THE ART AND SCIENCE OF EMC DESIGN

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Purpose of these Presentations

- The Art is how we tackle a task with the tools available.
- The Science is the physics and mathematical implementations that enable the tools.
- The Art and Science are tightly woven together.
- The primary goal is to show how to think clearly about EMC design so that it can be done efficiently

OUTLINE

- Art of EMC Design (how to apply the physics)
- Models & Tools
- Validation & Verification
- ESD Considerations

The Science of EMC Design

- EM Theory fully explains EM behaviors
  - Coupling
  - Radiation
  - Current distribution
- Special cases are also common, and are used to simplify analysis
  - Shielding
  - Antenna equations
- However, understanding the models and knowing what to put into the equations …..
- What did you do and why did you do it

Some Definitions

- Model
- Tool

What is a Model?

- This is how we manage our world
- A model is a representation of a system that enables us to analyze that system
  - Physical (scale)
  - Mathematical
  - Analog or empirical
- How much detail is needed

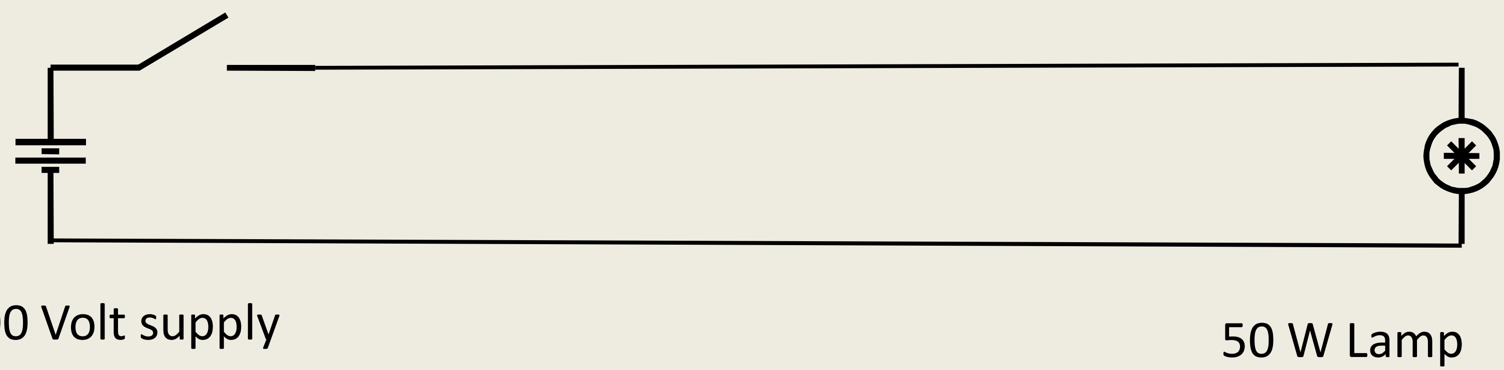
What is a Tool?

- Something that helps us do our work
- Measurement
- Computer model
- Analytic model
- Copper tape

Models and Tools are Different

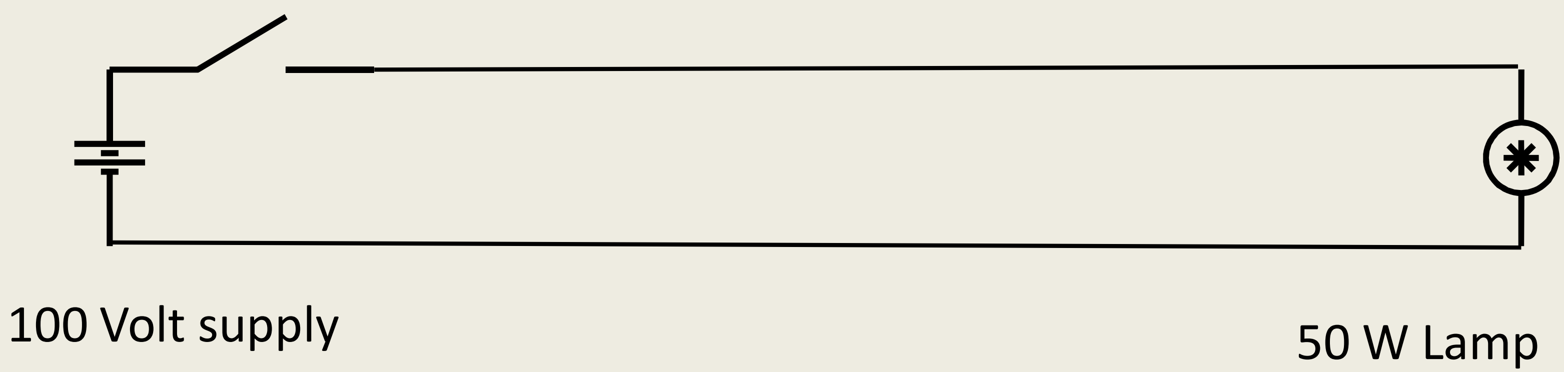
- May seem basic, but failing to make this distinction can lead to difficulties
- Computational models are created using different tools and so can have different characteristics or errors
- Always ask "What are the capabilities of the tools being used?"

What Happens When the Switch is Closed?



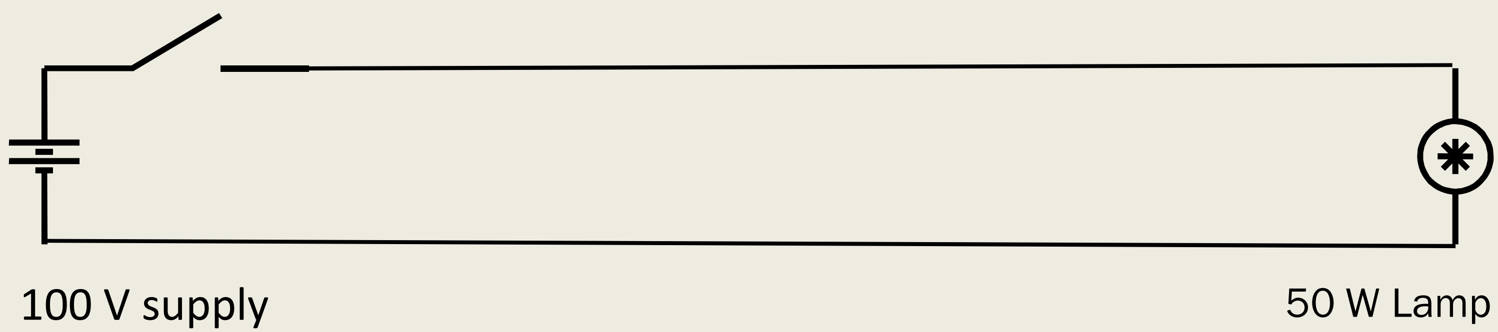
Same Model, Different Levels of Detail

- DC or low frequency analysis
  - 50 W at 100 V = 0.5 A (200 Ohm)



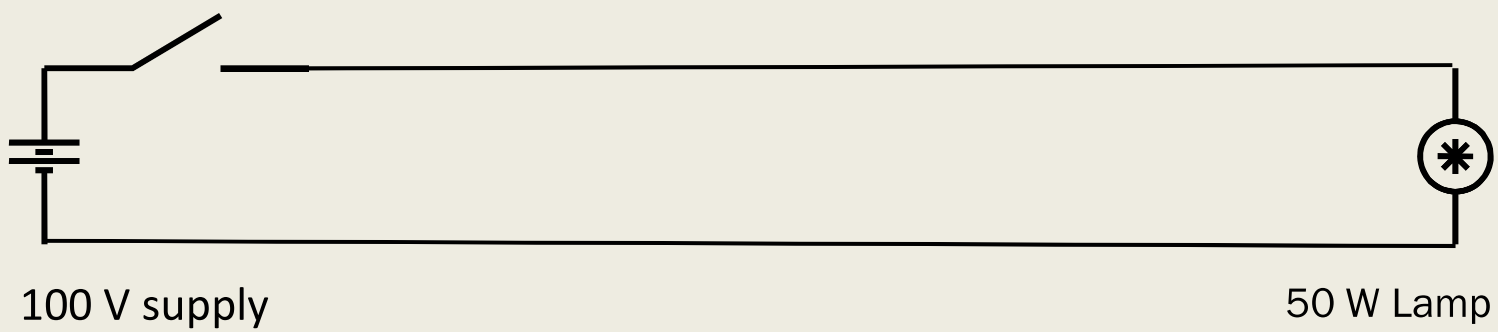
Same Model, Different Levels of Detail

- High frequency behavior
  - If the line is long and has a characteristic impedance different to 200 Ohm then there is ringing at high frequencies
  - Initial (surge) current will be V/line Z



