How to Measure Low PDN Impedance

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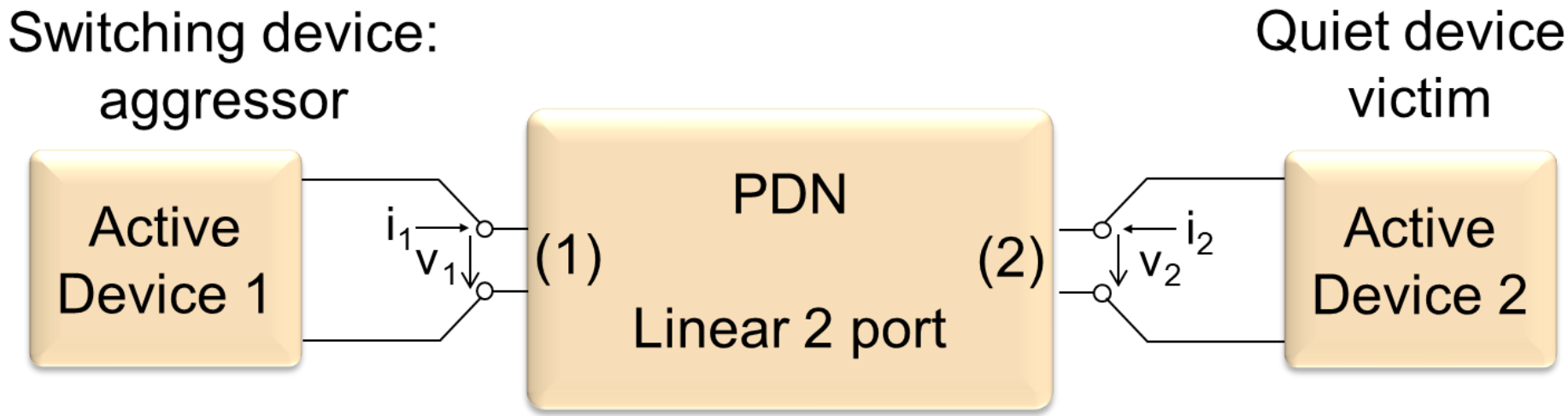
Outline

- Why impedance?
- What values do we need to measure?
- One-port impedance measurement
- Two-port shunt-through impedance measurement
- The cable braid error
- Reducing cable braid error
- Dynamic range requirement
- New challenges
- Good measurement practices

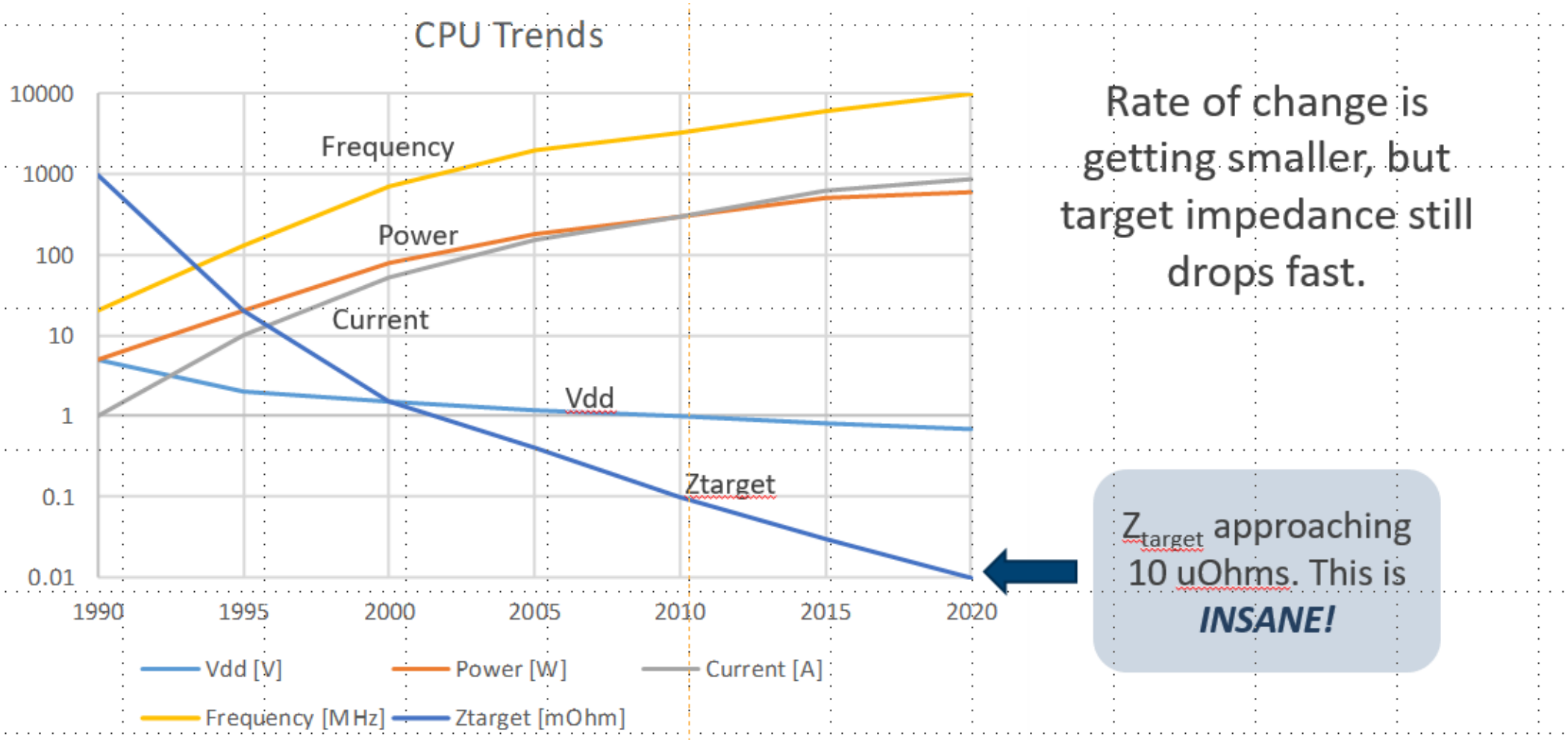
Why Impedance?



Transfer function for self-inflicted noise: $v_1/i_1 = Z_{11}$, while $I_2 = 0$ >> Self impedance

Transfer function for propagated noise: $v_2/i_1 = Z_{21}$, while $I_2 = 0$ >> Transfer impedance

What Values Do We Need to Measure?



Rate of change is getting smaller, but target impedance still drops fast.

