Electromagnetic Compatibility

Network Analysis

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ELL 032

EPFL

Outline

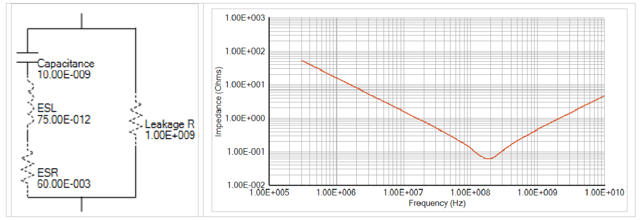
- Motivation: Why network analysis?
- Transmission line parameters
- Vector network analysers
  - Operation
  - Hardware
  - Calibration
- Lab introduction

Why network analysis?

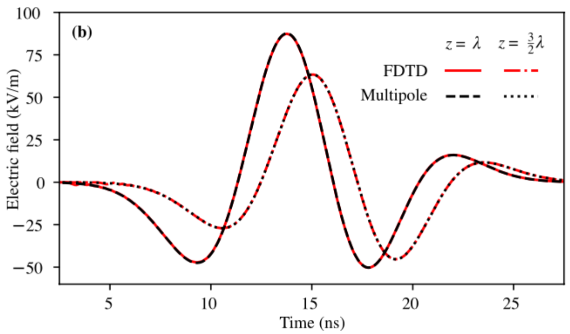
Understanding high-frequency phenomena

Signal and power integrity

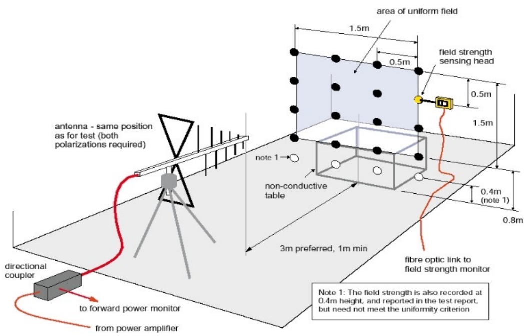
Component characterisation, including parasitic effects



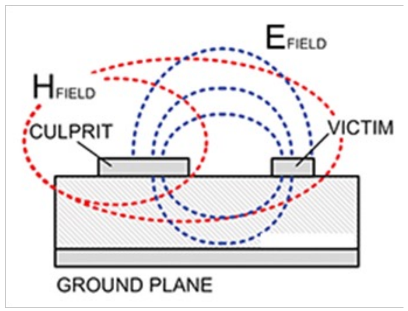
Validation of designs, theoretical models, and simulations



Electromagnetic compatibility (EMC) standards compliance



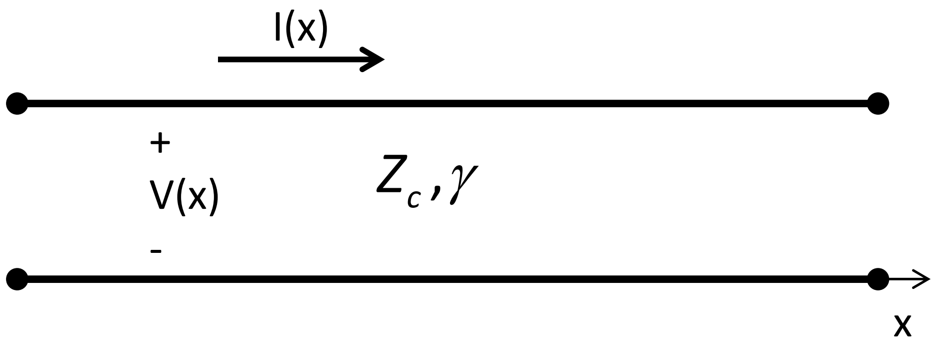
Coupling analysis, e.g., crosstalk



Bibliography

- 2018 Network Analysis course by Nicolás Mora at EPFL
- David Ballo, “Network Analyzer Basics,” Hewlett-Packard, 1998

General solution transmission line propagation

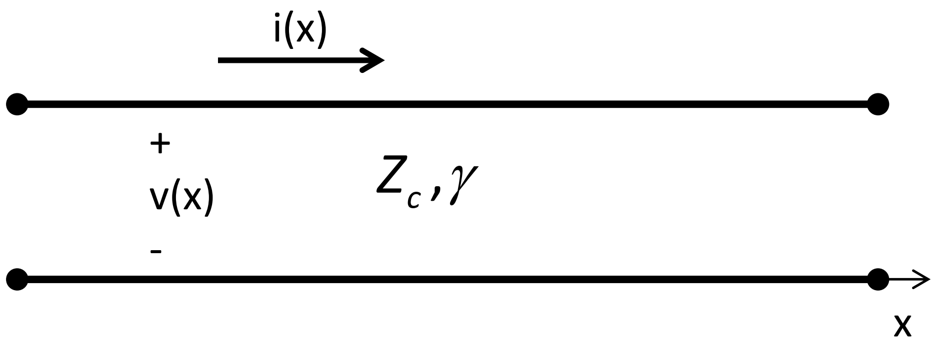


$$V(x) = V^{+}(x) + V^{-}(x) = V^{+}(x)(1 + \Gamma(x))$$

$$I(x) = \frac{V^{+}(x)}{Z_c} - \frac{V^{-}(x)}{Z_c} = \frac{V^{+}(x)}{Z_c}(1 - \Gamma(x))$$

