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ESRP · EMI TEST RECEIVER · 10 Hz ... 7 GHz

TABLE OF CONTENTS

REFERENCE SECTION

Solid State Power Amplifier System Exodus AMP2142DB-100 10KHz – 1000MHz, 100 Watts rated, 150 Watts typical

Exodus model AMP2142DB-100 is a superb 10kHz – 1000MHz, 100-Watt Amplifier System. This dual-band amplifier features 50 dB Minimum Gain, Type N Female RF Input, Sample & RF output ports. Built-in VVA circuits for gain control local & remote functionality, designed for high reliability and ruggedness. Our Rack Mountable drawer can be housed in a cabinet or benchtop for ease of use. This system is suitable for all single channel modulation standards, harsh automotive BCI tests and any application requiring high power and wide band coverage such as EMI/RFI General and specialized test equipment requirements.

Exodus AMP2071A-LC, 80 1000 MHz, 750 Watts with our Quiet-Cool Technology

Exodus AMP2071A-LC is a powerhouse is a compact chassis! Covering 80-1000MHz, produces >750W minimum, >1100W nominal power, P1dB >500W minimum. Excellent gain flatness with a minimum power gain of 58dB. Included are amplifier monitoring parameters for Forward/Reflected power, VSWR, as well as voltage, current & temperature sensing for optimum reliability & ruggedness. Nominal weight is <40Kg, and dimensions of 19"W x 22"L x 8.75"H.

700MHz-6.0GHz, 300W Solid State Power Amplifier System Exodus AMP2030A, 200W P1dB

Exodus AMP2030A, 700MHz – 6.0GHz 300W amplifier provides >200 watts minimum P1dB power with a gain of >53dB. The unit has excellent gain flatness, superior for lab applications with Exodus Quiet-Cool technology. Available are amplifier monitoring parameters for Forward/Reflected power, as well as VSWR, voltage, current & temperature sensing for optimum reliability & ruggedness for all applications. Nominal weight is <90Lbs, and dimensions of 19"W x 22"D x 8.75"H.

Exodus 18.0-40.0GHz, 10-Watt SSPA replaces aging TWT technology

Exodus Advanced Communications 18.0-40.0GHz, 10W+ Solid State Amps are replacing aging TWT Amplifiers. Designed for General EMC Testing Applications as well as Mil-Std 461(RS103) standards. Exodus Model AMP4037 is a compact 5U design that provides superb RF Performance with **Unprecedented P1dB power as compared to TWT's**. It provides 40dB min-gain, -20dBc harmonics as well as gain control with < 10dB noise figure.

Exodus AMP2085D 2.0–8.0GHz, 300W, an Outstanding TWT replacement

Exodus AMP2085D, a rugged SSPA replacing aging TWT technology. Ultra-broadband, class A/AB design for all industry standards. 2.0-8.0GHz, 300W Minimum, 400W typical & 55dB gain. Excellent P1dB power/gain flatness compared to TWT's. Forward/Reflected power monitoring, VSWR, voltage/current/-temperature sensing for superb reliability and ruggedness. The nominal weight is 75lbs in a compact 6U chassis.

Exodus AMP2033LC, 6.0–18.0GHz, 100 Watts, another Exceptional TWT replacement

Exodus AMP2033LC is designed for replacing aging TWT technology. A broadband, rugged EMC Class A/AB linear design for all modulations & industry standards. Covers 6.0-18.0GHz, produces >100W Minimum, 50W P1dB, with a minimum 50dB gain. Excellent flatness, optional monitoring parameters for Forward/Reflected power, VSWR, voltage, current & temperature sensing for superb-reliability. Exodus Quiet-Cool technology in our compact 5U-chassis weighing a nominal 75lbs.

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INTRODUCTION

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Electromagnetic compatibility (EMC) and the related electromagnetic interference (EMI) seems to be one of those necessary evils that must be overcome prior to marketing commercial or consumer electronic products, as well as military and aerospace equipment. Unfortunately, few universities and colleges teach this important information, with the result that products are rarely designed to meet EMC/EMI requirements. EMC or EMI compliance is often left to the end of a project with all the associated schedule delays and unplanned cost.

The purpose of this short guide is to help product designers or EMC engineers learn enough of the basics of EMC and EMI so that the usual design failures are addressed early, when costs and design delay is minimized. Achieving EMC/EMI is easy once the basics are understood.

Today, with all the myriad of electronic products, including wireless and mobile devices, compatibility between devices is becoming even more important. Products must not interfere with one another (radiated or conducted emissions) and they must be designed to be immune to external energy sources. Most countries now impose some sort of EMC standards to which products must be tested.

Basic Definitions

Let's start with some basic definitions, and there's a subtle difference. EMC implies that the equipment being developed is compatible within the expected operating environment. For example, a ruggedized satellite communications system when mounted in a military vehicle must work as expected, even in the vicinity of other high-powered transmitters or radars. This implies both emissions and immunity in close environments. This usually applies to military and aerospace products and systems, as well as automotive environments.

EMI, on the other hand, is more concerned with one product interfering with existing radio, television, or other communications systems, such as mobile telephone. It also includes immunity to external energy, such as electrostatic discharge and power line transients. This usually applies to commercial, consumer, industrial, medical, and scientific products.

Why Do Products Radiate or Are Susceptible?

So, why do electronic products radiate or are susceptible to external energy sources? It's all about controlling the energy from internal sources from coupling out causing interference and external energy sources (ESD, etc.) from getting into and disrupting sensitive circuitry.

For example, the most common issue for most products is radiated emissions. We have an energy source, and somehow, this energy source couples harmonic currents to an "antenna-like structure", such as an I/O cable. See *Figure 1*.

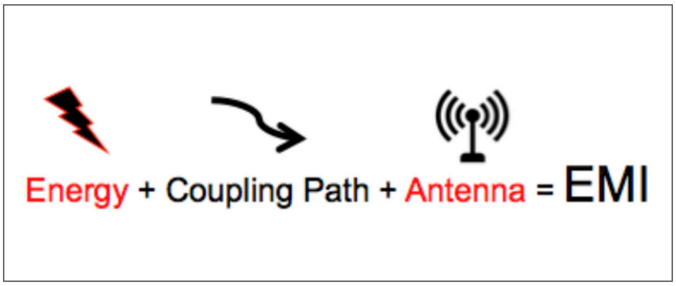

Figure 1: A simple model for radiated emissions. Take away any of the three elements and you have no EMI.

Internal energy sources might include high-frequency clocks or any high-speed, fast-edged digital signal. These may be transferred via conduction, radiation, inductive, or capacitive coupling mechanisms. For example, a common situation is harmonics of a fast-edged clock (say an Ethernet clock) coupling to an I/O cable, which acts as an antenna and radiates. If these harmonic emissions are over certain limits, the product fails the compliance test and must be redesigned to reduce or eliminate the coupling.

The reverse is also common. A good example is external ESD energy coupling to a poorly shielded or terminated I/O cable and allowing the resulting high transient current to disrupt (or destroy) sensitive circuitry.

The three top product failures I see all the time as a consultant are (1) radiated emissions, (2) radiated susceptibility, and (3) electrostatic discharge. In many cases, these failures are due to poorly-designed PC boards.

We'll start off with some very basic EMC theory, and wrap up with a host of additional reference material, such as lists of common EMC standards, additional reference articles, books, and many other charts and tools.

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- **Magnetics**
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- **Power Filters**
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- **Specialty Connectors**
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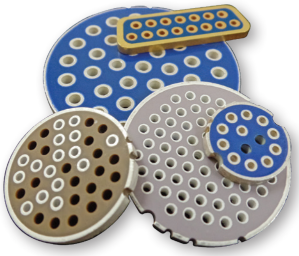

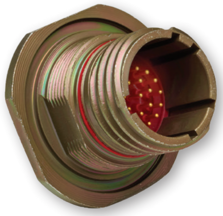

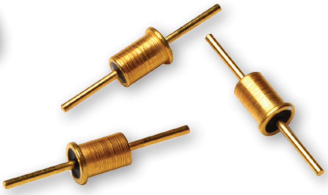

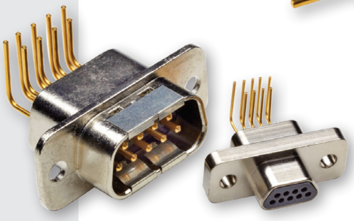

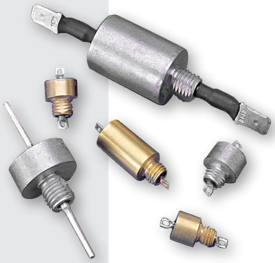

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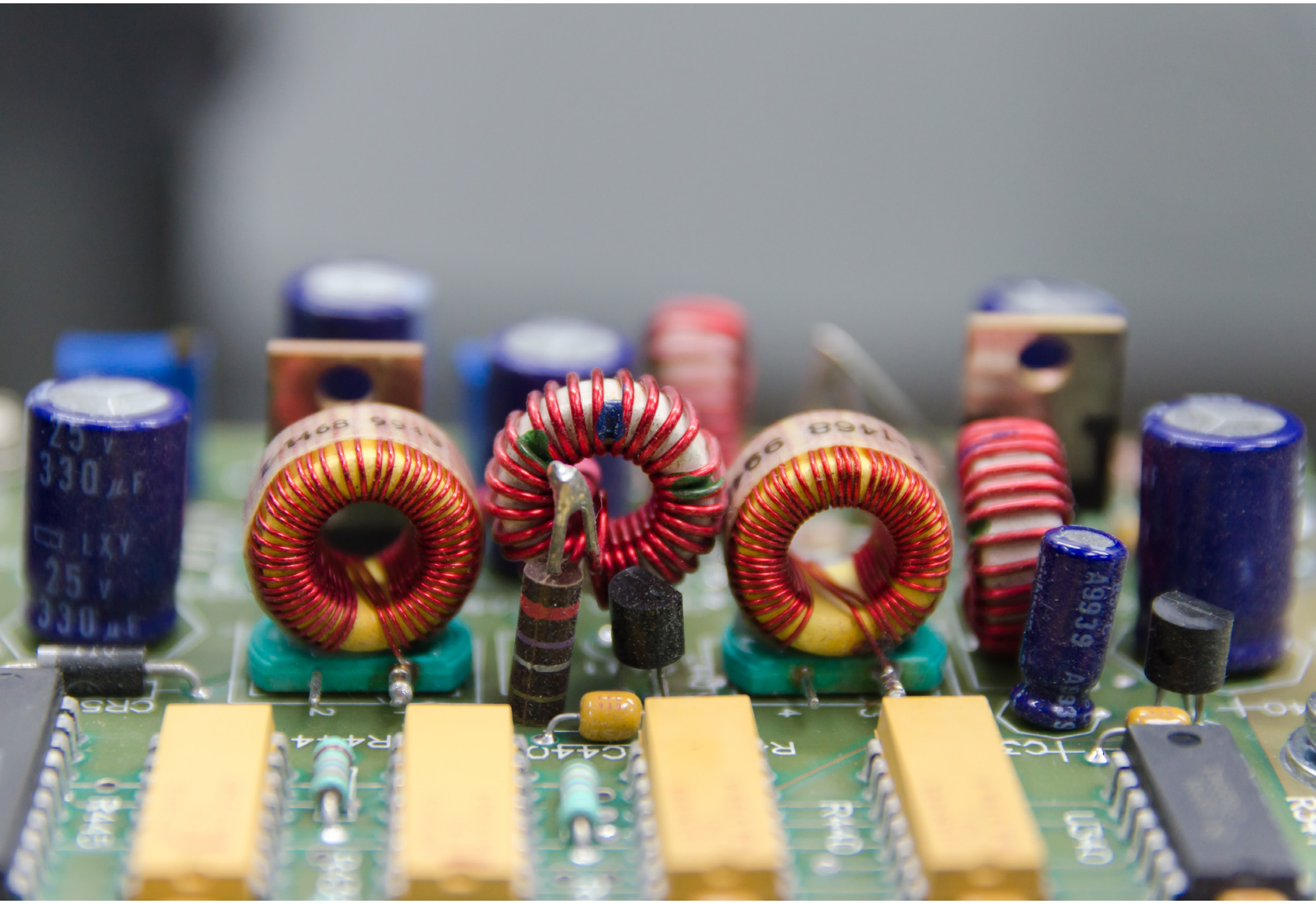
2020 EMC SUPPLIER GUIDE

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 jennifer@lectrixgroup.com for further supplier contacts.