Z_{target} approaching 10 uOhms. This is ***INSANE!***

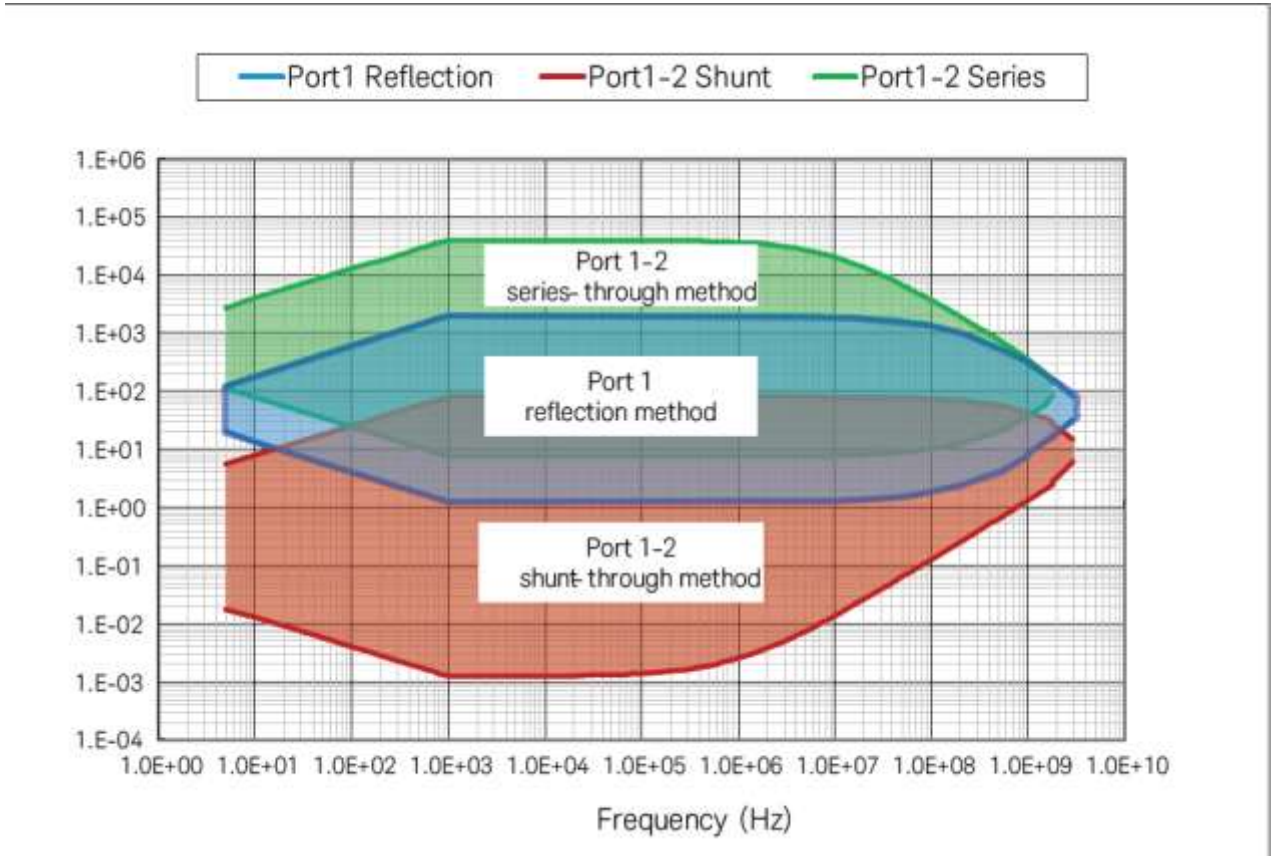
Is Power Integrity the New Black Magic?, Cadence E-Learning Forum, 2021

Can We Measure uOhms Based on Reflection?

Terminal adapter on Port1
Recommended impedance range:
1 Ohm to 10 kOhm

Keysight Application Note 5991-0213A

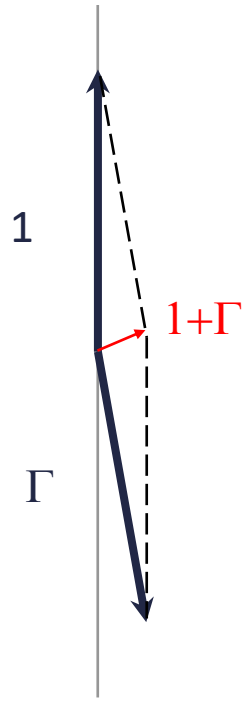
Port1 Reflection dynamic range: 1 : 10,000

