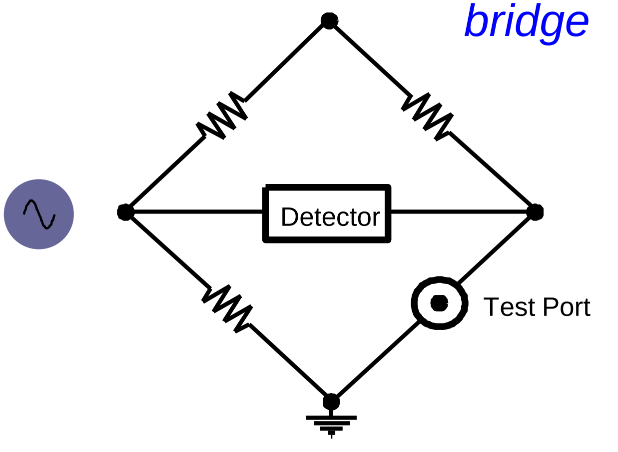
splitter





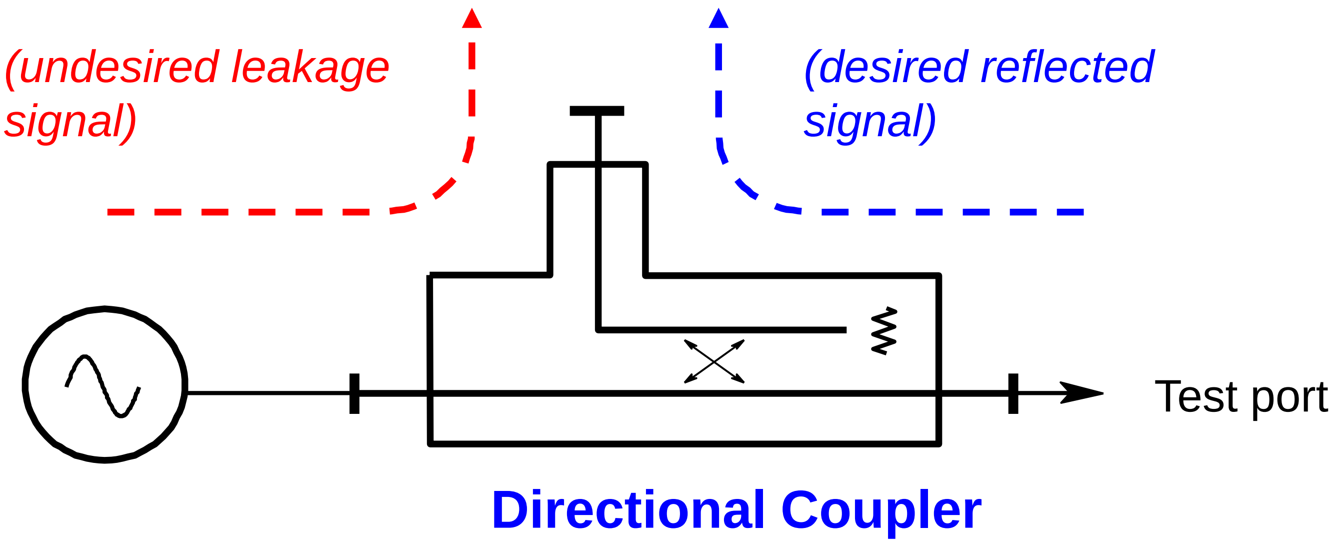
directional coupler

bridge



Directivity

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

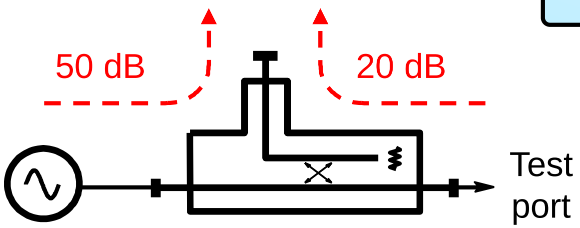


Directional Coupler *Directivity*

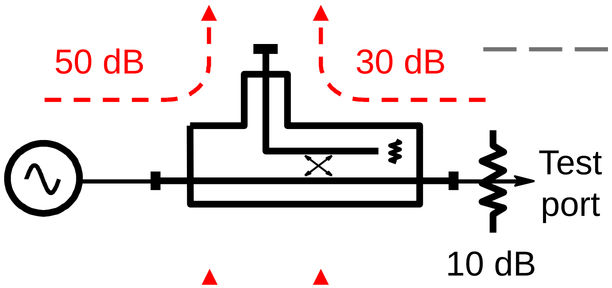
$$\text{Directivity} = \frac{\text{Coupling Factor}_{\text{(fwd)}} \times \text{Loss}_{\text{(through arm)}}}{\text{Isolation}_{\text{(rev)}}}$$

Directivity (dB) = Isolation (dB) - Coupling Factor (dB) - Loss (dB)

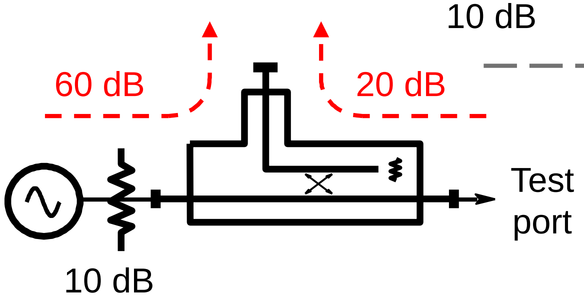
Examples:



