Welcome to

DESIGNCON® 2021
WHERE THE CHIP MEETS THE BOARD

Conference
August 16 – August 18, 2021

Expo
August 17 – August 18, 2021

San Jose McEnery Convention Center

Impact of Power Plane Termination on System Noise

Ethan Koether, (Project Kuiper – Amazon)

Kristoffer Skytte (Cadence), Joseph Hartman (Oracle)
Shirin Farrahi (Cadence), Istvan Novak (Samtec)

SPEAKERS / AUTHORS

Ethan Koether

Power Integrity Engineer, Project Kuiper – Amazon

koether@amazon.com

Ethan Koether earned his master's degree in Electrical Engineering and Computer Science in 2014 from the Massachusetts Institute of Technology and has spent the last seven years as a hardware engineer at Oracle. He recently began his new role as a Power Integrity Engineer with Amazon's Project Kuiper. His interests are in commercial power solutions and power distribution network design, measurement, and analysis.

Kristoffer Skytte

Senior Principal Application Engineer, Cadence

kskytte@cadence.com

Kristoffer Skytte is Senior Principal Application Engineer at Cadence focusing on chip, package, board and full system analysis. He is helping companies in Europe apply simulation tools to solve some of their toughest SI & PI and EMC related challenges in their design process. One of his interest is system level immunity / emissions and how these affect overall system performance. Kristoffer has a M.Sc.EE. degree from the Technical University of Denmark.

SPEAKERS / AUTHORS

Joseph 'Abe' Hartman

Principal Hardware Engineer, Oracle

abe.Hartman@oracle.com

Abe Hartman is a Principal Hardware Engineer focusing on system signal and power integrity at Oracle. Abe has worked as a signal integrity engineer at Amphenol TCS, Juniper Networks, and Enterasys. Abe also worked at General Motors. Abe holds a MS in Electrical Engineering from the University of Massachusetts-Lowell, a MS in Engineering Science from Rensselaer Polytechnic Institute, a BS in Mechanical Engineering and a BS in Electrical Engineering from Kettering University in Flint, MI.

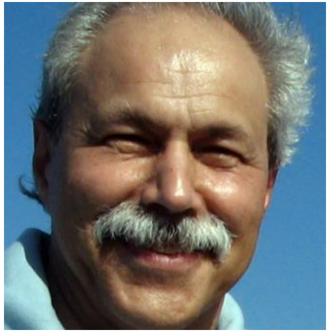
Shirin Farrahi

Principal Software Engineer, Cadence

shirinf@cadence.com

Shirin Farrahi is a Principal Software Engineer at Cadence working on the development of signal and power integrity tools for automated PCB design. Prior to joining Cadence, she spent four years as a Hardware Engineer in the SPARC Microelectronics group at Oracle, working on the design of high-speed electrical and optical interconnects in servers. She received her Ph.D. in Electrical Engineering from the Massachusetts Institute of Technology.

SPEAKERS / AUTHORS



Istvan Novak

Principal Signal Integrity and Power Integrity Engineer, Samtec

istvan.novak@samtec.com | electrical-integrity.com

Istvan Novak is a Principal Signal and Power Integrity Engineer at Samtec, working on advanced signal and power integrity designs. Prior to 2018 he was a Distinguished Engineer at SUN Microsystems, later Oracle. He worked on new technology development, advanced power distribution, and signal integrity design and validation methodologies for SUN's successful workgroup server families. He introduced the industry's first 25 µm power-ground laminates for large rigid computer boards and worked with component vendors to create a series of low inductance and controlled-ESR bypass capacitors. He also served as SUN's representative on the Copper Cable and Connector Workgroup of InfiniBand, and was engaged in the methodologies, designs and characterization of power-distribution networks from silicon to DC-DC converters. He is a Life Fellow of the IEEE with twenty-nine patents to his name, author of two books on power integrity, teaches signal and power integrity courses, and maintains a popular SI/PI website. Istvan was named Engineer of the Year at DesignCon 2020.

OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- Conclusion

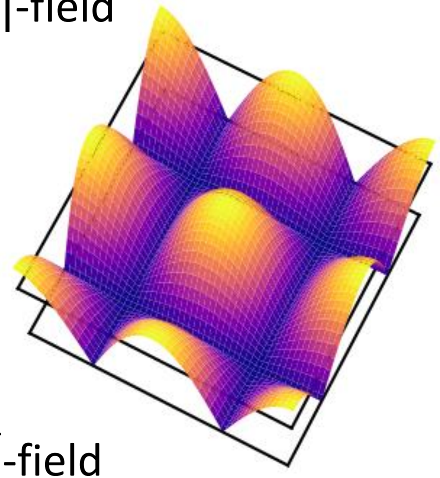
OUTLINE

- **Power Plane Resonances**
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- Conclusion

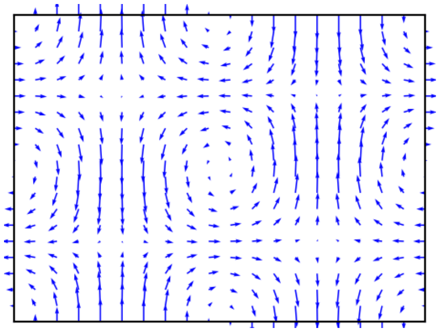
Power Plane Resonances

- When the wavelength of excitation approaches same order of magnitude as dimensions of power plane, spatially motivated resonances occur
  - Power planes are naturally “open” at boundary
  - Resonances often pushed out to higher frequencies by distributed decoupling capacitors
- Resonances allow for storing and radiation of energy and so affect integrity of other system planes and signals.
- First power plane resonance mode in modern system boards often in 100 MHz – 1 GHz range.
  - Midfrequency noise from signals, power converters, clocks can create perfect storm

Resonant $|\vec{E}|$-field



Resonant $\vec{H}$-field



OUTLINE

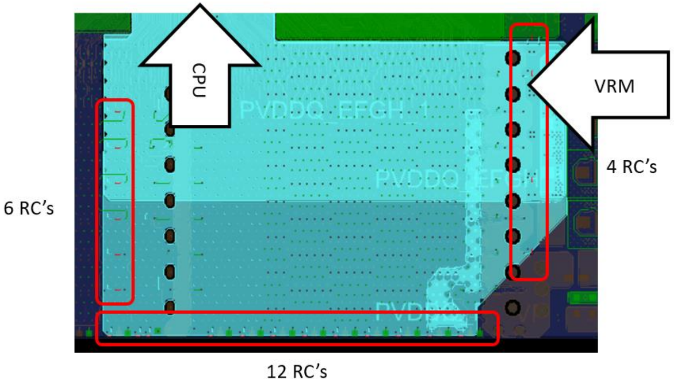
- Power Plane Resonances
- **Power Plane Termination Simulation and Measurements**
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- Conclusion

Plane Termination Exploration

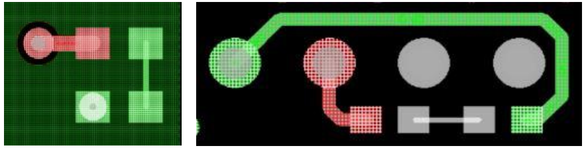
- Can terminate power plane as 2D transmission line with matched R and series C
  - Series C prevents DC power loss
- Approximate impedance of rectangular plane pair:

$$|Z_{Plane}| \sim \frac{535}{\sqrt{\varepsilon_r}} \cdot \frac{h}{P}$$

- Our board had bare plane areas where could not fit decoupling capacitors
- Could fit 22 R-C termination elements around perimeter of power plane.



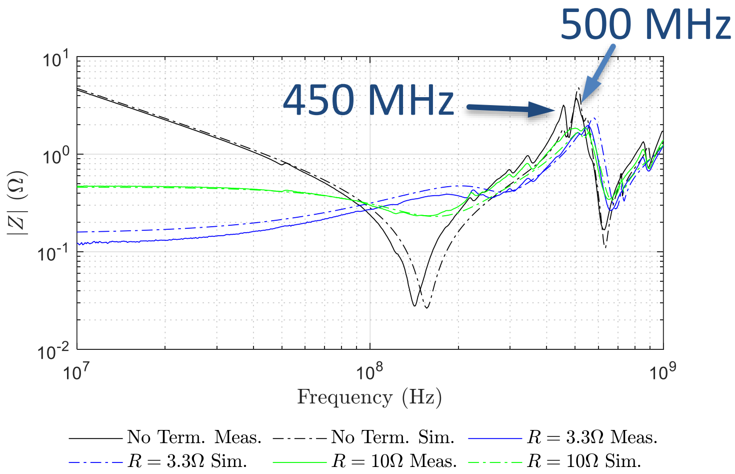
Example power plane with RC termination placement highlighted.

