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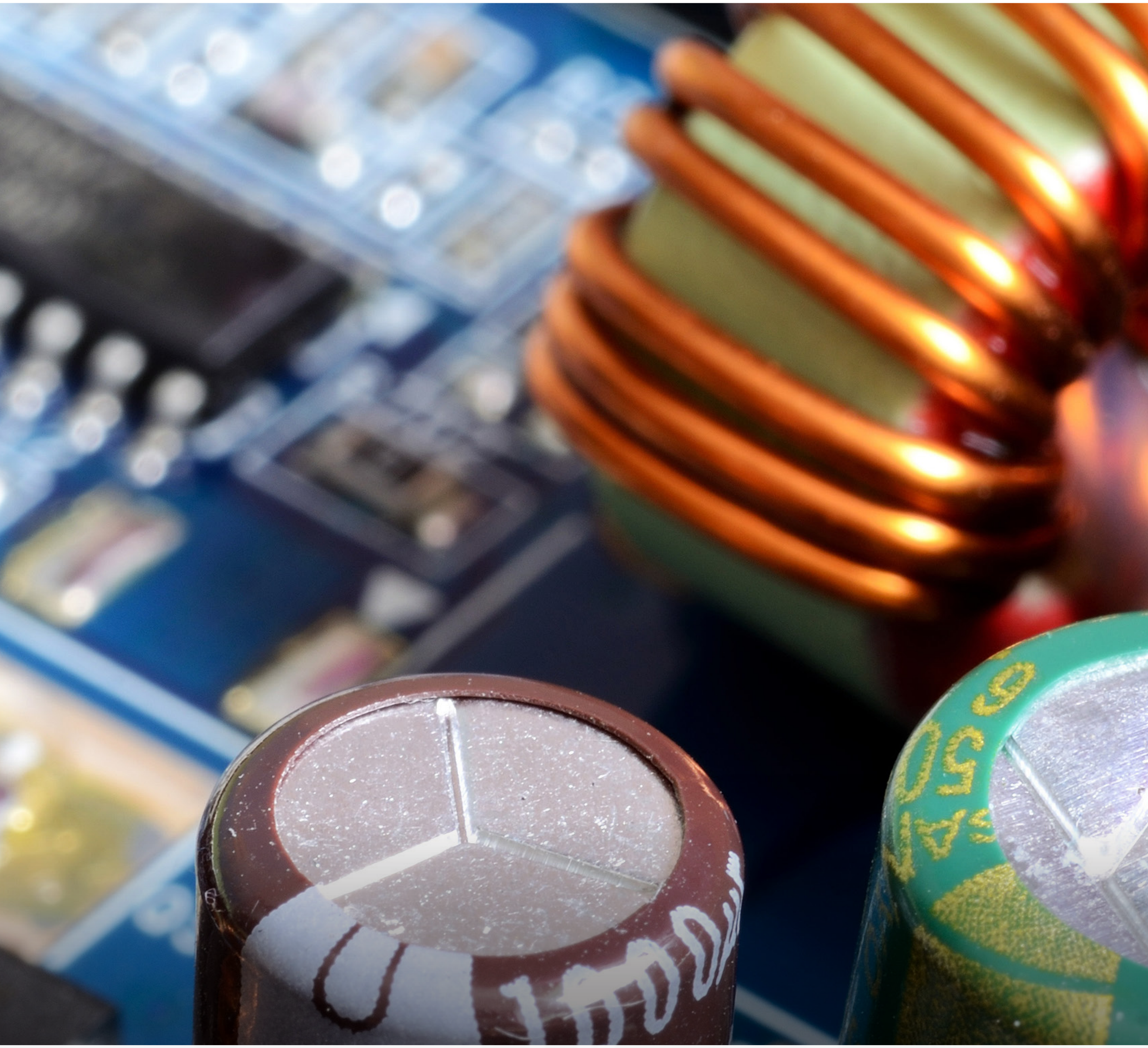

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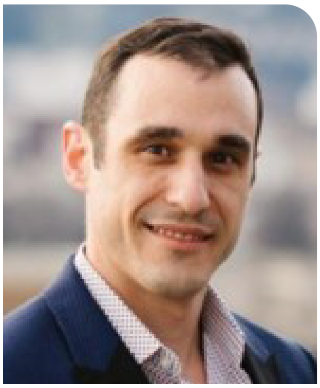

ZACHARIAH PETERSON | PCB Design Expert & Electronics Design Consultant

Zachariah Peterson has an extensive technical background in academia and industry. He currently provides research, design, and marketing services to companies in the electronics industry. Prior to working in the PCB industry he taught at Portland State University and conducted research on random laser theory, materials, and stability. His background in scientific research spans topics in nanoparticle lasers, electronic and optoelectronic semiconductor devices, environmental sensors, and stochastics. His work has been published in over a dozen peer-reviewed journals and conference proceedings, and he has written 2000+ technical articles on PCB design for a number of companies. He is a member of IEEE Photonics Society, IEEE Electronics Packaging Society, American Physical Society, and the Printed Circuit Engineering Association (PCEA). He previously served as a voting member on the INCITS Quantum Computing Technical Advisory Committee working on technical standards for quantum electronics, and he currently serves on the IEEE P3186 Working Group focused on Port Interface Representing Photonic Signals Using SPICE-class Circuit Simulators.

VOLUNTEER WORK

Printed Circuit Engineering Association (2020 - present)
INCITS Quantum Computing Technical Advisory Committee (2020 - 2022)
IEEE P3186 Working Group (2022 - present)

PROFESSIONAL SOCIETIES

IEEE Photonics Society, Electronics Packaging Society
American Physical Society

RELEVANT LINKS

Company site - https://www.nwengineeringllc.com/
Linkedin - https://www.linkedin.com/in/zachariah-peterson-391895142/
Personal site - http://zachariahpeterson.com/

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He has worked in the military and aerospace environment for his entire career and worked with commercial electronics for over 25 years. Projects worked on vary from semiconductors, satellite equipment, industrial and test equipment, cellular installations, to writing the procedures and reports, and performing or supervising EME testing of many panels for the flight deck of several aircraft. He has successfully worked with, and given input to, all branches of the military, NASA, the RTCA, the FAA, as well as several of their subcontractors. He has a strong ability in the test, measurement, and troubleshooting of EMC, and is president of André Consulting, Incorporated.

He is a third-party auditor for local governments and has provided expert opinions on the use of cellular transmitters, including health and safety concerns. Patrick has published numerous articles for a variety of magazines. He is the co-author of EMI Troubleshooting Cookbook for Product Designers.

Patrick has been a senior member of the IEEE EMC Society which he joined in 1984, serving as chairman, vice chairman, secretary, and arrangements chairman of the Puget Sound Section, and has received The Legends of the IEEE Seattle Section Award in 2010. He also been on the Board of Trustees of the Seattle Gilbert and Sullivan Society where he also works as the sound engineer and. He enjoys audio and video recording musical groups, mostly in the Seattle area, and has engineered and mastered several CD's. And when he is not busy with all this, he can be found hiking somewhere with his camera.

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Ghery S. Pettit received the BSEE degree from Washington State University in 1975. He has worked in the areas of TEMPEST and EMC for the past 47 years. Employers were the US Navy, Martin Marietta Denver Aerospace, Tandem Computers and Intel Corporation, prior to retiring from industry in 2015 and becoming an independent consultant.

Mr. Pettit is presently serving as Chair of CISPR SC I and is one of CISPR's representatives on the Advisory Council on EMC (ACEC) within the IEC. He has been involved in CISPR activities since 1998, both as a member of the US Technical Advisory Groups to CISPR SC G and CISPR SC I and as an active member of CISPR SC I and its maintenance teams, CISPR SC I MT7 (CISPR 32 maintenance) and CISPR SC I MT8 (CISPR 35 maintenance). He is also a member of the working groups preparing the next editions of ANSI C63.4, C63.9 and C63.16.

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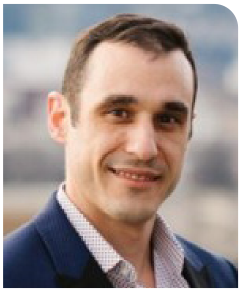
Meet the 2023 Editorial Board



ZACHARIAH PETERSON | PCB DESIGN EXPERT & ELECTRONICS DESIGN CONSULTANT

Zachariah Peterson received multiple degrees in physics from Southern Oregon University and Portland State University, and he received his MBA from Adams State University. In 2011, he began teaching at Portland State University while working towards his Ph.D. in Applied Physics. His research work originally focused on topics in random lasers, electromagnetics in random materials, metal oxide semiconductors, sensors, and select topics in laser physics; he has also published over a dozen peer reviewed papers and proceedings. Following his time in academia, he began working in the PCB industry as a designer and technical content creator. As a designer, his experience focuses on high-speed digital systems and RF systems for commercial and mil-aero applications. His company also produces technical content for major CAD vendors and consults on technology strategies for these clients. In total, he has produced over 2,000 technical articles on PCB design, manufacturing, simulation, modeling, and analysis. Most recently, he began working as CTO of Thintronics, an innovative PCB materials startup focusing on high-speed, high-density systems.

He is a member of IEEE Photonics Society, IEEE Electronics Packaging Society, American Physical Society, and the Printed Circuit Engineering Association (PCEA). He previously served as a voting member on the INCITS Quantum Computing Technical Advisory Committee working on technical standards for quantum computing and quantum electronics. He now sits on the IEEE P3186 Working Group focused on Port Interface Representing Photonic Signals Using SPICE-class Circuit Simulators.

MIKE VIOLETTE | iNARTE CERTIFIED EMC ENGINEER

Mike is President of Washington Laboratories and Director of American Certification Body. He has over 35 years of experience in the field of EMC evaluation and product approvals and has overseen the development of engineering services companies in the US, Europe and Asia. Mike is currently on the Board of Directors of the IEEE EMC Society.

He is a Professional Engineer, registered in the State of Virginia. He has given numerous presentations on compliance topics and is a regular contributor to technical and trade magazines.