Directivity = 50 dB - 20 dB = 30 dB

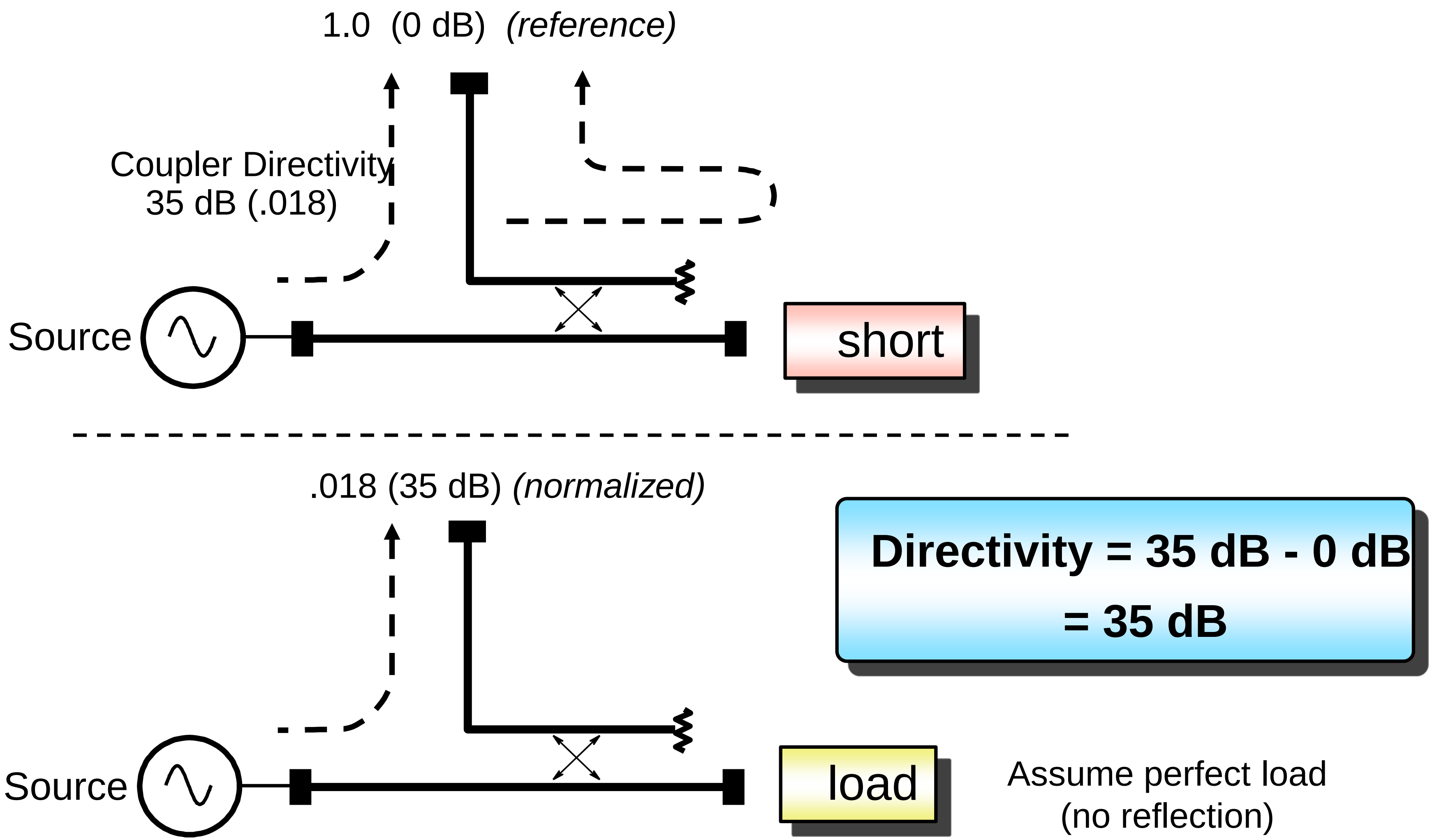


Directivity = 50 dB - 30 dB - 10 dB = 10 dB

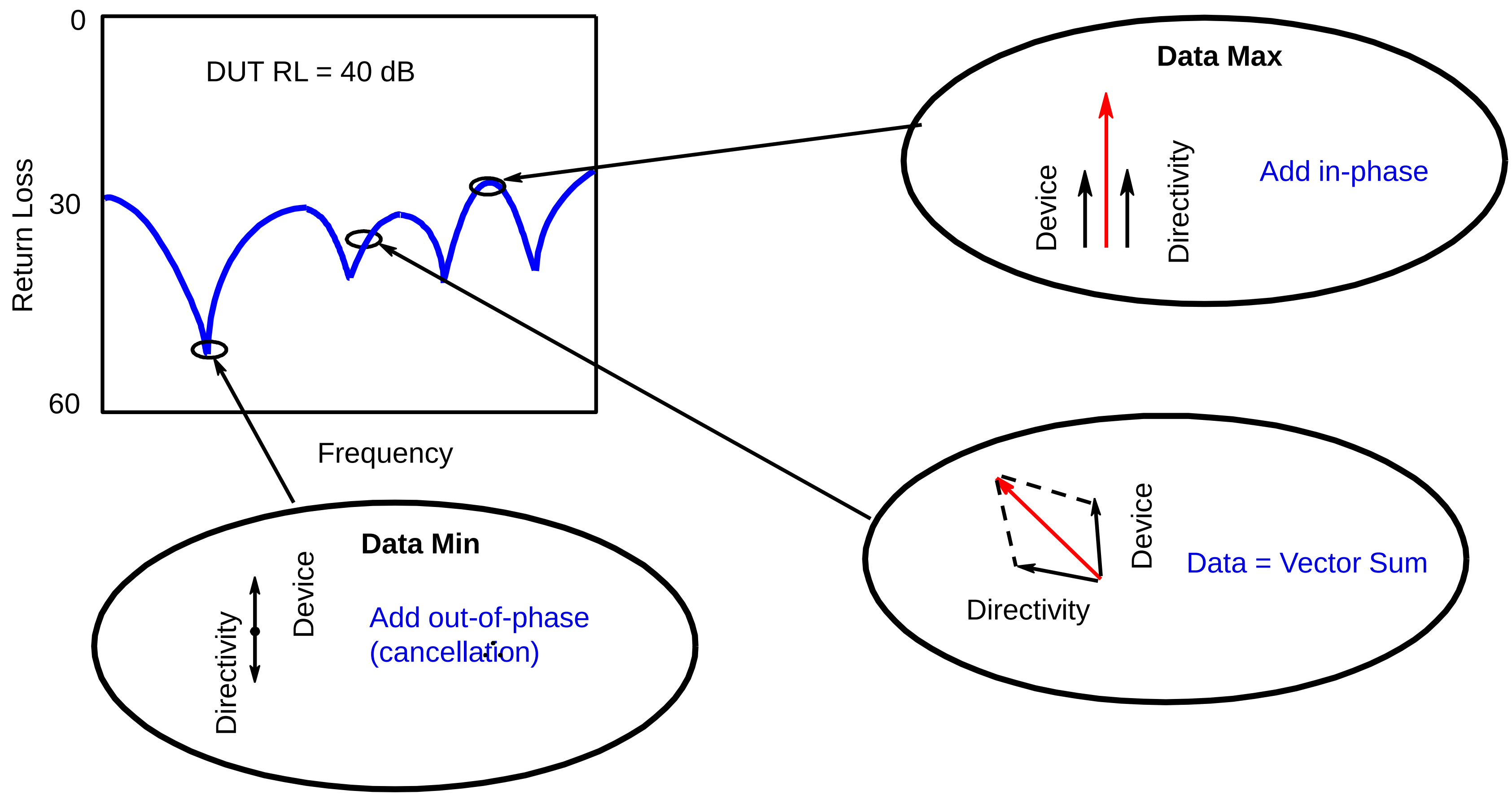


Directivity = 60 dB - 20 dB - 10 dB = 30 dB

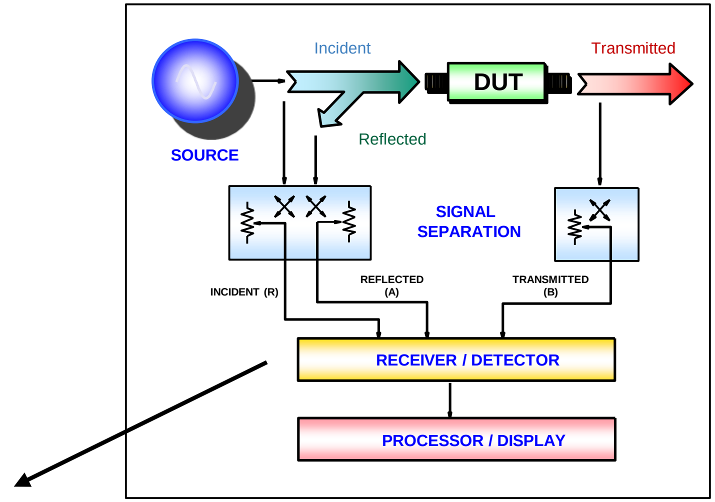
One Method of Measuring Coupler Directivity



Interaction of Directivity with the DUT (Without Error Correction)

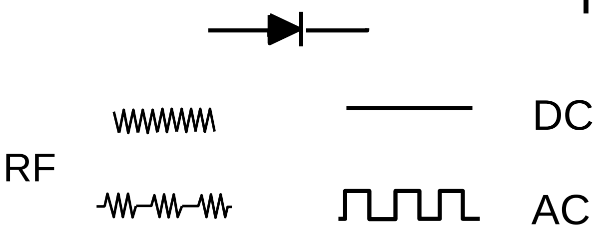


Detector Types

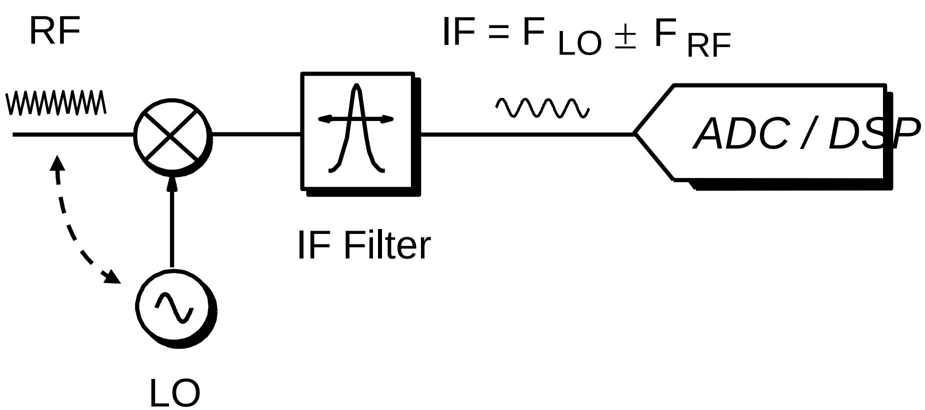


Scalar **broadband**
(no phase
information)

