Wyatt Technical Services, LLC
EMC Seminars & Design

2021 MINNESOTA EMC EVENT

Introduction to EMC Basics

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Speaker

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Kenneth Wyatt was employed as a product development engineer for 10 years for various aerospace firms, working on projects ranging from DC-to-DC power converters, to RF and microwave systems for shipboard and space platforms. For over 20 years, he worked as a senior EMC engineer for Hewlett-Packard and Agilent Technologies (now Keysight Technologies) in Colorado Springs where he provided comprehensive EMC design and troubleshooting services. During that time, he managed the product compliance and environmental test lab and provided advanced EMC training and corporate leadership for EMC.

His specialty is EMI troubleshooting and pre-compliance testing and is a co-author of the popular EMC Pocket Guide and Radio Frequency Interference (RFI) Pocket Guide and in 2014 coauthored the book with Patrick André, *EMI Troubleshooting Cookbook for Product Designers*, with forward by Henry Ott. He authors The EMC Blog, hosted by EDN.com, and besides his regular consulting, served as Senior Technical Editor for Interference Technology Magazine for three years.

He may be contacted through: www.emc-seminars.com | @EMC_Guru (Twitter)

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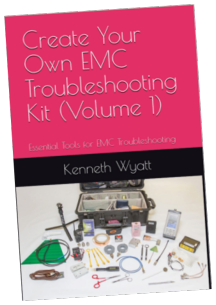

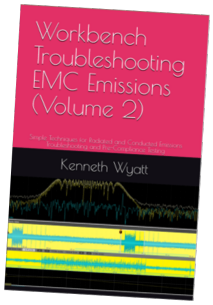

All available on Amazon

www.design-4-emc.com

Blogs → http://www.edn.com/ > Community > Blogs > "The EMC Blog"

http://www.interferencetechnology.com

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Agenda

1. Introduction to basic EMC concepts
2. Six ways to create emissions (and immunity!)
3. Designing PC boards for low EMI

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What is EMC?

Electromagnetic Compatibility:

- Electronic products do not interfere with their environments (Emissions)
- The environments do not upset the operation of electronic products (Immunity)
- The electronic product does not interfere with itself (self-interference)

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Today's EMI issues

- Radiated emissions (RE)
- Radiated immunity (RI)
- Electrostatic discharge (ESD)

- Receiver Desense in Wireless IoT

- Violation of best engineering practices for EMC
- Lower IC supply voltages: 5 > 3.3 > 1.8 > etc.
- More low cost mobile devices
- Proliferation of wireless and high power transmitters

- On-board energy sources

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Why do products radiate?

- Energy + Coupling Path + Antenna = EMI
- *Take away any of the three elements and no EMI…*
  - No energy >>> No EMI
  - No coupling path >>> No EMI
  - No antenna >>> No EMI

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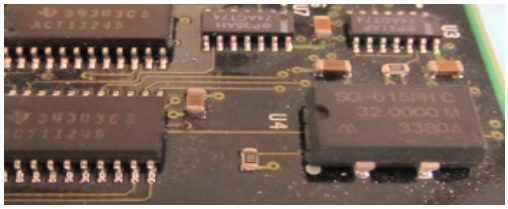
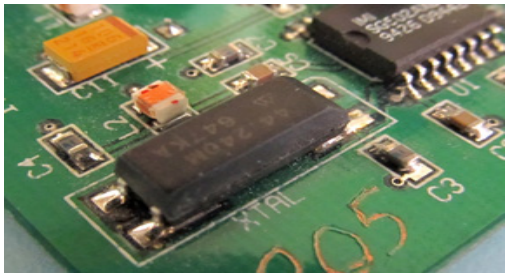
A primary source of harmonic energy



Clock Oscillators



But also,
PLL clocks, high-speed ASICs, uP or A/D, D/As, and
fast DC-DC converters, plus "Zero" address/data bus lines

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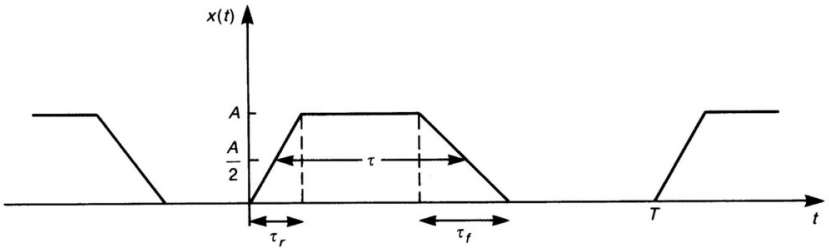
Generalized trapezoidal waveform



The key contributor to high-frequency harmonic emissions is due to the *rise/fall-times* of the waveform.

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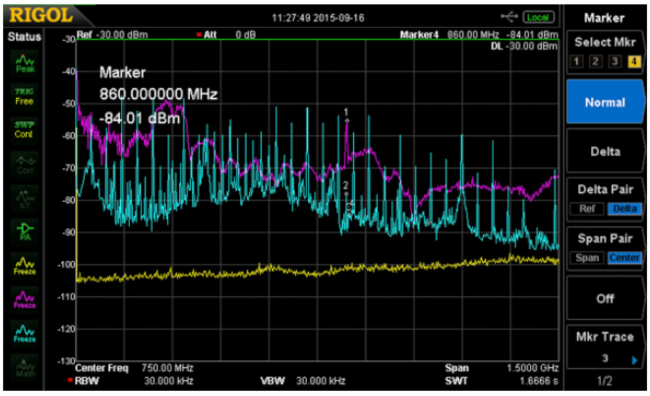
Narrow band versus broadband emissions



Broadband (DC-DC, addr/data)

Narrow band (clocks)

Ambient (yellow)

According to most commercial EMC standards, the normal resolution bandwidth (RBW) for 30 to 1000 MHz should be set to 120 kHz (100 kHz may also be used for troubleshooting purposes).