DAVID A. WESTON | iNARTE EMC ENGINEER

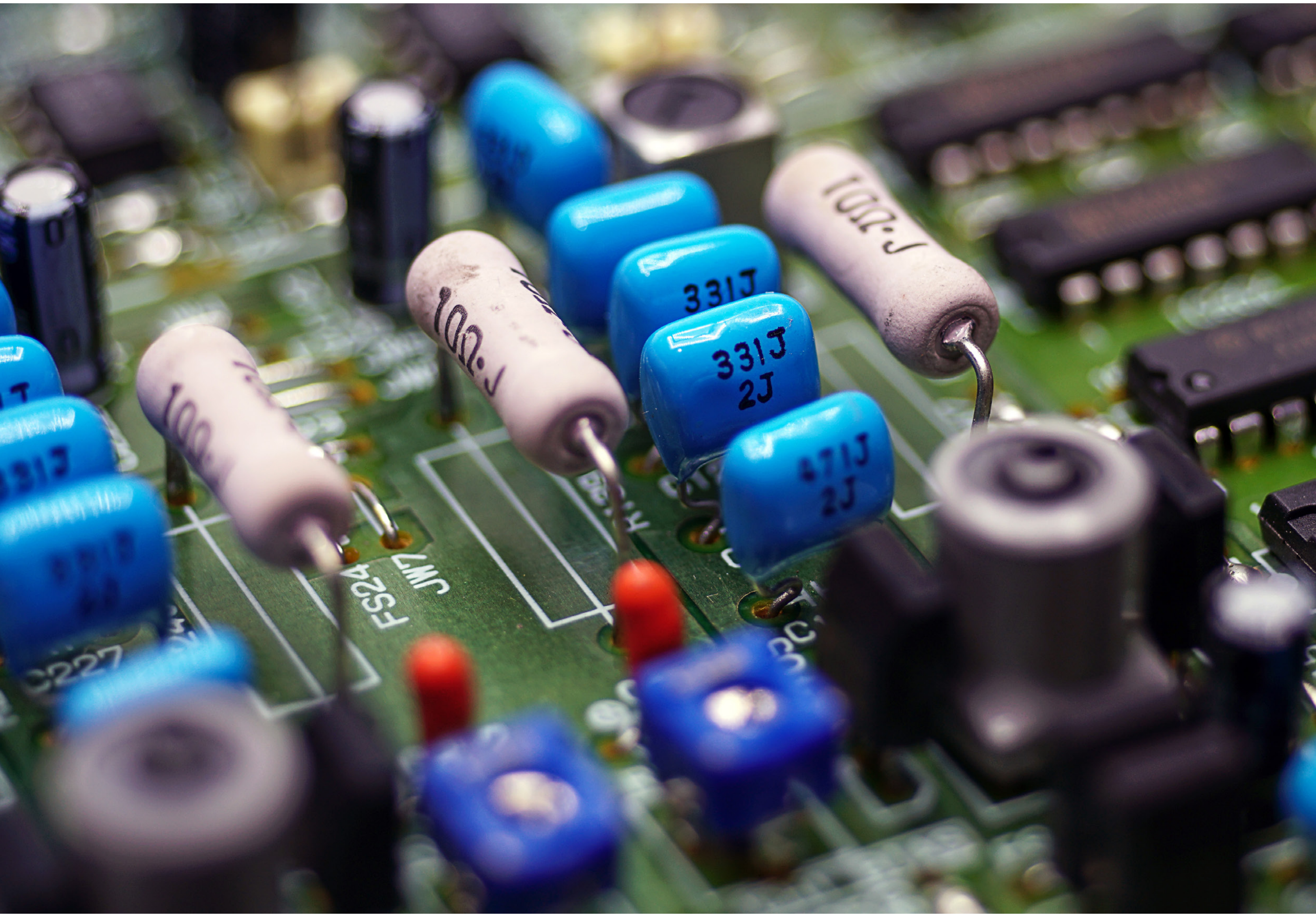
David A. Weston is an electromagnetic compatibility (EMC) consultant and certified National Association of Radio and Telecommunications Engineers (iNARTE) EMC engineer at EMC Consulting Inc. Merrickville, Ontario, Canada. A life member of the Institute of Electrical and Electronics Engineers, Weston has worked in electronic design for 55 years, specializing in the control, prediction, measurements, problem solving, analysis, and design aspects of EMC for the last 44 years.

He is the author of the third edition of the 1,157-page book Electromagnetic Compatibility, Methods, Analysis, Circuits, and Measurement published by CRC press in 2017, as well as numerous papers of a practical nature.

2023 EMC SUPPLIER GUIDE

Introduction

In this section, we provide a quick guide to some of the top suppliers in each EMC category–test equipment, components, materials, services, and more. To find a product that meets your needs for applications, frequencies, standards requirements, etc., please search these individual supplier websites for the latest information and availability. If you have trouble finding a particular product or solution, email info@interferencetechnology.com for further supplier contacts.



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	Advanced Test Equipment Corp. (ATEC)	www.atecorp.com	X	X		X				X		X			X	X	X	X	X	X	X		
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B	Beehive Electronics	www.beehive-electronics.com																			X		
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F	F2 Labs	www.f2labs.com				X	X														X	X	X
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K	Keysight Technologies	www.keysight.com								X							X		X	X			
	Kikusui America, Inc.	www.kikusuiamerica.com/solution/	X															X					
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N	Narda Safety Test Solutions	www.narda-sts.com	X	X						X							X			X			
	Noise Laboratory Co., Ltd.	www.noiseken.com																				X	
	NTS	www.nts.com																			X		
O	Ohmite	www.ohmite.com								X													
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Q	Quell Corporation	www.eeseal.com			X						X	X									X		
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S	Schaffner EMC, Inc.	www.schaffner.com						X			X										X	X	
	Schurter, Inc.	www.schurter.com			X		X	X			X												
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	Siglent Technologies	www.siglentna.com																X					
	Signal Hound	www.signalhound.com						X		X							X				X		
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	Spectrum Control	www.spectrumcontrol.com			X			X			X	X									X	X	
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	Teledyne LeCroy	www.teledynelecroy.com																X					
	TESEQ Inc.	www.teseq.com																X					
	Test Equity	www.testequity.com	X							X							X		X				
	Thurlby Thandar (AIM-TTi)	www.aimtti.com								X							X						
	Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X							X						
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EMC DESIGN IN POWER ELECTRONICS PART 1: REGULATORS

Zachariah Peterson
Owner, Northwest Engineering Solutions

INTRODUCTION

Modern electronics demand low EMI and EMC conformance, both of which are related to component selection and physical layout in the power supply section of a device. Many more designs are demanding higher power levels alongside high power efficiency, as well as low-noise power supplied to mixed-signal systems. As a result, EMI and EMC challenges are more apparent in many systems, oftentimes leading to re-spins and re-designs.

In this 2-part series, I'll give an overview on the mechanisms and physical principles that influence the production and propagation of electrical noise. The focus will be on the origination of noise in power supplies and how noise can radiate or conduct to other areas of an electrical system. We will conclude with a discussion on PCB layout for these systems with a focus on suppression of EMI and ensuring compliance in EMC design.

First, let us focus on power regulators, the noise they produce, and how noise is related to circuit design and component selection. Voltage regulators are common in nearly every system that does not use an external power supply, so the selection and design of voltage regulators for power conversion is critical to achieving EMC.

EXAMINING NOISE FROM VOLTAGE REGULATORS

Voltage regulators are the simplest type of power regulator: they accept voltage at one level and convert it to another level while attempting to maximize power efficiency. Voltage regulators come in two forms: switching regulators and linear regulators. Each has different noise characteristics and power conversion capabilities. The trade-off between different types of regulators and power supplies can significantly impact battery life, EMI/EMC compliance, and even the basic operation of a product in development.

Linear Regulators

Linear regulators and LDOs (low dropout regulator) operate by stepping down input voltages to a lower level, and their efficiency depends on the step-down mechanism in the circuit or component. They do not generate EMI directly as they do not rely on switching action to generate and regular a target voltage. For low-power, low-noise requirements, LDOs are a standard option used in modern electronics.

These two types of regulators have simple noise suppression mechanisms, as summarized in the *Table 1*. For low-noise, high-efficiency power delivery directly to a small circuit, the LDO is clearly superior as long as the input voltage overhead is set correctly. For step-up or step-down operation, as well as high efficiency with high power delivery, designers typically choose switching regulators.

	Standard Linear Regulators	LDO
Power Output	Less than input	Less than input
Efficiency	Can be inefficient	Can be >90% at low dropout voltage
Noise Suppression	Can be poor; some circuits only scale down noise linearly	Very high: provides nonlinear suppression with PSRR reaching 60 dB or higher

Table 1

Switching Regulators

LDOs are preferable for low-power digital and analog systems thanks to their low noise power delivery, and they do not transfer excessive EMI at the circuit level thanks to their high PSRR values. However, when higher currents are required, switching regulators are often needed. Switching regulators deliver power through periodic storage and release of energy in a reactive component (inductor and capacitor), which exchanges low-frequency noise for higher frequency ripple at the circuit's switching frequency.

Today's switching regulators create conducted and radiated noise, although in most cases, the design and layout of a circuit can be optimized such that certain emissions can be reduced. Conducted emission is generally a larger issue for fixed systems as they tend to require more current, thus the system will generate larger dV/dt and dI/dt events during switching. In contrast, in a portable device running on batteries, there will be no external connections to provide an outlet for conducted noise, thus the device must primarily produce radiated emissions.

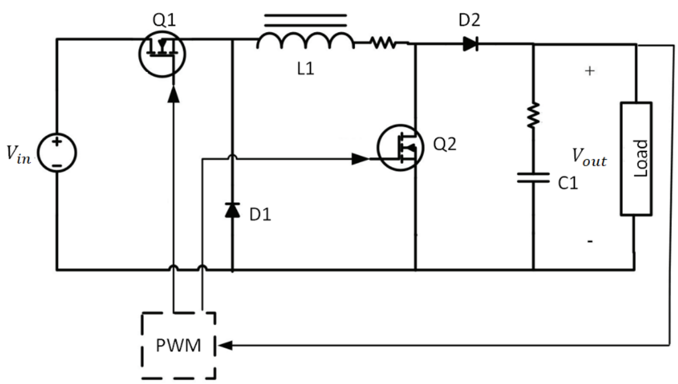
Example: DC-DC Converter With Integrated Gate Driver

As an example that can be implemented in a real system, take a look at the circuit diagram below. This system uses a control block to modulate the FETs in the design and produce the required power output in a step-down topology. The control circuit is normally available as a gate driver chip that is designed for specific regulator topologies. The external FETs are the switching nodes that generate the high dV/dt and dI/dt action seen elsewhere in the system.

The resistances in series with L1 and C1 are parasitics in these respective components (ESR values), although it should be noted that parasitic inductance is also present in capacitors (ESL values), as well as in component leads/vias, lands, and connecting traces. There are several options to suppress transients in these circuits, depending on the location where the noise originates:

- Input noise filtering is typically applied with capacitors across Vin
- High-frequency ringing at the switching node can be compensated with a snubber circuit
- Oscillations on the output can be slowed with a small (few Ohms) resistance in series with C1, although this increases the turn-on time
- Oscillations in any output filter must be compensated with small series resistances in the filter circuit

These steps attempt to bring any LC transient response into the critically damped regime.



Example. Non-inverting buck-boost converter with gate driver circuit

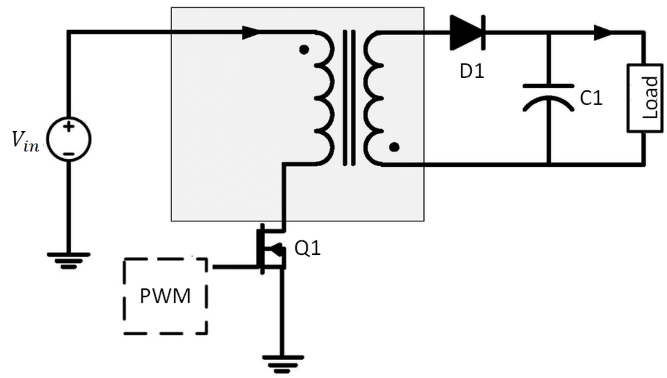
This regulator has the typical conducted EMI problems that would be observed in any switching regulator. Diode noise (e.g., from D2) is a significant issue in radiated emissions. As the FET switches very fast, diodes can ring in the 50-250 MHz range, and FET transitions create bursts of noise that can be found in radiated emissions measurements.

In this type of regulator, there are two levers that can be used to reduce conducted noise: the cutoff in the LC filter section and the switching frequency. Because the frequency is generally fixed by the internal circuitry of the controller, you'll have no choice but to tune the output LC circuit to provide ripple reduction and noise reduction by adjusting the inductor.

