Network Analysis Basics

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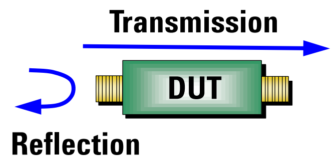
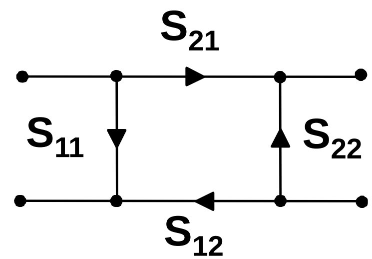
Agilent Technologies

Agenda

- Overview
- What Measurements do we make?
- Network Analyzer Hardware
- Error Models and Calibration
- Example Measurements

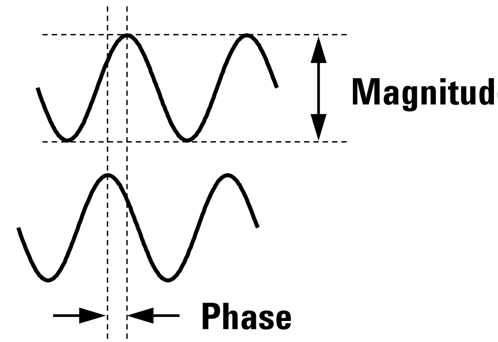
What is a Network Analyzer?

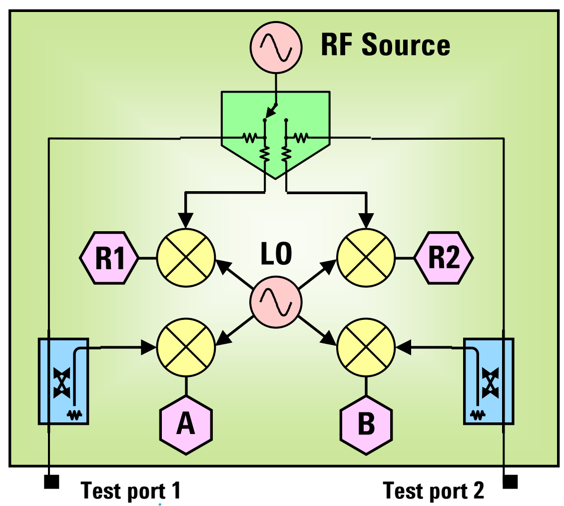




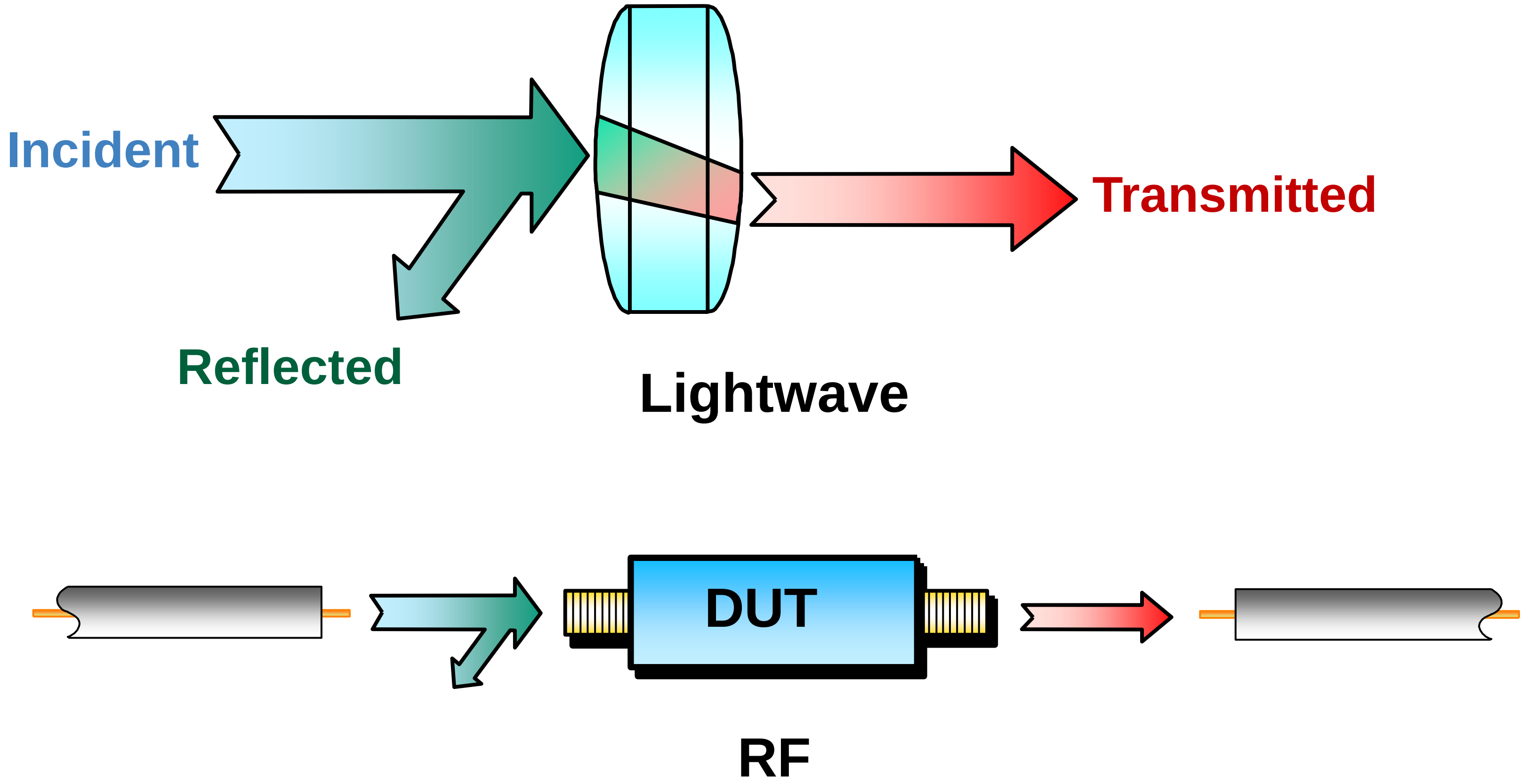
Vector network analyzers (VNAs)...

- 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**





Lightwave Analogy to RF Energy



Why do we need to test components?

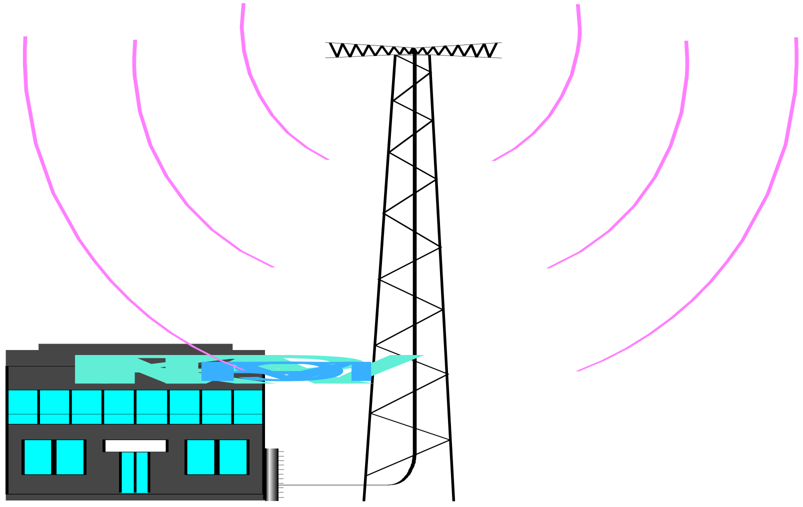
Verify specifications of “building blocks” for more complex RF systems

Ensure distortionless transmission of communications signals

linear: constant amplitude, linear phase / constant group delay

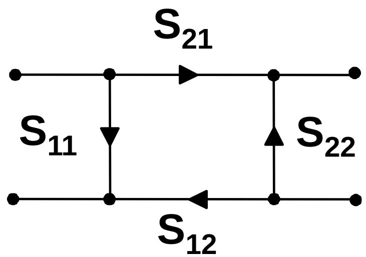
nonlinear: harmonics, intermodulation, compression, AM-to-PM conversion

