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S and Z Parameters for PDN Measurements and Simulations

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Outline

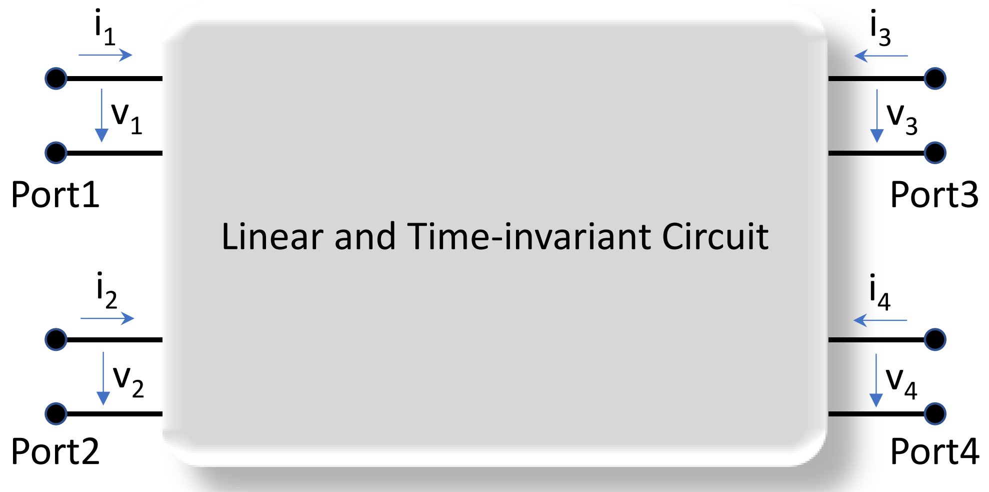
- Background
- Network matrices
- Linearity and time invariance
- Impedance matrix
- Scattering matrix
- Making scattering matrix work for PDN measurements
- Scattering parameters in simulations
- Conclusions

Background

- Simulation and measurement of PDNs raise multiple questions
  - Time-domain vs. frequency domain
  - Time duration and frequency range
  - Linearity vs. nonlinearity
  - Time variance vs. time invariance
  - Causality
  - Passivity
- Network matrix vs. circuit description of PDN

Network Matrix Description of PDNs

- Black box approach, any number of ports: 1…N



Impedance or admittance matrix

$$\underline{\boldsymbol{v}} = \boldsymbol{Z}\,\boldsymbol{i}, \quad \text{or} \quad \boldsymbol{i} = \boldsymbol{Y}\,\underline{\boldsymbol{v}}$$

Scattering matrix

$$\underline{\boldsymbol{b}} = \mathbf{S}\,\underline{\boldsymbol{a}}$$

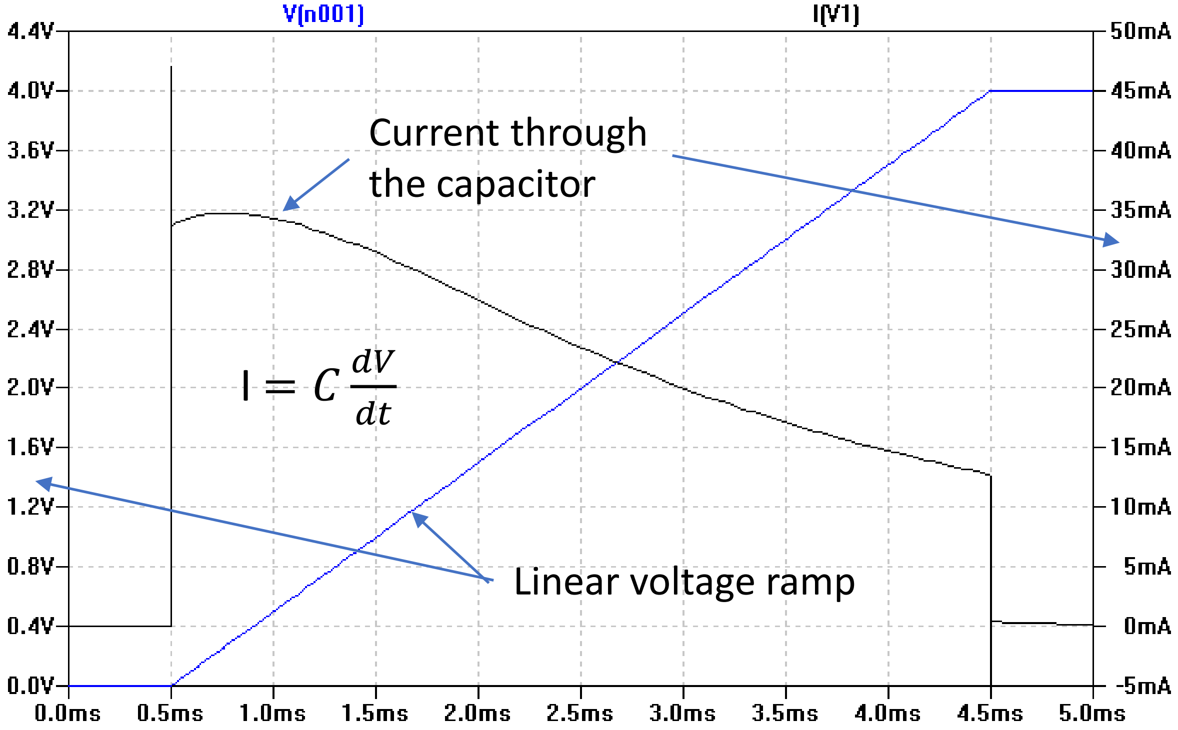
$$a_i = \frac{1}{2}\frac{(v_i + Z_0 i_i)}{\sqrt{Re\{Z_0\}}}, \qquad b_i = \frac{1}{2}\frac{(v_i - Z_0 i_i)}{\sqrt{Re\{Z_0\}}}$$