Typically, designers will opt for a larger inductor in the event they have no control over switching frequency as this directly reduces ripple on the output voltage and current, but it increases size and cost. Depending on the power output in the above converter, it may be preferable to use a simple linear regulator. As long as you don't mind exchanging some input power for heat, a linear regulator can provide a good solution when you need to convert between low input and low output voltages.

Isolated Topologies

A related converter topology shown below couples power to the output via a transformer (flyback converter). The switching FET modulates the current drawn into the circuit, which then inductively couples to the secondary side of the transformer. Switching action is then rectified in the output stage to produce a DC output with superimposed high frequency ripple.



Flyback converter topology

This converter topology is resilient against ESD propagating from the input to the output. The gap in the transformer and the optocoupler on the feedback line provide physical separation that confines ESD between two sections and ultimately forces it to dissipate into the nearest PE connection. A similar topology is implemented with industrial Ethernet, but the topology is just coupling high speed digital data instead of power. This design also suppresses EMI in the form of dangerous DC currents that might reach any IOs in the system via the ground plane.

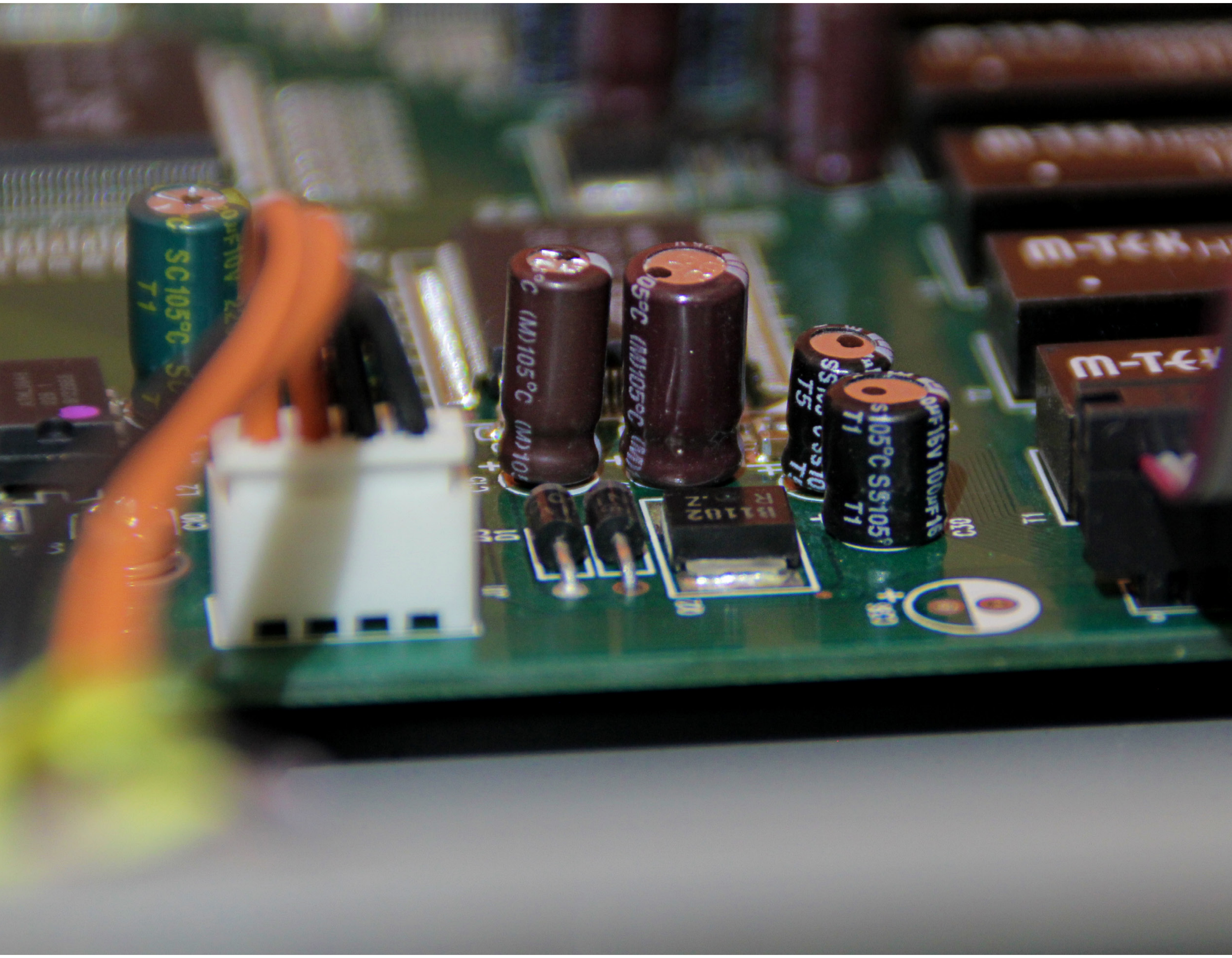
However, this design has a new high frequency coupling mechanism through the transformer. Shielded transformers, planar transformers, or another low-capacitance transformer is needed to prevent noise transmission across the primary and secondary sides of the transformer. This is often done by providing a Y-type capacitor across the primary and secondary GND regions, where the capacitance is larger than the winding capacitance of the transformer.

CONCLUSION

So far, we have looked at important examples and concepts used to understand noise propagation in an electronic system. The resulting noise from these designs can produce significant EMI (both conducted and radiated) seen on data lines or analog signals, thus noise must be suppressed at various points in the system. Some options include shielding, filters, proper component selection, and more careful physical layout. The next section will look at the physical mechanisms by which noise will couple around a system and provide some insight into how these noise sources can be addressed.

EMC DESIGN IN POWER ELECTRONICS PART 2: NOISE COUPLING MECHANISMS

Zachariah Peterson
Owner, Northwest Engineering Solutions



In the previous article of this series, we looked at some of the major noise considerations in different power regulator topologies. Noise from these sources eventually makes its way to other components, and it could interfere with other portions of a system. Depending on the types of components used elsewhere in the system, noise may be innocuous or it may cause a design to fail. At minimum, an understanding of the primary noise coupling mechanisms will help designers prevent or correct design defects that can lead to an EMI failure.

In this section, we'll look more at the physical mechanisms by which noise will couple from a power system to other components and circuits in an electronic device. These same mechanisms govern noise transfer in other circuits that are not meant for power delivery, although many EMI design problems originate from the power delivery system in an electronic system.

FIELDS AND NOISE

Fundamentally, the electromagnetic field is responsible for carrying energy between different circuits. A designer should be able to identify how the electromagnetic field could couple between certain critical regions in a design, thus they can engineer the system layout to minimize noise coupling. Should noise coupling remain a problem in a design, a designer can apply targeted solutions to the problem if they can determine the coupling mechanism.

Common-Mode and Differential-Mode Noise

All noise is radiated from a design in two modes: common-mode and differential mode. Technically, every wire carries a differential-mode current and emits radiation. However, in the EMC world, we normally care more about radiation from common-mode currents because common-mode noise is much more intense than differential mode noise. The two are related: common-mode noise can induce currents that generate differential-mode noise, and vice versa. Conducted currents can create near field radiation (e.g., crosstalk between signal lines) as well as emit into the far field, and this radiation in either regime can induce conducted noise. These effects are entirely driven by the electric field and magnetic field.

The table below summarizes the coupling mechanisms and generation mechanisms by which noise can be produced and received throughout an electronic system.

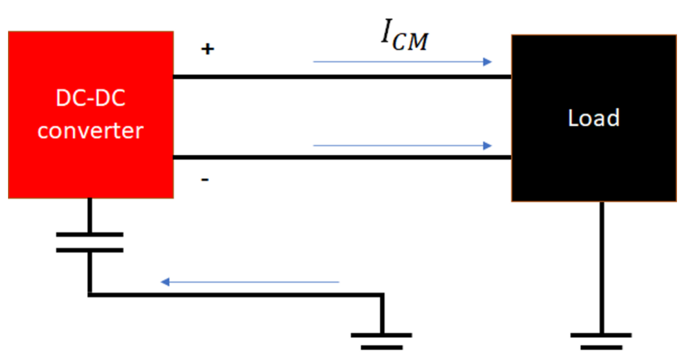
	Electric	Magnetic
Emission Mode (Common vs. Differential)	Both	Both
Coupling Mechanism	Capacitance	Inductance
Generation Mechanism	Changing voltage (dV/dt)	Changing current (dI/dt)

This table should be instructive as it relates a voltage/current change in one area of a system to the noise received in some other area of a system. For example, in switched-mode power supplies, certain nodes experience high dI/dt events, and a nearby parasitic inductance will enable reception of lower frequency noise.

Similarly, nodes on switching FETs experience high dV/dt events, so parasitic capacitance can easily couple noise into a nearby circuit or conductor at higher frequencies. Capacitive coupling should be reduced around these nodes to prevent noise transfer via a displacement current in nearby structures.

Parasitic capacitance is difficult to deal with and is one reason for common-mode noise coupling throughout a system. Common-mode noise in electronics, including PCBs or packages with multiple ground regions like a chassis, arises due to capacitive coupling around closed loops. Such capacitive coupling between one ground region and multiple conductors via a power system is a well-known mechanism that allows noise coupling throughout a circuit.

In a system with an earth ground (PE) connection in the physical layout, it's possible to create closed loops via the PE region and the power supply as shown in the image below. Some of this noise can propagate to an IO and possibly over a cable, later reaching a destination component. This is one reason a differential protocol might be used for data transfer, as well as the resilience against ground offsets when routed over long cable runs.



Common-mode noise path via ground and a DC-DC converter.

Why should this noise couple around the system at all? The answer lies in the fundamental behavior of the electromagnetic field.

Coupling Via the Electric Field

The electric field is related to the force that exists between electric charges. The strength of the electrical field is directly proportional to the potential difference between two conductors and is inversely proportional to their distance from each other. Essentially, this means that any two conductors separated by some distance between in a PCB or package will have some capacitance and can transfer energy between each other via the electric field.

If there is capacitive coupling that possibly leads to common-mode currents, it likely appears due to coupling between the nodes with highest voltage magnitude and/or highest dV/dt values. If you can identify these regions of the device, some steps can be taken to weaken coupling to nearby conductors and circuits.

Coupling Via the Magnetic Field

Magnetic coupling occurs due to induction as described in Faraday's law. All currents produce a magnetic field, while a changing current produces a changing magnetic field. Since only changing magnetic fields can induce noise in other circuits according to Faraday's law, DC currents will never induce noise in other circuits. Instead, it is the dI/dt nets and nodes in a design that will be responsible for coupling noise into nearby current loops via a changing magnetic field. The strongest coupling between two nets will occur in the following conditions:

- When the source current loop is parallel to the receiving current loop
- When the dI/dt value on the aggressor loop is maximized

A circuit can be shielded by enclosing it in high-μ material, although this method is complicated and expensive, and stops being effective above ~300 kHz. Magnetic field emissions can usually be controlled best when they are minimized at the source. In general, this requires the use of transformers and inductors designed to reduce radiated magnetic fields. It is also critical that the circuit board layout and interconnect wiring be designed to limit the current loops' size, particularly in paths with high current.

CONCLUSION

With these noise conduction and emission mechanisms in mind, we can now start to think about some practical solutions to noise coupling in order to achieve EMC compliance in power systems and in their supporting circuitry. This can involve several techniques implemented in power supplies, embedded power converters, and many other designs that require noise suppression.