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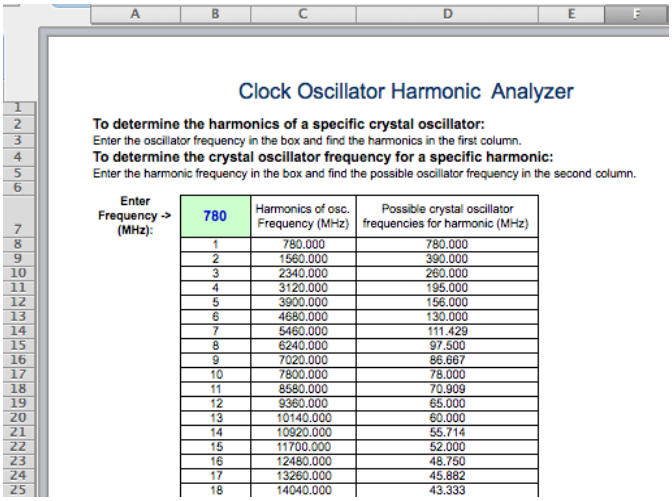
Clock harmonic analyzer



Clock Oscillator Harmonic Analyzer

To determine the harmonics of a specific crystal oscillator:
Enter the oscillator frequency in the box and find the harmonics in the first column.
To determine the crystal oscillator frequency for a specific harmonic:
Enter the harmonic frequency in the box and find the possible oscillator frequency in the second column.

Enter Frequency -> (MHz):	780	Harmonics of osc. Frequency (MHz)	Possible crystal oscillator frequencies for harmonic (MHz)
	1	780.000	780.000
	2	1560.000	390.000
	3	2340.000	260.000
	4	3120.000	195.000
	5	3900.000	156.000
	6	4680.000	130.000
	7	5460.000	111.429
	8	6240.000	97.500
	9	7020.000	86.667
	10	7800.000	78.000
	11	8580.000	70.909
	12	9360.000	65.000
	13	10140.000	60.000
	14	10920.000	55.714
	15	11700.000	52.000
	16	12480.000	48.750
	17	13260.000	45.882
	18	14040.000	43.333

Download here: http://www.emc-seminars.com/Harmonics.xls

Source: Patrick André, https://andreconsulting.com

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Video – harmonic analyzer

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And click on the “Video Demos” link.
Select “Harmonic Analyzer”

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Five ways to create emissions (and immunity!)

1. Simultaneous switching noise
2. Discontinuous return paths
3. Gaps in the return plane
4. Poor cable shield termination
5. Unbalanced geometries
   - Pigtailed cable shields
   - Unequal length differential pair traces

All the above can cause radiated emissions *and allow susceptibility from radiated sources and ESD*

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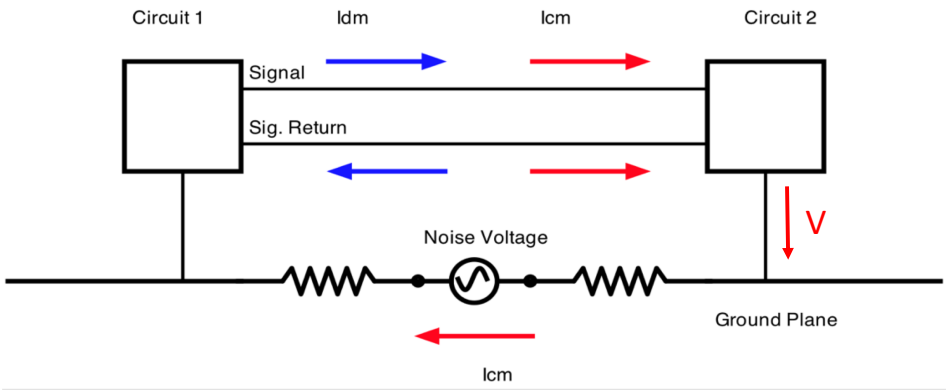
1. Simultaneous switching noise (SSN)



Differential versus common-mode currents >> SSN causes Icm

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DM emission equation (over a reflecting surface)

$$\left|E_{D,\max}\right| = 2.63\times10^{-14}\,\frac{\left|I_D\right| f^2 L s}{d}$$

High frequency currents in a LOOP

Assuming electrically short lengths, (*L< half wavelength)*.

To reduce E_D, we can:

1. Reduce the current level (also by slowing rise times)
2. Reduce the loop area

Note the relatively small factor 1x10^{-14}

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Common-mode emission equation

$$\left|E_{C,\max}\right| = 1.257\times10^{-6}\,\frac{\left|I_C\right| f L}{d}$$

High frequency currents in a WIRE or CABLE

Assuming electrically short length, *(L< half wavelength)*.

To reduce E_C, we can:

1. Reduce the current level (also by slowing rise times)
2. Reduce the line length (shorter PC traces)
3. Diverting or blocking the current

Note the relatively <u>larger</u> factor, 1x10^{-6}

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2. Discontinuous return paths

Most EMI issues are due to PC board problems and can be traced to discontinuous signal return paths. This is becoming more of an issue with increasing clock frequencies used today.

- Ideally, the signal travels out a trace and returns immediately under that trace (ideally, using a solid signal return plane)
- All too often, the return path is broken by a discontinuity, such as a gap or slot in the ground return plane or power plane
- PDNs are transmission lines and must not have gaps
- The signal trace passes through a via and changes reference planes (this is typically a second-order effect)
- Add extra vias or stitching capacitors for return currents when switching reference planes

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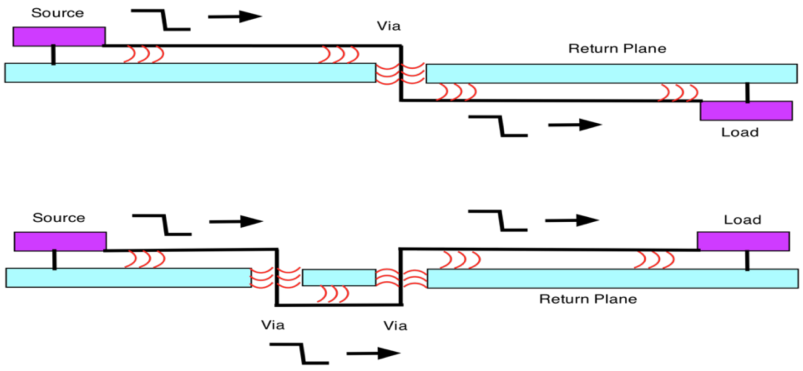
Trace passing through plane with via



Wave propagates through the dielectric material (not shown for clarity).