$$\Gamma(x) = \frac{V^{-}(x)}{V^{+}(x)}$$

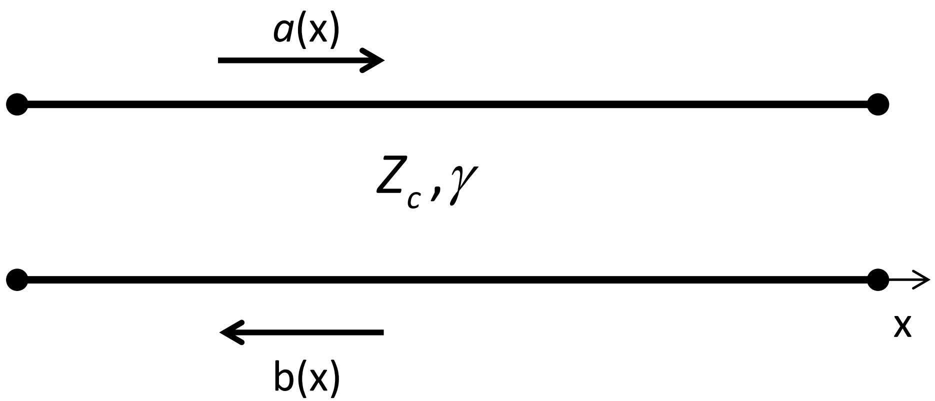
Power waves definition



$$v(x) = \frac{V(x)}{\sqrt{Z_c}} = \frac{V^+(x)}{\sqrt{Z_c}} + \frac{V^-(x)}{\sqrt{Z_c}}$$

$$i(x) = \sqrt{Z_c} I(x) = \frac{V^+(x)}{\sqrt{Z_c}} - \frac{V^-(x)}{\sqrt{Z_c}}$$