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A	Aaronia AG	www.aaronia.com	X	X						X							X						
	Advanced Test Equipment Rentals (ATEC)	www.atecorp.com	X	X		X				X		X			X	X	X	X	X	X	X		
	AH Systems, Inc.	www.ahsystems.com	X	X	X													X	X	X			
	Altair- US	www.altair.com					X		X														
	American Certification Body Inc.	www.acbcert.com				X	X		X												X	X	X
	Ametek- CTS Compliance Test Solutions	www.ametek-cts.com	X	X														X		X			X
	Anritsu Company	www.anritsu.com		X													X	X		X	X		
	API Technologies	www.apitech.com						X			X												
	AR RF/Microwave Instrumentation	www.arworld.us	X	X	X				X									X	X				
	Astrodyne	www.astrodyneTDI.com									X												
B	Beehive Electronics	www.beehive-electronics.com																			X		
	BHD	https://bhdtm.com	X							X							X		X				
C	Captor Corporation (EMC Div.)	www.captorcorp.com									X												
	Coilcraft	www.coilcraft.com						X			X												
	Compliance Direction, LLC	https://compliancedirection.com					X																X
	CPI- Communications & Power Industries (USA)	www.cpii.com/emc	X																				
D	Dassault System Simulia Corp	www.3ds.com/products-services/simulia							X														
	Delta Electronics (Americas) Ltd.	www.delta-americas.com									X												
	DLS Electronic Systems, Inc.	www.dlsemc.com																				X	
	Don Heirman Consultants	https://donheirman.com					X																
E	Electro Rent	www.electrorent.com	X							X				X			X		X				
	Elite Electronic Engineering Co.	www.elitetest.com																				X	
	EMC LIVE	www.emc.live																					X
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	Empower RF Systems, Inc.	www.empowerrf.com	X																				
	EM TEST USA	www.emtest.com																X					
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F	F2 Labs	www.f2labs.com				X	X														X	X	X
	Fischer Custom Communications	www.fischercc.com																		X			
	Frankonia Solutions	www.frankonia-solutions.com													X	X		X				X	
G	Gauss Instruments	www.gauss-instruments.com								X							X						
	Gowanda Electronics	www.gowanda.com						X															
H	Haefely	www.haefely.com							X									X			X		
	Heilind Electronics, Inc	www.heilind.com									X												
	Henry Ott Consultants	www.hottconsultants.com					X																
	HV TECHNOLOGIES, Inc.	www.hvtechnologies.com	X	X						X		X				X	X	X		X			
I	Interference Technology	www.interferencetechnology.com																					X
	Intertek	www.intertek.com																				X	
	ITG Electronics	www.itg-electronics.com						X			X												
K	Keysight Technologies	www.keysight.com/us/en								X							X		X	X			
	Krieger Specialty Products	www.kriegerproducts.com														X							
L	Laird Electronics	www.lairdtech.com									X			X									
	Langer EMV-Technik	www.langer-emv.de/en/index																		X			
M	Magnetic Shield Corp.	www.magnetic-shield.com													X								
	Master Bond Inc.	www.masterbond.com												X									
	MILMEGA	www.ametek-cts.com	X																				
	Montrose Compliance Services	www.montrosecompliance.com					X																
	MVG Microwave Vision Group	www.mvg-world.com		X							X				X	X							
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	Ophir RF	www.ophirrf.com	X																				
P	Parker Chomerics	www.chomerics.com													X								
	Pearson Electronics	www.pearsonelectronics.com						X															
	PPG Cuming Lehman Chambers	www.cuminglehman.com													X	X					X		
	PPG Engineering Materials	www.dexmet.com													X								
	Pulse Power & Measurement Ltd	https://ppmtest.com/																		X			
Q	Quell Corp.	www.eeseal.com			X						X	X									X		

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R	Radiometrics	www.radiomet.com																				X	
	R&B Laboratory, Inc.	www.rblaboratory.com																				X	
	Retlif Testing Laboratories	www.retlif.com																			X	X	X
	RIGOL Technologies	www.rigolna.com	X					X									X	X		X			
	R&K Company Limited	www.rk-microwave.com	X					X															
	Rohde & Schwarz GmbH & Co. KG	www.rohde-schwarz.com/de	X	X						X					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												
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T	TDK	www.tdk.com						X			X					X				X			
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	Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X							X						
	TPI	www.rf-consultant.com					X																
	Transient Specialists	www.transientspecialists.com																	X				
	TRSRenTelCo	www.trsrentelco.com/categories/spectrum-analyzers/emc-test-equipment	X	X						X							X	X	X		X		
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	V Technical Textiles / Shieldex US	www.vtechtextiles.com													X								
W	Washington Laboratories	www.wll.com				X	X		X			X									X	X	X
	Windfreak Technologies	www.windfreaktech.com																X			X		
	Würth Elektronik eiSos GmbH & Co. Kg	www.we-online.com		X	X			X	X		X	X			X								
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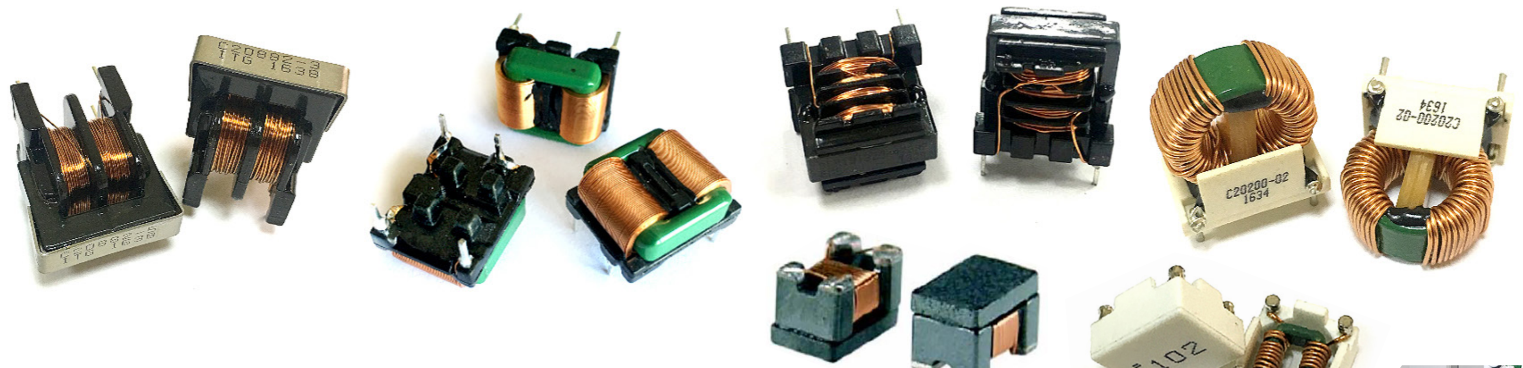

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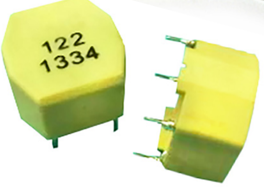

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WHAT IS EMC?

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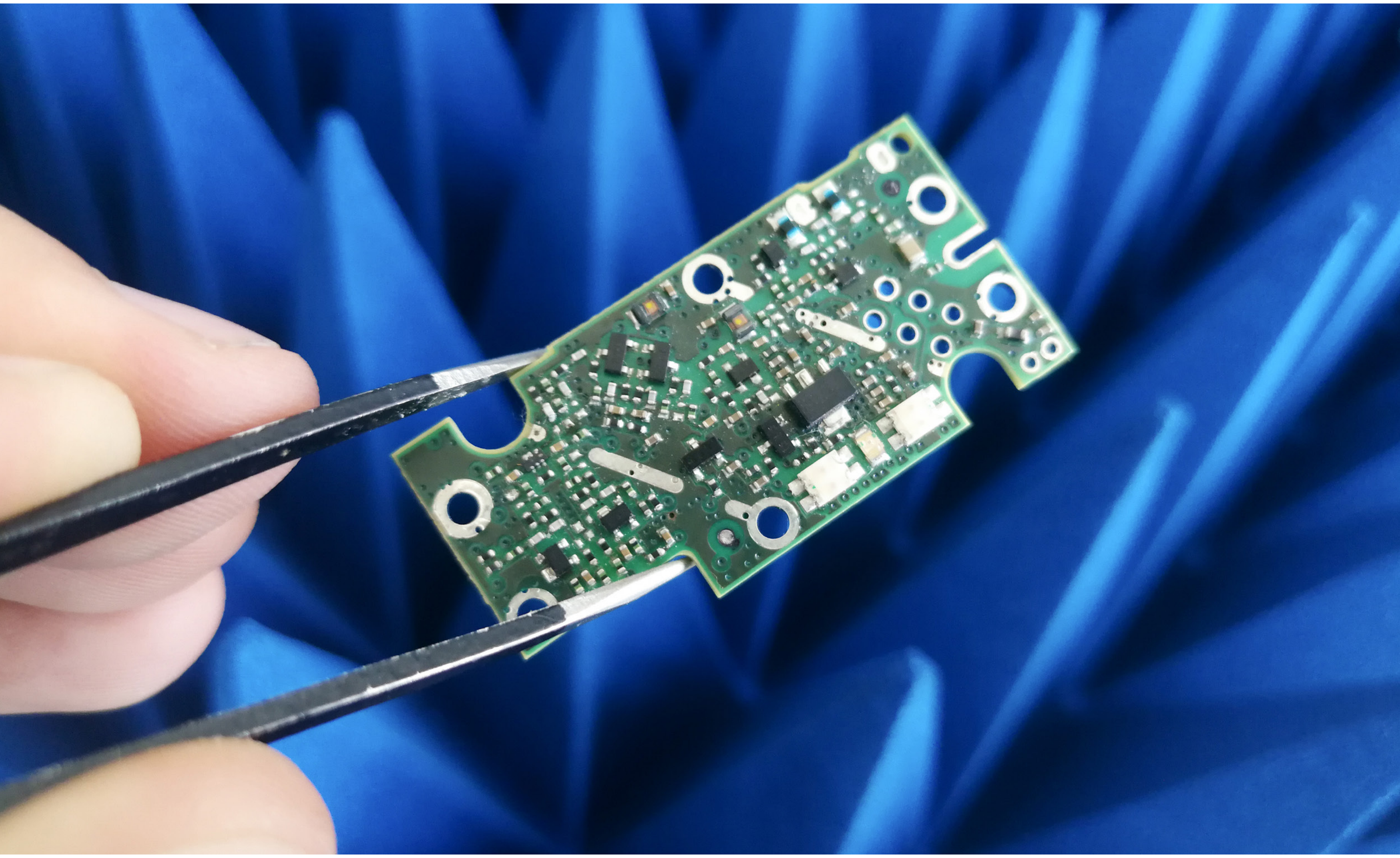
Introduction

This article will serve as an introduction to the topic. It is aimed at the people who have been told by their management, "You are now my EMC person. Go figure out what it is and how we must deal with it!" It will not be an all encompassing treatment of the subject, but it will provide the reader with a start and some ideas of where to go for more information.