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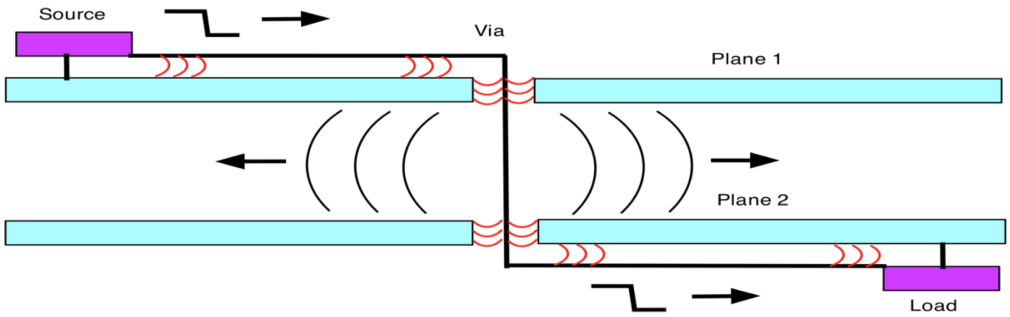
Trace passing through two planes with via



Scenario: signal traces referenced to different planes.

Differential-mode to common-mode conversion contaminates the planes with CM currents!

Wave propagates through the dielectric material (not shown for clarity).

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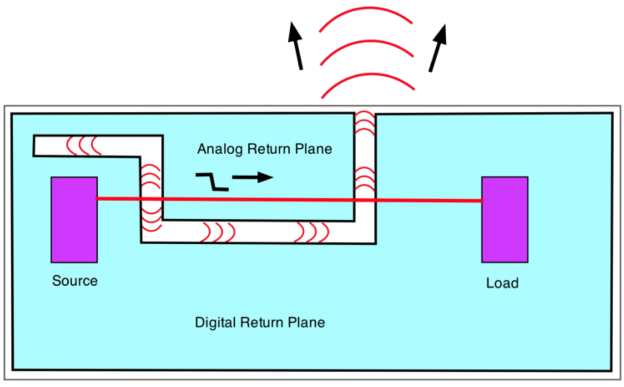
Discontinuous return paths (examples)



Routing a trace over an unrelated (eg. analog) plane can cause noise coupling to other circuitry. Traces should never cross analog planes.

Crossing gaps with high speed digital signals causes “mode conversion” and creates CM currents and corresponding PC board emissions.

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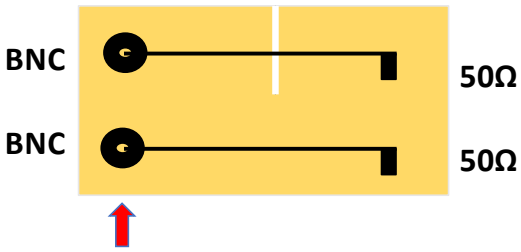
3. Gaps in the return plane (Demo)

High-frequency traces crossing gaps in the return plane can lead to:

- An increase in radiated emissions
- An increase in radiated susceptibility
- An increase in ESD susceptibility

We'll use a loop probe to measure & compare the signal level along a transmission line with- and without a slot cut in the signal return plane.



Simulation of a high speed digital signal by injecting 3V, 2ns, pulses into either the gapped or un-gapped trace. The gap is 5 cm long.

Idea courtesy, Doug Smith, http://www.emcesd.com

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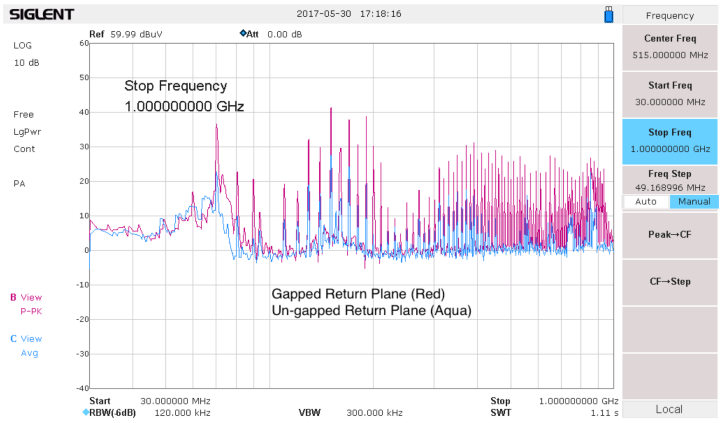
Difference between gapped and un-gapped



Violet = Gapped

Aqua = Un-gapped

The resulting common mode currents on an attached wire as measured with a current probe. The difference is 10 to 15 dB higher for the gapped trace.

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Video - gap in return plane

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http://www.emc-seminars.com
And click on the “Video Demos” link.
Select “Gap in Return Plane”

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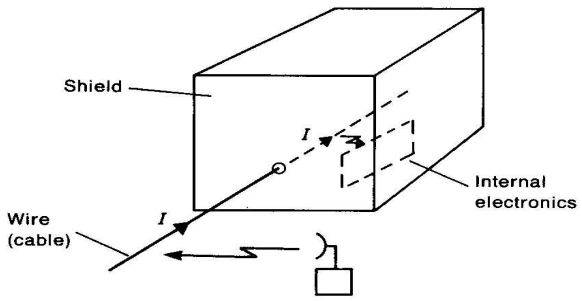
Never penetrate a shield with a wire or cable



Penetrating a shield with a wire defeats the shield!
Noise currents on the inside will couple to the wire and travel outside the shield, causing radiated emissions.
Transmitters on the outside may interfere with circuits.