Diode

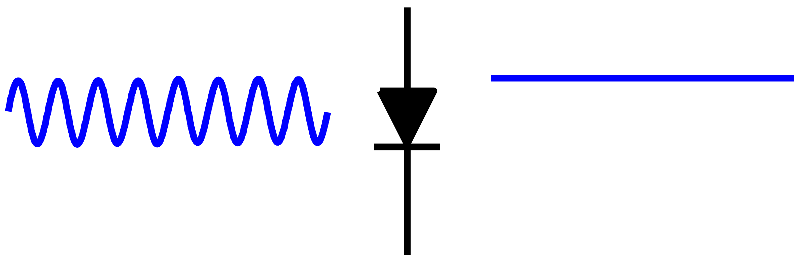


Tuned Receiver

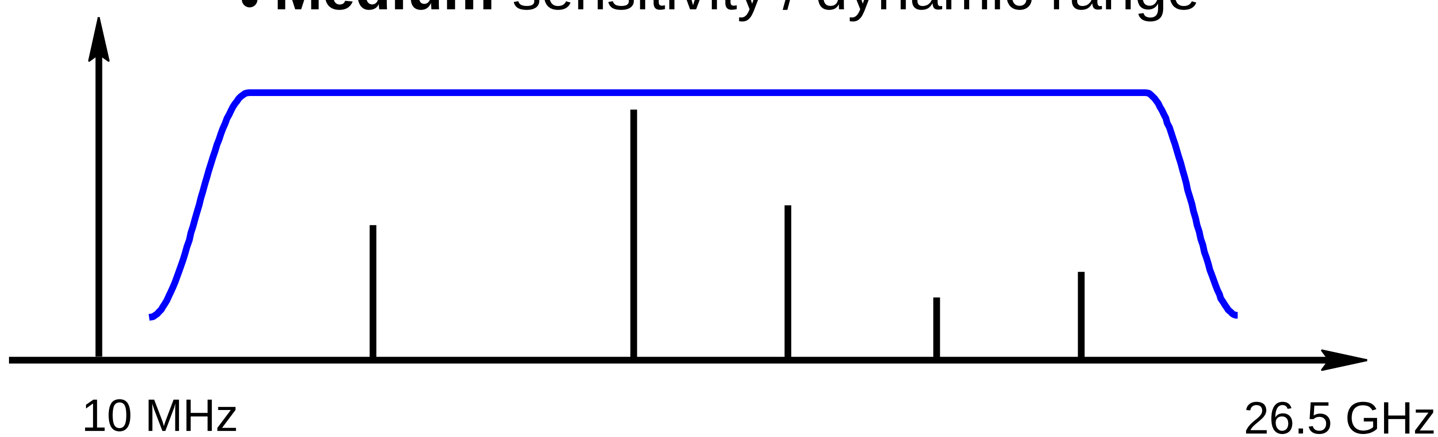


Vector
(magnitude and
phase)

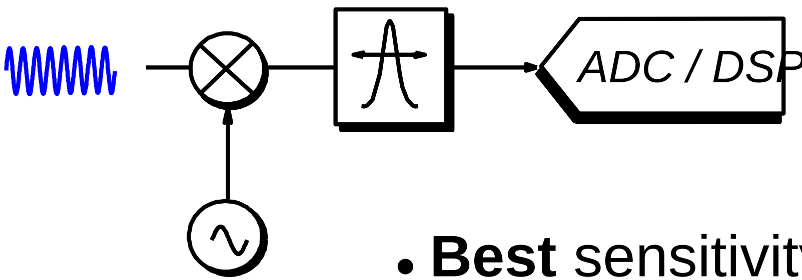
Broadband Diode Detection



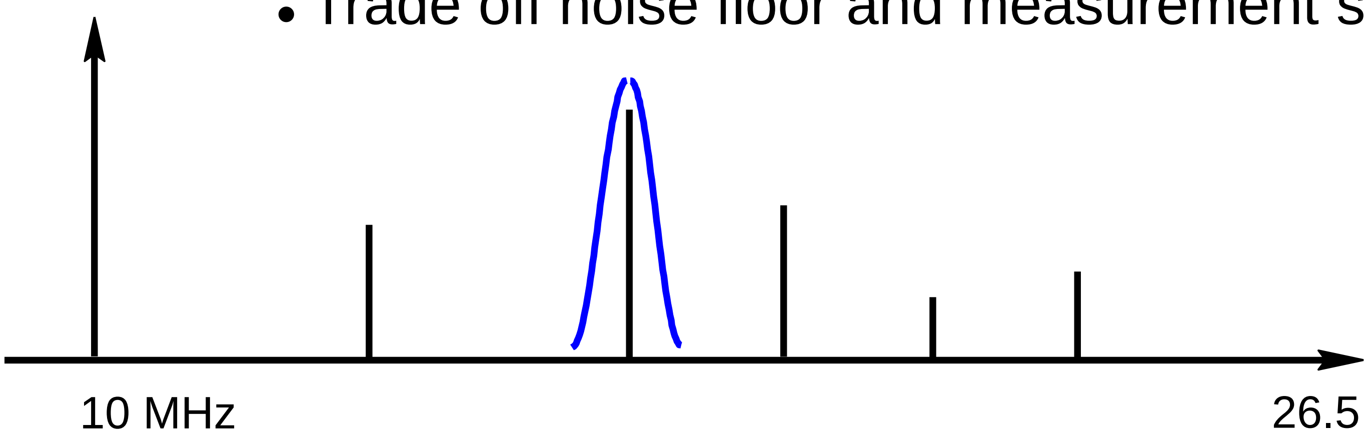
- Easy to make **broadband**
- **Inexpensive** compared to tuned receiver
- Good for measuring frequency-translating devices
- Improve dynamic range by increasing power
- **Medium** sensitivity / dynamic range



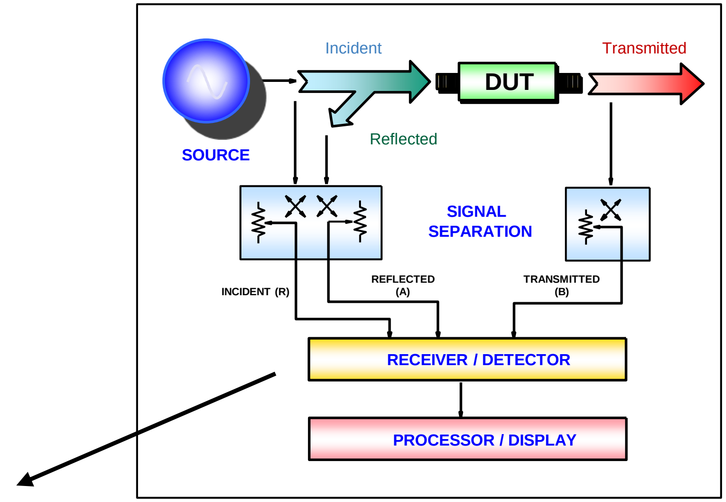
Narrowband Detection - Tuned Receiver

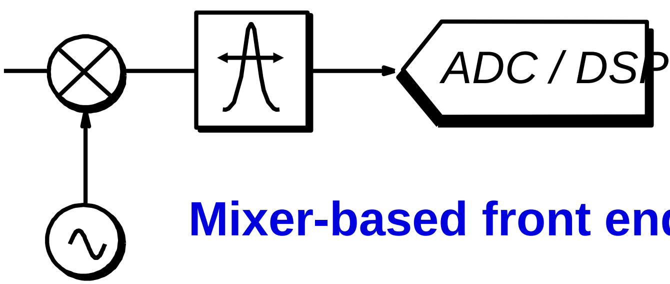


- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**, decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed



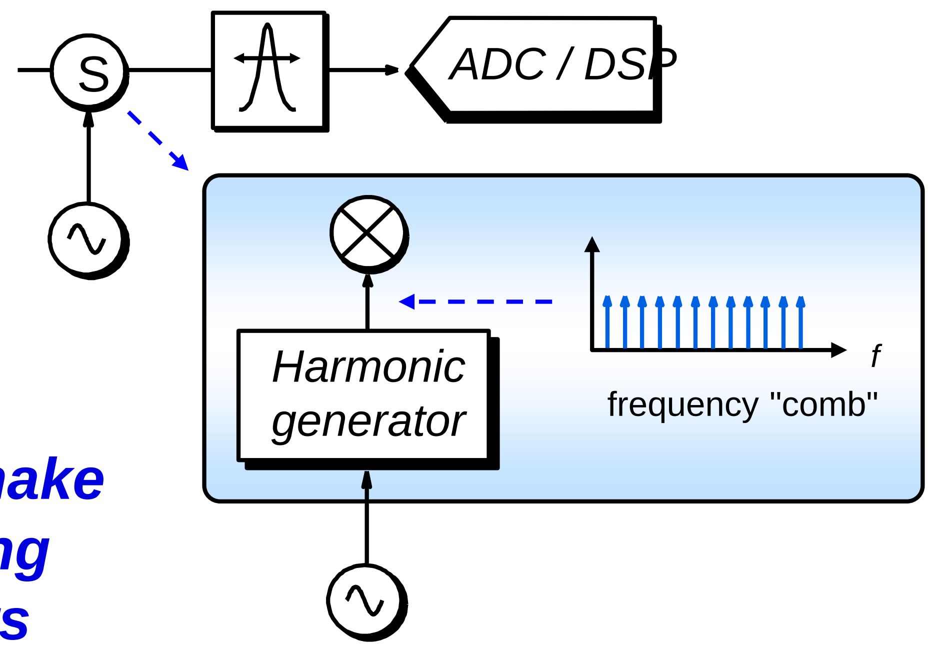
NA Hardware: Front Ends, Mixers Versus Samplers