Power waves definition



$$a(x) = \frac{V^+(x)}{\sqrt{Z_c}}$$

$$b(x) = \frac{V^-(x)}{\sqrt{Z_c}}$$

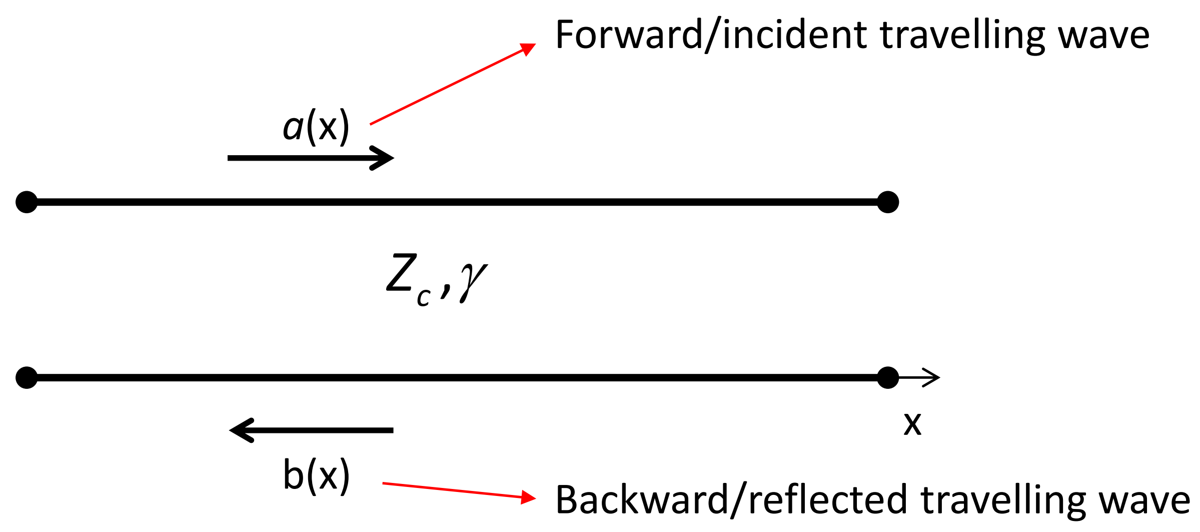
$\rightarrow$

$$v(x) = a(x) + b(x)$$

$$i(x) = a(x) - b(x)$$

$$b(x) = \Gamma(x) a(x)$$

Power waves definition



$$a(x) = \frac{V^+(x)}{\sqrt{Z_c}}$$

$$b(x) = \frac{V^-(x)}{\sqrt{Z_c}}$$

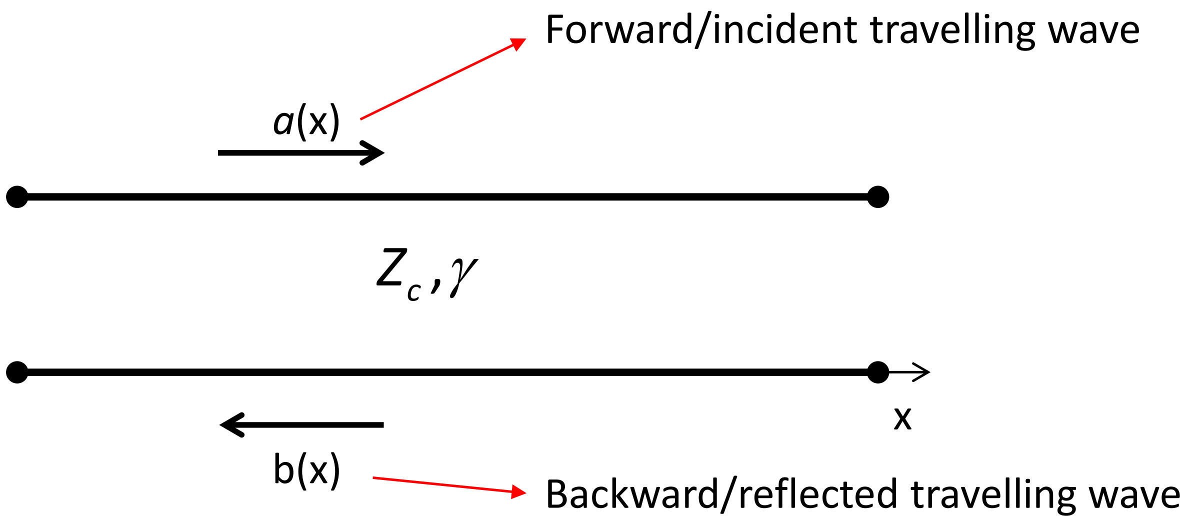
$\longrightarrow$

$$v(x) = a(x) + b(x)$$

$$i(x) = a(x) - b(x)$$

$$b(x) = \Gamma(x) a(x)$$

Power waves definition



$$a(x) = \frac{V^{+}(x)}{\sqrt{Z_c}} \qquad \longrightarrow \qquad a(x) = \frac{v(x)+i(x)}{2}$$

$$b(x) = \frac{V^{-}(x)}{\sqrt{Z_c}} \qquad\qquad\qquad b(x) = \frac{v(x)-i(x)}{2}$$

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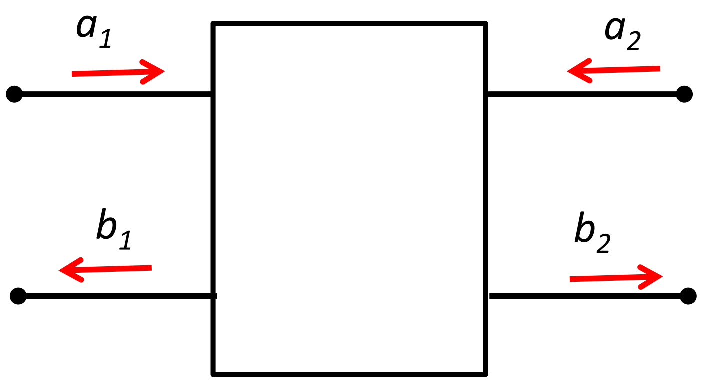
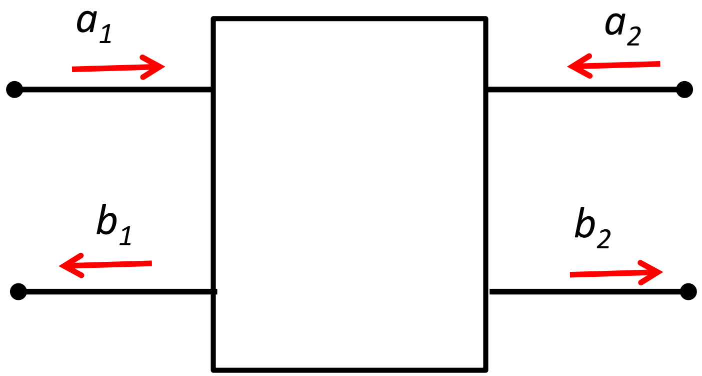
Two port network representation with power waves



$$b_1 = S_{11}a_1 + S_{12}a_2$$

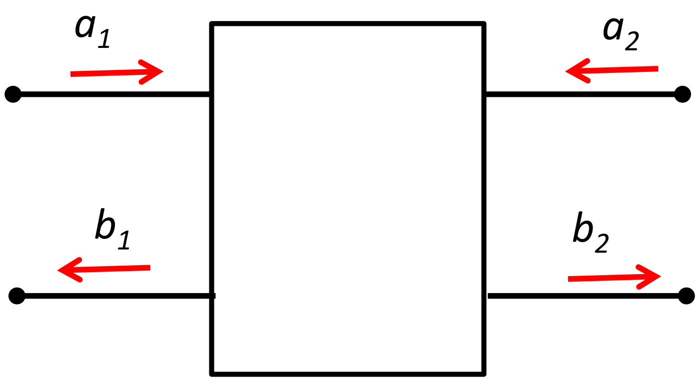
$$b_2 = S_{21}a_1 + S_{22}a_2$$

Two port network representation with power waves



$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$
$$\longrightarrow \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

Two port network representation with power waves



Scattering parameters matrix

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

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Determination of the scattering parameters

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

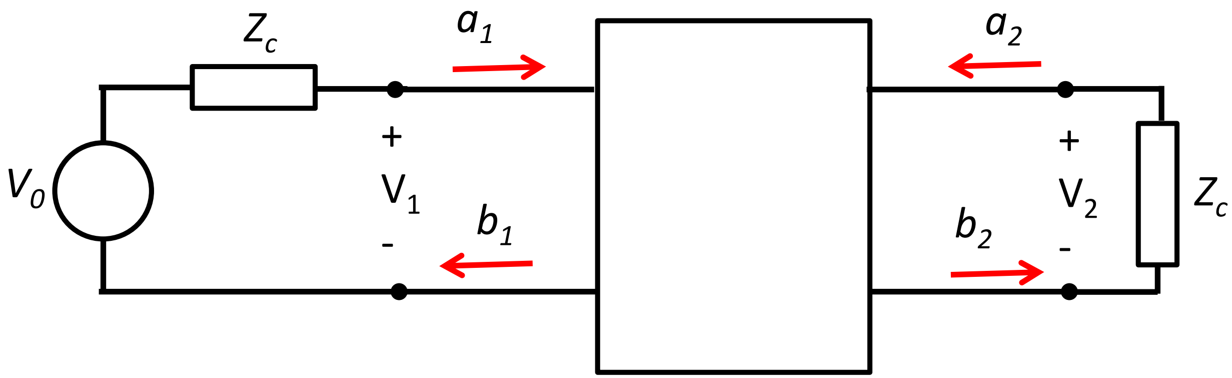
$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