Once the particular source of the noise (both location and noise mechanism) is identified, it can often be suppressed in two possible ways:

- Locate and eliminate ground discontinuities in the PCB layout
- Identify areas with large current loops or close spacing between dV/dt nodes
- Strategically place filters with appropriate components
- Judiciously apply shielding in the design

THINGS NOT ON THE SCHEMATIC

HOW THE PARASITIC ELEMENT AFFECT RESULTS

Patrick G. André
André Consulting, Inc.

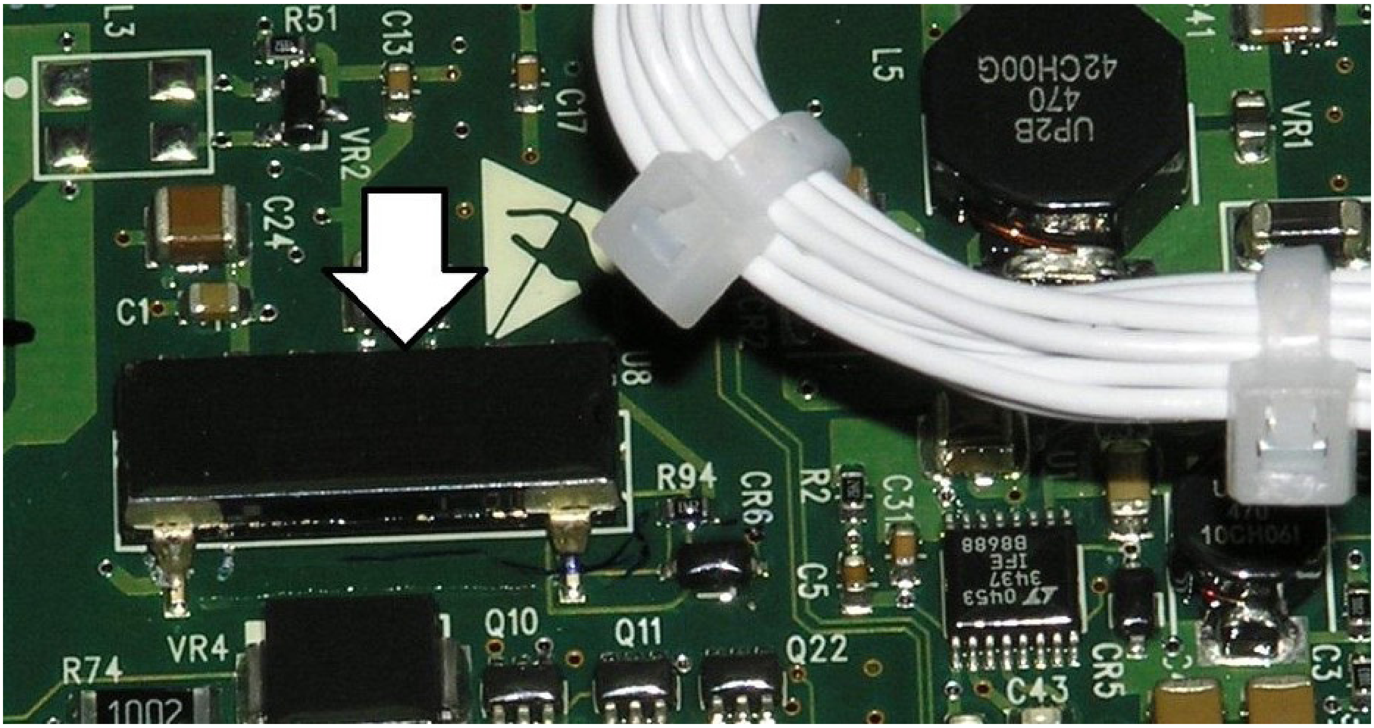


Figure 1 - Where are the fields from?

The engineer had found the use of a capacitor on a specific trace would solve a radiated emissions issue. However, placement on the connector where we put the capacitor during engineering work was not a production solution. So, the capacitor which was moved less than 1 inch away from the connector and turned sideways to fit on the circuit board. However, this degraded the emission results several dB and increased it above the limit. How could that be? They were identical on the schematic.

It has been said that the field of EMC is the design of circuits which consider things that do not appear on a schematic. These are the parasitic elements, the electric and magnetic field created by the circuit and coupled into adjacent circuits, wires, and components, and issues of unknown or uncontrolled current paths. To control these issues, it requires being aware of these fields, how they are generated, and the mechanism by which they couple, as well as how currents are generated and how they return to the source of the energy which created those currents.

When EMI problems occur, they are often due to unknown or unforeseen issues of components. Take the following for example: In ***Figure 1***, if there is a concern with cross coupled fields, we may want to reroute that white cable we see over the circuit board. Or maybe we would have concerns about the large inductor in the upper right corner, or the small one in the lower right under the cable. These may have uncontrolled magnetic fields which could couple energy into nearby traces. When testing was performed, neither of these were a problem. However, the conducted emissions measurements were over limit.

The issue arose from a DC-DC converter located to the left, and indicated with the arrow. This converter contains an internal transformer. The fields from this device ended up coupling into the input power trace running under the near side of the device indicated in this picture. Due to a misplaced filter, which was not located next to the input connector as it should have been, the input power conducted emissions increased by 20 dB and more due to

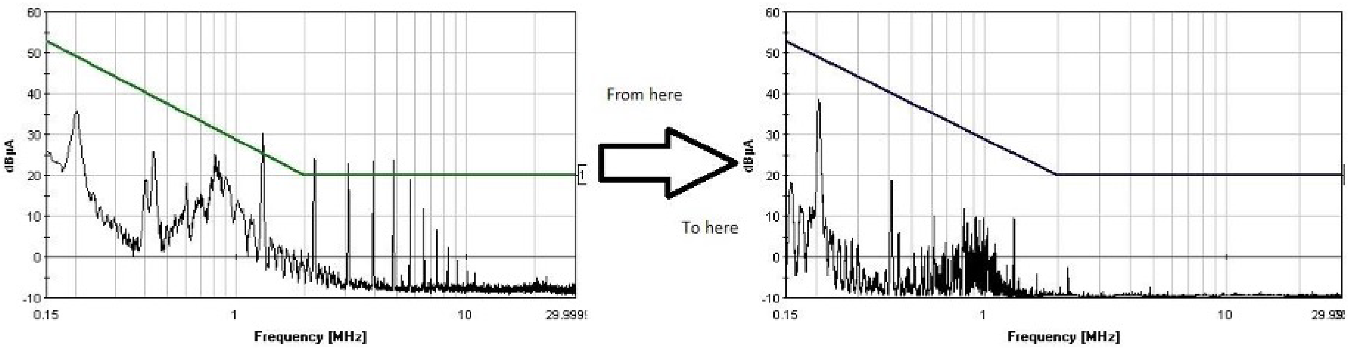


Figure 2 - Rerouted trace and the resulting conducted emissions

the proximity of this converter and internal transformer. Rerouting the trace away from this converter improved the results radically (see ***Figure 2***).

The cause of this issue was due to magnetic field coupling. Uncontrolled magnetic fields from the converter's internal transformer could couple into an adjacent trace, which induced a current in that trace at the switching frequency of the converter, and higher harmonics of that frequency. The specification for this component shows performance with a wide margin with respect to conducted emissions limits. And the power to the device may have been compliant by itself. However, due to the fields generated by the device, noise was allowed to be reintroduced into the trace in an uncontrolled manner.

These magnetic coupling issues are usually found in lower impedance circuits where currents can flow with greater ease. But what happens in high impedance circuits? These are more susceptible to capacitive coupling. One way to demonstrate that is using a standard MIL-STD 461 or DO-160 setup.

I took an inexpensive spectrum analyzer with a tracking generator. A tracking generator is an internal signal source that creates a signal at a set amplitude and the same frequency the analyzer is measuring. I ran the tracking generator signal into an unterminated 5-foot wire (150 cm), and the return signal was routed to a ground plane. A current probe was placed on the drive end of the wire. A simplified setup drawing is shown in ***Figure 3***.

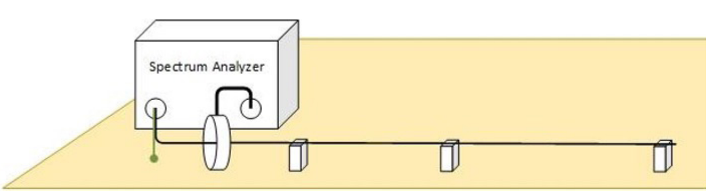


Figure 3 - An experiment on capacitive coupling

The figure shows the wire on 5 cm standoffs, as is commonly used for military and aerospace tests. For a second test, the wire was routed directly on the surface ground plane, and a third run with the wire routed the wire off the ground plane so that it was in space (held up with a plastic stand to avoid other parasitic coupling). The wire was swept with a signal from 100 kHz to 100 MHz. Only the wire was moved during the three scans, and no other changes were made to the setup, and the current probe was as close to the output port as physically possible. The results are shown in ***Figure 4***.

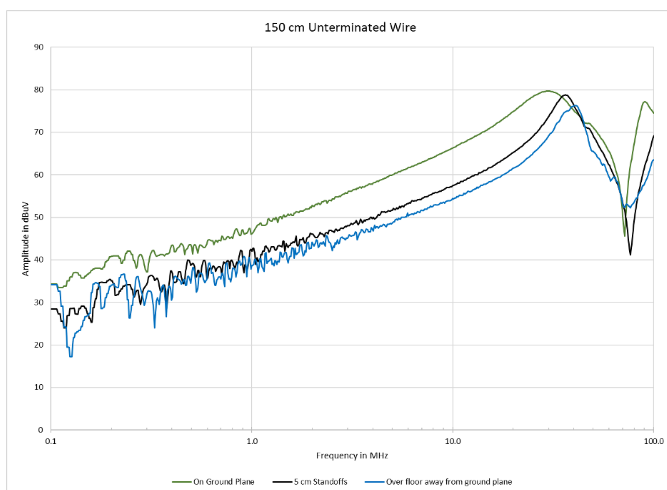


Figure 4 - Wire over a ground plane

Please note the following: At 10 MHz the induced current in the wire on the ground plane was 9 dB higher than the same wire on 5 cm standoffs, and 12 dB higher than the wire routed into "space", away from the ground plane. Above 30 MHz, this system starts to break down, likely due to the cross coupled energy at the source, the line impedances (inductance), and other setup parasitic elements. However, up to 30 MHz, the results were repeatable.

So, what does this tell us? First, there is some coupling of energy from wires on 5 cm standoffs over a ground plane.

That should not surprise most experienced military and aerospace test engineers. This is also how the wires are routed in most military and aerospace applications which often have wires over a metal structure. Also note that unterminated wires closely coupled to conductive surfaces can capacitively couple their own return path. Remember this is an unterminated wire, so I did not allow a connection to the ground plane to close the current loop. The loop is closed by displacement currents, a time varying electric field due to the voltage difference between the wire and the ground plane (which was the return). And as physicists will state, “displacement currents play a central role in the propagation of electromagnetic radiation, such as light and radio waves.”[1]

When a cable inside equipment should avoid radiating on to a sensitive circuit, when possible route the cable near a conductive surface, such as a chassis. In doing so, the conductor can couple more energy into the chassis instead of the circuit, and preferably route the induced return current back to the source in a controlled manner. Conversely, if that cable is sensitive to having energy picked up from high energy or noisy circuits or systems, routing the cable along the conductive surface will help minimize the energy induced or coupled onto it. This comes from Gauss’s Law, the concept that parallel electric fields at the surface of a perfect conductor go to zero.