WHAT IS EMC?

EMC stands for electromagnetic compatibility. You will see some people refer to EMC/EMI, but this is partially redundant. EMI (electromagnetic interference) is just a part of EMC. The two major parts of EMC are EMI and EMS (electromagnetic susceptibility) as it is called in the aerospace and military world and electromagnetic immunity (as it is called in the commercial world). Susceptibility and immunity are pretty much the same thing, just called by different terms. Susceptibility is a measure of how a device reacts to various items in the electromagnetic environment and immunity is simply a demonstration of its failure to react to certain levels of these phenomena. Emissions are regulated in the commercial world in various ways and immunity for commercial products is regulated in certain countries and not at all in many others.

In the aerospace and military world, a common standard for emissions and susceptibility is MIL-STD-461G. Various tests and levels are called out for various services and products. In the commercial world, it depends on what product is being discussed, but for information technology equipment (ITE), broadcast receivers, and multimedia equipment, CISPR 32 provides limits for emissions and CISPR 35 provides tests and test levels for immunity. In the U.S., the FCC in Part 15 of its rules provides limits for emissions and does not mandate immunity for digital devices. In fact, the rules specifically state that a Part 15 device must accept any interference received. Countries that mandate immunity, on the other hand, require that products not suffer inference when tested to the levels called out in the applicable standards.

WHAT CAUSES ELECTROMAGNETIC EMISSIONS IN THE FIRST PLACE?

Various functions within a product may contribute to the generation of emissions. These emissions may be radiated from the product, typically as radio waves, or they may be conducted from the product via the power mains cable or other I/O cables connected to the product. Limits on the magnitude of these emissions are specified by regulatory bodies in many countries to protect licensed and unlicensed users of the radio spectrum from harmful interference.

Emissions from the product may be created by various means within the product. The two major means by which these may be generated are harmonics of intentional signals or parasitic emissions, which can come from improperly terminated transmission lines and the lengths of these lines.

In the case of harmonics of clocks and other signals, these emissions will be related to the fundamental frequency and integral harmonics of these signals. *Figure 1* shows the relationship of these signals. An envelope, which will not be exceeded in level by these signals is shown in *Figure 2*. They may not get up to this envelope in value, but they will not exceed it. The example shown is for a 50% duty cycle signal with a frequency of 500 MHz, a rise and fall time of .03 x 10^{-9} seconds, a pulse width of .97 x 10^{-9} seconds and an amplitude of 3.3 volts.

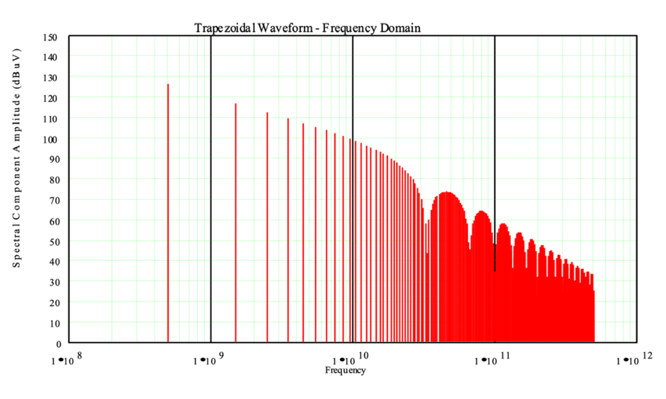


Figure 1: Frequencies resulting from a 500 MHz trapezoidal waveform

There are a couple of key things to note in *Figure 1*, including that the computed harmonics do not always rise to the envelope in *Figure 2*, but never exceed it. If you were to look at the signal (ideal) in both the time and frequency domains, it will look something like the following:

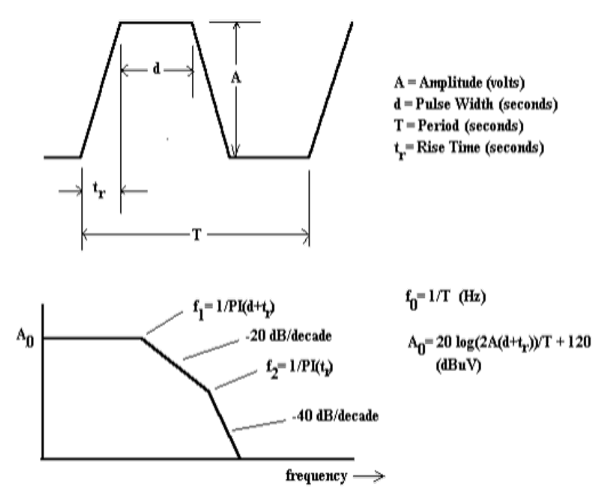


Figure 2: Trapezoidal waveform and envelope containing all harmonics

The fundamental of this 50% duty cycle signal actually falls above the first break point in frequency when the envelope starts falling at -20 dB/decade of frequency. Above f_2 the envelope falls off at -40 dB/decade of frequency. So, lowering the rise time of the signal moves this breakpoint to the left, decreasing the harmonics levels at higher frequencies faster. In reality, circuit designers are going to use the fastest products they can find, but the EMC engineer can always dream.

You may run into digital designers who say that 500 MHz isn't very high. Just remember, 470 MHz is the bottom of the UHF television broadcast band, so 500 MHz is very definitely RF. It may not be high to a digital circuit designer, but it definitely is RF and will certainly radiate and cause interference to licensed services.

Why is this preceding information important? It gives the EMC engineer a tool for computing the frequencies that may come from the product, at least as harmonics of intentionally generated digital signals. It also gives a tool for computing the amplitudes of these signals. The next step, at least for computing the radiated or conducted emissions, will be to compute the coupling factor or factors, as a function of frequency. Or, if the measurements have already been performed, then troubleshooting to bring them into compliance may be the next thing on the agenda.

Another means by which RF energy can be created by a product is due to transmission lines that are not properly terminated. The frequency of these emissions will not necessarily be harmonically related to the frequency of the signal being sent down the transmission line, but, will instead, be related to the propagation velocity of the wave down the transmission line and its length. This termination may be designed into the product at either end of the transmission line and each has its advantages and disadvantages. Troubleshooting these emissions can take more detective work.

There are a number of ways that RF energy created by a product through its normal operation can generate and radiate unintentional emissions that can cause interference or simply failure to pass emissions limits. This paper will not go into detail on each as this would be way beyond the scope of a single paper, but things to consider are current loops, exit points from PWBs for cables, bypassing (all filters are not created equal and installation methods are critical), component layout, trace routing, chassis and packaging design, and “grounding”. Notice that I put quotation marks around grounding. Grounding in the EMC sense does not mean connection to earth ground. Ask yourself how this would be possible for a satellite in geosynchronous orbit around the earth. Obviously, it isn’t, and satellites typically have to meet far more stringent EMC requirements than your computer on your desk.

WHAT IS A MODEL FOR INTERFERENCE?

There are three basic components in the interference model that must be considered.

There is a source. This may be a board, a complete device, or natural event. It generates the emission that is causing the problem.

There is a victim. This is the device (component, board, or full product) that suffers interference that causes whatever malfunction is being noted. This may be an unintended operation or a failure to operate on the part of the device suffering as a victim.

Finally, there is a path for the interfering emission to travel from the source to the victim. This may be a direct radiation path or a conducted path. It may fall under the control of the operator of the source, it may fall under the control of the operator of the victim, or a combination of both.

HOW DO I FIX AN EMC PROBLEM?

To quote a retired professor (Todd Hubing), “It depends.” What is the problem? Did your product fail an EMC test? Is it causing harmful interference to another device or service? Fix your product. This is especially important if you only control the source (in the case of emissions) or the victim (in the case of immunity testing). If you control both the source and victim, you may be able to alter the path and leave the source and/or victim alone.

Let’s assume that your product is failing an emissions test. This is not the best time to find out that you have an EMC problem as marketing probably wants to ship the product soon and you are being called the roadblock to shipping and are therefore the bad guy. Never mind that you have been telling the project team for a year that there are areas they need to address, and they have refused to make changes you’ve recommended. This is where a prime requirement to being an EMC engineer comes in—you must have a thick skin and stick to your guns. No data showing compliance, no shipment of product. Get to know the project lawyers well in advance, they likely will be on your side. You’ll spend long hours in the lab finding and fixing the problem(s). Oh, and your fixes must be manufacturable and, ideally, cheap (or even free). Sometimes these are, and sometimes they aren’t. Sometimes a product that passed in the lab last week or last month will have had a change made by a vendor as it was easier for them to make the part and your company’s specification wasn’t tight enough to prevent the change. Can you find this problem quickly and tell the program team how to fix it? Oh, and there are some problems that you will find repeatedly over a career as new designers come and go, creating job security for EMC engineers. So, from a personal point of view, these easy to find and fix problems aren’t all bad. At least not after you’ve found and fixed them a few times over the years. It you are new to the game it will take a bit longer.

IMMUNITY

I haven’t discussed immunity as a separate issue much in this paper. The good news (at least on the commercial side of the discussion) is that immunity isn’t typically a major issue for designers and EMC engineers. Prior to immunity requirements being published for the first time about 30 years ago one major manufacturer only had internal specifications for electrostatic discharge and power line surges. Nothing else in their experience showed itself to be an issue. Some of the commercial immunity requirements are so low that the EMC engineer can tell the project designers 6 months in advance that he will run the test only because it is required, but not to worry as the product will pass. Or the company may have internal requirements for significantly higher test levels, in which case more attention must be paid to the test phenomena. ESD and surge testing, however, do not fall in the camp of serious concern. If a designer lives and works in an area where humidity levels are typically high, he probably doesn't have much experience or worry about ESD failures. If, however, he lives and works in an area like the front range of Colorado or Washington D.C. where humidity levels can be very low, he likely will be a firm believer in ESD. Likewise for electrical surge, if the designer lives in an area where lightning storms are common surge is an issue. If not, no worries. However, the product must be sold and used in areas where these are common problems.

Then there are the immunity or susceptibility matters that must be considered to avoid problems like the U.S.S. *Forrestal* in the late 1960s. Susceptibility can be a serious matter. Three V/m may be adequate for some commercial environments, but the flight deck of an aircraft carrier is not one of those environments. Do a Google search and look for the video and discussion of what went wrong on the *Forrestal* to see what I mean.

CONCLUSION

EMC is a matter deserving of serious consideration. It may only be a matter of whether a product can ship on time, or it may be a matter of life and death. Learn about it, ask questions of people who are considered experts in the subject (I'll give you my definition of "expert" some time), and read books and articles on the subject. Also, attend events where you can learn more about EMC by listening to papers, talking with vendors, and networking with "your fellow wizards". You'll find in many of those places that EMC folks (engineers and technicians) are EMC professionals first and employees of X, Y, or Z company second. They won't disclose company secrets, but they will help you fight a common enemy—EMC issues.

Listed below are a few places where you can learn more about EMC.

- *Noise Reduction Techniques In Electronic Systems, Second Edition*, Henry W. Ott, John Wiley & Sons, 1988

  This is a great book for learning more about EMC.

- *Fields and Waves in Communication Electronics*, Ramo, Whinnery and Van Duzer, John Wiley & Sons, 1965

  I thought this was a lousy textbook when I was in college (maybe some bias there), but it is a fantastic reference book that I highly recommend you have.