Mixer-based front end

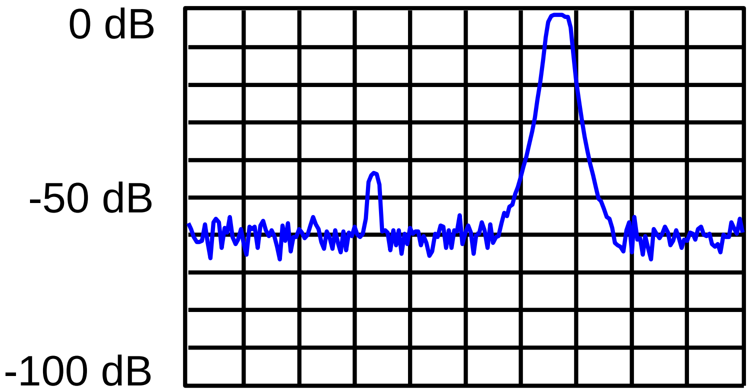
Sampler-based front end



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

Comparison of Receiver Techniques

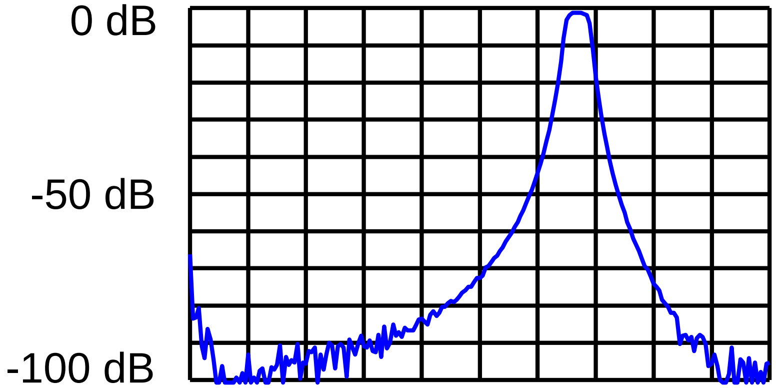
Broadband (diode) detection



-60 dBm Sensitivity

- higher noise floor
- false responses

Narrowband (tuned-receiver) detection



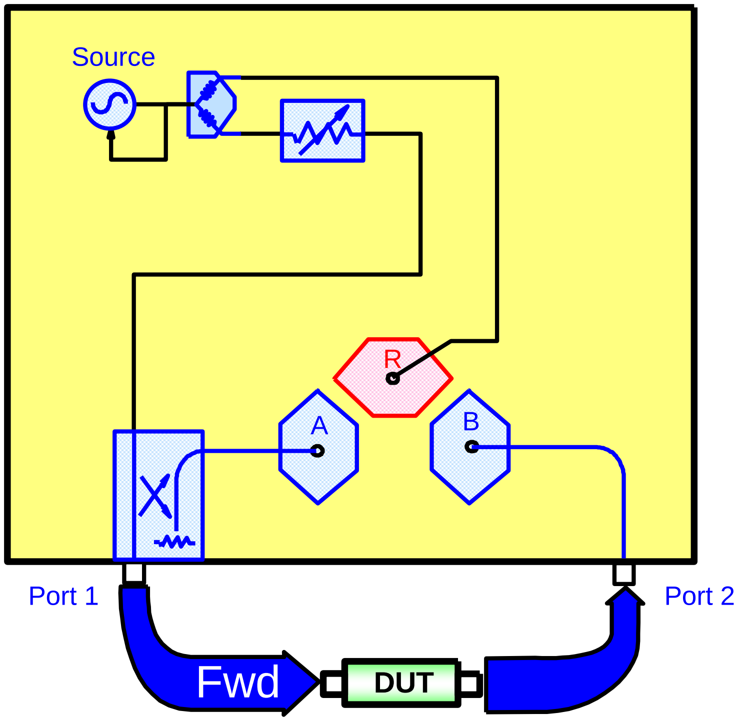
< -100 dBm Sensitivity

- high dynamic range
- harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor

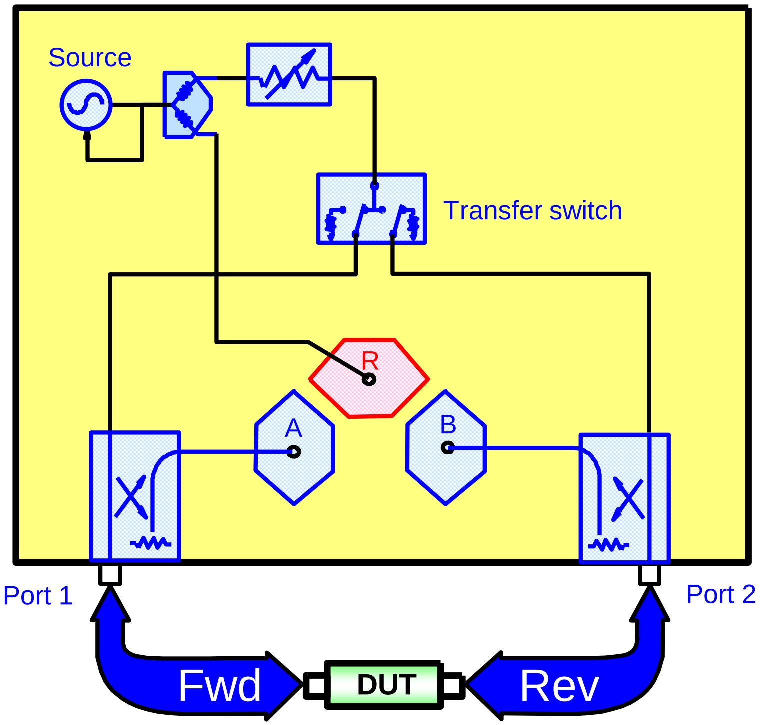
T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



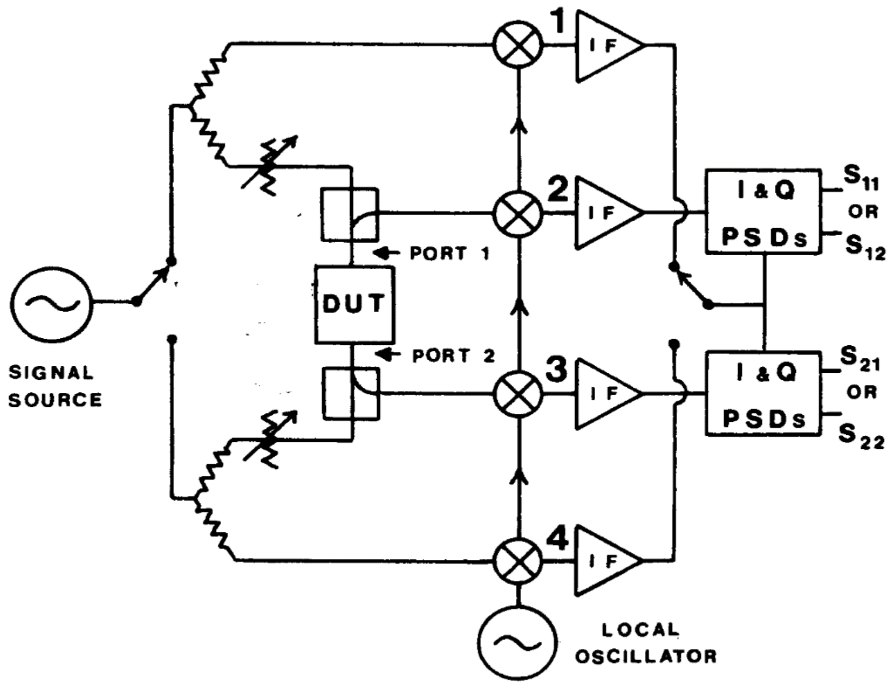
- RF always comes out port 1
- port 2 is always receiver
- **response**, **one-port** cal available