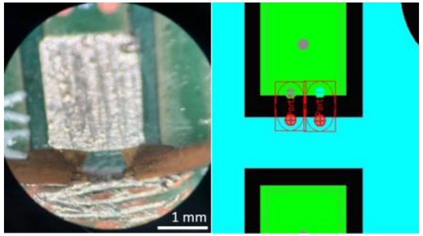


Example RC termination layout.

Termination – Simulations and Measurements

- Calculation gave optimal termination of $\mathbf{3.3\ \Omega}$, further tuning in simulation gave optimal termination of $\mathbf{10\ \Omega}$
- Bare board simulated and measured without and with termination
  - Measurement: Keysight N5225A PNA and E5061B ENA with model 40A-GS-500-VP Picoprobe, GGB Industries Inc.
  - Simulation: Cadence PowerSI
- Unterminated self-impedance shows two high Q resonances
  - $\boldsymbol{Q_{3dB} = 21.7\ (450\ MHz), Q_{3dB} = 26.6\ (500\ MHz)}$
- Termination reduced self-impedance Q's significantly
  - $\boldsymbol{Q_{3dB} = 5.65}$ for $\boldsymbol{R_{Term} = 3.3\ \Omega, Q_{3dB} = 3.91}$ for $\boldsymbol{R_{Term} = 10\ \Omega}$

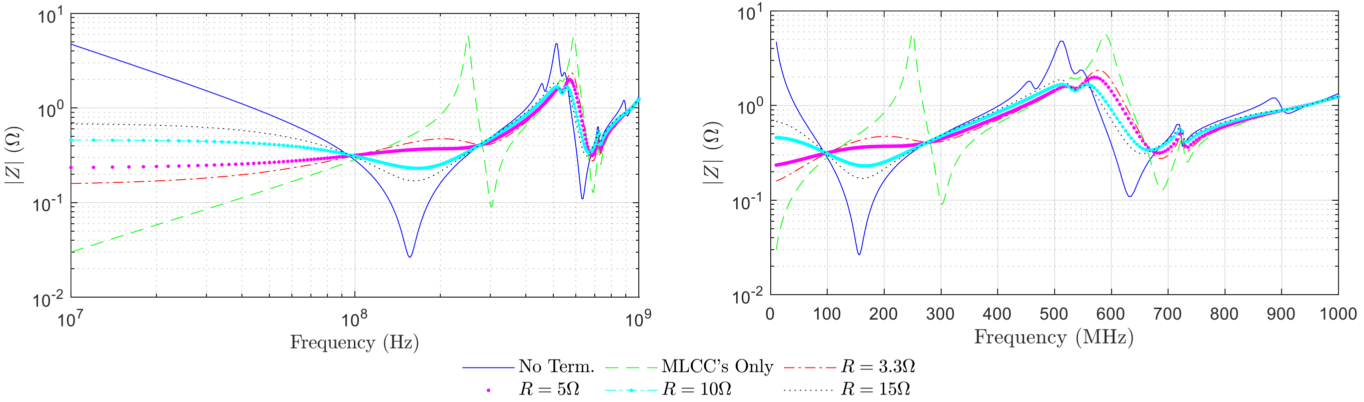




Measurement wafer probe landing and corresponding simulation probe location.

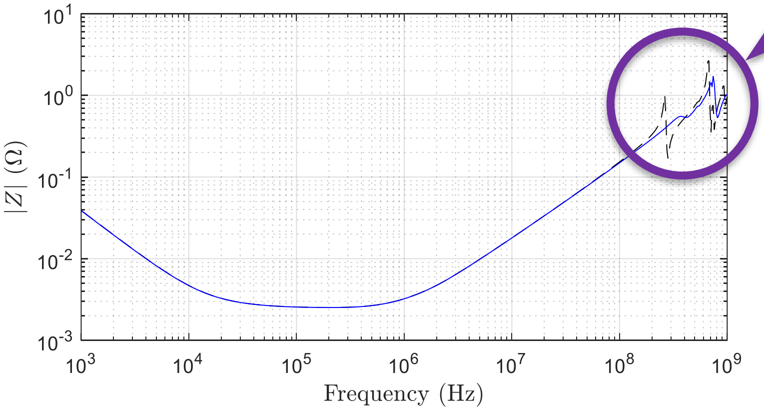
Termination – Simulations and Measurements