Same Model, Different Levels of Detail

- Non Linear behaviors
  - As the switch closes there will be an arc as the air breaks down, generates high frequency components
  - The load may be non linear with current and/or time



Schematic Elements Can Be Simple or Far More Complex

- Have no physical properties
  - Size or placement
- Are often simple over a nominal frequency range
- May need to be improved for EMC applications

Ferrite Core Circuit Schematic

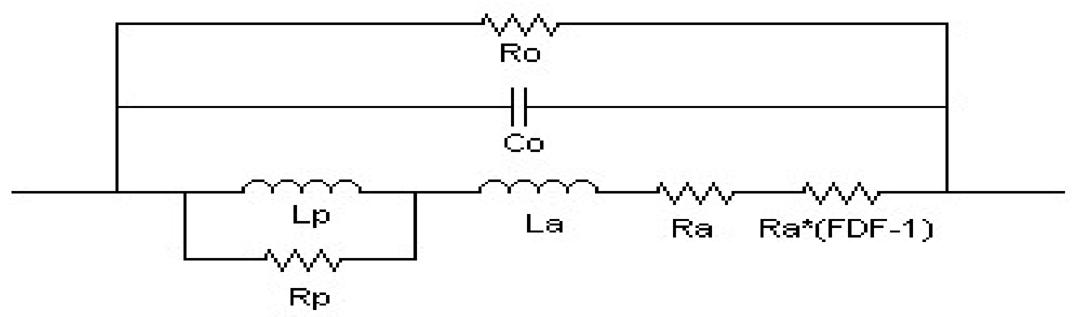


Fig. 1 - Simplified equivalent circuit of a ferrite cored inductor

- This is the low frequency model of a ferrite core
- Installing it on a PCB will add extra shunt C and perhaps series L components
- Operating at a high current changes even more

The Physics

- Always seems so complicated when you start with Maxwell's equations.
- What is the physics?
- Is it equally complicated?

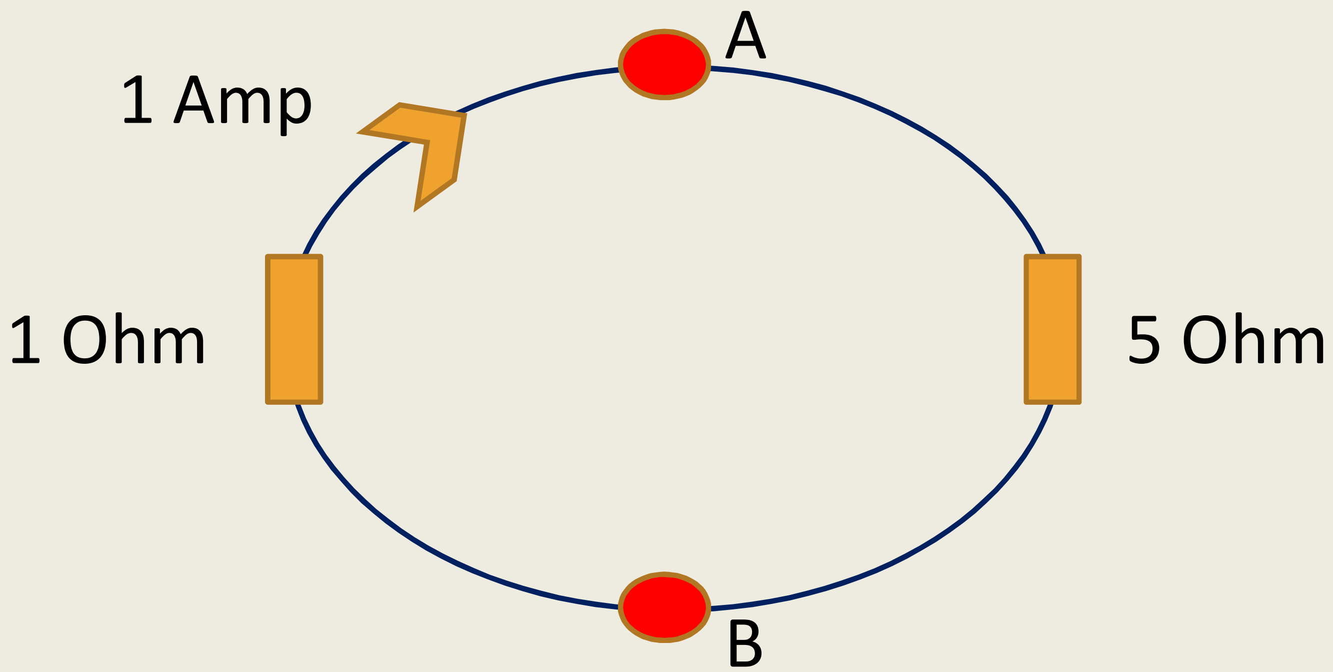
Physics – What is Fundamental

- Field theory is always a favorite subject!
- Stationary displaced electrons create a static electric field
- Electrons moving at a constant velocity give rise to static magnetic fields
- Accelerating electrons cause energy to radiate and our lives to have meaning

Physics – What is Fundamental

- We seem to have a preference for thinking about voltage
- For example, Ground is “zero” volts and is frequently considered to be zero impedance
- This falls apart rapidly when current is actually involved

What is the Voltage Between A and B?



Voltage Can Confuse

- What is voltage?
- Voltage is the integral of the E field over a defined path
- The current is fundamental
- The voltage is a derived term
- #1 EMC concern – what is the current path?
  - Decoupling caps are *coupling* caps

Where Does the Current Go?

- For solving Maxwell's equations and real EMC problems, it is all about the boundary conditions
- Conductors and all other materials create specific boundary conditions
- Computational tools, when set up correctly, do an excellent job at solving this type of problem

The Math That Drives Us

Maxwell's Equations

Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}$$

Maxwell's Equations

Integral form

$$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$$

$$\oint \vec{E} \cdot d\vec{l} = \boxed{-\int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{a}}$$

$$\oint \vec{B} \cdot d\vec{a} = 0$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \boxed{\mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}}$$

Special Cases

- Maxwell’s Equations are generic formulations for electromagnetic models
- Formulations can be implemented for specific cases that can be solved far more easily
- Specific cases come with pre-existing conditions

Special Cases

- Antennas
- Shielding
- Close in coupling

The Tools Used for EMC Design

In this section, the means of solving the above physics problems will be covered; that is, computational techniques, analytic techniques and more. Here, the importance of what is *not* known will also be discussed.

Computational Tools

- Volume based techniques
  - Time domain code such as FDTD
  - Frequency domain code such as FEM
- Surface based techniques
  - Best known: Numerical Electromagnetics Code (NEC)
- Hybrid techniques
  - Use layered models solved with the same or different techniques

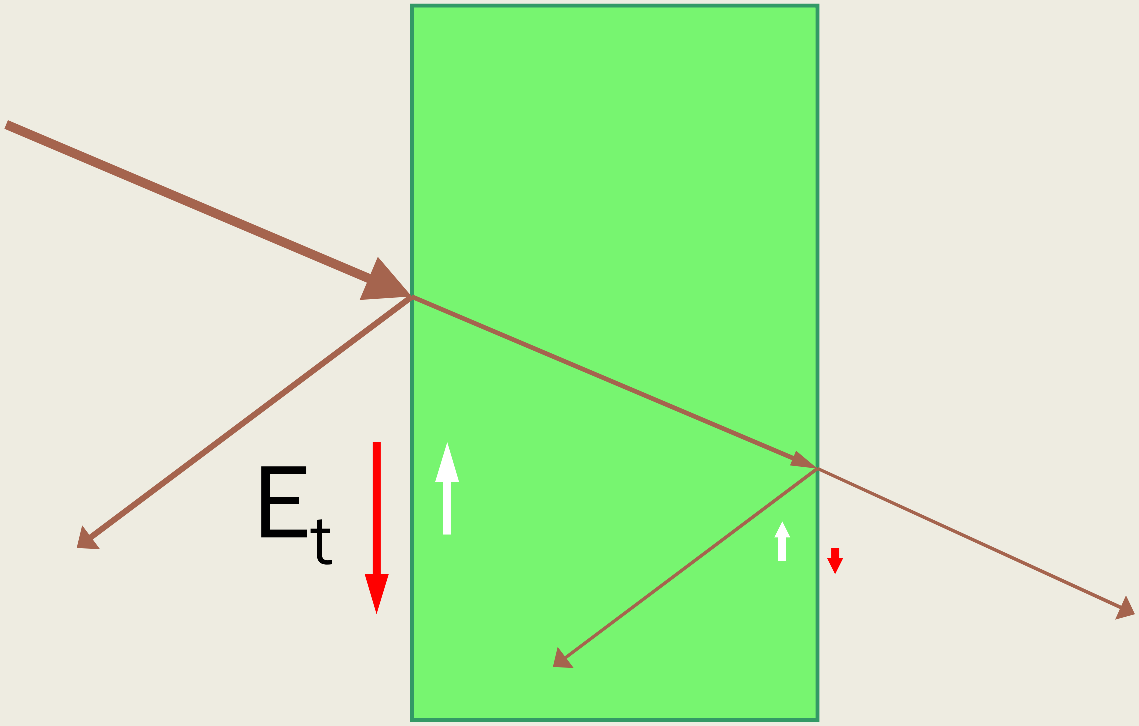
Analytic Tools

- Shielding effectiveness
- Basic antenna equations
- Simplified coupling equations