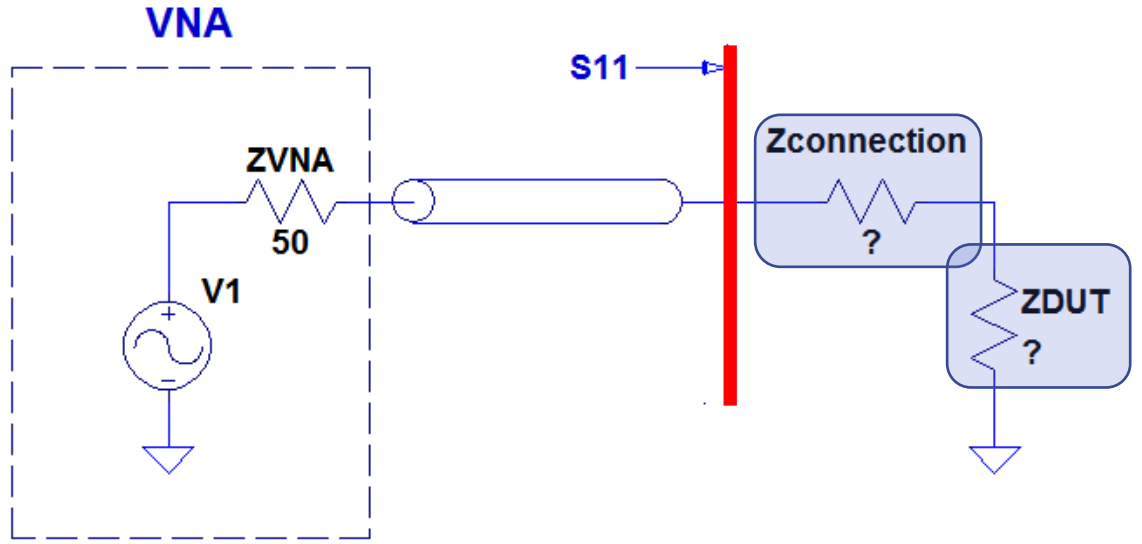


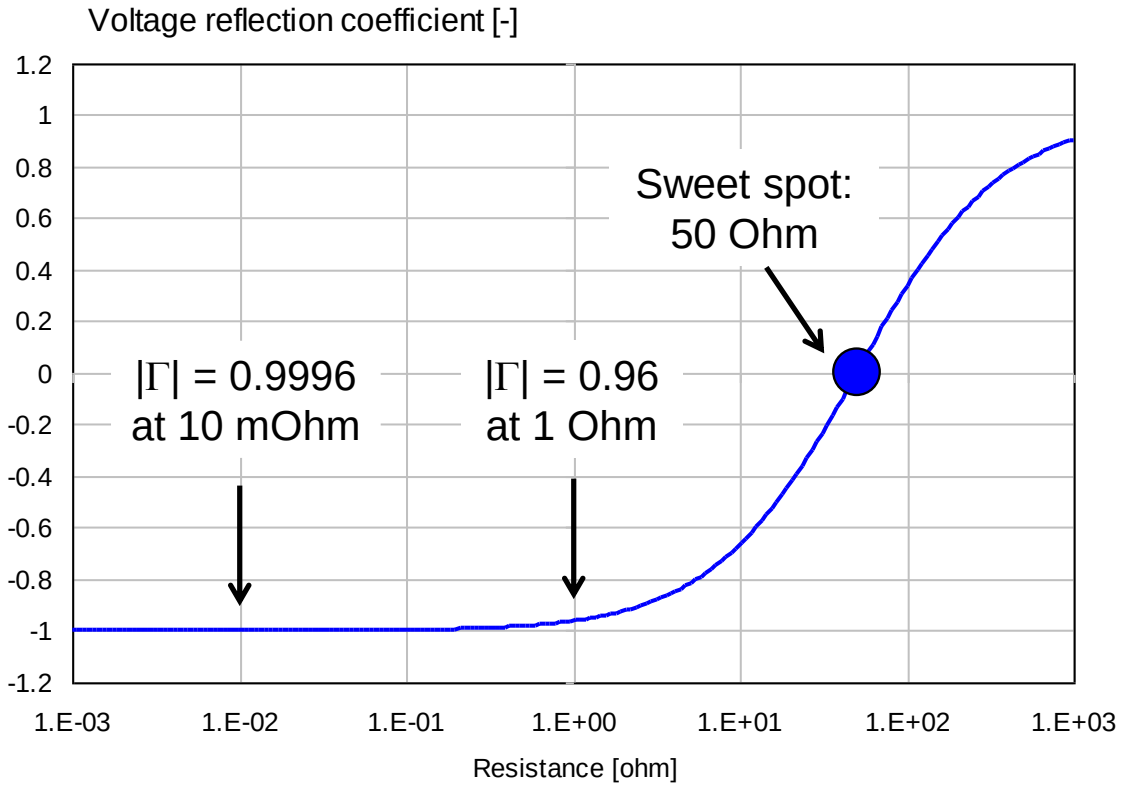
The Problem

$$\Gamma = \frac{Z_{DUT} - Z_{VNA}}{Z_{DUT} + Z_{VNA}}$$

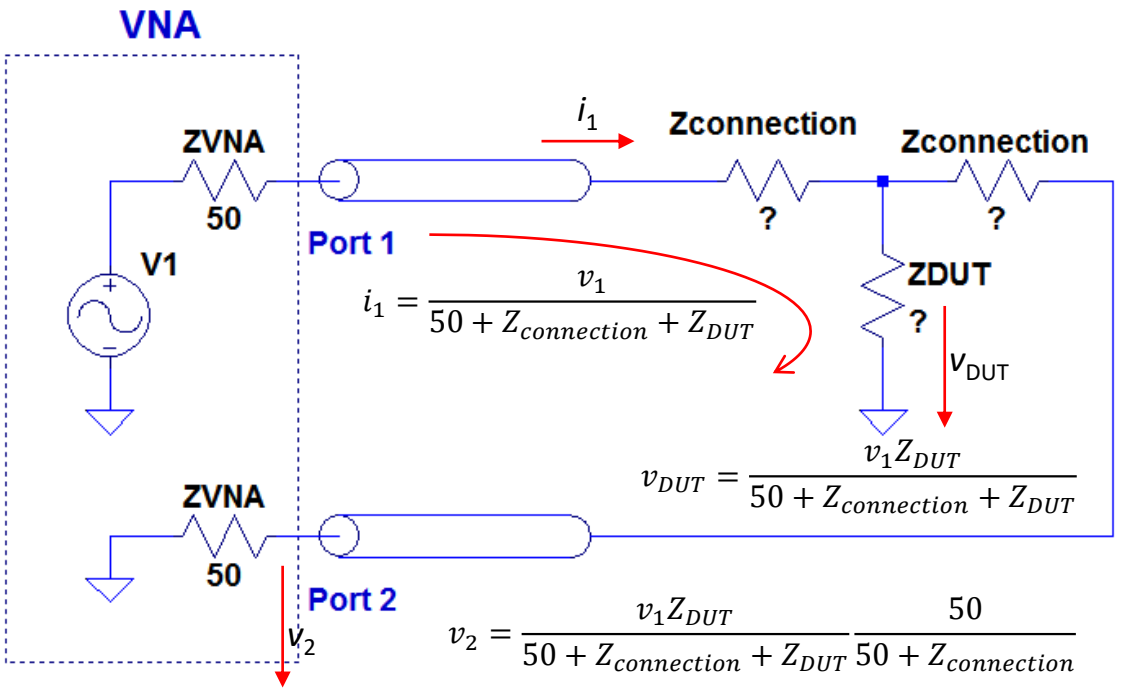
$$Z_{DUT} = Z_{VNA} \frac{1+\Gamma}{1-\Gamma}$$







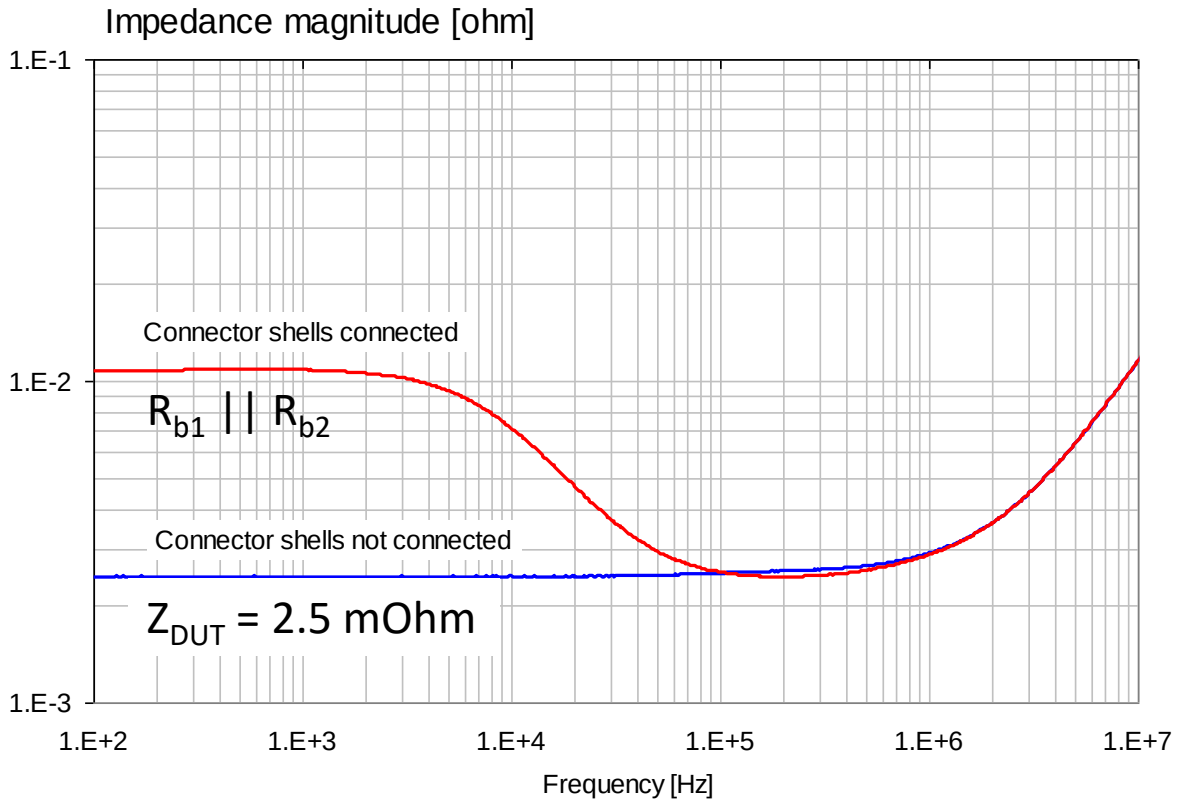
The Solution: Two-port Shunt-through Connection

