ITEM

INTERFERENCE TECHNOLOGY ENGINEER'S MASTER

Tools & Calculators

Directories:
- Suppliers Guide
- Test Lab
- Government
- Consultants

Standards

Design Fundamentals

Testing Fundamentals

Featured Industries:

Wireless/5G/IoT EMC

Automotive EMC

Military/Aerospace EMC

INTERFERENCE TECHNOLOGY®

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Table of Contents

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2020 Interference Technology Engineer's Master (ITEM)

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WELCOME TO *ITEM 2020*

JENNIFER ARROYO

Interference Technology (and *ITEM* Media before that) has had a long history of providing engineers with the information they need regarding all things EMC, and we are continuing that tradition with this new publication. We are paying homage to our roots with this comprehensive reference guide, including directories and standards information that we hope you will turn to week after week throughout the year.

However, we are still incorporating the lessons that we have learned recently through our mini guides, and keeping *ITEM* convenient to browse through by sectioning off the major industries that deal with EMC issues:

- Wireless/5G/IoT
- Automotive
- Military/Aerospace

We feel that this combination will best serve you, our readers, and provide you with the articles, resources, and EMC content that you've come to expect from *Interference Technology*. The information in *ITEM* will offer engineers the opportunity to quickly find contact information for a test lab, or dive deeply into a technical article on the main considerations on designing a product with EMC. After all, *ITEM* stands for *Interference Technology Engineer's Master*. Having all of this information in one place that is easy to refer to will be invaluable to anyone in the world of EMI and EMC.

EMI affects practically every electronic device on the market, and with the onset of 5G and IoT, and the flood of gadgets that it will bring, dealing with EMC has never been more relevant. It will change the way we look at vehicles, aircraft, and computing technology. This evolution, however, will only strengthen *Interference Technology*'s drive and resolve to serve our readers with the latest news and developments in EMI, as well as tried and true articles and resources that will help you solve your issues.

We hope to see you on that journey with us, and we hope you enjoy reading *ITEM 2020*.

Jennifer Arroyo
Editorial Director
Jennifer@lectrixgroup.com

EMC–EVER EVOLVING CHALLENGES

STEVE FERGUSON

Welcome to the Technical Editorial Board—a team assembled by *Interference Technology* to assist in keeping the technical content relevant and current. The board members include Patrick Andre, Ghery Pettit, Mike Violette, David Weston, and myself—Steve Ferguson. We all bring a lot of EMC experience, and each of us has particular interests spanning a broad range of subject matter from standards to testing, components to design, and agency approvals in a variety of applications such as military, wireless, commercial, medical, and international compliance. We work with the EMC community seeking authors on related topics and assisting them on getting their work out to interested parties around the globe. If you have worked a research project, uncovered an innovative solution, or discovered a better way to evaluate a risk—contact us to help get you on the path to publishing your work.

Speaking of help, we need your help to update the various contacts listed in the publication's directories. If you are new to a position appropriate for listing, manage a group with many contacts or are simply aware of changes, please let us know (names, office designation, email addresses, phone numbers, etc.) so we can update this information.

What about EMC? Maxwell's theory on electromagnetic waves circa 1846, confirmed by Hertz in 1888 with an airborne electromagnetic transmission, brought forth the "radio" often called wireless technology. Although EMI preceded this invention, Radio Frequency Interference (RFI) became apparent with the radio being the victim in the source-path-victim triad of EMC.

Prior to WWI, the U.S. military observed RFI with the radio installation in a vehicle, and by 1933 the IEC established the International Special Committee on Radio Interference (CISPR). In 1960, the Defense Radio Frequency Compatibility Program was formed to consolidate the various military department's efforts to manage RFI or by now EMI/EMC. In 1967, MIL-STD-461 was published to standardize the U.S. military work on EMC/EMC.

By 1970, *Interference Technology* was published to help engineers gain knowledge through articles prepared by a vast array of studies and laboratory experiments. This publication has remained a mainstay in the EMI/EMC community providing tutorials and guidance on developing and implementing EMI/EMC control measures. My collection of these annual publications started about 1978, when I started work in the EMI/EMC arena, and thanks to the electronic media, I can now house those well-worn issues in a smaller space.

Let's not forget that the commercial electronics industry was also bringing EMI/EMC technology forward with standards from the IEC, and in 1989, the E.U. issued the EMC Directive legislating EMC requirements into products and installations. The Radio Equipment Directive (RED) is the companion legal entity to manage wireless communications.

Throughout the evolvement of EMI/EMC technology, the EMC engineer has been vital in product development touching every phase of the electronics industry and every department in companies producing products. Working with EMC has always been challenging with a new wrinkle appearing daily to keep the work interesting and always a learning experience.

So, add this issue of *ITEM* to your reference shelf after perusing the pages—your quest for knowledge will bring you back the guide many times.

INTERFERENCE TECHNOLOGY

MEET THE EDITORIAL BOARD

DAVID A. WESTON

iNARTE EMC ENGINEER

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

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

GHERY PETTIT

PRESIDENT, PETTIT EMC CONSULTING LLC

Ghery S. Pettit received the BSEE degree from Washington State University in 1975. He has worked in the areas of TEMPEST and EMC for the past 44 years. He was with the Naval Electronic Systems Engineering Center, Vallejo starting in 1976. In 1979 he joined Martin Marietta Denver Aerospace where he worked on what became the Peacekeeper missile system, as well as other projects, providing TEMPEST and EMC design and analysis support. In 1983 he joined Tandem Computers in Cupertino, California providing EMC design, troubleshooting, and EMC compliance testing services to a number of projects and oversaw the construction of Tandem's 30 meter Open Area Test Site (OATS) and 10 meter RF semi-anechoic chamber. In 1995 Ghery joined Intel Corporation where he was involved in the construction of EMC test facilities, providing design guidance, and troubleshooting support to various projects and representing Intel on a number of industry committees and national and international standards bodies. Since retiring from Intel in 1995, he is now continuing his work on national and international standards development organizations and consulting in the areas of EMC design, troubleshooting, testing, standards interpretations, and laboratory design.

Mr. Pettit is presently serving as Chair of CISPR SC I and is one of CISPR's representatives on the Advisory Council on EMC (ACEC) within the IEC. He has been involved in CISPR activities since 1998, both as a member of the U.S. Technical Advisory Groups to CISPR SC G and CISPR SC I and as an active member of CISPR SC I and its maintenance teams, CISPR SC I MT7 (CISPR 32 maintenance) and CISPR SC I MT8 (CISPR 35 maintenance). He is also a member of the U.S. TAG for IEC SC77B and the working group preparing the next edition of ANSI C63.4.

Ghery has written eight papers and articles for publication and contributed a chapter for the 2nd and 3rd Editions of the ARRL's Radio Frequency Interference Handbook. He is a member of the dB Society and serves as a Technical Advisor for the ARRL in the area of EMC. He holds an Amateur Extra radio license and is an instrument rated private pilot.

MIKE VIOLETTE

iNARTE CERTIFIED EMC ENGINEER

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

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

PATRICK ANDRE

iNARTE CERTIFIED MASTER DESIGN ENGINEER

Patrick G. André received his physics degree in 1982 from Seattle University, with post graduate work in Electrical Engineering and Physics. He has worked in the Electromagnetic Compatibility (EMC) field for over 35 years. He is an iNARTE Certified Engineer in both EMC (Electromagnetic Compatibility – EMC-001335-NE) and ESD (Electrostatic Discharge – ESD-00078-NE). He was honored as an iNARTE Certified Master Design Engineer - EMCD-00053-ME.

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

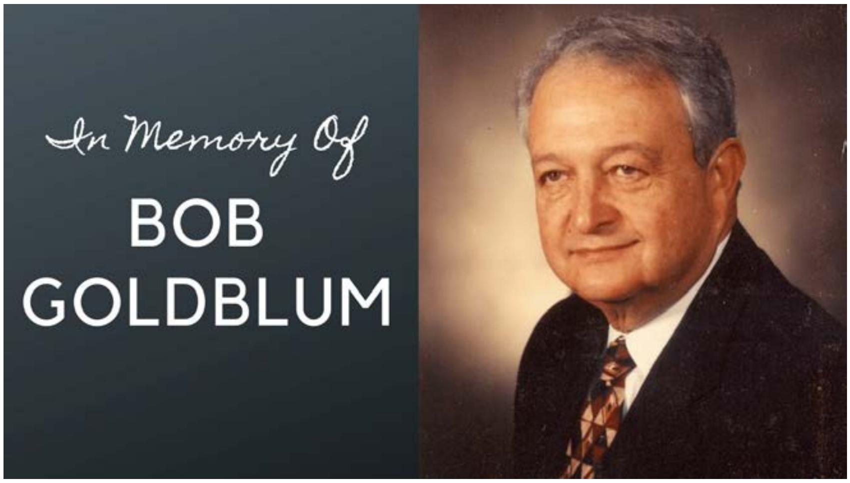
He is a third-party auditor for local governments and has provided expert opinions on the use of cellular transmitters, including health and safety concerns. Patrick has published numerous articles for a variety of magazines. He is the coauthor of *EMI Troubleshooting Cookbook for Product Designers*.

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

STEVE FERGUSON

OWNER, COMPLIANCE DIRECTION, LLC | iNARTE EMC ENGINEER

Steven G. Ferguson is the owner of Compliance Direction, LLC and has been working in the compliance test arena for over 40 years at test laboratories and manufacturing companies designing products, developing procedures and performing tests. He presents various courses on EMI/EMC compliance including EMC for Nuclear Power Facilities, Architectural Shielding, Environmental qualification and MIL-STD-461 & DO-160 testing at customer facilities on-site for multiple government and industrial clients. He is versed on Electrical Safety evaluations including Risk Analysis for medical and information technology equipment. He holds an iNARTE EMC engineer certification. Contact him at stevef@compliancedirection.com



Robert "Bob" Goldblum
1935 - 2019

In May 2019, the world of EMC lost a "key player"—Bob Goldblum. He was one of the first in the industry and helped to build the EMC community into what it is today. Even in retirement, he never stopped giving back to it, primarily through writing, mentorships, and friendships. He founded this publication, *Interference Technology* (aka *ITEM*) in 1971, and in 1999, he passed the reins to me. So, for me, I lost not only a father-in-law, but also a mentor and the guy who gave me a shot at the thing I wanted most in my career—the chance to run a company. At his funeral, I had the immense privilege to write and deliver his eulogy, which follows here. I'm sure Bob the editor would have had a few edits, but I'm also sure that Bob the friend and father-in-law would have liked it.

My name is Graham Kilshaw and it is my honor to offer this eulogy in honor of my father-in-law, Bob Goldblum.

It was only 35 degrees outside when Bob was born, December 18, 1935 in Philadelphia, and the economy wasn't that warm either. After all, most of the country was considered far from comfortable at that time. The Wall Street Crash had occurred just six years prior, and the effects of Roosevelt's New Deal were only just beginning to show.

So like many, Bob's parents, Harry and Rose Goldblum, were not wealthy. From those humble beginnings (Bob even remembered making ketchup sandwiches for lunch), he went on to become the epitome of the self-made man.

After repeating a year and finally graduating high school in West Philadelphia, he joined the U.S. Air Force in 1954, and became a Radar Technician, which initiated his lifelong love of electronics. Taking advantage of the Korean War G.I. Bill, he went to Penn State University. I seem to remember Bob once telling me that he ultimately earned three things from Penn State:

1. A BSEE
2. An MSEE
3. And a BFG—his wife of over 50 years, Barbara, also a graduate of Penn State.

Like many new graduates, Bob's early career gained him valuable experience in his chosen field of electronics engineering. He worked at ARK in Willow Grove, Sylvania in Mass., and AEL in Lansdale.

Even by this early stage, Bob was already a recognized specialist in the new, emerging field of electromagnetic interference (EMI), but this EMI thing was no esoteric, weird subject even if it seemed that way to some.

In the late 1960s the world was beginning to fill with electronics of all kinds—in our houses and homes, in our cars, in offices and factories, and most critically in the field of military electronics. And interference was everywhere. So, it's no exaggeration to say that Bob Goldblum, along with a relatively small group of other brilliant young engineers at that time, made sure that our world of technology today all works together successfully and safely.

While working at GE in King of Prussia around ‘68 on military and space projects, he helped to safely launch some of the early satellites; he helped to bring some of the monkey space flights safely back to earth; he helped to design safe systems for the Minuteman missile program and the underground nuclear tests in the Nevada desert at that time.

After a while, he realized that this new field of EMI needed a publication—and that he was the guy to do it. And so, in 1971, he started what ultimately became highly recognized as *ITEM*—the *interference technology* publication.

Many great businesses start in a garage; this one started in the family’s spare bedroom in Plymouth Meeting, until my wife Becky was born. And then Bob was kicked out into the garage. Family members stuffed envelopes with magazines, kids attached stamps and address labels, friends edited articles, printers gave him credit to get started, and a business was born.

Little did he know at the time that the publication would lead to connections with hundreds of companies looking for help in this new emerging field. And so, by 1974, he was ready to leave GE to form yet another new business: offering consulting and engineering services to solve the increasing electronic interference problems in the world.

Working in a 400 square foot office above a local restaurant, Bob formed “Robert and Barbara Enterprises”, aka R&B Enterprises, which comprised both the engineering business and the publishing company. It’s a great testament to Bob’s first-to-market vision that both of those businesses continue to thrive today.

When you look around your world today, you wouldn’t know that so many of our electronics work because of his contributions.

He once described to me, after the British destroyer HMS Sheffield was sunk during the Falklands War in 1982, how he helped to solve the interference problem that caused that fateful attack. He once appeared in a New York courtroom, when the New York Times was wrongly accused by the typesetters’ union of the newspaper’s computers giving them cataracts. He worked on some really fascinating world-scale problems throughout his life.

But for Bob it wasn’t just about creating a successful business or career, he truly loved what he did. And, he knew he was solving problems that affected the real world. Bob was an engineer, a teacher, a publisher, a writer, an entrepreneur, a speaker, an event producer…even an early video producer. The early video he produced on the subject was adopted by governments all around the world as one of their key training tools.

He was recognized and admired as a thought leader and an industry pioneer. He launched training companies, acquired an Israeli company, started a testing lab and yet still helped others to launch their own businesses along the way. He trained thousands of government and military employees from the U.S., NATO, South Africa, India, and Israel on how to solve interference problems that would ultimately save many, many lives.

He helped to create the society that built an entire industry—the EMC Society. He was the society’s newsletter editor for 30 years, and was a lifelong member; he received numerous prestigious awards honoring his contributions to technology in the world today. But if you asked him, he would always credit those around him—his employees at R&B Enterprises, his mentors, his colleagues in the field, his friends, and the opportunities he was given—but rarely himself. Like I said, he truly loved what he did.

He once said in an interview that he “never considered himself a good businessman….” I can tell you as the young guy to whom he gave the opportunity of a lifetime 20 years ago that nothing could be further from the truth. Bob and Barbara—my family and I owe you a debt of gratitude for my own career. Bob, I’ll always remember two simple things you taught me:

1. “There has to be a need for what you do” and
2. “Guide your people well and then get out of their way.”

Thanks for everything Bob. I’ll miss you….

Graham Kilshaw
Publisher – *Interference Technology*, CEO - Lectrix

2020 EMC SUPPLIER GUIDE

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.

2020 EMC SUPPLIER MATRIX SPOTLIGHT

COMPANY	WEBSITE	AMPLIFIERS	ANTENNAS	CABLES & CONNECTORS	CERTIFICATION	CONSULTANTS	COMPONENTS	DESIGN / SOFTWARE	EMI RECEIVERS	FILTERS / FERRITE'S	LIGHTNING & SURGE	MEDIA	SEALANTS & ADHESIVES	SHIELDING	SHIELDED ROOMS	SPECTRUM ANALYZERS	TEST EQUIPMENT	TEST EQUIPMENT RENTALS	TEST EQUIPMENT OTHER	TESTING	TESTING LABORATORIES	TRAINING SEMINARS & WORKSHOPS
ATEC Advanced Test Equipment Rentals	ADVANCED TEST EQUIPMENT RENTALS t: (800) 404-ATEC (2832) e: rentals@atecorp.com w: www.atecorp.com	X	X	X				X	X							X	X	X	X			
A.H. SYSTEMS	AH SYSTEMS, INC. t: (818) 998-0223 e: sales@ahsystems.com w: www.ahsystems.com	X	X	X													X	X	X			
Coilcraft	COILCRAFT t: (800) 322-2645 e: sales@coilcraft.com w: www.coilcraft.com						X			X												
EA Exodus Advanced Communications	Exodus Advanced Communications t: (702) 534-6564 e: sales@exoduscomm.com w: www.exoduscomm.com	X	X	X													X					
Fair-Rite Products Corp.	Fair-Rite Products Corp. t: (888) 337-7483 e: ferrites@fair-rite.com w: www.fair-rite.com						X			X												
Magnetic Shield Corp.	MAGNETIC SHIELD CORP. t: (888) 766-7800 e: shields@magnetic-shield.com w: magnetic-shield.com			X										X	X							
Quell A HEICO Company	QUELL CORPORATION t: (505) 243-1423 e: eeseal@quell.us w: www.eeseal.com			X						X	X									X		
R&K	R&K Company Limited t: (408) 520-4550 e: rkproducts@cornestech.com w: www.rk-microwave.com	X																				
SPIRA	SPIRA Manufacturing Corporation t: (818) 764-8222 e: info@spira-emi.com w: www.spira-emi.com													X								

	COMPANY	WEBSITE	AMPLIFIERS	ANTENNAS	CABLES & CONNECTORS	CERTIFICATION	CONSULTANTS	COMPONENTS	DESIGN / SOFTWARE	EMI RECEIVERS	FILTERS / FERRITE'S	LIGHTNING & SURGE	MEDIA	SEALANTS & ADHESIVES	SHIELDING	SHIELDED ROOMS	SPECTRUM ANALYZERS	TEST EQUIPMENT	TEST EQUIPMENT RENTALS	TEST EQUIPMENT OTHER	TESTING	TESTING LABORATORIES	TRAINING SEMINARS & WORKSHOPS
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		
C	Captor Corporation (EMC Div.)	www.captorcorp.com									X												
	Coilcraft	www.coilcraft.com						X			X												
	CPI- Communications & Power Industries (USA)	www.cpii.com/emc	X																				
D	Dassault System Simulia Corp	www.3DS.com/simulia							X														
	Delta Electronics (Americas) Ltd.	www.delta-americas.com									X												
	DLS Electronic Systems, Inc.	www.dlsemc.com																				X	
	Don Heirman Consultants	www.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
	EMC Partner	www.emc-partner.com																X					
	Empower RF Systems, Inc.	www.empowerrf.com	X																				
	EM TEST USA	www.emtest.com																X					
	Exemplar Global (iNarte)	www.exemplarglobal.org																					X
	EXODUS Advanced Communications	www.exoduscomm.com	X	X	X													X					
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	

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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	Instrument Rental Labs	www.testequip.com	X							X							X		X				
	Interference Technology	www.interferencetechnology.com																					X
	Intertek	www.intertek.com																				X	
	ITG Electronics	www.itg-electronics.com									X												
K	Keysight Technologies	www.keysight.com/us/en								X							X		X	X			
	Krieger Specialty Products	www.kriegerproducts.com														X							
L	Laird Electronics	www.laridtech.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									
	MBP Srl	www.gruppompb.uk.com							X											X			
	Microlease	www.microlease.com	X							X							X		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								
	Prana	www.prana-rd.com	X																				
	Pulse Power & Measurement Ltd	https://ppmtest.com/																		X			

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R	Radiometrics	www.radiomet.com																				X	
R	R&B Laboratory, Inc.	www.rblaboratory.com																				X	
R	Retlif Testing Laboratories	www.retlif.com																			X	X	X
R	RIGOL Technologies	www.rigolna.com	X					X									X	X		X			
R	R&K Company Limited	www.rk-microwave.com	X					X															
R	Rohde & Schwarz GmbH & Co. KG	www.rohde-schwarz.com/de	X	X						X					X	X	X	X					
R	Rohde & Schwarz USA, Inc.	www.rohde-schwarz-usa.com	X	X						X					X	X	X	X					
S	Schaffner EMC, Inc.	www.schaffner.com						X			X										X	X	
S	Schurter, Inc.	www.schurter.com			X						X												
S	Schwarzbeck Mess-Elektronik	www.schwarzbeck.com		X																			
S	Select Fabricators	www.select-fabricators.com													X	X							
S	Siglent Technologies	www.siglentna.com																X					
S	Signal Hound	www.signalhound.com						X		X							X				X		
S	Solar Electronics	www.solar-emc.com		X																			
S	Spira Mfg. Corp.	www.spira-emi.com													X								
T	TDK	www.tdk.com						X			X					X				X			
T	TekBox Technologies	www.tekbox.net	X					X										X			X		
T	Tektronix	www.tek.com																X					
T	Teledyne LeCroy	www.teledynelecroy.com																X					
T	TESEQ Inc.	www.teseq.com																X					
T	Test Equity	www.testequity.com/leasing/	X							X							X		X				
T	Thurlby Thandar (AIM-TTi)	www.aimtti.com								X							X						
T	Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X							X						
T	TPI	www.rf-consultant.com					X																
T	Transient Specialists	www.transientspecialists.com																	X				
T	TRSRenTelCo	www.trsrentelco.com/categories/spectrum-analyzers/emc-test-equipment	X	X						X							X	X	X		X		
V	Vectawave Technology	www.vectawave.com	X																				
V	V Technical Textiles / Shieldex US	www.vtechtextiles.com													X								
W	Washington Laboratories	www.wll.com				X	X		X			X									X	X	X
W	Windfreak Technologies	www.windfreaktech.com																X			X		
W	Würth Elektronik eiSos GmbH & Co. Kg	www.we-online.com		X	X			X	X		X	X			X								
W	Wyatt Technical Services	www.wyatt-tech.net					X																X
X	XGR Technologies	www.xgrtec.com													X								

2020 EMC TEST LAB DIRECTORY

WHEREVER YOU ARE IN THE COUNTRY you now have access to local testing facilities. We have created an easy-to-use directory of national labs and their services grouped alphabetically by state and city, so that our readers can identify labs closest to them. We have strived to make this directory as accurate as possible; our goal is to have the most concise, informative, and up-to-date information. E-mail any additions, revisions, and suggestions to Jennifer@lectrixgroup.com.

USA

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
ALABAMA																						
Huntsville	EMC Compliance www.emccompliance.com	(256) 650-5261			•									•						•		
Huntsville	National Technical Systems www.nts.com	(256) 837-4411		•	•		•	•	•	•	•			•	•	•	•		•	•	•	
ARIZONA																						
Chandler	DNB Engineering, Inc. www.dnbenginc.com	(480) 405-6160			•	•	•				•		•	•	•			•		•	•	
Mesa	Compliance Testing, LLC, aka Flom Test Lab www.compliancetesting.com	(480) 926-3100		•	•		•	•	•		•				•	•		•			•	
Mesa	Robinson's Engineering Consultants www.robinsonsenterprises.com	(480) 361-2539	Contact lab for testing capabilities.																			
Scottsdale	General Dynamics Missions Systems www.gdc4s.com	(480) 441-3033												•	•						•	•
Tempe	Lab-Tech, Inc. www.advancedtechnologieslab.com	(480) 317-0700					•															
Tempe	National Technical Systems www.nts.com	(480) 966-5517	•	•	•	•	•	•	•	•	•	•	•	•				•		•	•	
CALIFORNIA																						
Brea	Compatible Electronics, Inc. www.celectronics.com	(714) 579-0500		•	•		•	•	•		•			•	•					•		
Anaheim	EMC TEMPEST Engineering http://emctempest.com	(714) 778-1726			•		•					•		•				•		•	•	
Brea	CKC Laboratories, Inc. www.ckc.com	(714) 993-6112		•	•		•	•	•		•				•	•					•	
Brea	Compatible Electronics, Inc. www.celectronics.com	(714) 579-0500	•	•	•		•	•	•	•	•			•	•					•		
Carlsbad	NEMKO www.nemko.com	(760) 444-3500	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	
Costa Mesa	Independent Testing Laboratories, Inc. www.itltesting.net	(714) 662-1011			•			•			•			•						•		
Dana Point	NTS https://www.nts.com/locations/danapoint	(949) 429-8602		•	•	•	•	•	•		•	•		•				•		•		

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
El Dorado Hills	Sanesi Associates	(916) 496-1760		•	•		•	•	•		•										•	
Fremont	CKC Laboratories, Inc. www.ckc.com	(510) 249-1170		•	•	•	•	•	•		•	•		•	•	•		•		•	•	
Fremont	Underwriters Laboratories, Inc. www.ul.com	(510) 319-4000	•	•	•		•	•	•	•	•				•	•						
Fremont	Elma Electronics, Inc. www.elma.com	(510) 656-3400			•				•												•	
Fremont	HCT America http://hctamerica.com	(510) 933-8848		•	•		•		•		•			•		•				•		
Fullerton	DNB Engineering, Inc. www.dnbenginc.com	(714) 870-7781			•	•	•					•	•	•	•			•		•	•	
Fullerton	National Technical Systems (NTS) www.nts.com	(714) 879-6110		•	•	•	•	•	•		•	•	•	•	•			•		•	•	
Irvine	7Layers, Inc. www.7layers.com	(949) 716-6512		•	•		•	•	•		•											
Irvine	Element EMC www.nwemc.com	(949) 861-8918		•	•		•		•		•				•							
Lake Forest	Compatible Electronics, Inc. www.celectronics.com	(949) 587-0400		•	•		•	•	•		•			•	•	•				•		
Lake Forest	Intertek (Lake Forest) www.intertek.com	(800) 967 5352		•	•	•	•	•	•		•				•	•						
Los Angeles	Field Management Services www.fms-corp.com	(323) 937-1562																			•	
Mariposa	CKC Laboratories, Inc. www.ckc.com	(209) 966-5240		•	•		•	•	•		•			•	•	•					•	
Menlo Park	Intertek (Menlo Park) www.intertek.com	(800) 967-5352	•	•	•	•	•	•	•		•			•	•	•						
Milpitas	CETECOM Inc. www.cetecom.com	(408) 586-6200		•	•		•	•	•		•				•	•						
Moffett Field	RMV Technology Group LLC - NASA Ames Research Center: www.esdrmv.com	(650) 964-4792					•									•					•	
Mountain View	Electro Magnetic Test, Inc. www.emtlabs.com	(650) 965-4000		•	•		•	•	•	•	•	•			•	•						
Newark	NTS https://www.nts.com/locations/silicon_valley	(877) 245-7800		•	•			•	•		•					•						
North Highlands	Northrop Grumman ESL www.northropgrumman.com	(916) 570-4340			•		•		•		•			•						•	•	•
Orange	G & M Compliance, Inc. www.gmcompliance.com	(714) 628-1020	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•
Pleasanton	Intertek (Pleasanton) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Pleasanton	MiCOM Labs www.micomlabs.com	(925) 462-0304			•		•	•	•		•				•							
Pleasanton	TÜV Rheinland of North America, Inc. www.tuv.com	(925) 249-9123		•	•		•	•	•		•				•	•	•					
Poway	APW Electronic Solutions www2.eem.com	(858) 679-4550						•		•			•									
Rancho St. Margarita	Aegis Labs, Inc. http://aegislabsinc.com	(949) 751-8089	•		•			•	•		•				•	•						

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Redondo Beach	Northrop Grumman Space Tech. Sector www.northropgrumman.com	(310) 812-3162			•	•	•				•		•	•			•	•		•	•	•
Riverside	DNB Engineering, Inc. www.dnbenginc.com	(951) 637-2630	•		•		•	•	•	•	•					•						
Riverside	Global Testing www.global-testing.com	(951) 781-4540	•		•		•			•	•	•				•						
Sacramento	Northrop-Grumman EM Systems Lab www.northropgrumman.com	(916) 570-4340			•		•		•		•			•						•	•	•
San Clemente	Stork Garwood Laboratories, Inc. www.garwoodlabs.com	(949) 361-9189			•	•	•		•	•	•	•		•		•				•		
San Diego	Intertek (San Diego) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
San Diego	TDK-Lambda Electronics www.lambda.com	(619) 575-4400			•				•		•											
San Diego	TÜV SÜD America, Inc. www.tuvamerica.com	(858) 678-1400		•	•		•	•	•		•	•	•		•	•				•		
Santa Clara	Montrose Compliance Services, Inc. www.montrosecompliance.com	(408) 247-5715			•			•	•		•					•						
Santa Clara	MET Laboratories, Inc. www.metlabs.com	(408) 748-3585	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•		•	•	
Santa Clara	TÜV Rheinland EMC Test Center www.tuv.com	(408) 492-9395		•	•		•	•	•		•				•	•	•					
San Jose	Arc Technical Resources, Inc. www.arctechnical.com	(408) 263-6486					•	•	•	•	•	•	•	•				•		•	•	
San Jose	ATLAS Compliance & Engineering Inc. www.atlasce.com	(866) 573-9742			•		•	•	•		•	•			•	•					•	
San Jose	EMCE Engineering, Inc. www.universalcompliance.com	(510) 490-4307	•	•	•		•	•	•	•	•			•		•		•				
San Jose	Safety Engineering Laboratory www.seldirect.com	(408) 544-1890						•								•						
San Jose	Underwriters Laboratories, Inc. www.ul.com	(408) 754-6500	•		•		•	•	•	•	•				•	•					•	
San Marcos	RF Exposure Lab, LLC www.rfexposurelab.com	(760) 471-2100													•		•					
Sunnyvale	Bay Area Compliance Labs. www.baclcorp.com	(408) 732-9162	•	•	•	•	•	•	•	•	•				•	•						
Sunol	ITC Engineering Services, Inc. www.itcemc.com	(925) 862-2944			•		•	•	•	•	•			•	•	•		•				
Torrance	Lyncole XIT Grounding www.lyncole.com	(310) 214-4000	•									•										
Trabuco Canyon	RFI International www.rfiinternational.com	(949) 888-1607			•				•	•	•					•						
Union City	MET Laboratories, Inc. www.metlabs.com	(510) 489-6300	•	•	•		•	•	•	•	•	•		•	•	•		•		•	•	
COLORADO																						
Boulder	Ball Aerospace & Technology Corp. www.ballaerospace.com	(303) 939-4618			•		•				•		•	•				•		•	•	
Boulder	Intertek (Boulder) www.intertek.com	(800) 967-5352		•	•	•	•	•	•		•			•	•	•			•			

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Denver	Element www.element.com	(720) 340-7810	Contact lab for testing capabilities.																			
Lakewood	Electro Magnetic Applications, Inc. www.ema3d.com/location/	(303) 980-0070			•	•	•					•							•			
Longmont	NTS www.nts.com/location/longmont-co-vista-view/	(303) 776-7249		•	•		•	•	•		•			•	•					•	•	
CONNECTICUT																						
Newtown	TÜV Rheinland of North America, Inc. www.tuv.com	(203) 426-0888		•	•		•	•	•		•				•	•	•					
FLORIDA																						
Lake Mary	Test Equipment Connection www.testequipmentconnection.com	(800) 615-8378																	•			
Newberry	Timco Engineering, Inc. www.timcoengr.com	(352) 472-5500		•	•		•	•	•	•	•				•	•						
Orlando	NTS www.nts.com/location/orlando-fl-emi/	(407) 313-4230		•	•		•	•	•		•			•	•			•		•		
Orlando	National Technical Systems NTS www.nts.com/location/orlando-fl-environmental/	(407) 293-5844		•	•	•	•	•	•		•			•	•			•		•	•	
Tampa	TÜV SÜD America, Inc. www.tuv-sud-america.com/us-en	(813) 284-2715	•	•	•	•	•	•	•		•	•		•	•	•		•		•	•	
GEORGIA																						
Alpharetta	EMC Testing Laboratories, Inc. www.emctesting.com	(770) 475-8819			•		•		•	•	•		•			•					•	
Alpharetta	U.S. Technologies, Inc. www.ustechnologies.com	(770) 740-0717	•		•		•	•	•	•	•	•			•	•				•	•	
Duluth	Intertek (Duluth) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Peachtree	Panasonic Automotive: https://na.panasonic.com/us/automotive-solutions	(770) 487-3356			•		•				•				•							
Suwanee	SGS North America www.sgsgroup.us.com	(770) 570-1800			•		•	•	•		•				•	•				•		
ILLINOIS																						
Downers Grove	Elite Electronic Engineering, Inc. www.elitetest.com	(630) 495-9770	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Mundelein	Midwest EMI Associates, Inc. www.midemi.com	(847) 393-7316			•		•	•	•		•			•		•				•	•	
Northbrook	Underwriters Laboratories, LLC. www.ul.com	(847) 272-8800	•	•	•		•	•	•	•	•				•	•					•	
Mount Prospect	National Technical Systems NTS www.nts.com	(847) 934-5300	•	•	•	•	•	•	•		•	•		•	•	•				•	•	
Poplar Grove	LF Research EMC Design & Test Facility www.lfresearch.com	(815) 566-5655			•	•	•	•	•		•	•		•		•		•	•	•	•	
Rockford	National Technical Systems NTS www.nts.com	(815) 315-9250		•	•		•	•	•		•											

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Romeoville	Radiometrics Midwest Corp. www.radiomet.com	(815) 293-0772	•		•	•	•	•	•		•	•		•	•			•		•	•	
Wheeling	D.L.S. Electronic Systems, Inc. www.dlsemc.com	(847) 537-6400	•	•	•	•	•	•	•		•	•		•	•	•		•		•	•	
INDIANA																						
Indianapolis	Raytheon Technical Services Co., EMI Lab www.raytheon.com	(317) 306-4872			•						•			•	•							•
Indianapolis	F2 Labs, Inc. http://f2labs.com	(877) 405-1580			•	•	•	•	•	•	•	•			•	•				•		
KANSAS																						
Louisburg	Rogers Labs, Inc. www.rogerslabs.com	(913) 837-3214			•		•		•		•			•	•					•		
KENTUCKY																						
Lexington	Lexmark International EMC Lab www.lexmark.com	(859) 232-2000							•													
Lexington	Intertek (Lexington) www.intertek.com	(800) 976-5352	•	•	•	•	•	•	•		•			•	•							
MAINE																						
Portland	Enerdoor www.enerdoor.com	(207) 210-6511			•		•	•			•											
MARYLAND																						
Baltimore	MET Laboratories, Inc. www.metlabs.com	(410) 354-3300	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•		•	•	
Columbia	Advanced Programs Inc. www.advprograms.com	(410) 312-5800												•						•		•
Columbia	PCTest Engineering Lab www.pctestlab.com	(410) 290-6652		•	•	•	•	•	•	•	•				•		•					•
Damascus	F2 Labs, Inc. http://f2labs.com	(301) 253-4500			•	•	•	•	•	•	•	•			•	•				•		
Elkridge	ATEC Industries, Ltd. www.atecindustries.com	(443) 459-5080				•	•					•	•	•	•						•	
Frederick	The American Association for Lab Accreditation; www.a2la.org	(301) 644-3248													•							
Frederick	Washington Labs www.wll.com	(301) 216-1500							•							•						
Gaithersburg	Washington Laboratories, Ltd. www.wll.com	(301) 216-1500			•	•		•	•		•	•	•	•	•	•	•	•		•	•	
Rockville	P.J. Mondin, P.E. Consultants	(301) 460-5864							•					•							•	•
MASSACHUSETTS																						
Billerica	Quest Engineering Solutions www.qes.com	(978) 667-7000																			•	

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Boxborough	Intertek (Boxborough) www.intertek.com	(800) 967-5352		•	•	•	•	•	•	•	•			•	•	•		•		•	•	
Boxborough	National Technical Systems www.nts.com	(978) 266-1001	•	•	•	•	•	•	•	•	•	•	•	•	•			•		•	•	
Burlington	NELCO www.nelcoworldwide.com	(781) 933-1940																			•	
Littleton	TÜV Rheinland of North America, Inc. www.tuv.com	(978) 266-9500		•	•		•	•	•		•					•						
Littleton	Compliance Management Group www.cmgcorp.net	(978) 431-1985	•		•		•	•	•		•				•	•					•	
Milford	Test Site Services, Inc. www.testsiteservices.com	(508) 634-3444	•	•	•		•	•	•	•	•	•		•	•	•		•		•	•	
Newton	EMC Test Design, LLC www.emctd.com	(508) 292-1833															•					
Peabody	TÜV SUD America Inc. www.tuv-sud-america.com/us-en	(978) 573-2500	•	•	•	•	•	•	•		•	•		•	•	•		•		•	•	
Pittsfield	National Technical Systems www.nts.com	(413) 499-2135		•	•	•	•	•	•		•	•			•					•		
Woburn	Chomerics, Div. of Parker Hannifin Corp. www.chomerics.com	(781) 935-4850			•	•	•	•	•		•	•	•	•	•	•	•	•		•	•	
MICHIGAN																						
Brighton	Willow Run Test Labs, LLC www.wrtest.com	(734) 252-9785			•		•		•												•	
Burton	Trialon Corporation www.trialon.com	(810) 742-8500			•		•				•				•							
Detroit	National Technical Systems www.nts.com	(313) 835-0044		•	•		•	•	•		•				•			•				
Detroit	TÜV Rheinland of North America, Inc. www.tuv.com/en/middleeast/home.jsp	(734) 207-9852		•	•		•	•	•		•					•						
Grand Rapids	Intertek (Grand Rapids) www.intertek.com	(800) 967-5352		•	•	•	•	•	•		•	•			•	•		•		•		
Holland	TÜV SÜD America, Inc. www.tuv-sud-america.com/us-en	(616) 546-3902		•	•		•	•	•		•								•			
Novi	Underwriters Laboratories, Inc. www.ul.com	(248) 427-5300			•		•	•			•			•	•	•				•	•	
Plymouth	Intertek (Plymouth) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Plymouth	TÜV SÜD America, Inc. www.tuvamerica.com	(734) 455-4841	•	•	•	•	•	•	•		•	•		•	•	•		•			•	
Sister Lakes	AHD EMC Lab www.ahde.com	(269) 313-2433			•		•	•	•		•			•	•						•	
MINNESOTA																						
Brooklyn Park	Element www.element.com	(612) 638-5136		•	•		•		•		•				•							
Glencoe	International Certification Services, Inc. www.icsi-us.com	(320) 864-4444	•		•		•	•	•		•			•	•	•				•	•	

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Minneapolis	Element www.element.com	(952) 888-7795													•							
MISSOURI																						
St. Louis	Boeing-St. Louis EMC Lab www.boeing.com	(314) 232-0232												•	•			•			•	
NEBRASKA																						
Lincoln	NCEE Labs www.nceelabs.com	(402) 323-6233			•		•	•	•		•			•	•	•				•		
NEW HAMPSHIRE																						
Goffstown	Retlif Testing Laboratories www.retlif.com	(603) 497-4600		•	•	•	•	•	•	•	•	•		•	•	•	•	•		•	•	
Hudson	Core Compliance Testing Services www.corecompliancetesting.com	(603) 889-5545			•		•		•		•	•			•							
Sandown	Compliance Worldwide, Inc. www.cw-inc.com	(603) 887-3903			•		•		•	•	•	•			•							
NEW JERSEY																						
Annandale	NU Laboratories, Inc. www.nulabs.com	(908) 713-9300					•							•	•						•	
Bridgewater	Lichtig EMC Consulting www.lichtigemc.com	(908) 541-0213	•																			
Camden	L-3 Communication Systems-East www.l-3com.com/cs-east	(856) 338-3000	Contact lab for testing capabilities.																			
Clifton	NJ-MET www.njmetmtl.com	(973) 546-5393	•							•												•
Edison	Metex Corporation www.metexcorp.com	(732) 287-0800																			•	
Edison	TESEQ, Inc. www.teseq.com	(732) 417-0501				•				•												
Fairfield	Intertek (Fairfield) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Fairfield	SGS U.S. Testing Co., Inc. www.sgsgroup.us.com	(973) 575-5252	•		•			•							•	•						
Farmingdale	EMC Technologists A Div. of I2R Corp. www.emctech.com	(732) 919-1100	•		•		•	•	•	•	•			•								
Hillsborough	Advanced Compliance Laboratory, Inc. http://ac-lab.com	(908) 927-9288 ext. 106			•			•	•	•	•				•	•						
Lincroft	Don HEIRMAN Consultants www.donheirman.com	(732) 741-7723			•				•													•
Rutherford	SGS International Certification Services, Inc.; www.sgsgroup.us.com	(201) 508-3000						•														
Thorofare	NDI Engineering Company www.ndieng.com	(856) 848-0033																			•	
Tinton Falls	National Technical Systems (NTS) www.nts.com	(732) 936-0800	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•		•	•	•
NEW MEXICO																						
Albuquerque	Advanced Testing Services, Inc. www.advanced-testing.com	(505) 292-2032											•				•				•	

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
White Sands	USA WSMR, Survivability Directorate www.wsmr.army.mil	(575) 678-1621			•	•	•				•	•		•			•	•			•	
NEW YORK																						
College Point	Aero Nav Laboratories, Inc. www.aeronavlabs.com	(718) 939-4422	•			•			•		•	•		•	•			•		•	•	•
Deer Park	Universal Shielding Corp. www.universalshielding.com	(631) 392-4888																			•	
Endicott	BAE Systems Controls, Inc. www.baesystems.com	(607) 770-2000			•	•						•		•	•			•		•		
Liverpool	Source1 Solutions www.source1compliance.com	(315) 730-5667			•		•	•	•		•			•		•					•	
Medford	American Environments Co. www.aeco.com	(631) 736-5883	•		•	•	•	•	•		•	•		•		•				•	•	
Melville	Underwriters Laboratories, LLC. www.ul.com	(631) 271-6200	•	•	•		•	•	•	•	•				•	•					•	
Palmyra	Source1 Solutions www.source1compliance.com	(315) 730-5667			•			•			•			•		•					•	
Poughkeepsie	IBM Corp. Poughkeepsie EMC Lab www.ibm.com	(845) 433-1234		•					•													
Webster	TÜV Rheinland Of North America www.tuv.com	(585) 645-0125		•	•		•	•	•		•				•	•	•					
Ronkonkoma	Retlif Testing Laboratories www.retlif.com	(631) 737-1500		•	•	•	•	•	•	•	•	•		•	•	•	•	•		•	•	
NORTH CAROLINA																						
Cary	CertifiGroup www.certifigroup.com	(919) 466-9283		•				•							•	•						
Cary	MET Laboratories, Inc. www.metlabs.com	(919) 481-9319	•	•	•		•	•	•	•	•	•		•	•	•		•		•	•	
Greensboro	Schneider Electric Industrial Repair Services www.schneiderelectricrepair.com	(800) 950-9550																	•			
Greenville	Lawrence Behr Associates (LBA) www.lbagroup.com	(252) 757-0279															•				•	
Res. Triangle Pk.	Educated Design & Dev., Inc. (ED&D) www.productsafet.com	(919) 469-9434		•											•	•			•			•
Res. Triangle Pk.	IBM RTP EMC Test Labs www.ibm.com	(800) 426-4968			•				•		•											
Res. Triangle Pk.	Underwriters Laboratories, LLC. www.ul.com	(919) 549-1400	•	•	•		•	•	•	•	•				•	•					•	
OHIO																						
Cleveland	CSA International www.csa-international.org	(216) 524-4990						•								•						
Cleveland	NASA GRC EMI Lab www1.grc.nasa.gov	(216) 433-4000												•							•	
Colombus	Intertek (Colombus) www.intertek.com	(800) 967 5352		•	•		•	•	•		•											
Mason	L-3 Cincinnati Electronics www.cinele.com	(513) 573-6100			•		•				•			•				•		•		
Mentor	EU Compliance Services, Inc. www.eucs.com	(440) 918-1425			•		•	•			•					•					•	