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

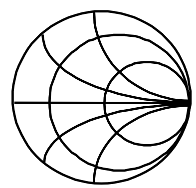


The Need for Both Magnitude and Phase

1. Complete characterization of linear networks

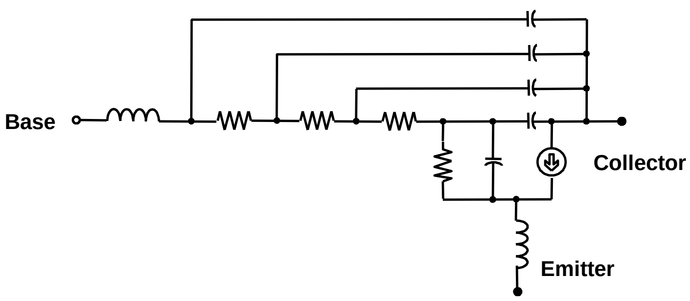


2. Complex impedance needed to design matching circuits

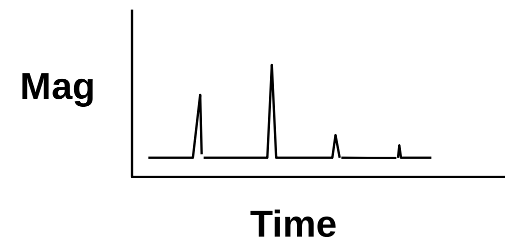


3. Complex values needed for device modeling

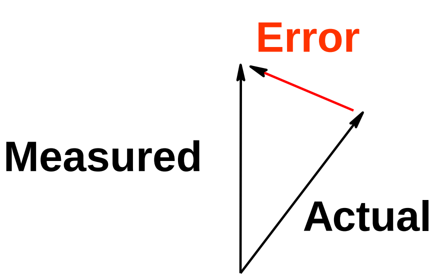
High-frequency transistor model



4. Time-domain characterization



5. Vector-error correction



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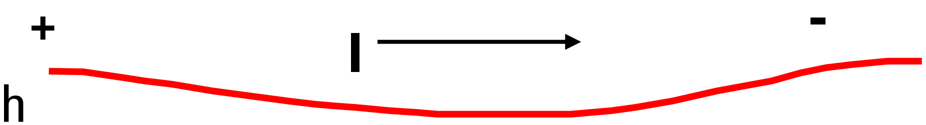
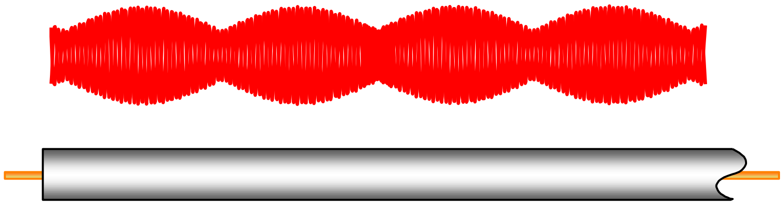
Transmission-line Basics



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

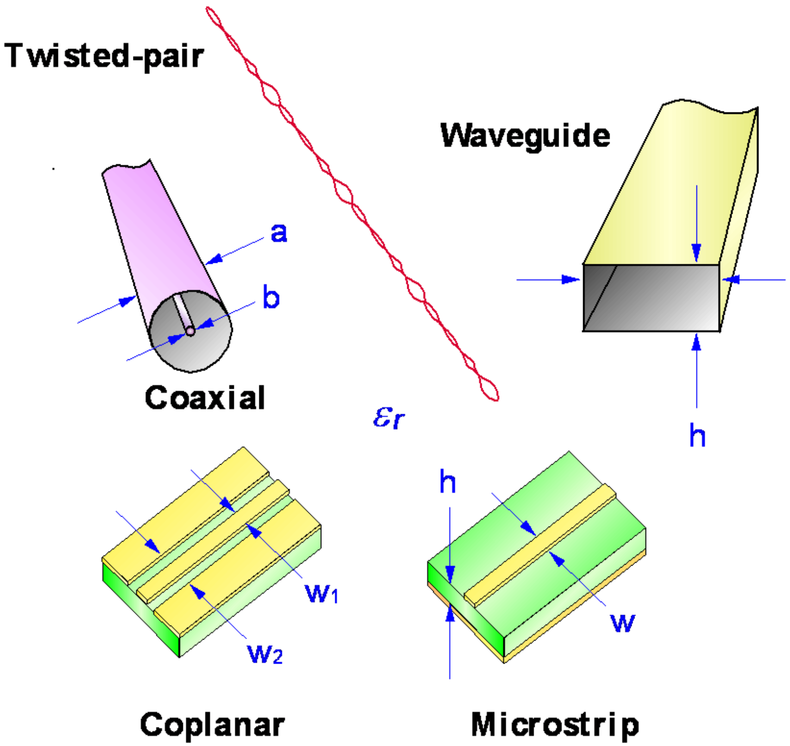
- wavelength << length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

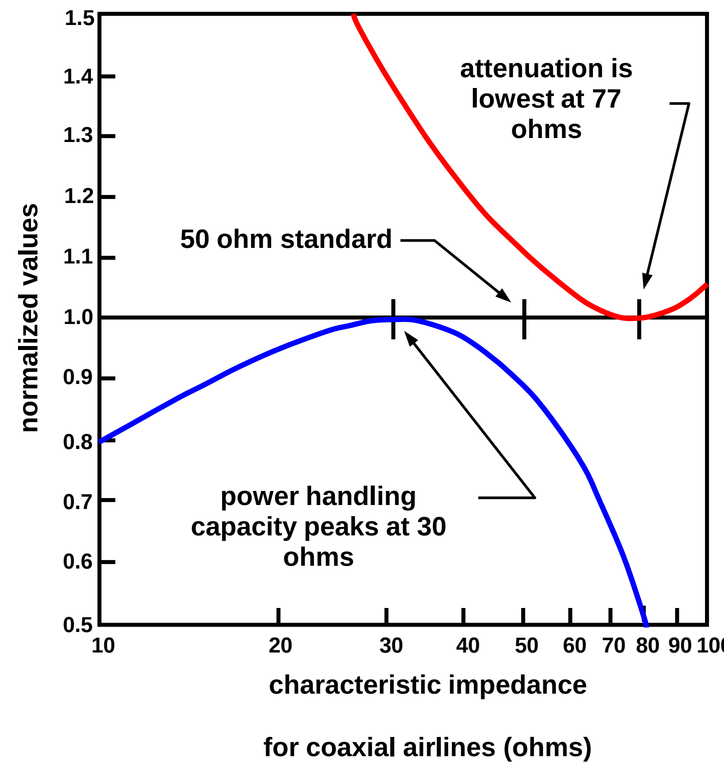
Transmission-line Zo

Zo determines relationship between voltage and current waves

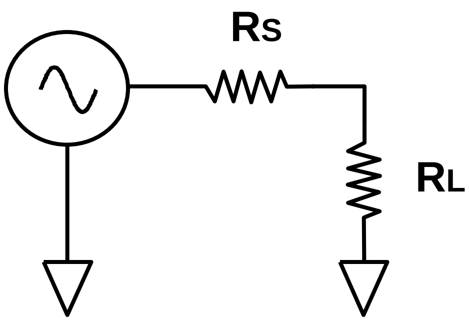
Zo is a function of physical dimensions and ε_r

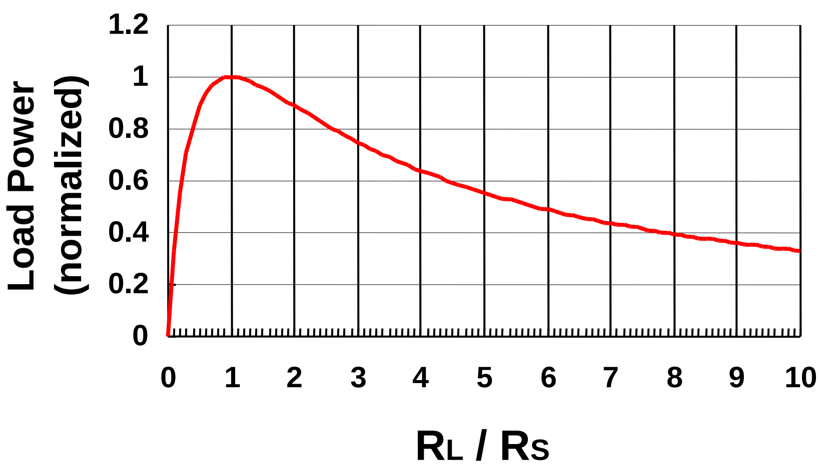
Zo is usually a real impedance (e.g. 50 or 75 ohms)