- *Introduction to Electromagnetic Compatibility, 2nd Edition*, Clayton R. Paul, John Wiley & Sons, 2006

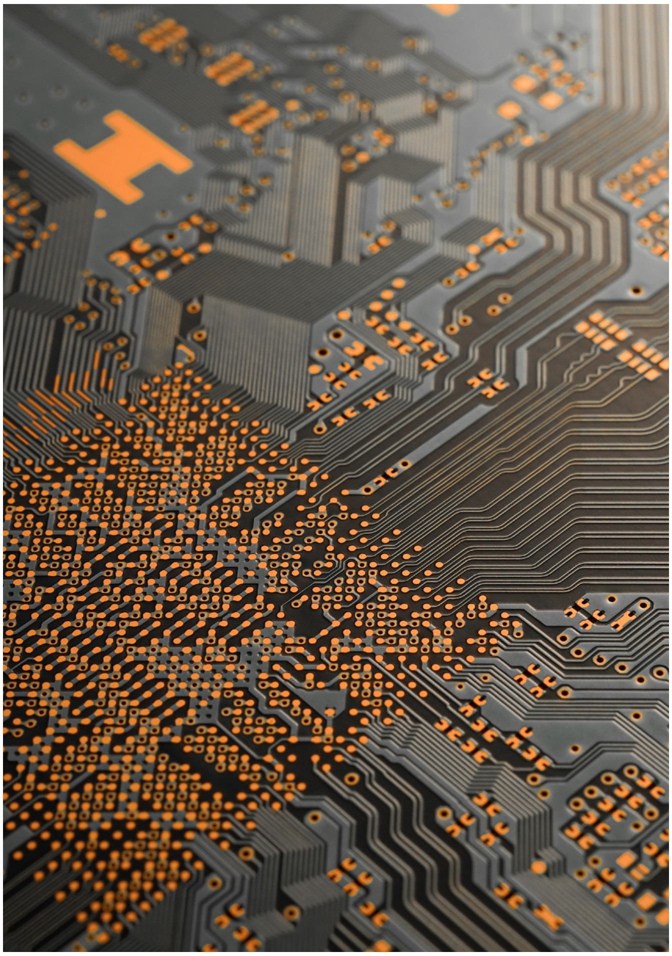
  Clayton has passed away, much to the sorrow of those of us who knew him, but if I was limited to a single book on EMC, this is the one I would have. Not a simple, easy to read, treatment on the subject, but complete and comprehensive. I highly recommend this book.

- *PCB Design for Real-World EMI Control*, Bruce Archambeault and James Drewniak, Kluwer Academic Publishers, 2002/2004

  The title says it all. It is limited to PCBs, but it is a great treatment on the subject, by two gentlemen who are well respected in the EMC world. Bruce is a past president of the IEEE EMC Society and has been around the block more than once.

There are plenty more books and papers that you can read and learn from. This is just a start, but for someone new to the EMC world this will be a great start.

Have fun and feel free to ask questions when you have some. I don't say "if" because after 44 years I still have many.



SEVEN FUNDAMENTAL CONSIDERATIONS FOR SELECTING EMI FILTERS

Rigoberto Rios[1], Jorge Varela[2], and Amanda Ison[3]
Engineering Manager[1], Application Engineer[2], Principal Engineer[3]
AVX Corporation

Introduction

Virtually every electronic device is subject to and, to at least some degree, must be protected from electromagnetic interference (EMI), or electrical noise. EMI is generated by both naturally occurring and engineered sources ranging from solar flares to cell phones, and, if left unmitigated, diminishes the integrity and accuracy of signal transmissions. Engineered EMI can even affect the very circuits it emits from in addition to other electronics in the surrounding environment. So, it's a pervasive problem in electronic design.

Although effective EMI filtering is particularly important in high-reliability electronics applications with low-power signals, strict signal fidelity demands, and a high cost of failure, such as satellites and pacemakers, it also plays a critical role in commercial applications that require sensitivity to low-power signals in noisy environments, like instrumentation equipment.

To protect electronic circuits from interference, device designers often employ board-level EMI suppression filters and, since EMI protection is fundamental to the proper operation of nearly every electronics application, there are a myriad filtering solutions available on the market. To ensure optimal filter selections, device designers should carefully consider the following seven characteristics of EMI filters in the context of the application at hand: filtering properties, circuit configuration, voltage conditions, construction, installation options, testing and inspection, and manufacturing costs.

SEVEN FUNDAMENTAL CONSIDERATIONS FOR SELECTING EMI FILTERS

1. FILTERING PROPERTIES

EMI filters are designed to suppress the transmission of selected frequencies of a given signal. One of the most common types of filters in commercial, consumer, and other less critical applications is a simple, low-pass EMI filter, which allows low-frequency signals to pass through while blocking out unwanted, higher frequency noise, as defined by its cutoff frequency, or the frequency at which a filter begins to attenuate part of the signal. Cutoff frequencies typically represent the point at which the signal amplitude is 3 dB below the nominal passband value, and along with frequency response, are directly affected by a filter's capacitance and inductance values.

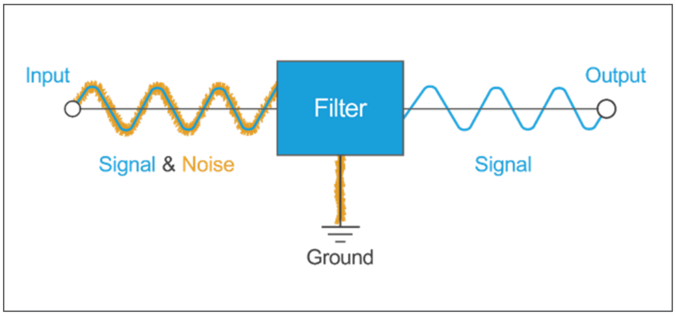


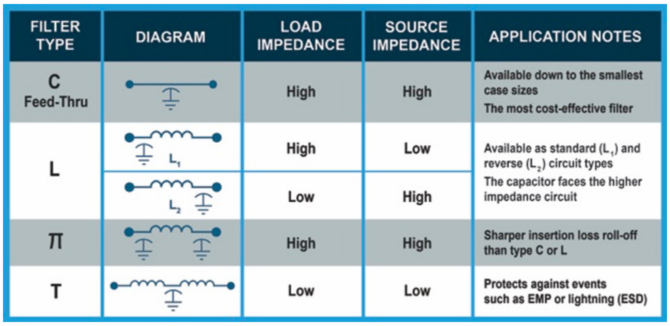
Figure 1: A diagram illustrating the basic concept of EMI filtering.

Insertion loss values, which refer to the ratio of the strength of an incoming signal to the strength of the transmitted signal and are typically expressed in decibels, are a prime characteristic of filter efficacy. Ideal insertion loss for the frequency range of interest is 0 dB and is infinite for all other frequencies, but filters are complex devices that are subject to variables including parasitic inductance, parasitic capacitance, component resonance, and circuit resonance; so, it's impossible to achieve ideal performance. However, once a filter has been designed and produced, users can analyze its insertion loss across a wide range of frequencies to identify the parameters of its performance envelope.

Other characteristics that effect filter performance include equivalent series resistance (ESR), dissipation factor (DF), and Q factor. Low ESR is an indication of a well-designed filter that will not dissipate much energy during its operation. Low DF, which takes into account both the ESR and reactance of the filtered capacitor, is another, as it its inverse, Q factor, which is also used to denote filter quality in some industries.

2. CIRCUIT CONFIGURATION

EMI filters are widely available in several different circuit configurations ranging from single grounded capacitors to circuits with up to three elements. Ideal selections depend on the unique characteristics and properties of the application at hand, such as device impedance.



FILTER TYPE	DIAGRAM	LOAD IMPEDANCE	SOURCE IMPEDANCE	APPLICATION NOTES
C Feed-Thru		High	High	Available down to the smallest case sizes The most cost-effective filter
L	L_1	High	Low	Available as standard (L_1) and reverse (L_2) circuit types The capacitor faces the higher impedance circuit
	L_2	Low	High	
π		High	High	Sharper insertion loss roll-off than type C or L
T		Low	Low	Protects against events such as EMP or lightning (ESD)

Figure 2: Common EMI filter circuit configurations and characteristics.

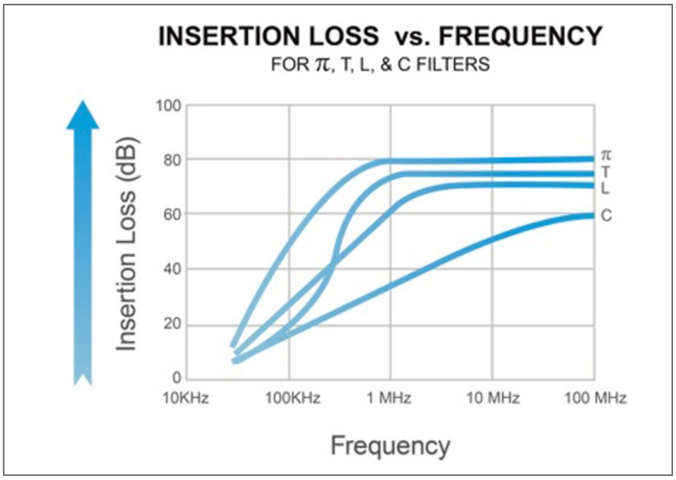


Figure 3: This graph illustrates the relationship between insertion loss and frequency for several different filter circuit configurations with a full load in a balanced 50 Ω system that already accounts for component and circuit resonance.

3. VOLTAGE CONDITIONS

For optimal EMI protection, EMI filter performance must be matched to corresponding capacitor performance, designed and tested for the given circuit's AC or DC voltage conditions, and designed to mitigate current leakage. For example, ceramic capacitors have very thin layers of ceramic dielectric that separate the conductive layers from one another to prevent the free flow of electricity and can be designed to withstand voltages in excess of 1,600 VDC. As such, effective filter designs have to employ the appropriate dielectric materials and dimensions best suited for each corresponding capacitor's unique set of performance requirements.

EMI filters must also be designed and tested for each circuit's AC or DC voltage conditions. DC filter ratings are not the same as AC filter ratings, so a filter's ability to successfully withstand high DC voltage does not adequately predict its performance when exposed to high AC voltage and vice versa. For instance, AC-rated filters will often have lower capacitance values to prevent overheating and damage resulting from reactive current heating, while DC-rated filters expected to experience short, irregular bursts of voltage, like those employed in implantable cardiac defibrillators, are likely to undergo a pulsed voltage test to verify capacitor integrity.

In addition to being able to withstand given circuit voltages, effective filters also help control current leakage across the capacitor. Although it's impossible to construct a capacitor that completely prevents this flow of electricity, EMI filters can leverage inherent material properties to mitigate leakage current and its impact on device performance.

4. FILTER CONSTRUCTION

Donut-shaped discoidal capacitors are one of the most common feed-through-style EMI filter constructions. The inside and outside diameters of these circular capacitors act as connection points for the case and the lead and serve as the poles of the capacitor. In applications where space is at a premium, several discoidal capacitors can be integrated into a single piece of ceramic to create a capacitor array. These filtered feedthrough assemblies provide the highest concentration of filters within the smallest physical space and are often employed in miniature, high-density implantable medical devices, as well as size- and weight-restricted commercial and military applications.

Complex electronic devices often require filtering on multiple signal or power lines. One way to isolate them from each another is to employ a special metal ferrule that both contains and acts as a common ground for multiple filters by connecting their cases together while keeping the pins isolated. Fully tested and assembled feedthrough filter capacitor arrays offer another optimal solution for more complex circuits, as they are widely available in custom shapes and sizes that facilitate seamless, single-step integration into more challenging device designs and reduce the potential for installation errors and resulting component damage. There is no hard limit on the number of capacitors that can be integrated into a single array, but component cost increases with capacitor quantity.