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Middlefield	F2 Labs, Inc. http://f2labs.com	(440) 632-5541		•	•	•	•	•	•	•	•	•			•	•					•	
Springboro	Pioneer Automotive Technologies	(937) 746-6600			•		•		•		•			•	•							
OREGON																						
Beaverton	Tektronix www.tek.com	(503) 627-4133	•												•					•		
Fairview	Intertek (Fairview) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Hillsboro	Element www.element.com	(503) 648-1818	•												•					•		
Hillsboro	ElectroMagnetic Investigations, LLC https://emicomply.com/contact/	(503) 466-1160			•		•	•	•		•			•	•						•	
Hillsboro	Element www.element.com	(503) 844-4066		•	•		•		•		•				•					•	•	
Portland	TÜV SÜD America, Inc. www.tuv-sud-america.com/us-en	(503) 598-7580		•	•	•	•	•	•		•					•						
PENNSYLVANIA																						
Chambersburg	Cuming Lehman Chambers http://cuminglehman.com	(717) 263-4101			•						•			•						•		
Glenside	Electro-Tech Systems, Inc. www.electrotechsystems.com	(215) 887-2196	•				•														•	
Harleysville	Retlif Testing Laboratories www.retlif.com	(215) 256-4133		•	•	•	•	•	•	•	•	•		•	•	•	•	•		•	•	
Hatfield	Laboratory Testing Inc. www.labtesting.com	(800) 219-9095													•				•			
New Castle	Keystone Compliance LLC www.keystonecompliance.com	(724) 657-9940	•		•	•	•	•	•		•	•	•	•	•	•	•	•		•	•	
Pottstown	BEC Inc. www.bec-ccl.com	(610) 970-6880			•		•		•		•				•						•	
State College	Videon Central, Inc. www.videon-central.com	(814) 235-1111			•		•	•	•											•		
West Conshohocken	R&B Laboratory www.rblaboratory.com	(610) 825-1960			•	•	•				•	•		•			•	•		•	•	
TENNESSEE																						
Knoxville	Global Testing Labs LLC www.globaltestinglabs.com	(865) 523-9972			•				•		•				•							
Knoxville	AMS Corporation www.ams-corp.com	(865) 691-1756			•		•				•			•								
TEXAS																						
Austin	BAE Systems IDS Test Services www.baesystems.com	(512) 926-2800											•					•				
Austin	MET Laboratories, Inc. www.metlabs.com	(512) 287-2500	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•		•	•	
Bartonville	Nemko USA www.nemko.com	(940) 294-7057		•	•		•	•	•	•	•			•	•	•	•	•		•	•	
Cedar Park	TDK RF Solutions, Inc. www.tdkrfsolutions.com	(512) 258-9478			•		•	•	•	•	•				•							
Elmendorf	Intertek (Elmendorf) www.intertek.com	(800) 967-5352		•	•		•	•	•		•											

USA continued

CITY/STATE	COMPANY NAME / WEBSITE	PHONE #	BELLCORE/TELCORDIA	CB/CAB/TCB CB/CAB/TCB	EMISSIONS	EMP/LIGHTNING EFFECTS	ESD	EURO CERTIFICATIONS	FCC PART 15 & 18	FCC PART 68	IMMUNITY	LIGHTNING STRIKE	MIL-STD 188/125	MIL-STD 461	NVLAP/A2LA APPROVED	PRODUCT SAFETY	RADHAZ TESTING	RS103 > 200 V/METER	REPAIR/CALIBRATION	RTCA DO-160	SHIELDING EFFECTIVENESS	TEMPEST
Plano	National Technical Systems www.nts.com	(972) 509-2566	•	•	•	•	•	•	•	•	•	•		•	•			•		•	•	
Plano	Element www.element.com	(469) 304-5255		•	•		•		•		•				•							
Plano	Intertek (Plano) www.intertek.com	(800) 967-5352		•	•	•	•	•	•		•				•	•						
Round Rock	Professional Testing (EMI), Inc. www.ptitest.com	(512) 244-3371			•		•		•		•	•		•	•	•			•	•	•	
San Antonio	Southwest Research Institute www.swri.org	(210) 684-5111	•		•	•	•	•	•	•	•	•	•	•	•	•		•		•	•	
UTAH																						
Coalville	DNB Engineering, Inc. www.dnbenginc.com	(435) 336-4433	•		•		•	•	•	•	•					•						
Draper	VPI Technology www.vpitechnology.com	(801) 495-2310			•		•	•	•	•	•			•	•	•						
Ogden	Little Mountain Test Facility (LMTF)	(801) 315-2320			•	•	•				•		•	•				•		•	•	
Salt Lake City	L3 Communication Systems-West www.l3harris.com	(801) 594-2000			•			•	•					•						•		
VERMONT																						
Middlebury	Green Mountain Electromagnetics, Inc. www.gmelectro.com	(802) 388-3390						•	•	•			•	•								
VIRGINIA																						
Fredericksburg	E-LABS INC. www.e-labsinc.com	(540) 834-0372			•		•				•			•	•		•			•	•	
Fredericksburg	Vitatech Engineering, LLC http://vitatech.net	(540) 286-1984	•		•				•	•	•		•	•							•	
Herndon	Rhein Tech Laboratories, Inc. www.rheintech.com	(703) 689-0368			•		•	•	•		•			•	•	•				•	•	
Reston	TEMPEST, Inc. (VA) www.tempest-inc.com	(703) 836-7378			•		•	•	•	•	•		•	•							•	•
Richmond	Technology International, Inc. www.techintl.com	(804) 794-4144		•	•		•	•			•					•						•
WASHINGTON																						
Bothell	CKC Laboratories, Inc www.ckc.com	(425) 402-1717		•	•	•	•	•	•		•	•	•	•	•			•		•	•	
Bothell	Element www.element.com	(425) 984-6600			•		•		•		•				•	•						
WISCONSIN																						
Genoa City	D.L.S. Electronic Systems, Inc. www.dlsemc.com	(262) 279-0210		•	•				•						•							
Middleton	Intertek www.intertek.com	(800) 967-5352		•	•		•	•	•		•											
Neenah	International Compliance Laboratories www.icl-us.com	(920) 720-5555			•		•		•		•				•							

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www.health.mil/About-MHS/OASDHA/Defense-Health-Agency
Defense Information Systems Agency (DISA)
www.disa.mil
Defense Intelligence Agency (DIA)
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Defense Nuclear Facilities Safety Board
www.dnfsb.gov
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Defense Security Service
www.dss.mil
Defense Technical Information Center (DTIC)
https://discover.dtic.mil
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www.dtra.mil
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www.defense.gov
Economic Adjustment Office
www.oea.gov
Fleet Forces Command
www.public.navy.mil/usff/Pages/default.aspx
Joint Chiefs of Staff
www.jcs.mil
Joint Forces Staff College
https://jfsc.ndu.edu
Joint Military Intelligence College
http://ni-u.edu/wp/
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www.jpeocbd.osd.mil/home
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www.nro.gov
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Southern Command
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Special Forces Operations Command
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Strategic Command
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Unified Combatant Commands
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Amtrak (AMTRAK)
www.amtrak.com/home.html
Animal and Plant Health Inspection Service (APHIS)
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Archives, National Archives and Records Administration (NARA)
www.archives.gov
Arms Control and International Security
www.state.gov/t/

B

Bonneville Power Administration
www.bpa.gov/Pages/home.aspx
Bureau of Industry and Security (BIS)
www.federalregister.gov/agencies/economics-and-statistics-administration
Bureau of Labor Statistics
https://stats.bls.gov
Bureau of Land Management (BLM)
www.blm.gov
Bureau of Ocean Energy Management
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Bureau of Safety and Environmental Enforcement
www.bsee.gov
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www.bts.gov

C

Census Bureau
www.census.gov
Center for Food Safety and Applied Nutrition
www.fda.gov/AboutFDA/CentersOffices/OfficeofFoods/CFSAN/default.htm
Centers for Disease Control and Prevention (CDC)
www.cdc.gov
Central Intelligence Agency (CIA)
www.cia.gov/index.html
Chemical Safety Board
www.csb.gov
Chief Acquisition Officers Council
www.cao.gov/cao-home
Chief Financial Officers Council
https://cfo.gov
Chief Information Officers Council
www.cio.gov
Community Oriented Policing Services (COPS)
https://cops.usdoj.gov
Community Planning and Development
www.hud.gov/program_offices/comm_planning
Compliance, Office of
www.ocwr.gov
Computer Emergency Readiness Team (US CERT)
www.us-cert.gov
Congress—U.S. Senate
www.senate.gov
www.senate.gov/senators/leadership.htm
www.senate.gov/committees/index.htm
www.senate.gov/pagelayout/history/one_item_and_teasers/officers.htm
Congressional Budget Office (CBO)
www.cbo.gov
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www.saferproducts.gov
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www.usace.army.mil
Council on Environmental Quality
www.whitehouse.gov/ceq/

D

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Department of the Treasury
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Department of Transportation (DOT)
www.transportation.gov
Director of National Intelligence
www.dni.gov
Drug Enforcement Administration (DEA)
www.dea.gov

E

Economic Development Administration
www.eda.gov
Economic Growth, Energy, and the Environment
www.state.gov/
Economics and Statistics Administration
www.usa.gov/federal-agencies/economics-and-statistics-administration
Education Department (ED)
www.ed.gov
Education Resources Information Center (ERIC)
https://eric.ed.gov
Energy Department (DOE)
www.energy.gov
Energy Star Program
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Environmental Protection Agency (EPA)
www.epa.gov
Equal Employment Opportunity Commission (EEOC)
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European Command
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Export-Import Bank of the United States
www.exim.gov

F

Farm Service Agency
www.fsa.usda.gov

Federal Aviation Administration (FAA)
www.faa.gov
Federal Bureau of Investigation (FBI)
www.fbi.gov
Federal Bureau of Prisons (BOP)
www.bop.gov
Federal Citizen Information Center
www.usa.gov/explore/
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Federal Consulting Group
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Federal Emergency Management Agency (FEMA)
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Federal Energy Regulatory Commission
www.ferc.gov
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www.fgdc.gov
Federal Highway Administration (FHA)
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Federal Housing Administration (FHA)
www.hud.gov/federal_housing_administration
Federal Labor Relations Authority (FLRA)
www.flra.gov
Federal Laboratory Consortium for Technology Transfer
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Federal Library and Information Center Committee
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www.fmc.gov/default.aspx
Federal Mine Safety and Health Review Commission
www.fmshrc.gov
Federal Motor Carrier Safety Administration (FMCSA)
www.fmcsa.dot.gov
www.fmcsa.dot.gov/pr
Federal Protective Service
www.dhs.gov/topic/federal-protective-service
Federal Railroad Administration (FRA)
https://railroads.dot.gov
Federal Register
www.archives.gov/f
Federal Trade Commission (FTC)
www.ftc.gov
www.consumer.ftc.gov/admongo/
www.consumer.ftc.gov/features/feature-0038-onguardonline
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www.transit.dot.gov
FedStats
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www.fsis.usda.gov/wps/portal/fsis/home
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G

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www.gpo.gov
Grain Inspection, Packers and Stockyards Administration
www.gipsa.usda.gov

H

Health and Human Services Department (HHS)
www.hhs.gov
Health Resources and Services Administration
www.hrsa.gov/
Homeland Security Department (DHS)
www.dhs.gov
House of Representatives
www.house.gov
www.house.gov/committees
www.house.gov/leadership
Housing and Urban Development, Department of (HUD)
www.hud.gov
Housing Office
www.hud.gov/program_offices/housing

I

Immigration and Customs Enforcement (ICE)
www.ice.gov
Industry and Security, Bureau of (BIS)
www.federalregister.gov/agencies/economics-and-statistics-administration
Information Resources Center (ERIC)
www.usa.gov/federal-agencies/education-resources-information-center
Innovation and Improvement Office
https://innovation.ed.gov
Inspectors General
https://ignet.gov
Institute of Museum and Library Services
www.imls.gov
Interior Department (DOI)
www.doi.gov
Internal Revenue Service (IRS)
www.irs.gov
International Labor Affairs, Bureau of
www.dol.gov/agencies/ilab
International Trade Administration (ITA)
www.trade.gov
International Trade Commission
www.usitc.gov
Interpol
www.justice.gov/interpol-washington

J

Job Corps
www.jobcorps.gov
Joint Chiefs of Staff
www.jcs.mil
Justice Department (DOJ)
www.justice.gov

L

Labor Department (DOL)
www.dol.gov
Labor Statistics, Bureau of
https://stats.bls.gov
Land Management, Bureau of (BLM)
www.blm.gov
Library of Congress (LOC)
www.loc.gov

M

Manufactured Housing Programs
www.hud.gov/program_offices/housing/rmra/mhs/mhshome
Marine Mammal Commission
www.mmc.gov
Maritime Administration (MARAD)
www.maritime.dot.gov
Marketing and Regulatory Programs
www.aphis.usda.gov/aphis/ourfocus/business-services
Marshals Service
www.usmarshals.gov//
Middle East Broadcasting Networks
www.alhurra.com
Migratory Bird Conservation Commission
www.fws.gov/refuges/realty/mbcc.html
Military Postal Service Agency
www.usa.gov/federal-agencies/military-postal-service-agency
Millennium Challenge Corporation
www.mcc.gov
Mine Safety and Health Administration (MSHA)
www.msha.gov
Mint
www.usmint.gov
Mississippi River Commission
www.mvd.usace.army.mil/About/Mississippi-River-Commission-MRC/

N

National Aeronautics and Space Administration (NASA)
www.nasa.gov
National Agricultural Statistics Service
www.nass.usda.gov
National Archives and Records Administration (NARA)
www.archives.gov
National Cancer Institute (NCI)
www.cancer.gov
National Geospatial-Intelligence Agency
www.nga.mil/Pages/Default.aspx
National Health Information Center (NHIC)
https://health.gov/nhic/
National Heart, Lung, and Blood Institute (NHLBI)
www.nhlbi.nih.gov
National Highway Traffic Safety Administration (NHTSA)
www.nhtsa.gov
National Institute of Food and Agriculture
https://nifa.usda.gov
National Institute of Occupational Safety and Health (NIOSH)
www.cdc.gov/niosh/
National Insts
www.nist.gov
National Institutes of Health (NIH)
www.nih.gov
National Laboratories
www.energy.gov/national-laboratories
National Nuclear Security Administration
www.energy.gov/nnsa/national-nuclear-security-administration
National Ocean Service
https://oceanservice.noaa.gov
National Oceanic and Atmospheric Administration (NOAA)
www.noaa.gov
National Park Foundation
www.nationalparks.org
National Park Service (NPS)
www.nps.gov/index.htm
National Railroad Passenger Corporation (AMTRAK)
www.amtrak.com/home.html
National Reconnaissance Office
www.nro.gov
National Science Foundation (NSF)
www.nsf.gov
National Security Agency (NSA)
www.nsa.gov
National Security Council (NSC)
www.whitehouse.gov/nsc/
National Technical Information Service
www.ntis.gov
National Telecommunications and Information Administration
www.ntia.doc.gov
National Transportation Safety Board
www.ntsb.gov/Pages/default.aspx
National Weather Service
www.weather.gov
Natural Resources Conservation Service
www.usa.gov/federal-agencies/natural-resources-conservation-service
Natural Resources Revenue
www.onrr.gov
Northern Border Regional Commission
www.nbrc.gov
Northwest Power and Conservation Council
www.nwcouncil.org
Northwest Power Planning Council
www.nwcouncil.org
Nuclear Energy
www.energy.gov/ne/office-nuclear-energy
Nuclear Regulatory Commission (NRC)
www.nrc.gov

O

Oak Ridge National Laboratory
www.ornl.gov
Occupational Safety and Health Administration (OSHA)
www.osha.gov
Ocean Energy Management
www.boem.gov
Office of Community Planning and Development
www.hud.gov/program_offices/comm_planning
Office of Compliance
www.usa.gov/federal-agencies/office-of-compliance
Office of Cuba Broadcasting
www.radiotelevisionmarti.com
Office of Environmental Management
www.energy.gov/em/office-environmental-management
Office of Fossil Energy
www.energy.gov/fe/office-fossil-energy
Office of Housing
www.hud.gov/program_offices/housing
Office of Management and Budget (OMB)
www.whitehouse.gov/omb/
Office of Natural Resources Revenue
www.onrr.gov
Office of Nuclear Energy
www.energy.gov/ne/office-nuclear-energy
Office of Policy Development and Research
www.huduser.gov/portal/home.html
Office of Science &Technology Policy
www.whitehouse.gov/ostp/
Office of Scientific and Technical Information
www.osti.gov
Director of National Intelligence
www.dni.gov
Office of the Federal Register
www.archives.gov/federal-register

P

Pacific Northwest Electric Power and Conservation Planning Council
www.nwcouncil.org

Patent and Trademark Office
www.uspto.gov
Pipeline and Hazardous Materials Safety Administration
www.phmsa.dot.gov
Policy Development and Research
www.huduser.gov/portal/home.html
Postal Inspection Service
https://postalinspectors.uspis.gov
Postal Regulatory Commission
www.prc.gov
Postal Service (USPS)
www.usps.com
Power Administrations
www.energy.gov/offices

R

Radio Free Asia (RFA)
www.rfa.org/english/
Radio Free Europe and Radio Liberty (RFE/RL)
www.rferl.org
Radio Sawa
www.radiosawa.com
Research and Innovative Technology Administration
www.transportation.gov/research-technology
Rural Business and Cooperative Programs
www.rd.usda.gov/about-rd/agencies/rural-business-cooperative-service
Rural Development
www.rd.usda.gov
Rural Utilities Service
www.rd.usda.gov/about-rd/agencies/rural-utilities-service

S

Safety and Environmental Enforcement, Bureau of
www.bsee.gov
Science and Technology Policy
www.whitehouse.gov/ostp/
Science Office
https://science.energy.gov
Scientific and Technical Information, Office of
www.osti.gov
Seafood Inspection Program
www.fisheries.noaa.gov/topic/seafood-commerce-certification#seafood-inspection
www.fishwatch.gov
Secret Service
www.secretservice.gov
Securities and Exchange Commission (SEC)
www.sec.gov
Selective Service System (SSS)
www.sss.gov
Senate
www.senate.gov
www.senate.gov/senators/leadership
www.senate.gov/committees
www.senate.gov/pagelayout/history/one_item_and_teasers/officers.htm
Small Business Administration (SBA)
www.sba.gov
Southeastern Power Administration
www.energy.gov/sepa/southeastern-power-administration
Southwestern Power Administration
www.swpa.gov
State Department (DOS)
www.state.gov
Supreme Court of the United States
www.supremecourt.gov
Surface Transportation Board
www.stb.gov/stb/index.html

T

Trade and Development Agency
www.ustda.gov
Transportation Department (DOT)
www.transportation.gov
Transportation Security Administration (TSA)
www.tsa.gov
Transportation Statistics
www.bts.gov

U

U.S. National Central Bureau - Interpol
www.justice.gov/interpol-washington
U.S. Transportation Command
www.ustranscom.mil
US-CERT (US CERT)
www.us-cert.gov
USAGov
www.usa.gov/explore/

W

Washington Headquarters Services
www.whs.mil
Weather Service
www.weather.gov
Weights and Measures Division
www.nist.gov/pml/we
Western Area Power Administration
www.wapa.gov/Pages/Western.aspx

White House
www.whitehouse.gov
Wireless Telecommunications Bureau
www.fcc.gov/

U.S. STATES AND PROVINCES

A

Alabama
www.usa.gov/state-government/alabama
Alaska
www.usa.gov/state-government/alaska
Arizona
www.usa.gov/state-government/arizona
Arkansas
www.usa.gov/state-government/arkansas

C

California
www.usa.gov/state-government/california
Colorado
www.usa.gov/state-government/colorado
Connecticut
www.usa.gov/state-government/connecticut

D

Delaware
www.usa.gov/state-government/delaware

F

Florida
www.usa.gov/state-government/florida

G

Georgia
www.usa.gov/state-government/georgia

H

Hawaii
www.usa.gov/state-government/hawaii

I

Idaho
www.usa.gov/state-government/idaho
Illinois
www.usa.gov/state-government/illinois
Indiana
www.usa.gov/state-government/indiana
Iowa
www.usa.gov/state-government/iowa

K

Kansas
www.usa.gov/state-government/kansas
Kentucky
www.usa.gov/state-government/kentucky

L

Louisiana
www.usa.gov/state-government/louisiana

M

Maine
www.usa.gov/state-government/maine
Maryland
www.usa.gov/state-government/maryland
Massachusetts
www.usa.gov/state-government/massachusetts
Michigan
www.usa.gov/state-government/michigan
Minnesota
www.usa.gov/state-government/minnesota
Mississippi
www.usa.gov/state-government/mississippi
Missouri
www.usa.gov/state-government/missouri
Montana
www.usa.gov/state-government/montana

N

Nebraska
www.usa.gov/state-government/nebraska
Nevada
www.usa.gov/state-government/nevada
New Hampshire
www.usa.gov/state-government/new-hampshire
New Jersey
www.usa.gov/state-government/new-jersey
New Mexico
www.usa.gov/state-government/new-mexico
New York
www.usa.gov/state-government/new-york
North Carolina
www.usa.gov/state-government/north-carolina
North Dakota
www.usa.gov/state-government/north-dakota

O

Ohio
www.usa.gov/state-government/ohio
Oklahoma
www.usa.gov/state-government/oklahoma
Oregon
www.usa.gov/state-government/oregon

P

Pennsylvania
www.usa.gov/state-government/pennsylvania

R

Rhode Island
www.usa.gov/state-government/rhode-island

S

South Carolina
www.usa.gov/state-government/south-carolina
South Dakota
www.usa.gov/state-government/south-dakota

T

Tennessee
www.usa.gov/state-government/tennessee
Texas
www.usa.gov/state-government/texas

U

Utah
www.usa.gov/state-government/utah

V

Vermont
www.usa.gov/state-government/vermont
Virginia
www.usa.gov/state-government/virginia

W

Washington
www.usa.gov/state-government/washington
Wisconsin
www.usa.gov/state-government/wisconsin
Wyoming
www.usa.gov/state-government/wyoming

CAPITAL

Washington, D.C.
www.usa.gov/state-government/district-of-columbia

PROVINCES

Puerto Rico
www.usa.gov/state-government/puerto-rico
U.S. Virgin Islands
www.usa.gov/state-government/u-s-virgin-islands

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 60601-1-2	Medical electrical equipment–Part 1-2: General requirements for basic safety and essential performance - Collateral Standard: Electromagnetic disturbances - Requirements and tests
IEC 60601-2-2	Medical electrical equipment–Part 2-2: Particular requirements for the basic safety and essential performance of high frequency surgical equipment and high frequency surgical accessories
IEC 60601-4-2	Medical electrical equipment–Part 4-2: Guidance and interpretation - Electromagnetic immunity: performance of medical electrical equipment and medical electrical systems
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 modeling - 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 modeling - 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 modeling - 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 modeling - 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 modeling - 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 (to be withdrawn July 2020)
CISPR 24	Information technology equipment - Immunity characteristics - Limits and methods of measurement (to be withdrawn July 2020)
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

MEDICAL EMC STANDARDS

COLLATERAL STANDARDS

(https://www.webstore.iec.ch)

Document Number	Title
IEC 60601-1-1	Safety requirements for medical electrical systems
IEC 60601-1-2	Electromagnetic disturbances - requirements and tests
IEC 60601-1-3	Radiation protection in diagnostic x-ray equipment
IEC 60601-1-6	General requirements for basic safety and essential performance - Usability
IEC 60601-1-8	General requirements for basic safety and essential performance - Alarm systems
IEC 60601-1-9	Requirements for environmentally conscious design
IEC 60601-1-10	Requirements for the development of physiologic closed-loop controllers
IEC 60601-1-11	Medical electrical equipment and medical electrical systems used in the home healthcare environment
IEC 60601-1-12	Medical electrical equipment and medical electrical systems used in the medical services environment

OTHER RELEVANT STANDARDS

(https://www.webstore.iec.ch)

Document Number	Title
CISPR 11	Emission requirements for ISM equipment
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

For more extensive listings of medical standards, download the 2017 Medical EMC Guide:
https://interferencetechnology.com/wp-content/uploads/2017/08/2017_Medical-EMC_Low-Res-1.pdf

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://www.cnca.gov.cn/cnca/cncatest/20040420/column/227.htm

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

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

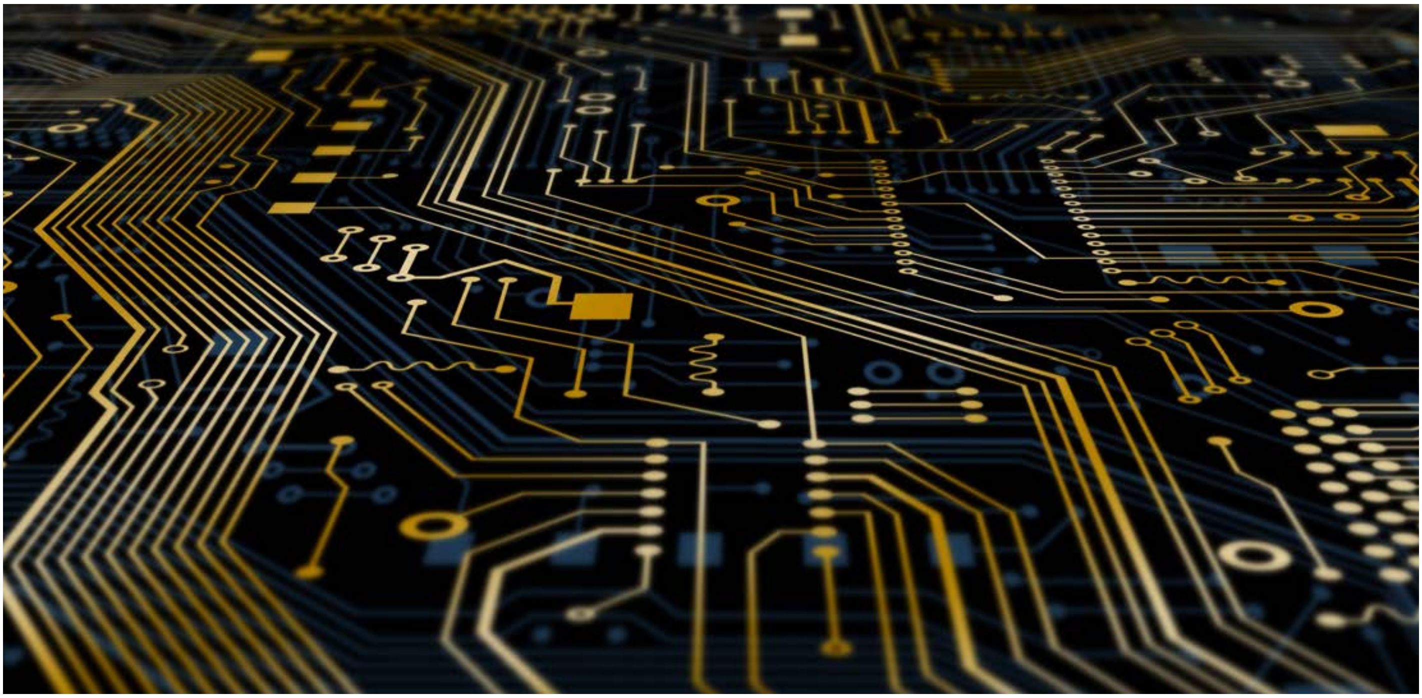
ISO (International Organization for Standards)
http://www.iso.org/iso/home.html

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

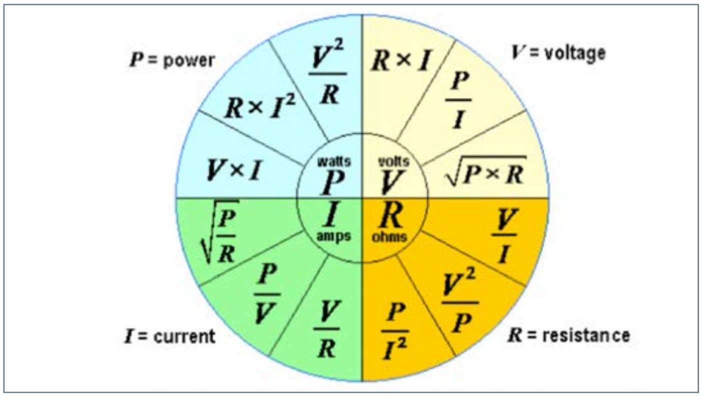
VCCI (Japan, Voluntary Control Council for Interference)
http://www.vcci.jp/vcci_e/



REFERENCES & TOOLS

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 sine-wave 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

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

RETURN LOSS, GIVEN VSWR

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

Return Loss, given reflection coefficient (ρ)

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

E-FIELD FROM DIFFERENTIAL-MODE CURRENT

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

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

REFERENCES & TOOLS

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:	$V = 10^{((dBuV=120)/20)}$
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:	$V/m= 10^{(((dBuV/m)-120)/20)}$
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):

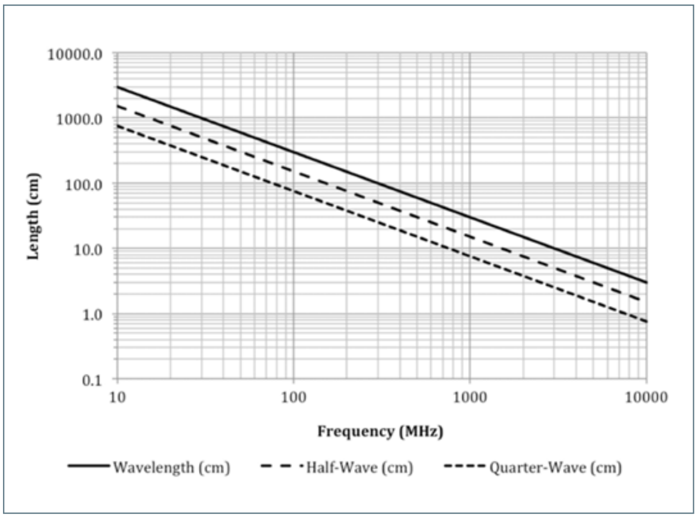
dBm to dBμV, use: dBμV = dBm + 107

REFERENCES & TOOLS

WAVELENGTH EQUATIONS (FREE SPACE)

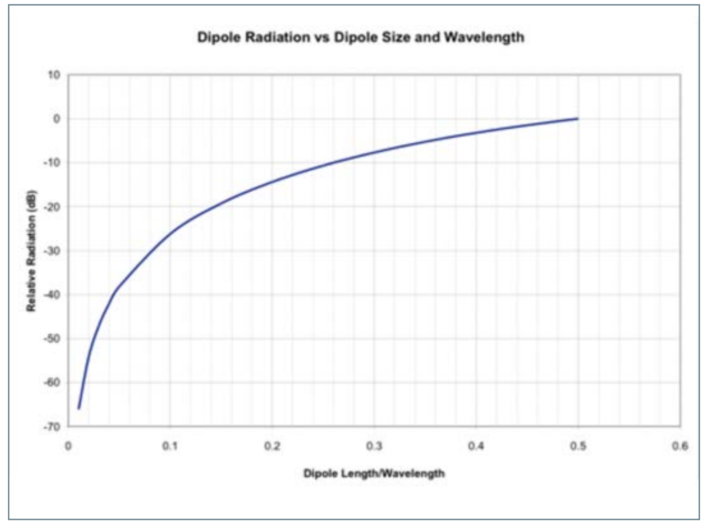
Wavelength(m) = 300/f(MHz)
Half wavelength(ft.) = 468/f(MHz)

RESONANCE OF STRUCTURES



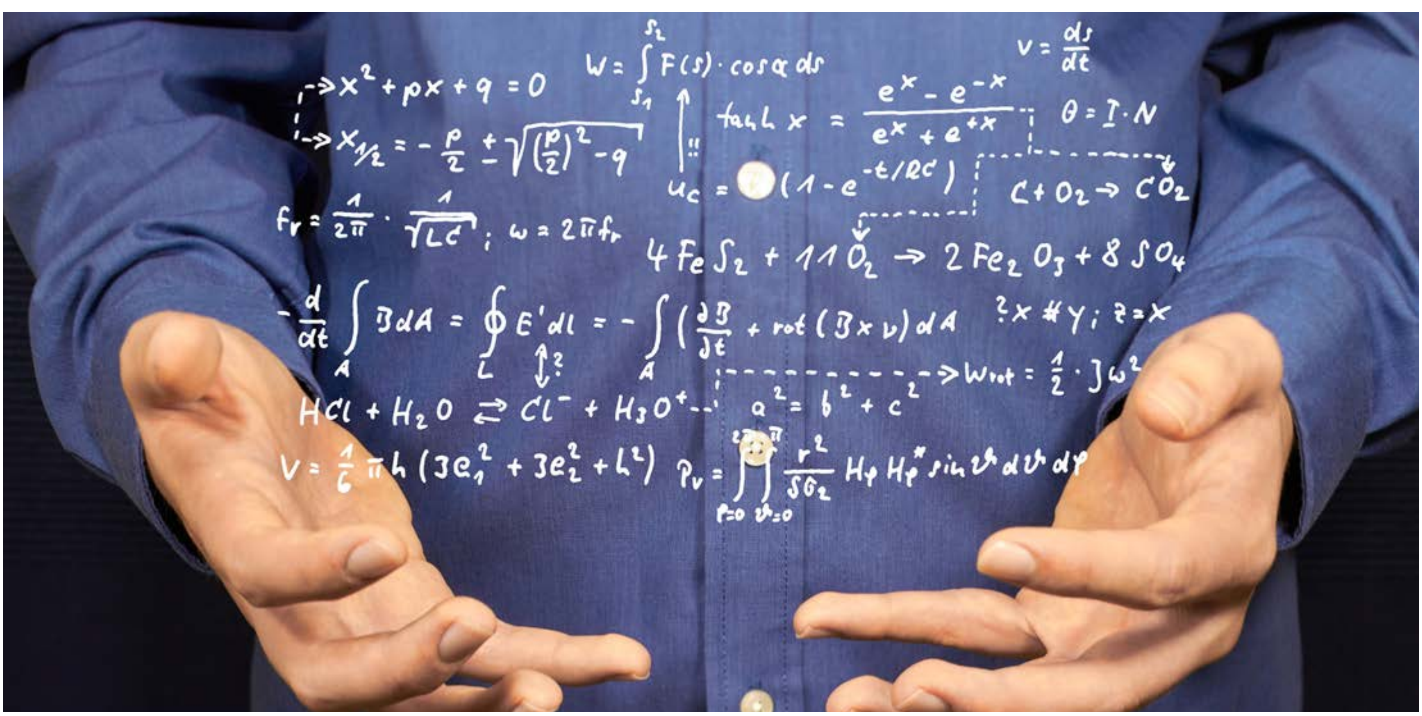
Use this handy chart for determining the resonant frequency versus cable or slot length in free space. Half-wavelength slots or cables simulate dipole antennas and are particularly troublesome. Image Source: Patrick André.

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/M	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 "Special International 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.
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.
RE	(Radiated Emissions) - The energy generated by a circuit or equipment, which is radiated directly from the circuits, chassis and/or cables of equipment.
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

2020 EMC Testing Guide
This guide offers insights and tools needed to plan for and prevent EMC failures before even entering the testing lab.
https://learn.interferencetechnology.com/2020-emc-testing-guide/

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

2019 Directory & Design Guide
Since 1971, this publication has set the standard for all things related to EMI/EMC.
https://learn.interferencetechnology.com/2019-directory-and-design-guide/

2019 EMC Fundamentals Guide
The Fundamentals Guide and keep 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/

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RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

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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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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

ESD Experts

Signal & Power Integrity Community

EMI/EMC Testing

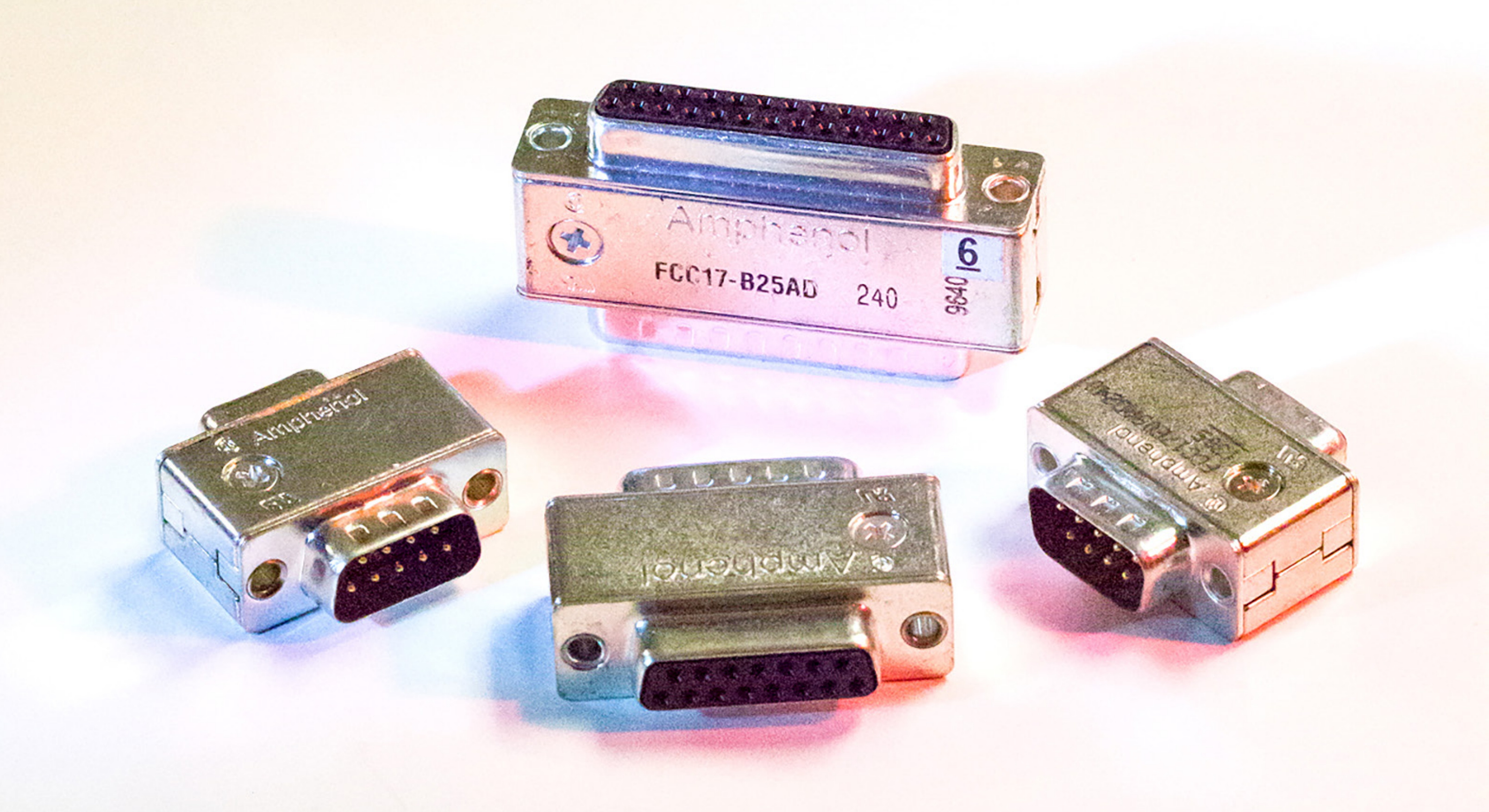
iNARTE

IEEE EMC Society region 8

For Industry Specific LinkedIn Groups, please see the Featured Industry sections on Wireless/5G/IoT, Automotive, and Military/Aerospace.

5G

DESIGN FUNDAMENTALS



BASIC EMI CONCEPTS

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BASIC EMI CONCEPTS

Understanding EMC is all about two important concepts: (1) all currents flow in loops and (2) high frequency signals are propagated as electromagnetic waves in transmission lines and the field energy travels through the dielectric. The two concepts are related because they are intertwined together. Digital signals create the propagating field, which induces the convection current to flow in the copper traces/planes.

CURRENTS FLOW IN LOOPS

These two concepts are closely related and coupled to one another. The problem we circuit designers miss is defining the return path back to the source. If you think about it, we don't even draw these return paths on the schematic diagram–just showing it as a series of various "ground" symbols.

So what is "high frequency"? Basically, anything higher than 50 to 100 kHz. For frequencies less than this, the return current will tend to follow the shortest path back to the source (path of least resistance). For frequencies above this, the return current tends to follow directly under the signal trace and back to the source (path of least impedance).

Where some board designs go wrong is when high dV/dt return signals, such as those from low frequency DC-DC switch mode converters or high di/dt return signals get comingled with I/O circuit return currents or sensitive analog return currents. We'll discuss PC board design in the next article. Just be aware of the importance of designing defined signal and power supply return paths. That's why the use of solid return planes under high frequency signals and then segregating digital, power, and analog circuitry (keeping them separate) on your board is so important.

HOW SIGNALS MOVE

At frequencies greater than DC, digital signals start to propagate as electromagnetic

waves in transmission lines. As shown in *Figure 1*, a high frequency signal propagates along a microstrip transmission line (circuit trace over return plane, for example), and the wave front induces a conduction current in the copper trace and back along the return plane. Of course, this conduction current cannot flow through the PC board dielectric, but the charge at the wave front repels a like charge on the return plane, which "appears" as if current is flowing. This is the same principle for capacitors and Maxwell called this effect "displacement current".

The signal's wave front travels at some fraction of the speed of light, as determined by the dielectric constant of the material, while the conduction current is comprised of a high density of free electrons moving at about 1 cm/second. The actual physical mechanism of near light speed propagation is due to a "kink" in the E-field, which propagates along the molecules of copper. Refer to *References 1, 2,* and *3* for further details.