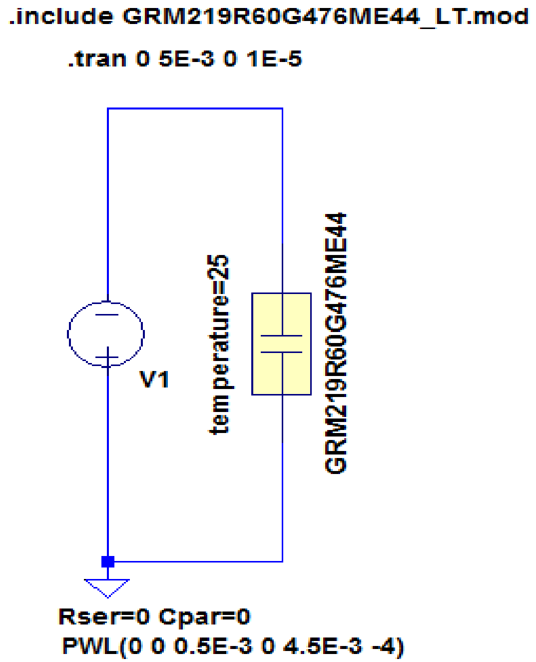
Network Matrix Description of PDNs

- Network matrices assume that the DUT is
  - Linear
  - Time invariant
- On a macro level, these assumptions are mostly valid
- On a micro level, many DUTs can be more or less nonlinear and/or time variant
- Sufficiently linear and time invariant: connectors, cables, PCB planes, traces, vias
- Can be slightly nonlinear and/or time variant: certain types of capacitors
- Can be more nonlinear and time variant: DC sources and noise sources