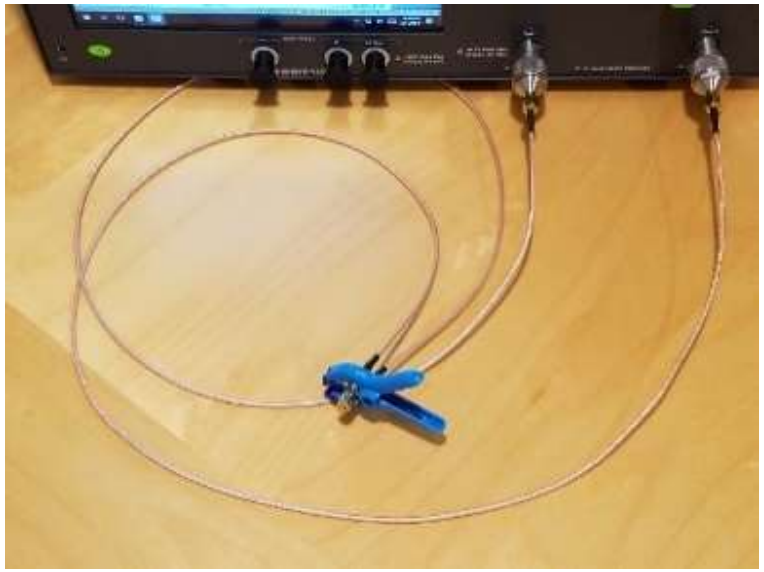


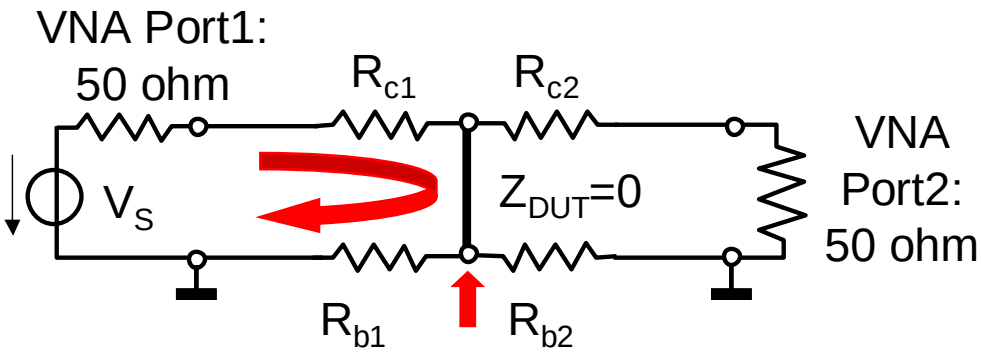
$$Z_{DUT} = \frac{50}{2} \frac{S_{21}}{1 - S_{21}}$$

- VNA Two-port Shunt-Through connection (RF Kelvin)
- First connection injects test current
- Second connection picks up voltage across DUT

But There is a New Problem





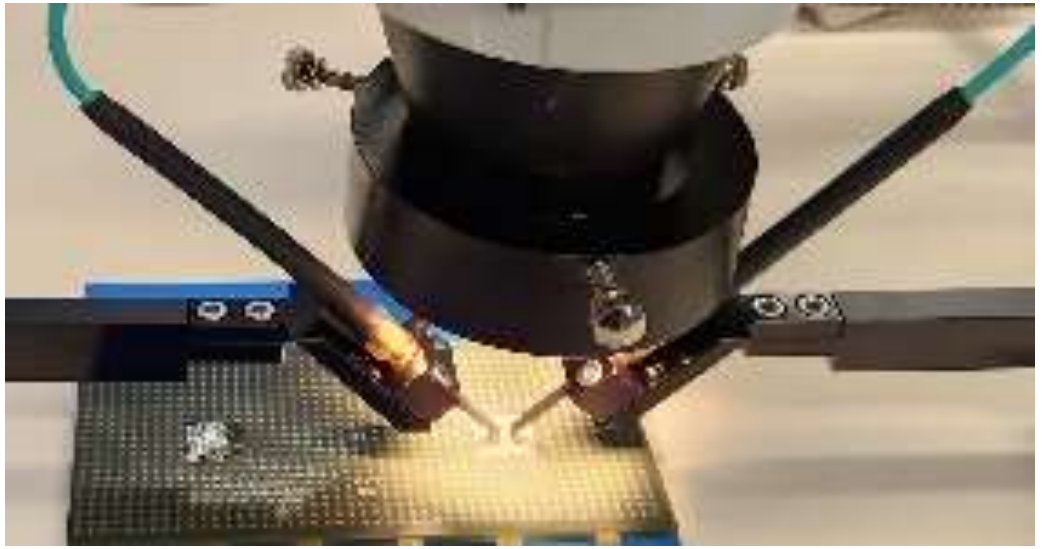


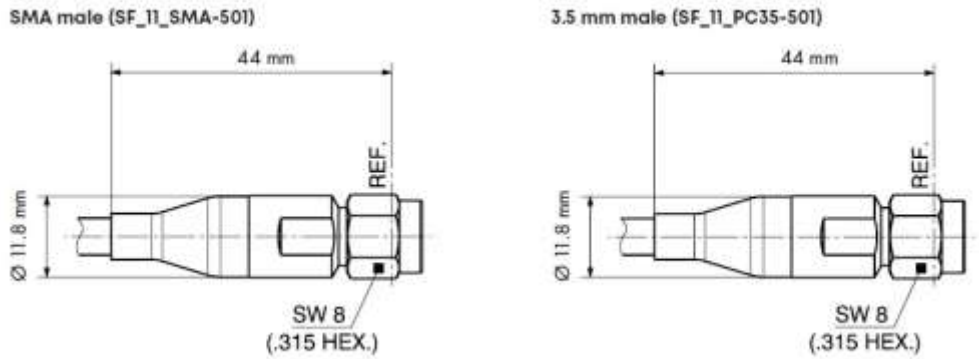
We measure the cable braid resistance instead of the DUT!

Can We Calibrate Out the Braid Error?

The short answer is NO

- No calibration method is available for it (though we could create it)
- The ‘braid’ error is not constant
  - It is the sum of resistances all along the return path, including the connectors and/or probes
  - The error will likely vary with cable/connector movement