So, is the solution to route wires near chassis? Maybe not. Consider it if it convenient to do so, but don’t create long cable paths to route wires along chassis. And the chassis must have a good, low impedance path back to the noise source, otherwise chassis noise will have to radiate back to the circuit board to close the path, and new issues would arise.

An area often neglected is the issue with chassis bonds. A common method of determining the quality of a shield was to consider the material conductivity, the thickness, and the screw spacing. The conductivity along with the thickness will provide the maximum capability of the material to shield. If it is not conductive enough, or thick enough, you may never get the desired results.

Now considering the screw spacing. A concept used for spacing is the amount of contact surface as shown in ***Figure 5***. This concept is that contact occurs for the first third of the spacing between fasteners, and again for the last third, but the middle third is open.

Some of these “rules of thumb” do not consider the stiffness of the materials, the spacing of the fasteners, nor the coatings. For example, a steel box with a sheet metal lid that is 50 cm wide and only has fasteners in the corners, the likelihood of gaps in the middle of the seam is rather significant. There is not enough rigidness in the lid to maintain a bond in the middle. In this case, fasteners may need to be 5 to 10 cm apart to assure a bond. But with a thick-walled chassis that has a thick lid, the spacings between fasteners may be a bit wider and still maintain the bond. And yet the whole thing can go to waste if there is a coating on the chassis.

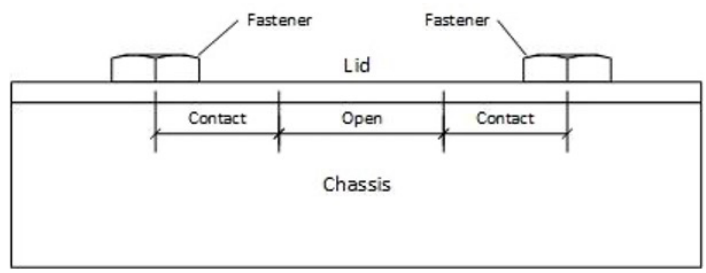


Figure 5 - Chassis bonds

If one only looks at the potential opening, or window created between fasteners, as the driving factor in shielding effectiveness, you may miss a critical aspect of shielding. For the sheet metal box with 50 cm spacing, if the window is the full 50 cm, that relates to the half wavelength of the leakage. The shield would become effective below 300 MHz. If we reduce the spacing to 5 cm, the shield should be 20 dB better across the frequency range. Yet often that is not the case.

In one situation, the unit under test had a thick-walled chassis made of aluminum, with fasteners about 5 cm apart. The emissions found were from 1-10 MHz and failed the MIL-STD 461 limit imposed. In this frequency range, the aluminum chassis should have a shielding effectiveness well over 100 dB. The important item noted was that the emissions did not change much when the lid was off. And it was found the emissions were not from the cables. However, when the engineer cleaned off all the oil and grease buildup on the chassis and lid from the handling and construction of the unit, the emissions dropped 20 dB and passed the test.

In this case, the unit under test was a power supply with significant currents flowing internally and several magnetic cores inside. The resulting fields from the magnetic fields of the wiring, traces, and inductors and transformers, induced currents in the aluminum chassis under and around the circuit board, and then over the lid of the chassis. Once these currents start to flow, they need to complete a loop. When the induced currents reached the seam, they met an impedance which prevented the flow of the current directly. This created a voltage between the

[1] Encyclopedia Britannica, https://www.britannica.com/science/displacement-current

lid and the chassis. Voltages between two pieces of metal are in essence antennas and tend to transmit their energy. This may have been viewed as a transfer impedance problem, or the creation of displacement currents across the seams. The impedance between these metal parts could have been due to insulating materials (dirt, grease), too thin to transmit radio frequencies through it from inside to outside the chassis. However, if currents cannot flow across the gap, even that small, then the resulting voltages on the two sides of this barrier will then transmit the energy.

Note that not all issues are from internal components, circuits, or even the equipment under test itself. In one situation, a large medical device was found to have emissions from 150 MHz to 250 MHz whenever a specific circuit was energized. Several engineers and technicians tried to solve the issue over months. When an EMC consultant was finally called in, the consultant asked about an external power supply used to power the circuit in question. It turned out the power supply had very intense radiated emission issues due to diodes used in the switching power supply, however nobody had bothered to verify that external source.

When trying to capture all the relevant issues concerning EMC on a schematic, it is very difficult to consider all aspects that will arise. They do not provide DC to DC converters with magnetic field maps, and often will not caution the user concerning induced field alongside the component. And inductors are best modeled with capacitance across them which represent the capacitance of the windings. Capacitors should be modeled with inductors in series to represent the lead or trace inductance. Wires and traces include a bit of both aspects. And diodes are well established noise generators over 30 MHz now.

As EMC engineers, we need to be proficient in several disciplines, in many fields of engineering, to fully support the engineers we work with. Schematics will only tell you part of the story. Many parasitic elements are not documented. Mechanical and manufacturing techniques play a role in passing EMC requirements. Maintain an open mind, considering the unlikely, and expect the unexpected. Or in the words of Sherlock Holmes, “When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth.”[2]

[2] The Casebook of Sherlock Holmes (1927), The Adventure of the Blanched Soldier, by Sir Arthur Conan Doyle.

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COMMON COMMERCIAL EMC STANDARDS

►COMMERCIAL STANDARDS

The following are some of the most common commercial EMC standards. Most standards have a fee associated and most on the list are linked back to the source where they're available. If you're purchasing the printed version of this guide, then refer to the Standards Organizations in the References section for standards purchase information. Note that many Euro Norm (EN) versions of IEC standards may be purchased at a considerable discount from the Estonian Centre for Standardization, https://www.evs.ee.

FCC

https://www.ecfr.gov

Electronic Code of Federal Regulations (e-CFR)
CFR 47 - Part 15 (Radio Frequency Devices)

ANSI

http://webstore.ansi.org

Document Number	Title
C63.4	Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz

IEC

https://webstore.iec.ch

Document Number	Title
IEC 61000-3-2	Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
IEC 61000-3-3	Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection
IEC 61000-4-2	Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
IEC 61000-4-3	Electromagnetic compatibility (EMC) - Part 4-3 : Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
IEC 61000-4-4	Electromagnetic compatibility (EMC) - Part 4-4 : Testing and measurement techniques - Electrical fast transient/burst immunity test
IEC 61000-4-5	Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
IEC 61000-4-6	Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields
IEC 61000-4-7	Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

IEC 61000-4-8	Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test
IEC 61000-4-9	Electromagnetic compatibility (EMC) - Part 4-9: Testing and measurement techniques - Impulse magnetic field immunity test
IEC 61000-4-10	Electromagnetic compatibility (EMC) - Part 4-10: Testing and measurement techniques - Damped oscillatory magnetic field immunity test
IEC 61000-4-11	Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests
IEC 61000-4-12	Electromagnetic compatibility (EMC) - Part 4-12: Testing and measurement techniques - Ring wave immunity test
IEC 61000-6-1	Electromagnetic compatibility (EMC) - Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments
IEC 61000-6-2	Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity standard for industrial environments
IEC 61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments
IEC 61000-6-4	Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
IEC 61000-6-5	Electromagnetic compatibility (EMC) - Part 6-5: Generic standards - Immunity for power station and substation environments
IEC 61000-6-7	Electromagnetic compatibility (EMC) - Part 6-7: Generic standards - Immunity requirements for equipment intended to perform functions in a safety-related system (functional safety) in industrial locations
IEC 61326-1	Electrical equipment for measurement, control and laboratory use – EMC requirements – Part 1: General requirements
IEC 61326-2-1	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-1: Particular requirements - Test configurations, operational conditions and performance criteria for sensitive test and measurement equipment for EMC unprotected applications
IEC 61326-2-2	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-2: Particular requirements - Test configurations, operational conditions and performance criteria for portable test, measuring and monitoring equipment used in low-voltage distribution systems
IEC 61326-2-3	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-3: Particular requirements - Test configuration, operational conditions and performance criteria for transducers with integrated or remote signal conditioning
IEC 61326-2-4	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-4: Particular requirements - Test configurations, operational conditions and performance criteria for insulation monitoring devices according to IEC 61557-8 and for equipment for insulation fault location according to IEC 61557-9
IEC 61326-2-5	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-5: Particular requirements - Test configurations, operational conditions and performance criteria for field devices with field bus interfaces according to IEC 61784-1

IEC 61326-2-6	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 2-6: Particular requirements - In vitro diagnostic (IVD) medical equipment
IEC 61326-3-1	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 3-1: Immunity requirements for safety-related systems and for equipment intended to perform safety-related functions (functional safety) - General industrial applications
IEC 61326-3-2	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 3-2: Immunity requirements for safety-related systems and for equipment intended to perform safety-related functions (functional safety) - Industrial applications with specified electromagnetic environment
IEC 61340-3-1	Electrostatics - Part 3-1: Methods for simulation of electrostatic effects - Human body model (HBM) electrostatic discharge test waveforms

CISPR

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Document Number	Title
CISPR 11	Industrial, scientific and medical (ISM) radio-frequency equipment - Electromagnetic disturbance characteristics - Limits and methods of measurement
CISPR 12	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers
CISPR 13	Sound and television broadcast receivers and associated equipment - Radio disturbance characteristics - Limits and methods of measurement
CISPR 14-1	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
CISPR 14-2	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 2: Immunity - Product family standard
CISPR 15	Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment
CISPR 16-1-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus
CISPR 16-1-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-2: Radio disturbance and immunity measuring apparatus - Coupling devices for conducted disturbance measurements
CISPR 16-1-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-3: Radio disturbance and immunity measuring apparatus - Ancillary equipment - Disturbance power
CISPR 16-1-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-4: Radio disturbance and immunity measuring apparatus - Antennas and test sites for radiated disturbance measurements
CISPR 16-1-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-5: Radio disturbance and immunity measuring apparatus - Antenna calibration sites and reference test sites for 5 MHz to 18 GHz
CISPR 16-1-6	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-6: Radio disturbance and immunity measuring apparatus - EMC antenna calibration
CISPR 16-2-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-1: Methods of measurement of disturbances and immunity - Conducted disturbance measurements