Slight Nonlinearity in PDNs

- High-density ceramic capacitors with DC and AC bias sensitivity



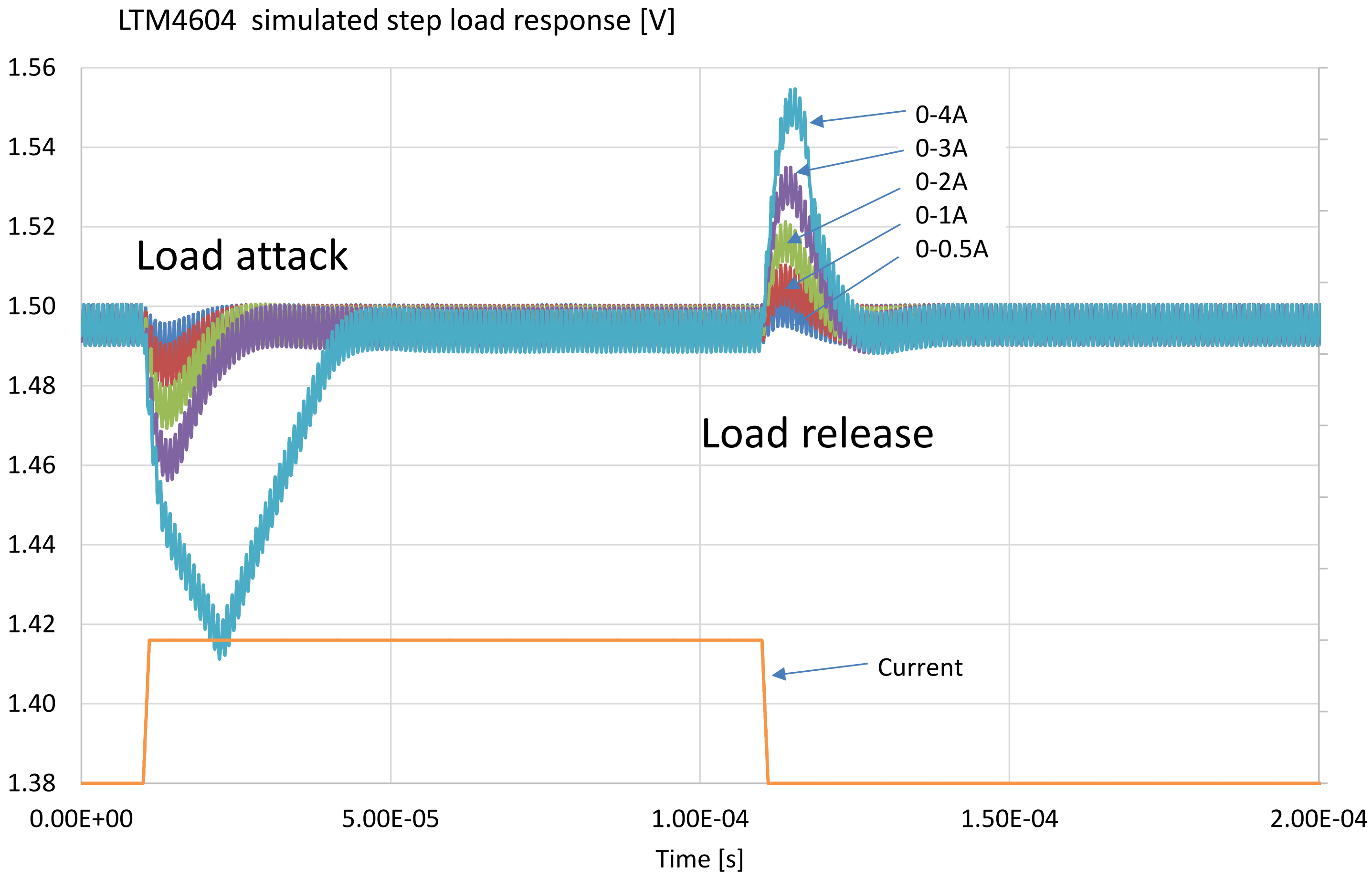


Murata GRM219R60G476ME44 dynamic model simulated with LTSPICE.

See: “What You Need to Know About Bypass Capacitor S-Parameter Models,” http://www.electrical-integrity.com/Quietpower_files/QuietPower-51.pdf

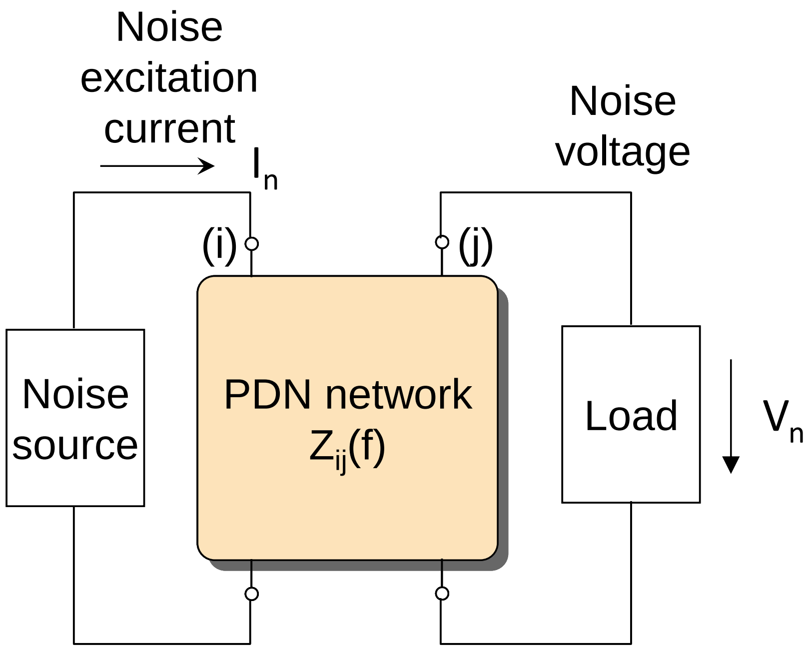
Potentially Stronger Nonlinearity in PDNs