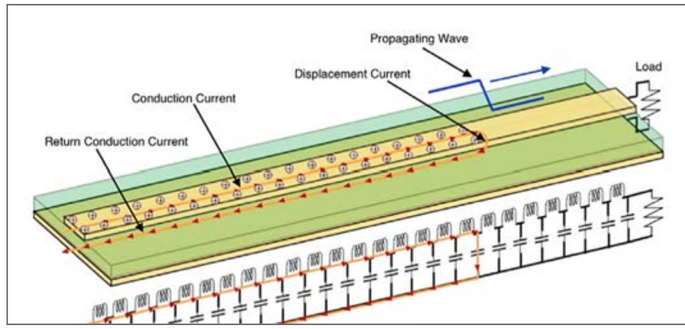

Figure 1: A digital signal propagating along a microstrip with currents shown.

The important thing is that this combination of conduction and displacement current must have an uninterrupted path back to the source. If it is interrupted in any way, the propagating electromagnetic wave will "leak" all around inside the PC board dielectric layers and cause electromagnetic coupling and "common mode" currents to form, which then couple to other signals (cross-coupling) or to "antenna-like structures", such as I/O cables or slots/apertures in shielded enclosures.

Most of us were taught the "circuit theory" point of view and it is important when we visualize how return currents want to flow back to the source. However, we also need to consider the fact that the energy of the signal is not only the current flow, but an electromagnetic wave front moving through the dielectric, or a "field theory" point of view. Keeping these two concepts in mind just reinforces the importance of designing transmission lines (power and signal traces with return path directly adjacent), rather than just simple circuit trace routing.

It is very important to note that all power distribution networks (PDNs) and high frequency signal traces are transmission lines and the energy is transferred as electromagnetic waves at about half the speed of light in normal FR4-type board dielectrics. We'll show what happens when the return path or return plane is interrupted by a gap in the next article. More on PDN design may be found in *Reference 4, 5*, and *6*.

DIFFERENTIAL MODE VERSUS COMMON MODE CURRENTS

Referring to *Figure 2*, the differential mode current (in blue) is the digital signal itself (in this case, shown in a ribbon cable). As described above, the conduction current and associated return current flow simultaneously as the signal wave front moves along the transmission line formed by the microstrip and return plane.

The common mode current (in red) is a little more complex in that it may be generated in a number of ways. In the figure, the impedance of the return plane results in small voltage drops due to multiple simultaneous switching noise (SSN) by the ICs. These voltage drops induce common noise currents to flow all over the return (or reference) plane and hence, couple into the various signal traces.

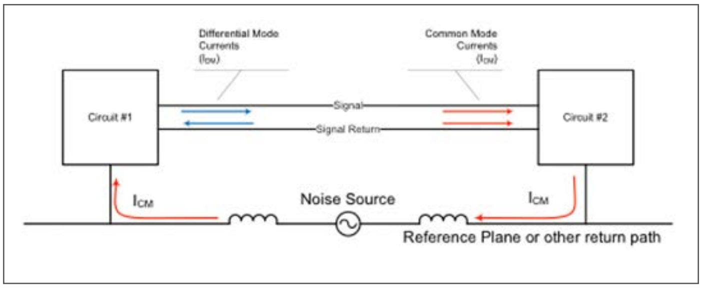

Figure 2: An example of differential and common mode currents.

Besides SSN, common mode currents can also be created by gaps in return planes, poorly terminated cable shields, or unbalanced transmission line geometry. The problem is that these harmonic currents tend to escape out along the outside of shielded I/O or power cables and radiate. These currents can be very small, on the order of µA. It takes just 5 to 8 µA of current to fail the FCC class B test limit.

SUMMARY

To summarize product design for EMI compliance, a properly designed PC board with adjacent return planes to all signals and PDNs, properly bonded I/O cable shields, well bonded shielded enclosures with minimal slots or gaps, and common mode filtering on all I/O and power cables for unshielded products is generally required for best EMI performance. Paying attention to these factors early in the design greatly reduces the risk of EMC and EMI compliance failures.

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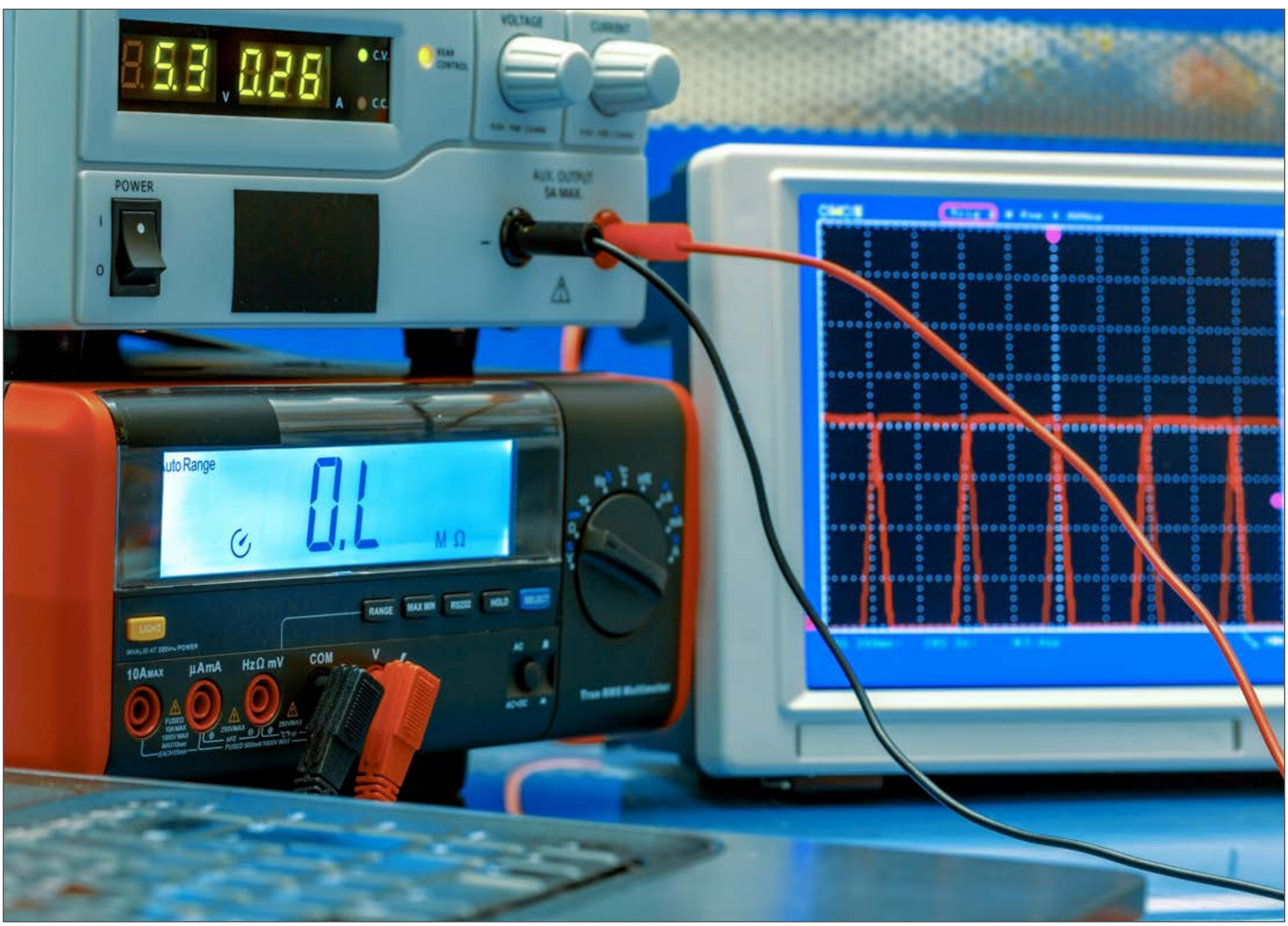

DESIGN FOR COMPLIANCE ESSENTIALS

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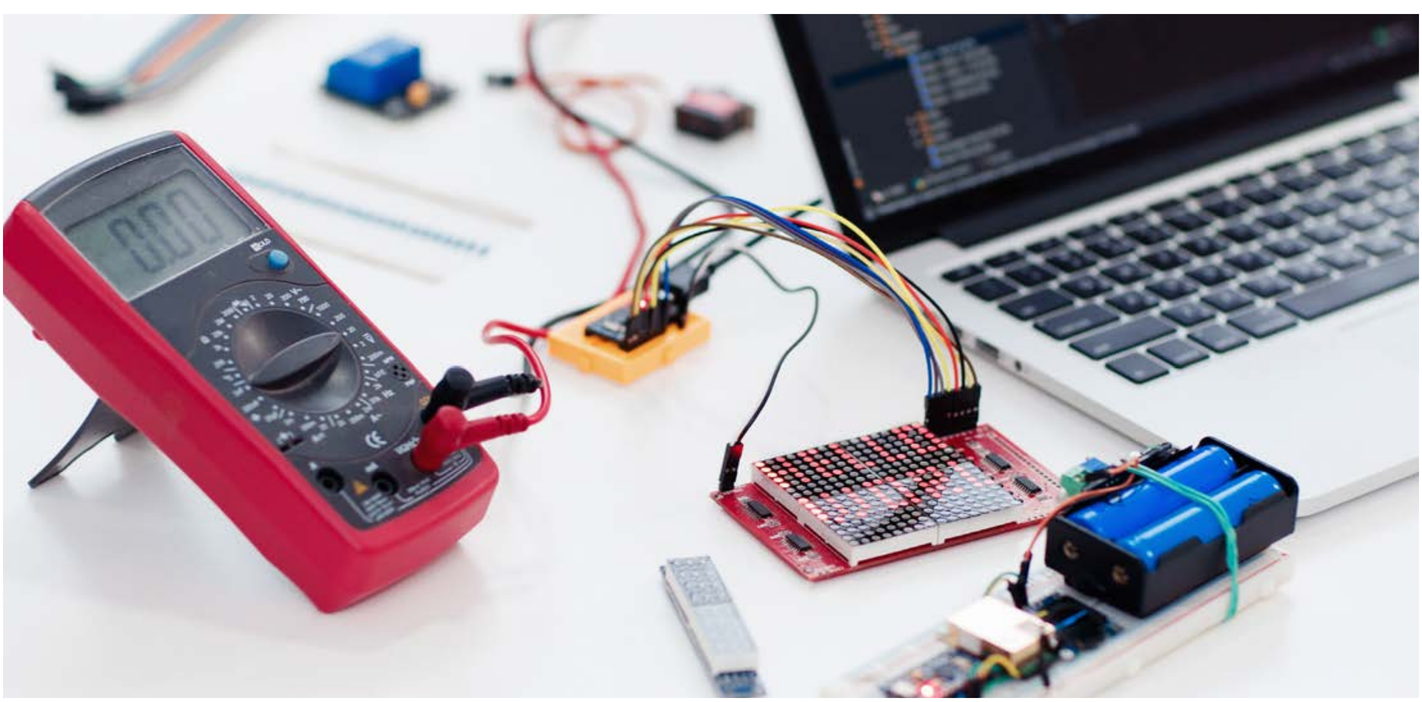
Introduction

While unrealistic to discuss all aspects of product design in a single article, I'll try to describe the most common design issues I find in the hundreds of client products I've had a chance to work on. These issues generally include PC board design, cables, shielding, and filtering. More detailed information may be found in the Reference section below.

As previously mentioned, the top three product failures I run into include (1) radiated emissions, (2) radiated susceptibility, and (3) electrostatic discharge. Other failures can include things like conducted emissions, electrically fast transient, conducted susceptibility, and electrical surge. Most of these last items are also the result of the same poor product designs, which cause the top three failures.

<u>NOTE</u>: I prefer to avoid the word "ground" in this article or in my consulting practice. The reason is that there are too many misinterpretations, which can also lead to EMC failures. It's much more clear to use power and power return, and signal and signal return–or just "return plane" or reference plane. Finally, cable shields or shielded enclosures are "bonded" together–not "grounded". The only exception is the so called "safety ground" or earth ground. But these have nothing at all to do with proper EMC design–just personal safety against electrical shock. I suppose the one exception would be the earth ground connection on a three-wire power line filter. Also, occasionally, there will be an earth ground on a PC board–especially for power supplies, but again, connecting a product or system to earth ground will not improve EMI, due to the very high inductance (length) of the wire.



DESIGN FOR COMPLIANCE ESSENTIALS

The single most important factor in achieving EMC/EMI compliance revolves around the printed circuit board design. It's important to note that not all information sources (books, magazine articles, or manufacturer's application notes) are correct when it comes to designing PC boards for EMC compliance–especially sources older than 10 years, or so. In addition, many "rules of thumb" are based on specific designs, which may not apply to future or leveraged designs. Some rules of thumb were just plain lucky to have worked.

PC boards must be designed from a physics point of view and the most important consideration is that high frequency signals, clocks, and power distribution networks (PDNs) must be designed as transmission lines. This means that the signal or energy transferred is propagated as an electromagnetic wave. PDNs are a special case, as they must carry both DC current and be able to supply energy for switching transients with minimal simultaneous switching noise (SSN). The characteristic impedance of PDNs is designed with very low impedance (0.1 to 1.0 Ohms, typically). Signal traces, on the other hand, are usually designed with a characteristic impedance of 50 to 100 Ohms.

The previous article introduced the concept of the circuit theory and field theory viewpoints. A successful PC board design accounts for both viewpoints. Circuit theory suggests that current flows in loops from source to load and back to the source. In many cases of product failure, the return path has not been well defined and in some cases, the path is broken. Breaks or gaps in the return path are major causes of radiated emissions, radiated susceptibility, and ESD failures.

Correspondingly, electric fields on PC boards exist between two pieces of metal, such as a microstrip over a return plane (or trace). If the return path is broken, the electric field will "latch on" to the next closest metal and will not likely be the return path you want. When the return path is undefined, then the electromagnetic field will "leak" throughout the dielectric and cause common mode currents to flow all over the board, as well as cause cross-coupling of clocks or other high speed signals to dozens of other circuit traces within that same dielectric.

Figure 1 shows a propagating wave within the dielectric between the signal trace and return plane (or trace). This shows both the conduction current flowing in the signal trace and back on the return plane (or trace) and the displacement current "through" the dielectric. The signal wave front travels at some fraction of the speed of light as determined by the dielectric constant. In air, signals travel at about 12 inches per nanosecond. In the typical FR4 dielectric, the speed is about half that at 6 inches per nanosecond. Refer to *Reference 1, 2,* and *3* for more information on the physics of signal propagation through PC boards.

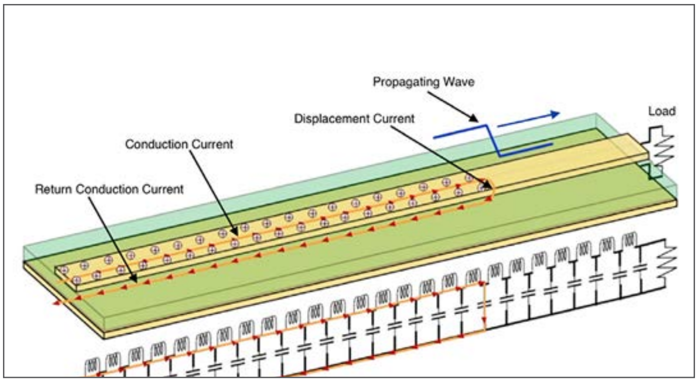


Figure 1: A propagating wave along a microstrip with reference plane. Image Source: Eric Bogatin.

In order to satisfy both the circuit and field theory viewpoints, we now see the importance of adjacent power and power return planes, as well as adjacent signal and signal return planes. PDN design also requires both bulk and decoupling "energy storage" capacitors.

The bulk capacitors 4.7 to 10 µF, typ.) are usually placed near the power input connector and the decoupling capacitors (1 to 10 nF, typ) nearest the noisiest switching devices–and most importantly, with minimal trace length connecting these from the power pins to signal return plane.

Ideally, all decoupling capacitors should be mounted right over (or close to) the connecting vias and multiple vias should be used for each capacitor to reduce series inductance.

Signal or power routed referenced to a single plane will always have a defined return path back to the source. *Figure 2* shows how the electromagnetic field stays within the dielectric on both sides of the return plane. The dielectric is not shown for clarity.

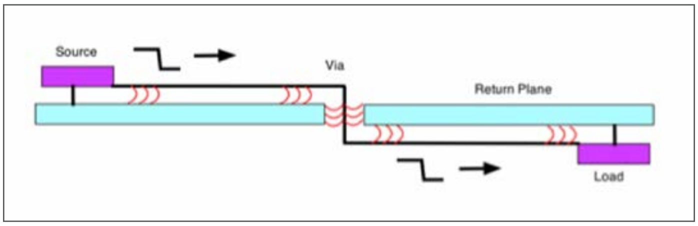


Figure 2: A signal trace passing through a single reference plane.

On the other hand, referring to *Figure 3*, if a signal passes through two reference planes, things get a lot trickier. If the two planes are the same potential (for example, both are return planes), then simple connecting vias may be added adjacent to the signal via. These will form a nice defined return path back to the source.

If the two planes are differing potentials (for example, power and return), then stitching capacitors must be placed adjacent to the signal via. Lack of a defined return path will cause the electromagnetic wave to propagate throughout the dielectric, causing cross coupling to other signal vias and leakage and radiation out the board edges as shown.

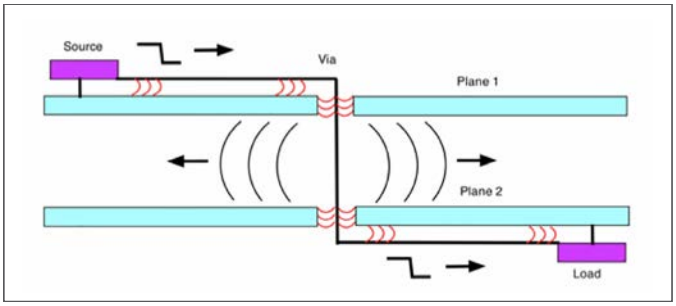


Figure 3: A signal trace passing through two reference planes. If the reference planes are the same potential (signal or power returns, for example), then stitching vias next to the signal via should be sufficient. However, if the planes are different potentials (power and return, for example), then stitching capacitors must be installed very close to the signal via. Lack of a defined return path will cause the electromagnetic field to leak around the dielectric, as shown, and couple into other signal vias or radiate out board edges.

For example, let's take a look at a poor (but very typical) board stack-up that I see often. See *Figure 4*.

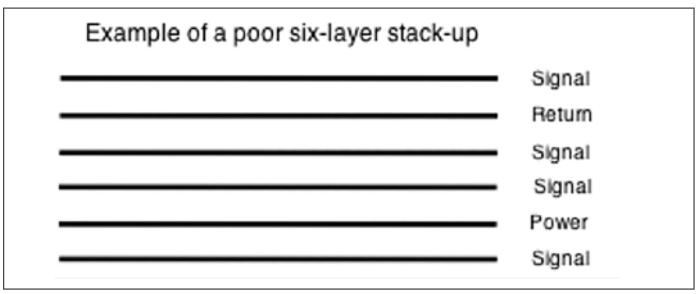


Figure 4: A six-layer board stack-up with very poor EMI performance.

Notice the power and power return planes are three layers apart. Any PDN transients will tend to cross couple to the two signal layers in between. Similarly, only signal layers 1 and 3 have an adjacent return plane. Signal layers 4 and 6 are referenced to power, rather than signal return, therefore, the propagating wave return path will jump all over to whatever is the closest metal on the way back to the source, which is referenced to signal return. Again, this will tend to couple clock and other digital noise throughout the board.

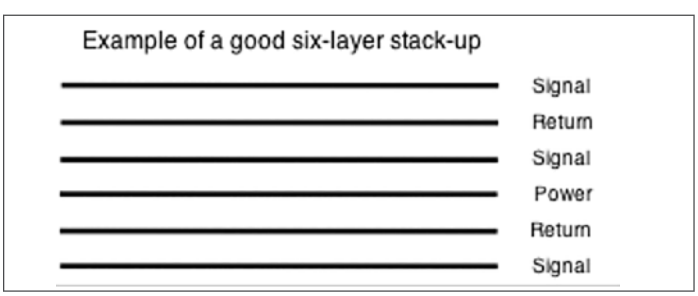


Figure 5: A six-layer board stack-up with good EMI performance. Each signal layer has an adjacent return plane and the power and power return planes are adjacent.

A better design is shown in *Figure 5*. Here, we lose one signal layer, but we see the power and power return planes are adjacent, while each signal layer has an adjacent signal (or power) return plane. It's also a good idea to run multiple connecting vias between the two return planes in order to guarantee the lowest impedance path back to the source. The EMI performance will be significantly improved using this, or similar designs. In many cases, simply rearranging the stack-up is enough to pass emissions.

Note that when running signals between the top and bottom layers, you'll still need to include "stitching" vias between the return planes and stitching capacitors between the power and power return planes right at the point of signal penetration in order to minimize the return path. Ideally, these stitching vias should be located within 1 to 2 mm of each signal via.

Other Tips–Other design tips include placement of all power and I/O connectors along one edge of the board. This tends to reduce the high frequency voltage drop between connectors, thus minimizing cable radiation. Also, segregation of digital, analog, and RF circuits is a good idea, because this minimizes cross coupling between noisy and sensitive circuitry in the return plane.

Of course, high-speed clocks, or similar high-speed signals, should be run in as short and as direct a path as possible. These fast signals should not be run long board edges or pass near I/O or power connectors.

Gaps in Return Plane–I'd like to come back to the gap or slot in the return plane mentioned earlier and show an example of why it's bad news for EMI. When the return path is interrupted, the conduction current is forced around the slot, or otherwise finds the nearest (lowest impedance) path back to the source. The electromagnetic field is forced out and the field will "leak" all over the board. I have an article and good demonstration video of this and how it affects common mode currents and ultimately, EMI. See *Figure 6* and *Reference 4*.

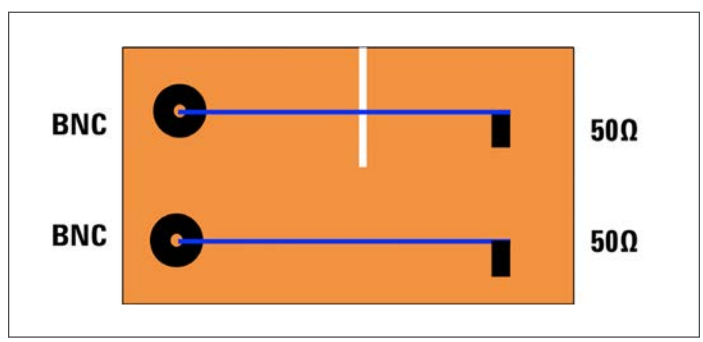


Figure 6: Shows a demonstration test board with transmission lines terminated in 50 Ohms. One transmission line has a gap in the return plane and the other doesn't. A harmonic comb generator (2 ns pulse) is connected to one of the two BNC connectors in turn and the harmonic currents in a wire taped to the return plane are measured with a current probe.

The difference between the gapped and un-gapped traces is shown in *Figure 7*. Note the harmonic currents are 10 to 15 dB higher for the gapped trace (in red). Failing to pay attention to the signal and power return paths is a major cause of radiated emissions failures.

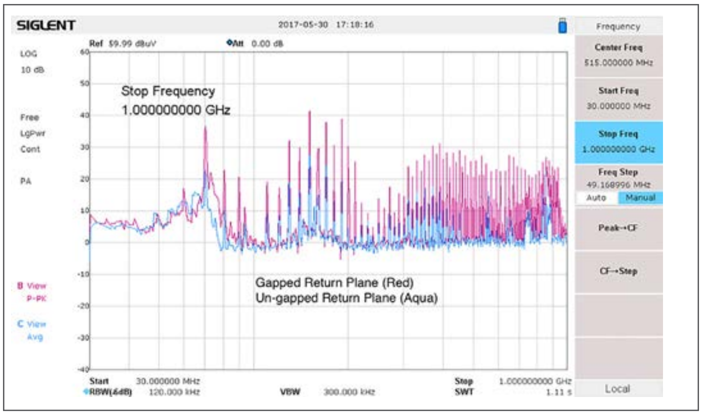


Figure 7: The resulting common mode currents on an attached wire (to the return plane) as measured with a current probe. The trace in aqua is the un-gapped return path and the trace in red, the gapped return path. The difference is 10 to 15 dB higher for the gapped return path. These harmonic currents will tend to radiate and will likely cause radiated emissions failures.

SHIELDING

The two issues with shielded enclosures is getting all pieces well-bonded to each other and to allow power or I/O cable to penetrate it without causing leakage of common mode currents. Bonding between sheet metal may require EMI gaskets or other bonding techniques. Slots or apertures in shielded enclosures become issues when the longest dimension approaches a half wavelength.

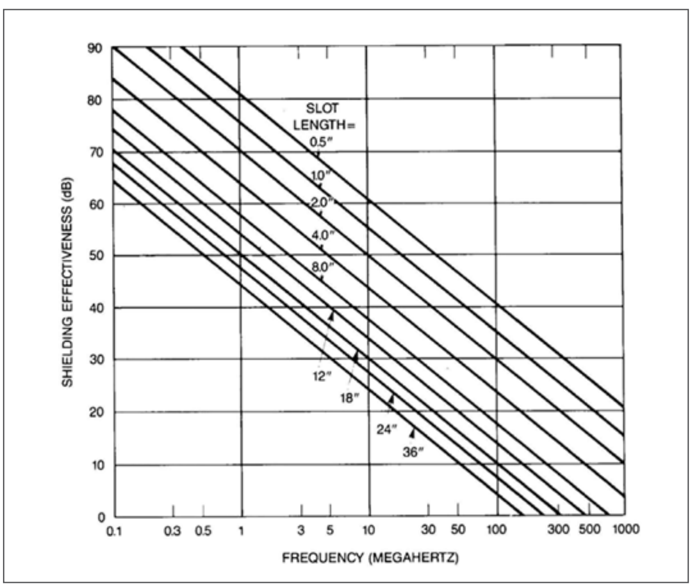


Figure 8: A chart of attenuation versus slot length. Image Source: Henry Ott.

Figure 8 shows a handy chart for determining the 20 dB attenuation of a given slot length. For example, if a product design requires at least a 20 dB shielding effectiveness, then the longest slot length can be just one-half inch. See *Reference 5* and *6* for more detail on shielding. *Interference Technology* also has a free downloadable *2017 EMI Shielding Guide* with excellent information (*Reference 7*).

Figure 9 is a chart of wavelength versa half wave resonance at 1,000 MHz. This is a handy tool for determining how efficient a cable or slot will act as an antenna.

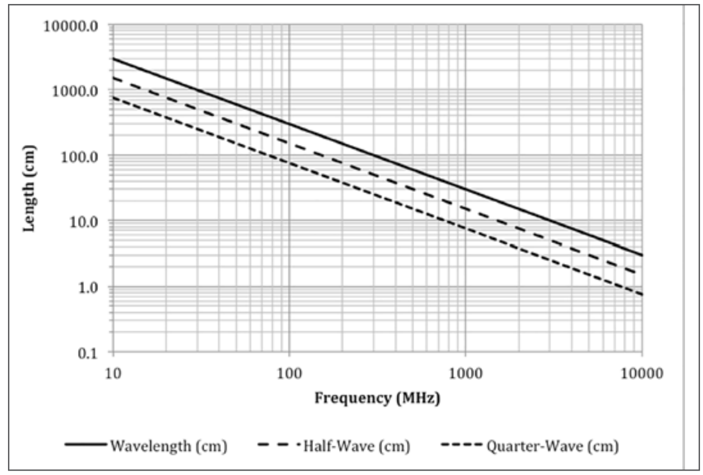


Figure 9: A handy chart for determining resonant frequency versus cable or slot length in free space. Half-wavelength slots simulate dipole antennas and are particularly troublesome. Image Source: Patrick André.

Cable Penetration–The number one issue I find when tracking down a radiated emissions problem is cable radiation. The reason cables radiate is that they penetrate a shielded enclosure without some sort of treatment–either bonding the cable shield to the metal enclosure or common mode filtering at the I/O or power connector (*Figure 10* and *11*). This occurs frequently, because most connectors today are attached directly to the circuit board and are then poked through holes in the shield. Once the cable is plugged in, it is "penetrating the shield" and EMI is the usual result.

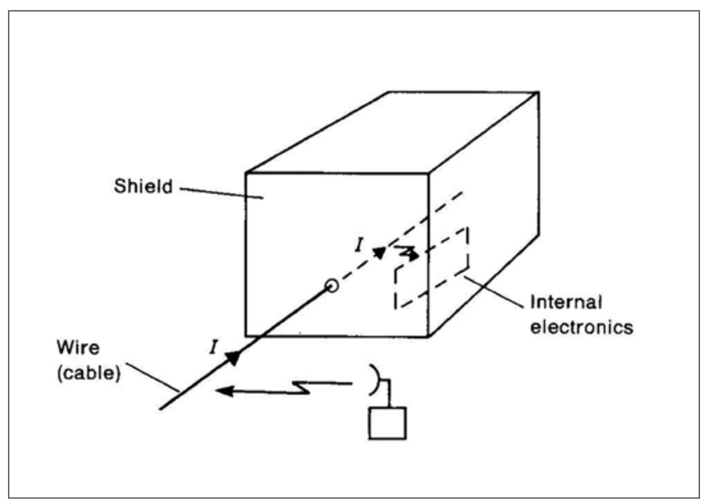


Figure 10: Penetrating the shield with a cable defeats the shield. This example shows how external energy sources can induce noise currents in I/O cables, which can potentially disrupt internal circuitry. The reverse is also true, where internal noise currents can flow out the cable and cause emissions failures. Image Source: Henry Ott.

There are four combinations or cases that must be considered: shielded or unshielded products, and shielded or unshielded cables. Power cables are usually unshielded for consumer/commercial products and so require power line filtering at the point of penetration or at the connector of the circuit board. Shielded cables must have the shield bonded (ideally in a 360 degree connection) to the product's shielded enclosure. If the product does not have a shielded enclosure, then filtering must be added at the point of penetration or at the I/O connector of the PC board. *Figure 11* shows the usual result when connectors simply poke through a shielded enclosure.

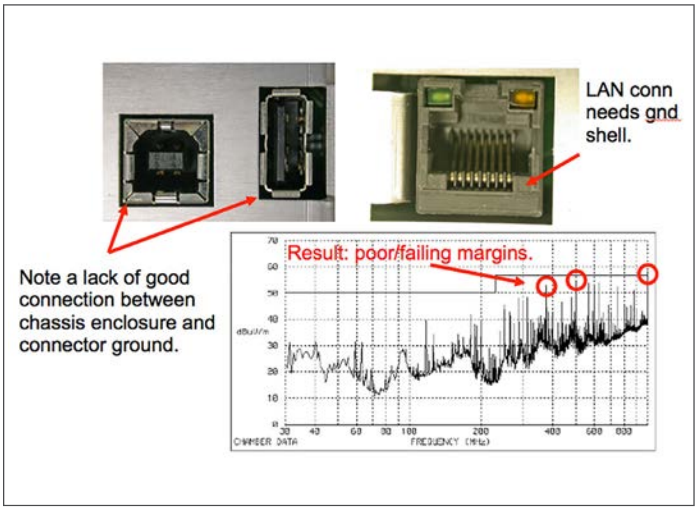


Figure 11: Result of a penetrating cable through a shielded enclosure, because of un-bonded I/O connectors to the shielded enclosure.

Cable Shield Terminations–Another potential issue is if the I/O cable uses a "pigtail" connection to the connector shell. Ideally, cable shields should be terminated in a 360-degree bond for lowest impedance. Pigtails degrade the cable shield effectiveness by introducing a relatively high impedance. For example, a 1-inch pigtail connection has 12 Ohms impedance at 100 MHz and gets worse the higher you go in frequency. This is especially problematic for HDMI cables, because the HDMI working group (http://www.hdmi.org) originally failed to specify the method for terminating the cable shield to the connector. This may have been corrected in the latest edition of the standard released in 2017.

FILTERING

I won't go into very much detail here, because *Interference Technology* has an excellent *EMI Filter Guide* free for the downloading (see *Reference 8*). Suffice to say, filters, as well as transient protection, are important at power and I/O connectors. Typically, these will be common mode topologies, as shown in *Figure 12*. Most signal-level common mode chokes may be obtained in surface mount packaging. Power chokes are much larger to handle the current and may be obtained as either surface mount or through-hole mount, depending on the current rating. Many Ethernet connectors also have built-in common mode filtering.

Power supply input filters are generally designed to suppress both differential and common mode currents. A typical topology is shown in *Figure 13*. The "X" capacitor is designed to filter differential mode, while the CM choke and "Y" capacitors are designed to filter common mode. The resistor shown is usually 100 kOhm and the purpose is merely to bleed off the line voltage stored on the capacitors to a safe level.

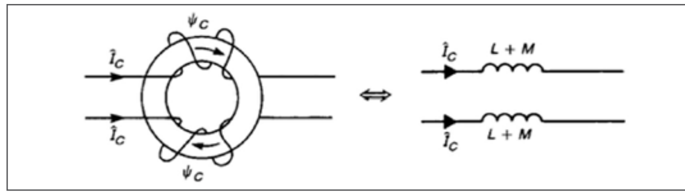


Figure 12: A typical common mode filter used for I/O filtering. The two windings are wound in opposite directions and so tend to cancel the common mode currents.

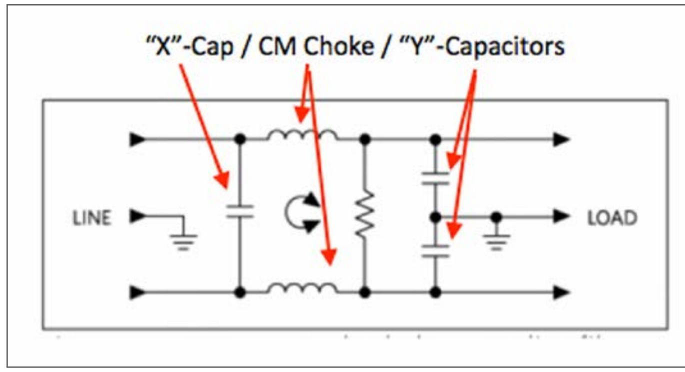


Figure 13: A general purpose filter typically used for power supply input filtering.

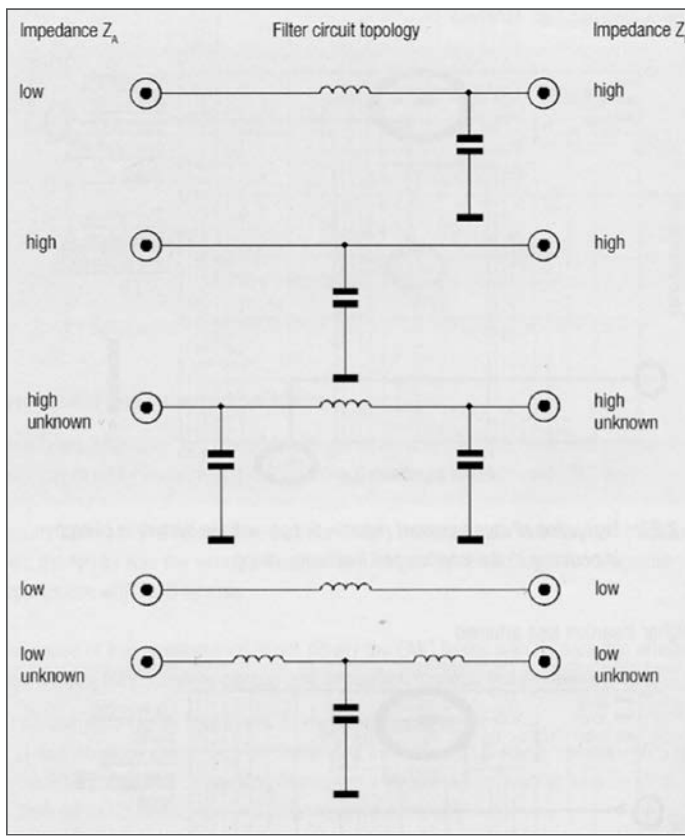


Figure 14: Five common filter topologies, depending on the source and load impedances. Figure, courtesy Würth Electronik.

For general purpose filtering of signals, the handy chart of possible filter topologies may be found in *Reference 9* and is reproduced here in *Figure 14*. The appropriate topology depends on the source and load impedances. If these impedances are not known, then either the "PI" or "T" topology may be used (#3 or #5 on the chart, respectively).

Ferrite or inductive components should not be used in series with the power pins of ICs, as this will only reduce the ability of the local decoupling capacitors to supply required energy during simultaneous switching of the IC output stages with the resulting higher power supply noise. If used, they should be inserted "upstream" from the bulk capacitor.

Ferrite Chokes–One common filter element usually added to I/O cables is the ferrite choke. Ferrite chokes come in either the clamp-on types or solid cores meant to be assembled along with the cable assembly. Often, these are used as a last resort to reduce cable emissions or susceptibility.

Ferrite chokes have an associated impedance versus frequency characteristic, often peaking around 100 to 300 MHz. Some materials are designed to peak below 100 MHz for lower frequency applications.

Maximum impedances can range from 25 to 1,000 Ohms, depending on the ferrite material used and style of choke.

You may have noticed that clipping a ferrite choke onto a cable sometimes has no effect. This is usually due to the fact the choke has the same, or lower, effective impedance than the source and load impedances. The attenuation of a ferrite choke is easily calculated.

Attenuation (dB) = 20 * log((Zin + Zferrite + Zload) / (Zin + Zload))

For example, if we add a 100 Ohm ferrite choke to a power supply cable with system impedance of 10 Ohms (source and load), the attenuation would be:

Attenuation = 20 * log((10 + 100 + 10) / (10 + 10)) = 15.5 dB

Refer to *Reference 9* for much additional detail on ferrite chokes and general filter design.

TRANSIENT PROTECTION

In order to protect internal circuitry from electrical transients, such as ESD, electrically fast transient (EFT), or power line surge, due to lightning, transient protective devices should be installed at all power and I/O ports. These devices sense the transient and "clamp" the transient pulse to a specified clamp voltage.

Transient protectors in signal lines must generally have a very low parallel capacitance (0.2 to 1 pF, typical) to the return plane (or earth ground), depending on the data rate in order to maintain signal integrity. These silicon-based devices may be purchased in very small surface mount packaging.

Power line surge protection usually requires much larger transient protection devices and they can come in a variety of types. Gas discharge or metal oxide varistors are the most common, but larger silicon-based devices are also available. More information on the design of surge protection may be found in *Reference 9*.

SUMMARY

Most EMC/EMI failures are due to poor shielding, penetration of cables through shields, poor cable shield termination, poor filtering, and above all, poor PC board layout and stack-up. Paying attention to these common design faults will pay off with a lower risk of compliance failures and result in lower project costs and schedule slippage.

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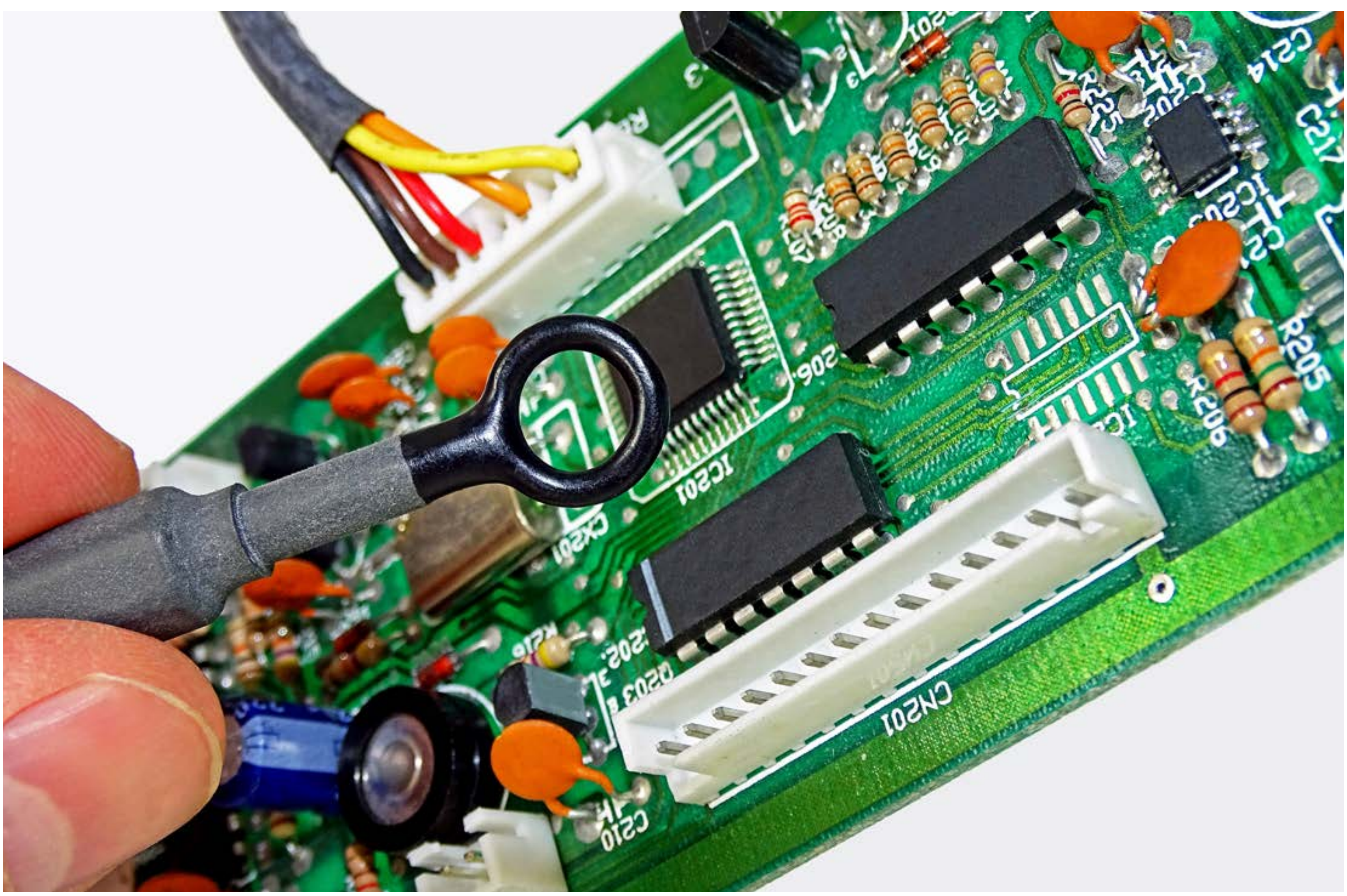
DIY NEAR FIELD PROBES & PREAMPLIFIERS

Fernando Oliveira

Introduction

A very useful tool for troubleshooting EMC issues is the near field probe. Due to its small size (compared against antennas) the most common use of these tools is to aid in detection of the source of a particular signal (emission), or as a local field-generating source (immunity), helping you to find weak spots in your device under test. There are several options available costing from hundreds up to thousands of dollars. In this article, I will show you how to build your own set of near field probes for a few bucks and a cheap pre-amplifier enabling you to get started troubleshooting EMC issues.