- A zero incident power wave denotes a matched termination in the port

$$a_i = 0 \rightarrow v_i + i_i = 0$$

$$V_i = -Z_c I_i$$

Determination of the scattering parameters

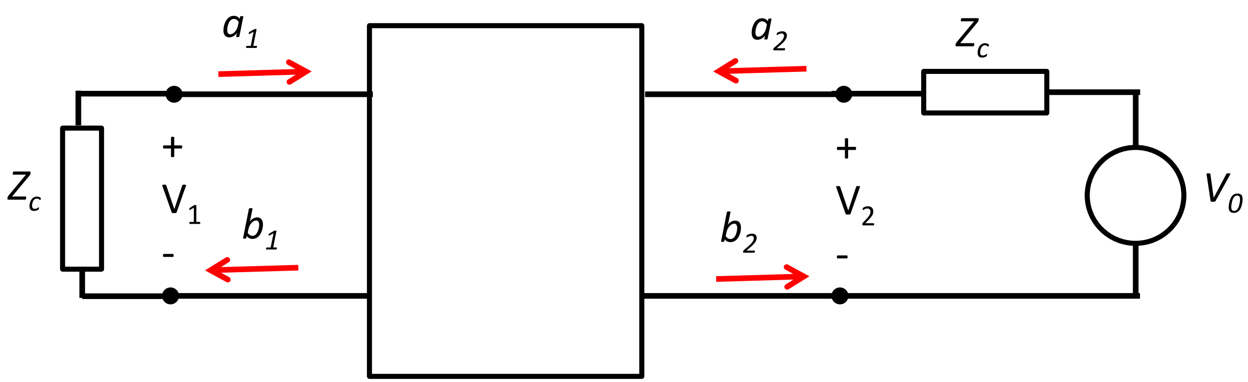


S_{11} and S_{21} are determined by terminating port 2 with the reference impedance

$$S_{11} = \frac{b_1}{a_1} = \frac{V_1^-}{V_1^+} = \frac{V_1^-}{\frac{V_0}{2}}$$

$$S_{21} = \frac{b_2}{a_1} = \frac{V_2^-}{V_1^+} = \frac{V_2}{\frac{V_0}{2}}$$

Determination of the scattering parameters



S_{12} and S_{22} are determined by terminating port 1 with the reference impedance

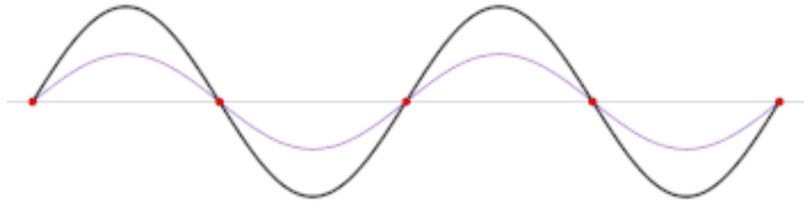
$$S_{12} = \frac{b_1}{a_2} = \frac{V_1^-}{V_2^+} = \frac{V_1}{\frac{V_0}{2}}$$

$$S_{22} = \frac{b_2}{a_2} = \frac{V_2^-}{V_2^+} = \frac{V_2^-}{\frac{V_0}{2}}$$

Why scattering parameters?

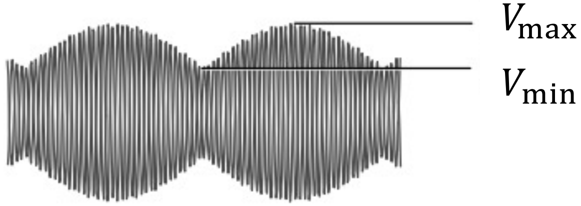
- vs. impedance/admittance/ABCD: travelling waves
  - Conversions between parameters are possible
- No need for short circuits
- Easy to relate to commonly used metrics (gain, loss, reflection coefficient)
- Cascading
- The de facto standard (e.g., simulation correlation)

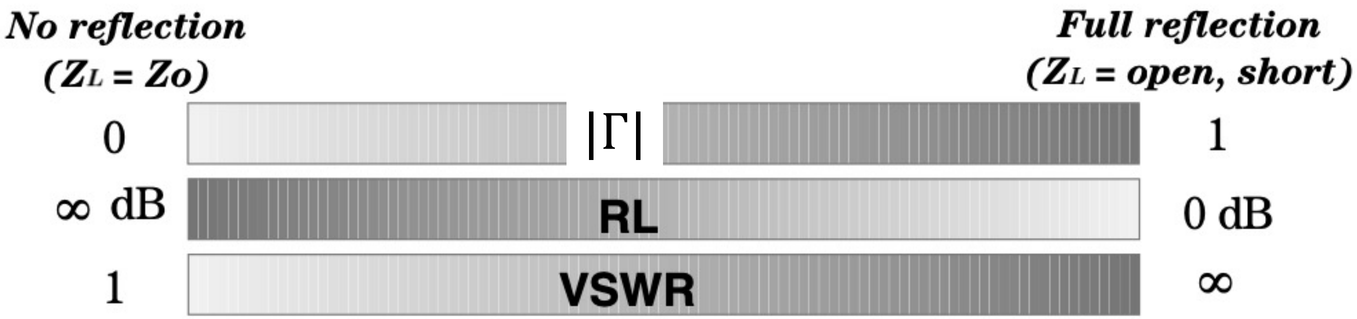
Reflection parameters



- Reflection coefficient $\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}}$
- Return loss $= -20\log_{10}(|\Gamma|)$! Power vs. voltage
- Voltage standing wave ratio:

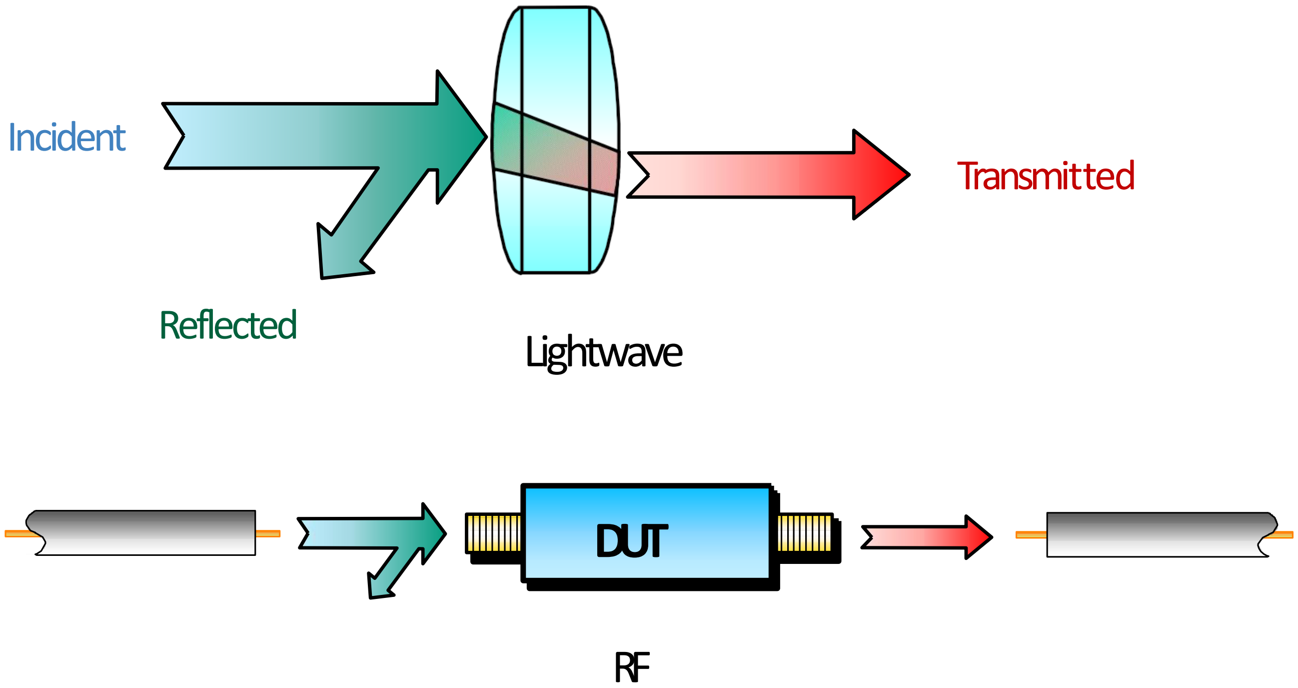
$$\text{VSWR} = \frac{V_{\max}}{V_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$$





Introduction to vector network analysers (VNAs)

Lightwave analogy to RF



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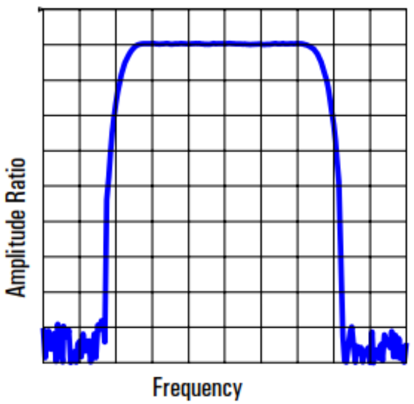
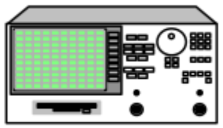
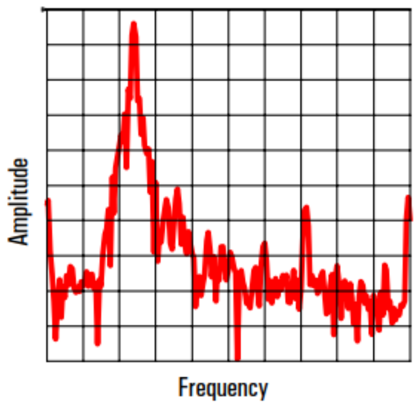
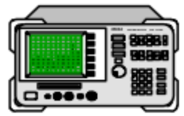
Difference between VNAs and Spectrum Analyzers





Measures known signal





Measures unknown signals

Network analyzers:

- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase (frequency or power sweeps)
- offer advanced error correction

Spectrum analyzers:

- measure signal amplitude characteristics carrier level, sidebands, harmonics...)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (*no phase*) with tracking gen. or ext. source(s)