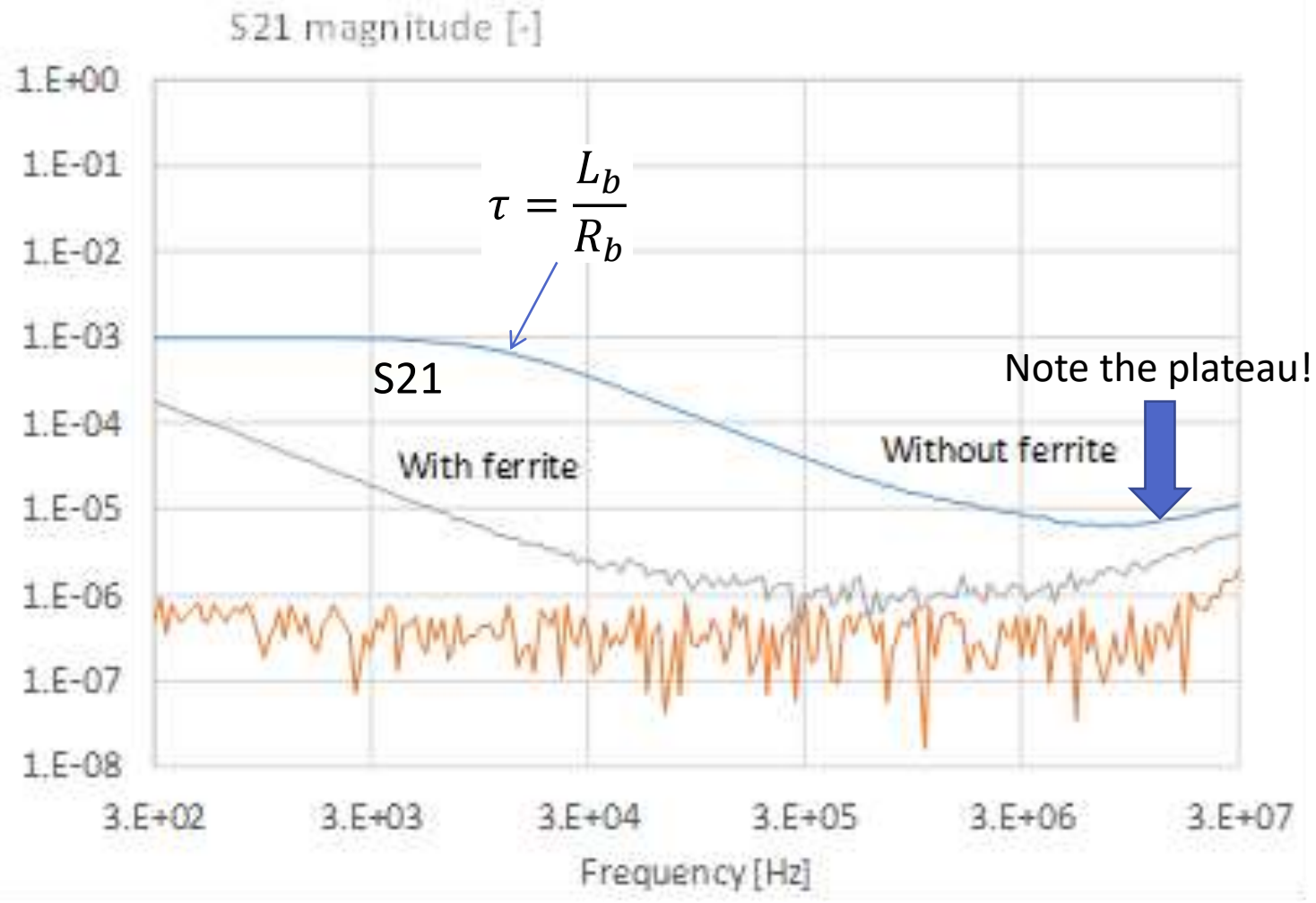




Huber-Suhner Microwave Cable Assemblies, 2022 Edition

What Can We Do?

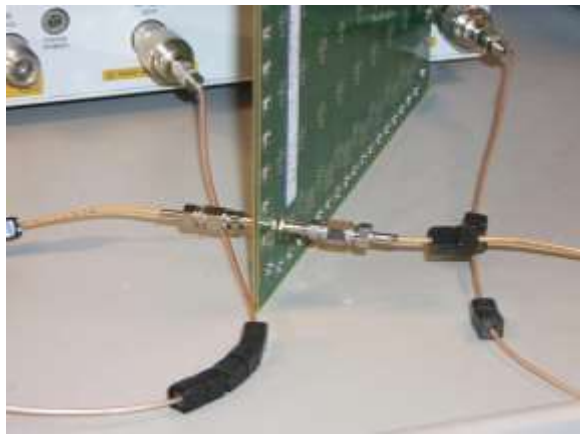
- We need to open up the cable-braid loop
- One option: use a common-mode choke to increase τ



How the Braid Impedance of Instrumentation Cables Impact PI and SI Measurements, DesignCon 2019

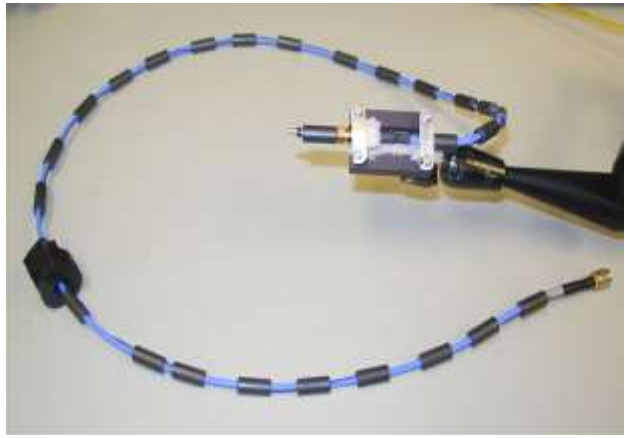
Common-mode Choke Options

We need to open up the cable-braid loop
A popular option: make use of common-mode inductance



Measuring Milliohms and PicoHenrys in Power Distribution Networks, DesignCon 2000

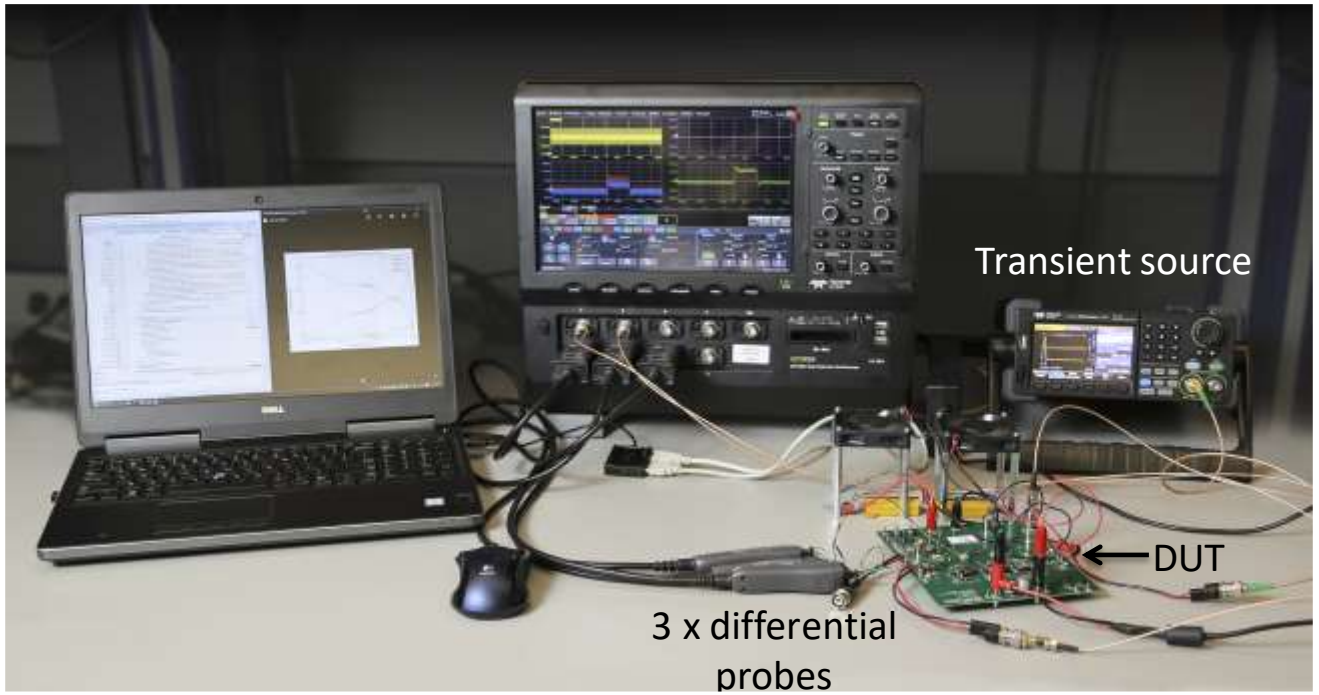
Accuracy Improvements of PDN Impedance Measurements in the Low to Middle Frequency Range, DesignCon 2010



Overview of Frequency-Domain Power-Distribution Measurements, DesignCon East 2003

Some Other Options

- Floating or semi-floating connections
- Differential amplifiers
- Current booster amplifiers