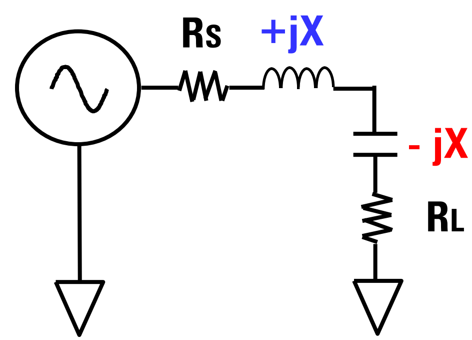


Power Transfer Efficiency



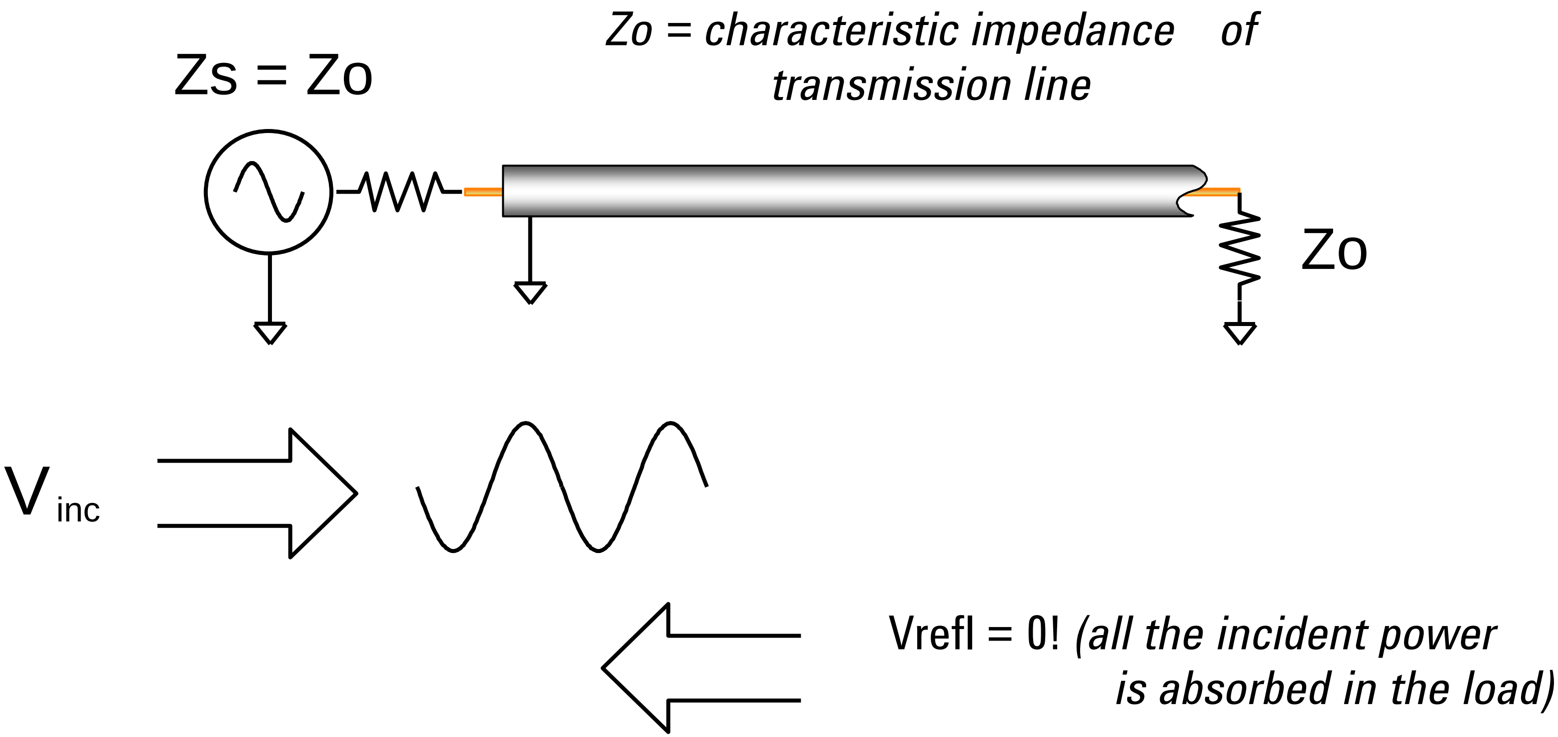


For complex impedances, maximum power transfer occurs when **ZL = ZS*** (conjugate match)



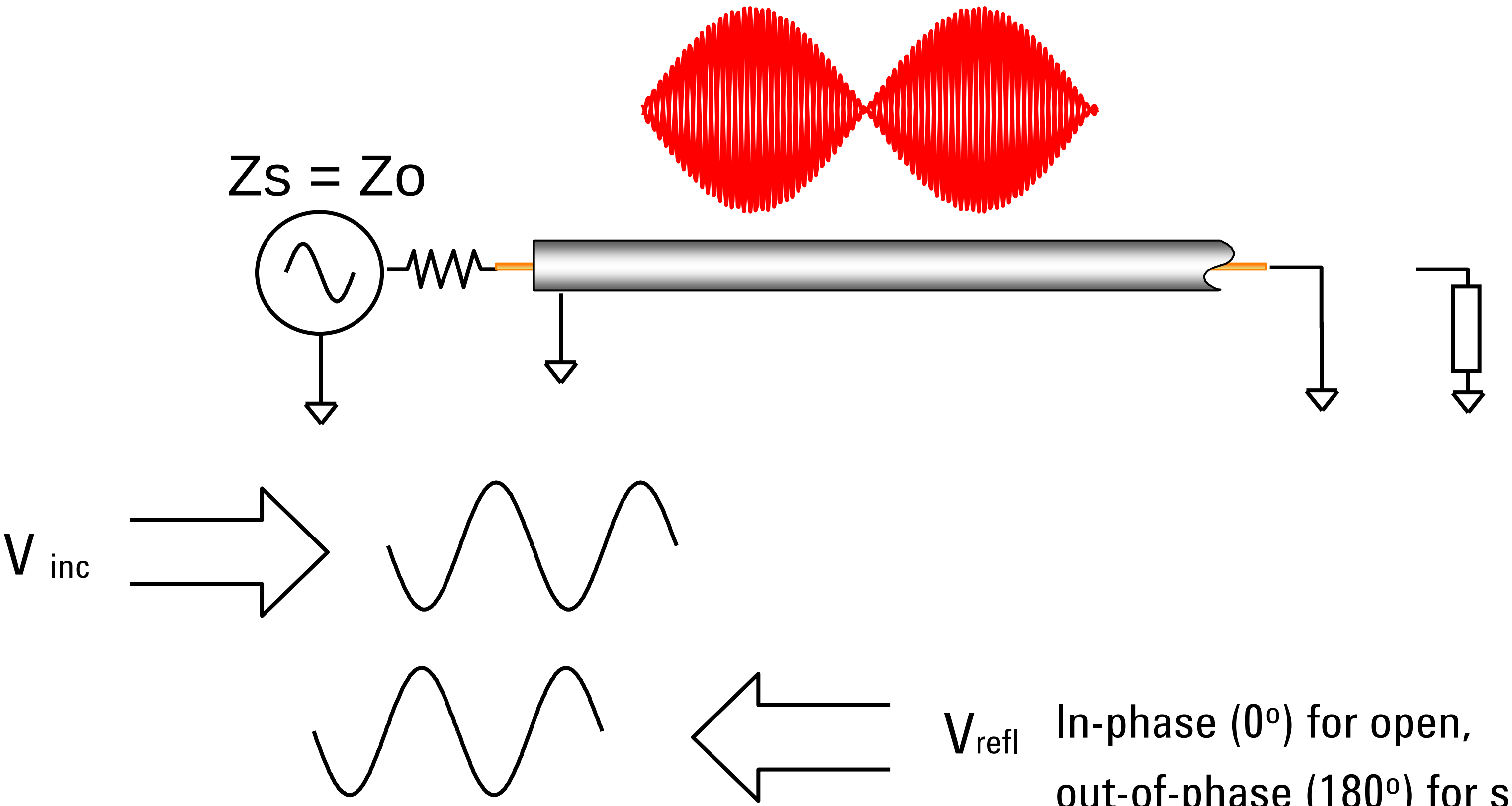
Maximum power is transferred when RL = RS

Transmission-line terminated with Zo



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

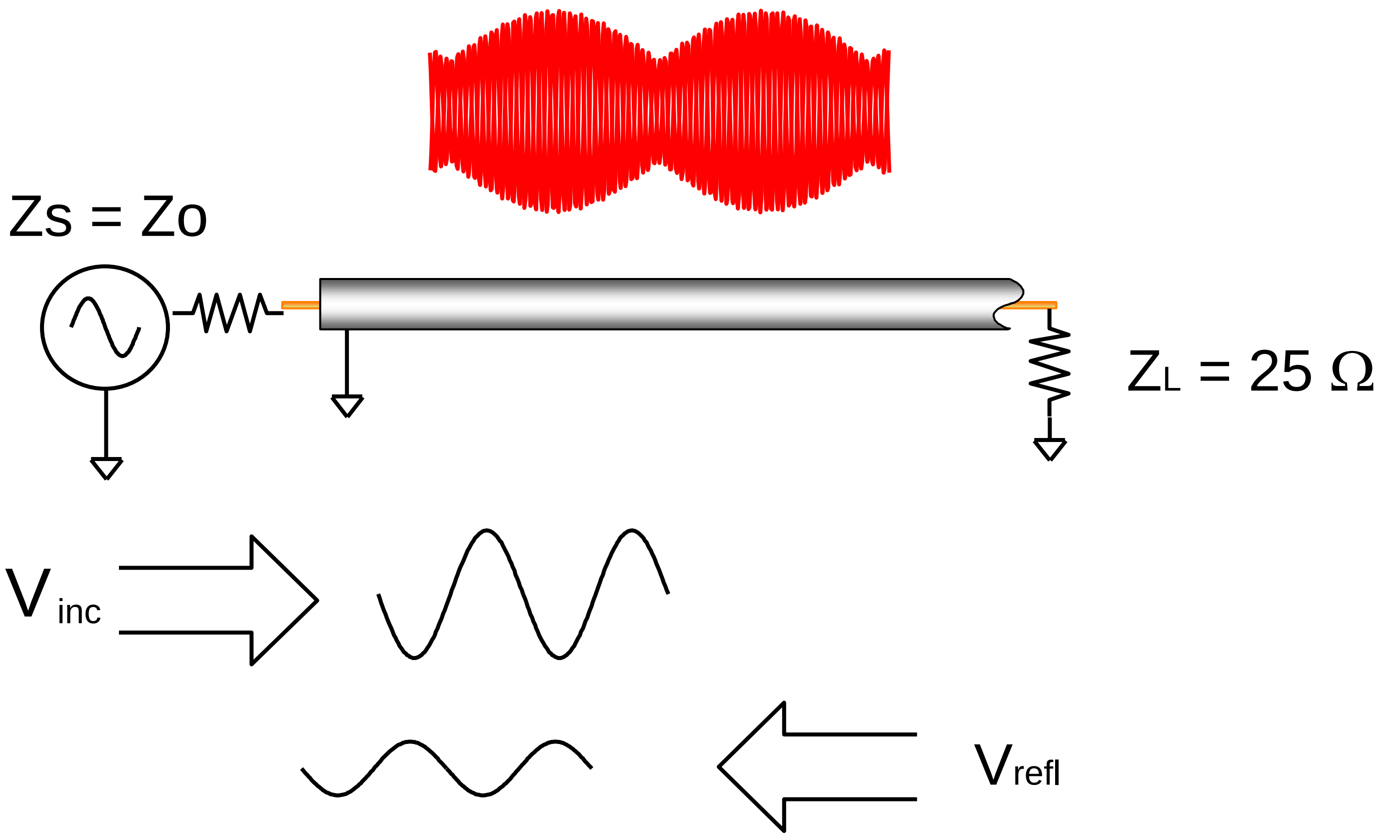
Transmission-line Terminated with Short, Open