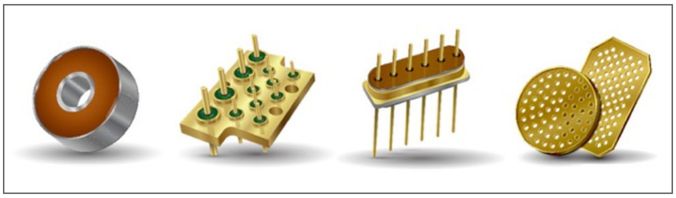


Figure 4: Common EMI filter constructions from left to right: a discoidal capacitor, a metal ferrule containing multiple filters, a filtered feedthrough array, and capacitor arrays.

EMI filters are also available in a wide variety of case sizes, lead lengths, and environmental sealing options for broad application suitability, and many filter manufacturers will develop custom designs when existing off-the-shelf options aren't an ideal fit. Hermetically sealed filters prevent the leakage of gasses and are often employed in aerospace applications, and environmentally sealed filters provide resistance against the ingress of dust, dirt, moisture, and other contaminants and are widely employed in harsh-environment automotive, industrial, medical, defense, and transportation applications.

5. INSTALLATION OPTIONS

Although filters must be installed in an EMI shield, such as a well-grounded conductive enclosure, for optimal performance, device designers can choose from a variety of installation options. Solder-in filters are ideally suited for compact installations, are designed to withstand brief exposure to high soldering temperatures, and typically achieve the best hermeticity of the top three installation styles. Other leading options include bolt-in filters, which have a threaded, typically hexagonal head, and screw-in cylindrical filters, which have the largest internal volume, can accommodate complex circuits, such as a Pi and T filters, in a single package, and are mounted using separate screws.

In addition to selecting the right installation method for a given application, device designers can further ensure the integrity of the filter both during and after installation by preheating solder joints before exposing them to the full soldering temperature to help mitigate thermal stress and gently handling filter cases to prevent mechanical deformation.

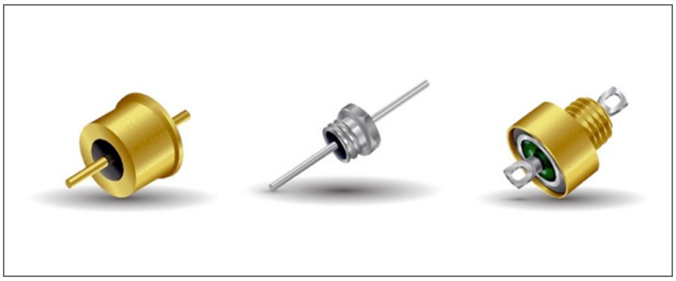


Figure 5: The three most common EMI filter installation styles from left to right: solder-in, bolt-in, and screw-in.

6. TESTING AND INSPECTION

When selecting filters for mission-critical applications, like manned spaceflights and implantable medical devices, options should be limited to filters that have been subjected to enhanced electrical and visual inspections and additional testing sequences to further ensure robust, long-lifetime performance. For instance, several military specifications contain extremely specific instructions and performance requirements for electrical, mechanical, and thermal testing procedures and can be useful for validating mission-critical application suitability. In addition, stress testing is often conducted on ceramic components since they typically have a high propensity for crack propagation and those with any hint of mechanical instability will generally fail early on and effectively eliminate any inferior parts that could cause future performance issues.

Well-experienced filter manufacturers should offer several different inspection and testing capabilities and help customers identify which procedures are best suited for verifying performance in terms of a given set of application demands.

Actual testing sequences may vary slightly depending on the filter manufacturer and any special device requirements, but often include tests outlined in the MIL-PRF-28861, MIL-PRF-31033, MIL-STD-202, and MIL-STD-220 specifications.

7. COST AND MANUFACTURING CONSIDERATIONS

Filter specifications including circuit complexity, voltage and current ratings, size, temperature resistance, reliability level, and the amount of testing required to verify reliability all impact filter cost to varying degrees. Many of these factors are governed by device-level requirements, but there are a few aspects of filter design that leave room for experienced manufacturers to reduce costs without notably affecting filter function.

Proper material selection is an important element of filter cost because prices and functionality can vary significantly between different material options. For example, the use of palladium rather than platinum for leads or capacitor terminations can result in significant material cost savings, but can also make installation more difficult. Variables including whether the leads will be soldered, welded, or otherwise inserted into the final device can also affect material selection due to the fact that certain material options are best suited for specific attachment methods. In order to make the best selections, it's important to consider capacitor dimensions, such as thickness and shape, and to establish a solid understanding of the assembly process environment. Seemingly minor changes to capacitor designs, like capacitance value, can have seriously adverse effects on manufacturing and device design processes and can occasionally require complete filter redesigns.

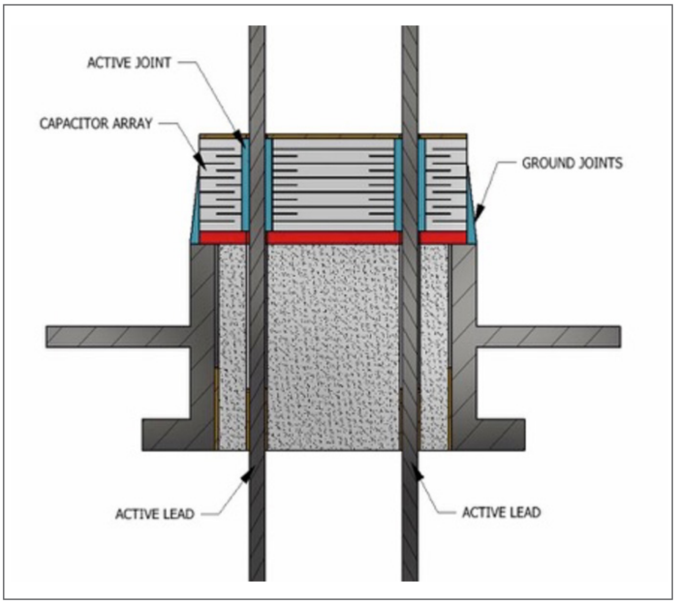


Figure 6: A cross-section of a medical filtered feedthrough with the capacitor, leads, and active and ground joints indicated with arrows.

Additionally, in some cases, device designers may have additional insights that filter manufacturers may not, such as the potential for greater cost savings via simplified or optimized installation methods that would make a costlier, more complex filter design worthwhile. So, it's important to discuss any potential cost/performance trade-offs early in the design cycle to ensure that a quality product can be specified from available selections or created at a reasonable cost. While some electronic devices will have particularly unique requirements that demand completely custom filters, many devices that require a slightly more complex solution than is already available can utilize an existing filter as a template to achieve a semi-custom design with shorter lead times and lower qualification and per-piece part costs for initial volumes.

ADDITIONAL APPLICATION-SPECIFIC CONSIDERATIONS FOR SELECTING EMI FILTERS

Commercial Filters—Regulations for commercial filters and devices can vary based on the country they're sold in. For example, some countries restrict the concentration of hazardous materials in electronics and require manufacturers to comply with RoHS or similar standards. Experienced filter designers are well versed in these requirements and can present customers with alternative options, such as employing cadmium-free terminations or conductive polyimide instead of solder.

Rules and regulations regarding the emission of electromagnetic radiation can drive the decision to use a filter as well. In addition to keeping harmful EMI out of a device, filters can also prevent EMI from escaping and interfering with other sensitive equipment in the surrounding environment. Almost every country has regulations that determine the approved type and amount of EMI that devices may generate.

Many countries and companies also enforce regulations regarding the selection of ethical component suppliers. Ethical filter suppliers comply with all labor regulations in their country of operation, as well as with larger international regulations, such as the Modern Slavery Act of 2015, SA8000, the EICC Code of Conduct, and ILO 18000, and may also hold accreditations such as ISO 9001, which can help ensure that suppliers follow ethical manufacturing practices.

Aerospace and Defense Filters—Aerospace and defense electronics must comply with an array of strict rules and regulations that govern almost every aspect of device performance, manufacturing, and testing. In addition, defense companies must often follow strict regulations regarding how they select and audit their suppliers, and may even be limited to a specific list of suppliers that have earned accreditation to certain governments' military and aerospace specifications. For example, the United States requires that companies comply with applicable export compliance regulations, such as Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). Aerospace and defense suppliers must also follow regulations regarding the security and confidentiality of the products they are manufacturing, as well as any information regarding the product's intended use or user.

Figure 7: Electronics employed in high-reliability and mission-critical military and aerospace applications have particularly rigorous filtering design, performance, and testing requirements to ensure optimal operation in even extreme environments.

Medical Device Filters—Medical device technology has advanced at an astonishing pace in recent years, offering greater functionality in smaller, lighter-weight form factors designed for increased comfort, ease of use, and environmental resistance. However, these and other sensitive electronic devices are subjected to ever-expanding levels of electromagnetic interference in both medical environments and the increasingly interconnected world at-large and, due to the critical nature of their reliability, are at particular risk for harmful interference from various sources of EMI. To ensure high levels of precision and reliability, most medical devices employ EMI filters to minimize noise and maintain signal fidelity.

Medical device filters have some of the most stringent spatial requirements and, as such, commonly specify filtered feedthrough arrays or miniature discoidal capacitors, which deliver high-density performance in low-volume packaging. In addition, since the vast majority of wearable and implantable medical devices are battery powered, device designers must select low-power filters to prolong device life. Measuring and minimizing ESR or DF can help keep unnecessary battery drain to a minimum and high insulation resistance (IR) can help minimize current leakage across the capacitor. Modern implantable medical devices typically employ primary cell, non-rechargeable batteries that are designed to last 10 or more years. However, since high-reliability implant battery technology hasn't quite kept pace with the miniaturization of many other medical components, minimizing power consumption is especially crucial to achieving target battery and device life expectancies.

Early implantable devices like pacemakers were not compatible with magnetic resonance imaging (MRI) due to the impact that such large amounts of EMI would have on device performance, but many designs have since evolved to safely withstand specific levels and durations of MRI exposure.

The test methods that medical device designers use to ensure their devices are MRI-compatible can be proprietary to each company but always require various types of filters. As such, filter manufacturers that supply to the medical device market must carefully consider how their testing procedures and any subsequent MRI exposure could potentially affect characteristics such as lead attachment methods or the selection of internal or external grounding mechanisms.

Figure 8: Implantable medical devices like the pacemaker shown here have understandably exacting mechanical and electrical performance requirements for every component specified as part of the system.

In addition, several global regulatory bodies impose proprietary series of stringent regulations on medical device manufacturers and their suppliers in an attempt to further ensure patient and operator safety. These can range from exacting design requirements to thorough onsite audits and complex documentation processes. So, it's critical for medical device designers to select filter manufacturers with a proven track record of regulatory compliance, reliable designs, and quality manufacturing processes. Medical device designers can also benefit from specifying existing filter products whenever possible, as doing so can achieve both significant reductions in device qualification lead-times and cost savings.

CONCLUSION

EMI is emitted by a number of both natural and engineered sources and is a hazard that virtually all electronic devices must be adequately protected from, regardless of application area. Board-level EMI suppression filters are one of the most common electromagnetic compatibility solutions and are widely available in a broad range of sizes, configurations, materials, capabilities, and costs. Although most electronics employ an EMI filter, most also have their own unique sets of application requirements. Factors including capacitance, voltage rating, dimensions, hermeticity, and cost must be carefully balanced to arrive at an optimal end result.