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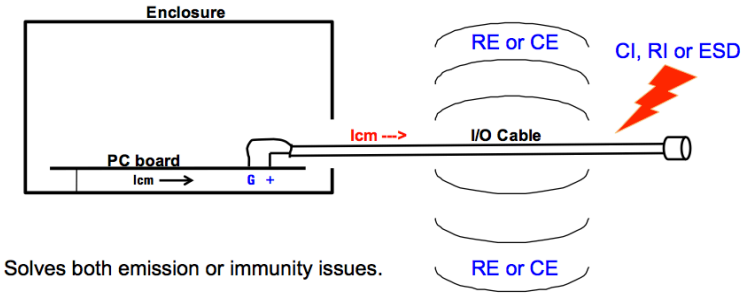
4. Poor cable shield bonding – typical attachment



- Divert the current back to the shielded enclosure
  - Proper termination of the cable shield back to the enclosure is the key
- Block the current with a high-impedance ferrite choke

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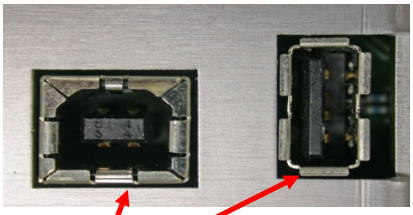
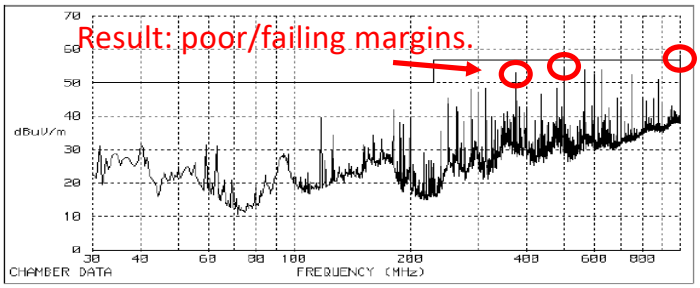
Importance of I/O connector bonds



Note a lack of good connection between chassis enclosure and connector ground shell.



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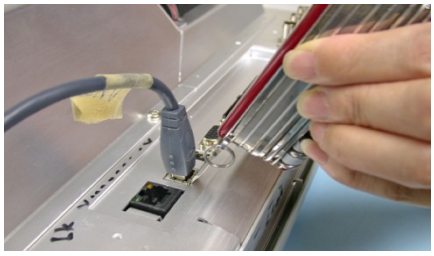
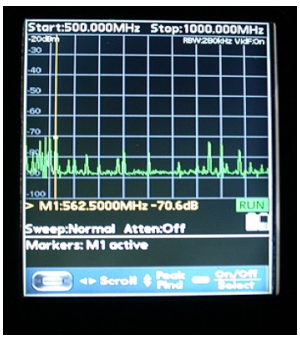
Result after simple connection to chassis



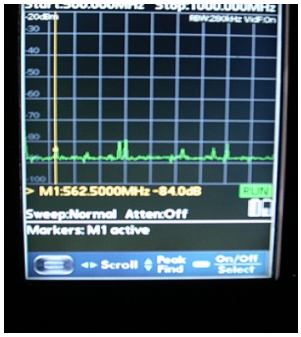
Test setup:

Current probe on USB cable. Connection between connector ground shell and chassis enclosure made with screwdriver blade.

Looking from 500 to 1000 MHz



Before



After

Some harmonics dropped by 10-15 dB!

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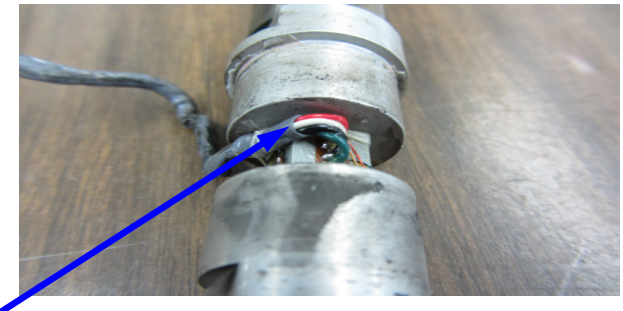
Poor cable shield bonding to enclosure



Poor cable shield bonding – cable shield disconnected.

Good cable shield bonding – cable shield connected to chassis.

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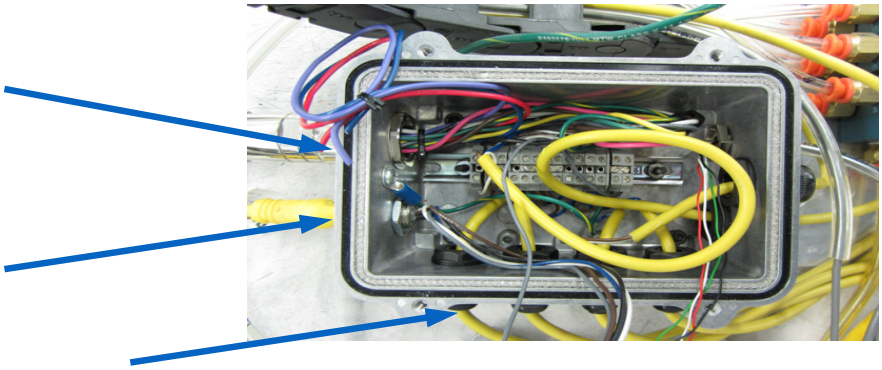
Poor cable shield bonding to enclosure



Poor cable shield bonding – cable penetrating through metal enclosure.