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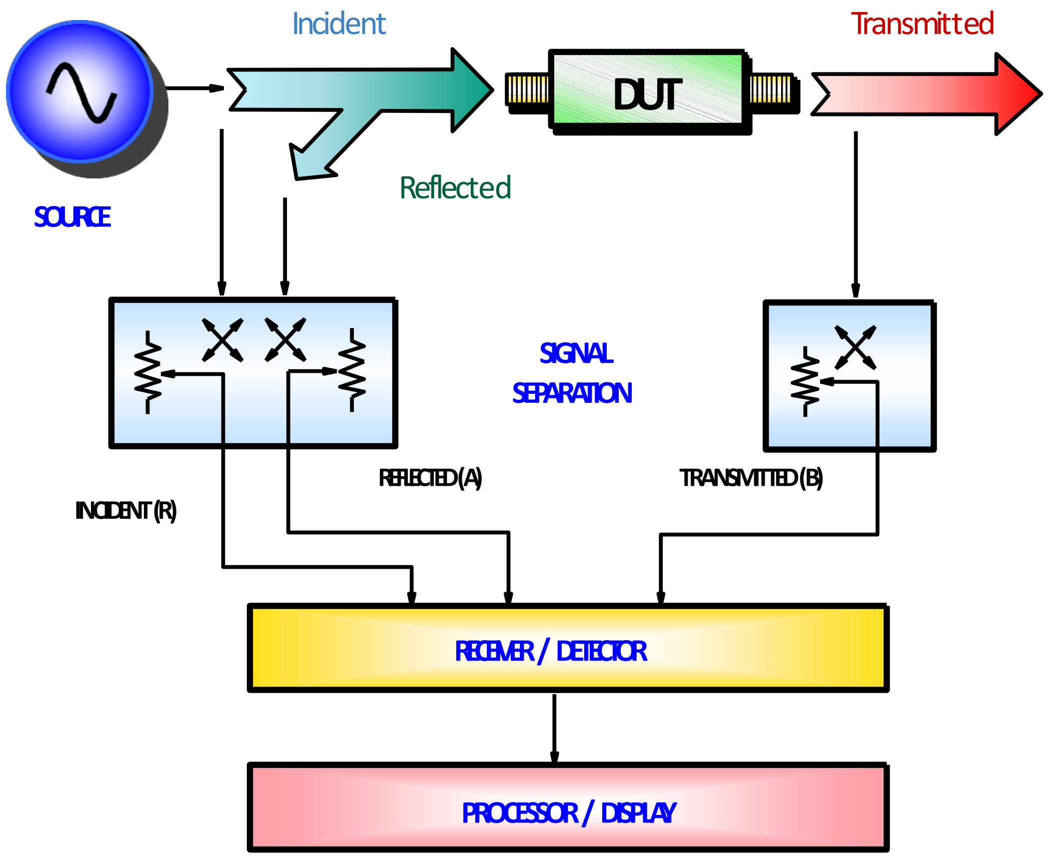
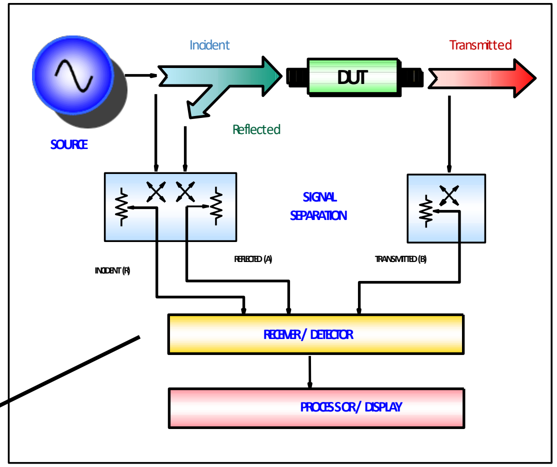
Generalized VNA Block Diagram

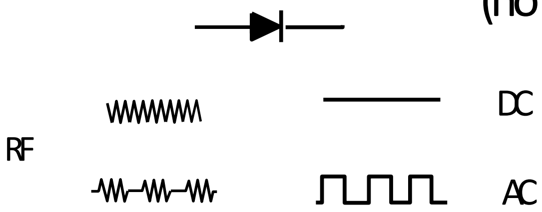


Detector types

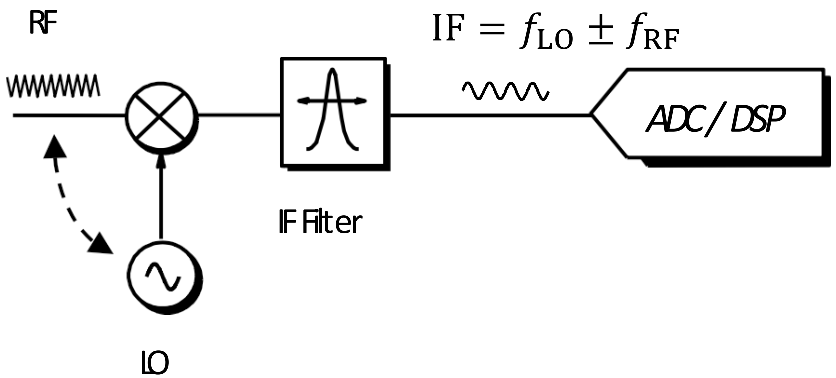


Diode

Scalar **broadband**
(no phase information)



Tuned Receiver



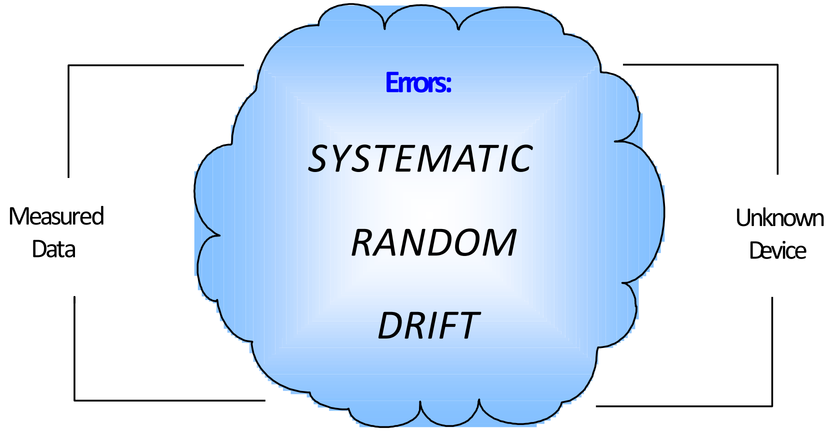
Vector
(magnitude and phase)