Shielding

- The Physics of Shielding
  - Skin depth
  - Reflection loss
  - Absorption loss
- Shield Imperfections
  - Apertures and seams
- Shielding Design & Evaluation
  - Shielding Effectiveness
  - Transfer Impedance

Shielding Behavior



Predicting Shield Attenuation: Material Shielding

- SE = Reflection + Absorption
- $SE = 20 * \log_{10}(Z_w / 4 * Z_s) + 8.7\ (t/\delta)$ dB

where: Z_w = wave impedance
Z_s = shield impedance
t = shield thickness
δ = skin depth

Full Shielding Effectiveness Equations

$SE = 20 * \log_{10}(\lambda/2w)$	size of aperture
$-10 \log_{10}(N)$	number
$+ k*(t/w)$	thickness

where: k = 27.3 or 32

Shielding Calculations

- Shielding effectiveness is specific to plane wave sources, remote measurements, and a single aperture
- These equations have been extended to include:
  - Multiple apertures
  - Source location
  - Shield thickness

Shielding Calculations - Limitations

- Shielding effectiveness calculations are our best tool for *easily estimating* shield behavior, but they have their limitations
- The effects of source distribution, surface details, and extraneous conductors cannot be included
- In general, levels of shielding are under predicted

Antenna Equations

- Small loops – PCB trace
- Monopole effects – vertical daughter card
- Slots – in an infinite surface
- Antennas are usually designed in free space
- Are assumed to be ‘good’ antennas
- Need to look for violations of the assumptions

Rules of Thumb

- Some are shoot from the hip ideas
- Some are based on previous experience
- Some are based on very specific cases
- Are any valid for your design?

Capacitor placement, trace separation from board edge, “grounding” points, terminations – all are prior lore.

If the Tool is Perfect – Still Beware

- Even if a tool does exactly what is wanted, there may still be some surprises for the user
- These can often be easily addressed but only if the user is aware

What Don’t You Know?

- Does the tool have pre-existing conditions?
  - ‘smart’ accelerators
  - Inherent assumptions
- About the actual design challenge
  - Geometry details
  - Tolerances
  - Contact pressure and area at bond points

Perfect Sources of “Error”

- Grid alignment
- Pure polarization
- Perfect symmetry
- Ideal source impedance
- Non-invasive observation points

Perfect Grid Alignment

- Snap-to-grid provides elements that are perfectly parallel or orthogonal
- The result of this is the creation of structures with much higher Q values than expected

Pure Polarization

- EMC sources seldom have perfectly plane-polarized characteristics
- Even a small cross-polarized component may be significant if it couples more effectively than the dominant polarization

Model Symmetry

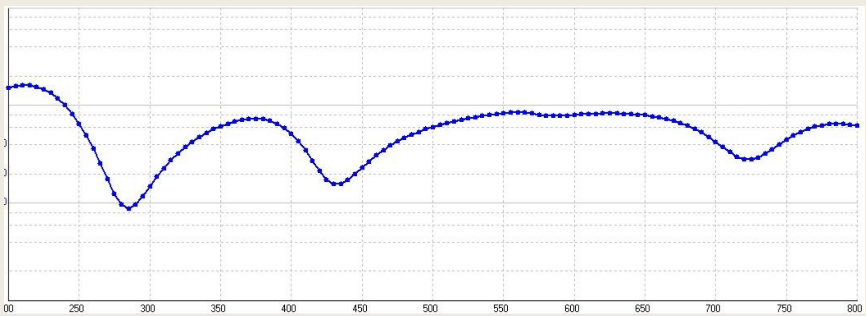
- It is natural to create symmetrical models, but in doing so, not all modes can be excited
- In reality, it is very difficult to build a perfectly symmetrical geometry without great care
  - Draw angle in plastic
  - Bowing in sheet metal
- Example of hemispheric chamber

Source Impedance Effects

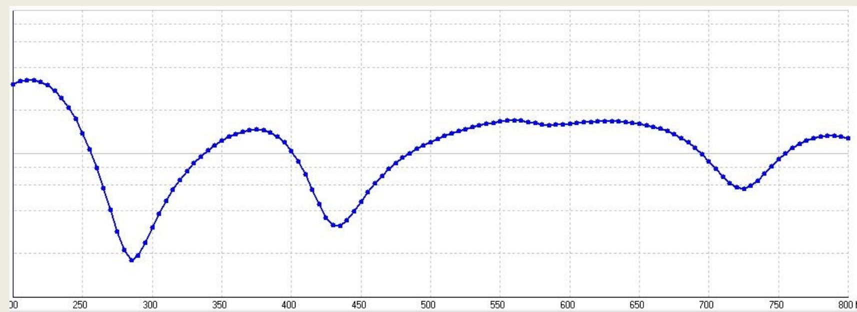
- A perfect voltage source has zero source impedance
- A perfect current source has infinite source impedance
- Naturally these do not give the same results!
- Real sources have a finite source impedance that must be included in the model