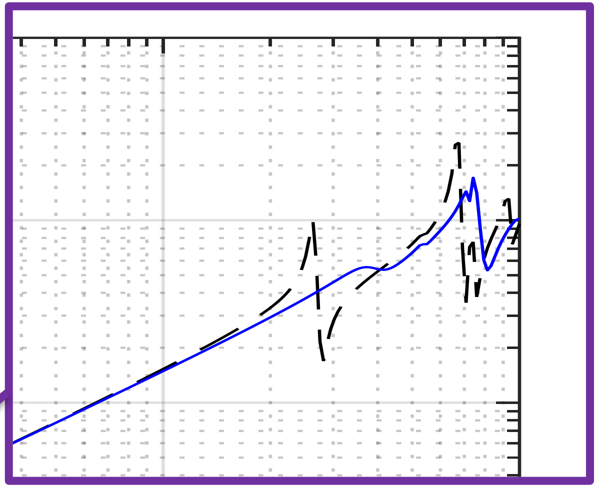
- Explored several termination options in simulation to find optimal value
  - Purely capacitive termination resonates with ‘shorted’ boundary condition instead of original ‘open’ resonance.
- RC terminations cannot be placed optimally around boundary but reduced Q shows addition of loss from termination elements more important than exact termination distribution and value



Termination – Plane/Capacitor Resonances

- On board capacitors can resonate with power planes
- Self-impedance with and without termination elements re-simulated with voltage regulator's bulk capacitance included
- Resonances between bulk capacitors and power plane clearly dampened with power plane termination



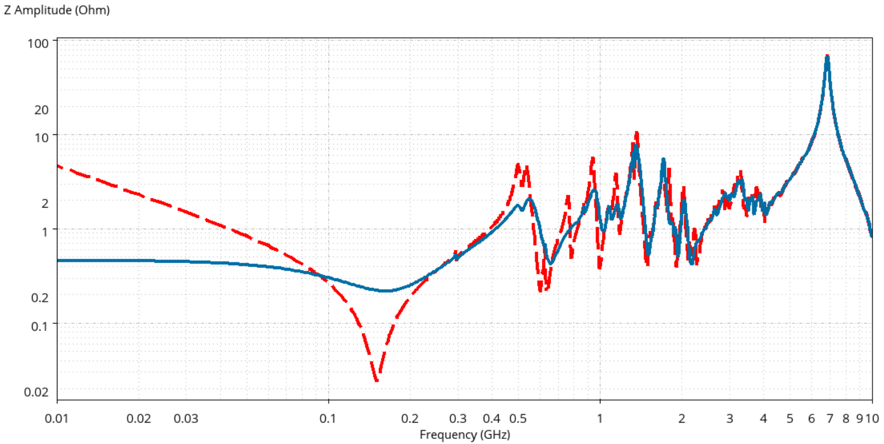


Simulation of terminated and unterminated power plane self-impedance with bulk capacitors included

– – – No. Term $R = 3.3\Omega$

Termination – Effective Frequency Range

- Discrete termination 'looks' continuous to excitation if wavelength >> space between termination RC's.
- 6.8 mm average spacing between elements corresponds to 20 GHz in FR4
- Expect RC termination to be effective up to ~2 GHz
- Simulation shows RC termination effective up to ~1.5 GHz



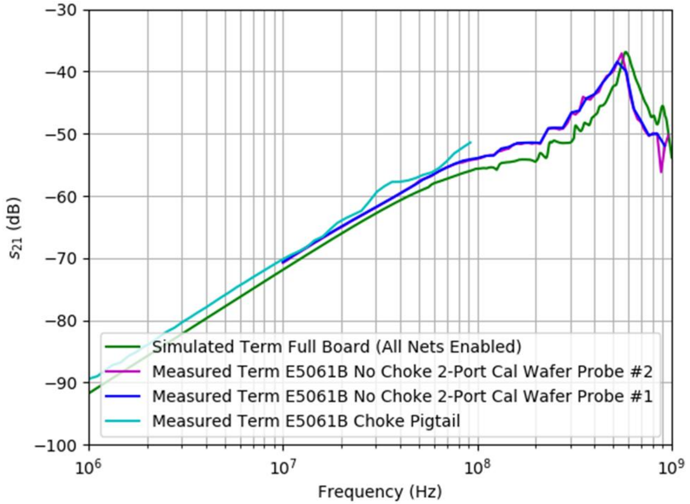
Simulation of effective frequency range of discrete RC termination