- DC sources, clipping
  - Intentional
  - Unintentional
- Noise sources



Impedance Matrix: Why and When

- Power rails are expected to be voltage sources >> unloaded output voltage
- Noise sources are expected to be much higher impedance than the power rail >> current sources
- Users need noise voltage as a result of noise current >> self or transfer impedance



$$Z_{ji} = \frac{V_{n(j)}}{I_{n(i)}}$$

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Impedance Matrix: Pros and Cons

Pros:

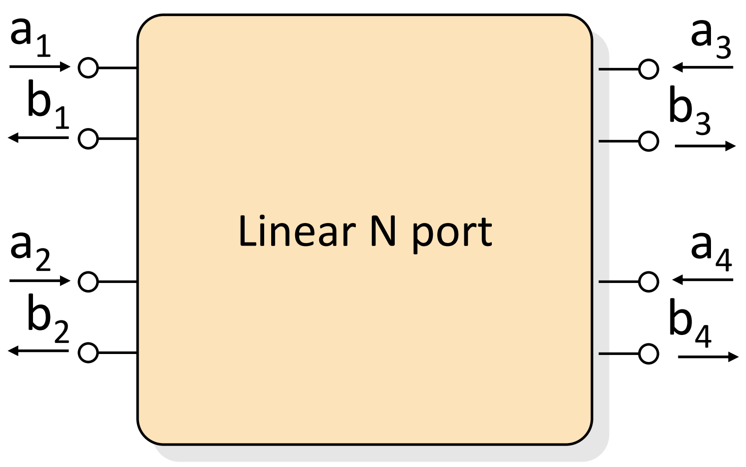
- Frequency-domain PDN design process uses impedance
- Easy to measure (at low frequencies and at not very low values), because we have
  - High-impedance voltage sensors
  - High-impedance current sources
- Unused ports can be left open, no need for any termination
- Impedance matrix size can easily be changed
  - Ports can be added or dropped without recalculating the rest

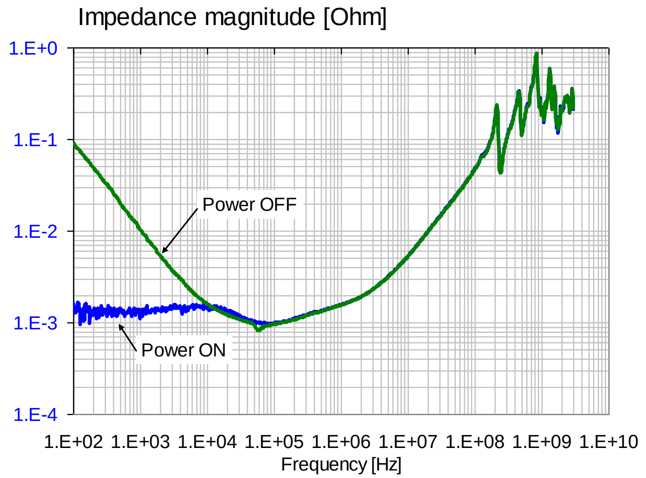
Cons:

- Not easy to measure low impedances and/or at higher frequencies

Scattering Matrix: Why and When

- Easier to measure at higher frequencies
- Well-established instrumentation
- Well-established calibration procedures





"Accuracy Improvements of PDN Impedance Measurements in the Low to Middle Frequency Range,"
http://www.electrical-integrity.com/Paper_download_files/DC10_12-TH3_Novak-Mori-Resso.pdf

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Scattering Matrix: Pros and Cons

Pros:

- Frequency-domain instruments for scattering parameters are readily available
- Can measure microohm AC impedances
- Many models are available in Touchstone format

Cons:

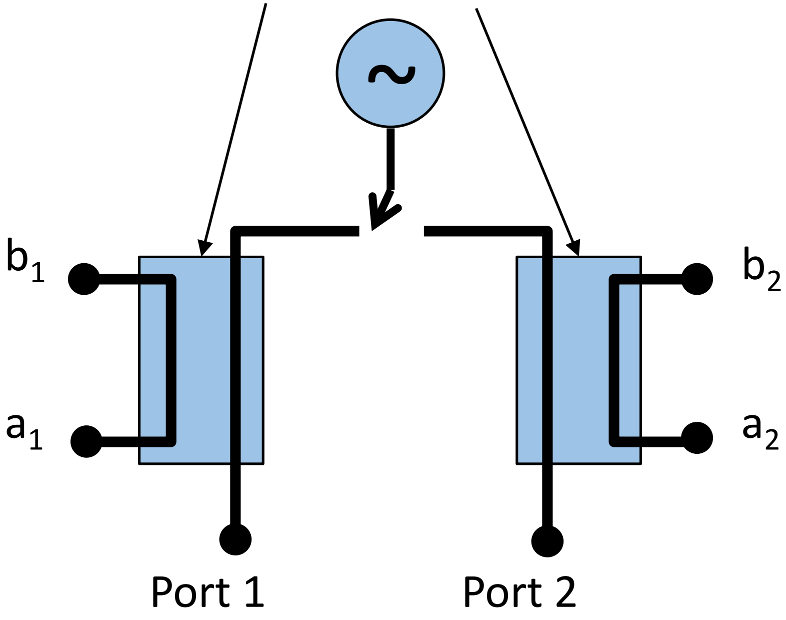
- Proper termination of all ports is necessary
- Need extra steps to do low-impedance measurements with regular Vector Network Analyzer (VNA)
- VNAs don’t measure at DC

Important note: when modeling a design, ports that were unused in the measurements need to be open circuited and reduced

The Vector Network Analyzer

Basic construction:

- Swept-frequency sinewave source
- Synchronous receivers
- Directional couplers to separate transmitted and reflected signals



The VNA measures the Scattering matrix:

$$S_{11} = \frac{b_1}{a_1} \qquad S_{22} = \frac{b_2}{a_2}$$

$$S_{21} = \frac{b_2}{a_1} \qquad S_{12} = \frac{b_1}{a_2}$$

How to Measure PDN with Scattering Parameters; Challenges

- Many PDN components and systems need cable(s) to connect to the instrument(s)
- Typical calibration requires coaxial connection
  - Not available on PDNs
- There is some interconnect beyond the coaxial calibration plane
  - Uncalibrated discontinuity
- One-port reflection measurement is not accurate for low impedances
- Two-port shunt-through connection helps
  - Throw away S_{11} and S_{22} and use S_{21} (or S_{12})
- But it creates cable-shield ground loop
  - Requires extra components or circuitry

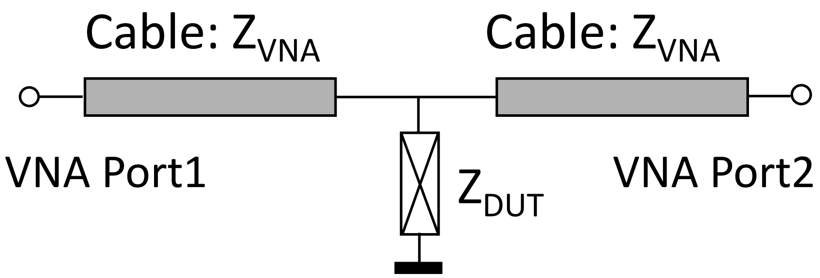
See "Preamplifier Options for Reducing Cable-Braid Loop Error," http://www.electrical-integrity.com/Quietpower_files/QuietPower-48.pdf

Measured S Parameters of PDNs; How to Use

Throw away reflection terms, use transmission term(s)

For small impedances:

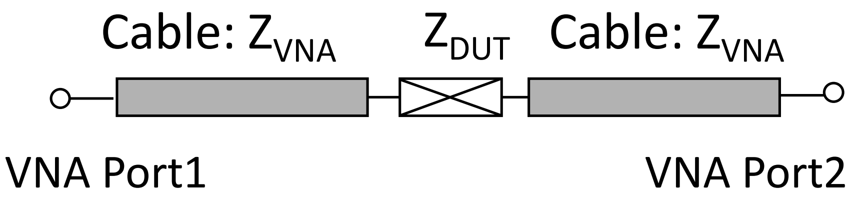
Two-Port Shunt-Through



$$Z_{DUT} = \frac{Z_{VNA}}{2} \frac{S_{21}}{1 - S_{21}}$$

For large impedances:

Two-Port Series-Through



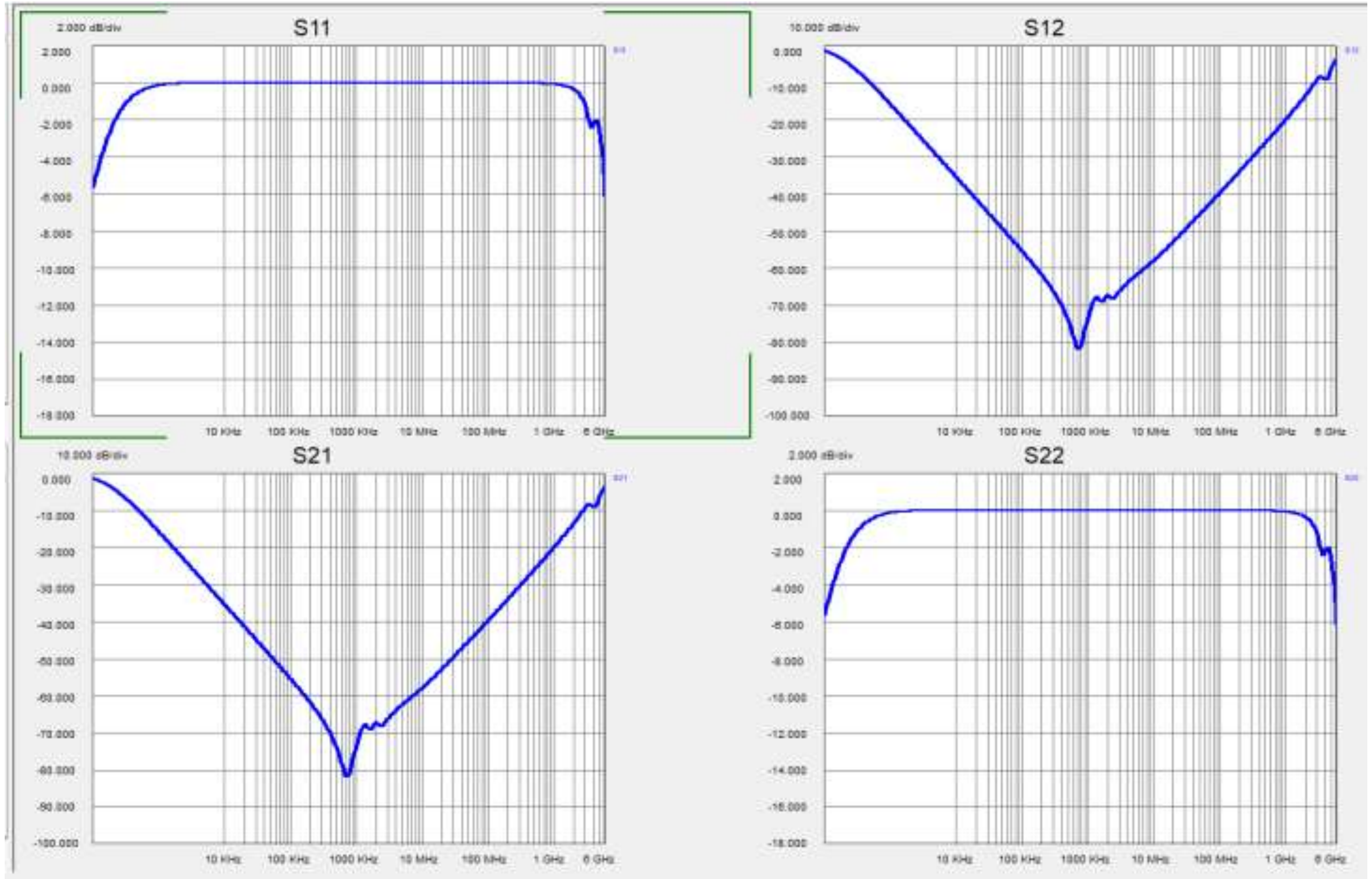
$$Z_{DUT} = 2Z_{VNA} \frac{1 - S_{21}}{S_{21}}$$

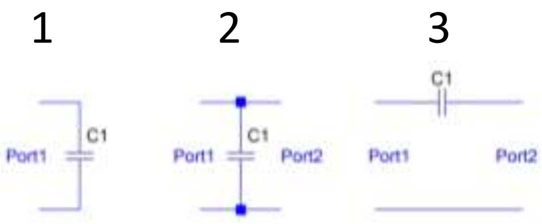
How to Simulate PDN with Scattering Parameters