Source Impedance Effects

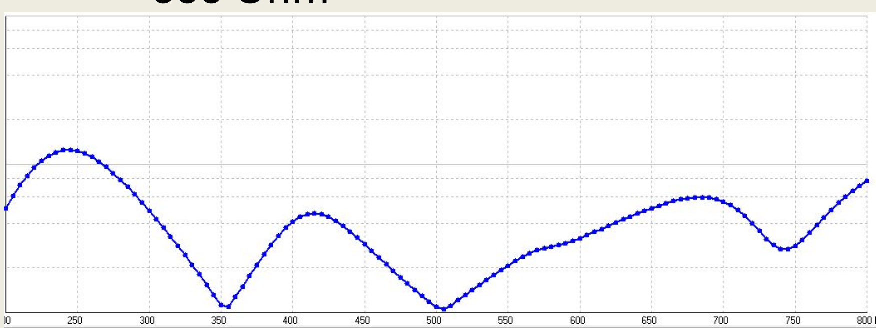
0.1 Ohm



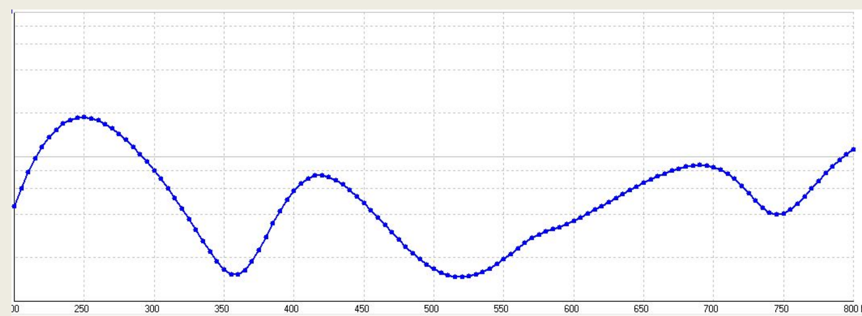
50 Ohm



600 Ohm



10 k Ohm



Design Verification and Validation

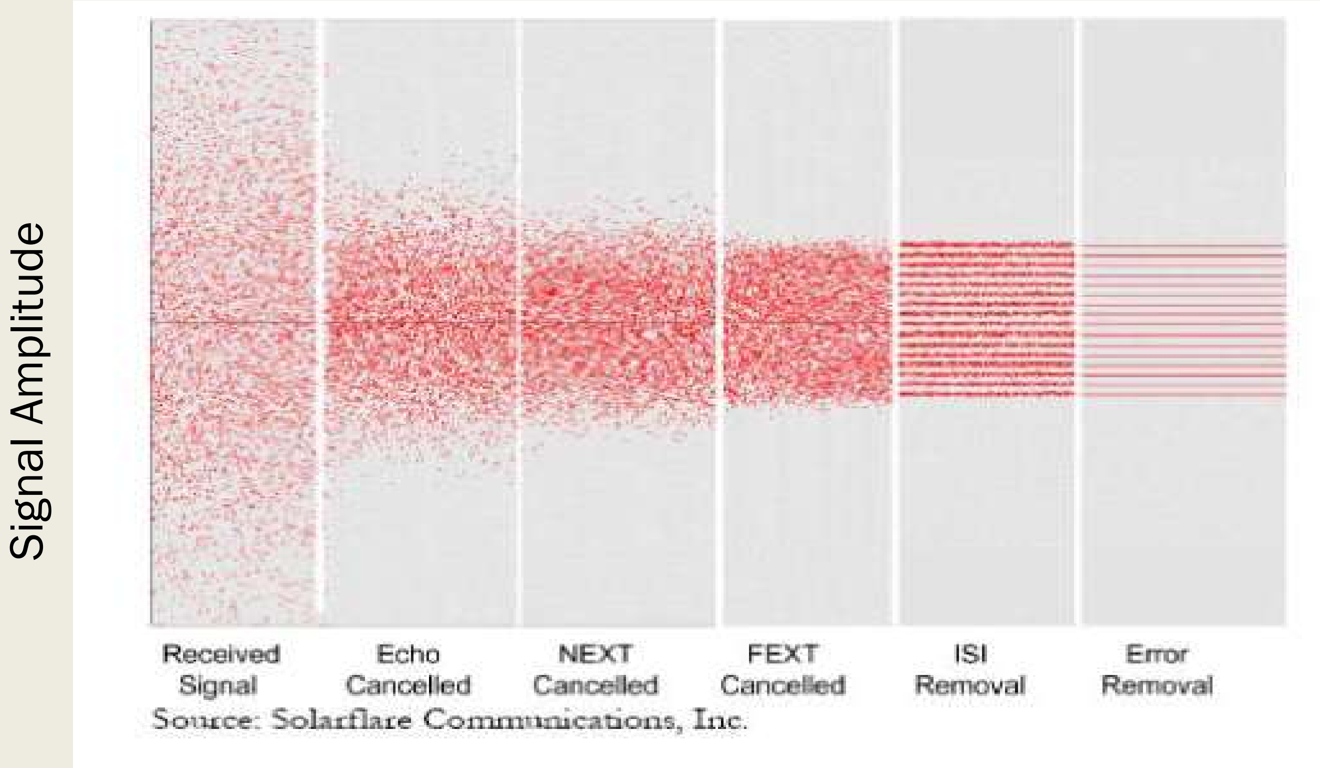
Validation of a design can include various measurements and the use of alternate design tools to confirm the design expectations.

All of this finally comes together at the qualification stage, but before this, the EMC design engineer should know what risks exist and have backup plans in place.

Know What is Correct!

- While often more of an SI consideration, firmware, software, and intelligent links change the game
- Signals can be modified to avoid emission peaks – dynamically changing the coding
- It all helps but we need to understand it

Signaling is Clean – Ethernet Example



Validation Techniques

- IEEE Standard 1597.2 details a number of ways in which computational models may be validated
- Similar techniques can be used to validate design work

Problem Found Albeit Too Late

- Problem was traced using a combination of new FDTD models and measurements
- Reason was a weaker cross-polarized component of the source which passed though without attenuation
- Lesson learned: never totally disregard your experience!

Three Levels of Validation

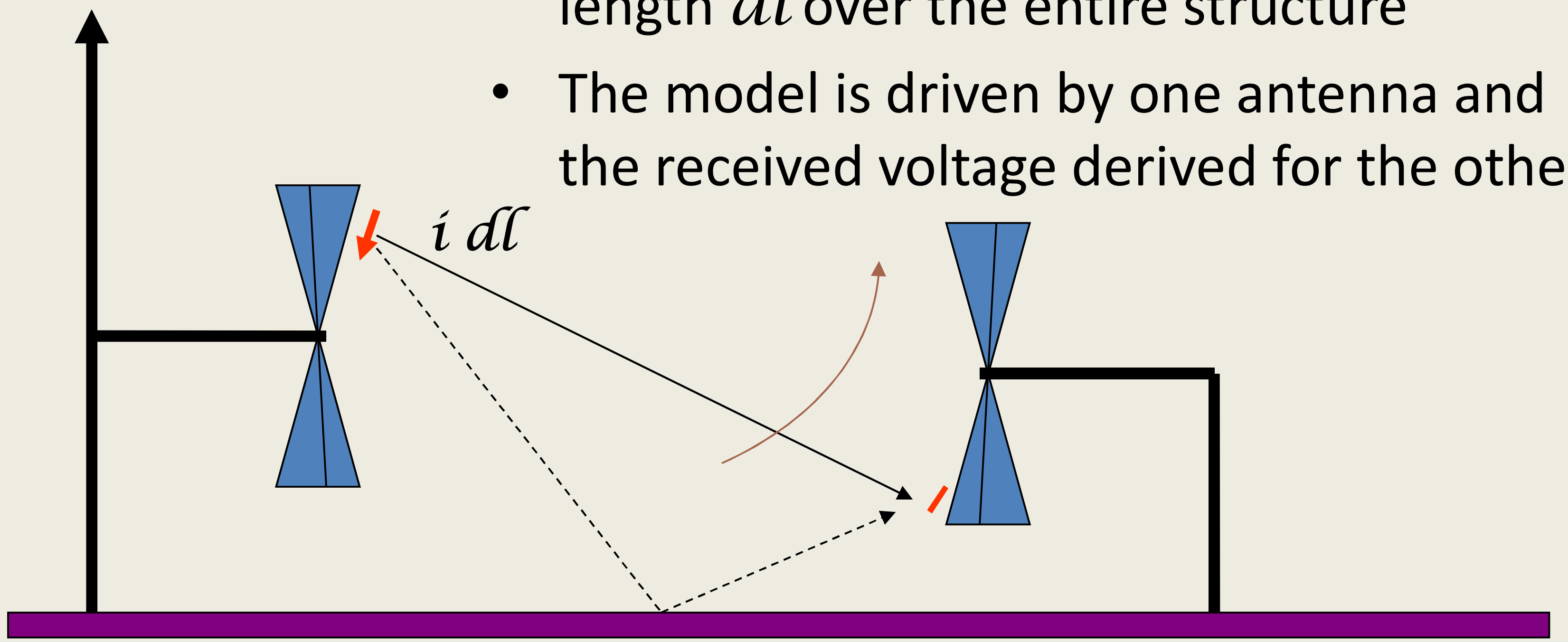
- Technique Validation
  - Is it appropriate for the problem at hand?
- Software Code Validation
  - Is it being used correctly?
- Specific Model Validation
  - Is the solution correct?

Measurements and Modeling

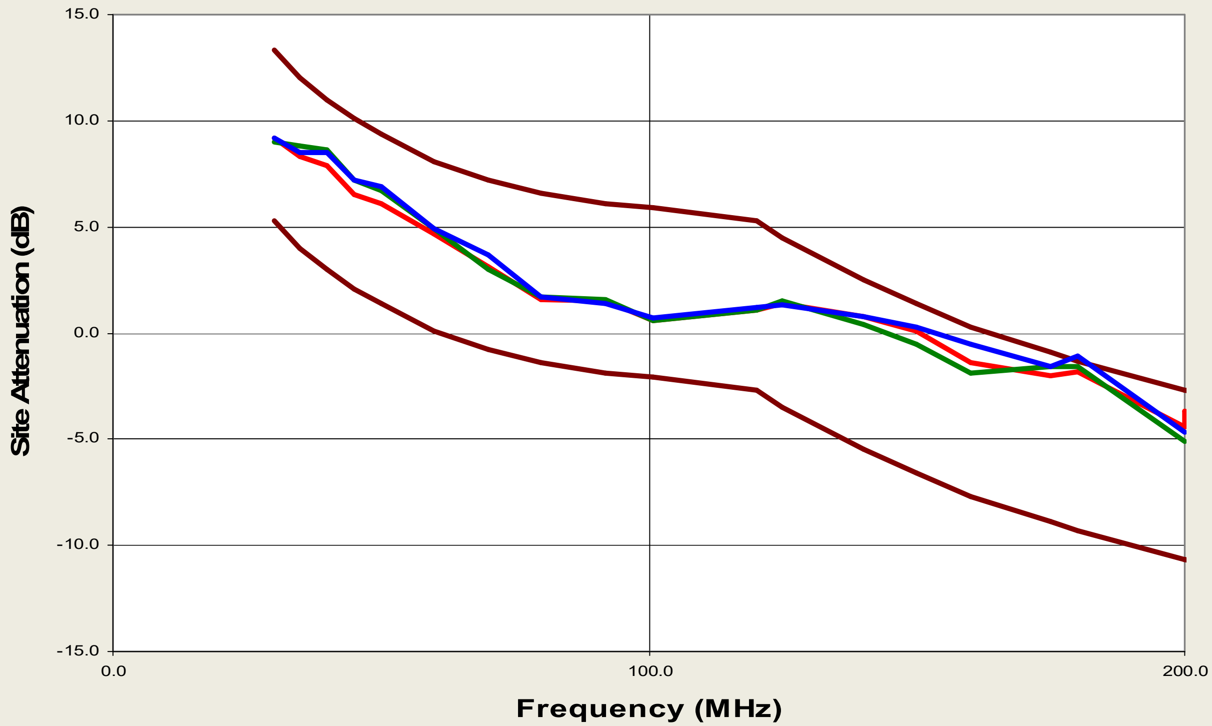
- While often seen as different things, they need to be combined in many cases
- Normalized site attenuation
- Making intermediate measurements
  - Current on a cable
  - Other bench top measurements