CISPR 16-2-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-2: Methods of measurement of disturbances and immunity - Measurement of disturbance power
CISPR 16-2-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-3: Methods of measurement of disturbances and immunity - Radiated disturbance measurements
CISPR 16-2-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-4: Methods of measurement of disturbances and immunity - Immunity measurements
CISPR TR 16-2-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-5: In situ measurements for disturbing emissions produced by physically large equipment
CISPR TR 16-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 3: CISPR technical reports
CISPR TR 16-4-1	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-1: Uncertainties, statistics and limit modelling - Uncertainties in standardized EMC tests
CISPR 16-4-2	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-2: Uncertainties, statistics and limit modelling - Measurement instrumentation uncertainty
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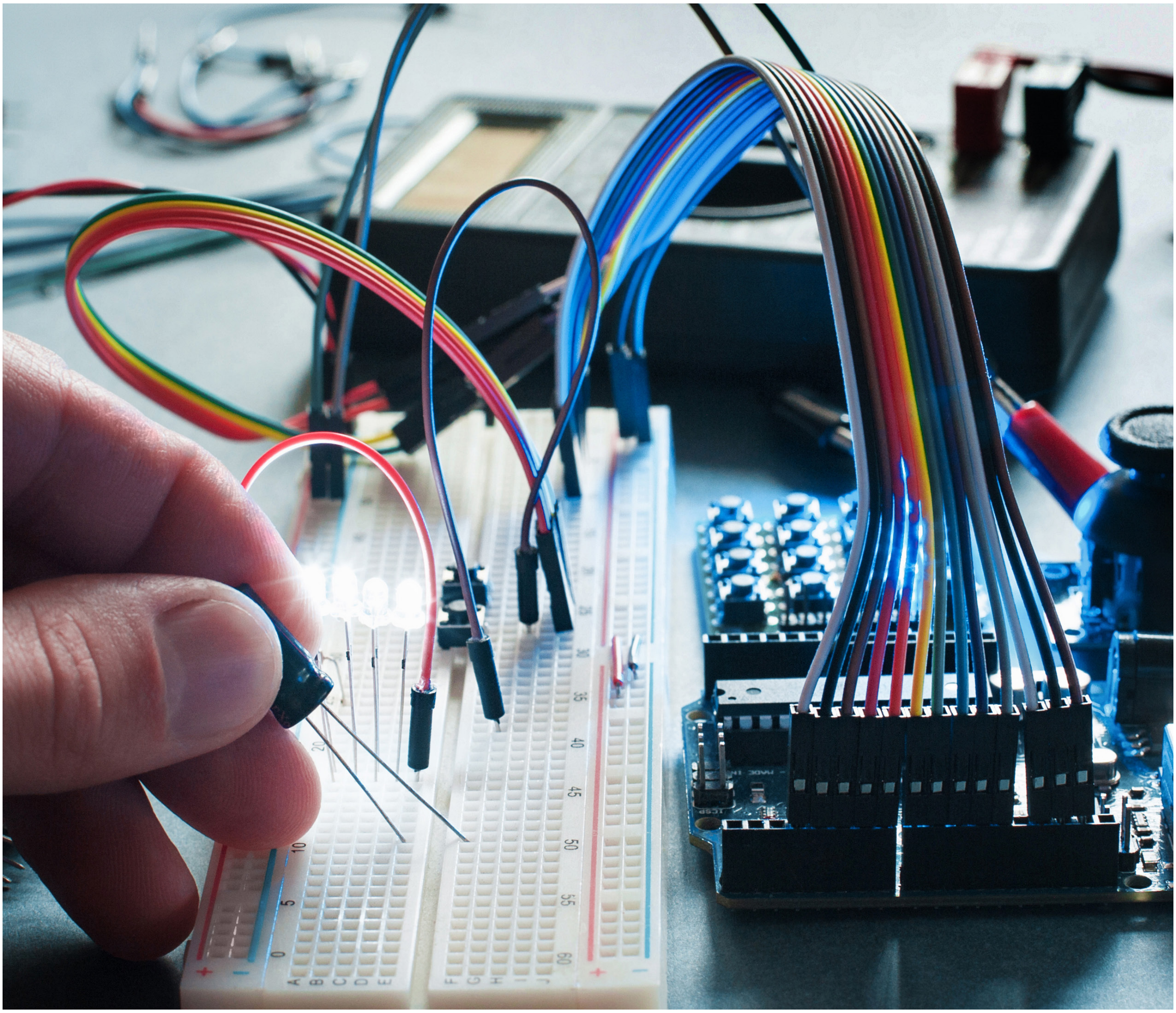
CISPR TR 16-4-4	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-4: Uncertainties, statistics and limit modelling - Statistics of complaints and a model for the calculation of limits for the protection of radio services
CISPR TR 16-4-5	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-5: Uncertainties, statistics and limit modelling - Conditions for the use of alternative test methods
CISPR 17	Methods of measurement of the suppression characteristics of passive EMC filtering devices
CISPR TR 18-1	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 1: Description of phenomena
CISPR TR 18-2	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 2: Methods of measurement and procedure for determining limits
CISPR TR 18-3	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 3: Code of practice for minimizing the generation of radio noise
CISPR 20	Sound and television broadcast receivers and associated equipment - Immunity characteristics - Limits and methods of measurement
CISPR 22	Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement (Withdrawn and replaced by CISPR 32:2015)
CISPR 24	Information technology equipment - Immunity characteristics - Limits and methods of measurement (Withdrawn and replaced by CISPR 35:2016)
CISPR 25	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers
CISPR 32	Electromagnetic compatibility of multimedia equipment – Emission requirements
CISPR 35	Electromagnetic compatibility of multimedia equipment - Immunity requirements

OTHER RELEVANT STANDARDS

https://webstore.iec.ch

Document Number	Title
IEC 60601-1	General requirements for basic safety and essential performance
IEC TR 60601-4-2	Electromagnetic immunity performance
IEC TR 60601-4-3	Considerations of unaddressed safety aspects in the third edition of IEC 60601-1
IEC TR 62354	General testing procedures for medical electrical equipment
ISO 14708-1	Active implantable medical devices



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BSMI (Taiwan)
http://www.bsmi.gov.tw/wSite/mp?mp=95

Canadian Standards Association (CSA)
www.csa.ca

CISPR
http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1298,25

CNCA (China)
http://english.cnca.gov.cn

Electromagnetic Compatibility Industry Association UK
http://www.emcia.org

FDA Center for Devices & Radiological Health (CDRH)
https://www.fda.gov/MedicalDevices/default.htm

Federal Communications Commission (FCC)
www.fcc.gov

Federal Standards
https://quicksearch.dla.mil/qsSearch.aspx

Gosstandart (Russia)
https://gosstandart.gov.by/en/

IEC
https://www.iec.ch/homepage

IEEE Standards Association
https://standards.ieee.org/

IEEE EMC Society Standards Development Committee (SDCOM)
https://standards.ieee.org/develop/index.html

Industry Canada (Certifications and Standards)
http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf06165.html

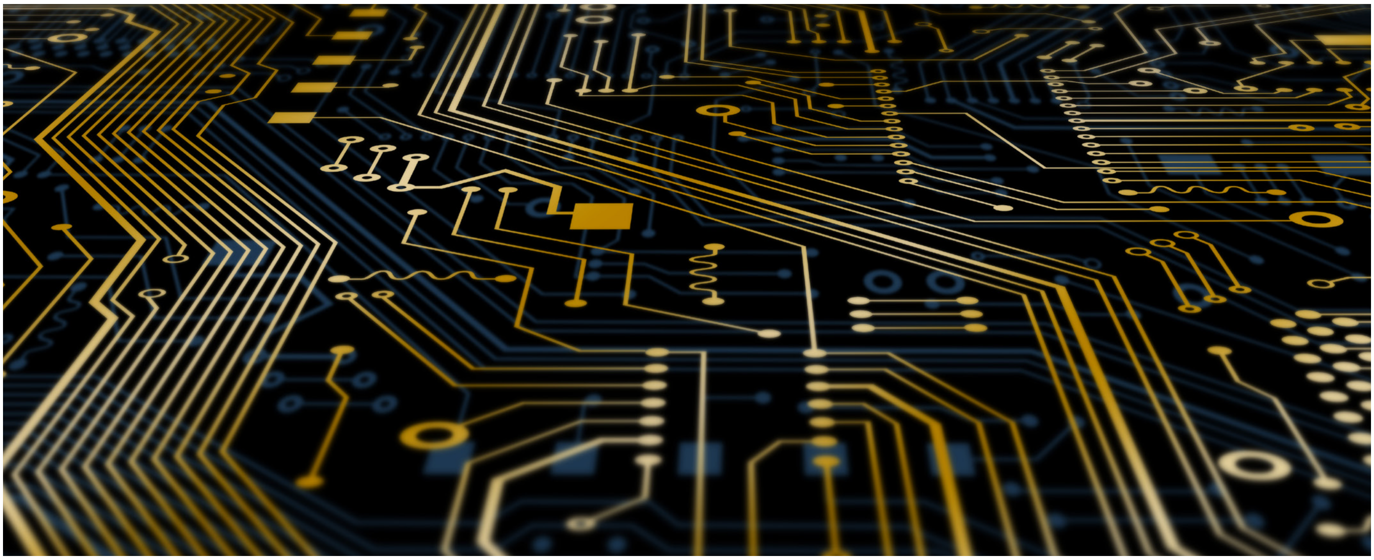
ISO (International Organization for Standards)
http://www.iso.org/iso/home.html

RTCA
https://www.rtca.org

SAE EMC Standards Committee
www.sae.org

SAE EMC Standards
http://www.sae.org/servlets/works/committeeHome.do?comtID=TEVEES17

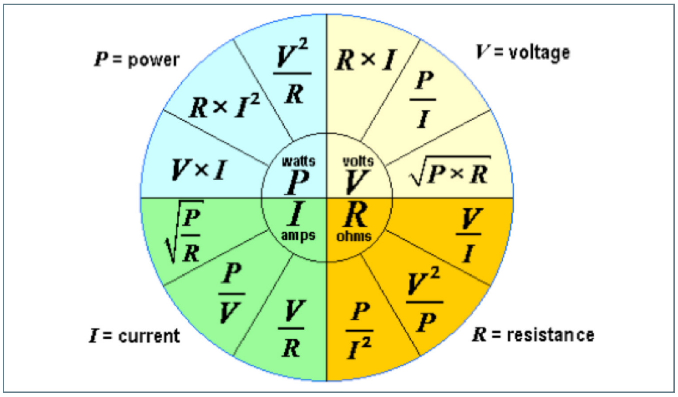
VCCI (Japan, Voluntary Control Council for Interference)
http://www.vcci.jp/vcci_e/



EQUATIONS, TOOLS, & CALCULATORS

COMMON EMC-RELATED EQUATIONS

OHMS LAW



Ohms Law "formula wheel" for calculating resistance (R), voltage (V), current (I) or power (P), given at least two of the other values.

BANDWIDTH VERSUS CLOCK FREQUENCY

$$BW_{Clock}(GHz) = 5\ X\ F_{Clock}(GHz)$$

Assuming the rise time of a clock is 7% of the period, we can approximate the bandwidth as shown.

Example, for a clock frequency of 100 MHz, the bandwidth is 500 MHz. That is, the highest significant sine-wave frequency component in a clock wave is the fifth harmonic.

PERIOD VERSUS FREQUENCY

$$F_{Clock}(GHz) = \frac{1}{T_{Clock}\ (nsec)}$$

SPEED OF SIGNALS

In air: 12 inches/nsec

In most PC board dielectrics: 6 inches/nsec

VSWR AND RETURN LOSS

VSWR given forward/reverse power $VSWR = \dfrac{1 + \sqrt{P_{rev}/P_{fwd}}}{1 - \sqrt{P_{rev}/P_{fwd}}}$

VSWR given reflection coefficient (ρ) $VSWR = \left|\dfrac{1+\rho}{1-\rho}\right|$

Reflection coefficient (ρ), given Z_1,Z_2 Ohms $\rho = \left|\dfrac{Z_1 - Z_2}{Z_1 + Z_2}\right|$

Reflection coefficient (ρ), given fwd/rev power $\rho = \sqrt{\dfrac{P_{rev}}{P_{fwd}}}$

RETURN LOSS, GIVEN FORWARD/REVERSE POWER

$$RL(dB) = -10\log(\frac{P_{OUT}}{P_{IN}})$$

EIRP (EFFECTIVE ISOTROPIC RADIATED POWER)

~~The antenna transmitted power. Equal to the transmitted~~ output power minus cable loss plus the transmitting antenna gain.