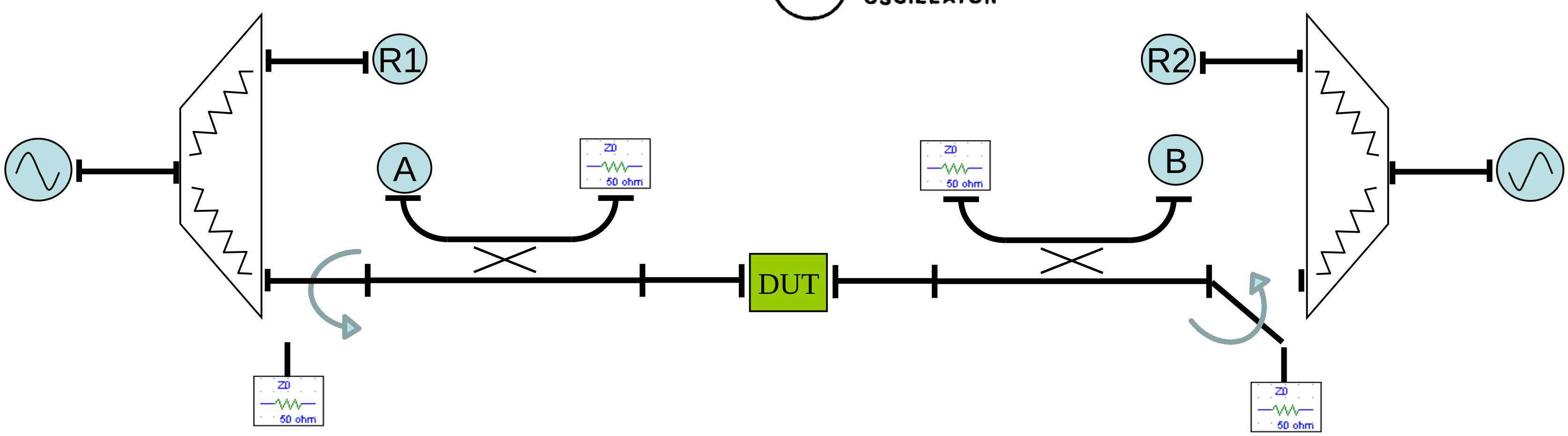
S-Parameter Test Set



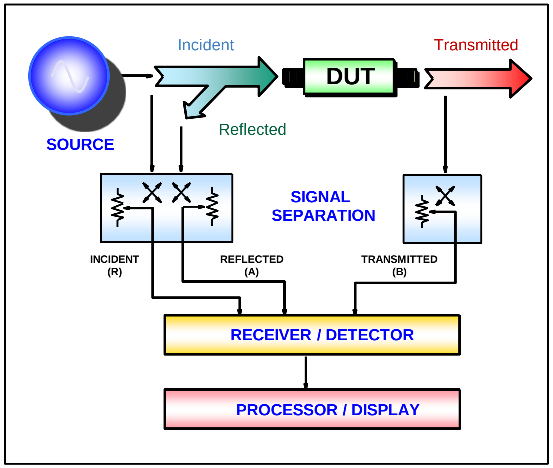
- RF comes out port 1 or port 2
- forward and reverse measurements
- **two-port** calibration possible

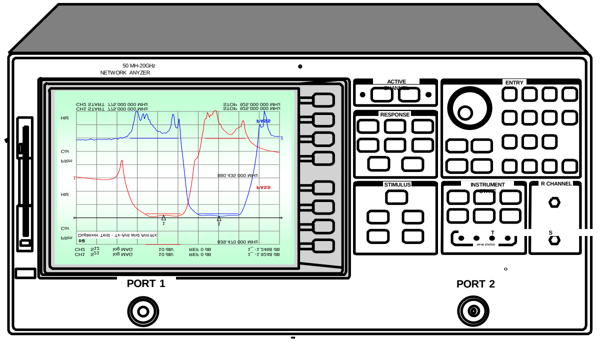
Example of realization schemes

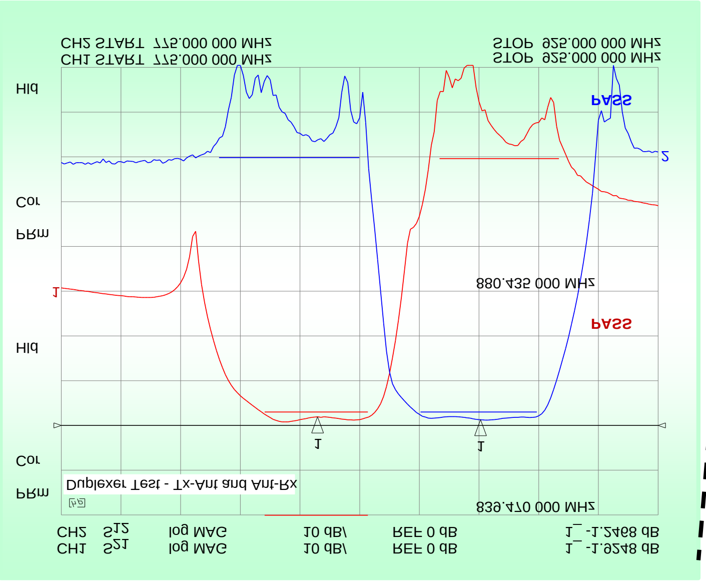




Processor / Display







- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts

Measurement Error Modeling

Systematic errors

- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

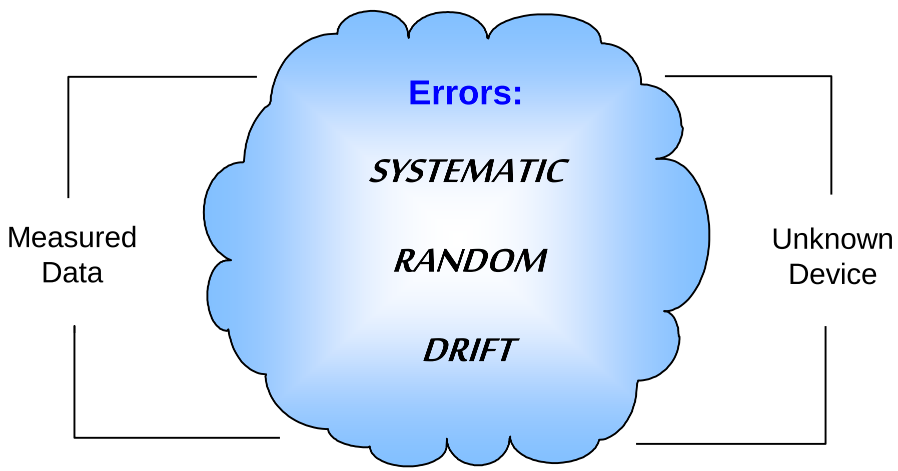
Random errors

- **vary** with time in random fashion (unpredictable)

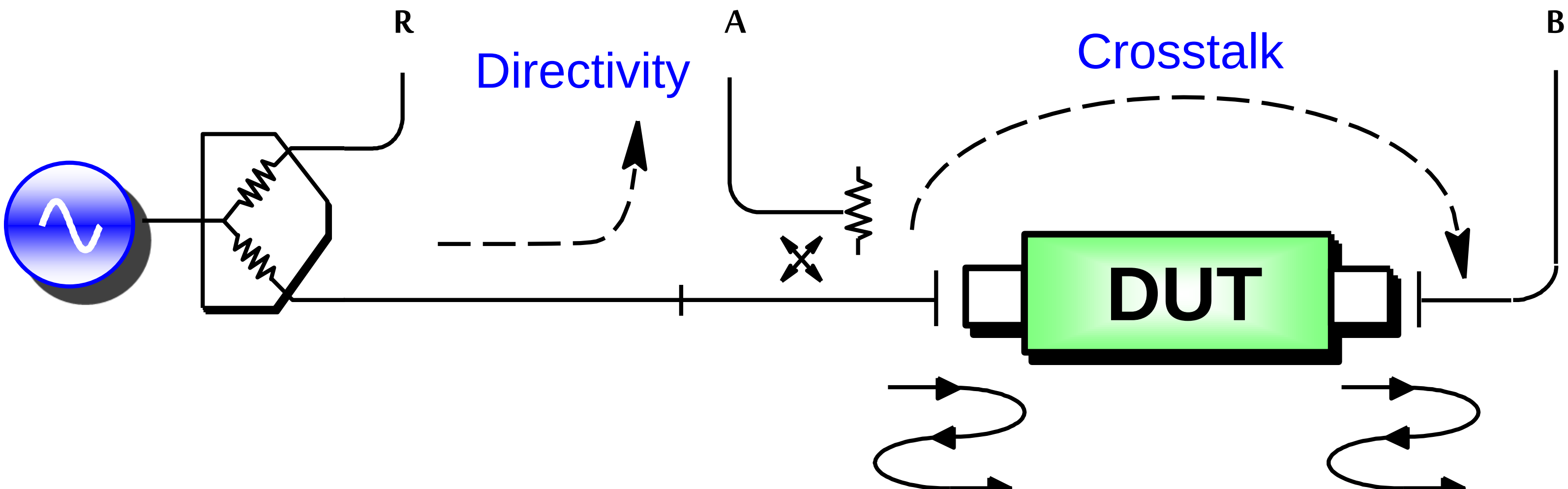
  main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors

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



Systematic Measurement Errors



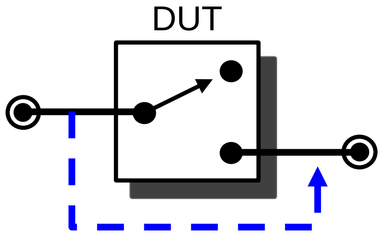
Frequency response
- reflection tracking (A/R)
- transmission tracking (B/R)