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

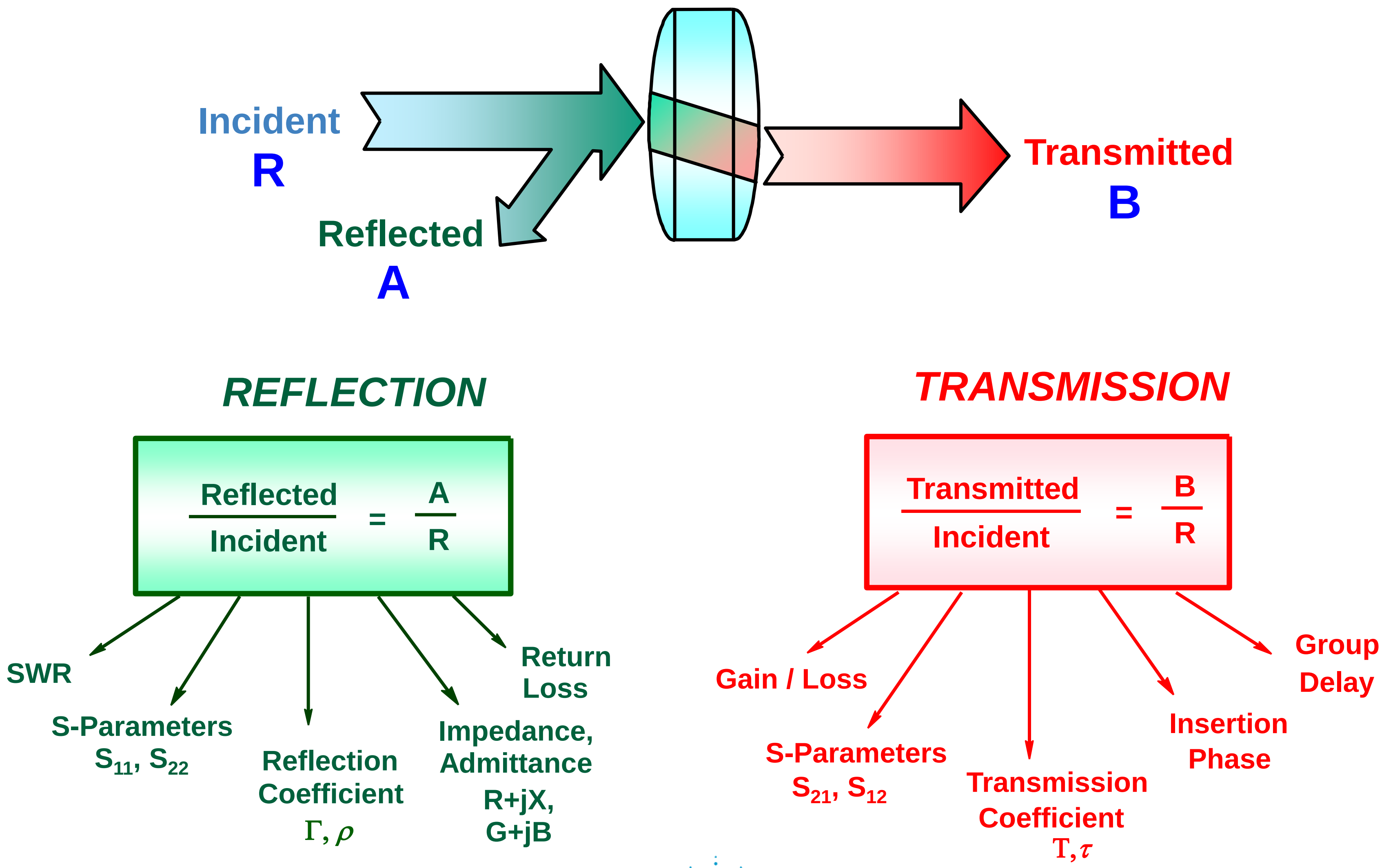
For reflection, a transmission line terminated in a short or open reflects all power back to source

Transmission-line Terminated with 25 Ω



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

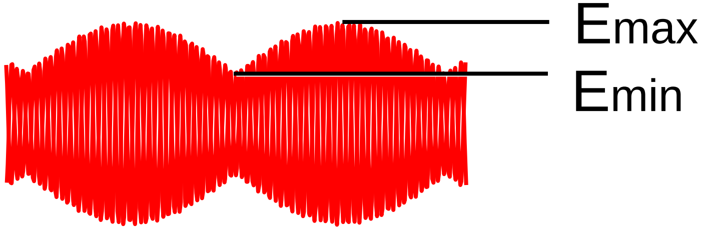
High-Frequency Device Characterization



Reflection Parameters

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

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



Voltage Standing Wave Ratio

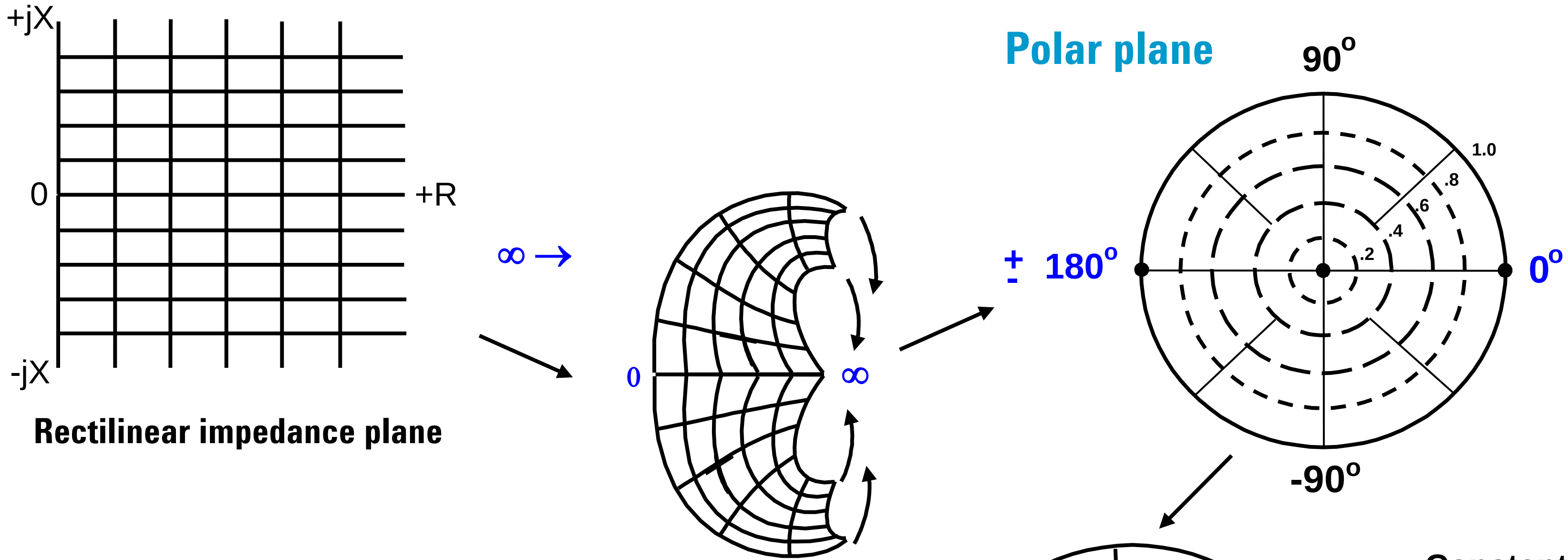
VSWR $= \dfrac{E_{max}}{E_{min}} = \dfrac{1 + \rho}{1 - \rho}$

No reflection *($Z_L = Z_O$)*

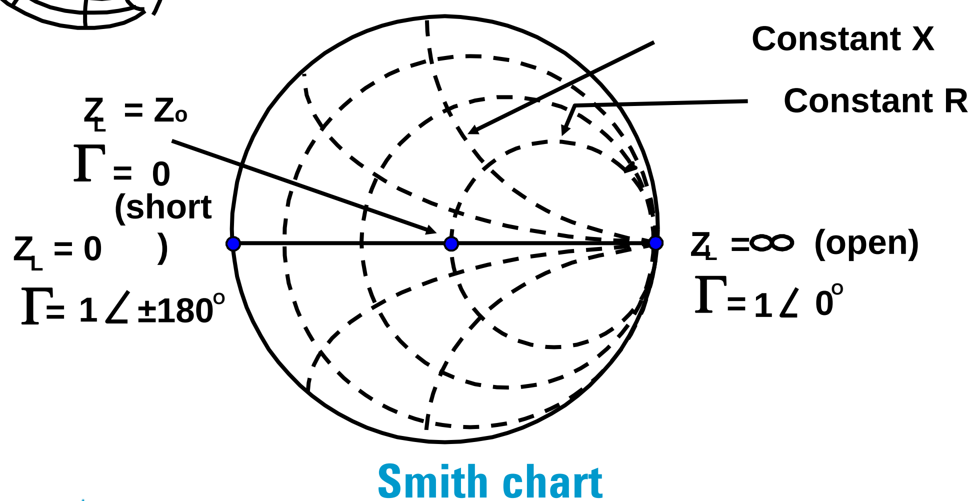
Full reflection *(Z_L = open, short)*

No reflection		Full reflection
0	ρ	1
∞ dB	RL	0 dB
1	VSWR	∞

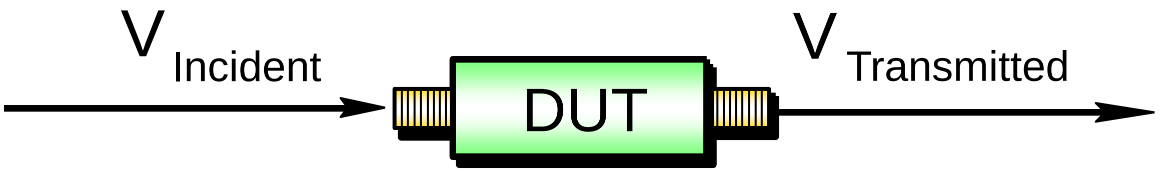
Smith Chart Review



Smith Chart maps rectilinear impedance plane onto polar plane



Transmission Parameters

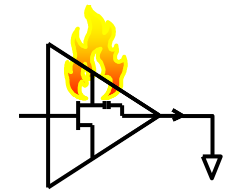


Transmission Coefficient = $T = \dfrac{V_{Transmitted}}{V_{Incident}} = \tau \angle \phi$