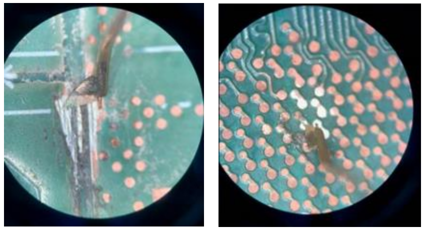
OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- **Measurement / Simulation Setup**
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- Conclusion

Measurement/Simulation Setup

- Tuned measurement and simulation with plane-signal coupling setup to establish data quality
- Full 2-port calibration completed prior for all measurements
- Common mode choke included for measurements in frequency range < 10MHz to reduce cable braid error
- Full board included in simulation to achieve shown level of measurement-simulation correlation





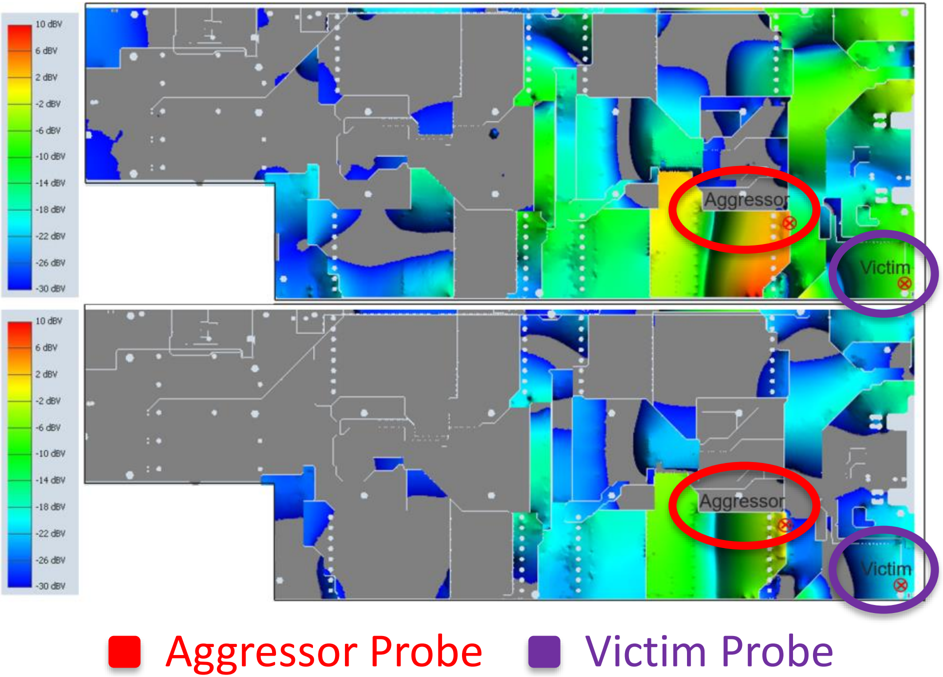
North: Measured and simulated data. Left: Wafer probe landings for measurements.

OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- **Impact of Termination on Power to Power Coupling**
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- Conclusion