Computational Model

- Current i is determined on each small length dl over the entire structure
- The model is driven by one antenna and the received voltage derived for the other



3m OATS Uncorrected NSA



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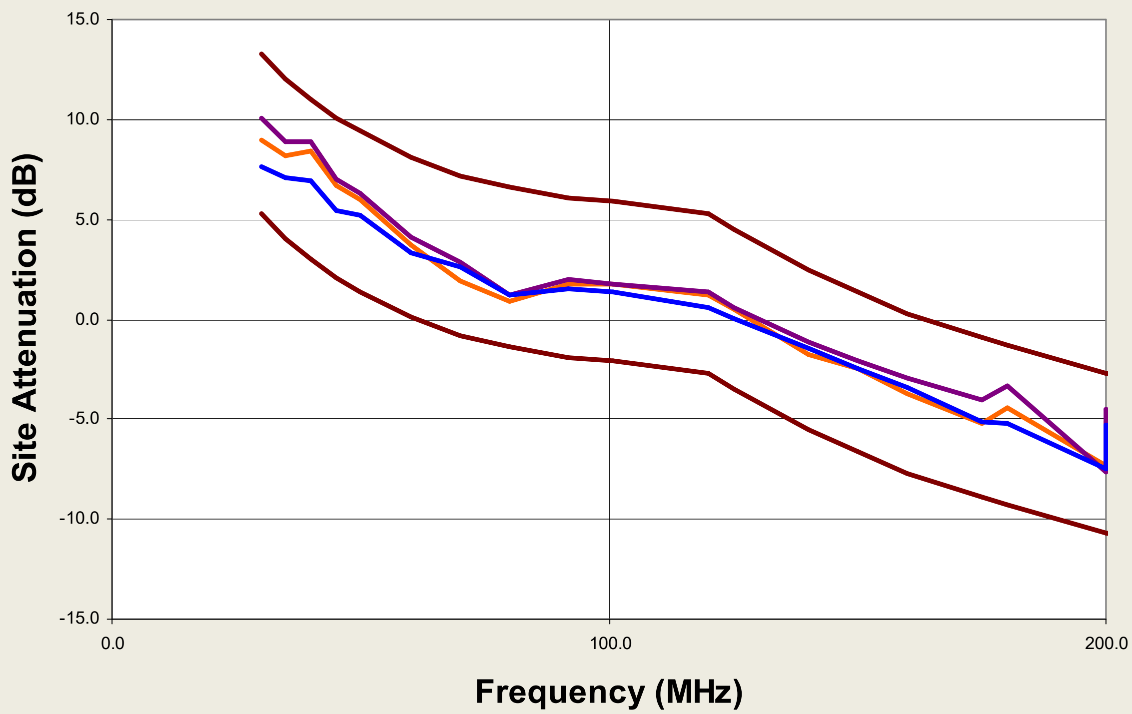


Model Validation

- Excellent agreement between the MoM simulation of NSA and measured results
- Does this validate the computer model or the test site?
  - NEC is a well proven tool used by an expert with back up data from a number of test sites
  - The test site is very close to ideal
  - *Which is more accurate?*

Example of Design Verification

- The design of an EMI shield was based upon a specific geometry and an assumed source polarization
- FDTD was used to create the final geometry
- Prototype measurements were made to validate the design and they looked good
- Real product failed EMI testing

Alternate Measurements

- Usual assumption when starting is that simulations should be used to predict emissions
- It is often better to look for some measure that is more consistent
  - Cable currents
  - Gap 'voltages'

Alternate Measurements

- Pre- FCC and CISPR, one accepted and possibly superior means of evaluating EMI risk was to make current clamp measurements on all interface cables below 300 MHz, and radiated measures above 300 MHz
- What can we learn or use?

Current Clamp Measurements

- Less variation in measured data with placement
- Easier to simulate in a computer model
- Simple bench top measurement, faster and easy
- Additional step of current on a ‘good’ antenna to predict emissions is not too complex

Voltage / E-Field Measurements

- Voltage across the seam of a large vent hole provides an indication of EMI risk
- Voltage across a connector interface (chassis to cable shield) provides the source for an appropriate antenna model

Animations for Validation

- First simulation is for a source radiating through a series of apertures
- Apertures in an infinite sheet
- Second shows the effects of having a floating wire near the outside of the apertures
  - Shows the tightly coupled behavior
  - Importance of all physical features

EMC Design Plan?

- Can you write a plan that justifies what you did and why you did it?
- Test plans are very often a requirement
- Can you defend your design with equal rigor?

SUMMARY

- EMC design is not black magic, but it can seem close
- Focus on what is known and what is not known to bound the problem and help create a design plan
- Use the appropriate tool for the job but know the capabilities and limitations
- Balance computational results with good engineering sense and experience
- Validate when confidence is not high
- Verification of the complete design comes late in the project; verify pieces as available using whatever measurement options are suitable if available

System ESD Design Considerations and a Means of Evaluation

Overview

- This part of the presentation will discuss work done to address ESD failures on high data rate interfaces
- Traditional ESD testing is not possible when the full system cannot be used; so an alternate method was sought
- Details of the selected test methodology are provided, as are the goals for that testing

What are High Data Rates Today?

- This is a continuously moving target!
- 25 Gb/s x 10 lanes in single connected cable
  - 25 GHz bandwidth
  - Spread spectrum clocking
- 224 Gb/s per pair backplane connector
  - 56 GHz bandwidth
  - PAM 4 encoded

Interesting Metrics

- Connector can be characterized by how many bits there are from end to end
  - These are electrically very large: 15 λ
- Clock cycle of 16 psec means that 10 to 20 transitions can occur during the rising edge of an ESD pulse
  - ESD is a "low frequency" effect

Typical Small Router

Multiple high data rate ports, well shielded

Many more low speed ports, unshielded

Link Background

- These are sophisticated links, and signal integrity does not mean getting a pulse from A to B without distortion
- In many signal paths, it is actually not possible to look at a signal line and know if the waveform is good

What are these Links

- Smart links provide for a number of corrections and signal conditioning
  - Near end cross talk
  - Far end cross talk
  - Inter-symbol interference
  - Error correction
  - Frequency dependent loss
  - Minimize power use
  - Emissions reduction
  - Echo effects

EMI Risk Reduction

- The software encodes the signals in such a way that no one frequency dominates for very long, thus avoiding emission peaks
- Older systems would often carry a clock that would be 20 dB higher than the data, or show up in the absence of data
- Such techniques reduce the need for shielding

How These Links Work

- When first connected, the link properties are learned and the system is trained to use the cable
- Known data patterns are sent along each of the lanes (e.g. 10 lane system)
- Cross talk and all other non ideal behavior is determined
- This information is used to generate the correction algorithms