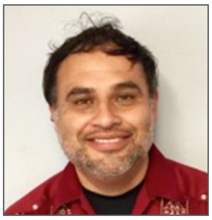
To ensure optimal filter selections, device designers should carefully consider the seven fundamental characteristics of EMI filters addressed here—filtering properties, circuit configuration, voltage conditions, construction, installation options, testing and inspection, and manufacturing costs—in the context of the application at hand.

Commercial and consumer applications with standard reliability requirements may be able to take advantage of off-the-shelf filter component capabilities, but each application is still likely to require its own unique combination of filter characteristics. These types of applications are also often subject to environmental, EMI radiation, and ethical manufacturing regulations that can vary by country. Higher reliability applications including military, defense, aerospace, and medical applications often require semi-custom modifications to existing filter components or fully custom solutions.

In these instances, it's vital for device designers and EMI filter designers to communicate and collaborate throughout the design cycle to develop a solution that meets price/performance ratios. Often times, experienced filter designers can help modify an existing solution to help customers achieve slightly more complex solutions than are readily available with shorter lead times and qualification processes, as well as lower per-piece and qualification costs for initial volumes. So, when selecting a filter manufacturer, it's important to select one that offers several different inspection and testing capabilities and, for higher reliability applications, a verifiable track record of regulatory compliance, reliable designs, and proven manufacturing processes.

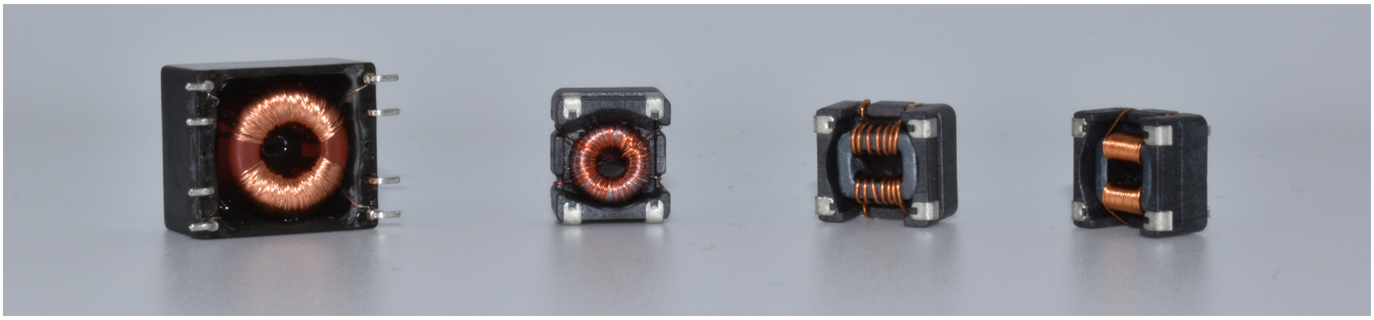
AUTHOR BIOGRAPHIES

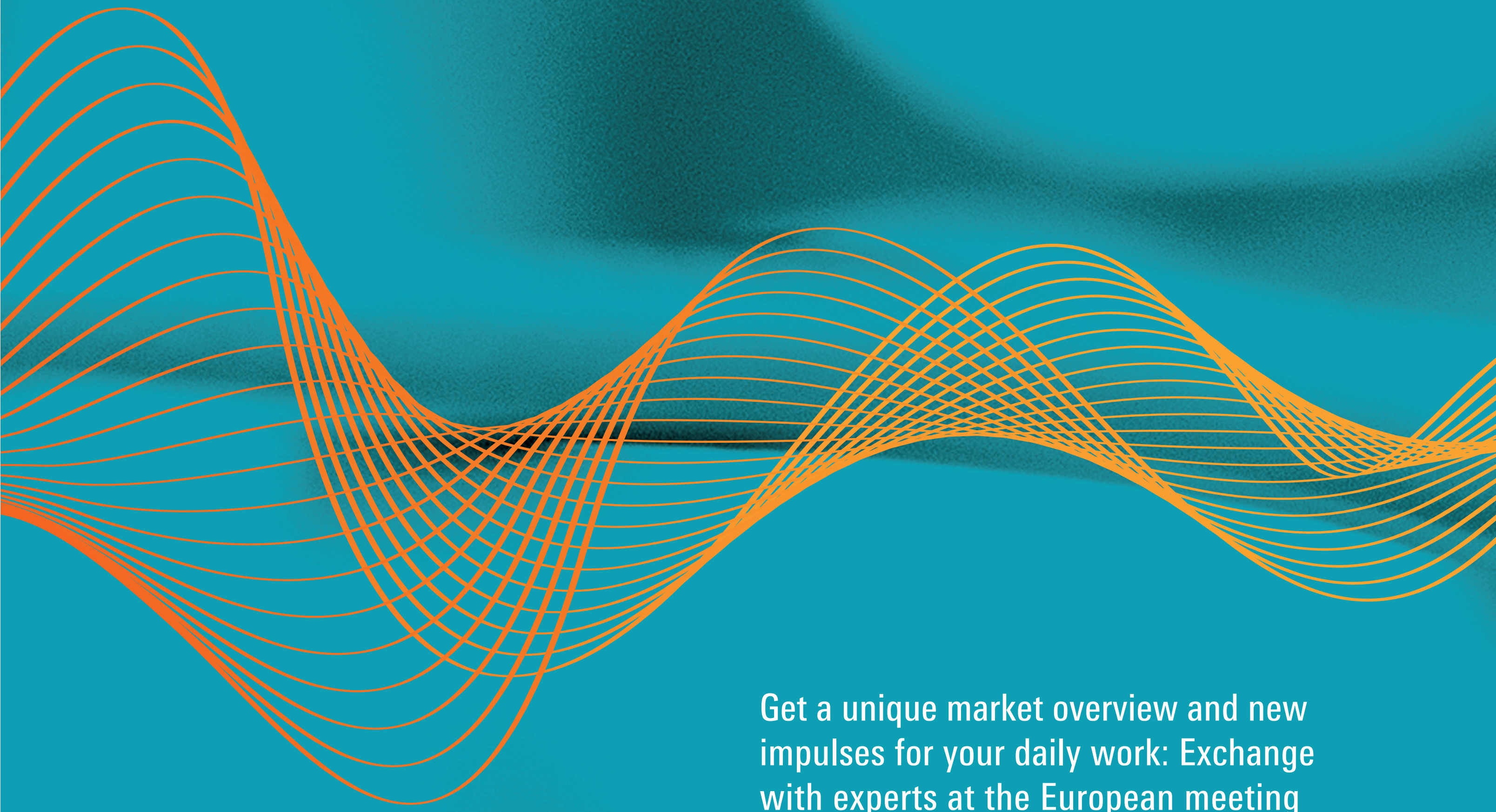
Rigoberto (Rigo) Rios began his career with AVX as an engineering technician in 1984, while still taking classes at California State University, Los Angeles (CSULA), for his BSEE and subsequent Master's degrees, and is currently an engineering section manager at AVX Filters Corporation in Sun Valley, CA. Rigo learned the filter business from the ground up and is meticulous in his evaluation and development of medical implantable applications. Over the years, Rigo and his team have developed several generations of AVX's medical implantable filters, which must often function at high voltages with low ESR and fit into tight mechanical dimensions with pristine cosmetic features. Rigo was raised in the Los Angeles community, where he currently lives with his family. In his spare time, he keeps active by running to stay fit, and, like many Angelenos, he enjoys watching soccer games on the weekends.



Jorge Varela joined the AVX Filters group as a senior engineer in March 2020. Prior to joining AVX, Jorge served several years in the U.S. Marine Corps and graduated from California State University, Northridge, with a BSEE. He is well experienced in electronic circuit design, capacitor applications and sales, and working with vendors on hardware design and the implementation of medical instrumentation devices. Jorge was raised in the Los Angeles area and currently lives with this family in the coastal community of Port Hueneme. He is an avid cycler and hiker around the Santa Monica and Santa Paula wilderness areas. For more information about AVX EMI filters, please reach out to Jorge via email: jorge.varela@avx.com

Amanda Ison earned a bachelor's degree in biomedical engineering from the University of Southern California. In December 2016, she joined AVX, where she worked as a principal engineer, specializing in electrical and mechanical test design. Prior to AVX, Amanda served in engineering roles at Shire and Medtronic.





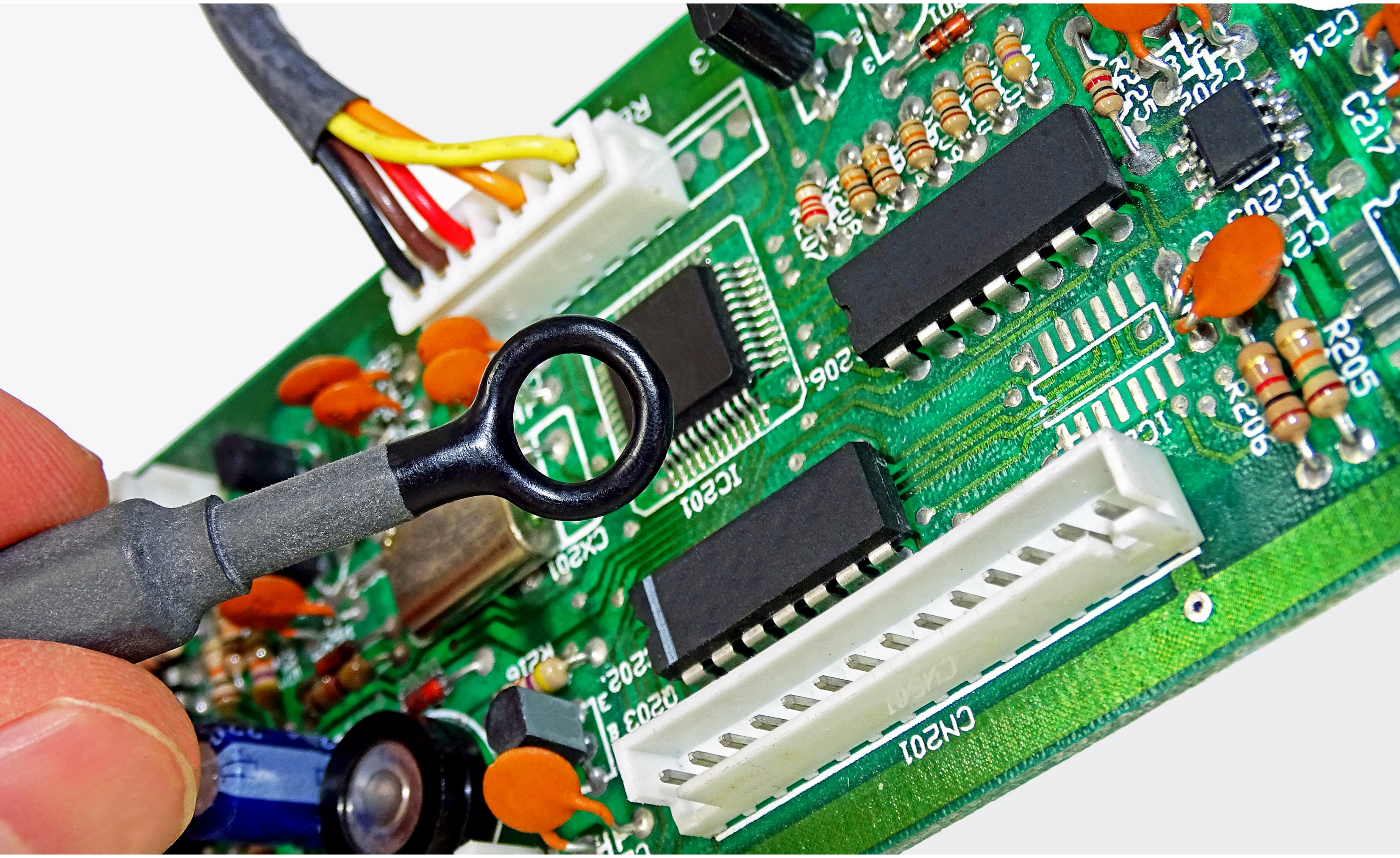
DOING THINGS THAT USUALLY DO NOT WORK

Patrick Andre
pat@andreconsulting

Introduction

"If you're not making mistakes, then you're not doing anything." — John Wooden

Over the years, I have seen several things that make me scratch my head. Many of them are things I have done (there, I admitted it). I would like to look at these situations to (maybe) help not to make the same mistakes. So, to be clear: Do not do these things.