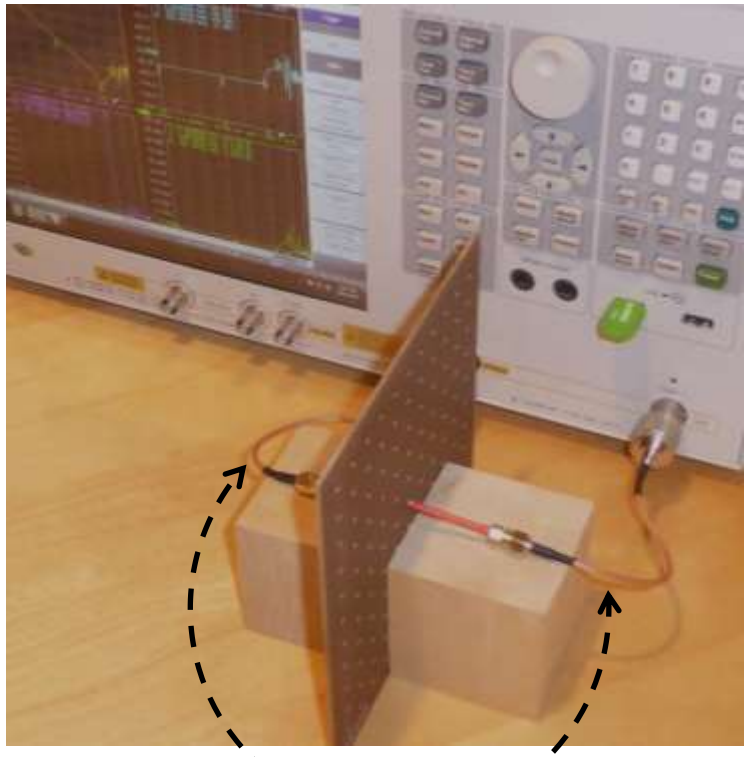
"A Generic Test Tool for Power Distribution Networks," Designcon 2017

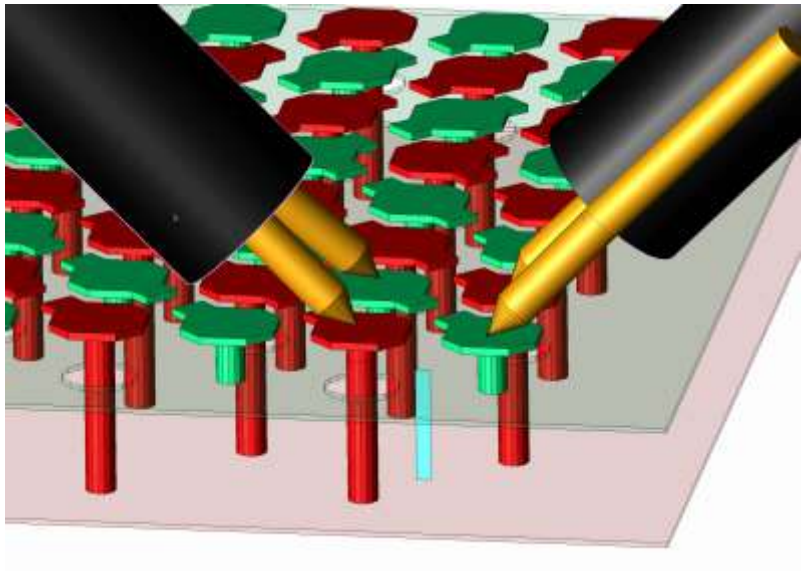
Keysight E5061B – 3LO

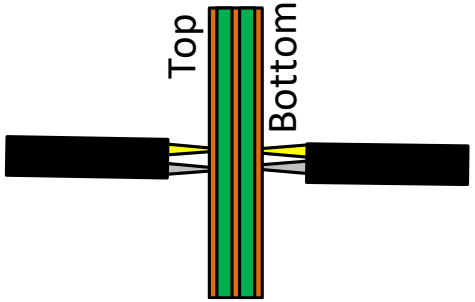
Picotest J2113A amplifier

http://www.electrical-integrity.com/Quietpower_files/QuietPower-48.pdf

Two-sided vs. One-sided Connections





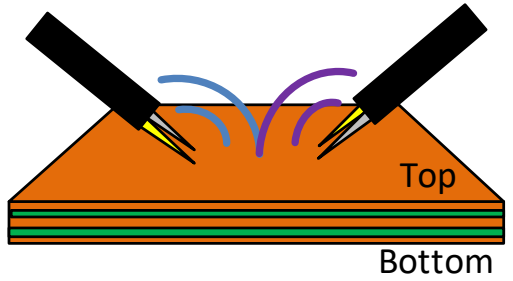


Coupling is minimized

- Cable-to-cable
- Probe-to-probe
- Via-to-via

If two-sided connection is not possible

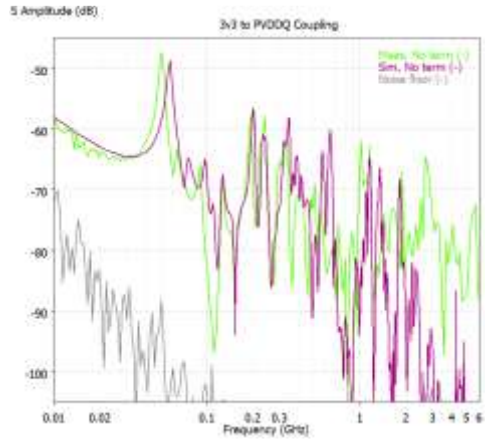
- Use nearby via pairs
- Coupling in probe loops and via loops is present

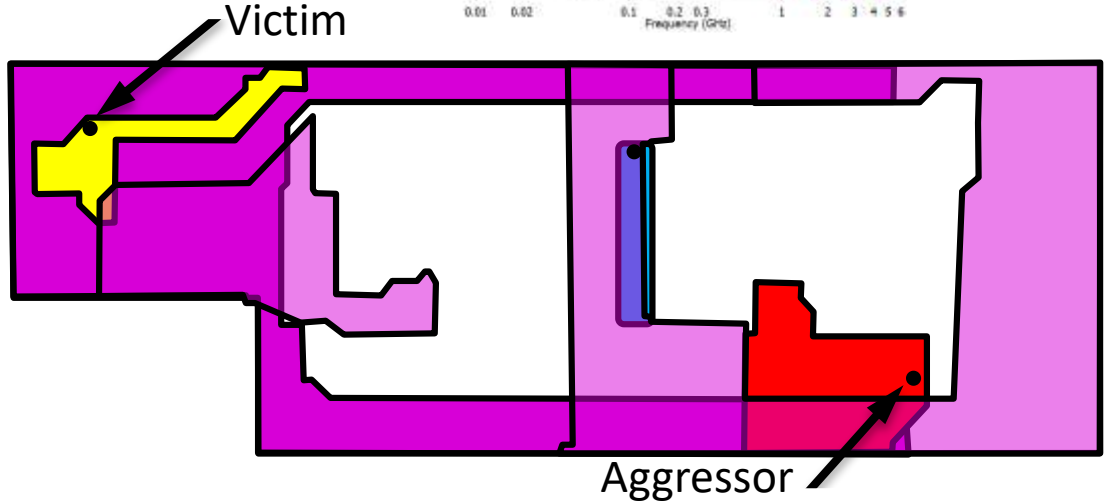


What Dynamic Range Do We Need?