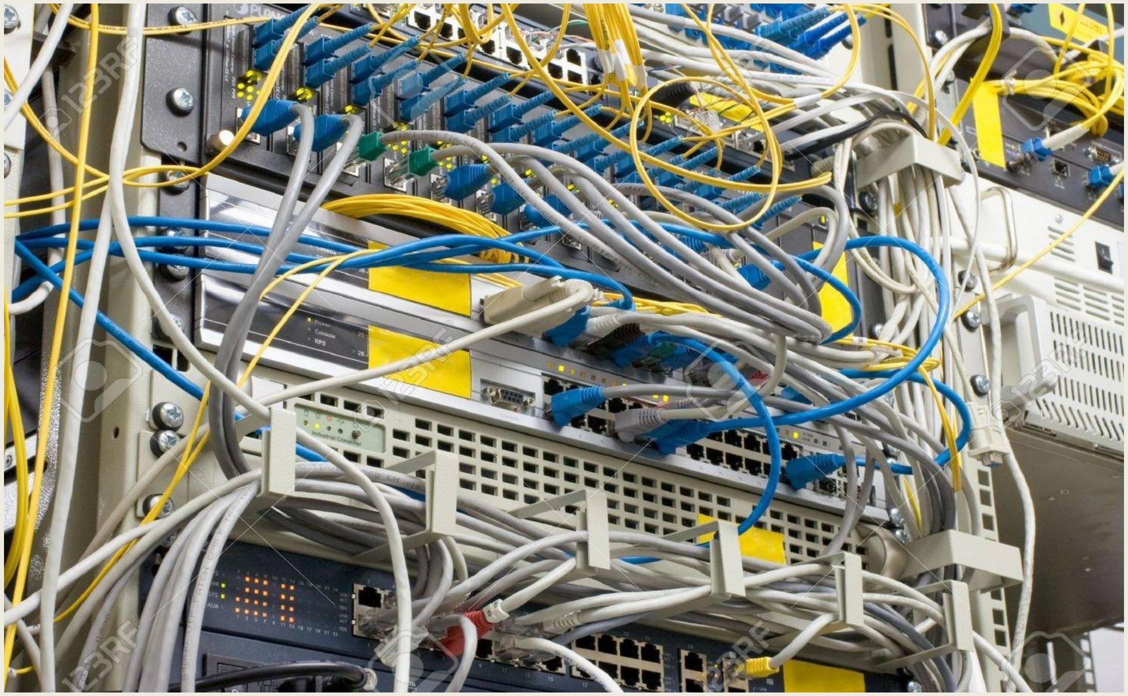
Is the Link Robust to ESD Events?

- Signal levels will be sensitive to 10’s mV
- Excessive errors will cause the link to fail over to a slower connection rate or to re-train
- Given the data rate, an ESD event takes a long time and can easily cause soft failures
- What does ESD protection look like?

Software and Firmware Factors

- How the system responds to an upset is determined not by a hard failure but by how the various algorithms react to the errors
- Must use realistic system code
  - Not one that detects all errors !
  - Not one that ignores all errors (EMI test)

Standard Cable Installation ☺



Interconnect Nightmares

- Some data centers have cables with no jackets
- Some data centers use no EMI shields
- ESD protection is therefore often compromised
- Why is this done? To make cables more flexible and smaller in the ‘protected’ environment of the data center

ESD Testing 101

- Apply the gun to the outside of a well shielded system and see what happens
- If there is an issue, what is really coupling into the system?

Upsetting Waveform

- Shielding causes a high pass filter effect
- Secondary breakdown can cause lower amplitude but much shorter pulses
- ESD induced EM bandwidth can exceed that of the initially applied pulse
  - Including longer duration effects from ringing

Should We Define a New Source?

- Simple answer is no
- The actual properties of the ESD upset current (frequency content, radiated fields and current distribution) is fully defined by the structure and contact point
- The sources in use do sufficiently represent the external stimulus

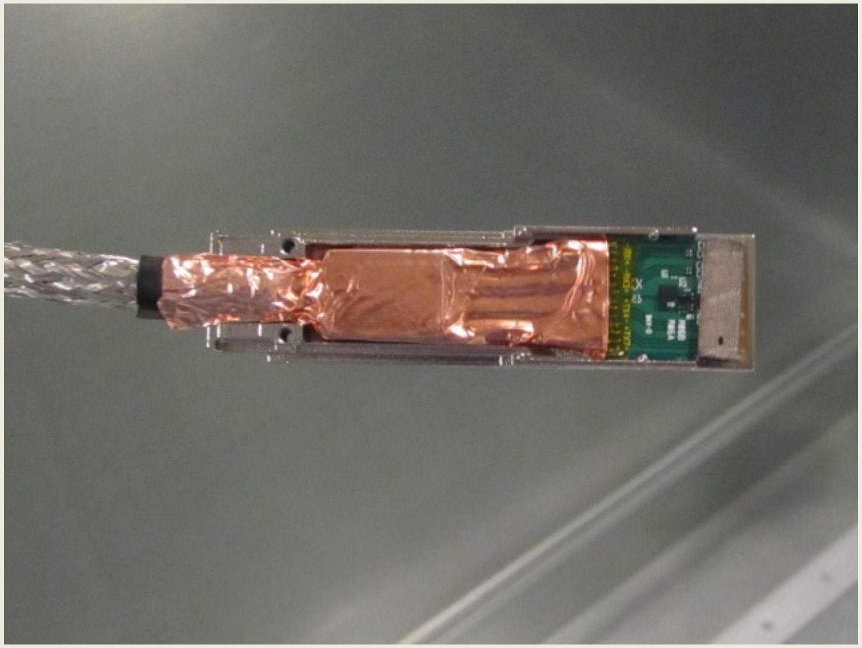
So How Do We Test?

- A lot of painful discussions and experiments lead to one, fortunately simple, approach
- It was found that a higher sensitivity to ESD correlated to the low frequency EMI shielding of the cable interfaces
- The focus of all this work was to improve the confidence of ESD behavior for these interfaces

Nature of EMI Shielding

- Low frequency (500 MHz to 2 GHz): the shielding performance is often limited by the contact resistance
- High frequency (10 GHz to 40 GHz): the shielding performance is limited by gaps

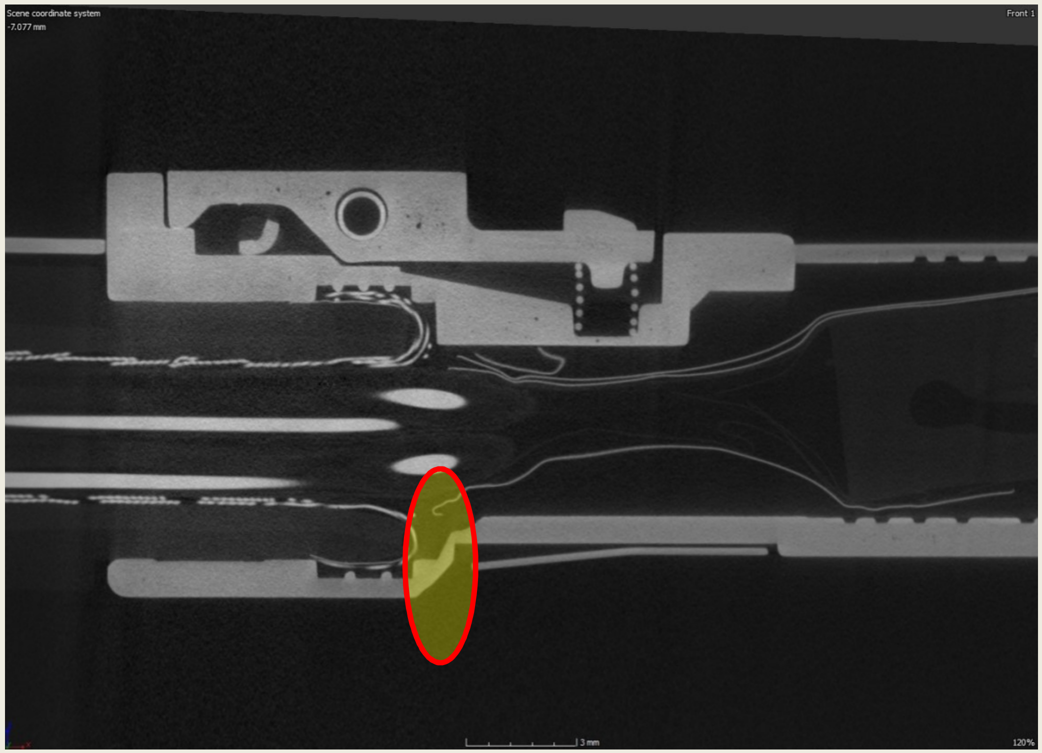
High Data Rate Connector Detail



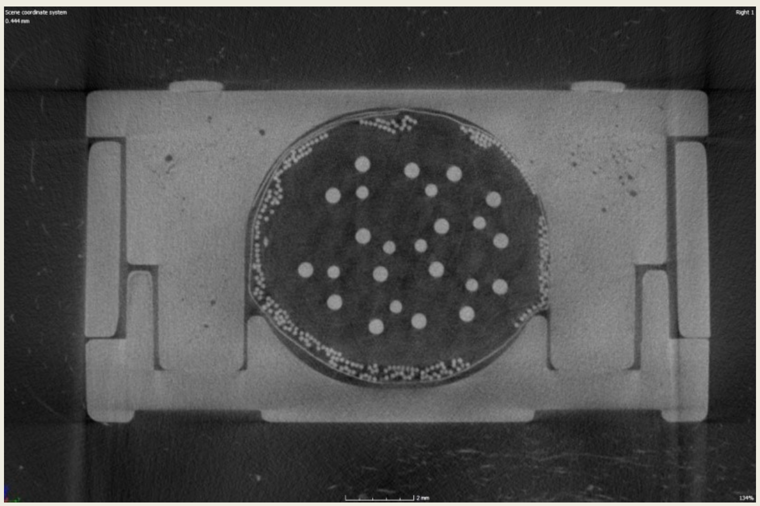
Shield current path must be well planned to avoid ESD from infiltrating the cavity and coupling onto the data lines.