DOING THINGS THAT USUALLY DO NOT WORK

CONCERNING SHIELDING

One would think that a thick aluminum chassis with a number of screws would be a good shield, but on one power supply, we were failing an aerospace radiated emissions scan in the 1 to 10 MHz range by several decibels. We chased the problem for several days, if not weeks, before I noticed we were making a mess of the metal by how we handled the chassis when we opened the unit. The aluminum case was covered with fingerprints and getting a bit greasy. So, I took some alcohol and wiped down the surfaces. The emissions dropped 20 dB, and we passed the test. Repeatedly.

This is the concept of good chassis bonds. Metal-to-metal contact must be in the micro-ohm range to work well for many shields. This is because if a current is flowing in the chassis, when it reaches the slightest impedance, a voltage will appear across that impedance, which will be the source of the radiation. Chassis coatings, whether for environmental protection (such as anodizing or conversion coating), or esthetics (e.g. paints), or by contamination, will degrade the contact quality. So even my aluminum chassis that should have had over 100 dB of shielding effectiveness was degraded because of fingerprints.

Some may wonder if more screws would help. In this case, not likely. First if the screw surfaces were coated, the screw would not make a good bond to the chassis. Also, screws are inherently inductive, and if the surface the screw is threaded into is an insert or captive nut, the impedances increase. If the concern is that the screw spacing must be less than 1/20th of a wavelength apart, the real issue may be missed. The problem looks more like a folded dipole than an aperture. Openings and apertures are when we consider wavelengths and frequencies. However, considering two metal surfaces in contact as an aperture may be misleading.

Overlaps and bonding from metal to metal is a bit of an art as much as sound engineering when designing chassis. Do you overlap seams? Do you use a conductive gasket, or do you need to? How far apart do you need to put the screws? In the words of consultants worldwide: It depends.

I had a client who was evaluating shielded cables for a computer peripheral. One set of cables appeared to have no shielding effectiveness. Upon investigation, it was a shielded cable, with a foil shield, and the drain wire was grounded on both ends. However, the aluminum-over-mylar foil shield had been installed with the drain wire on the inside of the shield, but the aluminum was on the outside of the shield. No contact was made between the drain wire and the shield—thus no effective shield.

As consultants, we see countless cable shields that are terminated in a pig tail or wire, typically with a “service loop” that is 10 cm long or more. Or, they are bonded only at one end—which is an article all on its own on why that does not work—or both.

CONCERNING CAPACITORS

But, even a perfectly shielded enclosure must have wires running from inside to outside. Any conductor that pierces the shield will allow signals on the inside to come out, or outside in—unless there is an excellent filter at the point of penetration. This is typically a capacitor that has low impedance from conductor to chassis over the frequency range that is needed.

Thus, we place a filter at or very near the connector, which often includes capacitance from line to chassis (or whatever structure and return path is needed to return the current to its source). And on the schematic, a capacitor of the proper value is shown. When constructed, the capacitor is placed very near the connector pin. So far so good. Then what? It goes to a ground symbol on the schematic, but how is that constructed? Does that “ground symbol” involve a long trace to some corner of the circuit board where a capacitor connects to a pad that casually touches a screw that mounts the circuit board to the chassis? How long, and thus, how inductive, is that path? Remember that inductance is a high-frequency impedance. So, is the path inductance filtering the capacitive filter to keep it from working?

I once worked with a client on a project in which we got the design to pass conducted emissions. The engineer submitted the final drawings for qualification of the product. Upon qualification testing, the unit failed conducted emissions. In fact, the emissions were about 20 dB worse than they were for the design we saw pass earlier. I asked if he changed anything. No, I was told. So, I asked if he improved anything—well yes, he did. He made one of the filter capacitors 10 times larger. Since I knew we had some large ceramic caps installed, I asked him where he found such large ceramic capacitors. He said, “Oh, they are not ceramic, they are electrolytic.”

The construction and dielectrics used in capacitors are very important. For example, the electrolytic capacitors in question have high equivalent series resistance and inductance, which render them poor filters above 100 kHz or so. While great for bulk storage, these caps do not provide the high-frequency filtering needed for our test. When we replaced the caps with ceramics, all was well with significant margins across the frequency range. That engineer soon afterward quit the industry and went into another line of work. True story. Bottom line, more is not always better.

Not all caps are alike, even among the same style. Maybe ceramic capacitors are the most finicky.

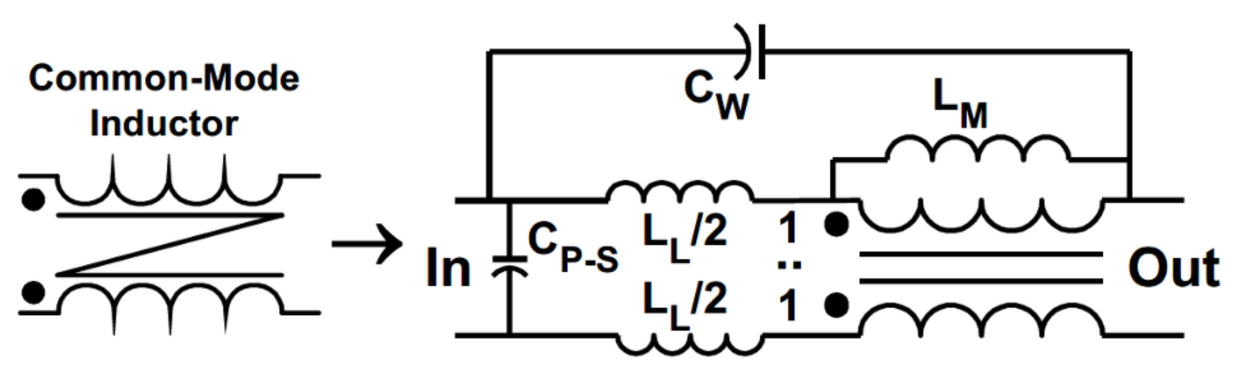


Figure 1: Equivalent Circuit for Common Mode Inductor, courtesy of Dr. M. Schutten.

Class I ceramics are nice and stable over temperature and bias voltages but are bulkier as a result. Class II and Class III may have wide swings in effective capacitance over temperature ranges and have significantly reduced capacitance with a bias voltage but are physically smaller and less expensive.

STORIES ABOUT COMMON MODE INDUCTORS

To reduce common mode energy from an AC to DC power supply, an engineer wound a common mode inductor. Once installed, we repeated the measurement only to find the emissions went way up. Having seen this before, I asked if he was careful about how he connected the inductor. He was not, not thinking it was important. The inductor was connected with the line and neutral currents adding to the core magnetic field, not cancelling, as should be with a common mode inductor. As a result, the core was going in and out of saturation with each half sinewave, 800 times a second (on a 400 Hz power source). This radical change of impedance turned the inductor into an emissions generator instead of an absorber or filter.

To pass radiated emissions, a common mode inductor was created with a few turns on a nickel-zinc ferrite (permeability about 700). When this worked well, the engineer decided to use a higher permeability core in the design—something with a permeability about 2,500. However, this material was a manganese-zinc compound, which did not have the needed bandwidth for radiated emissions.

Another engineer heard that the inductance increases as the square of the number of turns. Wonderful—let us double the number of turns and we have four times the inductance. Well, yes and no. Parasitics and core saturation must be accounted for. For example, in the case of a common mode inductor, it can be modelled as shown in *Figure 1*. Notice the presence of the following components:

- C_W which is the inter-winding capacitance. Each turn will capacitively couple to the next. Adding more turns will increase this capacitance
- C_{P-S} which is the capacitance from winding to winding, line to line. Some baluns are wound with turns on opposite sides of the core to minimize this. However, this can lead to increases
- $L_{L/2}$ which is the leakage inductance. In a common mode inductor, leakage inductance can appear as a series inductance in each lead, but that reduces the mutual inductance from the coupled fields between the two windings
- L_M which is the mutual inductance value, the inductance we use for the common mode rejection

In his talk, Dr. Michael Schutten (reference below) describes how to measure each of these components in a common mode inductor. I suppose if all the parasitics of all the components were modeled, we would have a better idea what to expect from the performance.

So, adding more turns may increase CW, which will decrease the impedance of the core at higher frequencies—the thing we don't want to happen. More is not always better.

I have found that ferrites are great for common mode inductors, but often not for differential mode inductors. Ferrite material is susceptible to saturation, which can render the core ineffective. I've found that magnetic fields from hidden structures can cause problems. A trace ran next to a DC-DC switching regulator was known to couple the switching frequency into that trace from an internal transformer inside the integrated circuit, causing a conducted emissions failure. I've found that when you try to filter common mode currents with differential mode techniques, it does not work well. A line-to-line capacitor may work great on differential mode currents, but it might make the common mode currents more common mode as it were. And, I've found the best way to control EMI is to understand where the currents flow, and remember they have to flow in complete loops—from a source and back again. It is how they do that which gets us into trouble. And finally, "ground" is not a hole you can pour circuit noise into and it goes away. Many in the EMC world avoid the use of that term except for safety purposes and prefer to think of reference planes and current return paths.

So maybe Charles Dickens was an EMC consultant, since he wrote in *A Tale of Two Cities:* “It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness.” I have made some foolish mistakes, been a partner with others’ mistakes, but hopefully learned from them. And, hopefully you can learn from ours.

Below are some lectures, papers, and talks I have heard, which I believe would be useful. These are brilliant people who explain difficult concepts in easy to understand manners, and which I used in the creation of this article. There are numerous other sources of excellent information I can highly recommend.