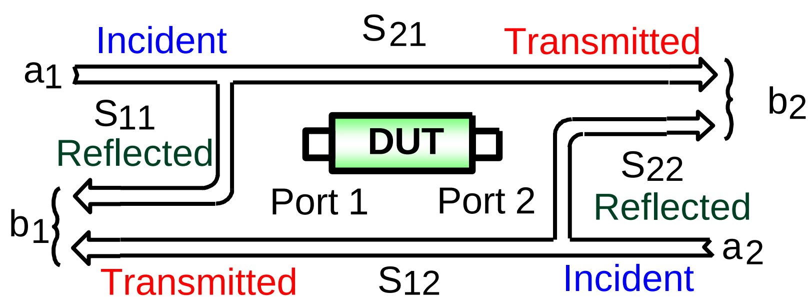
Insertion Loss (dB) = $-20 \text{ Log} \left| \dfrac{V_{Trans}}{V_{Inc}} \right| = -20 \log \tau$

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

Why Use S-Parameters?



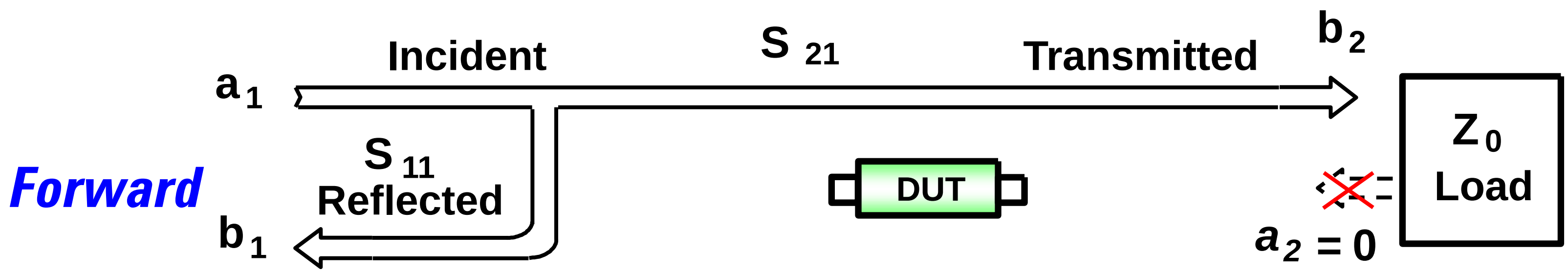
- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** 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 our **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

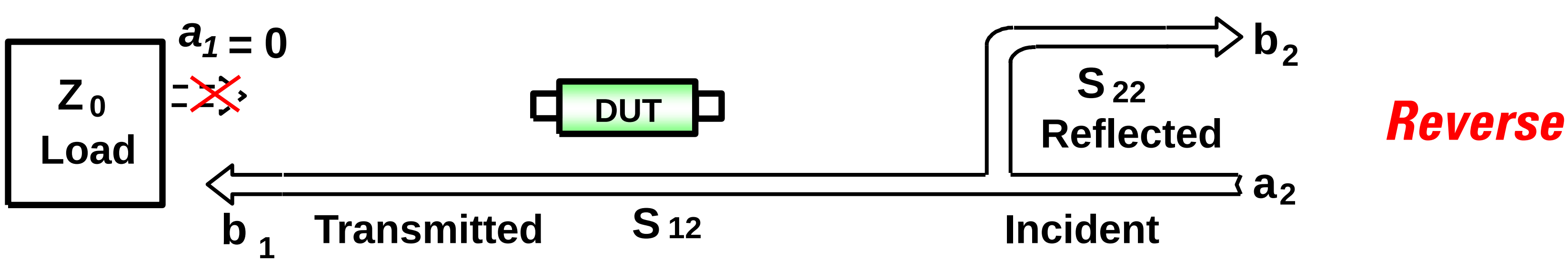


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1}\Bigg|_{a_2 = 0}$$

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

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

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



S-Parameters and Common Measurement Terms

S11 = forward reflection coefficient *(input match)*

S22 = reverse reflection coefficient *(output match)*

S21 = forward transmission coefficient *(gain or loss)*

S12 = reverse transmission coefficient *(isolation)*

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

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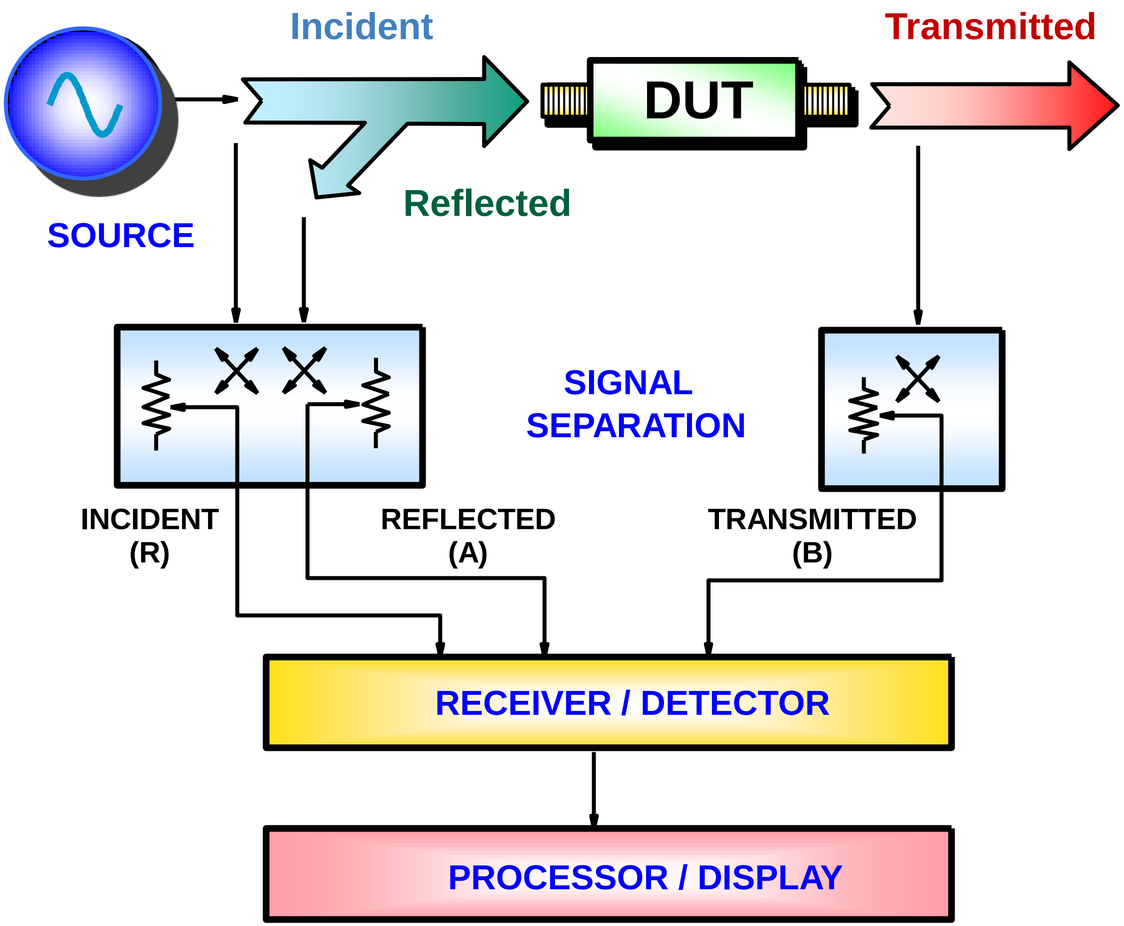
Generalized Network Analyzer Block Diagram



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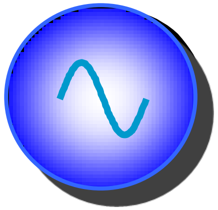
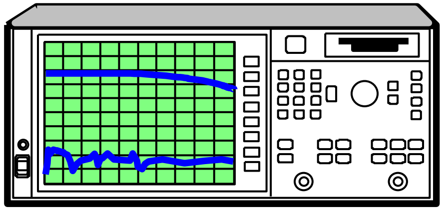
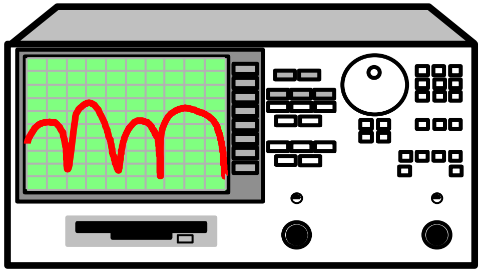
Source