$EIRP = P_{out} - C_t + G_t$
$P_r = P_{out} - C_t + G_t - P_l + G_r - C_r$

Where
- P_{out} = Output power of transmitted in dBm
- C_t = Transmitter cable attenuation in dB
- G_t = Transmitting antenna gain in dBi
- G_r = Receiving antenna gain in dBi
- P_l = Path loss in dB
- C_r = Receiver cable attenuation in dB
- P_r = Received power level at receiver input in dBm
- P_s = Receiver sensitivity in dBm

EQUATIONS, TOOLS, & CALCULATORS

RETURN LOSS, GIVEN VSWR

$$RL(dB) = -20\log(\frac{VSWR - 1}{VSWR + 1})$$

Return Loss, given reflection coefficient (ρ)

$$RL(dB) = -20\log(\rho)$$

E-FIELD FROM DIFFERENTIAL-MODE CURRENT

$$|E_{D,max}| = 2.63 * 10^{-14} \frac{|I_D| f^2 Ls}{d}$$

ID = differential-mode current in loop (A)

f = frequency (Hz)

L = length of loop (m)

s = spacing of loop (m)

d = measurement distance (3 m or 10 m, typ.)

(Assumption that the loop is electrically small and measured over a reflecting surface)

E-FIELD FROM COMMON-MODE CURRENT

$$|E_{C,max}| = 1.257 * 10^{-6} \frac{|I_C| fL}{d}$$

IC = common-mode current in wire (A)

f = frequency (Hz)

L = length of wire (m)

d = measurement distance (3 m or 10 m, typ.) (Assumption that the wire is electrically short)

ANTENNA (FAR FIELD) RELATIONSHIPS

Gain, dBi to numeric $Gain_{numeric} = 10^{dBi/10}$

Gain, numeric to dBi $dBi = 10\log(Gain_{numeric})$

Gain,dBi-to-Antenna Factor $AF = 20\log(MHz) - dBi - 29.79$

Antenna Factor-to-gain indBi $dBi = 20\log(MHz) - AF - 29.79$

Field Strength given watts, numeric gain, distance in meters

$$V/m = \frac{\sqrt{30 * watts * Gain_{numeric}}}{meters}$$

Field Strength given watts, dBi gain, distance in meters

$$V/m = \frac{\sqrt{30 * watts * 10^{(dBi/10)}}}{meters}$$

Transmit power required, given desired V/m, antenna numeric gain, distance in meters

$$Watts = \frac{(V/m * meters)^2}{30 * Gain_{numeric}}$$

Transmit power required, given desired V/m, antenna dBi gain, distance in meters

$$Watts = \frac{(V/m * meters)^2}{30 * 10^{dBi/10}}$$

PC BOARD

1 oz. copper = 1.4 mils = 0.036 mm

0.5 oz. copper = 0.7 mils = 0.018 mm

Convert mils to mm: multiply by 0.0254 mm/mil

Convert mm to mils: multiply by 39.4 mil/mm

Signal velocity in free space: approx. 12 in/ns

Signal velocity in FR-4: approx. 6 in/ns

EQUATIONS, TOOLS, & CALCULATORS

WORKING WITH DB

The decibel is always a ratio

Power Gain = P_{out}/P_{in}

Power Gain(dB) = $10\log(P_{out}/P_{in})$

Voltage Gain(dB) = $20\log(V_{out}/V_{in})$

Current Gain(dB) = $20\log(I_{out}/I_{in})$

We commonly work with:

dBm (referenced to 1 mW)

dBµV (referenced to 1 µV)

dBµA (referenced to 1 µA)

Power Ratios

3 dB = double (or half) the power

10 dB = 10X (or /10) the power

Voltage/Current Ratios

6 dB = double (or half) the voltage/current

10 dB = triple the voltage or current

20 dB = 10X (or /10) the voltage/current

DBM, DBµV, DBµA (CONVERSION)

Volts to dBV:	dBV = 20log(V)
Volts to dBµV:	dBµV = 20log(V) + 120
dBV to Volts:	$V = 10^{(dBV/20)}$
dBµV to Volts:	$V = 10^{((dB\mu V=120)/20)}$
dBV to dBµV:	dBµV = dBV +120
dBµV to dBV:	dBV = dBµV - 120

Note: For current relationships, substitute A for V

FIELD STRENGTH EQUATIONS

dBµV/m to V/m:	V/m= $10^{(((dB\mu V/m)-120)/20)}$
V/m to dBµV/m:	dBµV/m = 20log(V/m) + 120
dBµV/m to dBµA/m:	dBµA/m = dBµV/m - 51.5
dBµA/m to dBµV/m:	dBµV/m = dBµA/m + 51.5
dBµA/m to dBpT:	dBpT = dBµA/m + 2
dBpT to dBµA/m:	dBµA/m = dBpT - 2
µT to A/m:	A/m = µT/1.25
A/m to µT:	µT = 1.25 * A/m

DBM TO DBUV CHART

dBm	dBµV
20	127
10	117
0	107
-10	97
-20	87
-30	77
-40	67
-50	57
-60	47
-70	37
-80	27
-90	17
-100	7

A common formula for converting default spectrum analyzer amplitudes (dBm) to the limits as shown in the emissions standards (dBµV):

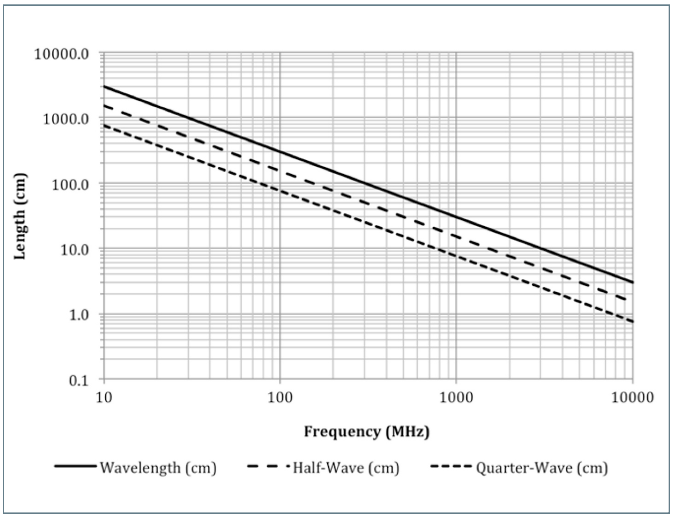
dBm to dBµV, use: dBµV = dBm + 107

EQUATIONS, TOOLS, & CALCULATORS

WAVELENGTH EQUATIONS (FREE SPACE)

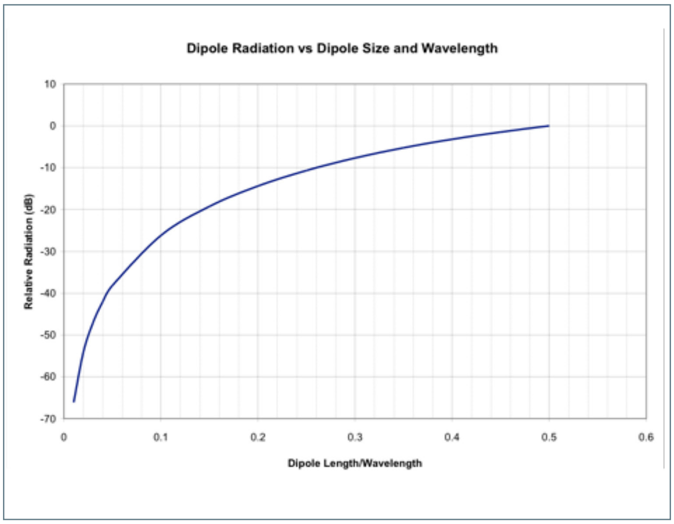
Wavelength(m) = 300/f(MHz)
Half wavelength(ft.) = 468/f(MHz)

RESONANCE OF STRUCTURES



Use this handy chart for determining the resonant frequency versus cable or slot length in free space. Half-wavelength slots or cables simulate dipole antennas and are particularly troublesome.

DIPOLE RADIATION VERSUS LENGTH



Use this chart to for determining the relative radiation versus size in wavelength. Image Source: Bruce Archambeault.

For example, a wire or slot whose length is 0.2 wavelength at a particular frequency, would radiate about 15 dB down from the equivalent half-wavelength wire or slot.

GAIN OF A HALF-WAVE DIPOLE ABOVE AN ISOTROPIC ANTENNA GAIN - G_{dBi}:

$G_{dBi} = 10*\log(G_r) = 10*\log(1.64) = 2.15$ dB

VOLTAGE AND POWER RECEIVED BY A HALF-WAVE DIPOLE:

(Assumes receiver input impedence is 50 Ohms)

$V(\mu V) = E(\mu V/m) * 39.4667/f(MHz)$

$W(dBm) = -90 + 10*\log[V^2(\mu V)/50]$

LINKEDIN GROUPS

Electromagnetic Compatibility Forum
Electromagnetics and Spectrum Engineering Group
EMC - Electromagnetic Compatibility
EMC Experts
EMC Troubleshooters
ESD Experts
Signal & Power Integrity Community
EMI/EMC Testing
iNARTE
IEEE

COMMON SYMBOLS

A	Amperes, unit of electrical current
AC	Alternating Current
AM	Amplitude modulated
dBm	dB with reference to 1 mW
dBμA	dB with reference to 1 μA
dBμV	dB with reference to 1 μV
DC	Direct Current
E	"E" is the electric field component of an electromagnetic field.
E/H	Ratio of the electric field (E) to the magnetic field (H), in the far-field this is the characteristic impedance of free space, approximately 377 Ω
EM	Electromagnetic
EMC	Electromagnetic compatibility
EMI	Electromagnetic Interference
FM	Frequency modulated
GHz	Gigahertz, one billion Hertz (1,000,000,000 Hertz)
H	"H" is the magnetic field component of an electromagnetic field.
Hz	Hertz, unit of measurement for frequency
I	Electric current
kHz	Kilohertz, one thousand Hertz (1,000 Hertz)
λ	Lambda, symbol for wavelength
MHz	Megahertz, one million Hertz (1,000,000 Hertz)
mil	Unit of length, one thousandth of an inch
mW	Milliwatt (0.001 Watt)
mW/cm^2	Milliwatts per square centimeter, a unit for power density
Pd	Power density, unit of measurement of power per unit area (W/m^2 or mW/cm^2)
R	Resistance
RF	Radio Frequency
RFI	Radio Frequency Interference
V	Volts, unit of electric voltage potential
V/m	Volts per meter, unit of electric field strength
W/m^2	Watts per square meter, a unit for power density, one W/m^2 equals 0.1 mw/cm^2
Ω	Ohms, unit of resistance

Ref: ANSI/IEEE 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms, 1984.