Source Mismatch

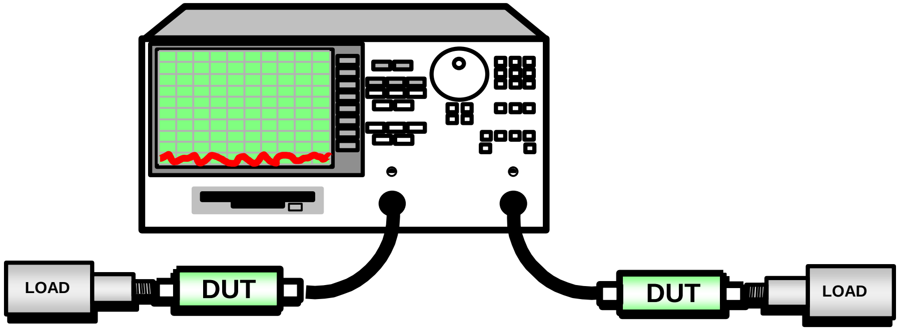
Load Mismatch

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

Crosstalk: Signal Leakage Between Test Ports During Transmission



- Can be a problem with:
  - high-isolation devices (e.g., switch in open position)
  - high-dynamic range devices (some filter stopbands)
- Isolation calibration
  - adds noise to error model (measuring near noise floor of system)
  - only perform if really needed (use averaging if necessary)
  - if crosstalk is **independent** of DUT match, use two terminations
  - if **dependent** on DUT match, use DUT with termination on output



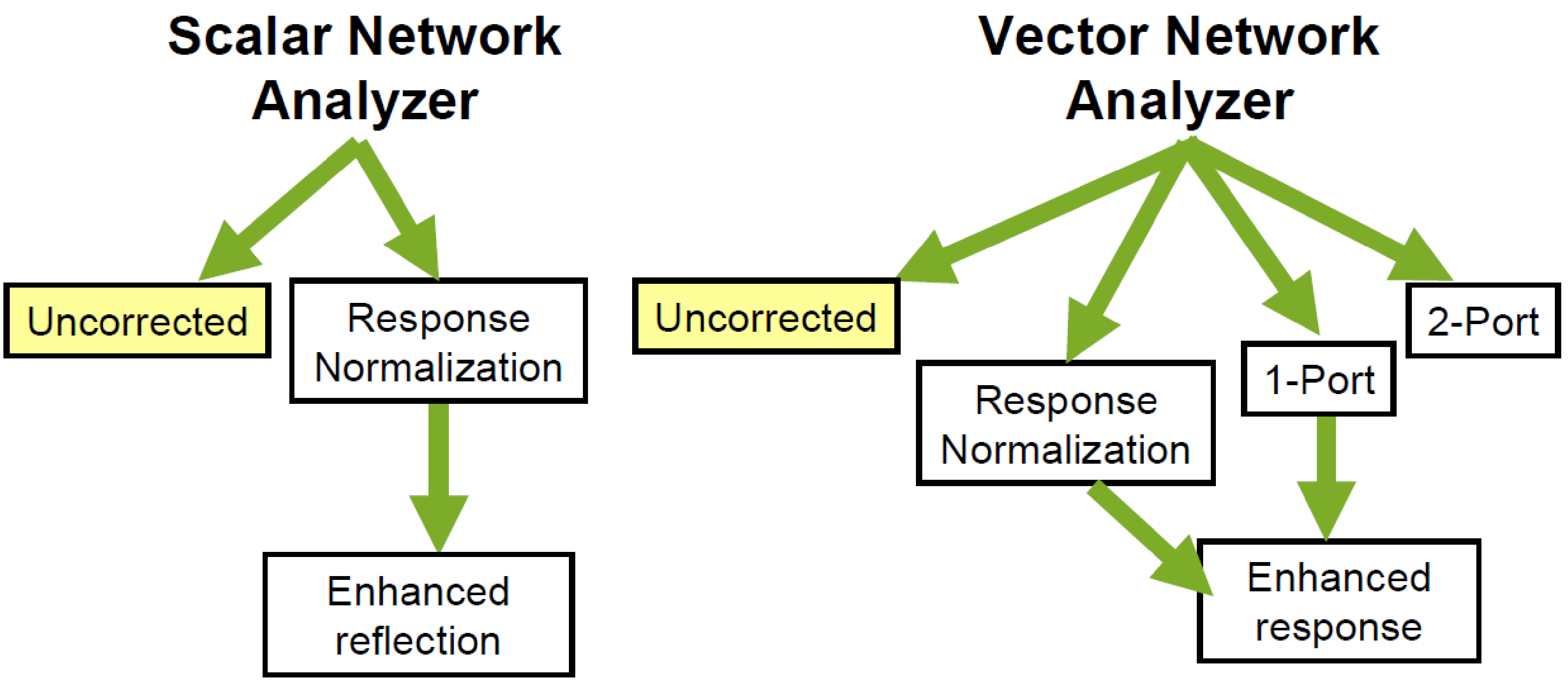
Systematic Measurement Errors

Six Error Terms

- Directivity
- Crosstalk
- Source match
- Load match
- Transmission frequency response
- Reflection frequency response

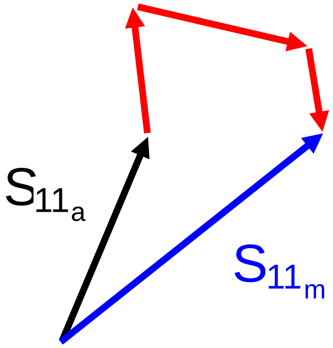
Complete characterization of a two port device requires ***forward and reverse*** measurements, for a total of 12 error terms.

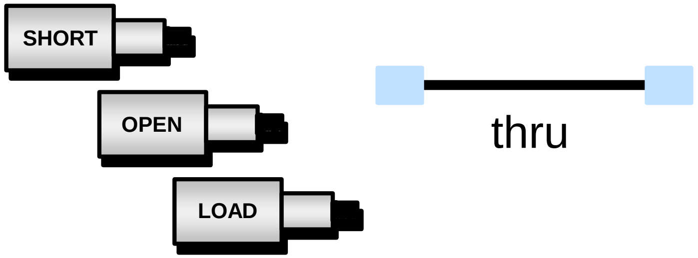
Error Correction



Types of Error Correction

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory
- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements
- **1-port calibration** (reflection measurements)
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** (reflection and transmission measurements)
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT)

- Standards defined in cal kit definition file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit

Error Correction Procedure

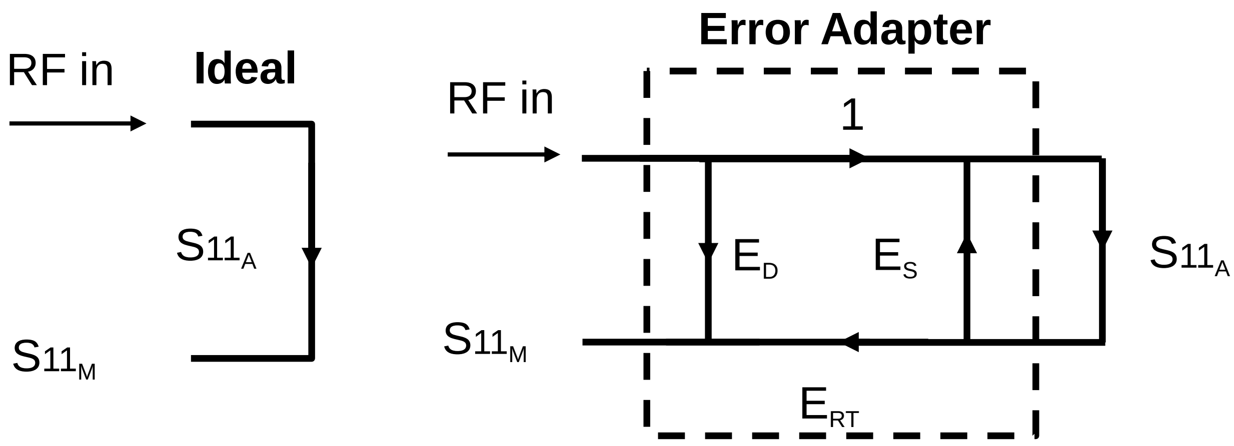
1. Measure the calibration (impedance) standards.

2. Compute and store the error-correction terms.

3. Measure the DUT and apply the correction data.

Calibration standards are devices whose characteristics are precisely known.