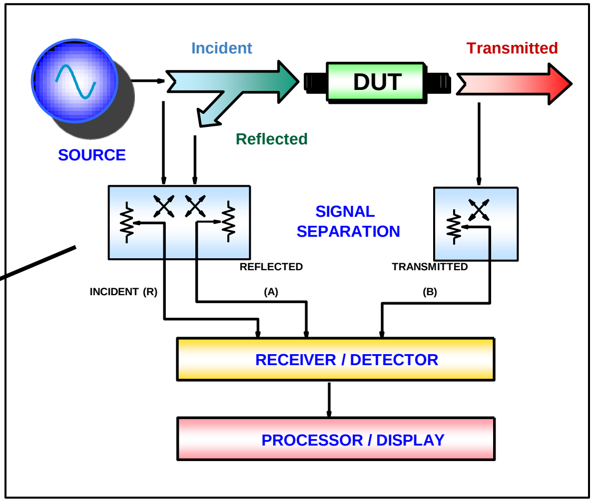
- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Agilent analyzers sold today have ***integrated, synthesized*** **sources**





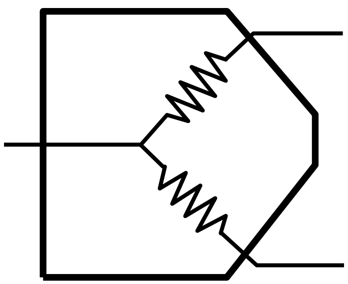


Signal Separation

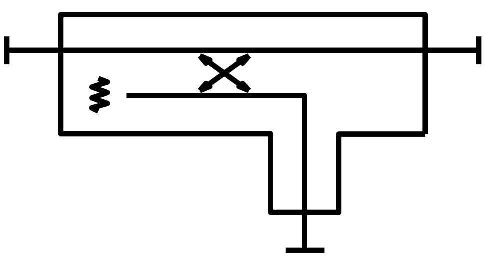


- **measure incident signal for reference**
- **separate incident and reflected signals**

splitter

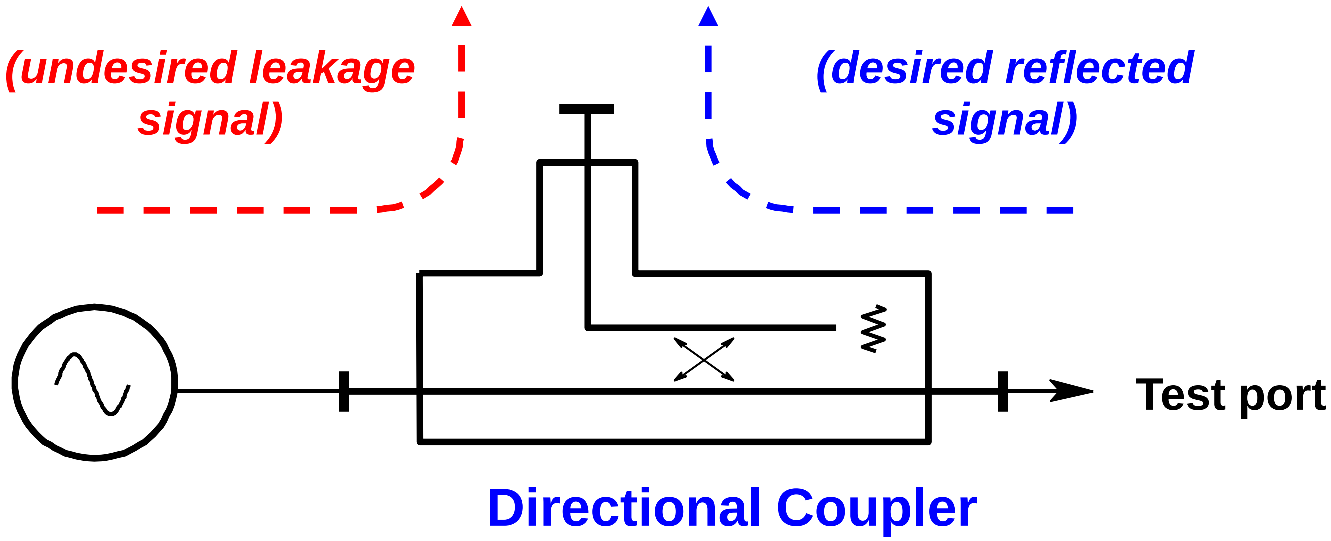


directional coupler

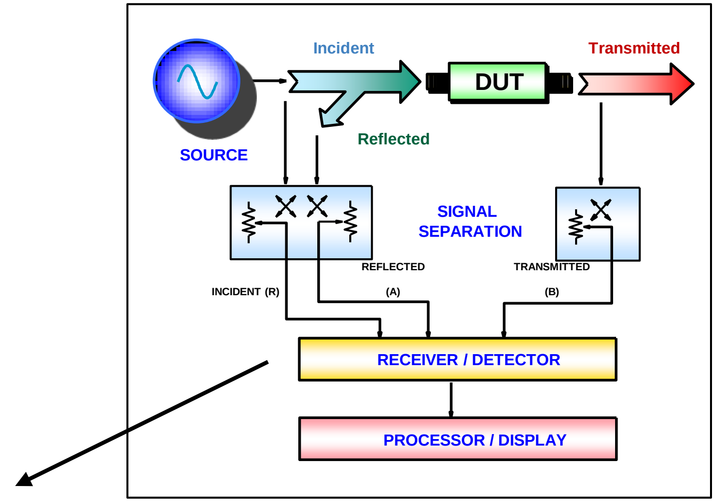


Directivity

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

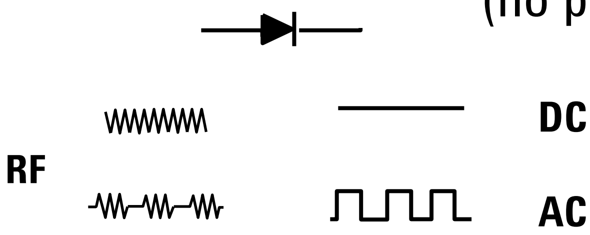


Detector types

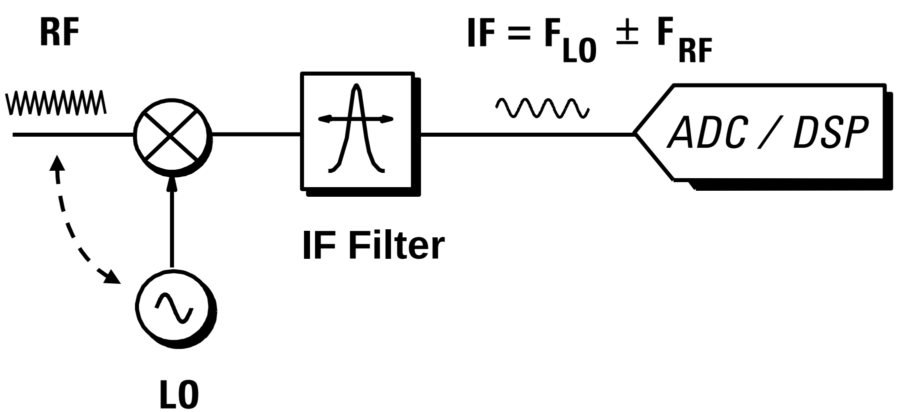


Diode

Scalar **broadband**
(no phase information)



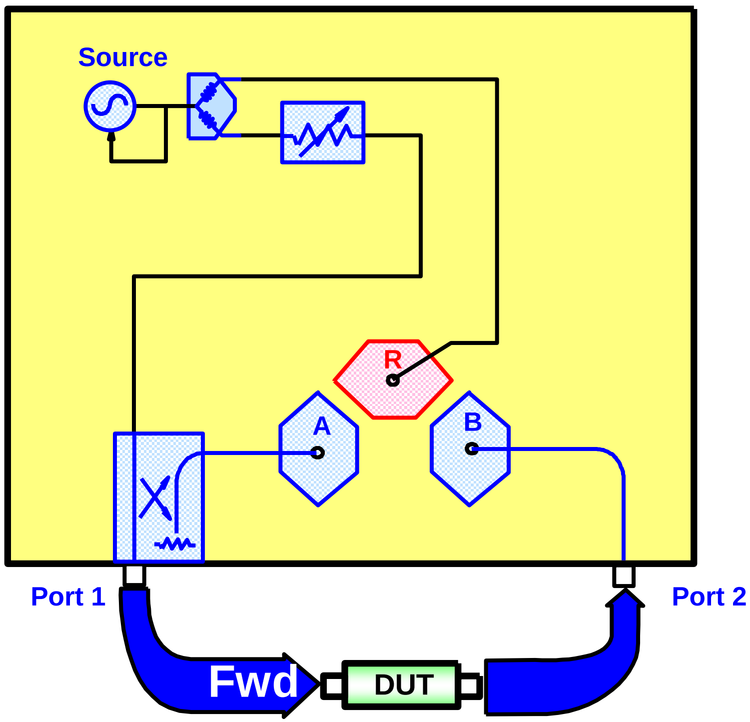
Tuned Receiver



Vector
(magnitude and phase)