DIY NEAR FIELD PROBES & PREAMPLIFIERS

MY PROBES

I have been making my own EMC gear for a while, so last year I built two H-field probes (red ones on *Figure 1*). I also have an extra probe (unshielded) which was a gift from a lab technician. He built it in a fashion to comply with a certain standard that I am not aware of (so I am probably not making the best use of it!). It has a lot of external interference for emissions (due to poor shielding) but it is quite effective for immunity testing.

Figure 1: H-field probes. At right details of the ones that I made myself.

I followed the article "Probing the magnetic probe" from Roy Ediss [1] to make what he calls a "King type with central gap" probe. The basic idea is to create a closed loop on a coax cable and cut a single slot in the outer sheath (gap). You can find other designs in his article that are even easier to make and the main difference between them is their self-resonating frequency, which will vary according to the parasitic capacitances and inductances of the probe, which depends on how you build it (among other things).

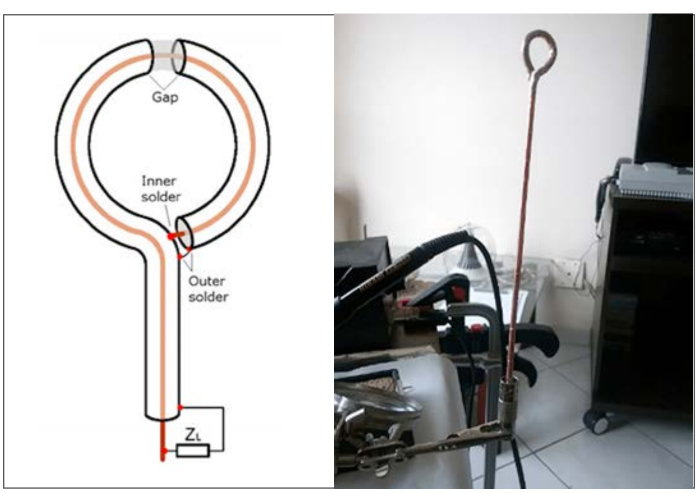


Figure 2: a) H-field probe based on Roy Ediss' design b) Making my own probe at home.

To make the probe I got a regular 50 Ω coax cable with rigid center conductor that I had on hand, removed the outer jacket, the foil and braided shield, and wrapped a copper tape around the dielectric to replace the braid. I am not sure if this would significantly change the probe characteristic impedance but replacing the braid by the copper tape made it very easy to solder, cut the small gap and keep it rigid. It may be a good idea to replace the flexible coax cable by a semi-rigid one, but they are not so easy to find.

To build the loop you have to solder the inner conductor in the tip to the outer sheath (inner solder on *Figure 2*) and then the outer sheath in the tip to itself (outer solder on *Figure 2*). Cut a slice of the outer sheath to make the gap in the center of the loop. It is important to keep the gap small (around millimeter). After that, I soldered the inner conductor on the base to one end of a BNC adapter (double female), two 100 Ω SMD resistors between BNC adapter's inner and outer conductors diametrically opposed and finally the shielding copper tape to the outside of the BNC. Then I acquired a can of red liquid electrical tape and applied some coats of it to the entire thing until I got a thick wall and an even finish. For the smaller one I could simply dip the tip into the can. Finally, I placed a shrinkable sleeve between probe and BNC connector. As an alternative, you can skip the outer solder and the gap cutting, leaving only the inner solder done and you will have another probe design (not the "King type with central gap").

On one occasion, I had access to a Beehive Electronics' probe set (very nice stuff if you can afford it) and did some quick comparison between them and my probes and, for my surprise, they have a quite similar sensitivity. Of course, my test setup was not reproducible enough to compare the readings numerically, but at least I could see similar emission patterns as shown on *Figure 3*.

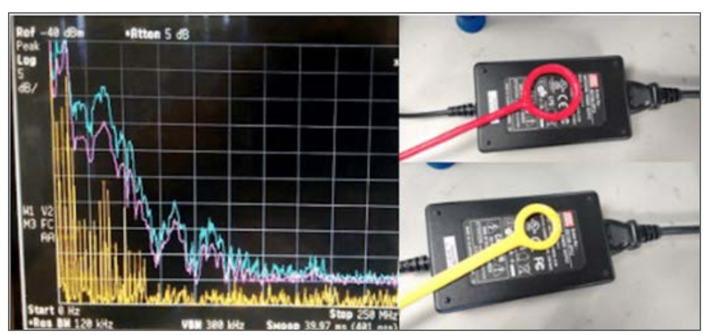


Figure 3: Comparison between mine (pink trace) and Beehive's probe (green trace).

MAKING A TINY PROBE

Since I often use near field probes for finding a source of magnetic field, it is helpful to have a probe that can find exactly the trace generating the unwanted emission. To achieve this resolution, you will need a probe with a tiny tip. I will show you how to build one based on Kenneth Wyatt's course "EMC Troubleshooting and Pre-Compliance Testing for Product Designers" available on Fast Pass Online Training Hub [2].

To do my own tiny probe, I got a spare Wi-Fi antenna used for an old project, which has a thin wire (probably RG316) and an SMA connector. I took the antenna apart and made three levels of cut to the coax cable like shown on *Figure 4* (1st cut: expose braid; 2nd cut: expose dielectric; 3rd cut: expose inner wire).

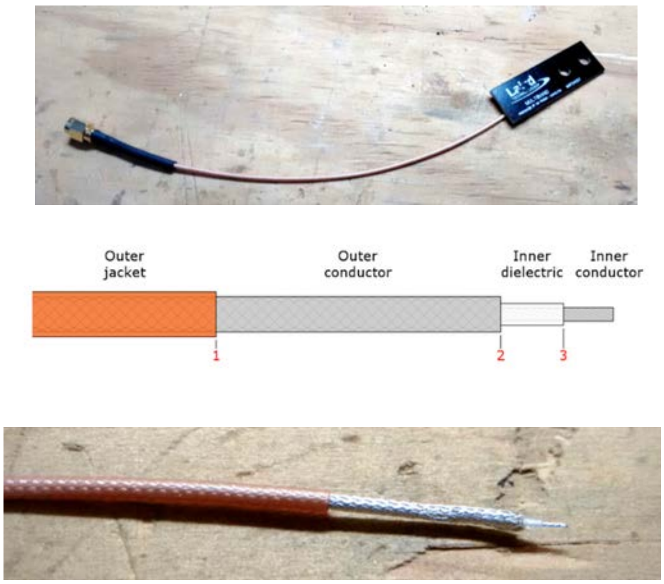


Figure 4: a) Spare Wi-Fi antenna; b) Layers diagram; c) Coax with exposed layers

I put a little drop of solder to the end of the braid to hold it together for the next steps. After that, I soldered the inner wire to the braid creating a loop. The loop shape is around 5x2 mm and it is not perfectly round because the braid solder made it rigid.

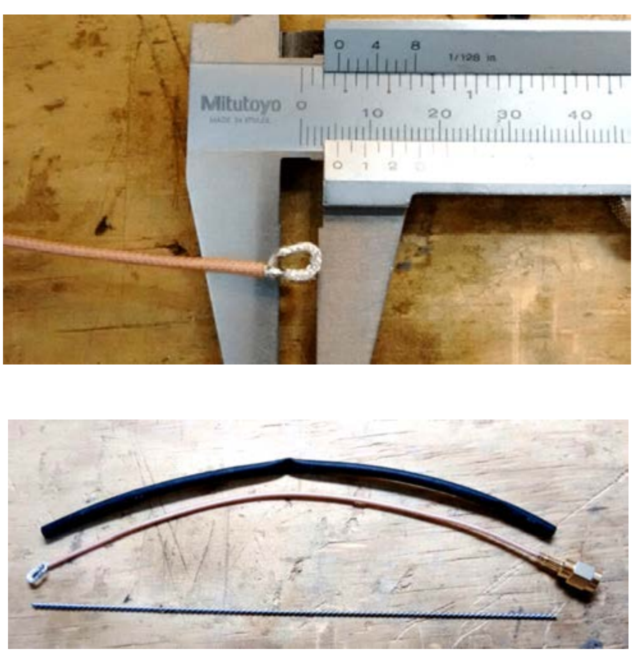


Figure 5: a) Inner conductor soldered to braid forming a loop; b) Shrinkable sleeve, probe and twisted rod

I thought it would be nicer if the cable was not too flexible for the probe to reach the inside of an equipment without bending, so I came out with an idea: I got a pair of 0.8 mm steel wires and twisted them tight together with a drilling machine to get a nice straight rod. After that, I placed the rod along with the coax cable and squeezed all together with a shrinkable sleeve from the outside.

After heating the sleeve, I dipped the tip into the can of liquid electrical tape. I really liked the finishing and, of course, I like the fact that the probe works just fine! One day after and the coating was completely dry and shrunk a little, exposing details of the inner shape.

Figure 6: a) Finished probe; b) Right after applying insulation coating; c) Coating in the day after

LOW NOISE PREAMPLIFIER

It is handy to have a preamplifier to amplify the signal of your freshly made H-field probes. I have a low noise amplifier (LNA) module from Mini-Circuits model ZX60-3018G+ [3] that is very helpful in finding small signals (especially if you are using the tiny probe). I like to build stuff, so I've got a chunk of aluminum and made myself a shiny base to place a connector, switch and LED to seat my amplifier on (after a lot of filing and sanding). Despite being a simple project, I am very proud on how it came out. The amplifier can be powered by battery or any DC supply through the power jack.

Figure 7: Making the amplifier: from the aluminum chunk to the shiny assembly

Another cheap solution that I tested (and works very well) is the LNA4ALL from 9A4QV based on Mini-Circuits part number PSA4-5043+ [4]. Even CATV amplifiers can do a good boost to your signals but it will be a little noisier. A good practice is to know your environment when using near field probes outside a shielded room or when using a noisy amplifier: always check if the emission spikes you are looking at remain visible when you move the probes away from the device under test.

SUMMARY

If you, just like myself, don't have a large budget or live in a place where it is difficult to buy equipment for troubleshooting your EMC issues, you would only need a couple bucks or maybe recycle parts from old projects and a few hours to make your own near field probes. Even if you already have a set of probes, learning how to make near field probes can be useful to create custom probes if you need. You should now be able to get yourself a spectrum analyzer (or even a good oscilloscope), a bunch of wires and go outside exploring equipment RF emissions and troubleshooting some (or maybe most) EMC test issues!

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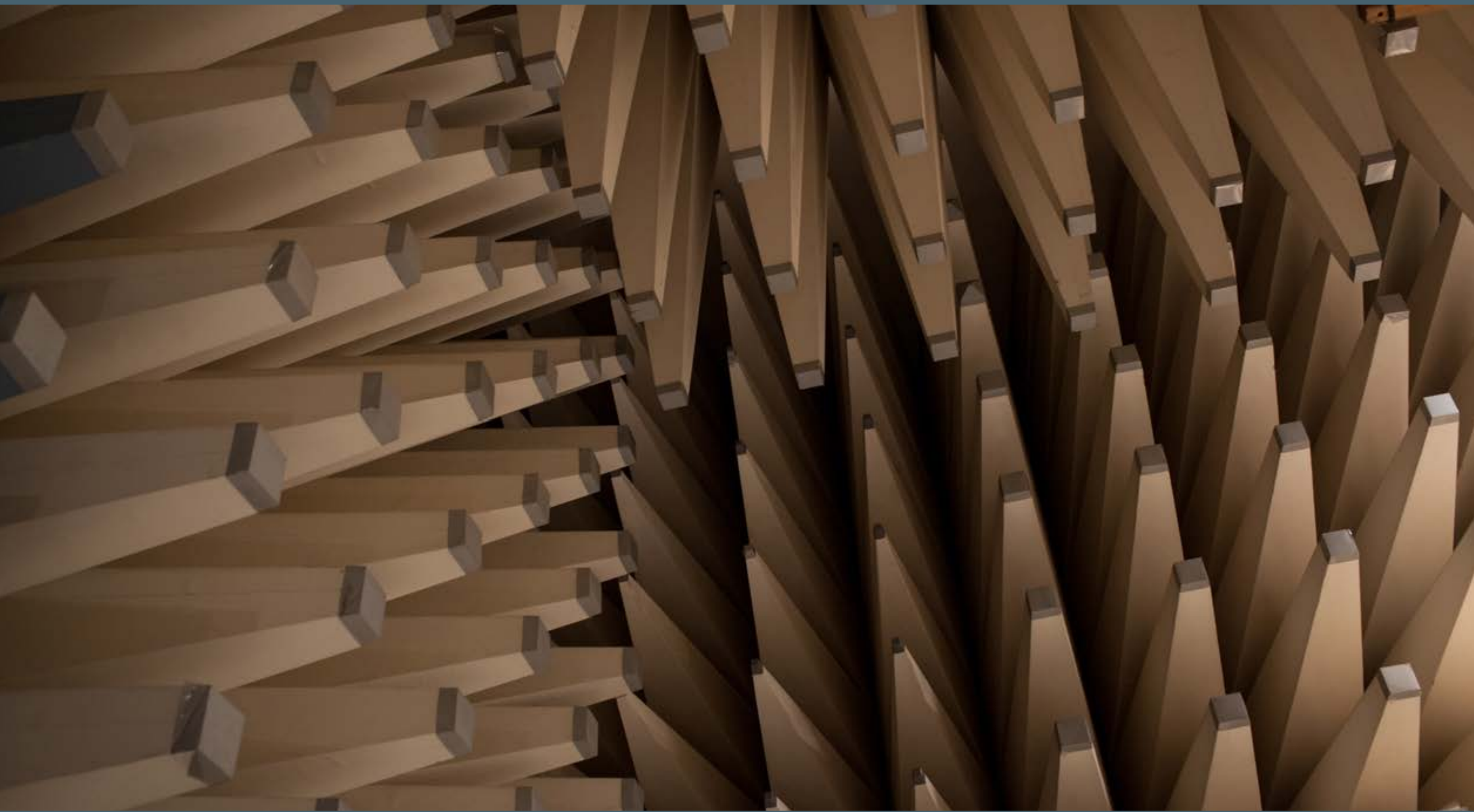
3. Find this amplifier and more RF circuits at https://www.minicircuits.com/
4. Purchase LNA4ALL and find more information at http://lna4all.blogspot.com

TESTING FUNDAMENTALS



THE TOP FIVE REASONS PRODUCTS FAIL EMI TESTING

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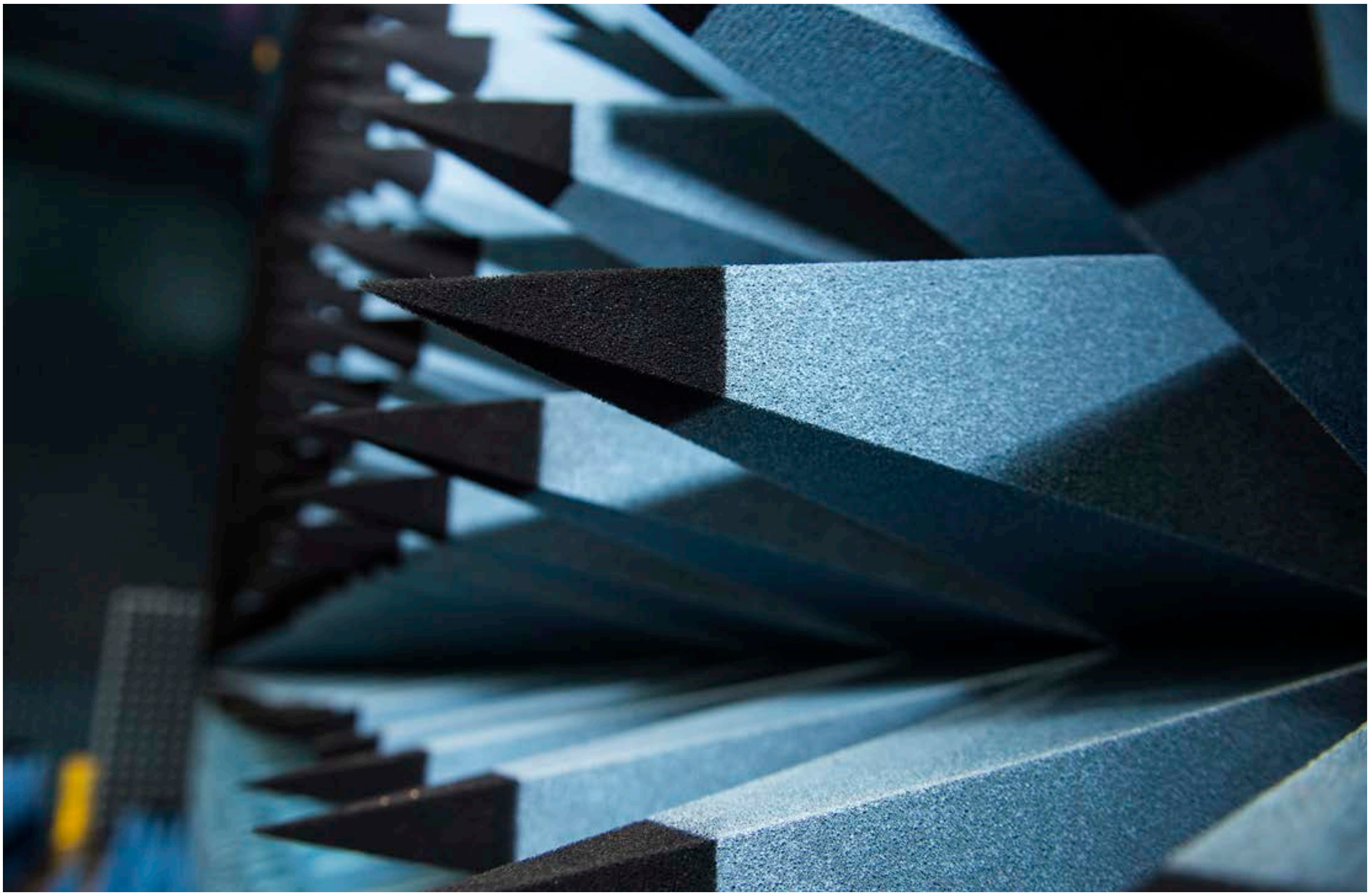
Introduction

The three top product failures I see constantly in my consulting practice are (1) radiated emissions, (2) radiated susceptibility, and (3) electrostatic discharge. After reviewing and testing hundreds of products over the years, I've come to the conclusion that products fail these tests for five common reasons (somewhat in order of incidence):

1. ***PC Board Design****—Poor layout and layer stack-up*
2. ***Cable Shield Termination and Pigtails****—Cable shields are not terminated to enclosure or lack of common mode filtering for unshielded products, plus shield pigtails used*
3. ***Gaps in the Return Path****—High frequency clocks or signals crossing gaps in the return path*
4. ***Power Distribution Design****—Poor power distribution network (PDN) design*
5. ***Shielding Design****—Apertures or slots in the shielded enclosure that are too long*



THE TOP FIVE REASONS PRODUCTS FAIL EMI TESTING

1. PC BOARD DESIGN

The single most important factor in achieving EMC/EMI compliance revolves around the printed circuit board design. It's important to note that not all information sources (books, magazine articles, or manufacturer's application notes) are correct when it comes to designing PC boards for EMC compliance–especially sources older than 10 years, or so. In addition, many "rules of thumb" are based on specific designs, which may not apply to future or leveraged designs. Some rules of thumb were just plain lucky to have worked.

PC boards must be designed from a physics point of view and the most important consideration is that high frequency signals, clocks, and power distribution networks (PDNs) must be designed as transmission lines. This means that the signal or energy transferred is propagated as an electromagnetic wave. PDNs are a special case, as they must carry both DC current and be able to supply energy for switching transients with minimal simultaneous switching noise (SSN). The characteristic impedance of PDNs is designed with very low impedance (0.1 to 1.0 Ohms, typically). Signal traces, on the other hand, are usually designed with a characteristic impedance of 50 to 100 Ohms.

Understanding PC board design is all about two important concepts: (1) all currents flow in loops and (2) high frequency signals are propagated as electromagnetic waves in transmission lines. These two concepts are closely related and coupled to one another.

Currents Flow In Loops—Circuit theory suggests that current flows in loops from source to load and back to the source. In many cases of product failure, the return path has not been well defined and in some cases, the path is broken. The problem we circuit designers often miss is defining the return path of a high frequency signal back to the source. If you think about it, we don't even draw these return paths on the schematic diagram–just showing it as a series of various "ground" symbols.

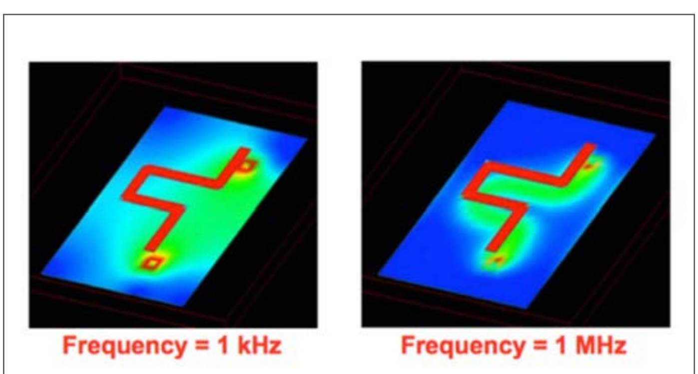


Figure 1: Simulation showing the return path (in green) at low and high frequencies. Image Source: Keysight Technologies.

So what is "high frequency"? Basically, anything higher than 50 to 100 kHz. For frequencies less than this, the return current will tend to follow the shortest path back to the source (path of least resistance). For frequencies above this, the return current tends to follow directly under the signal trace and back to the source (path of least impedance). See *Figure 1*.

To reduce EMI, we need to minimize the area of these loops. Undefined return paths often result in large current loops from source to load and back to source. These large current loops start to look like loop antennas, coupling noise currents to "antenna-like" structures, such as cables, in your product or system.

Where some board designs go wrong is when high dV/dt return signals, such as those from low frequency DC-DC switch mode converters or high di/dt signals from digital logic and clock return signals get comingled with I/O circuit return currents, sensitive RF modules (especially receivers), or sensitive analog return currents. Just be aware of the importance of designing defined signal and power supply return paths. That's why the use of solid return planes under high frequency signals and then segregating digital, power, and analog circuitry on your board is so important.

How Signals Move—At frequencies greater than about 50 to 100 kHz, digital signals start to propagate as electromagnetic waves in transmission lines. As shown in *Figure 2*, a high frequency signal propagates along a transmission line (circuit trace over return plane, for example), and the wave front induces a conduction current in the copper trace and back along the return plane. Of course, this conduction current cannot flow through the PC board dielectric, but the charge at the wave front repels a like charge on the return plane, which "appears" as if current is flowing. This is the same principle where capacitors appear to "pass" AC current, and Maxwell called this effect "displacement current".

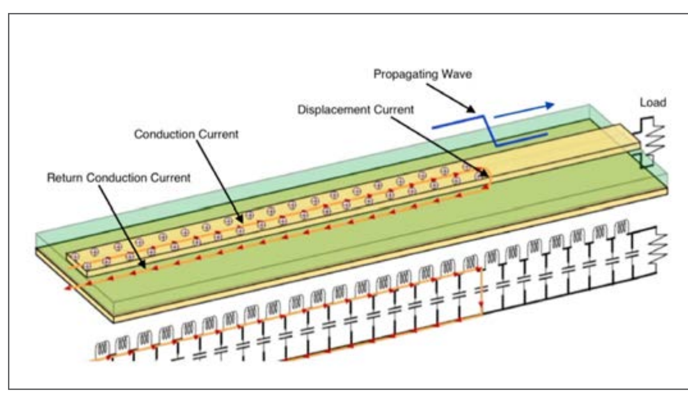


Figure 2: A digital signal propagating along a microstrip with currents shown. Image Source: Eric Bogatin.

The signal's wave front travels at some fraction of the speed of light, as determined by the dielectric constant of the material, while the conduction current is comprised of a high density of free electrons moving at about 1 cm/second. The actual physical mechanism of near light speed propagation is due to a “kink” in the E-field, which propagates along the molecules of copper. The important thing is that this combination of conduction and displacement current must have an uninterrupted path back to the source.

A high electric field is generated by high frequency digital signals occurring between the microstrip and return plane (or trace). If the return path is broken, the electric field will “latch on” to the next closest metal, which will not likely be the return path you want. When the return path is undefined, then the electromagnetic field will “leak” throughout the dielectric and cause common mode currents to flow all over the board. The uncontrolled field will also cause cross-coupling of clocks or other high speed signals to dozens of other circuit traces within that same dielectric through coupling to vias within the dielectric layer. The resulting common mode currents will tend to couple to “antenna-like structures”, such as I/O cables or slots/apertures in shielded enclosures, resulting in EMI.

Circuit Board Stack-Ups—Most of us were taught the “circuit theory” point of view and it is important when we visualize how return currents want to flow back to the source. However, we also need to consider the fact that the energy of the signal is not only the current flow, but an electromagnetic wave front moving through the dielectric, or a “field theory” point of view. Keeping these two concepts in mind just reinforces the importance of designing transmission lines (signal trace with return path directly adjacent), rather than just simple circuit trace routing. A successful PC board design accounts for both viewpoints.

In order to satisfy both the circuit and field theory viewpoints, we now see the importance of adjacent power and power return planes, as well as adjacent signal and signal return planes. Signal or power routed referenced to a single plane will always have a defined return path back to the source. *Figure 3* shows how the electromagnetic field stays within the dielectric on both sides of the return plane. The dielectric is not shown for clarity.

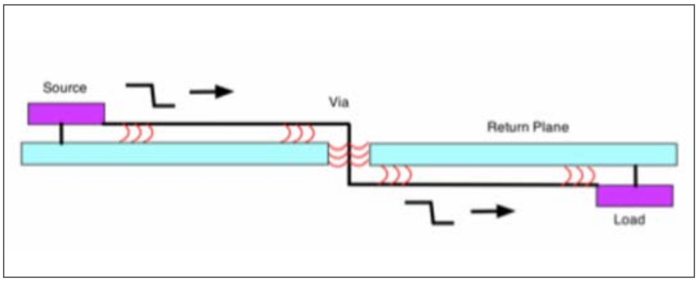


Figure 3: A signal trace passing through a single reference plane.

On the other hand, referring to *Figure 4*, if a signal passes through two reference planes, things get a lot trickier. If the two planes are the same potential (for example, both are return planes), then simple connecting vias may be added adjacent to the signal via. These will form a nice defined return path back to the source.

If the two planes are differing potentials (for example, power and return), then stitching capacitors must be placed adjacent to the signal via. Lack of a defined return path will cause the electromagnetic wave to propagate throughout the dielectric, causing cross coupling to other signal vias and leakage and radiation out the board edges as shown.

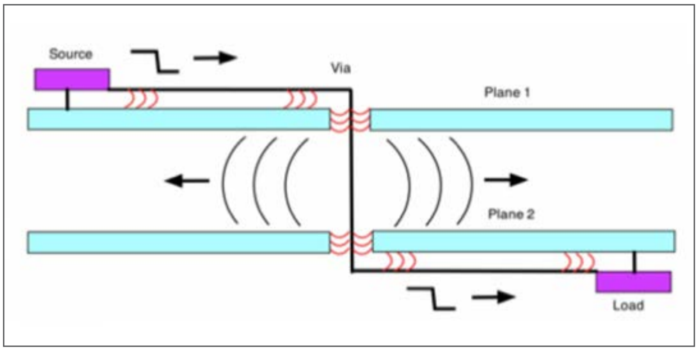


Figure 4: A signal trace passing through two reference planes. If the reference planes are the same potential (signal or power returns, for example), then stitching vias next to the signal via should be sufficient. However, if the planes are different potentials (power and return, for example), then stitching capacitors must be installed very close to the signal via. Lack of a defined return path will cause the electromagnetic field to leak around the dielectric, as shown, and couple into other signal vias or radiate out board edges.

For example, let’s take a look at a poor (but very typical) board stack-up that I see often (*Figure 5*).

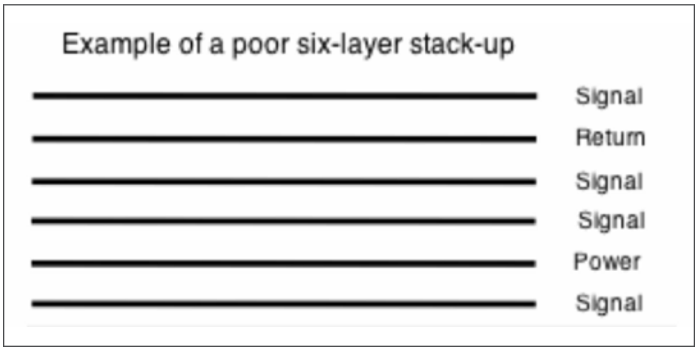


Figure 5: A six-layer board stack-up with very poor EMI performance.

Notice the power and power return planes are three layers apart. Any PDN transients will tend to cross couple to the two signal layers in between. Similarly, few of the signal layers have an adjacent return plane, therefore, the propagating wave return path will jump all over to whatever is the closest metal on the way back to the source. Again, this will tend to couple clock noise throughout the board.

A better design is shown in *Figure 6*. Here, we lose one signal layer, but we see the power and power return planes are adjacent, while each signal layer has an adjacent signal (or power) return plane. It’s also a good idea to run multiple connecting vias between the two return planes in order to guarantee the lowest impedance path back to the source. The EMI performance will be significantly improved using this, or similar designs. In many cases, simply rearranging the stack-up is enough to pass emissions.

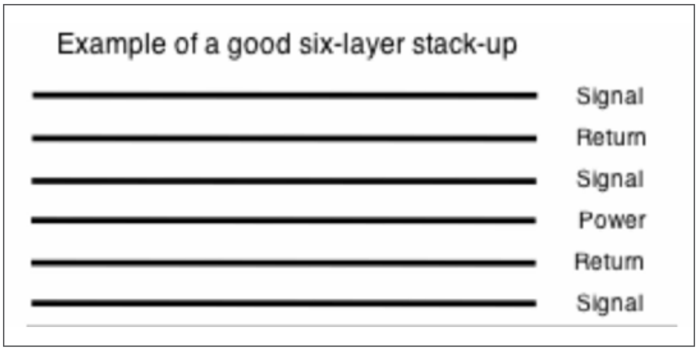


Figure 6: A six-layer board stack-up with good EMI performance. Each signal layer has an adjacent return plane and the power and power return planes are adjacent.

Note that when running signals between the top and bottom layers, you'll need to include "stitching" vias between the return planes and stitching capacitors between the power and power return planes right at the point of signal penetration in order to minimize the return path. Ideally, these stitching vias should be located within 1 to 2 mm of each signal via.

Other Tips—Other design tips include placement of all power and I/O connectors along one edge of the board. This tends to reduce the high frequency voltage drop between connectors, thus minimizing cable radiation. Also, segregation of digital, analog, and RF circuits is a good idea, because this minimizes cross coupling between noisy and sensitive circuitry. Of course, high-speed clocks, or similar high-speed signals, should be run in as short and as direct a path as possible. These fast signals should not be run long board edges or pass near connectors.

Refer to *References 1, 2, 3*, and *4* for further details on PC board design and how fields move through transmission lines

2. CABLE SHIELD TERMINATION

Cable Penetration—The number one issue I find when tracking down a radiated emissions problem is cable radiation. The reason cables radiate is that they penetrate a shielded enclosure without some sort of treatment–either bonding the cable shield to the metal enclosure or common mode filtering at the I/O or power connector *(Figure 7* and *8*). This occurs frequently, because most connectors are attached directly to the circuit board and are then poked through holes in the shield. Once the cable is plugged in, it is "penetrating the shield" and EMI is the usual result.

There are four combinations or cases that must be considered: shielded or unshielded products, and shielded or unshielded cables. Power cables are usually unshielded for consumer/commercial products and so require power line filtering at the point of penetration or at the connector of the circuit board. Shielded cables must have the shield bonded (ideally in a 360 degree connection) to the product's shielded enclosure. If the product does not have a shielded enclosure, then filtering (usually common mode) must be added at the point of penetration or at the I/O connector of the PC board. *Figure 8* shows the usual result when connectors simply poke through a shielded enclosure.

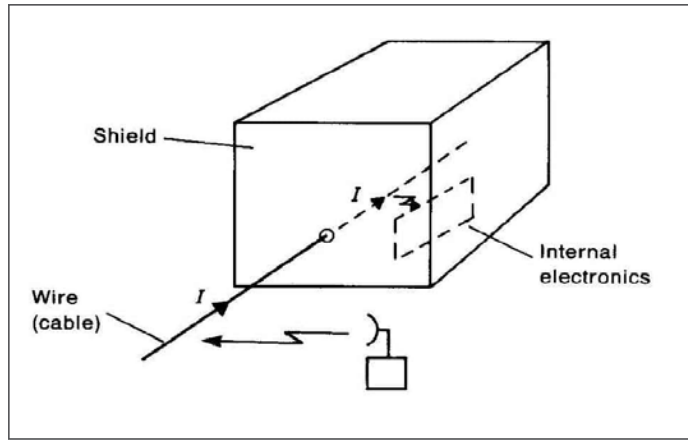


Figure 7: Penetrating the shield with a cable defeats the shield. This example shows how external energy sources can induce noise currents in I/O cables, which can potentially disrupt internal circuitry. The reverse is also true, where internal noise currents can flow out the cable and cause emissions failures. Image Source: Henry Ott.

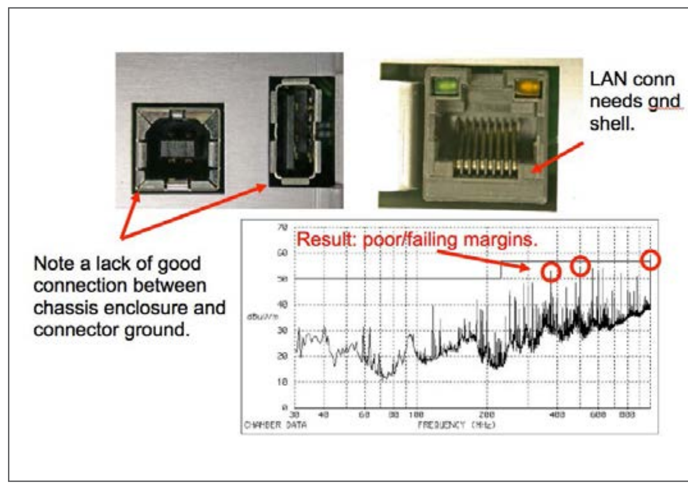


Figure 8: Result of a penetrating cable through a shielded enclosure, because of un-bonded I/O connectors to the shielded enclosure.

Cable Shield Terminations—Another potential issue is if the I/O cable uses a "pigtail" connection to the connector shell (*Figure 9*). Ideally, cable shields should be terminated in a 360-degree bond for lowest impedance. Pigtails degrade the cable shield effectiveness by introducing a relatively high impedance. For example, a 1-inch pigtail connection has 12 Ohms impedance at 100 MHz and gets worse the higher you go in frequency, thus defeating the cable shield.

This is especially problematic for HDMI cables, because the HDMI working group (http://www.hdmi.org) failed to specify the method for terminating the cable shield to the connector. Fortunately, they are aware of the issue and will better define a proper termination method in the next revision of the standard. In the meantime, there is no guaranty that a particular cable, when used for formal certification testing, will work well, or not. Trial and error of several brands is recommended.

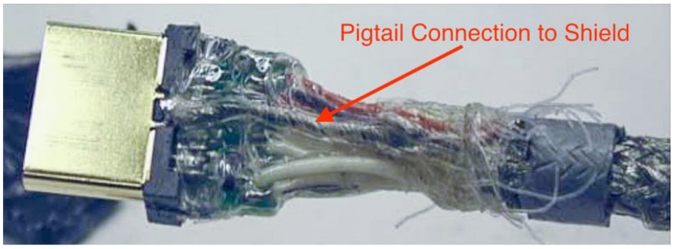


Figure 9: An example of a poor cable shield termination in an HDMI cable. Image Source: Dana Bergey.

Here are the results in testing eight different brands of HDMI cable (*Figure 10*). Each was driven with a signal generator and measured in an EMI chamber while sweeping the frequency. For a detailed report of this test, refer to *Reference 5*.

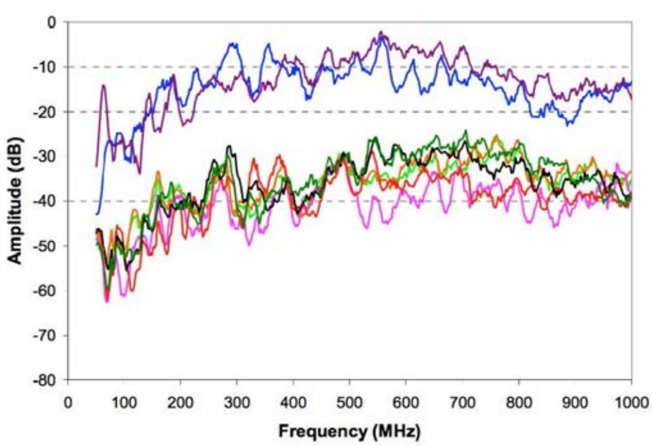


Figure 10: The results of testing eight HDMI cables from 30 to 1,000 MHz. As you can see, two of these exhibited 25 dB worse emissions across the band. Image Source: Dana Bergey.

3. GAPS IN THE RETURN PLANE

Breaks or gaps in the return path are major causes of radiated emissions, radiated susceptibility, and ESD failures. Let's come back to the issue of a gap or slot in the return plane mentioned earlier and show an example of why it's bad news for EMI. When the return path is interrupted, the conduction current is forced around the slot, or otherwise finds the nearest (lowest impedance) path back to the source. The electromagnetic field is forced out and the field will "leak" all over the board. I have an article and good demonstration video of this and how it affects common mode currents and ultimately, EMI. See *Figure 11* and *Reference 6*. This would be a great demo to construct and show your own colleagues!

The difference between the gapped and un-gapped traces is shown in *Figure 12*. Note the harmonic currents are 10 to 15 dB higher for the gapped trace (in red). Failing to pay attention to the signal and power return paths is a major cause of radiated emissions failures.

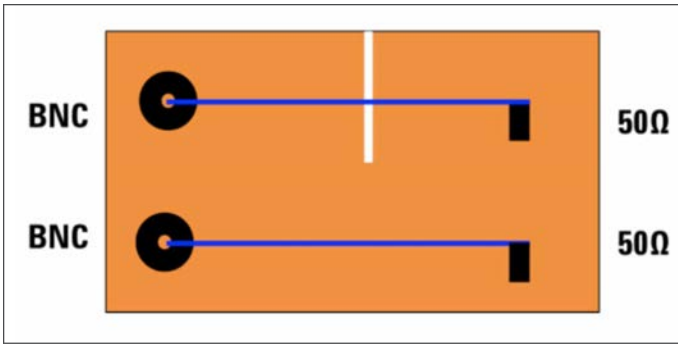


Figure 11: Shows a demonstration test board with transmission lines terminated in 50 Ohms. One transmission line has a gap in the return plane and the other doesn't. A 2 ns pulse generator is connected to one of the two BNC connectors in turn and the harmonic currents in a wire clipped to the return plane are measured with a current probe.

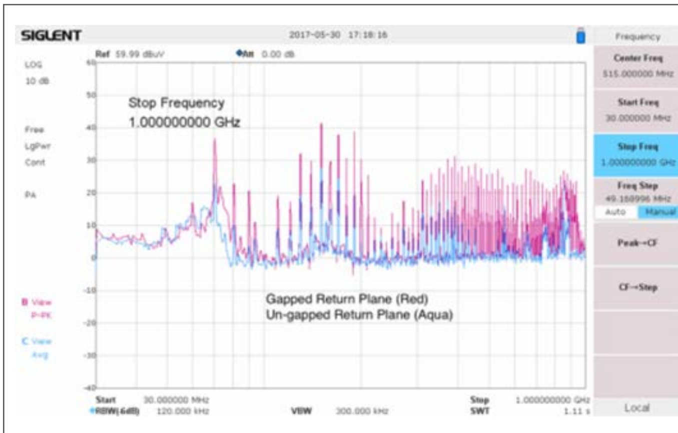


Figure 12: The resulting common mode currents on an attached wire as measured with a current probe. The trace in aqua is the un-gapped return path and the trace in red, the gapped return path. The difference is 10 to 15 dB higher for the gapped return path. These harmonic currents will tend to radiate and will likely cause radiated emissions failures.

4. POWER DISTRIBUTION NETWORK DESIGN

Power distribution network (PDN) design requires a low impedance (0.1 to 1.0 Ohms, typically) transmission line through at least 30 MHz. The purpose of a PDN is to transfer energy from the power source (often a voltage regulator module on the PC board) to the switching IC as fast as possible.

When the output stage of a digital IC switches from high to low or from low to high, there is a period of time when both output devices are partially turned on. This causes a large current pulse between the supply rail and power return pin of the IC. This "shoot through" current pulse tends to lower the supply voltage, causing what's known as simultaneous switching noise (SSN) on the power rail. This SSN tends to propagate throughout the PC board. A well designed PDN minimizes this SSN.

Capacitors, in the form of bulk, decoupling, and board capacitance, are used to store enough energy to overcome the tendency of the power rail voltage to decrease. *Figure 13* shows a typical circuit model of a PDN with the power source on the left, supplying energy to the IC on the right. In between, we have a series of energy storage capacitors and transmission lines (PC traces). Unfortunately, it takes significant time to transfer the required energy from the power source to the IC. It has been shown that it takes about 600 ps to transfer an amp of current across 1/16th inch of die bonds (*Reference 10*). That's why it's especially important to keep PDNs short and direct as possible.

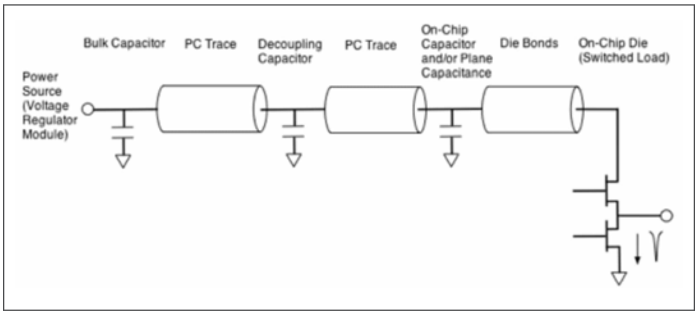


Figure 13: A typical circuit model of a power distribution network (PDN).