Self impedance

S21 [dB]	Z [Ohm]
0	25
-20	2.5
-40	0.25
-60	25m
-80	2.5m
-100	0.25m
-120	25u





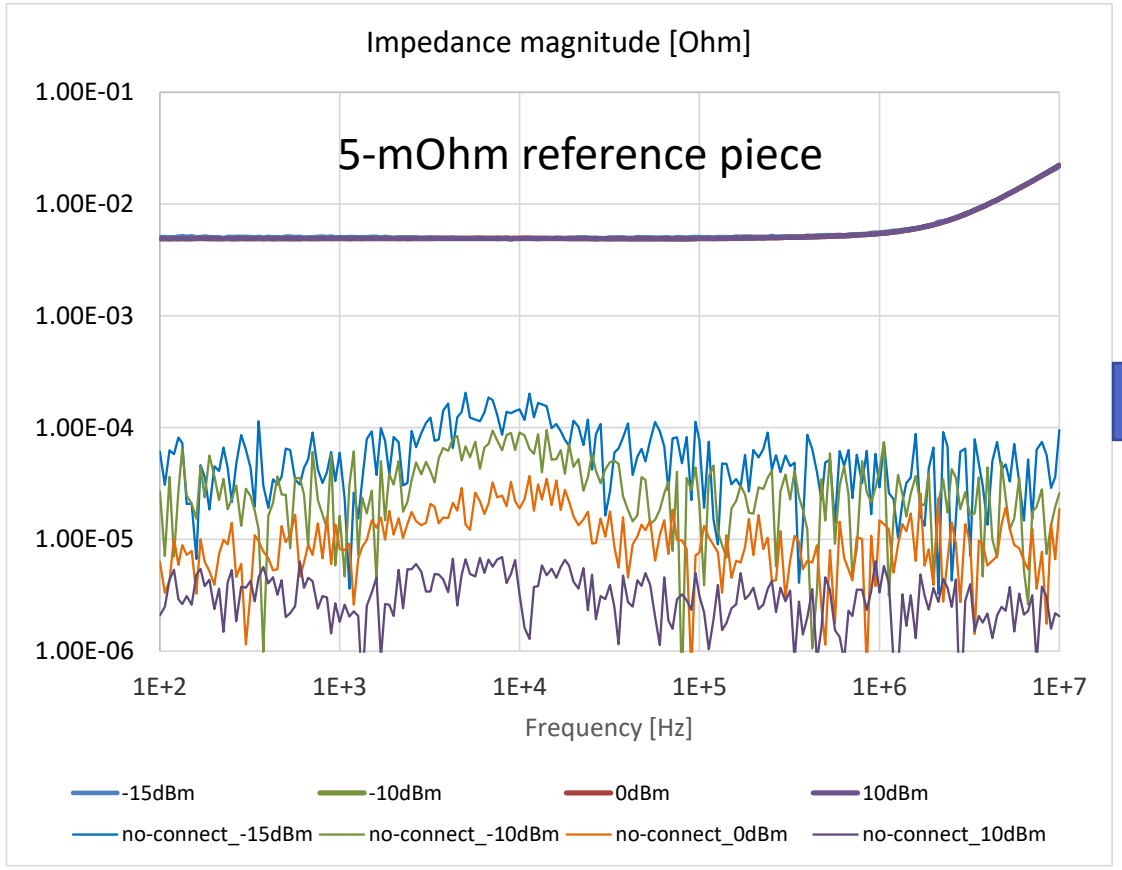
20” production board with multiple power rails

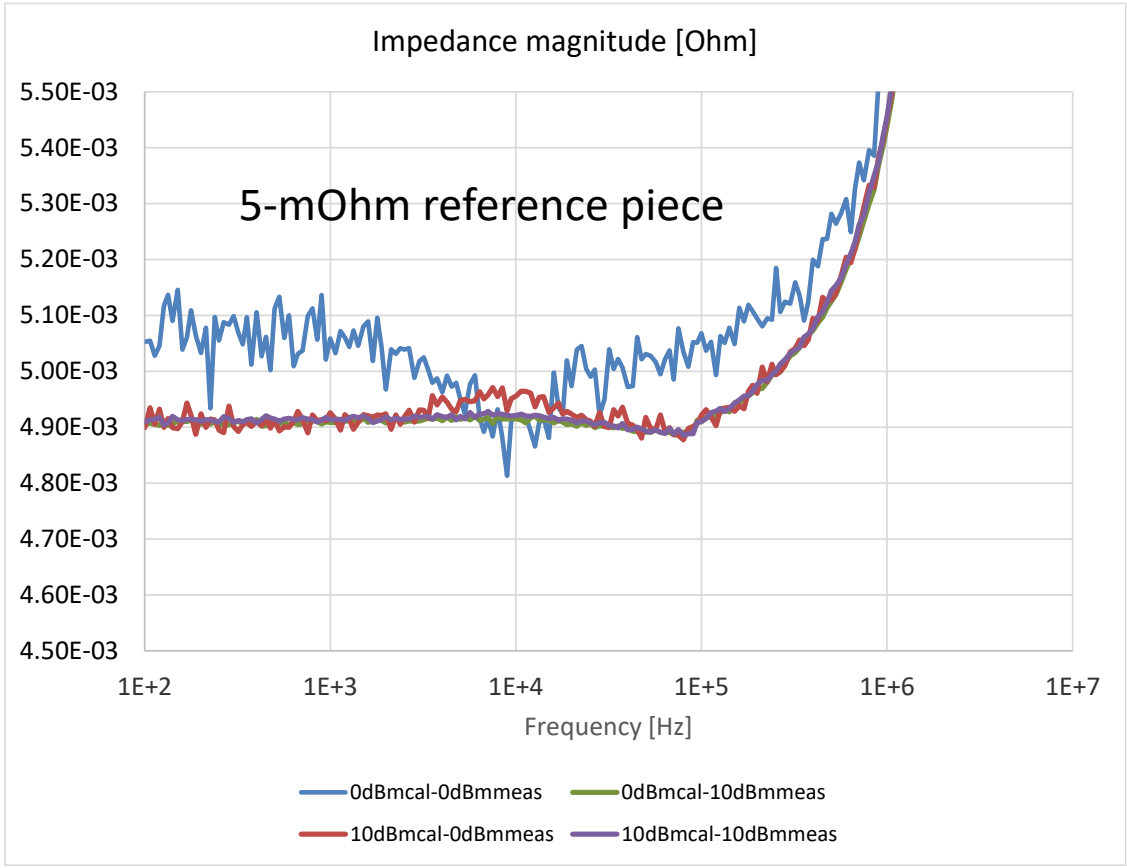
SI-PI transfer impedance

S21 [dB]	Level
0	100A aggressor
-20	
-40	With -120dB Xtk
-60	S/N=0dB
-80	
-100	
-120	100uA victim

What Dynamic Range Can We Achieve?

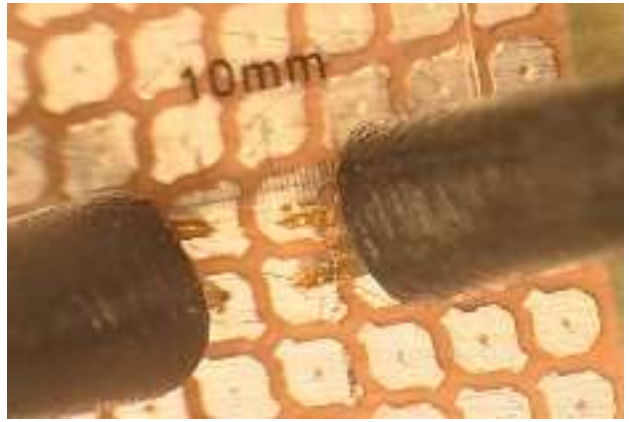
- With VNA only: 120 … 140dB
- With current booster: 140 … 160 dB