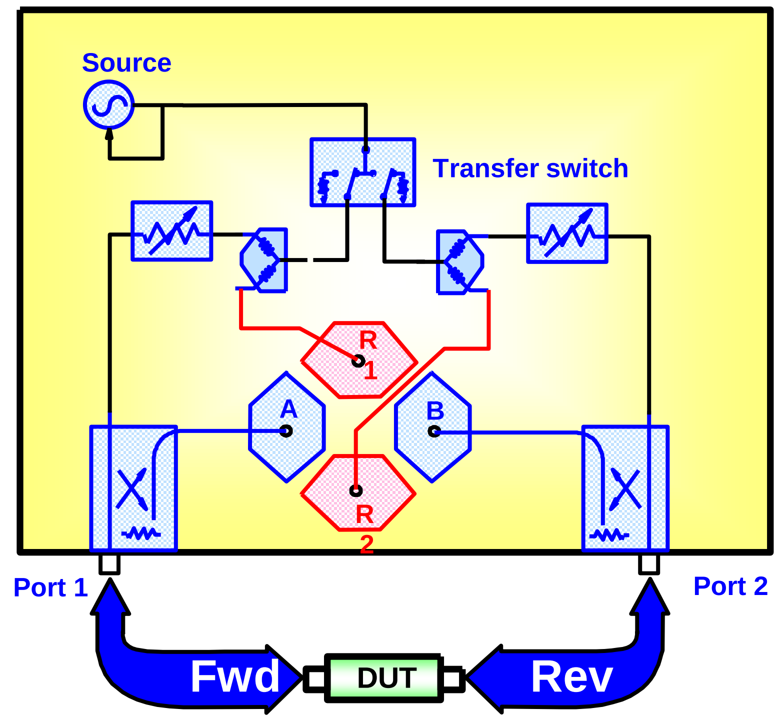
T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



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

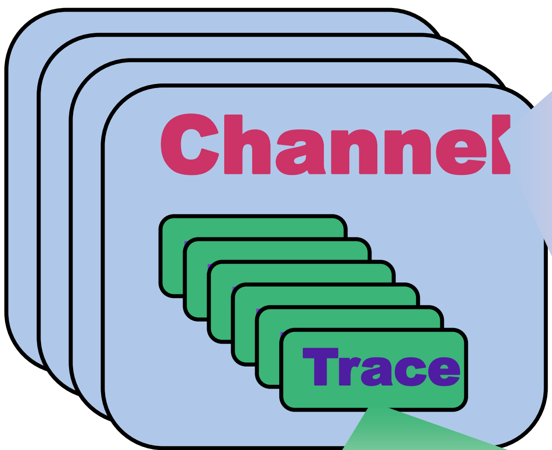
S-Parameter Test Set



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

Achieving measurement flexibility

- RF Performance
- Easy to learn and use
- Powerful measurement config.
- Advanced connectivity
- Flexible automation choices

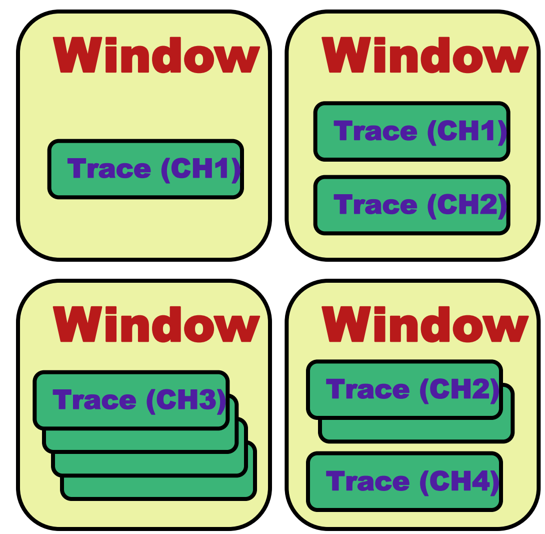


Channel
- Sweep type
- Frequency
- Power
- IF bandwidth
- # of points
- Trigger state
- Averaging
- Calibration

Rules of 4:
32 independent measurement channels
26 windows to view traces and channels
8 active and 8 memory traces per window
4-parameter display needs only one channel

Global
- Trigger source
- Port extensions
- RF power on/off

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



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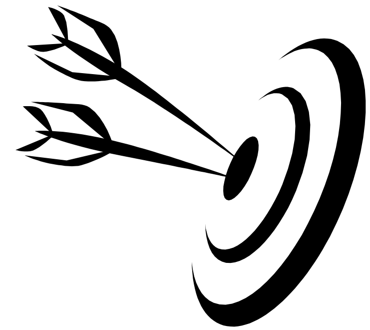
The Need for Calibration



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?

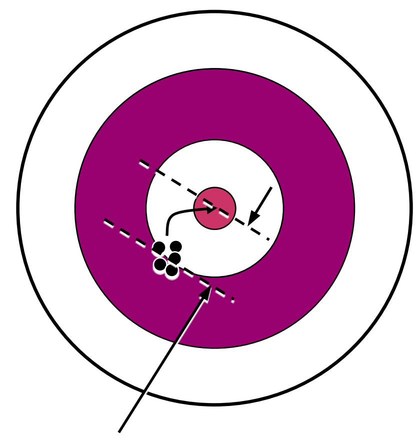
With vector-error-corrected calibration

Not the same as the yearly instrument calibration

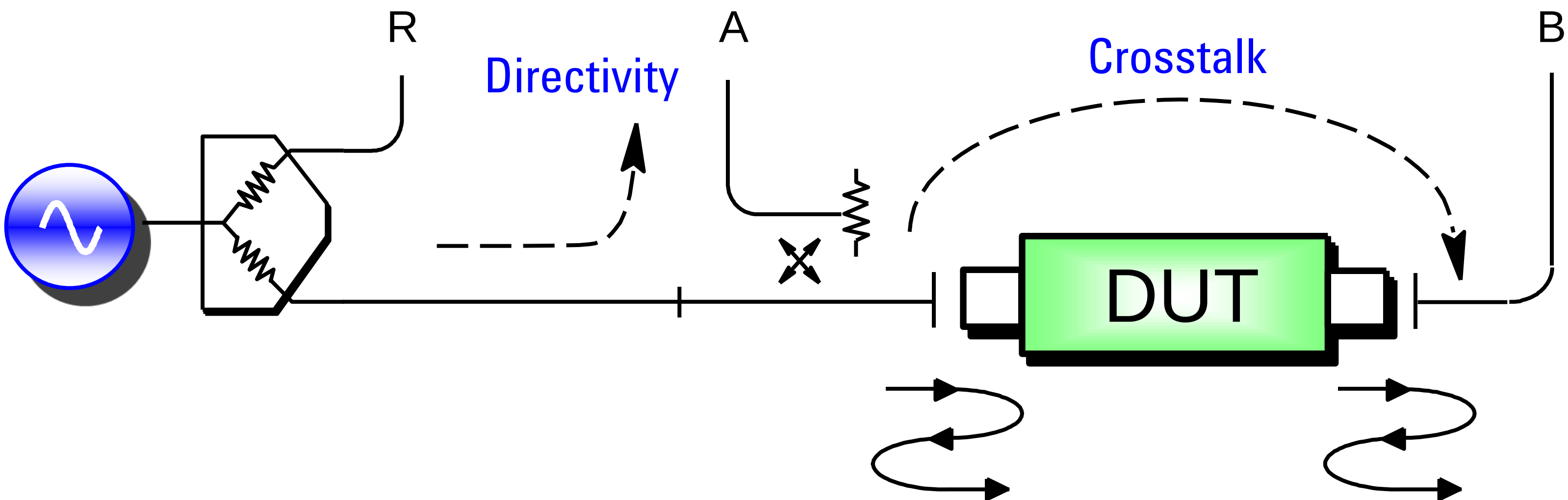
What does calibration do for us?

Removes the largest contributor to measurement uncertainty: systematic errors

Provides best picture of true performance of DUT



Systematic Measurement Errors



Frequency response

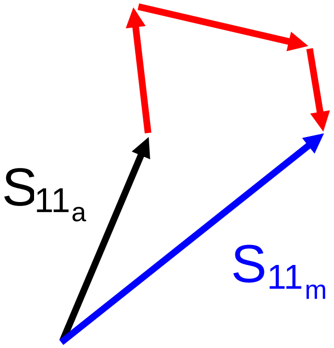
- reflection tracking (A/R)
- transmission tracking (B/R)

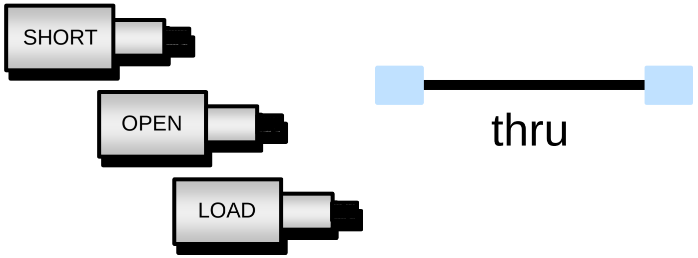
Six forward and six reverse error terms yields 12 error terms for two-port devices

Types of Error Correction

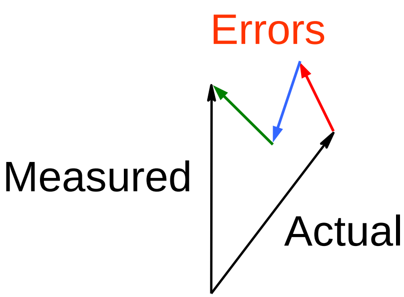
- response (normalization)
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- vector
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