VNA source

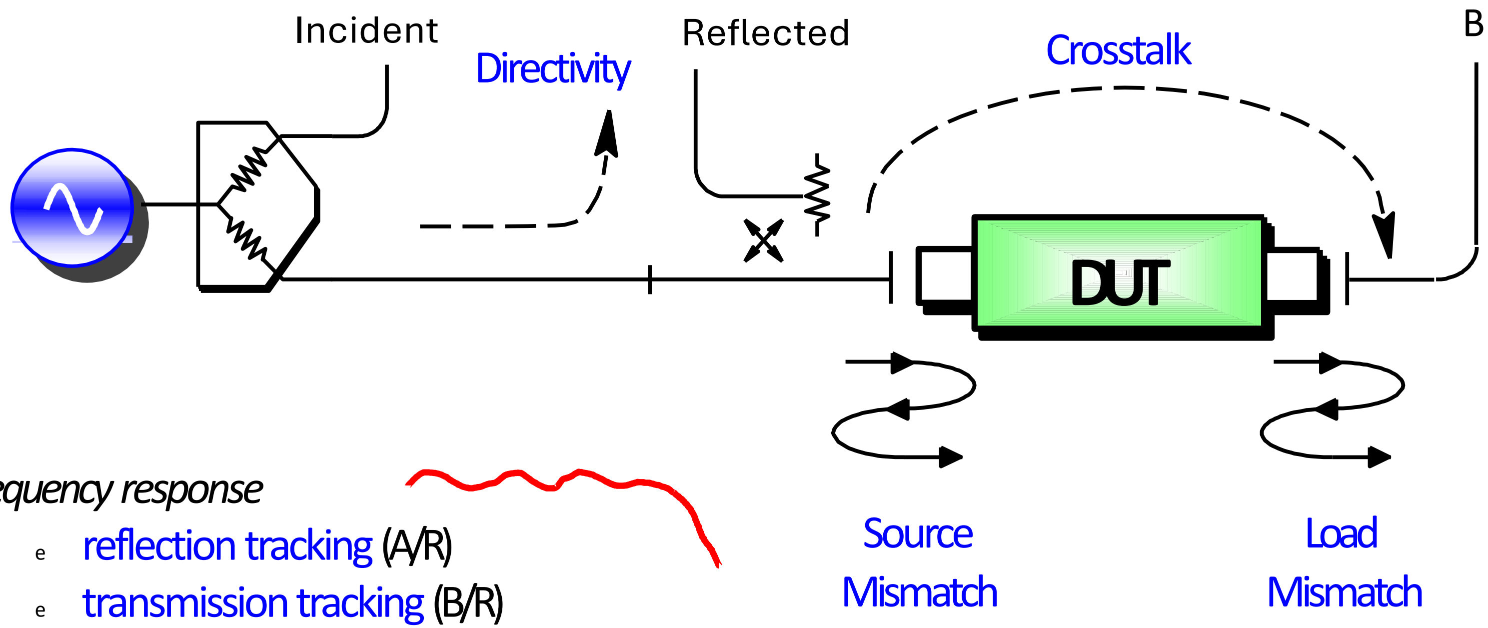
- Supplies the system stimulus => phase reference
- Swept frequency or power
  - A way to *experimentally* measure frequency-domain data!
  - “Intermediate frequency” (IF) bandwidth: trade-off between dynamic range and measurement speed
- (Mostly) integrated in the VNA