Ideally, the total energy demand will be met by the "on-chip" capacitors, if any, plus the energy stored in the power plane capacitance. However, these are seldom enough storage, so we depend a lot on nearby decoupling capacitors to supply the remaining energy demand. It is critical for the decoupling capacitors to have as little series inductance (in the form of internal inductance and trace inductance) as possible. The greater this series inductance, the harder it is to supply the required energy to the load and SSN results with related noise coupling throughout the PC board.

Assuming the decoupling and any built-in capacitance of the PC board can supply the energy needs, then the job of the bulk capacitor is to "recharge" the energy of the downstream capacitors in between switching transients. For the fastest recharge times, the PDN must be in the form of low impedance transmission lines.

The bulk capacitors 4.7 to 10 µF, typ.) are usually placed near the power input connector and the decoupling capacitors (1 to 10 nF, typ) nearest the noisiest switching devices To achieve the lowest series inductance, all decoupling capacitors should be mounted as close to the IC to be decoupled as possible and right over (or close to) the connecting vias. Multiple vias should be used for each end of the capacitor to further reduce series inductance. More on PDN design may be found in *References 7, 8*, and *9*.

5. SHIELDING DESIGN

The two issues with shielded enclosures is getting all pieces well-bonded to each other and to allow power or I/O cable to penetrate it without causing leakage of common mode currents. Bonding between sheet metal may require EMI gaskets or other bonding techniques. *Figure 14* shows a handy chart for determining the 20 dB attenuation of a given slot length. For example, if a product design requires at least a 20 dB shielding effectiveness, then the longest slot length can be just one-half inch.

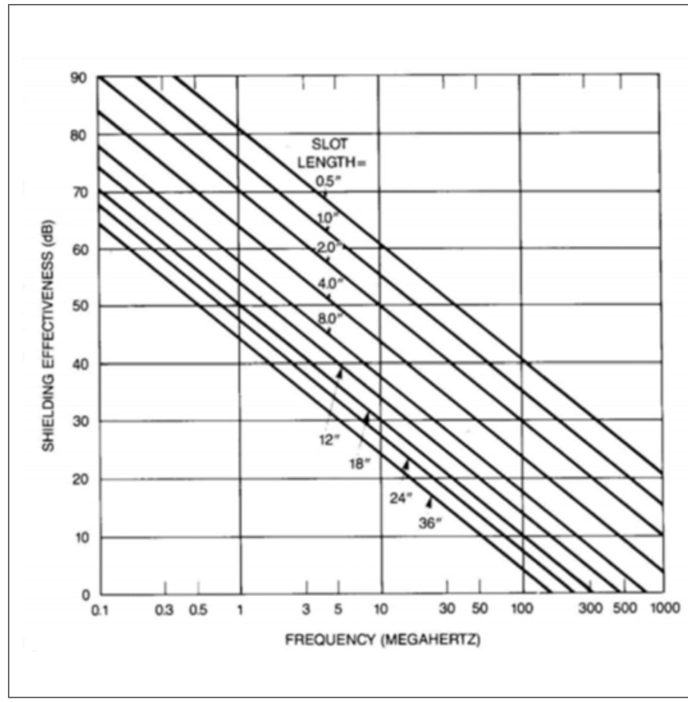


Figure 14: A chart of attenuation versus slot length. Image Source: Henry Ott.

Slots or apertures in shielded enclosures become issues when the longest dimension approaches a half wavelength. *Figure 15* is a chart of wavelength versus frequency. For example a 6-inch (15 cm) slot has a half wave resonance at 1,000 MHz. Generally, ventilation holes should be patterns of round holes no more than 1/4-inch diameter. Patterns of slots may be used, but they should be no longer than 1/2-inch in order to preserve an adequate shielding effectiveness.

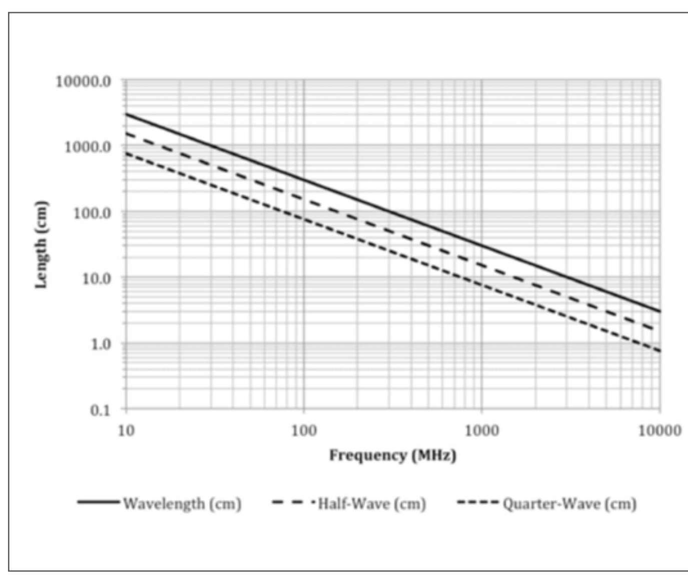


Figure 15: A handy chart for determining resonant frequency versus cable or slot length in free space. Half-wavelength slots simulate dipole antennas and are particularly troublesome. Image Source: Patrick André.

Reference 10 and *11* for more detail on shielding. *Interference Technology* also has a free downloadable *2016 EMI Shielding Guide* with excellent information (*Reference 12*).

SUMMARY

Paying attention to these five product design faults will go a long way towards lowering the risk of EMI failure during formal compliance testing. Considering a proper EMC design early in project development will save tons of time and money in the end.

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SUMMARY OF COMMERCIAL EMC TESTS

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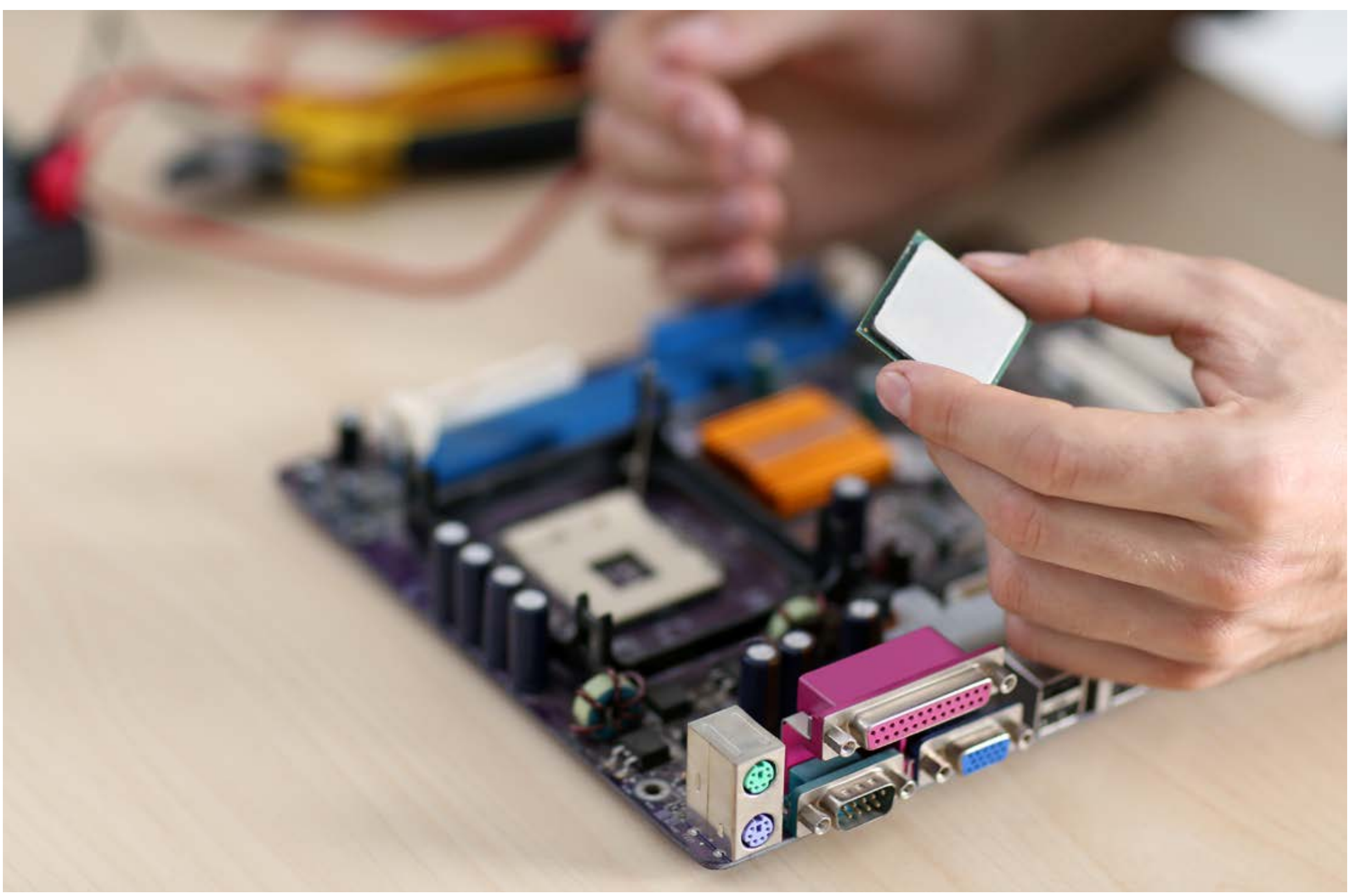
Introduction

Commercial EMC tests cover a wide range of products. These include the obvious ones like computers and their peripherals, but also cover household appliances, electric tools and a wide variety of other products. While the standards, including limits and test methods may differ, all EMC test standards have a few things in common. The most basic are the limits for emissions and the types and levels of immunity testing.



SUMMARY OF COMMERCIAL EMC TESTS

Emissions tests (and their associated limits) are put in place for commercial equipment primarily to protect radio and television broadcasting services. Other radio communications services are also protected. While a very few commercial emissions standards existed prior to the introduction of the personal computer to the marketplace, the proliferation of these devices spurred the development of standards and regulations around the world due to the large number of interference complaints directly traceable to these new devices. Early personal computing devices were designed and built with no regard to controlling radio frequency emissions and, as a result, they generated large amounts of RF emissions. Indeed, it could be argued that the early personal computing devices were broadband radio transmitters masquerading as computers. Mainframe computers had similar weaknesses, but as they typically weren't installed in residential areas the impact was smaller.

Emissions testing typically comprises of two parts. Conducted emissions on power and telecommunications ports and radiated emissions. The breakpoint between the two (conducted and radiated) in commercial standards is 30 MHz. This frequency was chosen as at the typical test distances involved (3 meters and 10 meters today) frequencies above 30 MHz tend to provide plane wave (far field) emissions, allowing for fairly repeatable measurements from laboratory to laboratory. Below 30 MHz this may not be the case. Thus, conducted emissions are measured. Limits for powerline conducted emissions were set based on the source and victim devices being connected to the same circuit. Limits for conducted emissions on telecommunication ports are set assuming a certain conversion of the differential mode (desired) signals on the cable being converted to common mode (due to characteristics of the cable) which then radiates.

CONDUCTED EMISSIONS

Conducted emissions on the incoming power lines are measured (typically) using a Line Impedance Stabilization Network (LISN) or Artificial Mains Network (AMN). These are two different names for the same box. The LISN or AMN is placed between the Equipment Under Test (EUT) and the incoming power line (mains) to provide a defined power line impedance and a coupling point to the receiver (*Figure 1*). The LISN or AMN is placed on the horizontal ground plane, or directly beneath it with the EUT connected directly to the EUT port. The block diagram below shows this test setup.
The EUT is placed either on the horizontal ground plane on the floor (with an insulating spacer) or on an 80 cm high non-conducting table, depending on the intended installation of the EUT (table top or ground mounted). The frequency range of interest is scanned with the appropriate detectors and bandwidth and the results are noted. Measurement are made on each conductor of the incoming line separately. Most commercial EMC standards have measurements made over the frequency range of 150 kHz to 30 MHz.

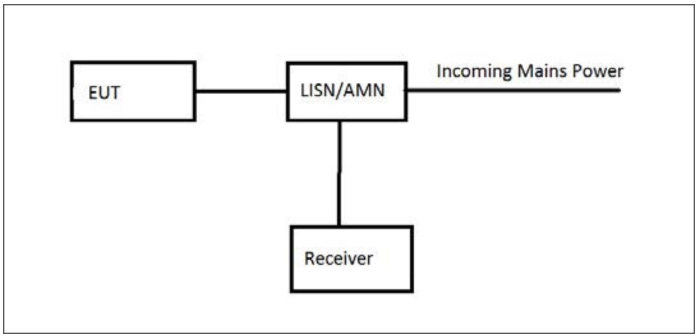


Figure 1: Generalized test setup for conducted emissions using a line impedance stabilization network (LISN).

RADIATED EMISSIONS

Radiated emissions may be measured in either an Open Area Test Site (OATS) or an RF Semi-Anechoic Chamber (SAC). The OATS is the "gold standard" test facility. It consists of a large open area free of objects which might reflect RF energy. It typically is equipped with a reflecting ground plane. The size of the clear area is defined in various standards as an elliptical area whose major axis is twice the measurement distance and whose minor axis is the square root of 3 times the measurement distance. Experience has shown over the decades that these dimensions are too small.

Doubling them has been tried and even that has been shown to have its weaknesses, especially when the OATS is surrounded by a chain link fence for security. The picture below shows a 30 meter OATS built in 1989 for Tandem Computers Incorporated near Hollister, CA. The clear area is at least twice the required dimensions for a 30 meter site and takes a considerable amount of land. This site is no longer in operation, but it illustrates the point. The building on the ground plane was constructed of RF transparent material and covered the turntable. All utilities were run underground, including the air conditioning ducts with the air conditioning units being installed outside the clear area. The site was never utilized at a measurement distance of 30 meters, so it was a superb 10 meter site.

Figure 2: A typical open area test site (OATS).

A significant weakness of the OATS facility is that in addition to measuring the emissions from the EUT it is a great facility to measure all the local RF ambient signals from broadcast and communications services, as well. If these signals are strong enough they will totally mask the emissions from the EUT that you were trying to measure. As a result, for best operation an OATS must be located in a very remote area. And this is no guarantee that the ambient level will remain low. Apple Computer had a great OATS near Pescadero, CA that had a very low ambient when it was built in the 1980s. Apple ultimately stopped using the facility when the local ambient signals grew to the point where operation was no longer possible and moved totally to 10 meter SACs near their development facilities.

Regardless of whether measurement are taken at an OATS or in a SAC, the block diagram of the test set-up remains the same. Emissions from the EUT are measured using an antenna for the appropriate frequency range, a pre-amplifier (if necessary) and a measuring receiver. Measurements are taken with the antenna in both the vertical and horizontal polarities. See the block diagram in *Figure 3*.

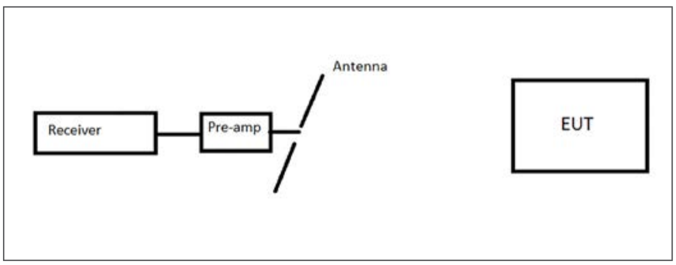


Figure 3: General test setup for radiated emissions testing.

The need for height scans is shown by the diagram in *Figure 4*. The objective is to adjust the antenna height until the direct and reflected signals are maximized. An example of an antenna mast for this purpose is shown in the photograph above of the Tandem 30 meter OATS (*Figure 2*).

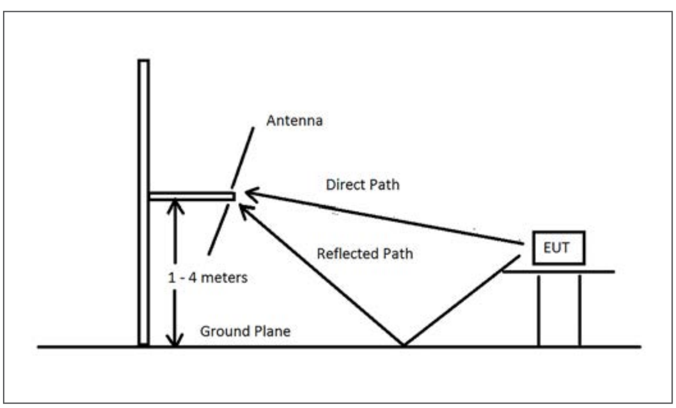


Figure 4: Diagram showing the direct and reflected waves. The antenna height is adjusted to maximize the measurement.

Emissions tests are required in many countries around the world. Immunity testing of commercial products is required in a smaller number of countries, but these are some major countries, so a manufacturer must be aware of them.

COMMERCIAL IMMUNITY TESTS

Commercial immunity testing typically covers the following types of tests:

1. Electrostatic Discharge (ESD)

There are two types of ESD tests–contact discharge and air discharge. In the contact discharge test the tip of the ESD simulator is placed on the test point of the EUT and the discharge is initiated. The discharge occurs inside the simulator and these tests are fairly repeatable. In the air discharge test the simulator is charged to the specified voltage and brought into contact with the EUT. The discharge, if it occurs, happens before contact is made jumping the air gap between the tip of the simulator and the EUT. How large this gap is depends of the atmospheric pressure, temperature, angle of approach, and relative humidity. It can also depend on how fast the operator approaches the EUT with the ESD gun Air discharge testing is not as repeatable, but it simulates a different ESD event. Both types of tests are typically required. For computer equipment CISPR 35 requires a contact discharge test at 4 kV and air discharge tests up to 8 kV. Tests are typically performed using the equipment and procedures called out in IEC 61000-4-2. The EUT is allowed to react to the test, but it must self-recover after the test.

A classic example is a computer playing music over a speaker. You hear a pop in the speaker when the ESD event occurs, but the music keeps playing afterwards. This is considered a pass. If the music stopped and required operator intervention to re-start, that would be considered a failure.

2. Radiated electric field immunity

This tests the immunity of the EUT to nearby radio transmitters. The frequency range of 80 MHz to 1 GHz is typically tested, although newer standards have tests required as high as 6 GHz. This test is performed in a fully anechoic chamber or a SAC with removable absorbers placed on the floor. Signal levels are used that would annoy the neighbors and cause the local regulators to issue fines, so a shielded environment is a necessity. The current requirements in IEC 61000-4-3 (a commonly used basic standard) call for the E-field to be uniform to within certain requirements before the EUT is brought into the test volume. Four sides of the EUT are typically evaluated. The EUT typically must continue to operate through the test as though nothing was happening to it or must self-recover with no loss of data to be considered a pass.

3. Electrical Fast Transients

This test introduces a series of rapid pulses into the EUT through the power and any signal lines that could exceed 3 meters in length. Like ESD testing, the EUT must operate after the test without operator intervention, but may react to the test as it occurs, so long as the system self-recovers with no loss of data. IEC 61000-4-4 calls out the test equipment and procedures for this test.

4. Electric Surge

This test simulates what happens on the power input to the EUT when there is a nearby lightning strike. High energy surges are applied to the EUT line input. IEC 61000-4-5 details the test equipment and procedures for performing surge testing.

5. Conducted RF

In commercial standards the breakpoint between conducted RF and radiated RF immunity testing is typically 80 MHz. Generating uniform fields much below 80 MHz is difficult. As a result, below that frequency RF energy is typically injected onto cables connected to the EUT. An example of a block diagram for such a test is shown in *Figure 5*. The 6 dB attenuator is placed as close to the Coupling Decoupling Network (CDN) as possible. While this isn't clearly shown in IEC 61000-4-6, the reason for placing it as close to the CDN as possible is that it provides a matching impedance to the transmission line, maximizing power transfer to the CDN, whose input impedance is not precisely known. Otherwise, you may be throwing away half the power you paid to generate.

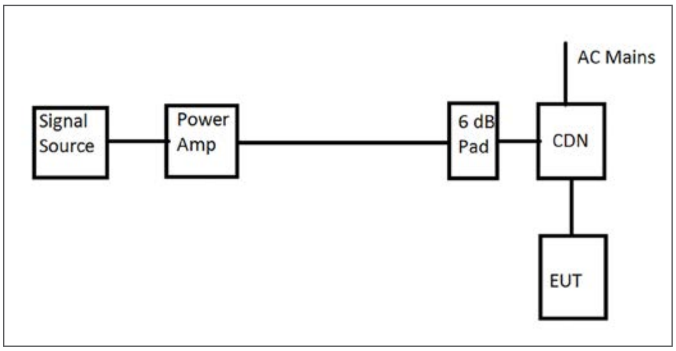


Figure 5: Typical test setup for the conducted immunity test.

The typical frequency range for conducted RF immunity testing of commercial equipment is 150 kHz to 80 MHz.

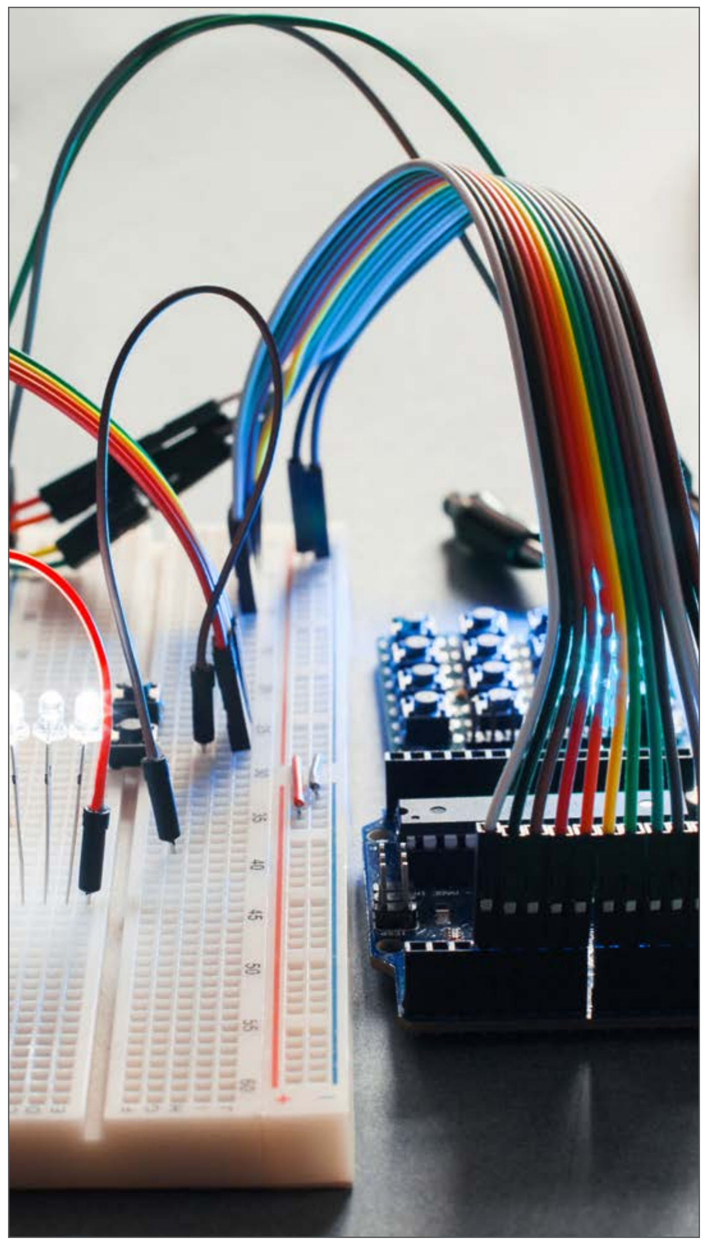
6. Power Frequency Magnetic Fields

This test is run for products which might reasonably be expected to have immunity problems with power frequency magnetic fields. Such products, as called out in CISPR 35 for example, might include cathode ray tube (CRT) displays, magnetic field sensors and Hall devices. The EUT is placed in the middle of a large coil of wire through which a power frequency current flows. The current level to generate the specified field level (for example, 1 Amp/meter in CISPR 35) is run through the coil and the EUT is checked for proper operation. All three axes are tested. Most products do not require this test, but it is included in the product family standards. IEC 62000-4-8 details how to perform this test.

7. Dips and dropouts

This test is designed to simulate real world examples of momentary input power voltage fluctuations. In the case of CISPR 35 there are three tests that are performed, typically by a computerized power source. The first is a >95% voltage reduction for one half cycle of the incoming power. The voltage change occurs at the zero crossover point on the power waveform. This simply means that one half cycle of the incoming power to the EUT is chopped off. The EUT is allowed to react, but must self-recover without operator intervention. The second test is a 30% reduction (70% residual voltage) for one half second (25 cycles at 50 Hz or 30 cycles at 60 Hz)–a short brown-out. Again, the EUT may react, but must self-recover. The third commonly used test is a >95% reduction in input voltage for 5 seconds. It's like the power cord was pulled out of the wall socket for 5 seconds and then plugged back in. Obviously, unless the EUT has a built in battery or UPS, it will crash. As long as function can be restored by the operator in accordance with the instructions and no data protected by battery back-up is lost or damaged, the EUT passes this test. IEC 61000-4-11 provides the details on how these tests are to be run.

The test levels utilized in commercial immunity tests are designed to provide a reasonable level of certainty that the product will operate in its intended environment. They do not represent the worst case that a product might experience in the field, but they have been shown over the years to be adequate. Indeed, most products exhibit higher levels of immunity that required when tested to their breaking point and the design features used to meet the emissions requirements typically are adequate for providing this level of immunity.



EMI TROUBLESHOOTING WITH REAL-TIME SPECTRUM ANALYZERS

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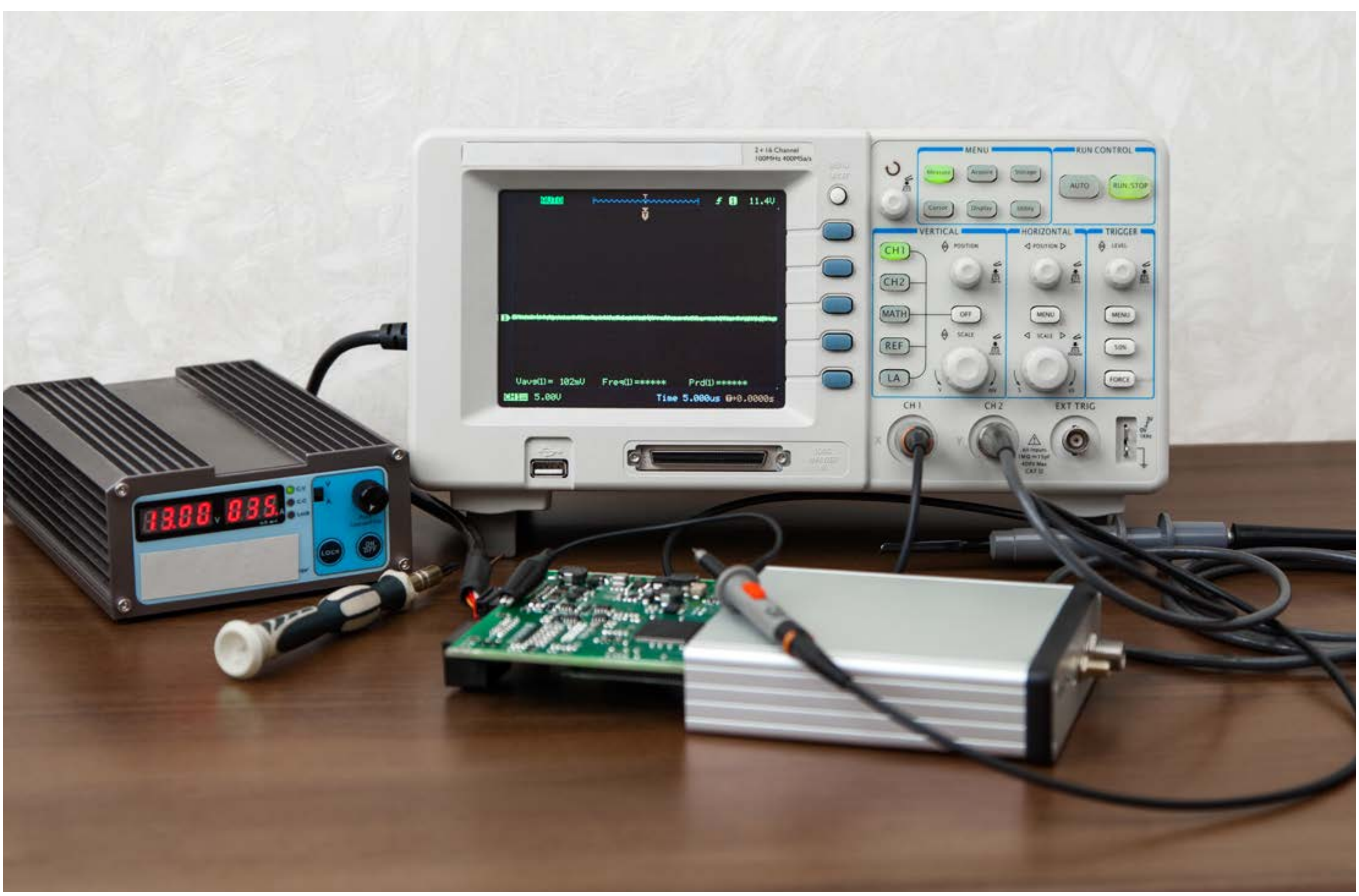
The latest tool for serious EMI troubleshooting or debugging has become the real-time (RT) spectrum analyzer. Because manufacturing costs have been decreasing, some RT analyzers are becoming more affordable than ever. In this article, I'll show you the advantages in using RT analysis for observing and troubleshooting unusual EMI.



EMI TROUBLESHOOTING WITH REAL-TIME SPECTRUM ANALYZERS

INTRODUCTION

First, let's review the differences between the conventional swept and real-time spectrum analyzers.

Swept-Tuned Analyzer–The swept analyzer uses a tunable local oscillator in a standard superheterodyne circuit. It can sweep over a specified frequency range and using a user-selected resolution (or "receiver") bandwidth. RF signals introduced to the input port are mixed with the local oscillator and the specified frequency span is display as RF power versus frequency. The only time data is captured is during the sweep time. After the frequency sweep, the captured data is processed and displayed. There is usually significant delay (or "dead" time) between sweeps, so its quite possible for the analyzer to miss capturing intermittent or fast-moving signals.

Real-Time Analyzer–A real-time analyzer uses a stationary LO, looks at narrow windows of bandwidth (real-time bandwidth), and digitizes the incoming spectrum. This digitized spectrum is stored in a time record buffer and held for processing by the FFT algorithm. Ideally, once digitized, FPGAs process FFTs at a rate equal, or faster, than the collection rate. However, this collection rate depends on the span and resolution bandwidth. The major difference between the swept-tuned analyzer and real-time analyzer is the sheer number-crunching ability of the real-time calculation, as well as a fast graphics processor, which allows for a data-dense display of various frequency-versus-time presentations and digital demodulation.

The advantages of a RT analyzer is the ability to capture RF pulses as short as 20 µs, digital modulations, and other pulsing or fast changing signals. In addition, they can capture and process data much faster than swept analyzers –there's no need to wait seconds or minutes to capture a spectrum. This allows very fast troubleshooting, since you can see the result of fixes immediately.

Finally, the RT analyzers have an addition feature called a spectrogram (or "waterfall") display, where signals are shown versus time. This is a great feature allowing you to determine the timing of intermittent EMI.

I'll be using the Tektronix RSA306B (*Reference 1*) real-time USB-controlled spectrum analyzer with Tekbox Digital Solutions (*Reference 2*) near field probes for this article, but there are many other choices available.

Figure 1 shows a typical advantage of the RT display over that of the swept display. Here, we see some broadband motor noise completely masking several narrow band harmonics. The swept analyzer has trouble capturing the motor noise, but we can see occasional captures indicating there was "something" there. Max Hold mode and waiting a while will help fill in the swept display, but then you'd miss seeing the narrow-band emissions.

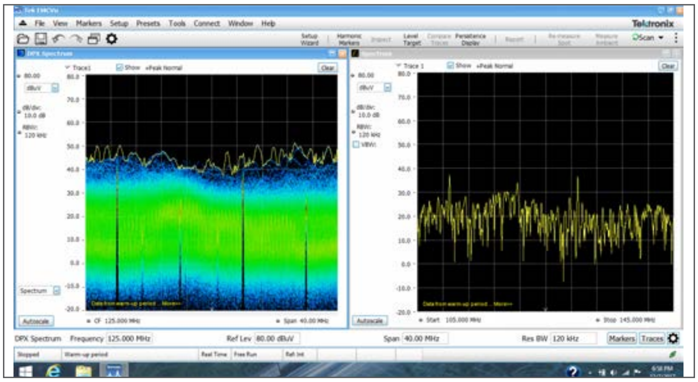


Figure 1: An example where the broadband emissions from a motor controller completely mask a series of narrow band harmonics. You can see on the right that the standard swept analyzer has trouble capturing this broadband noise.

Most RT analyzers will also have optional EMI software that will help collect data or even perform pre-compliance testing for radiated and conducted emissions. For example, Tektronix offers their SignalVu-PC software with the RSA306B, but also recently announced their EMI troubleshooting and pre-compliance software for the RSA-series, called "EMCVu". EMCVu includes some impressive EMI troubleshooting and pre-compliance test features and can switch from one mode to the other quickly. It comes with pre-defined transducer factors (antenna and cable loss tables), CISPR and FCC limit lines, and easy report generation.

In pre-compliance mode, it can scan the entire frequency range in a few seconds, numbering all the harmonics above the limit and within a certain margin to the limit. These captured harmonic signals can then be examined more closely and then switched over to troubleshooting mode to try various fixes.

Either SignalVu-PC or EMCVu will work fine for basic troubleshooting or debugging emission issues and I've actually used both for this article. If you also want pre-compliance test capability in-house (a wise decision) or more advanced troubleshooting tools, then you'll want to invest in EMCVu.

THREE-STEP PROCESS FOR EMI TROUBLESHOOTING

I've developed a three-step process for EMI troubleshooting, which I'll briefly explain below. We'll use Tektronix' SignalVu-PC or EMCVu as an example, but several other companies sell similar compliance software.

You'll want to download the free "2017 EMI Pre-Compliance Test Guide" from *Interference Technology* for more details on this troubleshooting process (*Reference 3*).

Step 1–Use near field probes (either H- or E-field) to identify energy sources and characteristic emission profiles on the PC board and internal cables. Energy sources generally include clock oscillators, processors, RAM, D/A, or A/D converters, DC-DC converters, and other sources, which produce fast-edged digital signals. If the product includes a shielded enclosure, probe for leaky seams of other apertures. Record the emission profile of each energy source.

Step 2–Use a current probe to measure high frequency cable currents. Remember, cables are the most likely structure to radiate RF energy. Move the probe back and forth along the cable to maximize the highest currents. Record the emission profile of each cable.

Step 3–Use a nearby antenna (I use a 1 m test distance) to determine which of the harmonic content actually radiates. Catalog these harmonics and compare to the internal and cable measurements. This will help you determine the most likely energy sources that are coupling to cables or seams and radiating.

ANALYZE THE DATA

Remember that not all near field signals will couple to "antenna-like" structures and radiate. Use a harmonic analyzer tool (see *Reference 4*) to help identify harmonics belong to specific energy sources. Note that in many cases, two, or more, sources will generate the some (or all) the same harmonics.

For example, a 25 MHz clock and 100 MHz clock can both produce harmonics of 100, 200, 300 MHz, etc. Oftentimes, you'll need to fix more than one source to eliminate a single harmonic. EMCVu includes some powerful data capture and documentation features that will help speed up the data collection process from steps one through three.

After the harmonics are analyzed and you have identified the most likely sources, the next step is to determine the coupling path from source and out the product. Usually, it's the I/O or power cables that are the actual radiating structure. Sometimes, its leaky seams or apertures (display or keyboard, for example).

There are four possible coupling paths; conducted, radiated, capacitive, and inductive. The latter two (capacitive and inductive) are so-called; "near field" coupling and small changes in distance between source and victim should create large effects in radiated energy. For example, a ribbon cable routed too close to a power supply heat sink (capacitive coupling or dV/dt) and causing radiated emissions can be resolved merely by moving the ribbon able further away from the heat sink.

The inductive coupling (di/dt) between a source and victim cable can also be reduced by rerouting. Both these internal coupling mechanisms (or similar PC board design issues) can lead to conducted (out power cables) or radiated (I/O or power cables acting as antennas, or enclosure seams/apertures) emissions.

In many cases, its simply poor cable shield bonding to shielded enclosures or lack of common-mode filtering at I/O or power ports that lead to radiated emissions.

HOW CAN RT ANALYZERS HELP TROUBLESHOOT EMI?

So, let's turn our attention back to probing the PC board and cables. How often have you probed, troubleshot, and fixed a product only to have it fail at the compliance test facility? Many of today's products, especially mobile products, include on board DC-DC converters that produce a very broadband EMI spectrum out past 1 GHz that can impact the operation of cellular or GPS wireless receivers. In addition, digital processors can change emission characteristics with time or operating mode. Add wireless features and you have a myriad of potential energy sources that can change emission characteristics with time.

I'd like to demonstrate a some examples where swept analyzers might very well miss a bursting increase in emissions or fail to capture broadband EMI that is greater in amplitude than the usual narrow band harmonics we're all used to.

Figure 2: Using a near field (H-field) probe on an on-board DC-DC converter in a small mobile device. I'm using the Tektronix RSA306B USB-controlled RT spectrum analyzer and Tekbox near field probe.

Example 1–Pulsating Harmonic EMI

Most of the time, you'll find narrow band harmonics are relatively stable in amplitude. However, there are times when the amplitude can change, due to gated digital signals or different operating modes. If the harmonic peaks upward at the wrong time, it can lead to compliance failures.

Swept analyzers can easily miss these infrequent amplitude peaks. Placing the swept analyzer in "Max Hold" mode can help, but it could take several minutes to capture the peak of the emission. Even so, peaks can be missed, due to dead time in between scans.

RT analyzers, on the other hand are adept at capturing fast changing signals. Here's an example where I was measuring the narrow band low frequency emissions from an on-board DC-DC converter on a small mobile device (*Figure 2*).

In *Figure 3*, we're looking from 9 kHz to 10 MHz and we see the swept measurement is even having a hard time capturing the regular peak emissions, while the RT measurement captures the peaks easily and even detects an occasional six dB pulsing increase in amplitude (as shown in the blue persistence display). That infrequent pulsing amplitude increase could easily cause a compliance failure should it couple out through conduction or radiation.

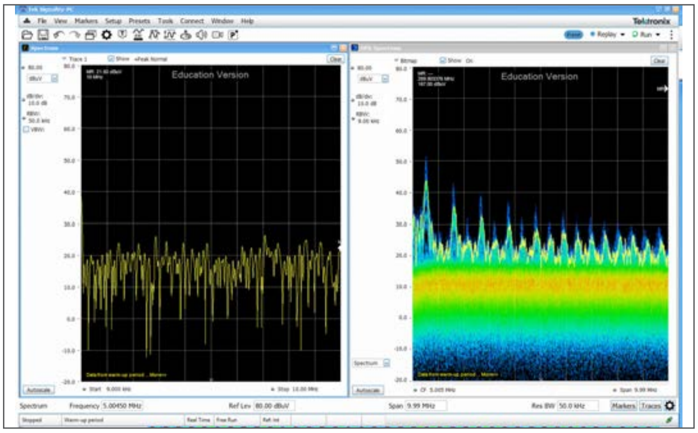


Figure 3: Measuring the emissions from an on-board DC-DC converter and comparing swept (left) and real-time (right). Note the 6 dB peaks in the blue persistence display.

Example 2–Identification of Emissions Due to Different Operating Modes

In this example, we're measuring that same DC-DC converter (*Figure 1*), but looking from 105 to 145 MHz, a frequent area of compliance failures due to radiated emissions. The surprising result was the three very different spectral responses, due to different operating modes of the mobile device. In some cases, the emission was about 25 dB higher than the swept measurement could capture. Now, would you be willing to take the risk that the swept measurement at the compliance test facility would either miss or manage to capture this should it couple out and radiate?

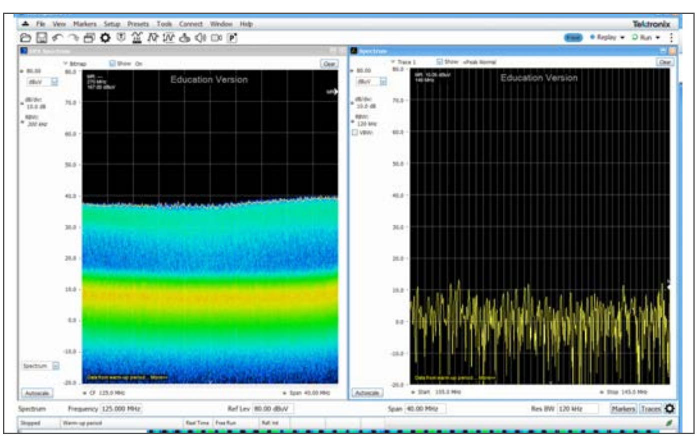


Figure 4: Broadband emissions from the DC-DC converter looking from 105 to 145 MHz. The swept measurement on the right was unable to successfully capture this, except for an occasional burst. Max Hold mode would have helped, but would have taken at least a minute to "fill in" the display. But once the display was filled in, you may not have been able to see the following two very different modes in *Figures 5* and *6*.

Figures 4, 5, and *6* show the three different spectral modes. Notice that the swept measurement managed to capture only two of the three spectrums. The near field probe was not moved during this sequence. Each mode was instantly viewable as the state changed from one mode to another.

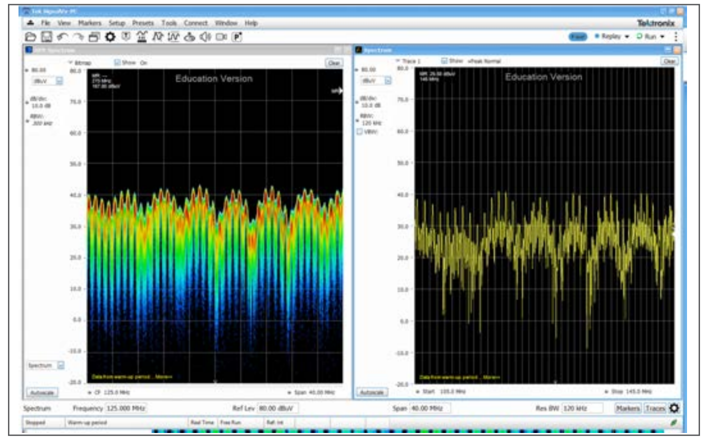


Figure 5: Without moving the probe, we see "mode 2" from the DC-DC converter, which briefly appeared.