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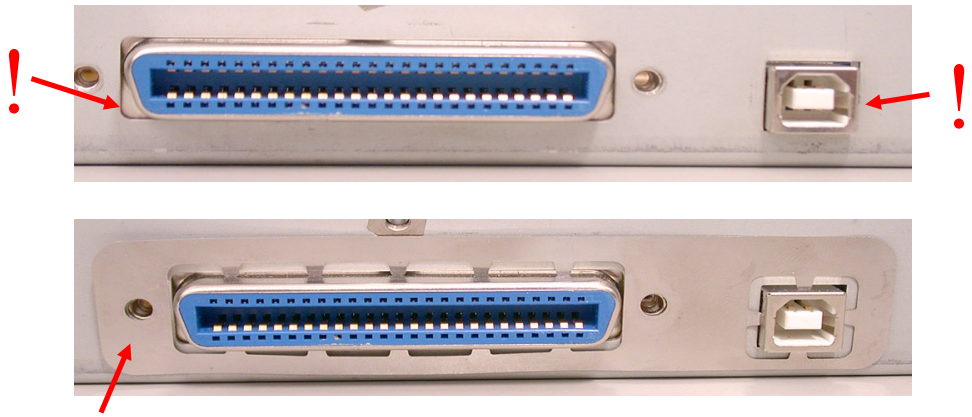
Penetration of I/O connectors through shield



Shim with contact fingers added to block gaps.

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Gasketed connectors

I/O connectors with integral gaskets. *Courtesy, Regal Electronics.*

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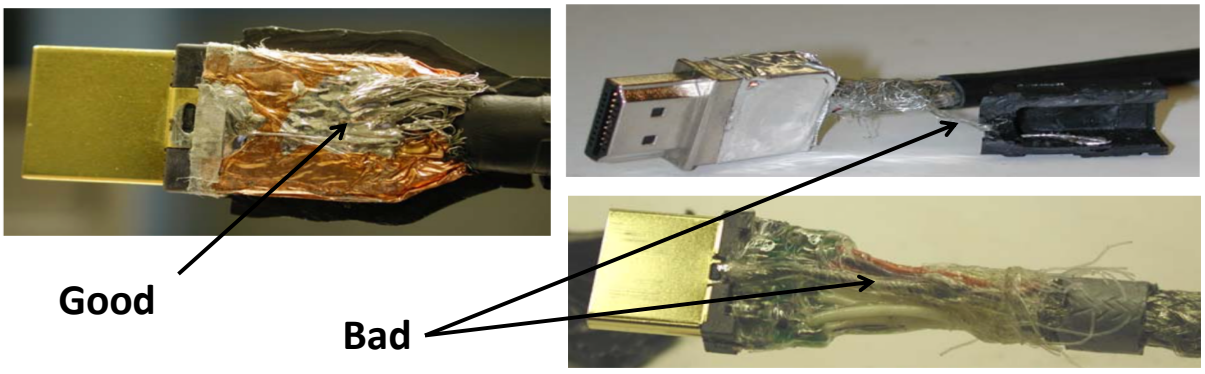
5. Pigtailed cable shield connection



The HDMI working group failed to specify an EMI-appropriate shield to connector bonding method within the standard. As a result, commercial HDMI cables have varying EMI performance because of pigtail shield bonds to the connector. Resolved in latest edition?

Source: Bergey & Altland, EMI Shielding of Cable Assemblies, DesignCon 2008 http://www.magazines007.com/pdf/DC08_Dana_Bergey.pdf

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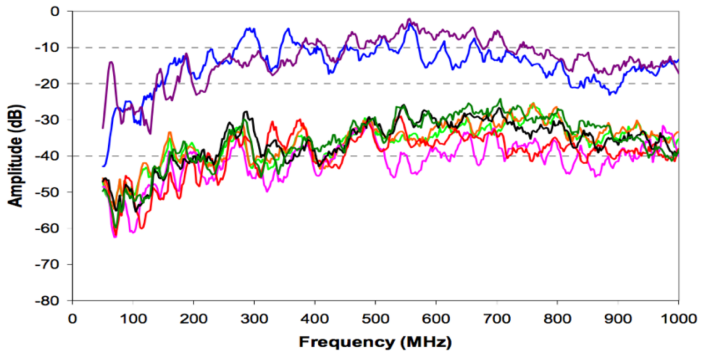
Measurements from six HDMI cables



Radiated emission plots from six HDMI cables driven by differential mode signals. Notice the emissions from the two poorly terminated shields are some 20 dB higher.

Bergey & Altland, EMI Shielding of Cable Assemblies, DesignCon 2008 http://www.magazines007.com/pdf/DC08_Dana_Bergey.pdf

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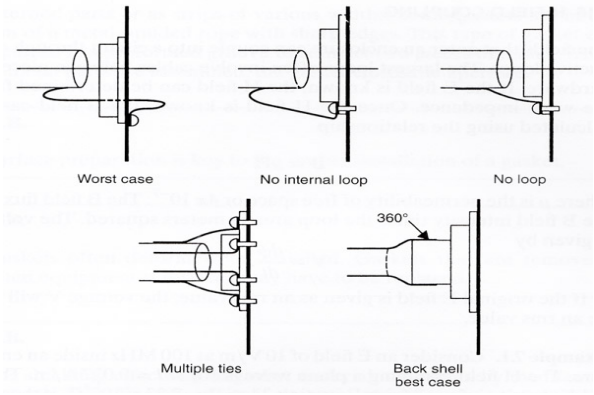
Examples of cable shield bonding



Many HDMI cables use a pigtail bond to connector ground shell!

High frequency common-mode currents are allowed to flow out the outside of the shield of the I/O cable and cause radiated emission failures.

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Demo – pigtail demo

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Video – pigtail demo

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Select “Pigtail Demo”

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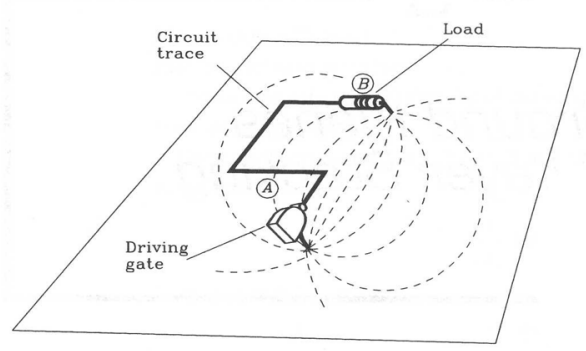
How digital signals move in circuit boards

Understanding this one topic will give you a real competitive advantage over your competitors!