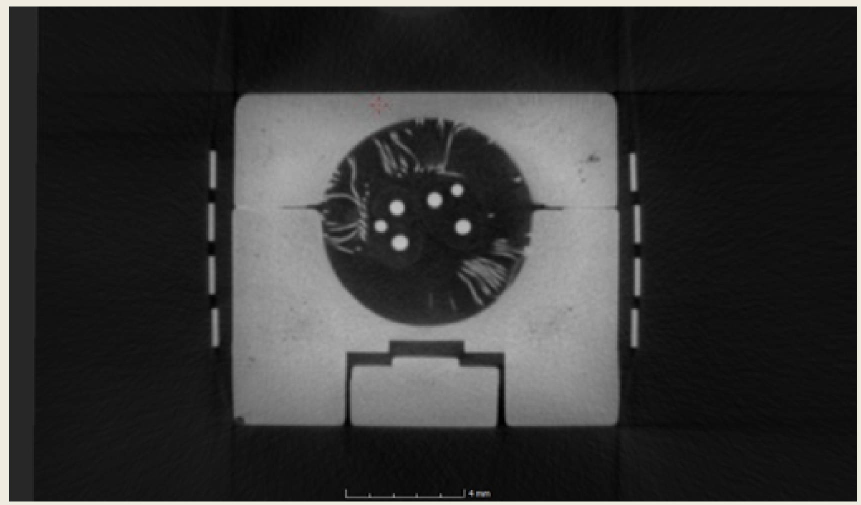
Avoid U turns!!

Braid Continuity

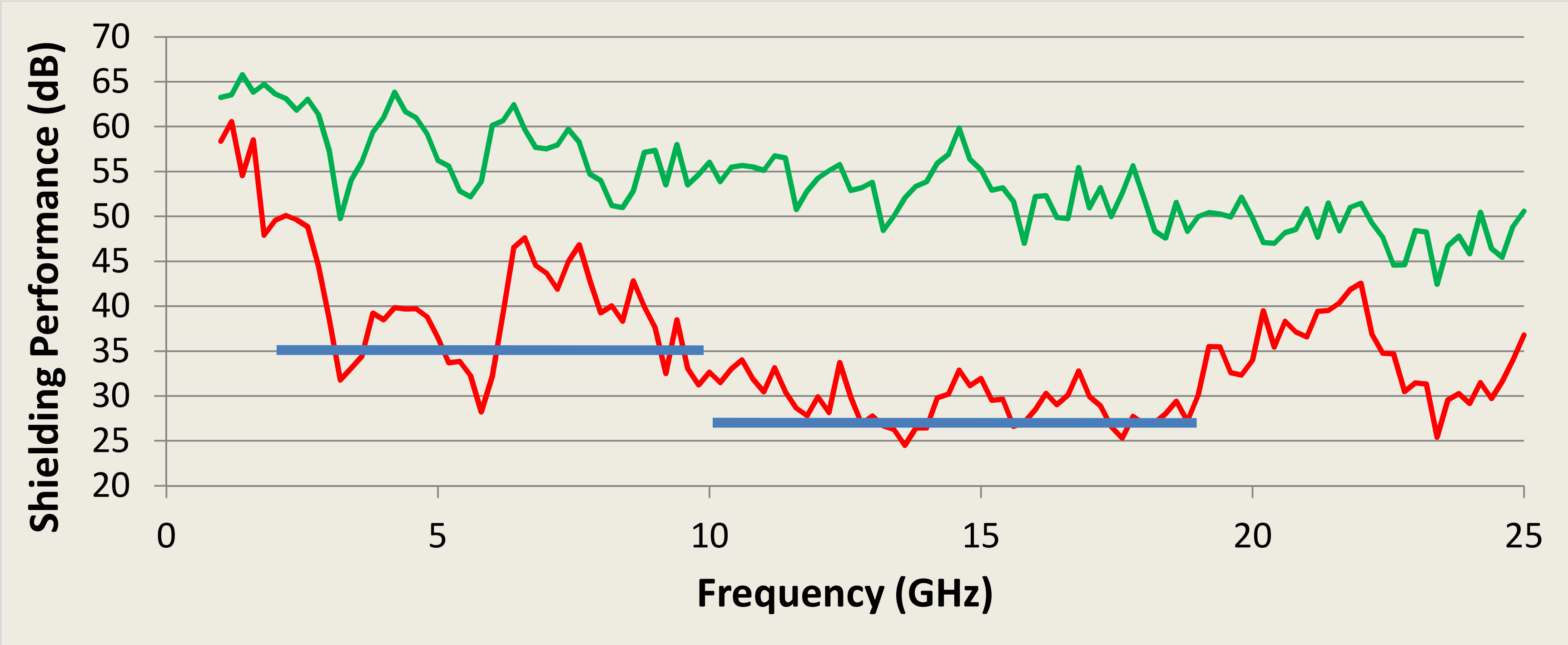


Good and Not So Good

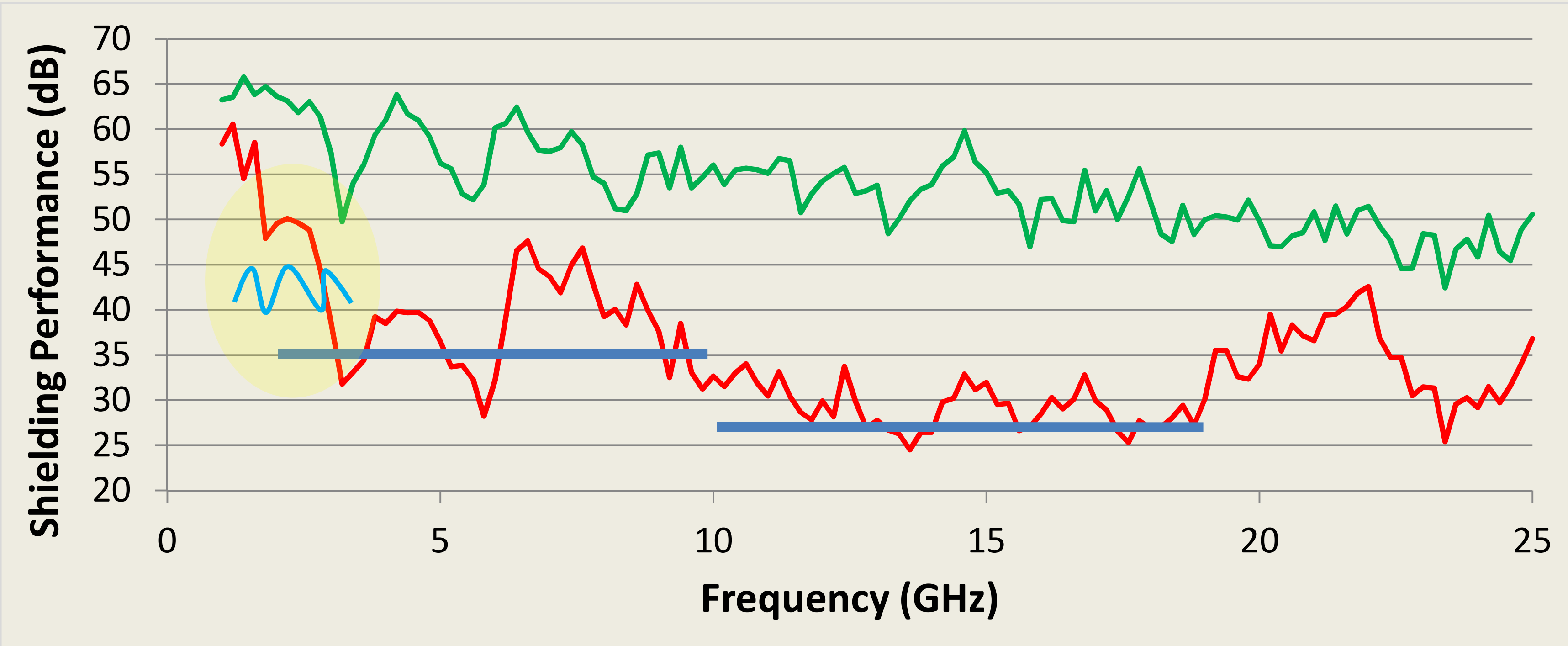




Example 1: 10 Gb/s Cables



Bad ESD Performance



Failure Indicator

- The shielding of both original cables worked for EMI and ESD testing
- The area that indicated ESD risk is the 1 to 3 GHz region
- As 35 dB performance is needed at 10 GHz, 1 GHz should be 20 dB better, but *<u>not</u>* always