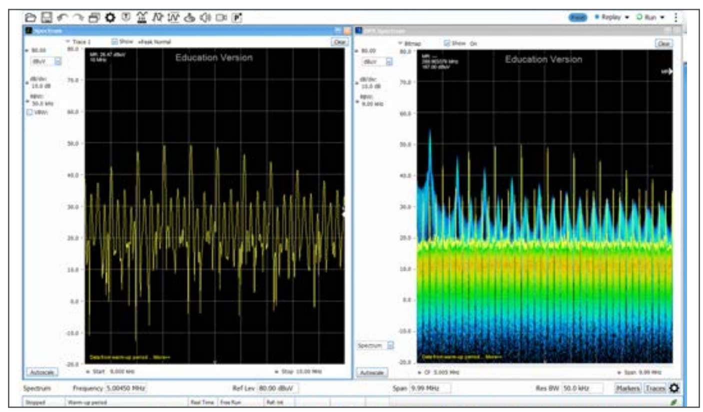


Figure 6: Again, without moving the probe, we see "mode 3" with much increased narrow band emissions measuring about 10 dB higher than modes 1 and 2. This brief occurrence could have been the mode that would have resulted in a compliance failure, should the emission get coupled out and radiate.

Example 3–Detection of Spurious Oscillation

In this example, we don't necessarily need the RT capture, but it does yield some interesting visual clues once we activate the spectrogram (waterfall) display feature. The board being measured is a demo board from Picotest Technologies (*Figure 7*) and I discovered one of the op-amps produced an interesting bimodal series of spurious oscillations at about 150 MHz intervals. I was able to induce this oscillation by "switching out" the output capacitance.

It turns out that when the op-amp was unloaded capacitively, it produced a very interesting oscillation at near its open loop bandwidth (*Figure 8*). Examining the RT measurement on the right, we can see there's a distinct bimodal (two-frequency) display, along with some cool sideband emissions. The swept display on the left can only capture one of these two frequencies at a time, at best, as the oscillation is switching from one frequency to the other.

Figure 7: Measuring an op-amp on the Picotest Technologies demo board.

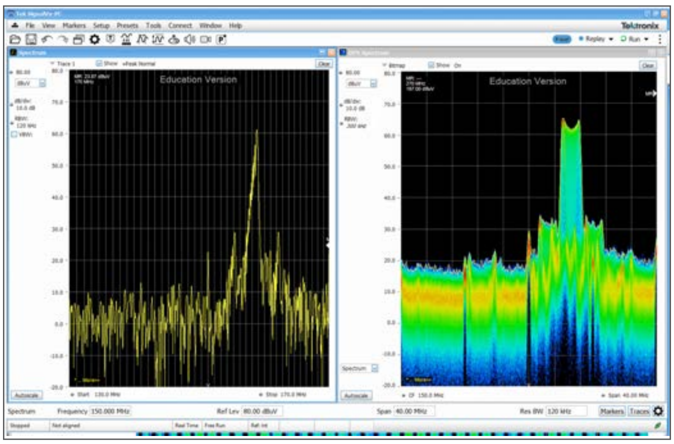


Figure 8: Measurement of an interesting spurious oscillation of an op-amp. Note that the swept measurement on the left can only capture one of the bimodal states at a time, while the RT capture on the right is very detailed.

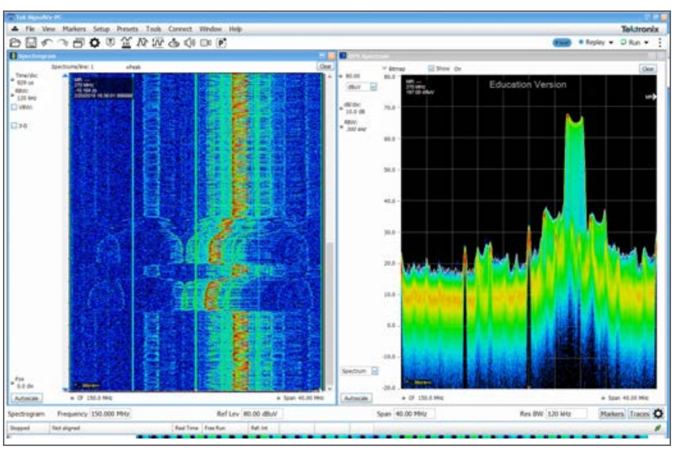


Figure 9: Replacing the swept display with a spectrogram (frequency versus time), we can observe some interesting details (see text).

But let's analyze the "bi-modal-ness" a little closer by replacing the swept display with a spectrogram of frequency versus time.

One thing I noticed (and this is very common for spurious oscillations) is that placing my finger on the area of the op-amp changed the parasitic characteristics enough to shift the oscillation frequency quite a bit downward. You can see that shift in the spectrogram display in *Figure 9* as I touched my finger to the area twice.

The other thing to note is that you can now easily observe the switching between one oscillation frequency and the other in the "zig zag" pattern in the spectrogram. Note that the oscillation spends more time at the lower frequency, rather than the upper frequency. This is also indicated by the slightly higher amplitude of the left side of the double peak.

CONCLUSION

As technology continues to advance, we EMC engineers and product designers need to upgrade our usual analysis and pre-compliance test tools to stay one step ahead and be able to better capture and display the more unusual emissions expected. Real-time spectrum analyzers have already proven to be invaluable for EMI debug and troubleshooting. Advanced spectral analysis will be especially important as mobile devices continue to shrink and more products incorporate wireless and other advanced digital modes.

AUTHOR BIO

Kenneth Wyatt is president and principal consultant of Wyatt Technical Services LLC, as well as the senior technical editor for *Interference Technology*. He has worked in the field of EMC engineering for 30 years. His specialty is EMI troubleshooting and pre-compliance testing and is a co-author of the popular *EMC Pocket Guide and RFI Radio Frequency Interference Pocket Guide*. He also coauthored the book with Patrick André, *EMI Troubleshooting Cookbook for Product Designers*, with forward by Henry Ott. He is widely published and authored *The EMC Blog* hosted by EDN.com for nearly three years. Kenneth is a senior member of the IEEE and a long time member of the EMC Society.

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Check out his web site for more technical information, training schedules, and links:
www.emc-seminars.com

TESTING REFERENCES

We are pleased to offer a number of Testing resources for you which can be found in the Suppliers Guide and Directory sections. Our Suppliers guide, on page 11, offers a comprehensive list of equipment manufacturers and service providers. Additionally, our full Test Lab Directory can be found on page 16.

Our Standards and Organizations section provides a list of Common Commercial Standards and Medical Standards. More specialized standards for the Military, Aerospace can be found in our Mil/Aerospace section beginning on page 140. We also feature Automotive EMC Standards in our Automotive Section on page 118, and Wireless EMC standards in our Wireless/5G/IoT section on page 88.

These resources extend into our articles, including “Summary of Commercial EMC Tests” by Ghery Pettit, which can be found on page 74, and “Summary of Military and Aerospace EMC Tests” also by Ghery Pettit, which is available on page 144.

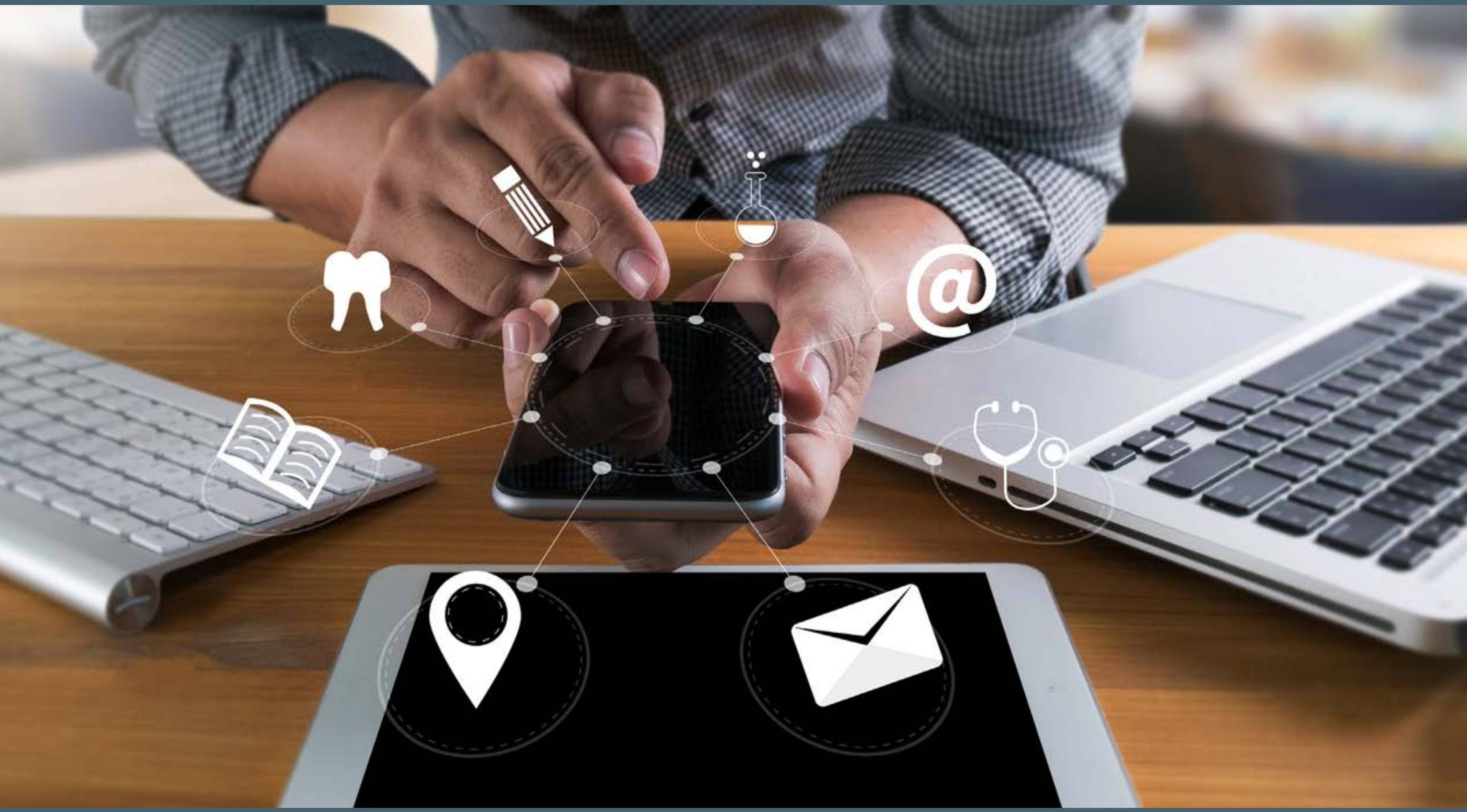
FEATURED INDUSTRIES

Wireless/5G/IoT EMC

Automotive EMC

Military/Aerospace EMC

WIRELESS / 5G / IoT



WIRELESS/5G/IoT EMC SUPPLIERS MATRIX

Introduction

There are two main categories of equipment in this handy supplier guide: EMI troubleshooting & measurement equipment and direction finding equipment.

EMI troubleshooting and measurement equipment includes spectrum analyzers, near field probes, current probes, antennas, and other pre-compliance equipment.

Direction finding (or DFing) equipment usually includes specialized portable, mobile, or base station spectrum analyzers with custom antennas and mapping software especially designed for locating interfering sources.

Wireless & IoT EMC Supplier Matrix		Type of Product/Service								
Manufacturer	Contact Information - URL	Amplifiers	Antennas	Current Probes	Fixed DF Systems	Mobile DF Systems	Near Field Probes	Portable DF Systems	Pre-Compliance Test	Spectrum Analyzers / Receivers
360Compliance	www.360compliance.co/								X	
Aaronia AG	www.aaronia.com	X	X		X	X		X	X	X
Alaris Antennas	www.alarisantennas.com		X							
Anritsu Company	www.anritsu.com		X						X	X
Avalon Test Equipment Corp	www.avalontest.com	X	X	X		X	X		X	X
CommsAudit	www.commsaudit.com/products/direction-finding		X		X	X				X
Doppler Systems	www.dopsys.com		X		X	X		X		
The EMC Shop	www.theemcshop.com	X	X	X			X		X	X
Gauss Instruments	www.gauss-instruments.com/en/									X
Intertek	www.intertek.com								X	
Kent Electronics	www.wa5vjb.com		X							

Wireless & IoT EMC Supplier Matrix		Type of Product/Service								
Manufacturer	Contact Information - URL	Amplifiers	Antennas	Current Probes	Fixed DF Systems	Mobile DF Systems	Near Field Probes	Portable DF Systems	Pre-Compliance Test	Spectrum Analyzers / Receivers
Keysight Technologies	www.keysight.com/main/home.jspx?cc=US&lc=eng						X		X	X
Morcom International	www.morcom.com/direction_finding_systems.html							X		X
MPB srl	www.gruppompb.uk.com		X	X					X	X
MVG, Inc	www.mvg-world.com/en		X				X		X	
Narda/PMM	www.narda-sts.it/narda/default_en.asp	X	X						X	X
Pearson Electronics	www.pearsonelectronics.com			X						
RDF Antennas	www.rdfantennas.com							X		
RDF Products	www.rdfproducts.com				X	X				X
Rhotheta America	www.rhothetaamerica.com/index.html				X	X		X		
Rigol Technologies	www.rigolna.com	X		X			X		X	X
R&K Company Limited	www.rk-microwave.com	X								
Rohde & Schwarz USA, Inc.	www.rohde-schwarz.com/us/	X	X	X	X	X	X	X	X	X
Siglent Technologies	wwwsignlentamerica.com						X		X	X
Signal Hound	www.signalhound.com			X			X		X	X
SPX/TCI	www.spx.com/en/our-businesses/detection-and-measurement/TCI/		X		X	X		X		X
SteppIR Communication Systems	www.steppir.com		X							
TechComm	www.techcommdf.com		X		X	X		X		X
Tektronix	www.tek.com					X	X	X	X	X
Teseq	www.teseq.com/en/index.php	X		X					X	
Thurlby Thandar (AIM-TTi)	www.aimtti.us								X	X
TMD Technologies	www.tmd.co.uk	X								
UST	www.unmannedsystemstechnology.com/company/marshall-radio-telemetry/							X		X

WIRELESS/5G/IoT STANDARDS

ETSI STANDARDS

(https://www.etsi.org)

Document Number	Title
ETSI EN 300 220	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 25 MHz to 1,000 MHz frequency range with power levels ranging up to 500 mW
ETSI EN 300 328	Electromagnetic compatibility and Radio Spectrum Matters (ERM); Wideband transmission systems; Data transmission equipment operating in the 2.4 GHz ISM band and using wide band modulation techniques; Harmonized EN covering essential requirements under article 3.2 of the R&TTE Directive
ETSI EN 300 330	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 9 kHz to 25 MHz frequency range and inductive loop systems in the 9 kHz to 30 MHz frequency range
ETSI EN 300 440	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 1 GHz to 40 GHz frequency range
ETSI EN 301 489-3	Electromagnetic compatibility and Radio spectrum Matters (ERM); Electromagnetic Compatibility (EMC) standard for radio equipment and services; Part 3: Specific conditions for Short Range Devices (SRD) operating on frequencies between 9 kHz and 40 GHz
ETSI EN 301 489-17	Electromagnetic compatibility and Radio spectrum Matters (ERM); Electromagnetic Compatibility (EMC) standard for radio equipment and services; Part 17: Specific conditions for Wideband data and HIPERLAN equipment
ETSI EN 301 893	Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering essential requirements of article 3.2 of the R&TTE Directive
ETSI EN 303 413	GPS receivers
ETSI EN 303 417	Wireless Power Transfer

WIRELESS/5G/IoT GROUPS & ORGANIZATIONS

MAJOR WIRELESS/5G/IoT LINKEDIN GROUPS

- Wireless Telecommunications Worldwide
- Wireless and Telecom Industry Network
- Cellular, Wireless & Mobile Professionals
- Wireless Communications & Mobile Networks
- 802.11 Wireless Professionals
- Wireless Consultant
- Telecom & Wireless World

MAJOR WIRELESS/5G/IoT ASSOCIATIONS AND ORGANIZATIONS

APCO International
https://www.apcointl.org
APCO International is the world's oldest and largest organization of public safety communications professionals and supports the largest U.S. membership base of any public safety association. It serves the needs of public safety communications practitioners worldwide–and the welfare of the general public as a whole–by providing complete expertise, professional development, technical assistance, advocacy and outreach.

ATIS
http://www.atis.org
In a rapidly changing industry, innovation needs a home. ATIS is a forum where the information and communications technology (ICT) companies convene to find solutions to their most pressing shared challenges.

Bluetooth Special Interest Group
https://www.bluetooth.com
Join thousands of the world's most innovative companies already developing and influencing Bluetooth technology.

CTIA - The Wireless Association
http://www.ctia.org
CTIA is an international nonprofit membership organization that has represented the wireless communications industry since 1984. The association's members include wireless carriers, device manufacturers, suppliers as well as apps and content companies.

ETSI - European Telecommunications Standards Institute
http://www.etsi.org
We produce globally applicable standards for Information & Communications Technologies including fixed, mobile, radio, broadcast, internet, aeronautical, and other areas.

NAB - National Association of Broadcasters
http://nab.org
The National Association of Broadcasters is the voice for the nation's radio and television broadcasters. As the premier trade association for broadcasters, NAB advances the interests of our members in federal government, industry and public affairs; improves the quality and profitability of broadcasting; encourages content and technology innovation; and spotlights the important and unique ways stations serve their communities.

Satellite Industry Association
http://www.sia.org
The Satellite Industry Association (SIA) is a Washington D.C. based trade association representing the leading global satellite operators, service providers, manufacturers, launch services providers, and ground equipment suppliers.

Telecommunications Industry Association
http://www.tiaonline.org
The Telecommunications Industry Association (TIA) is the leading trade association representing the global information and communications technology (ICT) industry through standards development, policy initiatives, business opportunities, market intelligence and networking events. With support from hundreds of members, TIA enhances the business environment for companies involved in telecom, broadband, mobile wireless, information technology, networks, cable, satellite, unified communications, emergency communications, and the greening of technology.

WIRELESS/5G/IoT GROUPS & ORGANIZATIONS

Wireless Infrastructure Association (WIA)
http://wia.org
The Wireless Infrastructure Association represents the businesses that develop, build, own, and operate the nation's wireless infrastructure.

Wireless Innovation Forum
http://www.wirelessinnovation.org
WInnForum members are dedicated to advocating for the innovative use of spectrum and advancing radio technologies that support essential or critical communications worldwide. Through events, committee projects, and initiatives the Forum acts as the premier venue for its members to collaborate to achieve these objectives, providing opportunities to network with customers, partners and competitors, educate decision makers, develop, and expand markets, and advance relevant technologies.

WiMax Forum
http://wimaxforum.org
The WiMAX Forum® is an industry-led, not-for-profit organization that certifies and promotes the compatibility and interoperability of broadband wireless products based upon IEEE Standard 802.16. The WiMAX Forum's primary goal is to accelerate the adoption, deployment, and expansion of WiMAX, AeroMACS, and WiGRID technologies across the globe, while facilitating roaming agreements, sharing best practices within our membership and certifying products.

ZigBee Alliance
http://www.zigbee.org
Our innovative standards are custom-designed by industry experts to meet the specific market needs of businesses and consumers. These market leading standards give product manufacturers a straightforward way to help their customers gain greater control of, and even improve, everyday activities.

USEFUL WIRELESS REFERENCES

WIRELESS WORKING GROUPS

802.11 Working Group
The 802.11 Working Group is responsible for developing wireless LAN standards that provide the basis for Wi-Fi.
http://grouper.ieee.org/groups/802/11/

802.15 Working Group
The 802.15 Working Group is responsible for developing wireless PAN standards that provide the basis for Bluetooth and ZigBee.
http://www.ieee802.org/15/

802.16 Working Group
The 802.16 Working Group is responsible for developing wireless MAN standards that provide the basis for WiMAX.
http://grouper.ieee.org/groups/802/16/

Bluetooth SIG
The Bluetooth SIG is responsible for developing wireless PAN specifications.
https://www.bluetooth.com

Cellular Telecommunications and Internet Association (CTIA)
The CTIA represents cellular, personal communication services, mobile radio, and mobile satellite services over wireless WANs for service providers and manufacturers.
http://www.ctia.org

Federal Communications Commission (FCC)
The FCC provides regulatory for RF systems in the U.S.
https://www.fcc.gov

GSM Association
The GSM Association participates in the development of development of the GSM platform–holds the annual 3GSM World Congress.
http://www.gsmworld.com

Wi-Fi Alliance
The Wi-Fi Alliance develops wireless LAN (“Wi-Fi”) specifications based on IEEE 802.11 standards and provides compliance testing of Wi-Fi products.
http://www.wi-fi.org

WiMAX Forum
The WiMAX Forum develops wireless MAN standards based on IEEE 802.16 standards and provides compliance testing of WiMAX products.
http://wimaxforum.org

ZigBee Alliance
The ZigBee Alliance develops standards for low-power wireless monitoring and control products.
http://www.zigbee.org

USEFUL WEBSITES

ARRL RFI Information
http://www.arrl.org/radio-frequency-interference-rfi

Jim Brown has several very good articles on RFI, including: A Ham’s Guide to RFI, Ferrites, Baluns, and Audio Interfacing.
www.audiosystemsgroup.com

FCC
http://www.fcc.gov

FCC, Interference with Radio, TV and Telephone Signals
http://www.fcc.gov/guides/interference-defining-source

IWCE Urgent Communications
http://urgentcomm.com has multiple articles on RFI

Jackman, Robin, Measure Interference in Crowded Spectrum, Microwaves & RF Magazine, Sept. 2014.
https://www.mwrf.com/technologies/test-measurement-analyzers/article/21845885/measure-interference-in-crowded-spectrum

RFI Services (Marv Loftness) has some good information on RFI hunting techniques
www.rfiservices.com

TJ Nelson, Identifying Source of Radio Interference Around the Home, 10/2007
http://randombio.com/interference.html

USEFUL BOOKS

2019 Wireless & IoT EMC Guide
This guide was designed for anyone installing or managing wireless networks, or designing and installing systems in the communications and broadcast industry.
https://learn.interferencetechnology.com/2019-wireless-and-iot-emc-guide/

The RFI Book (3rd edition)
Gruber, Michael
ARRL, 2010.

AC Power Interference Handbook (2nd edition)
Loftness, Marv
Percival Publishing, 2001.

Transmitter Hunting: Radio Direction Finding Simplified
Moell, Joseph and Curlee, Thomas
TAB Books, 1987.

USEFUL WIRELESS REFERENCES

USEFUL BOOKS (CONTINUED)

Interference Handbook
Nelson, William
Radio Publications, 1981.

Electromagnetic Compatibility Engineering
Ott, Henry W.
John Wiley & Sons, 2009.

Platform Interference in Wireless Systems - Models, Measurement, and Mitigation
Slattery, Kevin, and Skinner, Harry
Newnes, 2008.

Spectrum and Network Measurements, (2nd Edition)
Witte, Robert
SciTech Publishing, 2014.

Radio Frequency Interference (RFI) Pocket Guide
Wyatt and Gruber
SciTech Publishing, 2015.

USEFUL FORMULAS AND REFERENCE TABLES

E-Field Levels versus Transmitter Pout			
Pout (W)	V/m at 1m	V/m at 3m	V/m at 10m
1	5.5	1.8	0.6
5	12.3	4.1	1.2
10	17.4	5.8	1.7
25	27.5	9.2	2.8
50	38.9	13.0	3.9
100	55.0	18.3	5.5
1,000	173.9	58.0	17.4

Assuming the antenna gain is numerically 1, or isotropic, and the measurement is in the far field and greater than 100 MHz.

Using Decibels (dB)
The decibel is always a ratio…

- Gain = P_{out}/P_{in}, where P = power
- Gain(dB) = $10\log(P_{out} / P_{in})$, where P = power
- Gain(dB) = $20\log(V_{out}/V_{in})$, where V = voltage
- Gain(dB) = $20\log(I_{out}/I_{in})$, where I = current

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
Multiplying power by a factor of 2 corresponds to a 3 dB increase in power. This also corresponds to a 6 dB increase in voltage or current.

Commonly Used Power Ratios (dB)		
Ratio	Power	Voltage or Current
0.1	-10 dB	-20 dB
0.2	-7.0 dB	-14.0 dB
0.3	-5.2 dB	-10.5 dB
0.5	-3.0 dB	-6.0 dB
1	0 dB	0 dB
2	3.0 dB	6.0 dB
3	4.8 dB	9.5 dB
5	7.0 dB	14.0 dB
7	8.5 dB	16.9 dB
8	9.0 dB	18.1 dB
9	9.5 dB	19.1 dB
10	10 dB	20 dB
20	13.0 dB	26.0 dB
30	14.8 dB	29.5 dB
50	17.0 dB	34.0 dB
100	20 dB	40 dB
1,000	30 dB	60 dB
1,000,000	60 dB	120 dB

Multiplying power by a factor of 10 corresponds to a 10 dB increase in power. Multiplying a voltage or current by 10 is a 20 dB increase. Dividing by a factor of 10 corresponds to a 10 dB reduction in power, or 20 dB for voltage and current.

USEFUL WIRELESS REFERENCES
(LINKS & WHITEPAPERS)

COMMON WIRELESS FREQUENCY BANDS (LINKS)

GSM Bands:
https://en.wikipedia.org/wiki/GSM_frequency_bands

UMTS Bands:
https://en.wikipedia.org/wiki/UMTS_frequency_bands

LTE Bands:
https://en.wikipedia.org/wiki/LTE_frequency_bands

MMDS:
https://en.wikipedia.org/wiki/Multichannel_Multipoint_Distribution_Service

V Band (40 to 75 GHz):
https://en.wikipedia.org/wiki/V_band

DECT and DECT 6.0 (wireless phones and baby monitors):
https://en.wikipedia.org/wiki/Digital_Enhanced_Cordless_Telecommunications

Comparison of wireless internet standards:
https://en.wikipedia.org/wiki/Comparison_of_mobile_phone_standards

Wi-Fi Protocols (From Intel):
http://www.intel.com/content/www/us/en/support/network-and-i-o/wireless-networking/000005725.html

LINKS TO MANUFACTURER'S WHITE PAPERS

VIDEO / Handheld Interference Hunting for Network Operators (Rohde & Schwarz):
https://www.rohde-schwarz.com/us/solutions/wireless-communications/gsm_gprs_edge_evo_vamos/webinars-videos/video-handheld-interference-hunting_229255.html

Interference Hunting With The R&S FSH (Rohde & Schwarz):
https://www.rohde-schwarz.com/us/applications/interference-hunting-with-r-s-fsh-application-note_56280-77764.html

Interference Hunting / Part 1 (Tektronix):
http://www.tek.com/blog/interference-hunting-part-1-4-get-insight-you-need-see-interference-crowded-spectrum

Interference Hunting / Part 2 (Tektronix):
https://in.tek.com/blog/interference-hunting-part-2-4-how-often-interference-happening

Interference Hunting / Part 3 (Tektronix):
http://www.tek.com/blog/interference-hunting-part-3-4-use-mask-search-automatically-discover-when-interference-happenin

Interference Hunting / Part 4 (Tektronix):
https://www.tek.com/blog/interference-hunting-part-4-4-storing-and-sharing-captures-interference-hunter%E2%80%99s-safety-net

PC BOARD DESIGN FOR WIRELESS PRODUCTS

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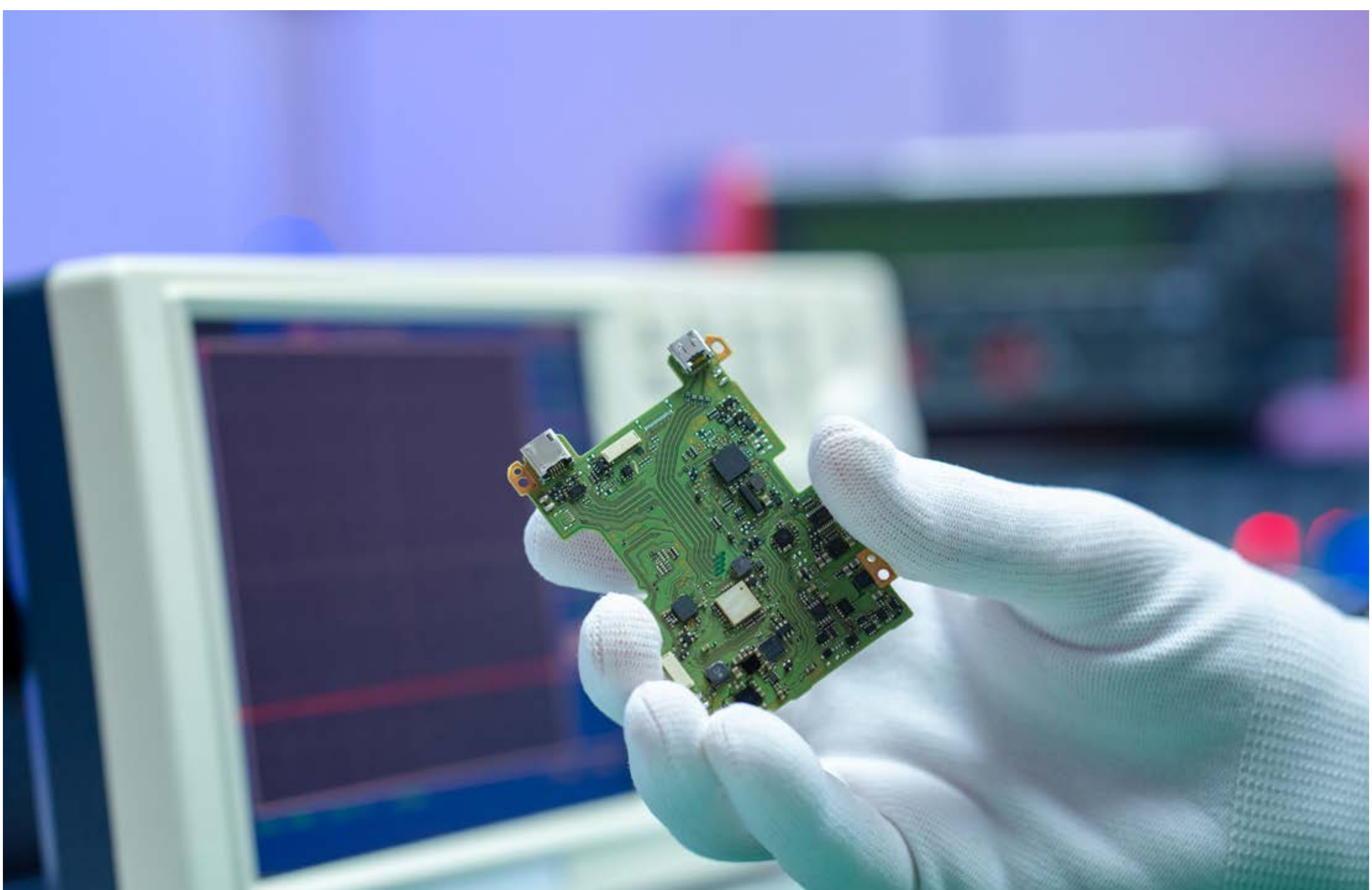


PC BOARD DESIGN FOR WIRELESS PRODUCTS

INTRODUCTION TO SELF-GENERATED EMI

It seems many manufacturers these days are developing products that incorporate wireless technologies–both in new and existing products. Many of these products are using LTE cellular connectivity and designers are finding that the on-board DC-DC converters and processor/memory bus noise are creating enough broadband electromagnetic interference (EMI) that the cellular receiver downlink channels are being desensed (decreased sensitivity) to a point where the product is non-compliant with the cellular provider's sensitivity requirements. Sometimes this broadband EMI even extends up to the GPS bands of 1575.42 MHz affecting navigational performance.

Cellular providers have strict receiver sensitivity requirements and the Total Isotropic Sensitivity (TIS) is one of the tests performed during CTIA compliance. If the receiver is not sensitive enough, the product will not be allowed onto the cellular system (*References 1* and *2*).

WHY PROPER PC BOARD DESIGN IS KEY

One factor that is always key to low-EMI designs is proper PC board design. If high-speed signals are not captured within transmission line structures, common mode current generation, EMI radiated leakage and crosstalk can result. Very often, I find clients use layer stack-up designs suggested in the 1990s for modern wireless designs of today and this is just asking for trouble, with associated schedule delays, debugging, and repeated compliance testing.

In order to understand why proper PC board design is a major key to success, let's first understand how high-peed signals move in circuit boards.

HOW SIGNALS MOVE IN PC BOARDS

I suspect many of us were taught in university or college that electric current was the flow of electrons in copper wires or circuit traces, and that signals travelled at near the speed of light. This is inaccurate. It was also unlikely we were taught much about how signals propagated in circuit board transmission lines during our fields and waves class.

Before you can understand how signals propagate in PC boards, you must first understand some physics (*References 3* and *4*).

This current flow is partially true, of course, for DC circuits (with exception of the initial battery connection transient). But for AC (or RF) circuits or for the switching transients from switch mode power supplies, we need to understand all connecting wires/traces must now be considered transmission lines.

First, let's consider how capacitors seemingly allow the "flow" of electrons. Referring to *Figure 1*, if we apply a battery to the capacitor, any positive charges applied to the top plate will repel positive charges on the bottom plate, leaving negative charges. If we apply an AC source to the capacitor, it might seem as if the current flows through the dielectric, which is impossible. James Clerk Maxwell called this "displacement current," where positive charges merely displace positive charges on the opposite plate leaving negative charges, and vice versa. This displacement current is defined as dE/dt (changing E-field with time).

Electrons and the positively-charged holes do not travel at near light speed in copper as was implied, but move at about 1 cm/sec, due to the very tight atomic bond of the copper molecules (*Reference 4*). There are certainly clouds of free electrons and holes, but these move slowly from molecule to molecule. This is called conduction current and is what we would measure with an ammeter. Conduction current is related to the tangential component of the B-field, that is the curl B = J.

The influence of one electron in the copper molecule to its neighbor (and on down the transmission line) propagates at the speed of the electromagnetic (EM) field in the dielectric material. In other words, jiggle one electron at one end of a microstrip and it jiggles the next, which jiggles the next, and so on, until it jiggles the last one at the load end of the

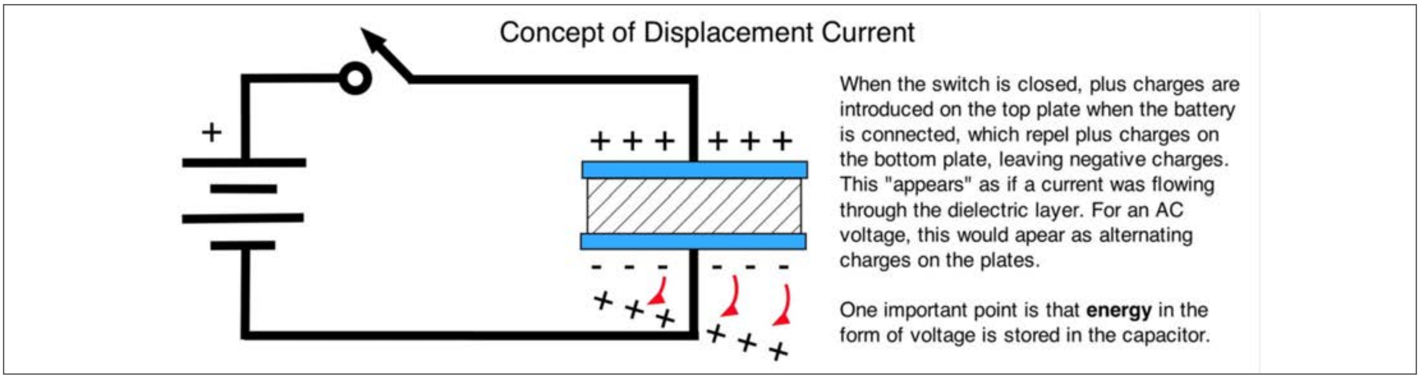


Figure 1: The concept of displacement current through a capacitor.

transmission line. This jiggling is called a kink in the E-field and can be envisioned as the Newton's Cradle toy, a mechanical analogy, where the first ball hits the next and this eventually pops off the end ball (*Figure 2*).

Figure 2: Newton's Cradle is a good analogy to EM field signal propagation in the dielectric of a circuit board.

Let's now consider a digital signal with a wave front moving at about half light speed (about 6 in/ns in FR4 dielectric) along a simple microstrip over an adjacent ground return plane (GRP) as illustrated in *Figure 3*.

The next important point is that the EM field of the digital signal travels in the dielectric space—not the copper. The copper merely "guides" the EM wave (*References 4* and *5*).

When the signal (EM wave) is first applied between the microstrip and GRP, it starts to propagate along the transmission line formed by the microstrip over an adjacent GRP. There is a combination of conduction current and displacement current (across the dielectric).

EMI harmonics originate at the wave front as the EM wave propagates. The fast rise or fall times of the signal contain all the harmonic energy and this is what creates the EMI.

If the load impedance is equal to the characteristic impedance of the transmission line, then there will be no reflections of the EM wave back to the source. However, if there is a mismatch, there will be reflected EM fields propagating back to the source. In reality, most realistic digital signals will have multiple reflections moving back and forth through the transmission line simultaneously. The transition zone (rise time or fall time) of these propagating waves will potentially produce EMI.

PHYSICS-BASED RULES FOR TRANSMISSION LINES

With a better understanding of how signals move in circuit boards, there are two very important principles when it comes to low EMI PC board design:

1. Every signal and power trace (or plane) on a PC board should be considered a transmission line.

2. Digital signal propagation in transmission lines is really the movement of electromagnetic fields in the space between the copper trace and GRP.

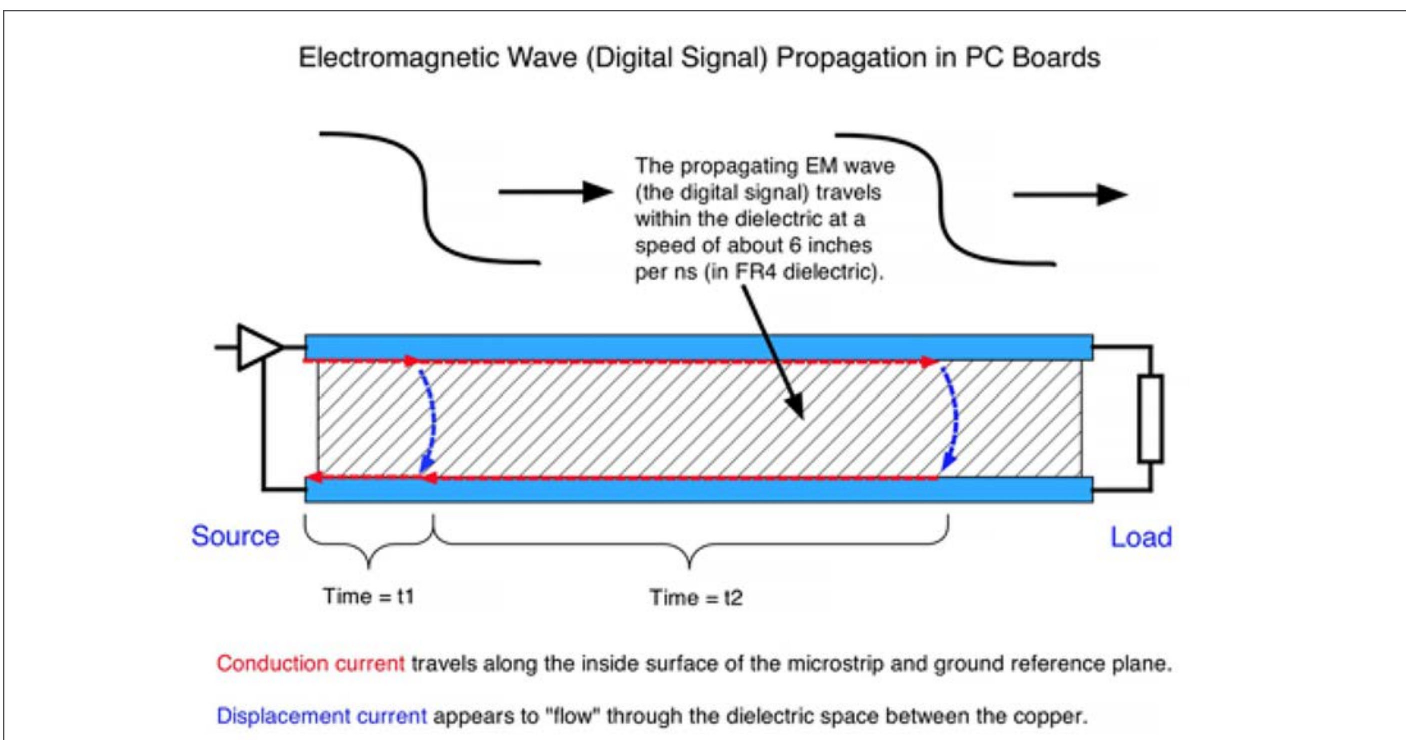


Figure 3: The digital signal (an electromagnetic wave) travels through the dielectric space between the microstrip and ground reference plane (GRP).

To construct a transmission line, you need two adjacent pieces of metal that capture or contain the field. Examples include a microstrip over an adjacent GRP or a stripline adjacent to a GRP or a power trace (or plane) adjacent to a GRP. Locating multiple signal layers between power and ground reference planes will lead to real EMI issues for fast signals.

IMPORTANT POINT #1–In other words, every signal or power trace (routed power) must have an adjacent GRP and all power planes should have an adjacent GRP. Many products end up violating these two rules, with resulting EMI issues.

IMPORTANT POINT #2–If you break the path of conduction current in the GRP through a gap or slot, we start to get "leakage" of the signal EM field throughout the dielectric space, which leads to edge radiation from the board and cross-coupling to other circuits through via-to-via coupling. This also occurs when we pass a signal through multiple ground reference or power planes if there is no nearby return path adjacent stitching via or stitching capacitor (to connect GRP to power planes). This self-generated EMI can easily conductively couple or radiate into sensitive cellular receivers. Please refer to the video demo explaining why gaps in the GRP are a disaster for EMI (*Reference 6*).

Via penetration: Very often, signals need to be run from the top side to the bottom side (or interior-to-interior layers), relying on vias to get there. If you only need to pass from one side of a GRP to the other, there's no issue, because the electromagnetic field of the signal is contained between a constant metallic transmission line along the entire path (*Figure 4*).