Reflection: One-Port Model



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

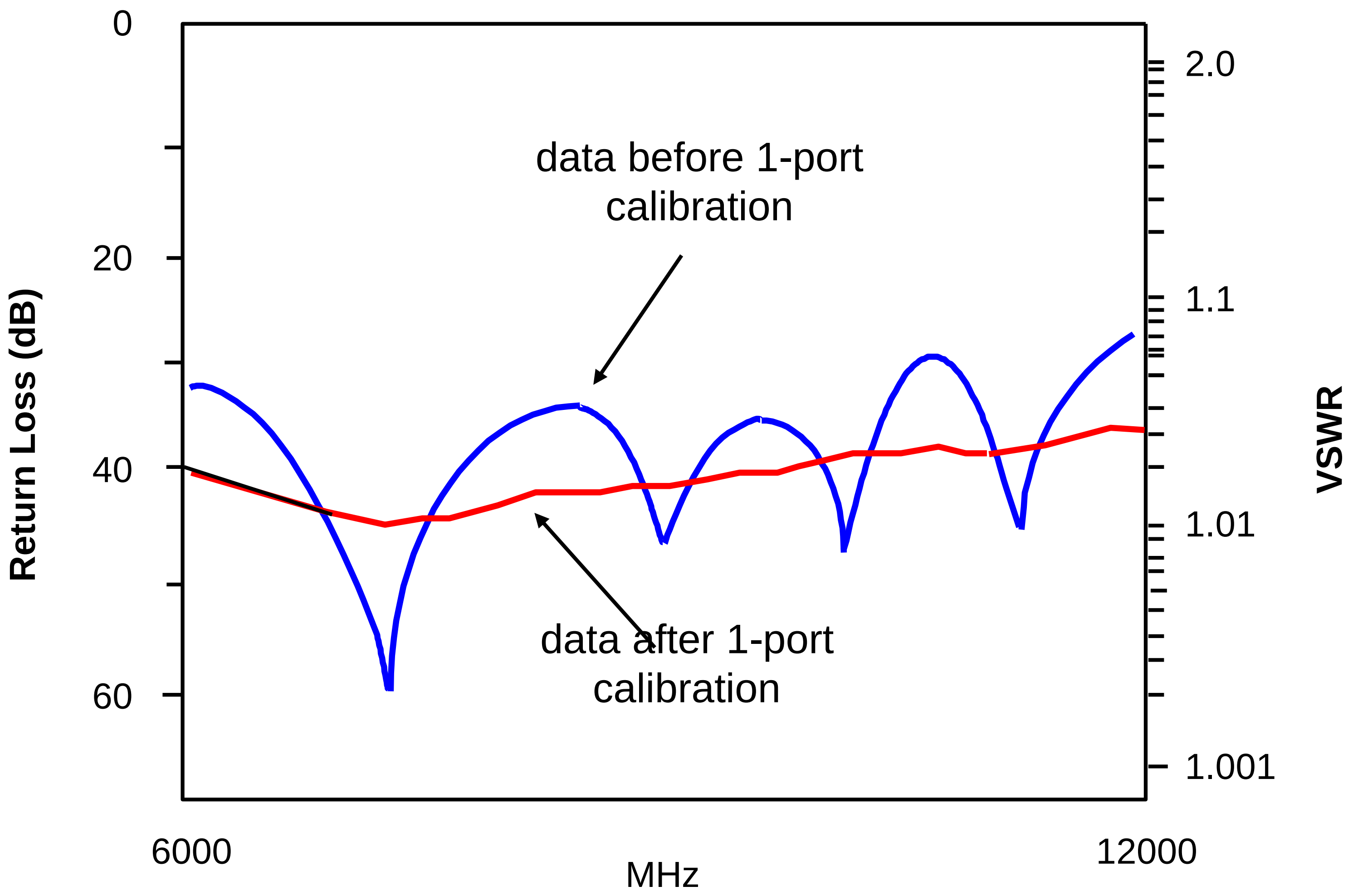
$S11_A$ = Actual

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

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

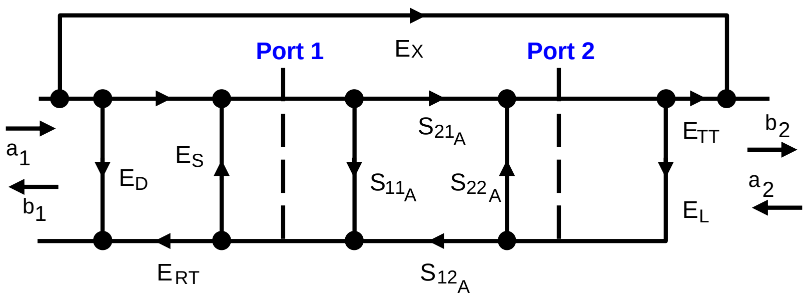
- Assumes good termination at port two if testing two-port devices
- If using port 2 of NA *and* DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results

Before and After One-Port Calibration

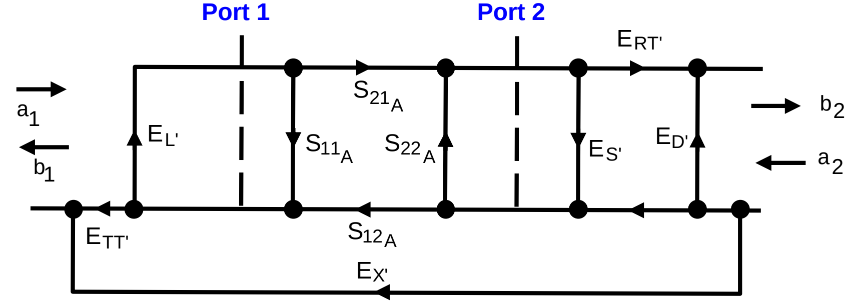


Two-Port Error Correction

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*** network analyzers!!!

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

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

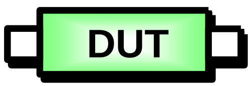
$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X{}'}{E_{TT}{}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L{}')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D{}'}{E_{RT}{}'}E_S{}'\right) - E_L{}'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X{}'}{E_{TT}{}'}\right)}$$

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

Errors and Calibration Standards

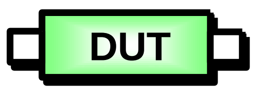
UNCORRECTED

FULL 2-PORT

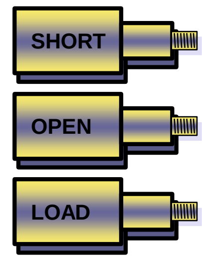


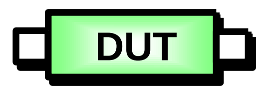
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



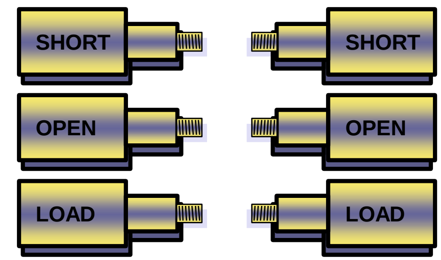
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