- *EMC Fundamentals for Switch-Mode Power Converters*, 2020 IEEE Symposium on EMC & SI - Michael Schutten, Ph.D., Cong Li, Ph.D.
- *Filter layout and mechanical design. Why filters can fail*, 2020 IEEE Symposium on EMC & SI - Dr. Arturo Mediano, Senior Member IEEE, University of Zaragoza
- *Design and Implementation of EMI Filters, EMI Filter Basics*, 2020 IEEE Symposium on EMC & SI - John G. Kraemer PE, Collins Aerospace
- *Conducted Emissions*, 2019, 2020 IEEE Symposium on EMC & SI - Lee Hill, SILENT Solutions LLC & GmbH
- *Filter for EMC*, 2016 IEEE Symposium on EMC & SI - Dr. Arturo Mediano, Senior Member IEEE, University of Zaragoza
- *Shielding*, 2015 IEEE Symposium on EMC & SI - Dr. Todd Hubing
- *Decoupling Capacitor Design on PCBs to Minimize Inductance and Maximize EMI Performance* – Bruce Archambeault, et al., April 2015

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

(https://webstore.iec.ch)

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
CISPR TR 16-4-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 4-3: Uncertainties, statistics and limit modelling - Statistical considerations in the determination of EMC compliance of mass-produced products
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://www.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

EMC STANDARDS ORGANIZATIONS

American National Standards Institute
www.ansi.org

ANSI Accredited C63
www.c63.org

Asia Pacific Laboratory Accreditation Cooperation (APLAC)
https://www.apac-accreditation.org/

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
http://www.iec.ch/index.htm

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

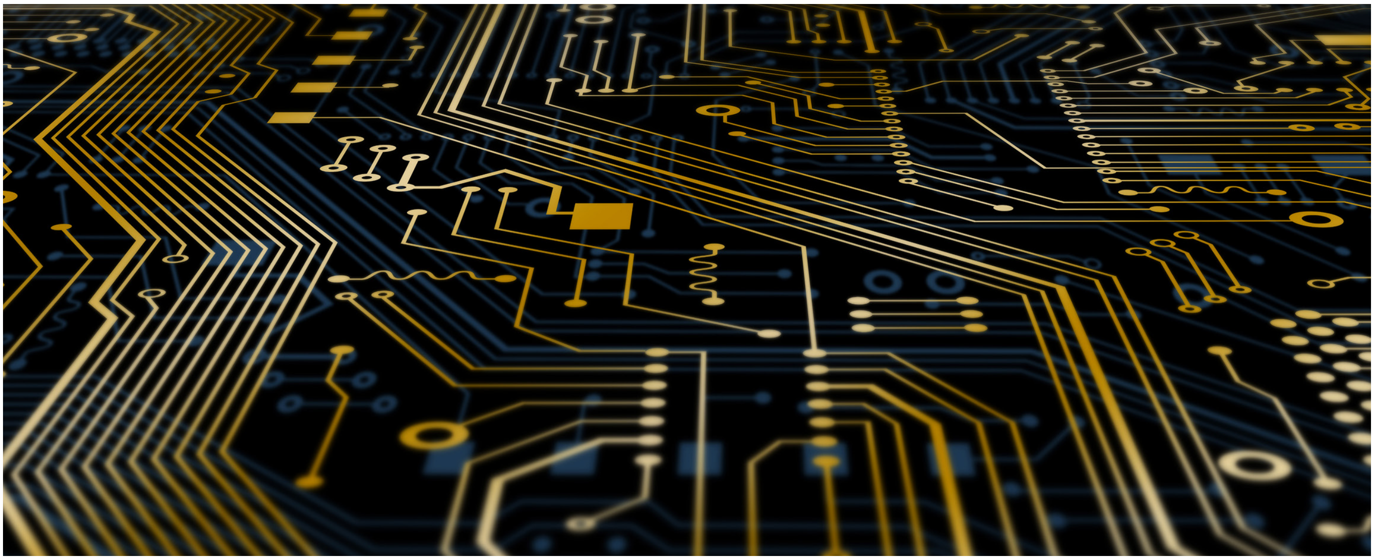
ISO (International Organization for Standards)
http://www.iso.org/iso/home.html

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

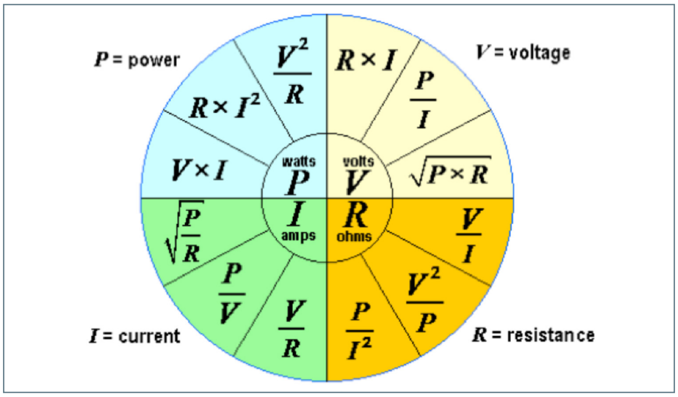
VCCI (Japan, Voluntary Control Council for Interference)
http://www.vcci.jp/vcci_e/



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 RISE TIME

$$BW\,(GHz) = \frac{0.35}{RT\,(nsec)}$$

Empirically derived and applies for a square wave, with rise time measured at 10 and 90%. Example, for a rise time of 1 nsec, the bandwidth is 350 MHz.

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 sinewave frequency component in a clock wave is the fifth harmonic.

PERIOD VERSUS FREQUENCY

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

PARTIAL SELF-INDUCTANCE OF A ROUND WIRE (1MM)

25 nH/inch or 1 nH/mm
Example, a 1.5 mm long via has a partial self-inductance of about 1.5 nH.

IMPEDANCE OF A WIRE

$$Z_{Wire}\,(Ohms) = 2\pi\,f\,(GHz)L(nH)$$

Example, a 1-inch wire (25 nH) has an impedance of 16 Ohms at 100 MHz.

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

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

EQUATIONS, TOOLS, & CALCULATORS

RETURN LOSS, GIVEN VSWR

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

Return Loss, given reflection coefficient (ρ)

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

E-FIELD FROM DIFFERENTIAL-MODE CURRENT

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

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)

TEMPERATURE CONVERSIONS

Celsius to Fahrenheit: °C = 5/9(°F - 32)
Fahrenheit to Celsius: °F = 9/5(°C) + 32

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 in dBi $dBi = 20\log(MHz) - AF - 29.79$

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 EQUATIONS

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 = Pout/Pin

Power Gain(dB) = 10log(Pout / Pin)

Voltage Gain(dB) = 20log(Vout/Vin)

Current Gain(dB) = 20log(Iout/Iin)

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 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):

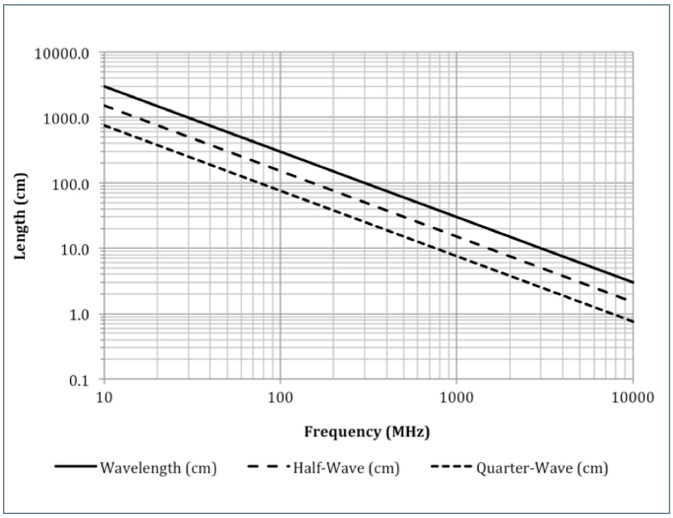
dBm to dBμV, use: dBμV = dBm + 107

EQUATIONS, TOOLS, & CALCULATORS

WAVELENGTH EQUATIONS (FREE SPACE)

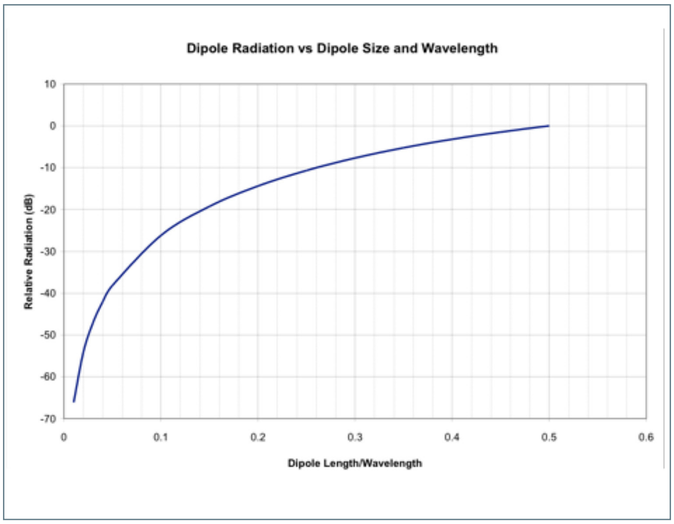
Wavelength(m) = 300/f(MHz)
Half wavelength(ft.) = 468/f(MHz)

RESONANCE OF STRUCTURES



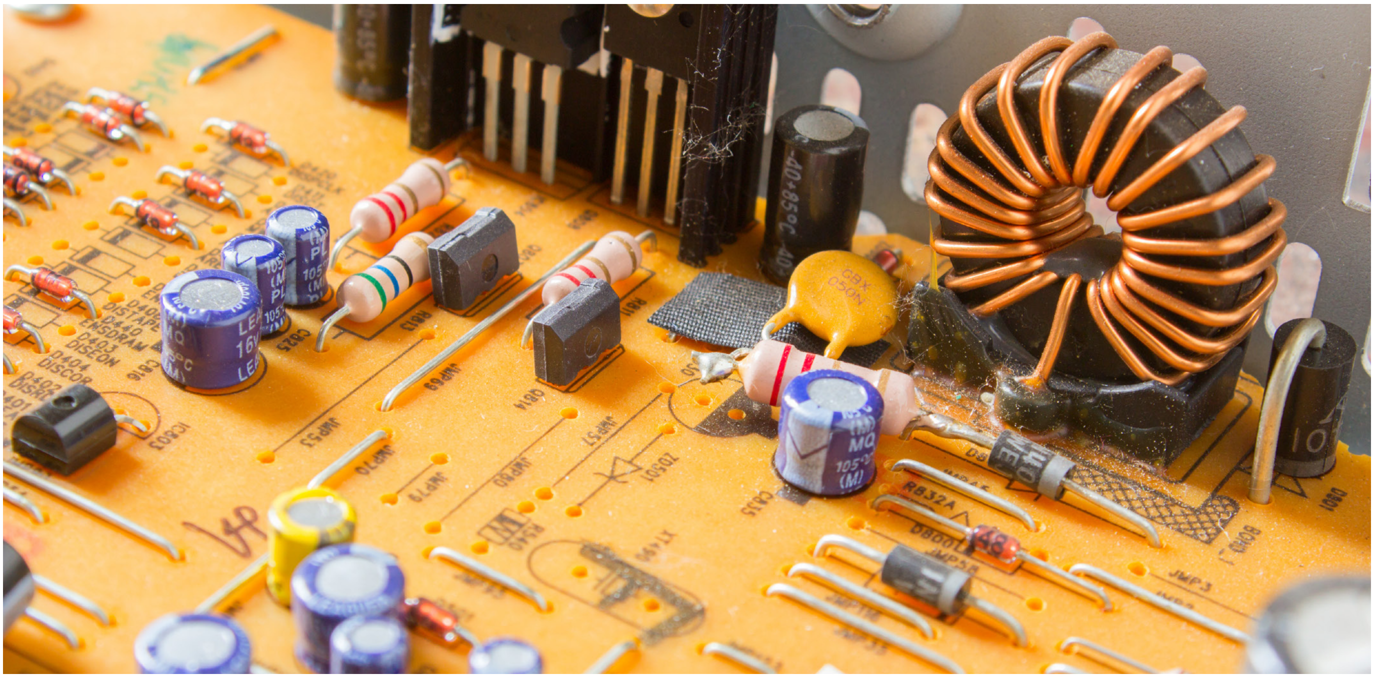
Use this handy chart for determining the resonant frequency versus cable or slot length in free space. Half-wavelength slots or cables simulate dipole antennas and are particularly troublesome. Image Source: Patrick André.

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.



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 2020
(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-2020/

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 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/2019-emc-fundamentals-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.

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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.

LINKEDIN GROUPS

Electromagnetic Compatibility Forum

Electromagnetics and Spectrum Engineering Group

EMC - Electromagnetic Compatibility

EMC Experts

EMC Troubleshooters

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