Power to Power Coupling

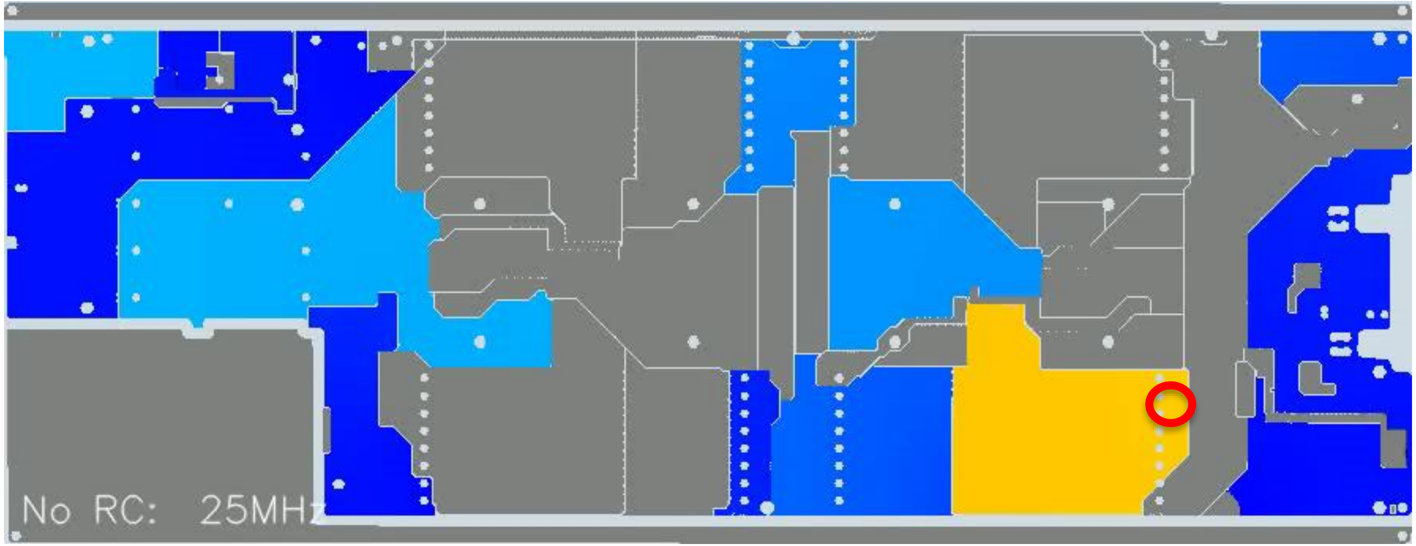
- Power planes can couple to other planes when overlapping (capacitive-coupling), or vias couple (inductive-coupling)
- Energy can couple over path consisting of multiple power planes
- Coupling in figure shows noise from aggressor VDD plane coupling to victim plane
  - Victim plane does not overlap nor is immediately next to aggressor plane
- Coupled energy reduced at resonant frequency when aggressor plane terminated



Both figures shows special voltage noise distribution for 1A forced on VDD plane at 500MHz. Top figure shows noise distribution for unterminated case. Bottom figure shows noise distribution for terminated case.

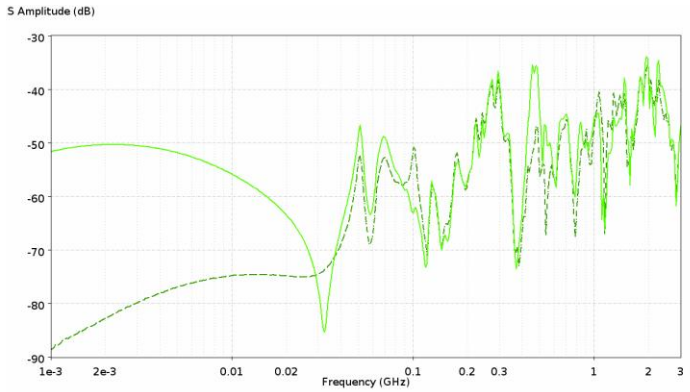
Power to Power Coupling

- Video of noise sprawl from unterminated power plane to neighboring planes as excitation frequency approaches 500 MHz resonant frequency (noise excitation location circled in red)

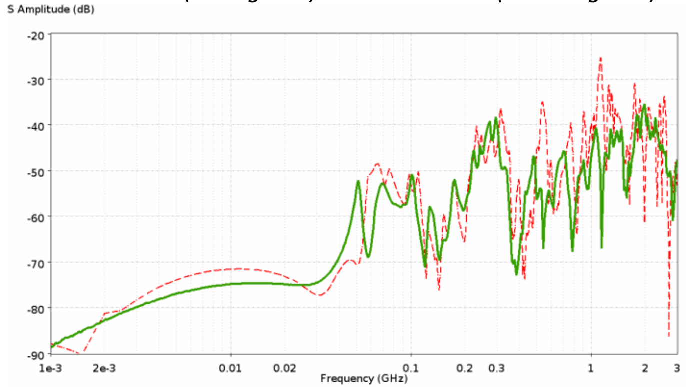


Power to Power Coupling

- Measurements show RC termination reduces coupling before first resonant frequency due to better confinement of fields
- RC termination reduces coupling at resonant frequency by 10 dB
- Simulation and measurement agree up to ~400 MHz
- >400 MHz, trends between simulation and measurement agree



Top figure shows measured s21 from aggressor plane to victim plane in unterminated (solid green) and terminated (dashed green) cases.