ACRONYMS

AF	(Antenna Factor) - The ratio of the received field strength to the voltage at the terminals of a receiving antenna. Units are 1/m.
ALC	(Absorber-Lined Chamber) - A shielded room with RF-absorbing material on the walls and ceiling. In many cases, the floor is reflective.
AM	(Amplitude Modulation) - A technique for putting information on a sinusoidal carrier signal by varying the amplitude of the carrier.
BCI	(Bulk Current Injection) - An EMC test where common-mode currents are coupled onto the power and communications cables of an EUT.
CE	(Conducted Emissions) - The RF energy generated by electronic equipment, which is conducted on power cables.
CE Marking	The marking signifying a product meets the required European Directives.
CENELEC	French acronym for the “European Committee for Electrotechnical Standardization”.
CI	(Conducted Immunity) - A measure of the immunity to RF energy coupled onto cables and wires of an electronic product.
CISPR	French acronym for “International Special Committee on Radio Interference”.
Conducted	Energy transmitted via cables or PC board connections.
Coupling Path	A structure or medium that transmits energy from a noise source to a victim circuit or system.
CS	(Conducted Susceptibility) - RF energy or electrical noise coupled onto I/O cables and power wiring that can disrupt electronic equipment.
CW	(Continuous Wave) - A sinusoidal waveform with a constant amplitude and frequency.
EMC	(Electromagnetic Compatibility) - The ability of a product to coexist in its intended electromagnetic environment without causing or suffering disruption or damage.
EMI	(Electromagnetic Interference) - When electromagnetic energy is transmitted from an electronic device to a victim circuit or system via radiated or conducted paths (or both) and which causes circuit upset in the victim.
EMP	(Electromagnetic Pulse) - Strong electromagnetic transients such as those created by lightning or nuclear blasts.
ESD	(Electrostatic Discharge) - A sudden surge in current (positive or negative) due to an electric spark or secondary discharge causing circuit disruption or component damage. Typically characterized by rise times less than 1 ns and total pulse widths on the order of microseconds.
ESL	(Equivalent Series Inductance) - Generally refers to the parasitic series inductance of a capacitor or inductor. It could also include the extra series inductance of any connecting traces or vias on a PC board.
ESR	(Equivalent Series Resistance) - Generally refers to the parasitic series resistance of a capacitor or inductor.
EU	European Union.
EUT	(Equipment Under Test) - The device being evaluated.
Far Field	When you get far enough from a radiating source the radiated field can be considered planar (or plane waves).
FCC	U.S. Federal Communications Commission.
FM	(Frequency Modulation) - A technique for putting information on a sinusoidal “carrier” signal by varying the frequency of the carrier.
IEC	International Electrotechnical Commission
ISM	(Industrial, Scientific and Medical equipment) - A class of electronic equipment including industrial controllers, test & measurement equipment, medical products and other scientific equipment.
ITE	(Information Technology Equipment) - A class of electronic devices covering a broad range of equipment including computers, printers and external peripherals; also includes, telecommunications equipment, and multi-media devices.

ACRONYMS

LISN	(Line Impedance Stabilization Network) - Used to match the 50-Ohm impedance of measuring receivers to the power line.
MLCC	(Multi-Layer Ceramic Capacitor) - A surface mount capacitor type often used as decoupling or energy storage capacitors in a power distribution network.
Near Field	When you are close enough to a radiating source that its field is considered spherical rather than planar.
Noise Source	A source that generates an electromagnetic perturbation or disruption to other circuits or systems.
OATS	(Open Area Test Site) - An outdoor EMC test site free of reflecting objects except a ground plane.
PDN	(Power Distribution Network) - The wiring and circuit traces from the power source to the electronic circuitry. This includes the parasitic components (R, L, C) of the circuit board, traces, bypass capacitance and any series inductances.
PLT	(Power Line Transient) - A sudden positive or negative surge in the voltage on a power supply input (DC source or AC line).
PI	(Power Integrity) - Refers to the quality of the energy transfer along the power supply circuitry from the voltage regulator module (VRM) to the die of the ICs. High switching noise or oscillations mean a low PI.
Radiated	Energy transmitted through the air via antenna or loops.
RE	(Radiated Emissions) - The energy generated by a circuit or equipment, which is radiated directly from the circuits, chassis and/or cables of equipment.
RFI	Radio Frequency Interference) - The disruption of an electronic device or system due to electromagnetic emissions at radio frequencies (usually a few kHz to a few GHz). Also EMI.
RI	Radiated Immunity) - The ability of circuits or systems to be immune from radiated energy coupled to the chassis, circuit boards and/or cables. Also Radiated Susceptibility (RS).
RF	(Radio Frequency) - A frequency at which electromagnetic radiation of energy is useful for communications.
RS	(Radiated Susceptibility) - The ability of equipment or circuits to withstand or reject nearby radiated RF sources. Also Radiated Immunity (RI).
SSCG	Spread Spectrum Clock Generation) - This technique takes the energy from a CW clock signal and spreads it out wider, which results in a lower effective amplitude for the fundamental and high-order harmonics. Used to achieve improved radiated or conducted emission margin to the limits.
SI	(Signal Integrity) - A set of measures of the quality of an electrical signal.
SSN	(Simultaneous Switching Noise) - Fast pulses that occur on the power bus due to switching transient currents drawn by the digital circuitry.
TEM	(Transverse Electromagnetic) - An electromagnetic plane wave where the electric and magnetic fields are perpendicular to each other everywhere and both fields are perpendicular to the direction of propagation. TEM cells are often used to generate TEM waves for radiated emissions (RE) or radiated immunity (RI) testing.
Victim	An electronic device, component or system that receives an electromagnetic disturbance, which causes circuit upset.
VRM	(Voltage Regulator Module) - A linear or switch-mode voltage regulator. Generally, there will be several of these mounted to a PC board in order to supply different levels of required voltages.
VSWR	(Voltage Standing Wave Ratio) - A measure of how well the load is impedance matched to its transmission line. This is calculated by dividing the voltage at the peak of a standing wave by the voltage at the null in the standing wave. A good match is less than 1.2:1.
XTALK	(Crosstalk) - A measure of the electromagnetic coupling from one circuit to another. This is a common problem between one circuit trace and another.

RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

ITEM 2022
(Interference Technology Engineer's Master)
ITEM is an exhaustive guide full of invaluable EMC directories, standards, formulas, calculators, lists, and "how-to" articles, compiled in easy-to-find formats.
https://learn.interferencetechnology.com/item-2022/

2022 EMC Fundamentals Guide
The Fundamentals Guide keeps your project running smoothly by better understanding how to address EMI and EMC in the early design phases.
https://learn.interferencetechnology.com/2022-emc-fundamentals-guide/

2020 Europe EMC Guide
This guide features technical articles, reference materials, a company directory, and a products and services list for more than 10 countries.
https://learn.interferencetechnology.com/2020-europe-emc-guide/

2019 Components & Materials Guide
This guide is updated with the most critical changes in standards, upcoming events, new product distributors, and more as they relate to EMI shielding and filtering.
https://learn.interferencetechnology.com/2019-components-and-materials-guide/

André and Wyatt,
EMI Troubleshooting Cookbook for Product Designers
SciTech Publishing, 2014. Includes chapters on product design and EMC theory & measurement. A major part of the content includes how to troubleshoot and mitigate all common EMC test failures.

Archambeault,
PCB Design for Real-World EMI Control
Kluwer Academic Publishers, 2002.

Armstrong,
EMC Design Techniques For Electronic Engineers
Armstrong/Nutwood Publications, 2010. A comprehensive treatment of EMC theory and practical product design and measurement applications.

Armstrong,
EMC For Printed Circuit Boards - Basic and Advanced Design and Layout Techniques
Armstrong/Nutwood Publications, 2010. A comprehensive treatment of PC board layout for EMC compliance.

ARRL,
The RFI Handbook
(3rd edition), 2010. Good practical book on radio frequency interference with mitigation techniques. Some EMC theory.

Bogatin,
Signal & Power Integrity - Simplified
Prentice-Hall, 2009 (2nd Edition). Great coverage of signal and power integrity from a fields viewpoint.

Brander, et al,
Trilogy of Magnetics - Design Guide for EMI Filter Design, SMPS & RF Circuits
Würth Electronik, 2010. A comprehensive compilation of valuable design information and examples of filter, switch-mode power supply, and RF circuit design.

Goedbloed,
Electromagnetic Compatibility
Prentice-Hall, 1990. Good general text on EMC with practical experiments. May be out of print.

Kimmel and Gerke,
Electromagnetic Compatibility in Medical Equipment
IEEE Press, 1995. Good general product design information.

Mardiguian,
Controlling Radiated Emissions by Design
Springer, 2016. Good content on product design for compliance.

Kunkel,
Shielding of Electromagnetic Waves, Theory and Practice
Springer. 2019. Provides efficient ways for design engineers to apply electromagnetic theory in shielding of electrical and electronic equipment.

Hall, Hall, and McCall,
High-Speed Digital System Design - A Handbook of Interconnect Theory and Design Practices
Wiley, 2000.

Joffe and Lock,
Grounds For Grounding
Wiley, 2010. This huge book includes way more topics on product design than the title suggests. Covers all aspects of grounding and shielding for products, systems, and facilities.

RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

Johnson and Graham,
High-Speed Digital Design - A Handbook of Black Magic
Prentice-Hall, 1993. Practical coverage of high speed digital signals and measurement.

Johnson and Graham,
High-Speed Signal Propagation - Advanced Black Magic
Prentice-Hall, 2003. Practical coverage of high speed digital signals and measurement.

Ott,
Electromagnetic Compatibility Engineering
Wiley, 2009. The "bible" on EMC measurement, theory, and product design.

Paul,
Introduction to Electromagnetic Compatibility
Wiley, 2006 (2nd Edition). The one source to go to for an upper-level course on EMC theory.

Mardiguian,
EMI Troubleshooting Techniques
McGraw-Hill, 2000. Good coverage of EMI troubleshooting.

Montrose,
EMC Made Simple
Montrose Compliance Services, 2014. The content includes several important areas of EMC theory and product design, troubleshooting, and measurement.

Morrison,
Digital Circuit Boards - Mach 1 GHz
Wiley, 2012. Important concepts of designing high frequency circuit boards from a fields viewpoint.

Morrison,
Grounding And Shielding - Circuits and Interference
Wiley, 2016 (6th Edition). The classic text on grounding and shielding with up to date content on how RF energy flows through circuit boards.

Sandler,
Power Integrity - Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems
McGraw-Hill, 2014. The latest information on measurement and design of power distribution networks and how the network affects stability and EMC.

Slattery and Skinner,
Platform Interference in Wireless Systems - Models, Measurement, and Mitigation
Newnes Press, 2008. The first publication to publicize the issue of self-interference to on-board wireless systems.

Smith,
High Frequency Measurements and Noise in Electronic Circuits
Springer, 1993. A classic book on high frequency measurements, probing techniques, and EMC troubleshooting measurements.

Smith and Bogatin,
Principles of Power Integrity for PDN Design - Simplified
Prentice-Hall, 2017. Getting the power distribution network (PDN) design right is the key to reducing EMI.

Williams,
EMC For Product Designers
Newnes, 2017. Completely updated text on product design for EMC compliance.

Weston,
Electromagnetic Compatibility - Methods, Analysis, Circuits, and Measurement
CRC Press, 2017 (3rd Edition). A comprehensive text, encompassing both commercial and military EMC.

Witte,
Spectrum and Network Measurements
(2nd edition), SciTech Publishing, 2014. The best text around explaining the theory and usage of spectrum and network analyzers.

Wyatt and Jost,
Electromagnetic Compatibility (EMC) Pocket Guide
SciTech Publishing, 2013. A handy pocket-sized reference guide to EMC.

Wyatt and Gruber,
Radio Frequency (RFI) Pocket Guide
SciTech Publishing, 2015. A handy pocket-sized reference guide to radio frequency interference.

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