Cable Shielding Specifications

- Exclusively focused on EMI
- Adding a more severe lower frequency requirement will increase the expectation that ESD requirements will also be fully met

Findings

- "Poor" low frequency performance can allow significant current to pass into the system
- In many cases, low frequency performance is expected to be very much higher than needed due to the focus on the high frequency needs
- Even the worst examples were marginal, and not failing 100% of the time

System Design BUT…

- No Systems are available in most cases
- Component level testing must be used
  - Cable assembly
  - Interface connector mounting
- System software sensitivities are not known

From the Interface Perspective

- We need a bullet proof approach
- Systems, software and data integrity all vary
- We can set a minimum shielding level and work towards meeting that goal

Test Possibilities

Since both ESD system failures from standard testing and ESD failures in the field were correlated with less than ideal shielding, we can use broadband shielding performance as a:

- first pass method of determining ESD risk
- diagnostic tool to evaluate improvements made

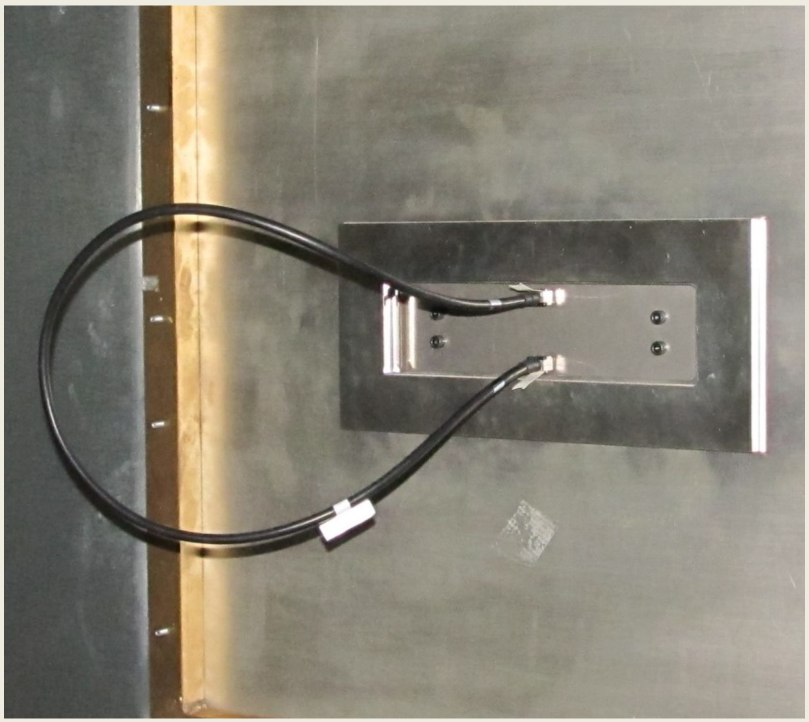
How to Measure EMI Shielding?

- Set the source (antenna) location close to the interface under test
  - Local complex coupling
- Impose a plane wave on the interface surface
  - Highly repeatable setup
- Use the reverberation technique
  - Very much a worst case measurement
  - Ensures that any weaknesses are exposed

Interface Shielding Performance

- Requirements typically range from 20 dB to 35 dB at 40 GHz
- This means that we may easily have 52 dB to 67 dB at 1 GHz if all things are equal
- However, poor bonding can degrade this

Test Cable and Interface



Chamber wall behaves as the system enclosure.

This approach permits a detailed examination of the cable and the connector interface features:

- Cable shielding
- Cable shield to connector
- Plug to socket mating
- Chassis bonding

Other Details

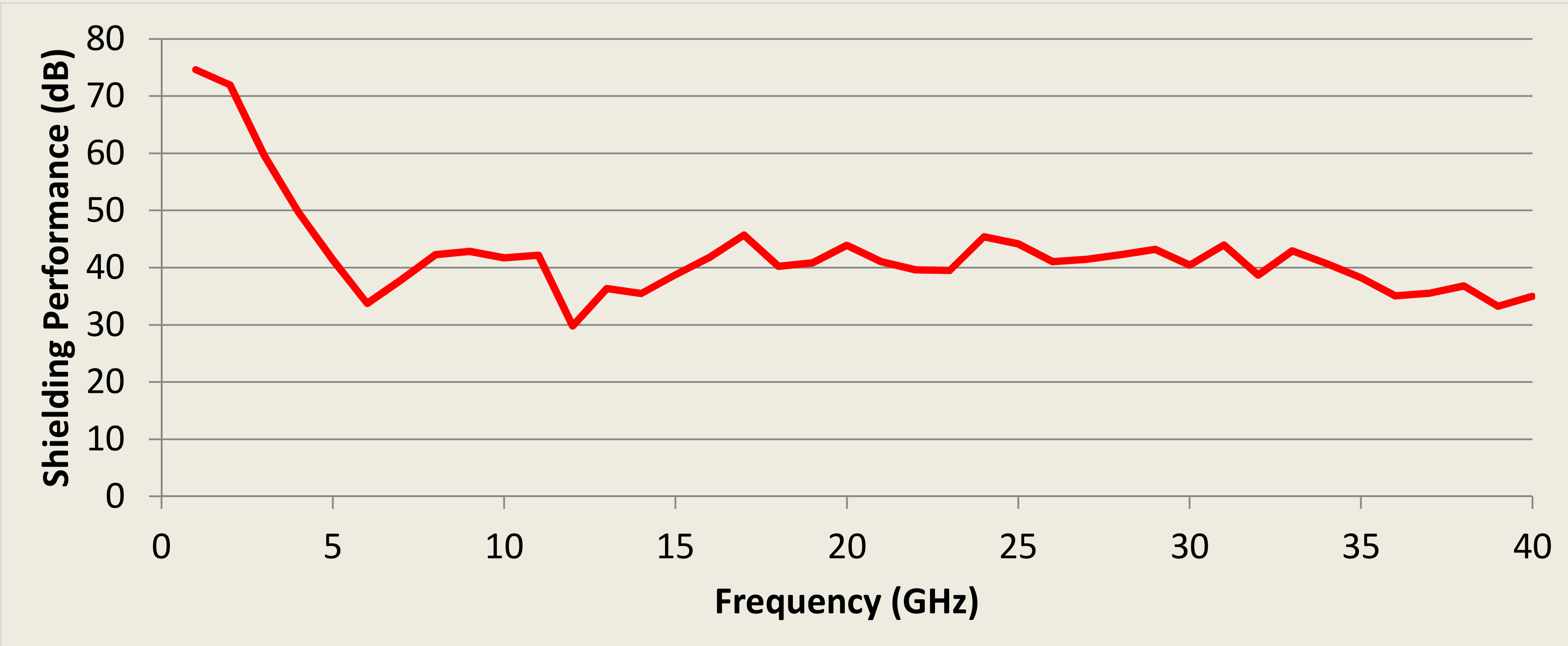
- Cable length of one wavelength at the lowest frequency is sufficient; 300 mm at 1 GHz
- Default to a 1 m cable for practical use
- Avoid inappropriate stress on the cable and the mating interface

Recommended Shielding

- For reliable EMC performance, a minimum of 45 dB shielding performance at 1 GHz is required for a fully shielded interface
- However, if only 50 dB is observed, it is likely that there is some fault with the shield as levels of 55 dB or greater should be expected
- For reliable ESD performance, 55 dB or greater is desired

Example 2: 28 Gb/s Cable

Excellent for both EMI and ESD



SUMMARY

- ESD effects are subtle and may require special software and/or firmware to properly evaluate
- For high data rate links, it is essential that cable shielding be effective from well below 1 GHz
- Severe shielding measurements are an excellent predictor of ESD risk