Low-frequency return current path



For low frequency signals (<100 kHz) the return (conduction) current follows the path of least *resistance* and the field energy is NOT as confined under the trace.

Courtesy, Henry Ott

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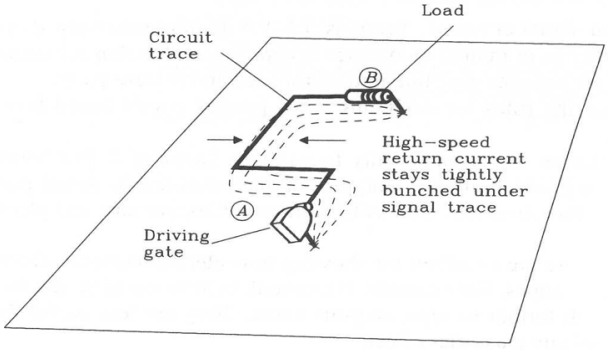
High-frequency return current path



For high frequency signals (>100 kHz) the return (conduction) current follows the path of least *impedance* and the field energy is confined under the trace.

Courtesy, Henry Ott

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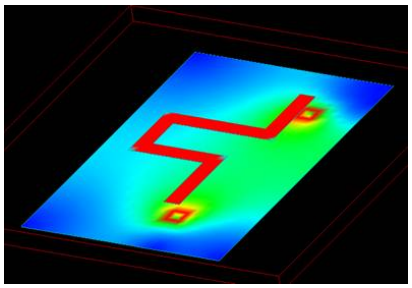
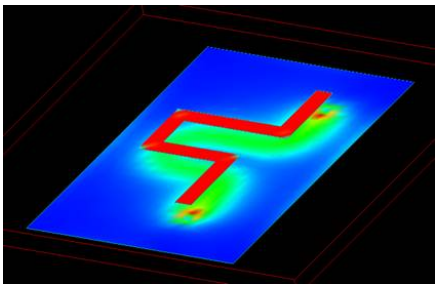
Return current paths versus frequency



Frequency = 1 kHz



Frequency = 1 MHz

At low frequencies (<100 kHz), current flows on the path of least resistance.
At high frequencies (>100 kHz), current flows on the path of least impedance.

Simulation, courtesy Agilent Technologies

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All circuit board traces are **Transmission Lines**!

Circuits point of view:

1. Signals and power require a *Return Path* back to source.
2. This return path loop area must be *Minimized*.

Fields point of view:

3. Signal and power transient *Fields* travel in the *Dielectric* at near light speed, while the conduction/displacement currents simultaneously flow back to the source at ~1 cm/s.

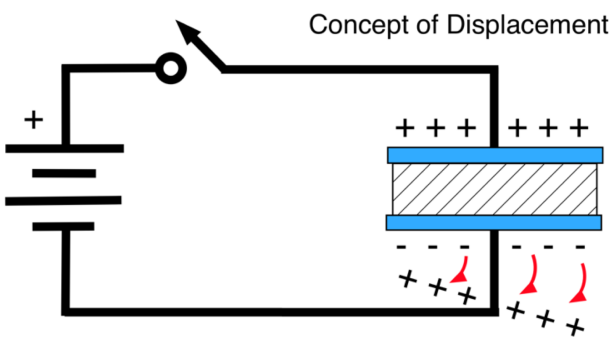
We need to understand BOTH are related!

The signal energy is in the fields, not the copper!

Energy movement in transmission lines

- A transmission line consists of two closely-spaced conductors used to move energy from point A to point B.
- The energy in a transmission line is not in the voltage or current, but in the *electric (E) and magnetic (H) fields*.
- E and H fields travel through the *dielectric* of the board, NOT through the copper.
- The fields attach themselves to the copper trace and nearest plane and are steered (or guided) by that copper.
- Thus, the copper trace acts as a *waveguide* to move the energy from point A to point B.

Displacement current in dielectrics



Current through a capacitor is related by: $I = \frac{\Delta Q}{\Delta t} = C\frac{dV}{dt}$

If V is increased, we must add + charges to one conductor and "push out" + charges on the other.

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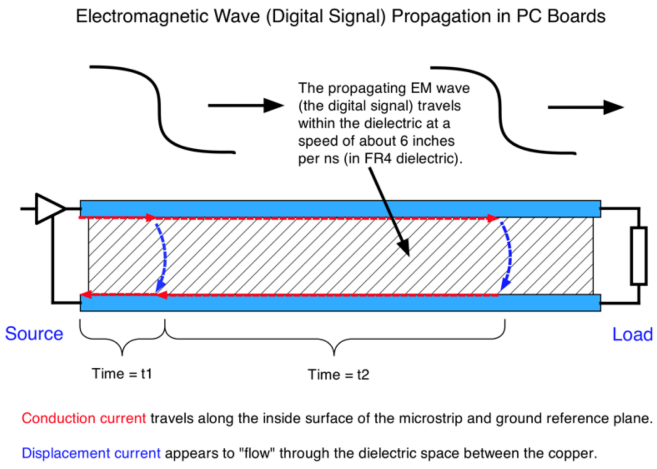
How a signal propagates on microstrip



Signal propagation is NOT through the flow of electrons in copper!

The conduction and displacement current is electron flow, but at ~1 cm/s.

The wave-front moves through the dielectric at about 6 in/ns in FR4.

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PC board design for low EMI - rules

1. Every signal trace needs an adjacent return plane (or trace)
2. Every power trace (or plane) needs an adjacent return path (trace or plane)
3. This includes return paths up/down through layers
   - Ground vias (return-to-return plane layers)
   - Stitching capacitors (return-to-power plane layers)

This will dictate the stack-up design!