It's only when you need to pass through multiple planes that many designs fail to provide a continuous return path for the electromagnetic wave as it travels through the dielectric space of the board (*Figure 5*).

A lack of transmission-line continuity between the planes (using a stitching via or capacitor), will result in field leakage throughout the dielectric space as the signal tries to find a way back to the source. This field energy will couple to other vias, as well as propagate out as "edge radiation."

If the two planes are GRPs, then you need to merely stitch them together in at least one location near the signal via. This allows field propagation along the entire path. A matrix of ground vias is always a good practice and if they're located very close together (5 mm spacing is good), there's no need to specifically locate one at each penetration.

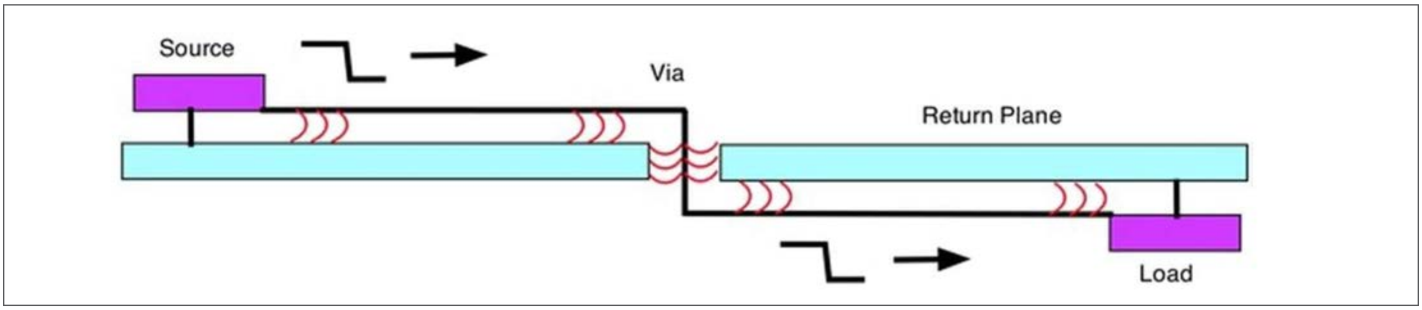


Figure 4: Passing a signal trace through a single GRP allows field propagation along the entire path. The dielectric layer is not shown for clarity and the field propagation is represented by the red "waves."

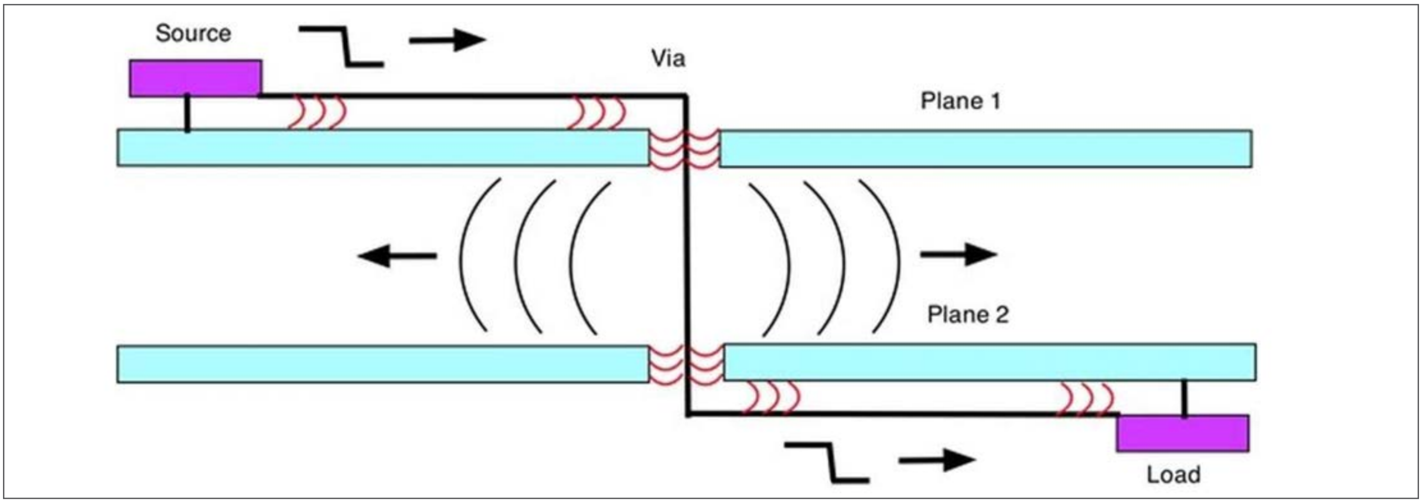


Figure 5: Passing a signal trace through two planes results in field leakage within the dielectric space, unless a defined path for return current is added. The dielectric layer is not shown for clarity and the field propagation is represented by the red "waves."

A challenge presents itself when the two planes are at different potentials, such as a GRP and power, then a stitching capacitor needs to be installed next to the signal via. If there are dozens of signal penetrations on such a board, it may be impractical to add a stitching capacitor for every signal penetration, so that's one reason to locate an even distribution of decoupling/stitching capacitors throughout the board. This will also help reduce "ground bounce" or simultaneous switching noise (SSN).

PROPER BOARD STACK-UP FOR LOW EMI

Observing these two important rules will dictate the layer stack-up. Following are some good and not so good EMI designs. More information on this topic may be found in *References 7* and *8*.

FOUR-LAYER BOARD: POOR (BUT TYPICAL) EXAMPLE

A typical four-layer board design I see often is (top to bottom): Signal–Ground Return Plane–Power Plane–Signal. This worked OK decades ago with relatively slow clock and signal frequencies, but is just asking for EMI issues in today's high frequency wireless technology. Let's show a couple four-layer examples that follow the rules. Note the lack of power planes.

FOUR-LAYER BOARD: GOOD DESIGN 1

Here is an example of a good four-layer board stack-up for improved EMI (*Figure 6*). Instead of a power plane, we use either routed or poured power, along with signals on layers 2 and 3. Thus, each signal/power trace is adjacent to a GRP. Also, it's easy to run simple vias between all layers, so long as the two GRPs are also connected together with a matrix of stitching vias. If you run a row of stitching vias along the perimeter (say, every 5 mm) you form a Faraday cage. This is an excellent option for critical wireless products.

FOUR-LAYER BOARD: GOOD DESIGN 2

If, on the other hand, you'd prefer to have access to the signal and routed/poured power traces, you may simply reverse the layer pairs, such that the two GRP layers are in the middle and the two signal layers are positioned at the top and bottom, with routed power and sufficient decoupling caps, rather than a power plane (*Figure 7*).

For both four-layer designs, you want to run a 5-mm matrix pattern of stitching vias connecting the two GRPs.

For routed or poured power, every digital device will need 2-3 decoupling capacitors per power pin, or tight groupings

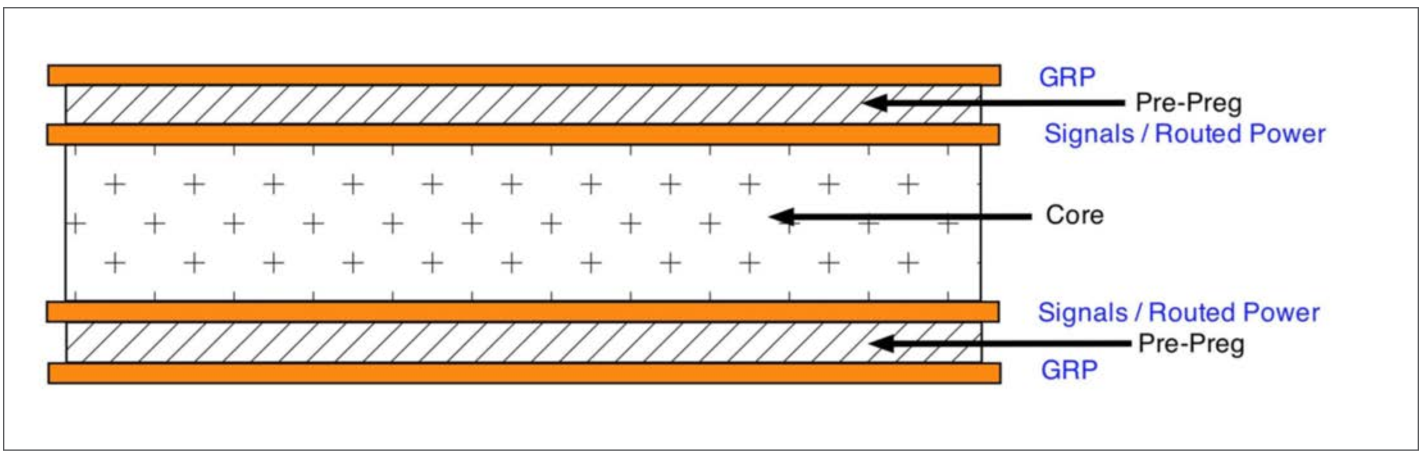


Figure 6: This good four-layer board stack-up for improved EMI keeps the signals and routed power near the ground reference planes.

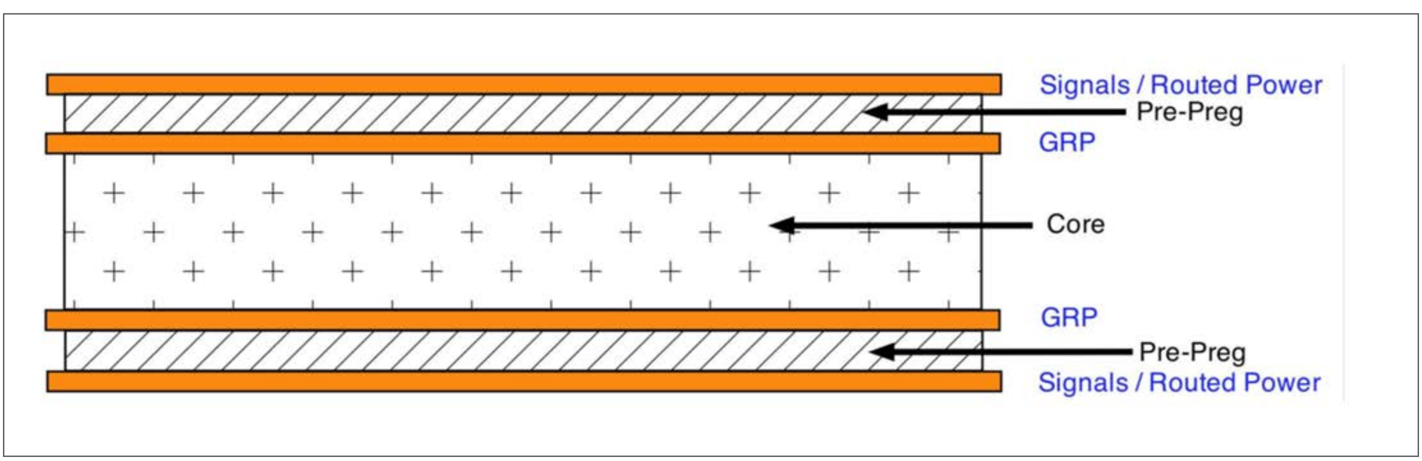
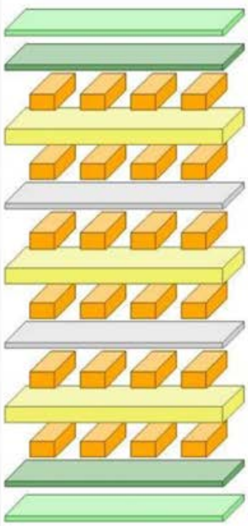


Figure 7: This good four-layer board stack-up for improved EMI places the ground reference planes inside the board.



Layer Name	Type	Material	Thickness (mil)	Dielectric Material	Dielectric Constant
Top Overlay	Overlay				
Top Solder	Solder Mask/Coverlay	Surface Material	0.4	Solder ...	3.5
Top Layer	Signal	Copper	1.4		
Dielectric	Dielectric	Core	7	FR-4	4.2
GND	Signal Gnd	Copper	1.4		
Dielectric 3	Dielectric	Prepreg	15	FR-4	4.2
Signal Layer 1	Signal	Copper	1.4		
Dielectric 5	Dielectric	Core	10	FR-4	4.2
Signal Layer 2	Signal	Copper	1.4		
Dielectric 4	Dielectric	Prepreg	15	FR-4	4.2
Power	Signal Power	Copper	1.4		
Dielectric 1	Dielectric	Core	7	FR-4	4.2
Bottom Layer	Signal	Copper	1.4		
Bottom Solder	Solder Mask/Coverlay	Surface Material	0.4	Solder ...	3.5
Bottom Overlay	Overlay				

Figure 8: A very common, but poor, EMI six-layer stack-up design.

of pins. In addition, rails (typically the main digital voltages) should have wider pours around any high di/dt devices, such as core voltage, drivers, ASICs, motor controllers, processors, etc. This will help serve as your high frequency decoupling.

TYPICAL SIX-LAYER DESIGN: POOR EXAMPLE

One stack-up I frequently see is this six-layer design (*Figure 8*). This probably worked well enough in the a decade or two ago, but like the poor four-layer design, is recipe for EMI disaster. There are two issues with this: the bottom two signal layers are referenced to the power plane and the power and ground return planes are non-adjacent and too far apart for best EMI decoupling.

With few exceptions (some DDR RAM power and signals, for example) currents want to return to their sources, which are referenced to the GRP. Referencing these signals to the power plane is very EMI-risky, because there is no clearly defined return path, except through plane-to-plane capacitance, which in this case, is relatively small. In addition, the indefinite return path can result in field leakage into other areas of the board's dielectric layers. That, in turn, leads to cross-coupling into wireless receivers and other circuitry and radiated EMI.

The second issue occurs when we have the power and GRP separated by two signal layers. Any power distribution network (PDN) transients will cross-couple to any signal traces on layers 3 and 4 within the dielectric layers. You also lose any plane-to-plane capacitance decoupling benefit if these planes are separated by more than 3-4 mils.

EIGHT-LAYER BOARD (GOOD EXAMPLE)

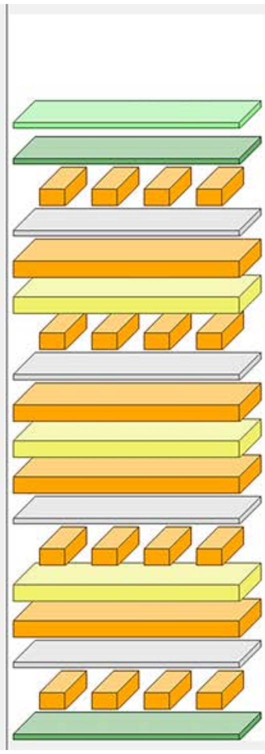
Both the four- and eight-layer board design examples (*Figures 6, 7,* and *9)* follow the two fundamental rules (IMPORTANT POINT #1) that preserve good transmission line design and resulting low EMI. In addition, for the eight-layer design, the power and GRP planes are now 4 mils apart, providing good plane-to-plane capacitance. Closer spacing would be even better. For example, a spacing of 1 mil to 3 mils is ideal for minimizing EMI. Multiple GRPs should be stitched together with a 5-mm matrix pattern of vias.

Of course, there are many more iterations on creating proper transmission line pairs between signal and GRP or power and GRP.

PARTITIONING OF CIRCUIT FUNCTIONS

The next most important consideration when laying out the circuitry for your wireless board is partitioning of circuit functions, such as digital, analog, power conversion, RF, and motor control or other high-power circuits.

To avoid signal coupling and crosstalk, you must not allow the various return signals from intermixing within the same dielectric space. Thus, you need to partition major circuit functions. *Figure 10* demonstrates one example of partitioning. Of course, this gets more challenging as board size shrinks. Henry Ott also describes this concept in *Reference 9*.



Layer Name	Type	Material	Thickness (mil)	Dielectric Material	Dielectric Constant
TOP SILK	Overlay				
TOP MASK	Solder Mask/Cover	Surface Material	0.04	Solder ...	3.5
Top	Signal	Copper	1.417		
Dielectric1	Dielectric	Prepreg	5	FR-4	4.2
Layer02	Internal Plane Gnd	Copper	0.7		
Dielectric 10	Dielectric	Core	10		4.2
Layer03	Signal	Copper	0.7		
Dielectric 5	Dielectric	Prepreg	10		4.2
Layer04	Internal Plane Gnd	Copper	0.7		
Dielectric 3	Dielectric	Core	4		4.2
Layer05	Internal Plane Pwr	Copper	0.7		
Dielectric 2	Dielectric	Prepreg	10		4.2
Layer06	Signal	Copper	0.7		
Dielectric 8	Dielectric	Core	10		4.2
Layer07	Internal Plane Gnd	Copper	0.7		
Dielectric 9	Dielectric	Prepreg	5		4.2
Bottom	Signal	Copper	1.417		
BOT MASK	Solder Mask/Cover	Surface Material	0.04	Solder ...	3.5

Figure 9: A good EMI stack-up design (8-layer example). All signal layers are referenced to an adjacent GRP, while power is also referenced to an adjacent GRP.

Another way to separate noisy circuits, such as digital and power conversion, from analog and RF circuitry is to locate the digital on the bottom side of the stack-up and the analog and RF modules on the top side. For practical applications, this often assumes at least an eight layer design with one, or more, GRPs near the middle to isolate the top and bottom sides. Great care must be taken to avoid coupling noisy circuitry with sensitive receivers, in the case of wireless designs.

Because low frequency (less than 50 kHz) or audio signal return currents tend to spread out more, that circuitry must be separated from digital, power conversion, or motor controller circuits. Likewise, sensitive RF receiver circuits, such as GPS, cellular, or Wi-Fi devices must also be kept separate from noisy digital, power conversion, or motor controller circuitry.

While *Figure 10* implies routed power, it is very common to use 3.3 V power planes under the digital circuitry for good EMI suppression. Power can also be routed as polygons under the appropriate circuit sections.

ADDITIONAL TIPS

Multiple ground vias: It's a good practice to create a matrix of ground vias connecting GRPs together using a spacing of about 5-mm. This will provide multiple return paths for signals penetrating more than one GRP layer. In addition, if you use multiple GRPs, you should design via stitching all around the periphery of the board to create a Faraday cage for those signal layers in between. This technique is especially useful when incorporating wireless technology in the design.

Ground fills: While it seems to be a fairly common practice to fill in unused areas within each layer with ground fills, besides being unnecessary, they can lead to the issue of the "trace crossing a gap in the return" problem for dense boards where all the transmission line rules may be difficult to achieve. Eric Bogatin explains this a bit more in *Reference 10*.

Routed power versus power planes: The conventional method is to start with one or more (depending on the number of layers) power-ground "cores" and build the signal layers from there, usually equally on each side of the core for best manufacturability. Typically, digital ground return is used for this. Another big advantage is that when spaced very close together (less than 3 mils), the power-ground core becomes a good high-frequency decoupling capacitor. As the number of layers increase, it's often best to locate two or more power-ground cores closer to the top and bottom of the stack-up–generally on layers 2-3 and 6-7 (on eight-layer boards, for example).

CONCLUSION

Most wireless products, especially smaller portable/mobile devices, now require greater care in their overall system

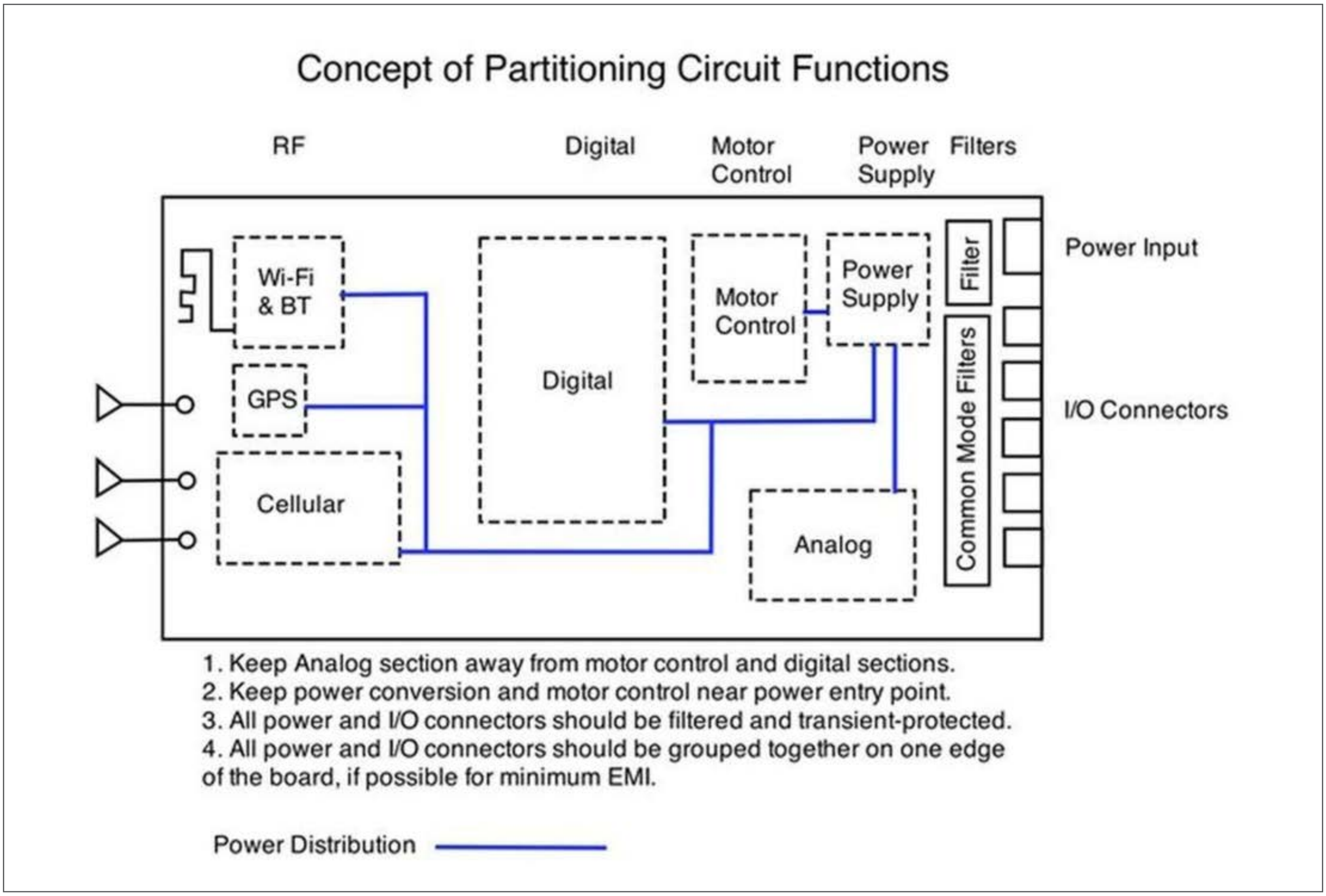


Figure 10: An example of how to partition circuit functions on a board.

design. An important key to low EMI and consequently, optimum performance, is the design of the PC board. You can largely "throw out" the layout rules used in past years, because at the clock and signal speeds used today, all copper traces become transmission lines and require more care to avoid gaps in the signal path where the electromagnetic wave can "leak out" and couple to sensitive circuits.

The important points to remember are that all signal and power networks should now be considered as transmission lines, the signals and power transients travel at about half light speed within the dielectric space, the copper traces "guide" the signals along the GRP, and circuit functions need to be partitioned across the board real estate in order to reduce coupling. Maintaining these guidelines will help assure the lowest EMI and best performing wireless designs.

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IDENTIFYING AND LOCATING RADIO FREQUENCY INTERFERENCE (RFI)

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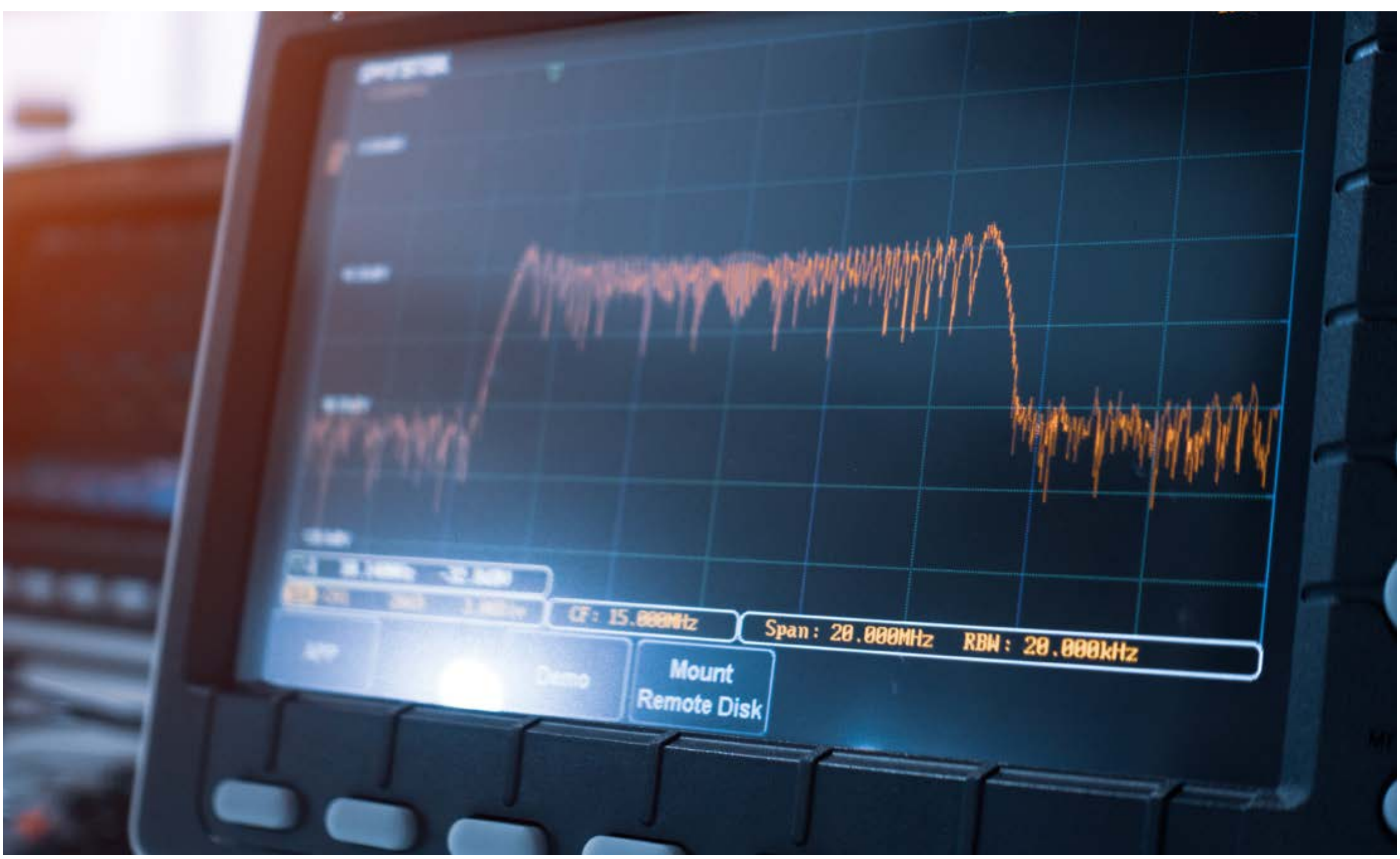
Introduction

With the plethora of wireless devices, increasing broadcast, communications, and other RF sources all competing for radio spectrum, the chances of radio frequency interference (RFI) will only increase. This article explains how to identify, characterize, and locate typical interfering sources.



IDENTIFYING AND LOCATING RADIO FREQUENCY INTERFERENCE (RFI)

CATEGORIES OF INTERFERENCE

There are two broad categories of interference; narrow band and broadband (*Figure 1*).

Narrow Band–this would include continuous wave (CW) or modulated CW signals. Examples might include clock harmonics from digital devices, co-channel transmissions, adjacent-channel transmissions, intermodulation products, etc. On a spectrum analyzer, this would appear to be narrow vertical lines or slightly wider modulated vertical bands associated with specific frequencies.

Broadband–this would primarily include switch-mode power supply harmonics, arcing in overhead power lines (power line noise), wireless digitally-modulated systems (such as Wi-Fi or Bluetooth), or digital television. On a spectrum analyzer, this would appear to be broad ranges of signals or an increase in the noise floor. Power line noise or switch-mode power supplies are the most common sources.

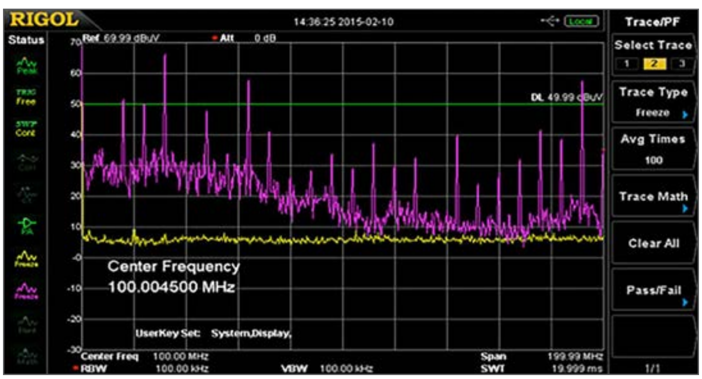


Figure 1: An example spectral plot from 9 kHz to 200 MHz of narrow band harmonics (vertical spikes) riding on top of broadband interference (broad area of increased noise floor). The yellow trace is the baseline system noise.

TYPES OF INTERFERENCE

Some of the most common types of interference are described below.

Co-Channel Interference–more than one transmitter (or digital harmonic) using, or falling into, the same receive channel.

Adjacent-Channel Interference–a transmitter operating on an adjacent frequency whose energy spills over into the desired receive channel.

Intermodulation-Based Interference–occurs when energy from two, or more, transmitters mix together to produce spurious frequencies that land in the desired receive channel. Third-order mixing products are the most common and usually, this occurs from nearby transmitters. An example of potential intermodulation might occur in a strong signal area for FM broadcast.

Fundamental Receiver Overload–this is normally caused by a strong, nearby, transmitter simply overloading the receiver front-end or other circuitry, causing interference or even suppression of the normal received signal. A common example is VHF paging transmitters interfering with receivers.

Power Line Noise (PLN)–This is a relatively common broadband interference problem that is typically caused by arcing on electric power lines and associated utility hardware. It sounds like a harsh raspy buzz in an AM receiver. The interference can extend from very low frequencies below the AM broadcast band, and depending on proximity to the source, into the HF spectrum. If close enough to the source, it can extend up through the UHF spectrum.

Switch-Mode Power Supplies–Switch-mode power supplies are very common and are used for a variety of consumer or commercial products and are a common source of broadband interference. Lighting devices, such as the newer LED-based lights or commercial agricultural "grow" lights, are another strong source of interference.

Other Transmitters–There are several transmitter types that commonly cause RFI:

- **Two-Way or Land Mobile Radio**–Strong interfering FM signals may result in "capture effect", or over-riding of the desired received signal.
- **Paging Transmitters**–Paging transmitters are generally very powerful FM or digitally modulated transmissions that can overload receiver Digital paging will sound very raspy, like a power saw or buzzing, and may interfere with a wide range of receive frequencies. Fortunately, most of the VHF paging transmitters moved to the 929/931 MHz frequency pairs, so this is not the issue it once was.
- **Broadcast Transmitters**–Broadcast transmitter interference will have modulation characteristics similar to their broadcasts–AM, FM, video carriers, or digital signals.

Cable Television–Signal leakage from cable television systems will generally occur on their prescribed channel assignments. Many of these channels overlap existing over-the-air radio communications channels. If the leaking signal is a digital channel, interference will be similar to wideband noise (a digital cable channel is almost 6 MHz wide).

Wireless Network Interference–Interference to wireless networks (Wi-Fi, Bluetooth, etc.) is increasingly common, and with the proliferation of mobile, household (IoT), and medical devices incorporating Wi-Fi and other wireless modes, this issue is likely to get worse. More details on wireless interference will be found in the companion article, Wireless Network Interference and Optimization.

LOCATING RFI

SIMPLE DIRECTION FINDING (DFING)

DF Techniques–There are two primary methods for DFing.

(1) "Pan 'N Scan" where you "pan" a directional antenna and "scan" for the interfering signal, recording the direction on a map, while keeping note of intersecting lines. (2) "Hot and Cold" where an omni-directional antenna is used while watching the signal strength. In this method, the rule of thumb is for every 6 dB change you've either doubled or halved the distance to the interfering source. For example, if the signal strength was -30 dBm at one mile from the source, traveling to within a half-mile should read about -24 dBm on the spectrum analyzer.

DF Systems–Radio direction-finding (RDFing) equipment can be installed into a vehicle or used portable. For vehicular use, there are several automated Doppler direction-finding systems available. Some examples include:

- Antenna Authority (mobile, fixed and portable) www.antennaauthorityinc.com
- Doppler Systems (mobile and fixed) www.dopsys.com
- Rohde & Schwarz (mobile, fixed, and portable) http://www.rohde-schwarz.com

Step Attenuator–You'll also find a step attenuator quite valuable during theprocess of DFing. This allows control over the signal strength indication (and receiver overload) as you approach the interference source. The best models come in steps of 10 dB and have a range of at least 80 dB, or more. Step attenuators may be purchased through electronics distributors, such as DigiKey, etc. Commercial sources would include Narda Microwave, Fairview Microwave, Arrow, and others.

LOCATING POWER LINE INTERFERENCE

For Low Frequency Interference–particularly power line noise (PLN)–the interference path can include radiation due to conducted emissions along power lines. Therefore, when using the "Hot and Cold" method you'll need to be mindful that the radiated noise will generally follow the route of the power lines, peaking and dipping along the route. The maximum peak usually indicates the actual noise source. As a complication, there may be several noise sources–some possibly long distances away.

Antennas–For simply listening to power line noise, the built-in "loopstick" antenna on an AM broadcast band radio or telescoping antenna on a shortwave radio may work well. However, for tracking down power line noise to the source pole, and typically for DFing other interfering sources, you'll want to use higher frequencies. A simple directional Yagi, such as the Arrow II 146-4BP (*Figure 17*) with three piece boom (www.arrowantennas.com) can be assembled quickly and attached to a short length of pipe and works well to receive this type of broadband RFI.

Use of VHF Receivers–Whenever possible, you'll generally want to use VHF or higher frequencies for DFing. The shorter wavelengths not only help in pinpointing the source, they also make smaller handheld antennas more practical.

Signature Analyzers–These are time-domain interference-locating instruments that produce a distinct "signature" of an interfering signal. This would include instruments produced by Radar Engineers (*Figure 2*). They are the best solution for tracking down power line noise and consumer devices that produce repetitive noise bursts with known periodicity.

Figure 2: A signature analyzer from Radar Engineers that tunes from 500 kHz to 1 GHz and which displays an electronic "signature" of a specific interference source. Receivers such as this are used by professional investigators to track down power line noise. (Image Source: Radar Engineers).

LOCATING NARROW BAND INTERFERENCE

For most narrow band interference sources, such as co-channel, adjacent channel, and intermodulation interference, the recommended tool is the spectrum analyzer, as this allows you to focus on particular frequency channels or bands and see the big picture of what's occurring. Once the interfering signal is identified, the analyzer can then be used to DF the signal.

USING SPECTRUM ANALYZERS

Spectrum analyzers display frequency versus amplitude of RF signals. They can be helpful in determining the type and frequencies of interfering signals, especially for narrow band interference. There are two types of analyzers; swept-tuned and real time.

Swept-tuned analyzers are based on a superheterodyne principle using a tunable local oscillator and can display a desired bandwidth from start to stop frequencies. They are useful for displaying constant, or near constant, signals, but have trouble capturing brief intermittent signals, due to the lengthy sweep time.

A real-time analyzer samples a portion of the spectrum using digital signal processing techniques to analyze the captured spectrum. They are able to capture brief intermittent signals and are ideal for identifying and locating signals that may not even show up on swept analyzers. Most real-time bandwidths are limited to 27 to 500 MHz, maximum. The Signal Hound BB60C and Tektronix RSA306 are both relatively inexpensive real-time spectrum analyzers that are USB-powered and use a PC for control and display.

One important point to keep in mind regarding the use of spectrum analyzers is that because they have an un-tuned front end, they are particularly susceptible to high-powered nearby transmitters off frequency from where you may be looking. This can create internal intermodulation products (spurious responses) or erroneous amplitude measurements that are very misleading. When using spectrum analyzers in an "RF rich" environment, it's important to use bandpass filters or tuned cavities (duplexers, for example) at the frequency of interest.

Spectrum analyzers are also useful to characterize commercial broadcast, wireless, and land mobile communications systems. For wireless or intermittent interference, real-time analyzers work best. If used for tracking PLN, it's best to place the analyzer in "zero-span" mode to observe the amplitude variation. Placing the analyzer in "Line Sync" may also be helpful.

COMMERCIAL INTERFERENCE HUNTING SYSTEMS

There are several manufacturers of interference hunting or direction-finding systems. I'd like to describe four of these, Aaronia, Narda, Rhode & Schwarz, and Tektronix. As mentioned previously, for intermittent interference (particularly for commercial communications installations) or digitally-modulated signals, a real-time spectrum analyzer is the best tool and has the ability to capture brief, intermittent, signals; some as short as a few microseconds. Examples might include the Aaronia Spectran V5 series. Tektronix RSA-series, or Narda IDA2.

Aaronia–Aaronia not only has the lightest portable system for Dfing, but the biggest and heaviest-looking. Their Spectran V5 Handheld is the smallest real time analyzer. Mapping is not an option on this model, but the larger Spectran V5 XFR PRO is a ruggedized laptop that can use open-source maps and has triangulation features. Aaronia also has a variety of affordable directional antennas and a combination GPS/compass may be mounted on some models.

Figure 3: The Aaronia Spectran V5 handheld real-time analyzer is the smallest self-contained unit and tunes from 9 kHz to 6 GHz. Other models have upper frequencies of 12 and 18 GHz.

Aaronia is also unique in that they've developed a drone detection system comprised of a 3D tracking antenna, the model IsoLOG 3D with options from 9 kHz to 40 GHz in 360 degrees. This matches up with their Spectran Command Center with triple LCD screens. See the references for more information on that system.

Figure 4: The Aaronia Spectran V5 XFR PRO in the field portable configuration.

Figure 5: The Narda IDA2 spectrum analyzer and interference hunting system. The frequency range is 9 kHz to 6 GHz. Image Source: Narda STS.

Narda Safety Test Solutions–Narda has a similar interference analyzer, the Model IDA2 with a real-time bandwidth of 32 MHz and frequency range of 9 kHz to 6 GHz. There are a variety of directional antennas available with built-in GPS and compass. This system also relies on open-source mapping tools, such as Open Street Maps (http://www.openstreetmaps.org). It is battery-operated for easy portable use.

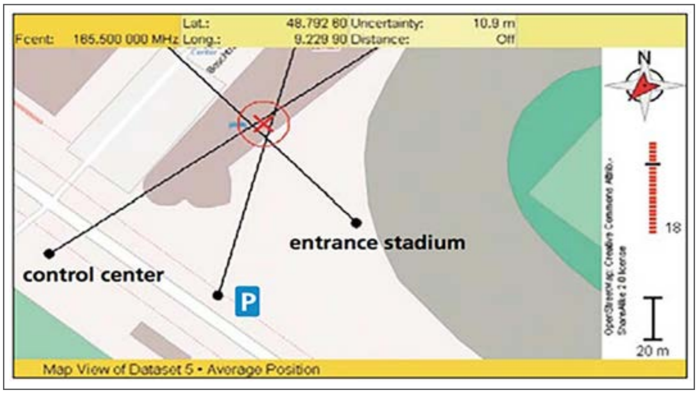


Figure 6: The mapping software with bearing lines drawn showing triangulation of an interference source. Image Source: Narda STS.

Rohde & Schwarz–Rohde & Schwarz has a portable system (*Figure 7*) that can quickly identify most interference sources and can also use imported mapping feature and GPS/compass in the antenna to triangulate the interfering source. Several fixed, mobile, or portable antennas are available for different frequency bands. This system also relies on open-source mapping tools, such as Open Street Maps (http://www.openstreetmaps.org). It is battery-operated for easy portable use.

Figure 7: The Rohde & Schwarz R&S®PR100 custom spectrum analyzer with mapping and triangulation and R&S®HE300 antenna. The R&S® FSH analyzer may also be used. Image Source: Rohde & Schwarz.

Tektronix–Tektronix also has a means of Dfing and mapping with their real time DSA-series spectrum analyzers. The USB-controlled RSA507A is noteworthy due to it's built-in battery and portable capability. It also offers 40 MHz real-time bandwidth. By connecting it to a tablet PC, such as the Panasonic Toughpad model FG-Z1 and with the Alaris DR-A0047 antenna, you have a self-contained portable DF hunting tool (*Figure 9*). This system also relies on open-source mapping tools, such as Open Street Maps (http://www.openstreetmaps.org).

Figure 8: The mapping application for the R&S® FSH analyzer. Image Source: Rohde & Schwarz.

Figure 9: The Tektronix spectrum analyzer with mapping/triangulation and Alaris DR-A0047 antenna. Image Source: Tektronix.

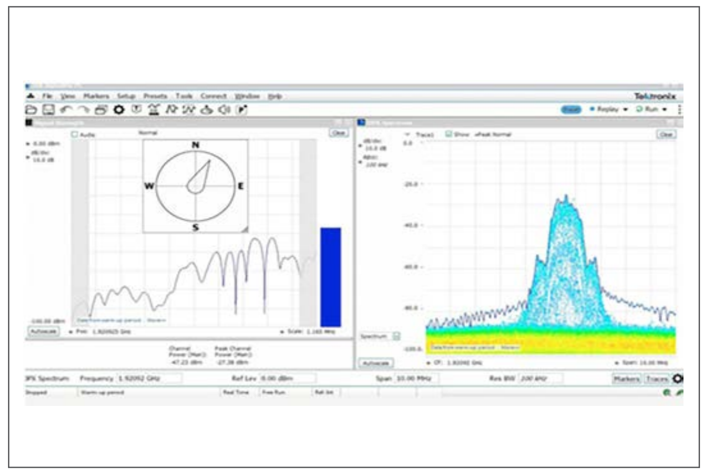


Figure 10: When the SignalVu-PC software with mapping option is connected to one of their RSA-series real time spectrum analyzers and Alaris directional antenna, the compass direction is automatically shown, along with the spectral display of the signal in question. Image Source: Tektronix.

Tektronix provides their SignalVu-PC with Mapping option to help identify and capture interfering signals. The mapping option allows bearing lines to be marked on the map to triangulate the source of interference.