Systematic Measurement Errors



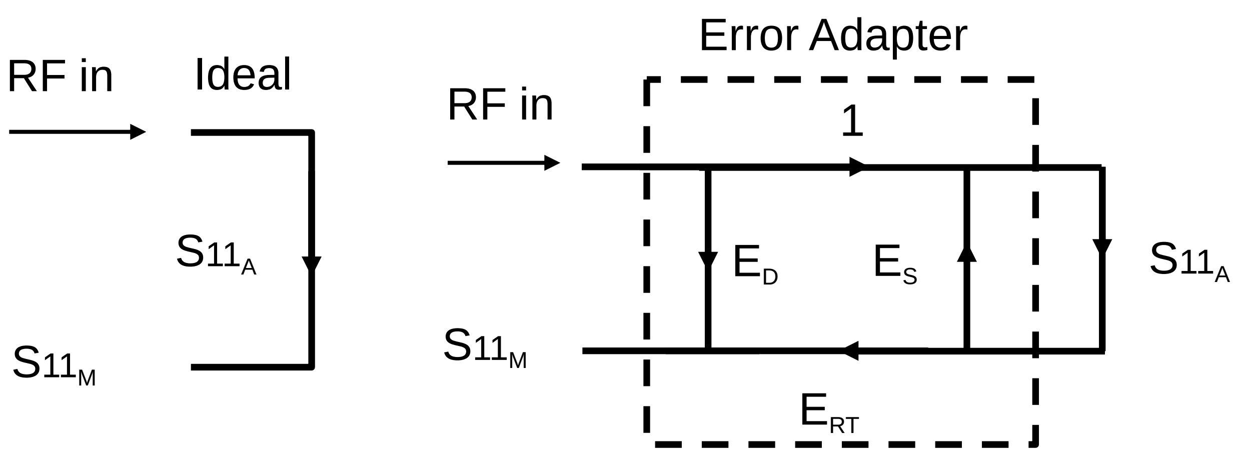
Vector-error correction...

- 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

Reflection: One-Port Model



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

$S11_A$ = Actual

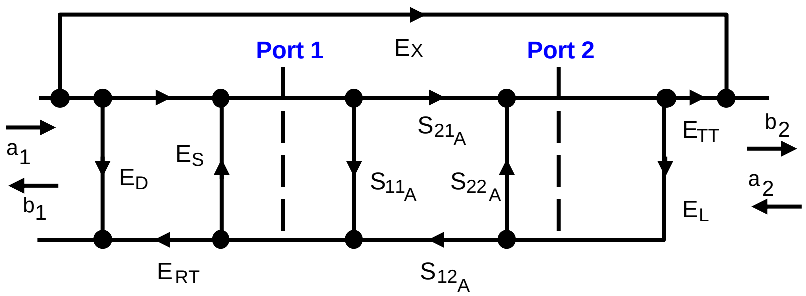
To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

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

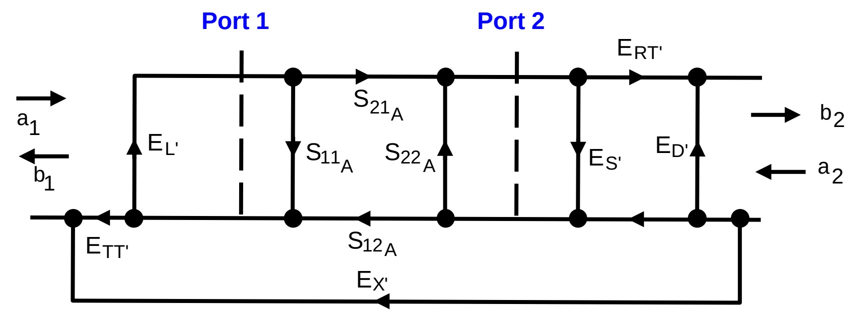
- Assumes good termination at port two if testing two-port devices
- If using port 2 of NA *and* DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results

Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
E_L = fwd load match
E_{TT} = fwd transmission trackir
E_X = fwd isolation

$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission trackir
$E_{X'}$ = rev isolation

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

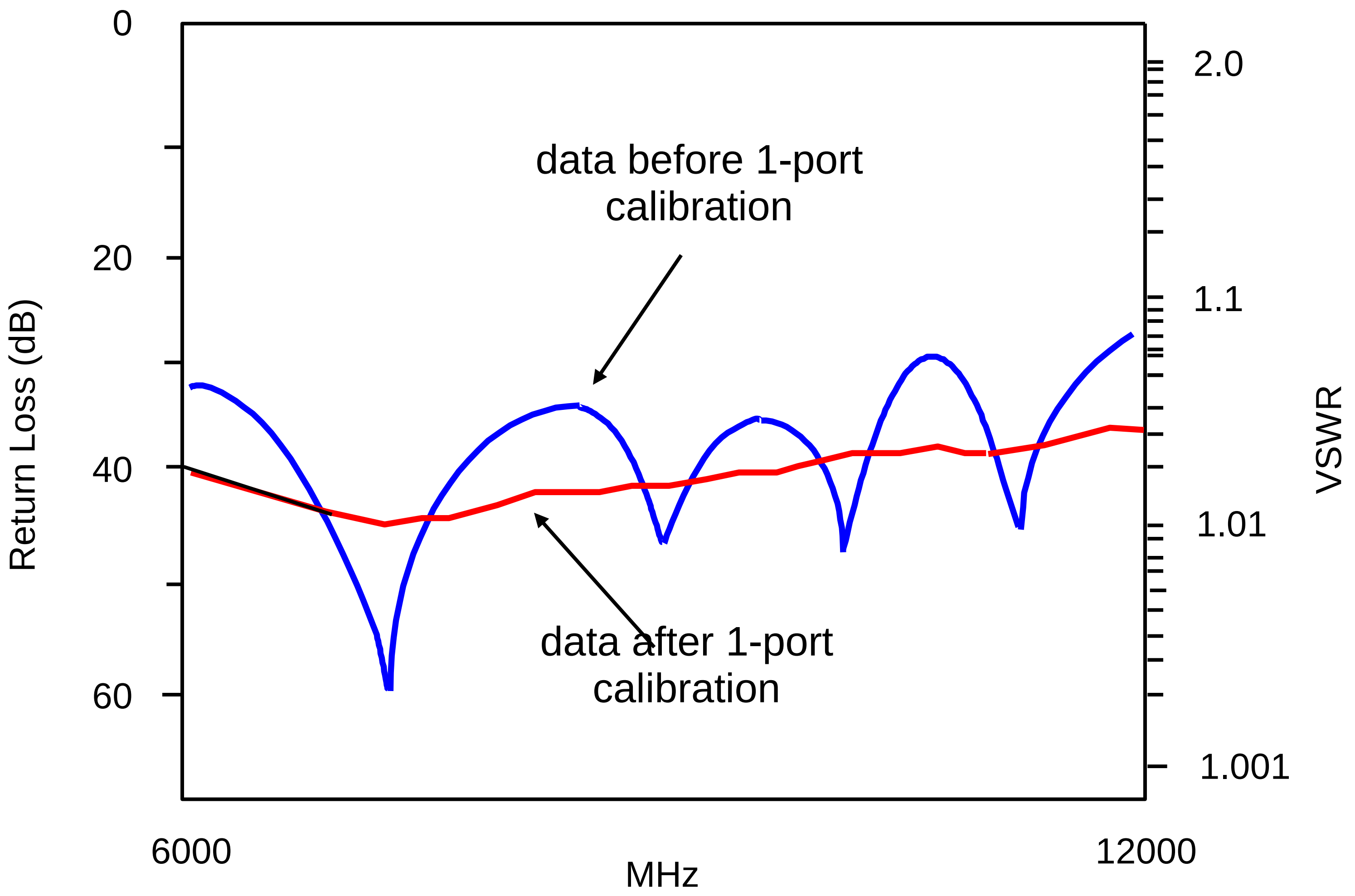
$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

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

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

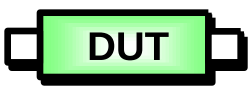
- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** network analyzers!!!

Before and After One-Port Calibration



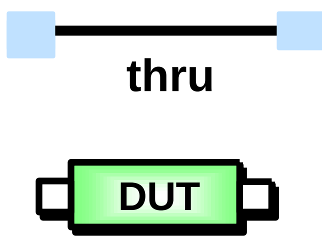
Errors and calibration standards

UNCORRECTED



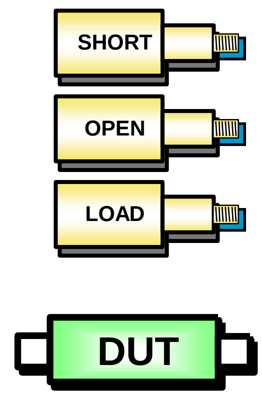
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



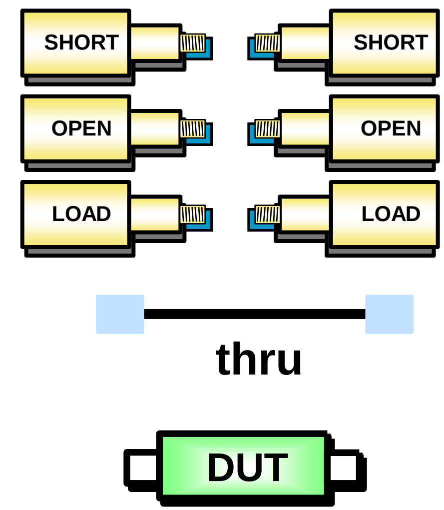
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

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

Agenda

- Overview
- What Measurements do we make?
- Network Analyzer Hardware
- Error Models and Calibration
- Example Measurements

Thank you!

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