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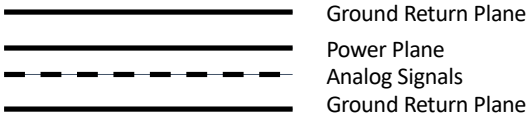
Energy coupling on PC boards

- If we allow fields from one circuit section A (motor control) to cross-couple with fields from circuit section B (analog) – due to poor stack-up or routing – this will lead to EMI, crosstalk, poor circuit performance.
- This can happen, for example, if we add a signal layer in between power and ground return planes.
- In this example, fields delivering power to the motor will occupy the same SPACE (dielectric) as the analog fields.



PCB stack-up configuration guide

"Signal / Ground / Signal" for high speed routing pairs. Routing either side of a single ground plane prevents losing the return current

"Ground / Signal / Signal / Ground" for high speed routing pairs. This allows for the use of ground to ground stitching via's to handle return current when switching from structure to structure

Use a 3-*4 mil Vcc-to-ground plane sandwich* to create a high frequency by-pass capacitor (for example, 3M "C-ply", etc.)

- *Predictable structure behavior → right the first time results*
- *Non-predictable structures → Trial and Error*
- *Better tools make more structures "predictable" (i.e., HyperLynx)*

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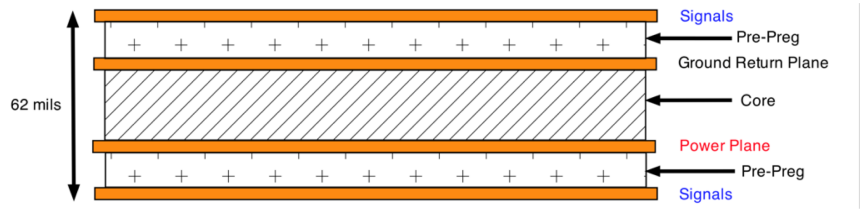
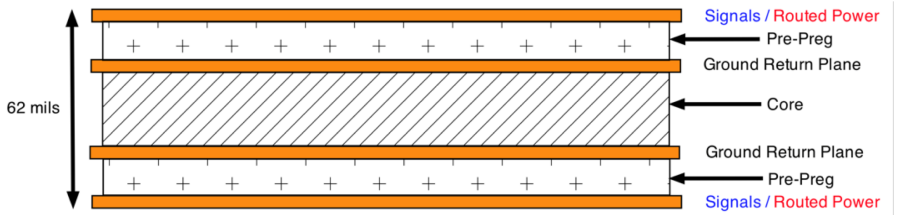
Typical, but poor, four-layer design



This common stack-up is a VERY HIGH EMI RISK!

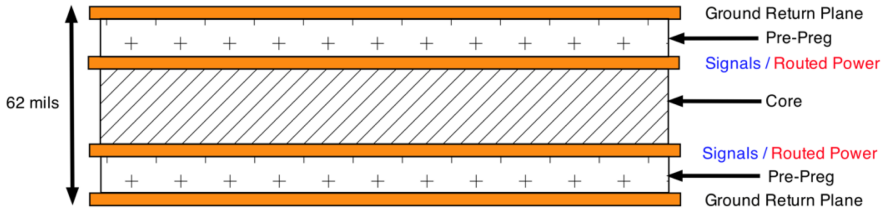
- Power and ground return plane are too far separated for good high frequency decoupling. Should be 2-3 mils, max.
- Signals on layer 4 are referenced to power, rather than signal return. This is OK, if and only if, the power and return planes are tightly coupled together and with adequate decoupling capacitors. This is not the case for four-layer stack-ups!

Lower EMI four layer board stack-up



External Signal Layers

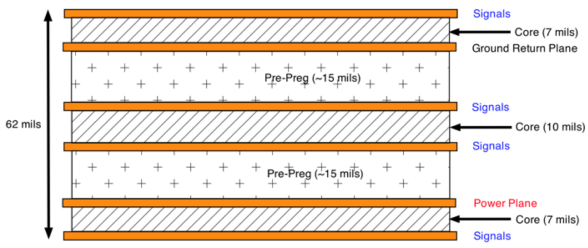
OR



Internal Signal Layers

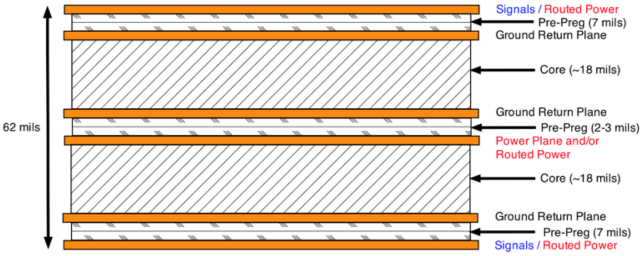
Six layer board stack up

POOR



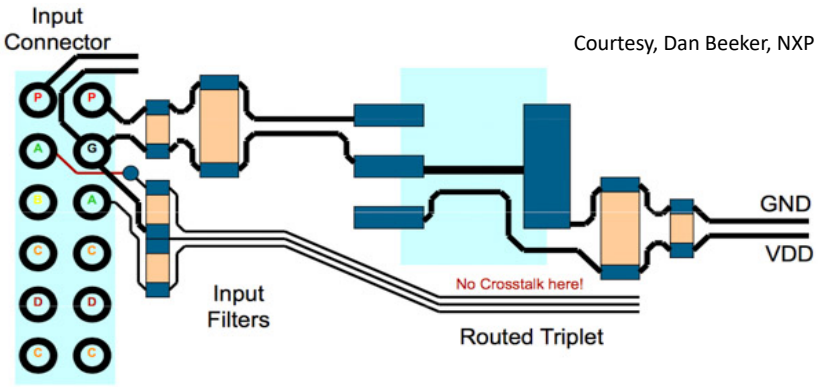
- *Very common* stack-up
- Signal referenced to power!
- Power and return plane too far separated!
- Power transients couple to inner signal layers!