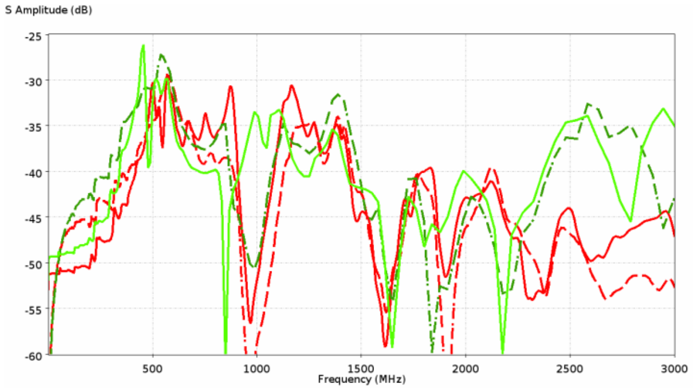
Bottom figure shows measured s21 (solid green) and simulated s21 (dashed red) from aggressor plane to victim plane in terminated case.

OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- **Impact of Termination on Power to Signal Coupling**
- Impact of Termination on Signal to Signal Coupling
- Conclusion

Power to Signal Coupling

- Looked at coupling from power net to clock-enable net
  - Signal traveled from ASIC to DIMM socket past vias of aggressor power net
  - Signal sandwiched between ground planes
  - Any via transition through power-ground cavities leaves potential for noise coupling from power domain
- RC termination reduces resonance significance by lowering Q and smearing the peak
- RC terminated case shows higher peak coupling around 900 MHz and 1400 MHz in measurement data
- General trend of reduced coupling with RC termination



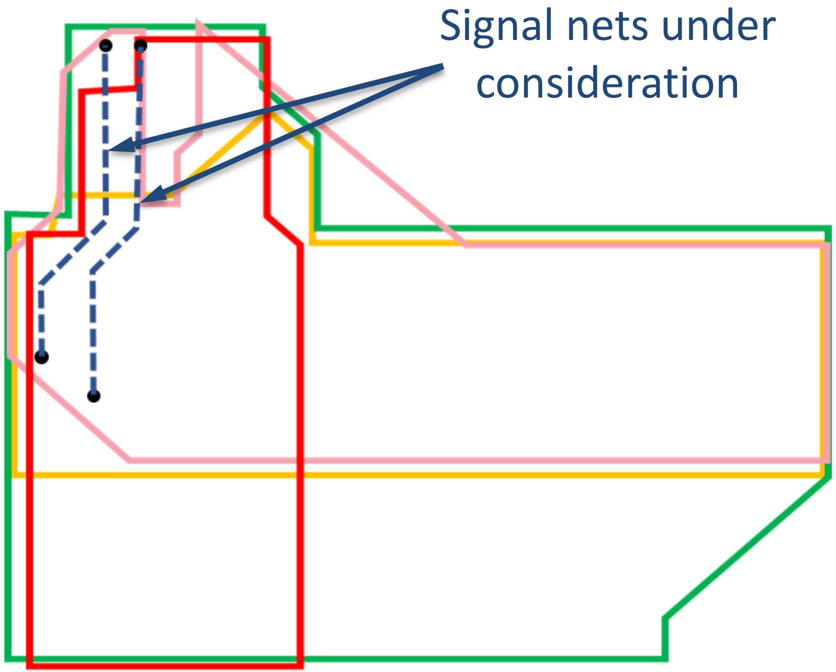
Power to signal coupling: unterminated measurement (solid green), RC terminated measurement (dashed green), unterminated simulation (solid red), and terminated simulation (dashed red).

OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- **Impact of Termination on Signal to Signal Coupling**
- Conclusion

Signal to Signal Coupling

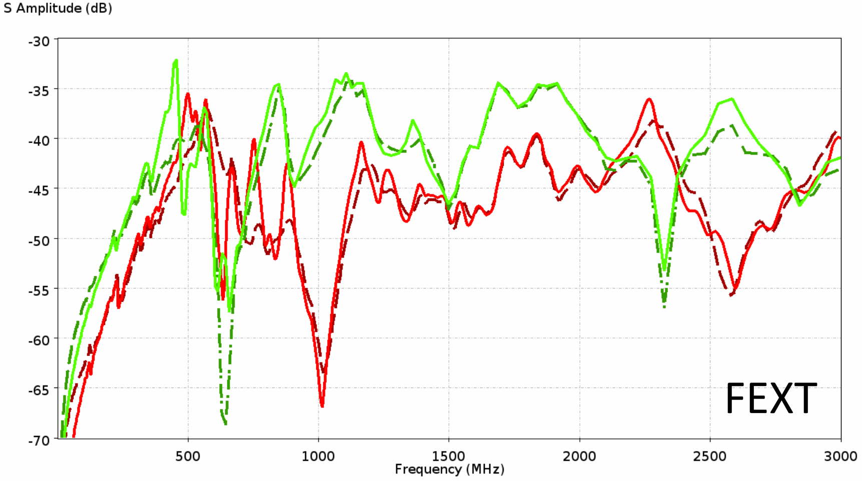
- Looked at coupling between signals routed from ASIC to DIMM connector
- Nets routed far apart on same layer
- Sandwhiched between two ground planes
- Signals have transition vias through power-ground cavity
    - Noise mechanism largely due to resonant power planes

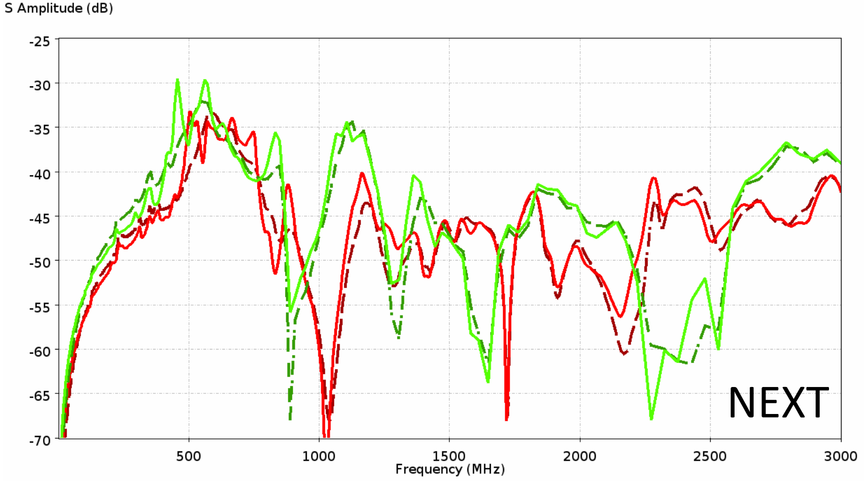


Signals analyzed overlaid on resonant power net's shapes

Signal to Signal Coupling

- RC termination reduces crosstalk peaking around 500 MHz and 900 MHz (reduction and smearing of Q)
- Simulations predict higher crosstalk reduction than shown in measurements





Signal to signal crosstalk: Upper plot shows FEXT. Lower plot shows NEXT. Measurement datasets are green. Simulated datasets are red. Unterminated cases are plotted with solid lines and terminated cases are plotted with dashed lines.

OUTLINE

- Power Plane Resonances
- Power Plane Termination Simulation and Measurements
- Measurement / Simulation Setup
- Impact of Termination on Power to Power Coupling
- Impact of Termination on Power to Signal Coupling
- Impact of Termination on Signal to Signal Coupling
- **Conclusion**

Conclusion

- Power plane resonances can impact electrical integrity of system (EMI, power-to-power crosstalk, power-to-signal crosstalk, and signal-to-signal crosstalk)
- Plane termination can be used to dampen impact of power plane resonances on systems
  - Termination loss more important than absolute value of R or distribution of termination elements
- At modal resonant frequencies, plane-to-plane crosstalk can be substantially reduced by use of RC termination, even if planes have minimal physical overlap
- Reduced Q from termination reduces crosstalk between power planes and victim signals
- Signal-to-signal crosstalk also reduced by inclusion of termination on peripheral power planes
- Future work planned to achieve better measurement-to-simulation correlation and to analyze plane resonance crosstalk mechanisms further.

Acknowledgements

- Sammy Hindi, Cadence Design Systems

Thank you!

QUESTIONS?