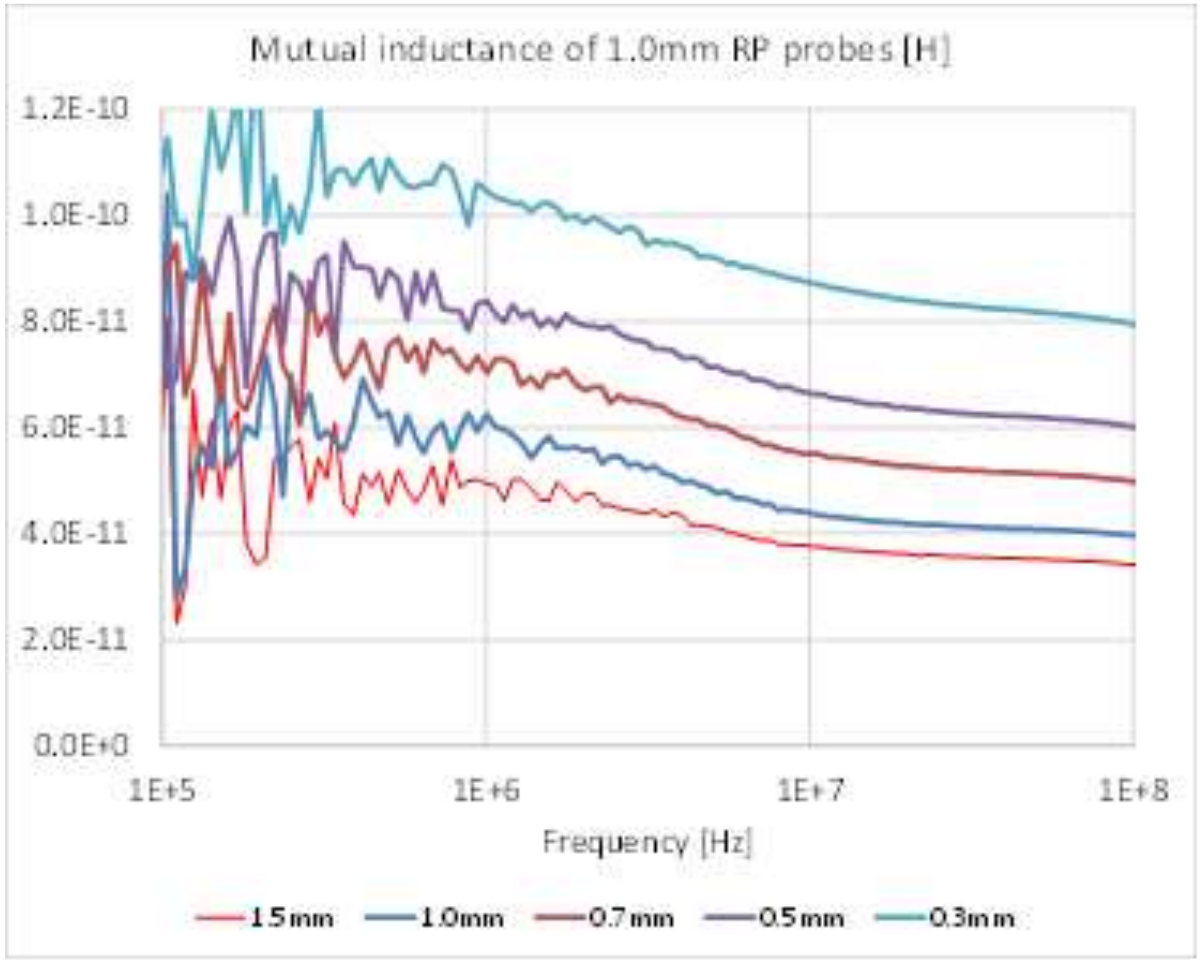


New Challenges

Wafer-probe (and via) crosstalk calibration/deembedding and coupling



3D Connection Artifacts in PDN Measurements, DesignCon 2023



3D Connection Artifacts in PDN Measurements, DesignCon 2023

New Challenges

Large currents through large arrays

- Horizontal connections cant be ignored
- Packages are growing beyond 70x70mm
- One square of (unperforated) copper sheet has approximately 0.6 mOm sheet resistance
- With < 1mOhm target impedance, the impedance is strongly location dependent
- Challenge for simulations
- Challenge for measurements

Is Power Integrity the New Black Magic?, Cadence E-Learning Forum, 2021

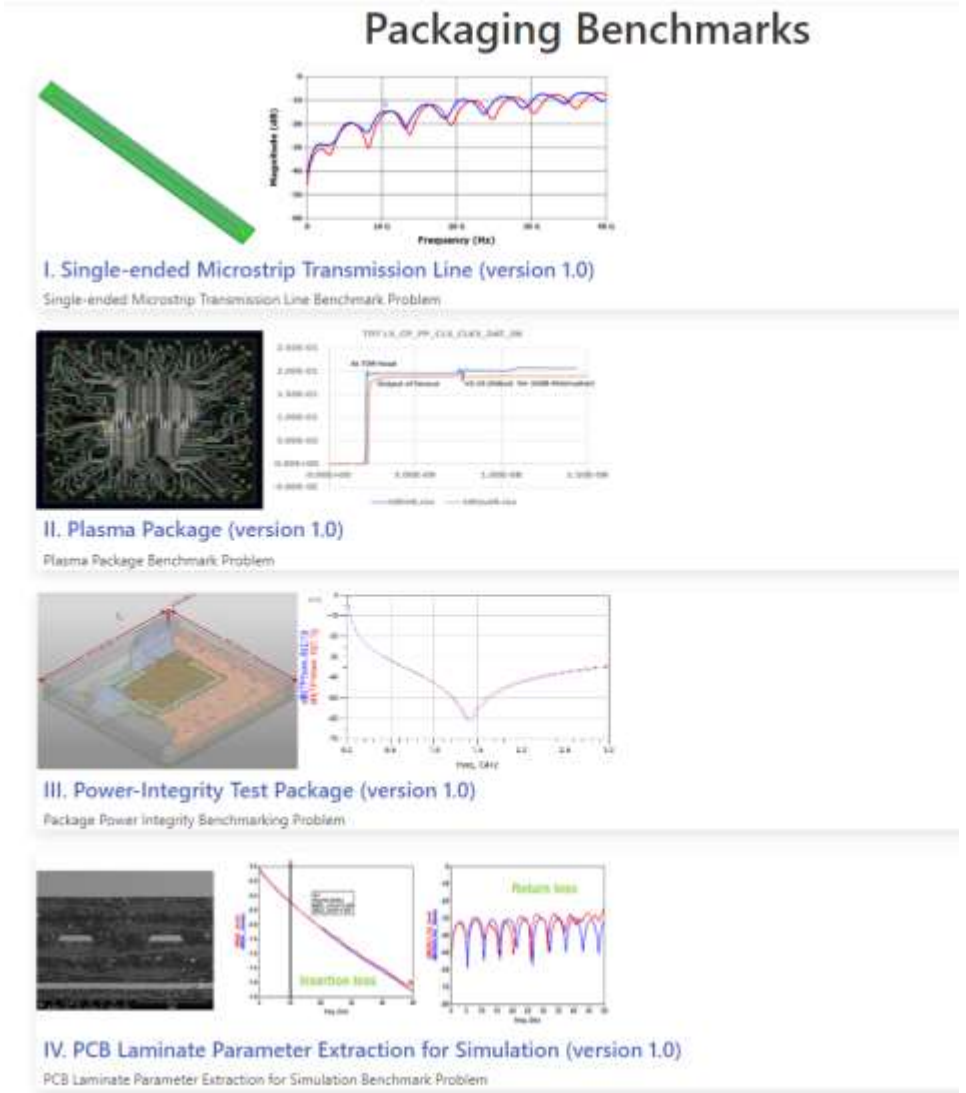
IEEE Pkg Benchmarks

IEEE Electronics Packaging Society (EPS) Technical Committee on Electrical Design, Modeling and Simulation (TC-EDMS)

- Users and CAD companies need to work together to create correlation cases that are
  - Open source
  - Verified
- Good example: IEEE Packaging

  Benchmark project

https://packaging-benchmarks.org/repository/



Good Measurement Practices

- Select the instruments, cables, probes and calibration methods carefully
- Be aware of uncertainty factors and limitations
- Maximize source power, minimize IFBW and number of sweep points for very low impedances
- Connections matter at any frequencies
- Keep ‘golden,’ well-characterized reference pieces on hand
- Check the test setup periodically with the ‘golden’ pieces
- Be aware of probe and via coupling artifacts
- Correlate as much as possible

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