GOOD



- Each signal layer has adjacent return plane
- Power and return plane adjacent
- You lose two signal layers
- Maybe best to use 8- or 10-layers

Suggested two-layer board layout



Courtesy, Dan Beeker, NXP Semiconductor

Assuming no return plane

- Keep space between traces minimized
- Filters and bypassing AT the power or I/O connector
- Run “triplets” for critical signals

Two layer boards with solid return plane don’t require minimum trace spacing

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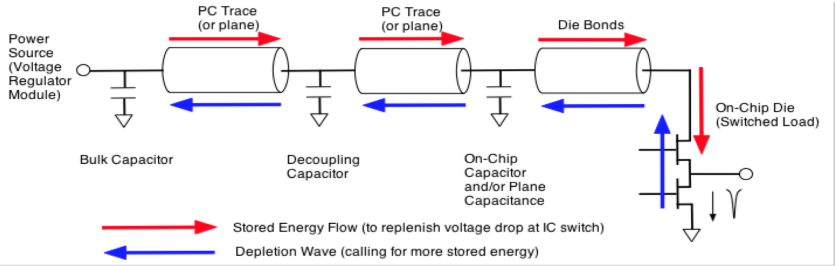
Energy Transfer in PDNs



When a switching element closes, this results in a drop in the PS voltage. The resulting field energy "request" (depletion wave) travels back until this request is filled, otherwise, it radiates.
The only way to reduce radiated emissions in a system is to reduce this distance and provide adequate sources of EM field energy (capacitive storage), when called for.
Energy sources hierarchy:

- On-chip capacitance
- Power planes, if present
- Local bypass capacitors
- Field energy stored across the PC board structure
- Bulk storage capacitors
- Finally, the power supply

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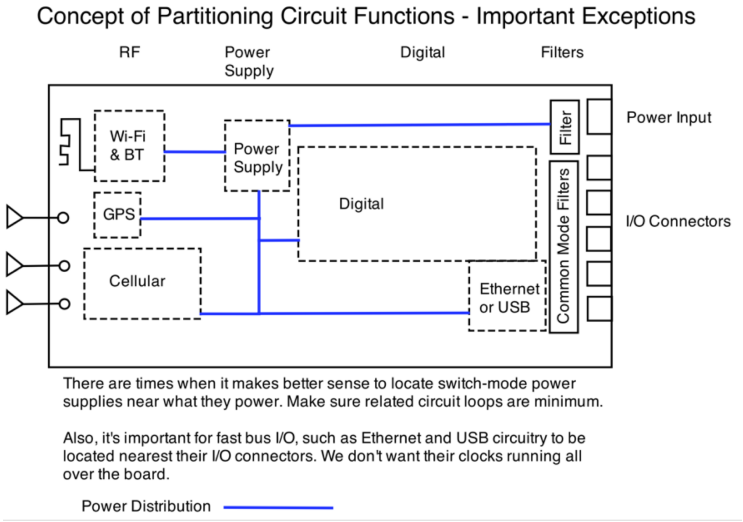
Segregating functional regions



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Routing power and power planes

It's almost always a good idea to run power planes and routed power on the same layer. This avoids overlapping power planes and resulting power noise coupling from one plane (or trace) to another.

Power planes, polygons or traces on the same layer should have at least 3 mm spacing for best high-frequency decoupling.

An exception could be made for plane pairs, such as +/-12V, where we might want to balance the two. In this case, they should be on different layers.

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Recommended experts on PC board design

Rick Hartley
Principal Engineer
Rhartley Enterprises

Two-day seminars
https://www.pcb2day.com

Dan Beeker
Senior Principal Engineer
NXP Semiconductors

See link below

https://www.nxp.com/files-static/training_pdf/WBNR_PCBDESIGN.pdf

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Recommended References

The following short articles should greatly help explain the usual EMC/EMI issues I often deal with.

1. Basic EMI Concepts – Wyatt. https://interferencetechnology.com/basic-emi-concepts/
2. Design For Compliance Essentials – Wyatt. https://interferencetechnology.com/design-for-compliance-essentials/
3. EMI Troubleshooting – Step-By-Step – Wyatt. https://interferencetechnology.com/emi-troubleshooting-step-step/#
4. Gaps in return planes - bad news for EMI – Wyatt. https://interferencetechnology.com/gaps-return-planes-bad-news-emi/
5. Troubleshooting radiated immunity for medical products - case study – Wyatt. https://interferencetechnology.com/troubleshooting-radiated-immunity-medical-products-case-study/
6. André and Wyatt, *EMI Troubleshooting Cookbook for Product Designers*, SciTech Publishers, 2014 (available from Amazon).
7. Gaps in Return Planes (video): https://www.youtube.com/watch?v=L44lTnQgv-o&t=9s
8. SMPS Ringing Demo (video): https://www.youtube.com/watch?v=dHDAuxRcReo
9. Designing PC boards for low EMI (part 1 of 4), Wyatt: https://www.edn.com/design-pcbs-for-emi-part-1-how-signals-move/

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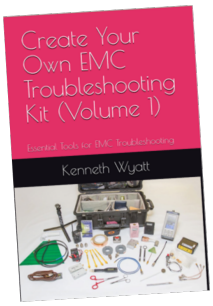
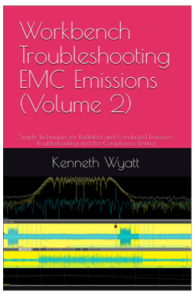
Questions?

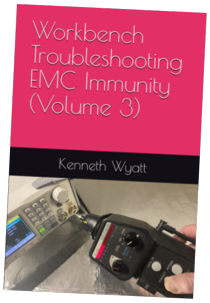
The EMC Troubleshooting "Trilogy"



Oct 2020



June 2021



Sept 2021

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www.design-4-emc.com

Blogs: https://www.edn.com/category/blog/the-emc-blog/

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