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

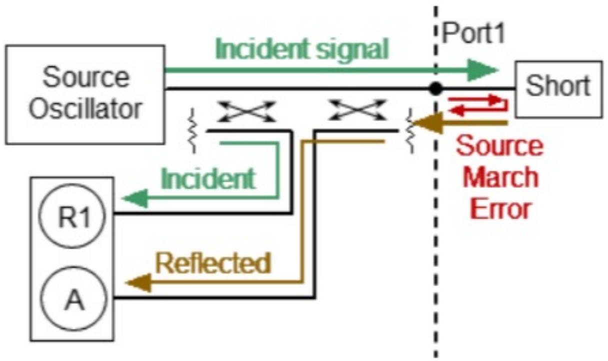


Frequency response

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

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

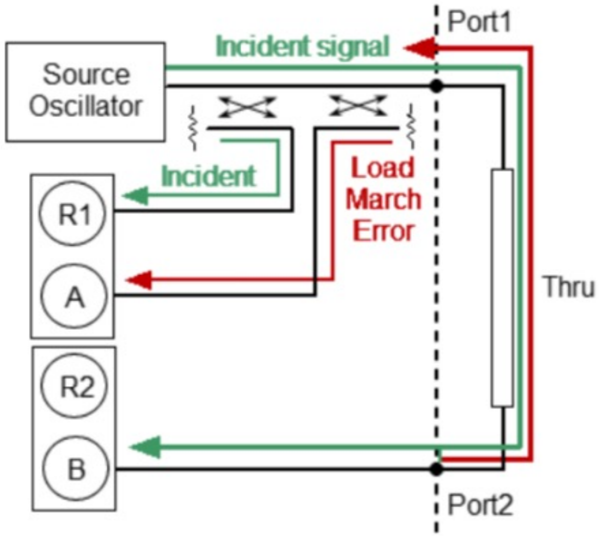
6 types of systematic errors



Source match error

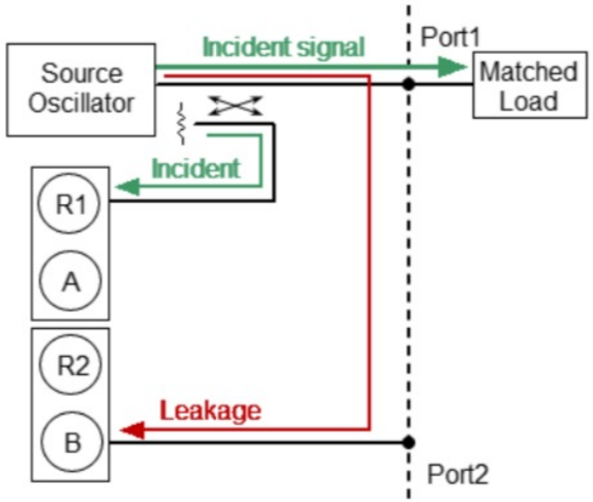
"Systematic Errors." Accessed: Feb. 24, 2025. [Online]. Available: https://coppermountaintech.com/help-s2/systematic-errors.html

6 types of systematic errors



Load match error

6 types of systematic errors



Crosstalk error

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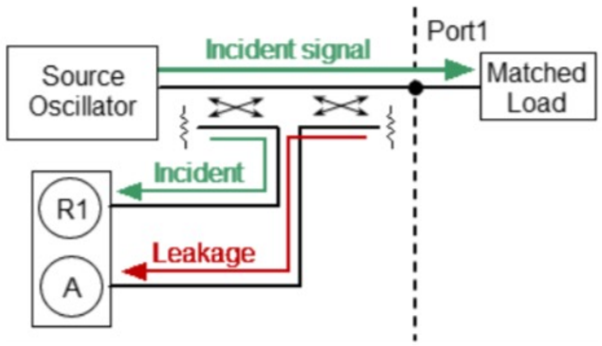
6 types of systematic errors



Directivity error

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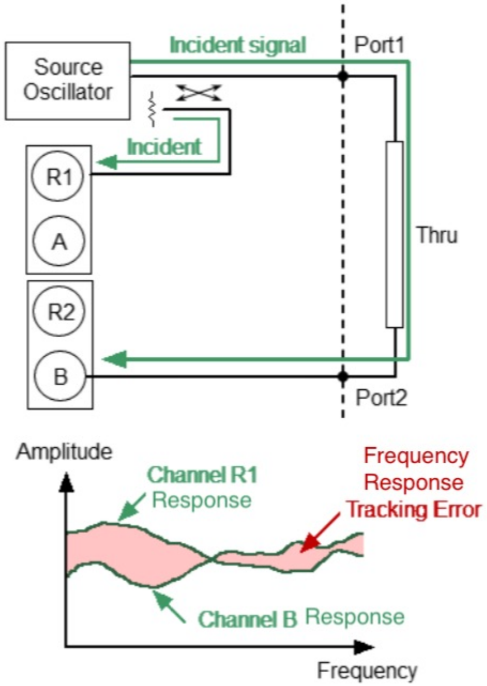
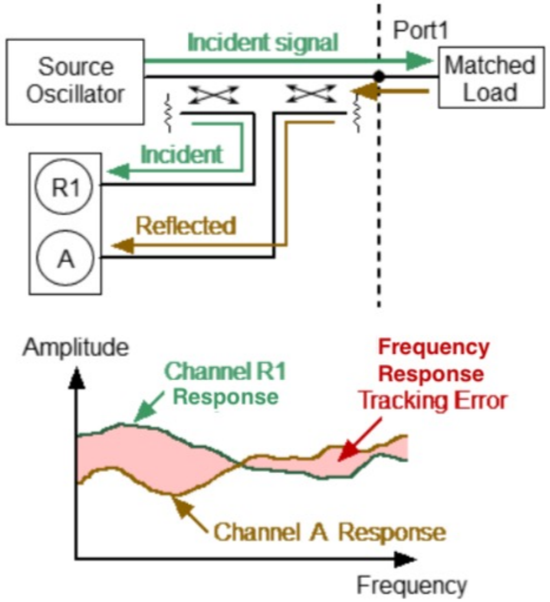
6 types of systematic errors



Transmission tracking error

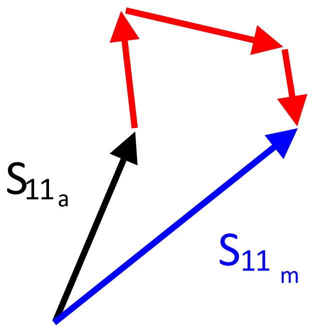
6 types of systematic errors

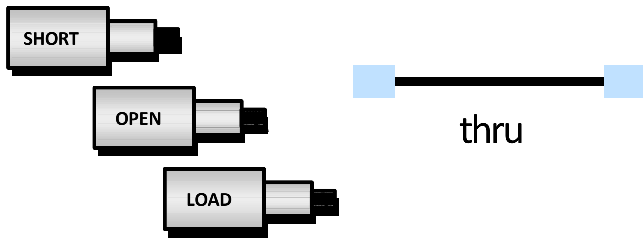


Reflection tracking error

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





Your VNA: LiteVNA

- 50 kHz - 3 GHz
- Measures S_{11} and S_{21}
- Cheap
- Calibration kit
- 70 dB dynamic range

Introduction to the lab

- Hands-on experience with a VNA
- Calibration
- Coaxial cables:
  - Reflection measurements
  - Transmission measurements
- Time-domain measurements thanks to integrated inverse Fourier transform