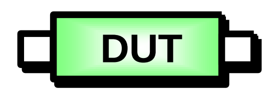




- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

1-PORT





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

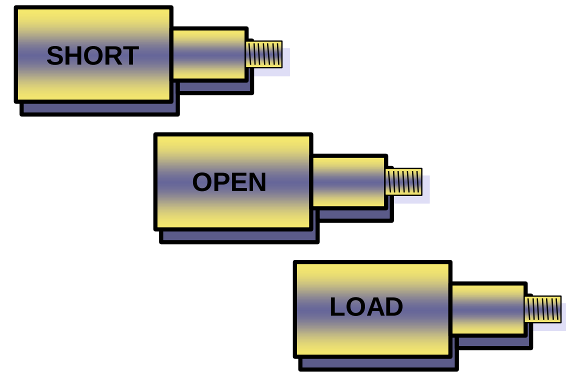
ENHANCED-RESPONSE

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

Calibration Summary

Reflection

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

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

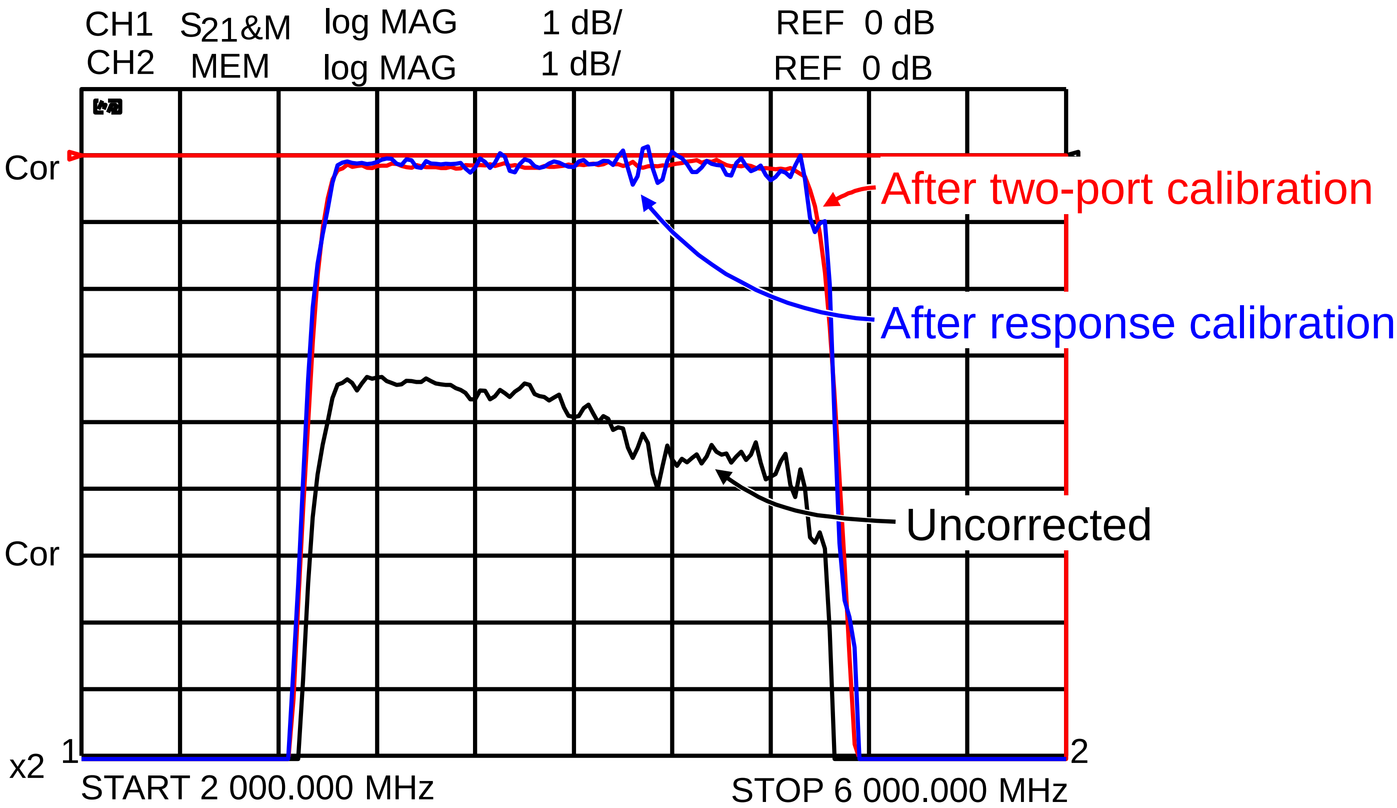
✓ ***error can be corrected***

✗ ***error cannot be corrected***

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

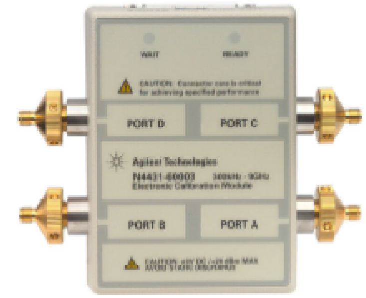
Response versus Two-Port Calibration

Measuring filter insertion loss



ECal: Electronic Calibration

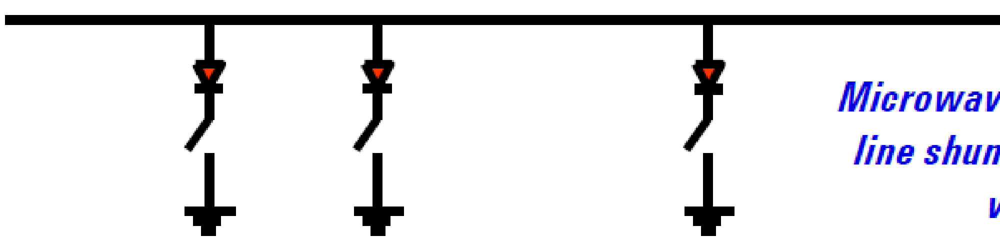
N4431A



- Variety of modules cover 30 kHz to 67 GHz
- Eight connector types available (50 Ω and 75 Ω)
- Single-connection
  - reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated terminations provide excellent accuracy

85092C

N4691A



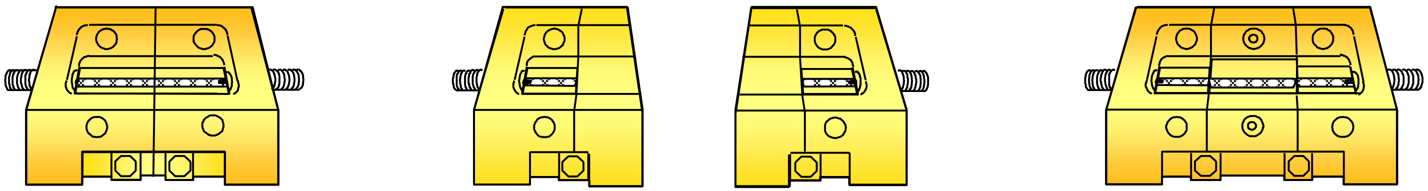
Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

Thru-Reflect-Line (TRL) Calibration

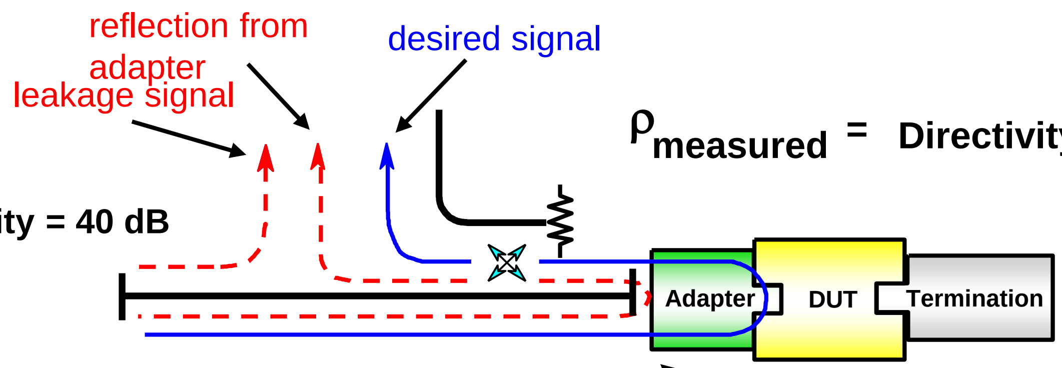
We know about Short-Open-Load-Thru (SOLT) calibration...
What is TRL?

- A two-port calibration technique
- Good for noncoaxial environments (waveguide, fixtures, wafer probing)
- Uses the same 12-term error model as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Two variations: TRL (requires 4 receivers) and TRL* (only three receivers needed)
- Other variations: Line-Reflect-Match (LRM),
- Thru-Reflect-Match (TRM), plus many others

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



Adapter Considerations



$$\rho_{measured} = \text{Directivity} + \rho_{adapter} + \rho_{DUT}$$

Coupler directivity = 40 dB

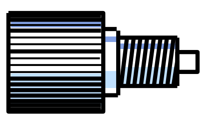
DUT has SMA (f) connectors

APC-7 calibration done here

Worst-case
System Directivity

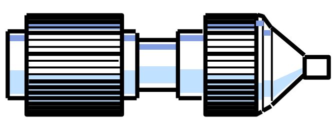
Adapting from APC-7 to SMA (m)

28 dB



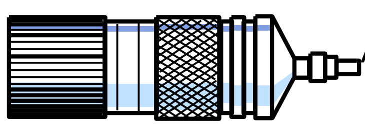
APC-7 to SMA (m)
SWR:1.06

17 dB



APC-7 to N (f) + N (m) to SMA (m)
SWR:1.05 SWR:1.25

14 dB

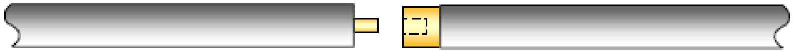


APC-7 to N (m) + N (f) to SMA (f) + SMA (m) to (m)
SWR:1.05 SWR:1.25 SWR:1.15

Calibrating Non-Insertable Devices

When doing a through cal, normally test ports mate directly

- cables can be connected directly without an adapter
- result is a zero-length through



What is an insertable device?

- has same type of connector, but different sex on each port
- has same type of sexless connector on each port (e.g. APC-7)

What is a non-insertable device?

- one that cannot be inserted in place of a zero-length through
- has same connectors on each port (type and sex)
- has different type of connector on each port
  (e.g., waveguide on one port, coaxial on the other)

What calibration choices do I have for non-insertable devices?

- use an *uncharacterized* through adapter
- use a *characterized* through adapter (modify cal-kit definition)
- swap equal adapters
- adapter removal