- Mimicking measurement is needed only if correlation to actual measurement details is required
- Simulate impedance directly
- If you simulate with scattering parameters, you can
  - Use reflection elements of the matrix
  - Leave out connection discontinuities
  - Use floating source and/or receiver

How to Simulate PDN with Scattering Parameters; Capacitor Models

Accurate S-parameter model of the GRM32ER60J476 capacitor in Shunt mode





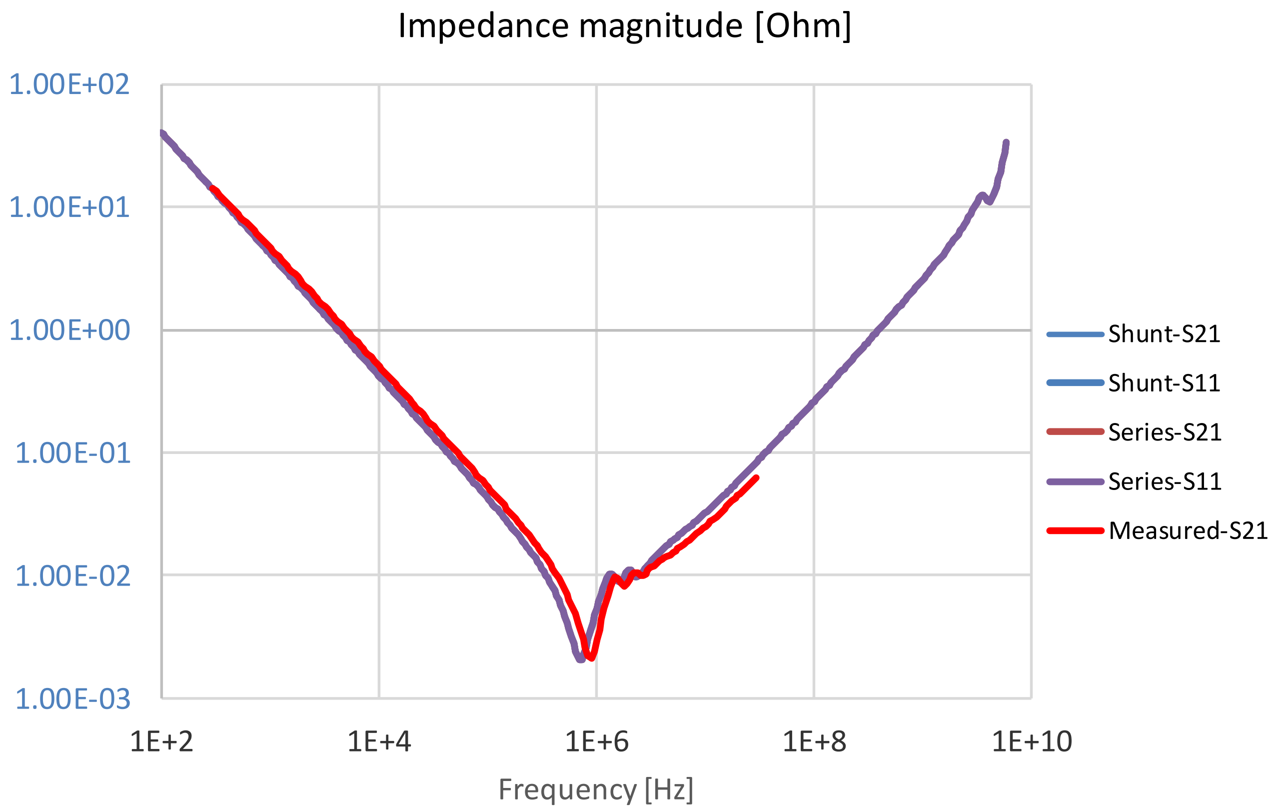
1: One-port model

2: Two-port Shunt model

3: Two-port Series model

How to Simulate PDN with Scattering Parameters

Measured and simulated impedance of Murata GRM32ER60J476



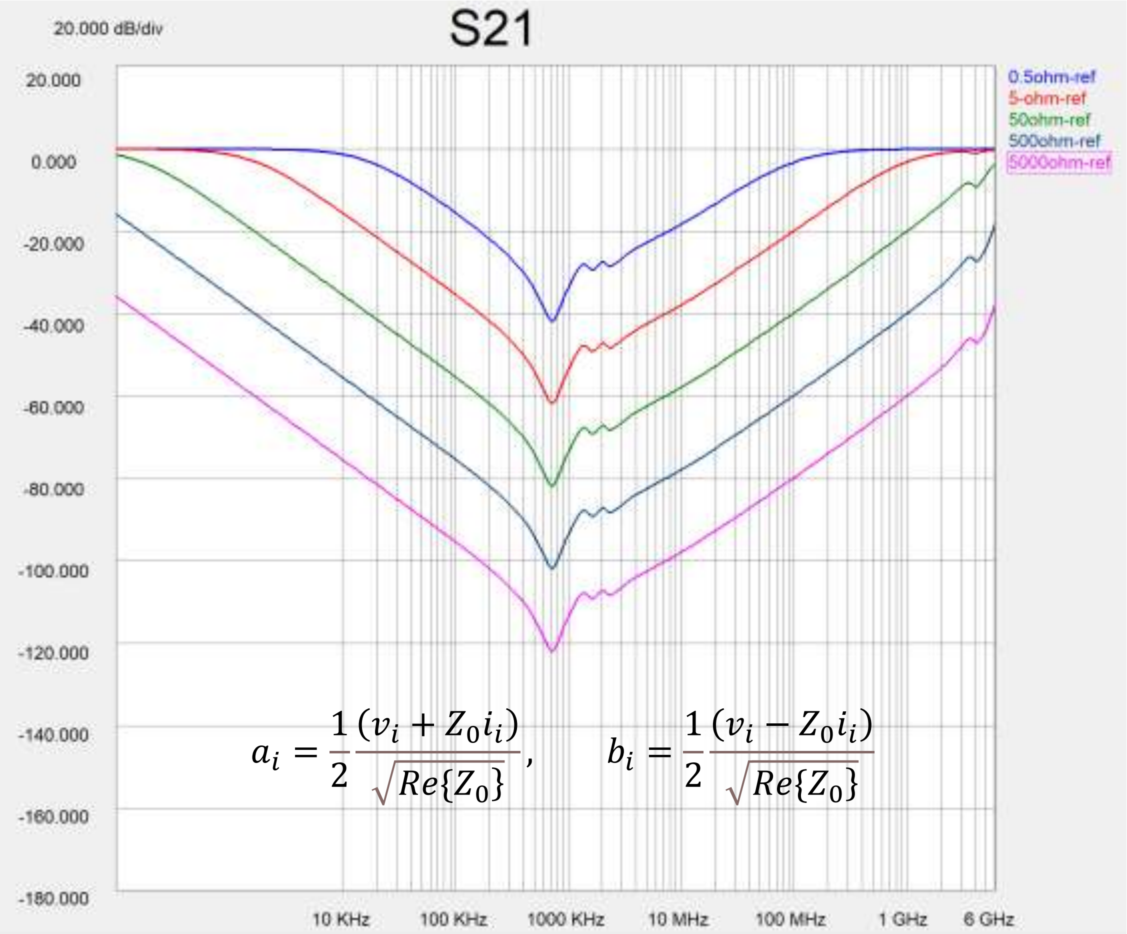
Capacitor S-parameter models are available in:

- Two-port Sunt and
- Two-port Series

connection schemes.

How to Simulate PDN with Scattering Parameters; Normalization Impedance

S-parameter model S_{21} of the GRM32ER60J476 capacitor with different normalization impedances



$$a_i = \frac{1}{2}\frac{(v_i + Z_0 i_i)}{\sqrt{Re\{Z_0\}}}, \qquad b_i = \frac{1}{2}\frac{(v_i - Z_0 i_i)}{\sqrt{Re\{Z_0\}}}$$

- S-parameters need a normalization impedance (Z_0)
- In SI, Z_0 is selected to be close to the system impedance
- In PI, there is no 'typical' impedance
- In PI, system impedance can vary significantly with frequency
- For a single component, normalization impedance can be in a wide range
- For complex PDN systems, 0.1 Ohm normalization impedance is typical

Summary and Conclusions

- We need to be familiar with both S and Z parameters
- Use S parameters in measurements
- Use Z parameters in design and validation
- As long as linearity and time invariance is guaranteed, time and frequency domains are also interchangeable
- Using S or Z parameters is just approximation
- If needed, source and load conditions can be taken into account

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