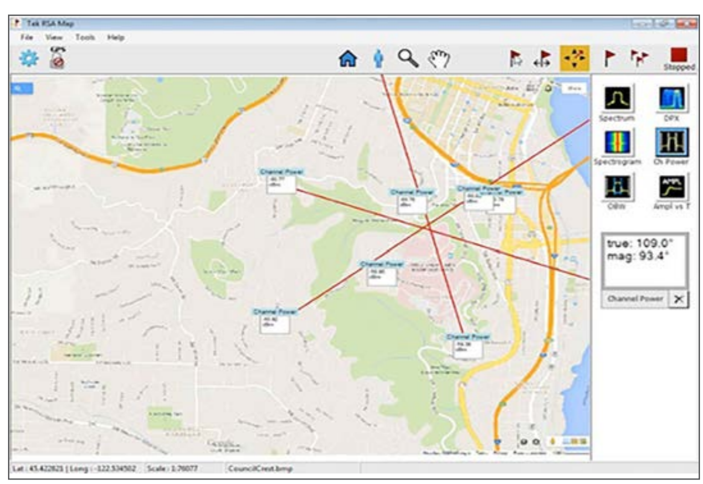


Figure 11: Flipping over to the mapping option of SignalVu-PC, allows you to record bearing lines to the interfering source, with the triangulation showing the approximate location of the source. Image Source: Tektronix.

SUMMARY

With today's increasing use of wireless devices, broadcast, communications, military and other RF sources all competing for radio spectrum, the chances of radio frequency interference (RFI) will only increase. With the proper tools, broadcast and communications engineers are able to quickly identify and eliminate sources of interference as they are detected. The latest real-time spectrum analyzers make the job even more efficient.

MANUFACTURERS MENTIONED

- Aaronia AG http://www.aaronia.com
- Narda Safety Test Solutions https://www.narda-sts.com/en/
- Radar Engineers http://www.radarengineers.com
- Rohde & Schwarz https://www.rohde-schwarz.com/us/home_48230.html
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COST EFFECTIVELY ENSURE ELECTROMAGNETIC COMPATIBILITY IN THE AGE OF IoT

Matthew Maxwell
Rohde & Schwarz

Wireless/RF is ubiquitous, so implement a pre-compliance regimen with off-the-shelf equipment.

COST-EFFECTIVELY ENSURE ELECTROMAGNETIC COMPATIBILITY IN THE AGE OF IOT

Every electronic product has to go through full electromagnetic compatibility (EMC) testing to get the much-coveted stamp of approval from the various regulatory bodies. This has traditionally been a costly undertaking with multiple trips to a distant testing facility, with multiple reworks required to get final approval. In the age of the Internet of Things (IoT), this is not the way to go about it. There is a better approach.

The IoT has changed everything, with wirelessly connected devices creating the opportunity to gather data to perform analytics in order to improve device usability for consumers. For industry, IoT-enabled analytics are improving process, safety, and production outcomes for manufacturing facilities, while opening the possibility of new business models. However, for electronic system and consumer product designers, it has created a number of headaches; some obvious, some more subtle and insidious.

To start with, there's the ubiquitous demand for wireless connectivity, whether it be Wi-Fi, Bluetooth, Zigbee, cellular, or the various flavors of long-range, low-power options such as LoRaWAN, Sigfox, Narrowband-IoT (NB-IoT) or LTE Cat 1. It's common to have multiple RF interfaces in the same device. This is great for users, but is a nightmare for designers, many of whom are not RF experts. They may have mastered the art of ensuring power supplies no longer interfere with digital circuits, but wireless connectivity adds a whole new dimension of difficulty. From the antenna placement and routing, to the design of high-frequency circuits from 900 MHz to 5 GHz, the difficulties have affected many product delivery schedules, and the problem is only going to get worse with 5G emerging with millimeter-wave operation at 28 GHz and up.

Brave designers will "roll their own" RF circuits, but these tend to be large design teams with high-volume expectations. It seems easy enough, get a good RF integrated circuit (IC) from a reputable vendor, put some shielding around it, place and route the antenna wire, and they're off and running. Maybe. However, a few trends have altered the design landscape and have forced designers to rethink their approach.

The primary influences on designs are smaller form factors, higher integration, and electronic component density per inch squared of printed circuit board (PCB) space, system complexity, higher clock speeds, multiple and distributed power rails with fast-switching transients, LCD emissions as displays get integrated into IoT devices, and faster data

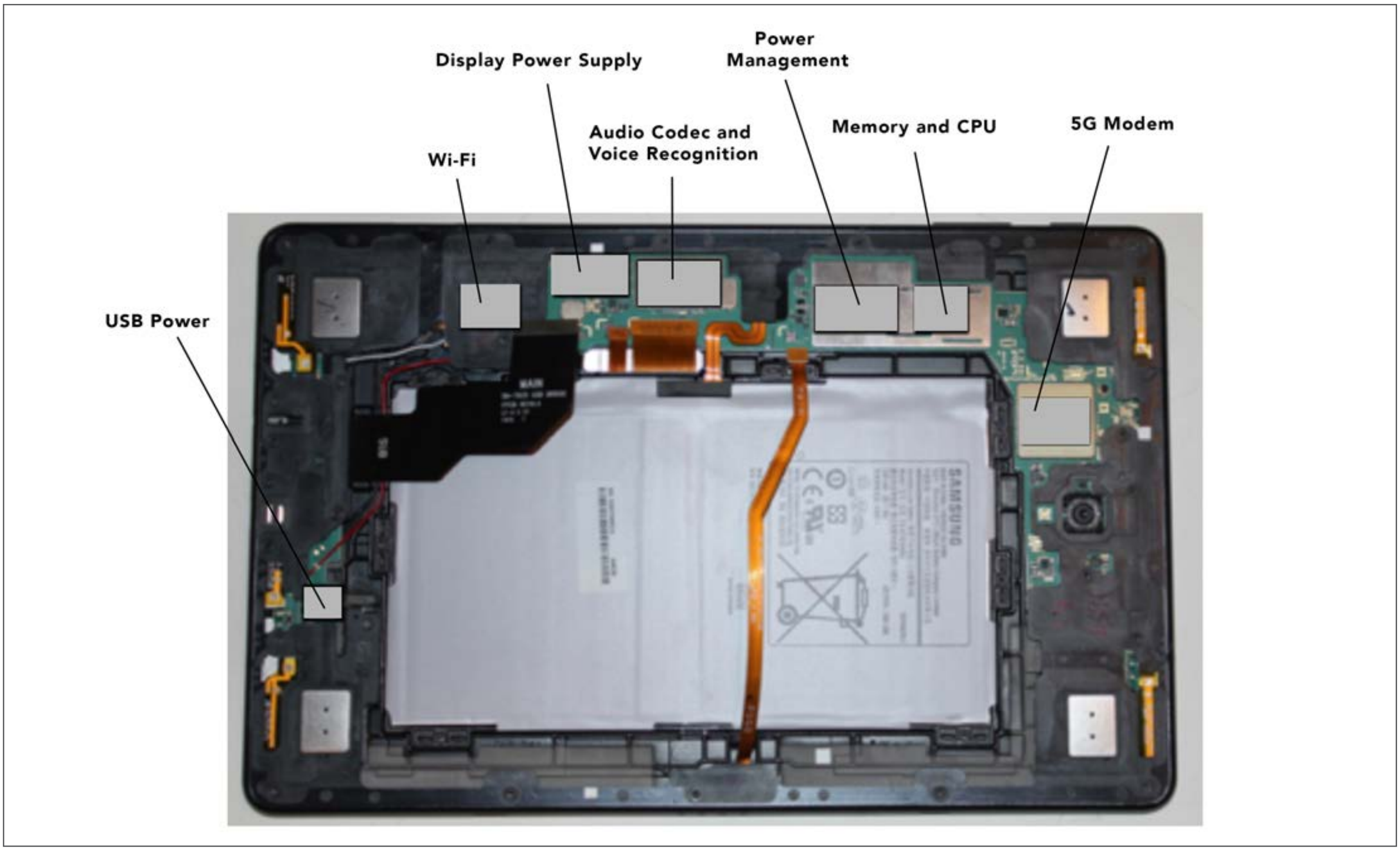


Figure 1: It used to be sufficient to shield a couple of key circuits, but the designers of the Samsung Tab S4 tablet shielded literally every circuit to ensure maximum EMC. The four rectangular silver elements on the corners are speakers, not circuits. (Image Source: Rohde & Schwarz)

transfer rates between central processing unit (CPU) and memory. These are the obvious and classic trends that create interesting challenges that designers actually enjoy solving, though time-to-market pressures and shrinking budgets can be a kill-joy for some, or an added challenge for others.

However, as mentioned, there are two more subtle trends, and these are the ones that are actually causing the most headaches, and the most opportunity for differentiation through innovative approaches to expediting the route to ensuring system EMC.

These trends, which are a direct result of the IoT, are the need to combine power supplies, high-performance digital circuits, and RF interfaces in compact form factors for products that are falling rapidly in price. So much so, that the complexity-to-price ratio is becoming untenable for high-quality, low-cost, smart-home-based systems that are the sweet-spot for IoT devices. Even mobile phone and tablet manufacturers, which have typically been able to charge a premium for higher margins, are getting squeezed as complexity increases and form factors shrink.

To address EMC and its associated electromagnetic interference (EMI) issues, it used to be sufficient to place shielding around key components, such as the RF circuits, to reduce their susceptibility to interference from high-speed digital clock and signal switching harmonics, and to prevent them from being an interferer. However, as density and complexity has increased, it's now not uncommon to shield literally everything, as in the case of the Samsung Tab S4, *Figure 1*.

The Tab S4 is an extreme example of cutting-edge consumer-level design in terms of density, performance, and complexity, with a price to match ($649). However, most designs in the IoT space, from white goods and audio streaming systems with built-in voice assistants, to wearables, cost much less, forcing designers to find ways to lower development and test costs.

ACCELERATING EMC TESTING–WHILE LOWERING COST

It's possible to accelerate the design and test cycle when using power-supply and RF modules. These come pre-certified and do save time and resources. However, many designers falsely assume that buying a module means they're home free with respect to national and international compatibility and compliance regulations. Nothing could be further from the truth.

It's true that the RF module may remain fully Bluetooth certified and interoperable, but once the power supply, RF module, antenna, and digital circuits are laid out and connected all regulatory certification bets are off. The full system now needs to be certified to CE, FCC, or CISPR requirements, due to the many and varied interactions be-

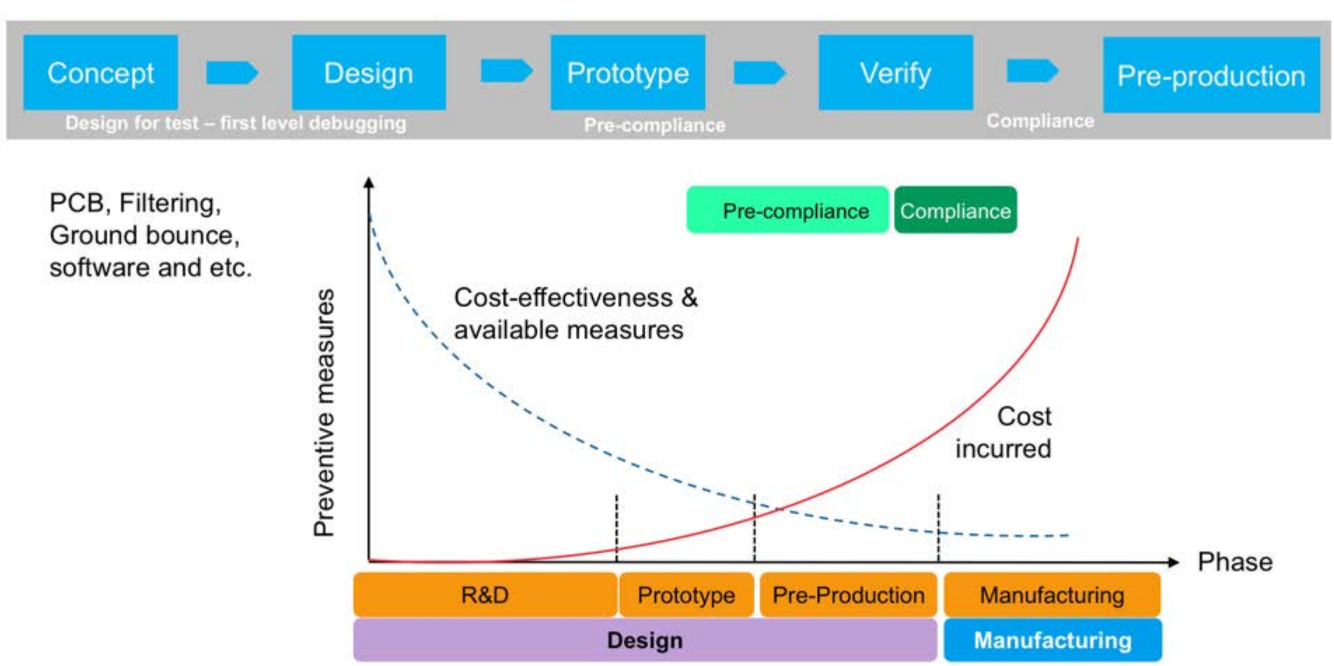


Figure 2: Implementing a regimen of pre-compliance checkpoint tests can greatly increase the chance of completing an IoT design on time and within budget. (Image Source: Rohde & Schwarz)

tween the subsystems. These include load transients, spurious power-supply emissions, various internal and ambient EMI sources, and RF harmonics.

The task for designers is to understand EMC and the effects and sources of EMI, and then performance pre-compliance testing on the system to identify and mitigate any issues–before sending it out to an external lab for certification. Along with the expense of time, the compliance tests themselves can cost up to $10,000 and up to 90 percent of devices fail the first time around, leading to rework and re-testing, sometimes multiple times. The costs add up quickly, especially if the fix requires a full or partial redesign. It's critical to initiate preventative measures, such as design-cycle checkpoints, to help avoid costly project delays, *Figure 2*.

Another important reason to perform pre-compliance testing is to avoid over-design of the device. Often, designers run the risk of adding additional shielding or other precautions, which adds weight, time, power consumption, and direct costs. The goal is to pass the test for full compliance without going overboard.

In order to minimize the chance of multiple rounds of compliance certification and rework, it helps to have some up-front education on EMC and EMI. Combined with off-the-shelf test equipment and some "tricks of the trade," it's possible to quickly identify and mitigate EMC issues before submitting a system for formal certification.

DEFINING EMC AND IDENTIFYING SOURCES OF EMI

EMC and EMI are often confused, but simply put, EMC is concerned with ensuring various pieces of electrical and electronic equipment can operate in the same electromagnetic environment. It requires the equipment to have minimal unwanted electromagnetic emissions and to also minimize its susceptibility to ambient electromagnetic energy, typically from nearby equipment or long-range radio transmitters.

EMI is the actual unwanted electromagnetic energy that designers need to suppress within their own designs, as well as protect their design from outside sources. These sources can be static electricity, other radios, sporadic emissions from motors or power supplies, mains hum, microwave ovens and the system's internal digital switching harmonics and sub-harmonics, and even audio signals. Their interference potential depends upon the operating frequency of the equipment under test (EUT) and they can manifest as continuous wave or pulsed EMI signals.

In EMC parlance, the system causing the interference is the source, and the system being affected is the victim. Between them are the four EMI coupling mechanisms: radiated, inductive, capacitive, and conductive, or any combination of the four, Figure 3. EMI can be viewed fractally in the sense that it applies between small or large systems that are near or far apart, as well as between subsystems, components, traces, and antenna within a system. Not that antennas are particularly interesting, as they not only transmit and receive intentional emissions, but also serve as perfect couplers of EMI into and out of a system.

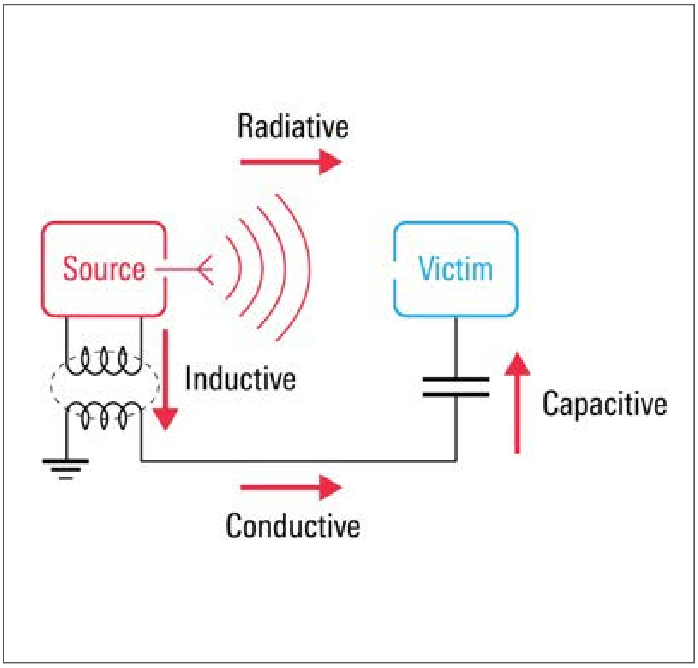


Figure 3: The four EMI coupling mechanisms are radiative, inductive, capacitive and conductive. (Image Source: ipfs. io)

The EMI and EMC principles are similar for nearby and within systems. For the sake of simplicity, this article will focus on a single system and how to design for EMC, perform pre-compliance testing, and debug using an off-the-shelf, mid-range oscilloscope.

DESIGNING FOR EMC

Let's consider the following basic principles to demonstrate that EMC hasn't changed since EE 101:

- Be careful on trace routing
- Be aware that higher speeds mean more EMI issues
- PCB stacking makes EMI worse
- Avoid sharp corners in traces (reasonable design tools can match the maximum trace angle to the operating frequency)
- Have larger ground planes
- Use shielded cables and housings
- Avoid discontinuities and resonances in the transmission path

Unfortunately, EMI cannot be eliminated entirely. Thus the designer's job is to manage and mitigate it, applying fundamental principles in combination with experiential know-how.

PRE-COMPLIANCE TEST AND DEBUG

Once the design is in the prototype stage and pre-compliance checkpoints have been established, the next task is to either isolate the EUT completely from ambient EMI, or to characterize the environment and account for detected interferers during the test cycle. Again, interferers also can-

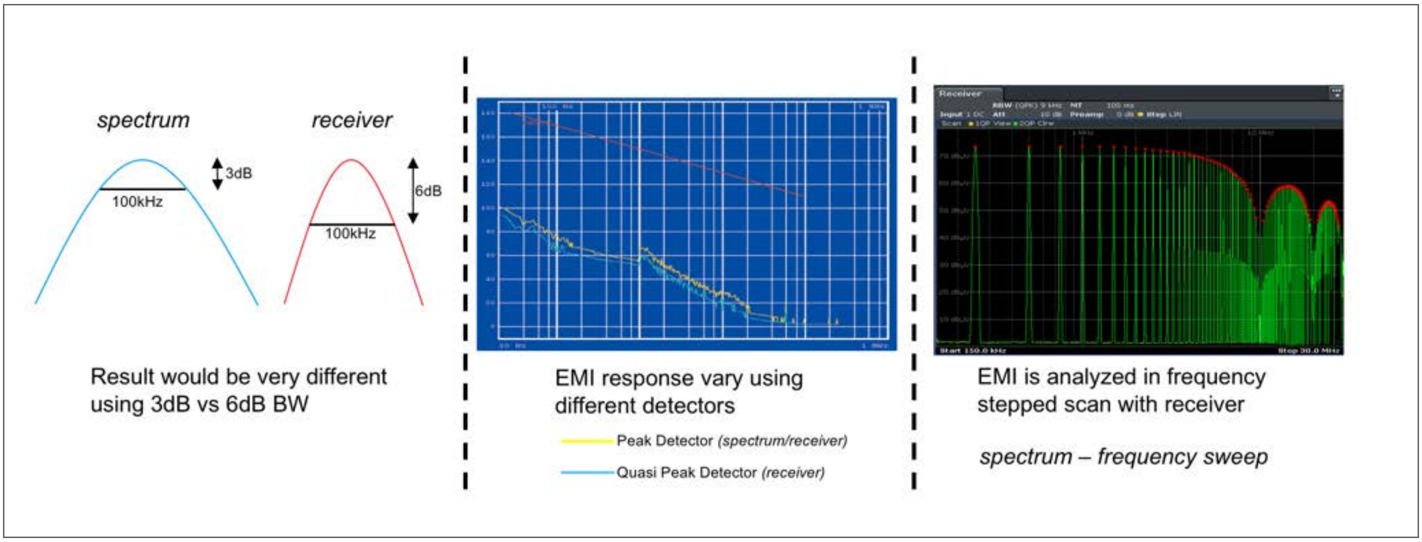


Figure 4: When in receive mode, spectrum analyzers can imitate higher cost EMI receivers, but make sure it has at least a quasi-peak (QP) detector with a directional antenna. (Image Source: Rohde & Schwarz)

not be eliminated, but the probability of interference can be determined and mitigated.

To scan a wide range of frequencies for interferers, a full EMI receiver with an array of filters and wide dynamic range is a good option, but can be expensive. Alternatively, a spectrum analyzer can come close to an EMI receiver's capabilities without breaking the bank. Start by getting a baseline and account for any present signals. Spectrum analyzers, such as the R&S®FPC1500, have optional PC EMI software (Elektra) that can set the compliance limits, or the user can do it manually, *Figure 4*.

The spectrum analyzer itself will need at least a quasi-peak (QP) detector with a directional antenna as part of the minimum viable feature sets to approximate a full EMI-compliant receiver. Look for an analyzer with a frequency range from 5 kHz to 5 GHz to detect sub-GHz signals and 5-GHz Wi-Fi network interferers. Also, a built-in vector network analyzer (VNA) is useful as it can be used to match the antenna impedance to the RF module if there isn't an RF antenna built in.

Some spectrum analyzers also have an integrated signal generator that can be used to generate an additional signal in the presence of the intended transmitter signal. This "interferer" tests to make sure there is sufficient blocking at the receiver to allow the intended signal to get through.

To start pre-compliance testing, do a limit-line test, or max hold sweep, with a max hold detector, as that's a fast and easy test. Then, use the QP detector to do spot checks on any potential problem areas. Use electric field (E-field) and magnetic field (H-field) near-field probes, *Figure 5*. The magnetic field probe has a loop through which the magnetic field passes perpendicularly, inducing a detectable voltage

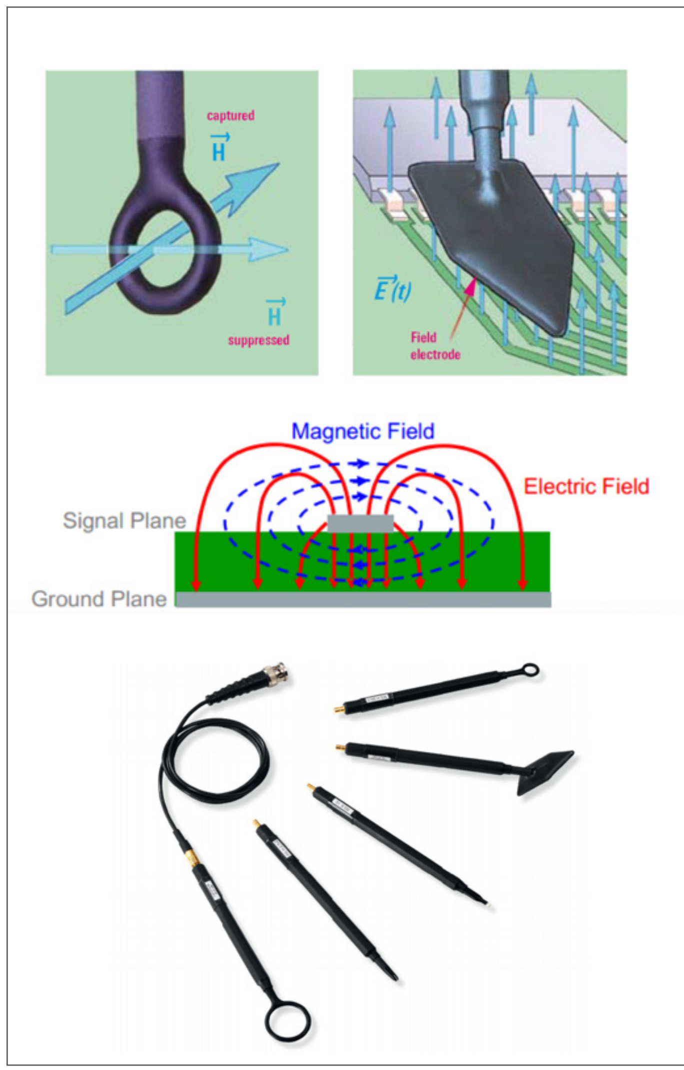


Figure 5: The larger the size of the E-field and H-field probes, the greater their sensitivity, at the cost of precision. It helps to zero in on the EMI source by reducing the size of the probe. (Image Source: Rohde & Schwarz)

When using the probes, it's important to keep in mind that the output of the probe very much depends upon the orientation of the probe relative to the emitters. Also, there is a trade-off to be made: the larger the probe, the greater the sensitivity, but the precision decreases. So, as the source of EMI gets more clearly defined, reduce the size of the probe to zero in on the source and verify that the readings are below the maximum power levels allowed.

This requires having a solid knowledge of the design to know where these might be. Many EMI sources can be anticipated by factoring in the clock frequencies, the power supply's switching frequency, and the expected harmonics.

Knowing the layout is critical, as it helps to know when a clock line might be too close to an RF module. This becomes something to watch for as it might be what's coupling in and causing another spur that's in a different part of the spectrum.

However, no matter how good a designer's knowledge of the physical layout and the circuit's design parameters, nothing beats running the system software and time-correlating the EMI to the running code.

TIME-CORRELATED TEST AND DEBUG WITH OSCILLOSCOPES

Given the budget and resource constraints of many IoT developers, a spectrum analyzer may be out of reach. However, every bench has an oscilloscope, and the right digital oscilloscope can also perform EMI test. This was not always the case, as the fast Fourier transform (FFT) processing capability wasn't available. That has changed, with some digital oscilloscopes now implementing FFT digital down-conversion and overlapping FFTs in hardware.

Look for a digital oscilloscope with these key characteristics: enough capture memory (can hold greater than 500 Ksamples), 50-Ω coupling impedance to ensure sufficient bandwidth and a sample rate >2x the maximum frequency, start with 2.5 Gsamples/s for 0 to 1 GHz. If testing systems with 2.45-GHz or 5-GHz radios, the sample rate will need to be upgraded accordingly. Also look for low noise and good vertical sensitivity capable of being set to 500 µV/div to 5 mV/div for high sensitivity over the full bandwidth.

As the probe will be moving around the board or system, it's important that the scope's response time be fast so there's no delay when trying to correlate EMI back to the time domain. Some scopes do include FFTs in software, so be careful to ensure the time and frequency domain are seen in real time. As the source of the EMI becomes clearer, the time-domain view should allow the EMI source to be correlated to changes such as bus level switching, *Figure 6.*

Other features to look for on a scope include a color table and screen persistence to easily detect and distinguish continuous wave signals, burst signals, and signal zoom: *Figure 7*.

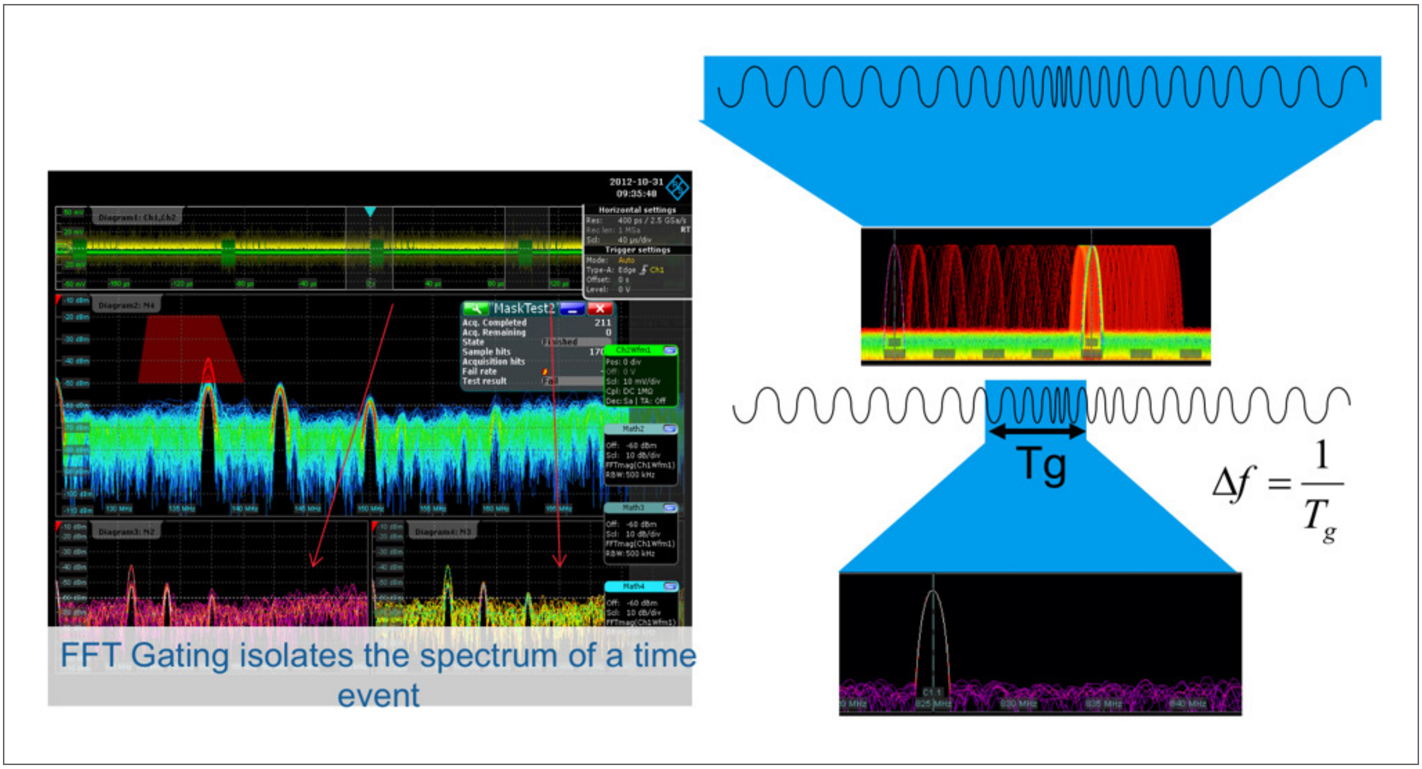


Figure 6: Multi-domain digital oscilloscopes with fast FFT capability and a gating feature help debug by allowing users to time-correlate EMI events and find their origin. (Image Source: Rohde & Schwarz)

CONCLUSION

In the age of IoT, with ubiquitous wireless connectivity, meeting EMC requirements for any standard is becoming more difficult and time consuming. The problem is exacerbated by the falling cost of IoT devices, which puts pressure on designers to get it right the first time to avoid extra certification costs and rework. That said, implementing a strict pre-compliance test regimen and checkpoints combined with typical benchtop equipment, such as digital oscilloscopes, can help limit formal and expensive EMC certification testing to one round.

Figure 7: The R&S®RTO2000's 10.1-inch capacitive touchscreen allows users to quickly navigate pop-up menus and adjust scaling by zooming in or moving a waveform. (Image Source: Rohde & Schwarz)

AUTOMOTIVE

Automated drive
Destination: 22° 34' 40.32" N 5° 11' 38.149" E
Arrival: 01:55 pm - Distance 46 miles
TCP/IP:192.74.375.961.1
Automated drive
Destination: 35° 23' 33.12" N 6° 10' 55.294" E
Arrival: 05:45 pm - Distance 483 miles
Automated drive
Destination: 22° 52' 50.11" N 6° 14' 35.174" E
Arrival: 02:55 pm - Distance 143 miles
TCP/IP:192.88.621.241.8
Automated drive
Destination: 50° 43' 50.34" N 6° 10' 55.294" E
Arrival: 08:55 pm - Distance 783 miles
TCP/IP:192.56.327.684.1

AUTOMOTIVE EMC EQUIPMENT MANUFACTURERS

The following chart is a quick reference guide of test equipment and includes everything you'll need from the bare minimum required for key evaluation testing, probing, and troubleshooting, to setting up a full in-house precompliance or full compliance test lab. The list includes amplifiers, antennas, current probes, ESD simulators, LISNs, near field probes, RF signal generators, spectrum analyzers, EMI receivers, and TEM cells. Equipment rental companies are also listed. The products listed can help you evaluate radiated and conducted emissions, radiated and conducted immunity, and a host of other immunity tests, such as ESD and EFT.

EMC Equipment Manufacturers		Type of Product/Service															
Manufacturer	Contact Information - URL	Antennas	Amplifiers	Filters/Ferrites	Near Field Probes	Current Probes	Spectrum Analyzers/EMI Receivers	Software Simulation	ESD Simulators	LISNs	Radiated Immunity	Components	Conducted Immunity	Pre-Compliance Test	TEM Cells	Rental Companies	RF Signal Generators
A.H. Systems	www.ahsystems.com	X	X			X								X			
Aaronia AG	www.aaronia.com	X	X				X							X			
Advanced Test Equipment Rentals	www.atecorp.com	X	X	X	X	X	X		X	X	X		X	X	X	X	X
Altair	www.altair.com				X	X		X							X		
AR RF/Microwave Instrumentation	www.arworld.us/	X	X				X	X		X	X		X	X			X
Anritsu	www.anritsu.com	X					X	X						X			X
Beehive Electronics	www.beehive-electronics.com	X			X									X			
Coilcraft	www.coilcraft.com			X								X					
CST Computer Simulation Technology	www.cst.com							X									
Electro Rent	www.electrorent.com		X				X		X	X	X		X	X		X	X
EM Test	www.emtest.com												X	X	X		
EMC Partner	www.emc-partner.com								X				X				
Empower RF Systems	www.empowerrf.com		X						X		X		X				
ETS-Lindgren	www.ets-lindgren.com	X	X		X	X			X	X	X		X	X	X		X
Fischer Custom Communications	www.fischercc.com				X	X				X				X			
Gauss Instruments	www.gauss-instruments.com						X										
Haefley	www.haefely.com								X				X				
Instrument Rental Labs	www.testequip.com		X				X		X	X	X		X	X		X	X
Instruments For Industry (IFI)	www.ifi.com		X								X		X				
Keysight Technologies	www.keysight.com				X		X			X				X			X
Microlease	www.microlease.com		X				X		X	X	X		X	X		X	X
Milmega	www.milmega.co.uk		X								X		X				
MVG	www.mvg-world.com	X		X	X									X			
Narda/PMM	www.narda-sts.it	X	X		X		X			X	X		X	X			
Noiseken	www.noiseken.com								X				X	X			
Ophir RF	www.ophirrf.com		X										X				
Pearson Electronics	www.pearsonelectronics.com					X											
Rigol Technologies	www.rigolna.com		X		X	X	X	X				X		X			X
Rohde & Schwarz	www.rohde-schwarz.com	X	X		X	X	X	X		X	X		X	X			X
Siglent Technologies	www.siglent.com/				X		X	X						X			X
Signal Hound	www.signalhound.com				X	X	X	X						X			X
Solar Electronics	www.solar-emc.com	X	X			X		X	X	X	X		X				
TekBox Technologies	www.tekbox.net		X		X			X		X				X	X		
Tektronix	www.tek.com				X		X	X						X			
Teseq	www.teseq.com		X			X			X		X		X	X	X		
Test Equity	www.testequity.com/leasing/		X				X		X	X	X		X	X		X	X
Thermo Keytek	www.thermofisher.com								X				X				X
Thurlby Thandar (AIM-TTi)	www.aimtti.com						X							X			X
Toyotech (Toyo)	www.oyotechus.com/emc-electromagnetic-compatibility/	X	X				X			X	X			X			
TPI	www.rf-consultant.com													X			X
Transient Specialists	www.transientspecialists.com										X		X		X		
TRSRenTelCo	www.trsrentelco.com	X	X				X			X	X		X	X		X	X
Vectawave Technology	vectawave.com		X														
Windfreak Technologies	windfreaktech.com													X			X

AUTOMOTIVE ELECTROMAGNETIC COMPATIBILITY STANDARDS

The following abbreviated list of automotive EMC standards was developed by Dr. Todd Hubing, Professor Emeritus of Clemson University Vehicular Electronics Lab (http://www.cvel.c lemson.edu/auto/auto_emc_standards.html). A few of these standards have been made public and are linked below, but many others are considered company confidential and are only available to approved automotive vendors or test equipment manufacturers. While several standards are linked on this list, an internet search may help locate additional documents that have been made public. For a more complete list, refer to the link above. Permission to republish has been granted.

CISPR (AUTOMOTIVE EMISSIONS REQUIREMENTS)

(https://webstore.iec.ch)

Document Number	Title
CISPR 12	Vehicles, boats, and internal combustion engine driven devices–Radio disturbance characteristics–Limits and methods of measurement for the protection of receivers except those installed in the vehicle/boat/device itself or in adjacent vehicles/boats/devices
CISPR 25	Radio disturbance characteristics for the protection of receivers used on board vehicles, boats, and on devices–Limits and methods of measurement

ISO (AUTOMOTIVE IMMUNITY REQUIREMENTS)

(https://www.iso.org)

Document Number	Title
ISO 7637-1	Road vehicles–Electrical disturbances from conduction and coupling–Part 1: Definitions and general considerations
ISO 7637-2	Road vehicles–Electrical disturbances from conduction and coupling–Part 2: Electrical transient conduction along supply lines only
ISO 7637-3	Road vehicles–Electrical disturbance by conduction and coupling–Part 3: Vehicles with nominal 12 V or 24 V supply voltage–Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines
ISO/TR 10305-1	Road vehicles–Calibration of electromagnetic field strength measuring devices–Part 1: Devices for measurement of electromagnetic fields at frequencies >0 Hz
ISO/TR 10305-2	Road vehicles–Calibration of electromagnetic field strength measuring devices–Part 2: IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz
ISO 10605	Road vehicles–Test methods for electrical disturbances from electrostatic discharge
ISO/TS 21609	Road vehicles–(EMC) guidelines for installation of aftermarket radio frequency transmitting equipment
ISO 11451-1	Road vehicles–Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 1: General principles and terminology
ISO 11451-2	Road vehicles–Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 2: Off-vehicle radiation sources
ISO 11451-3	Road vehicles–Electrical disturbances by narrowband radiated electromagnetic energy–Vehicle test methods–Part 3: On-board transmitter simulation
ISO 11451-4	Road vehicles–Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 4: Bulk current injection (BCI)

ISO 11452-4	Road vehicles–Component test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 4: Bulk current injection (BCI)
ISO 11452-7	Road vehicles–Component test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 7: Direct radio frequency (RF) power injection
ISO 11452-8	Road vehicles–Component test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 8: Immunity to magnetic fields
ISO 11452-10	Road vehicles–Component test methods for electrical disturbances from narrowband radiated electromagnetic energy–Part 10: Immunity to conducted disturbances in the extended audio frequency range

SAE (AUTOMOTIVE EMISSIONS AND IMMUNITY)

(http://standards.sae.org)

Document Number	Title
J1113/1	Electromagnetic Compatibility Measurement Procedures and Limits for Components of Vehicles, Boats (Up to 15 M), and Machines (Except Aircraft) (50 Hz to 18 Ghz)
J1113/2	Electromagnetic Compatibility Measurement Procedures and Limits for Vehicle Components (Except Aircraft–Conducted Immunity, 15 Hz to 250 kHz–All Leads
J1113/4	Immunity to Radiated Electromagnetic Fields-Bulk Current Injection (BCI) Method
J1113/11	Immunity to Conducted Transients on Power Leads
J1113/12	Electrical Interference by Conduction and Coupling–Capacitive and Inductive Coupling via Lines Other than Supply Lines
J1113/13	Electromagnetic Compatibility Measurement Procedure for Vehicle Components–Part 13: Immunity to Electrostatic Discharge
J1113/21	Electromagnetic Compatibility Measurement Procedure for Vehicle Components–Part 21: Immunity to Electromagnetic Fields, 30 MHz to 18 GHz, Absorber-Lined Chamber
J1113/26	Electromagnetic Compatibility Measurement Procedure for Vehicle Components–Immunity to AC Power Line Electric Fields
J1113/27	Electromagnetic Compatibility Measurements Procedure for Vehicle Components–Part 27: Immunity to Radiated Electromagnetic Fields–Mode Stir Reverberation Method
J1113/28	Electromagnetic Compatibility Measurements Procedure for Vehicle Components–Part 28–Immunity to Radiated Electromagnetic Fields–Reverberation Method (Mode Tuning)
J1752/1	Electromagnetic Compatibility Measurement Procedures for Integrated Circuits-Integrated Circuit EMC Measurement Procedures-General and Definition
J1752/2	Measurement of Radiated Emissions from Integrated Circuits–Surface Scan Method (Loop Probe Method) 10 MHz to 3 GHz
J1752/3	Measurement of Radiated Emissions from Integrated Circuits–TEM/Wideband TEM (GTEM) Cell Method; TEM Cell (150 kHz to 1 GHz), Wideband TEM Cell (150 kHz to 8 GHz)
J551/5	Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz To 30 MHz
J551/15	Vehicle Electromagnetic Immunity–Electrostatic Discharge (ESD)

J551/16	Electromagnetic Immunity–Off-Vehicle Source (Reverberation Chamber Method)–Part 16–Immunity to Radiated Electromagnetic Fields
J551/17	Vehicle Electromagnetic Immunity–Power Line Magnetic Fields
J1812	Function Performance Status Classification for EMC Immunity Testing
J2628	Characterization–Conducted Immunity
J2556	Radiated Emissions (RE) Narrowband Data Analysis–Power Spectral Density (PSD)

GM

(https://global.ihs.com/)

Document Number	Title
GMW3091	General Specification for Vehicles, Electromagnetic Compatibility (EMC)-Engl; Revision H; Supersedes GMI 12559 R and GMI 12559 V
GMW3097	General Specification for Electrical/Electronic Components and Subsystems, Electromagnetic Compatibility-Engl; Revision H; Supersedes GMW12559, GMW3100, GMW12002R AND GMW12002V
GMW3103	General Specification for Electrical/Electronic Components and Subsystems, Electromagnetic Compatibility Global EMC Component/Subsystem Validation Acceptance Process-Engl; Revision F; Contains Color; Replaces GMW12003, GMW12004 and GMW3106

FORD

(http://www.fordemc.com/)

Document Number	Title
EMC-CS-2009.1	Component EMC Specification EMC-CS-2009.1
FORD F-2	Electrical and Electronics System Engineering
FORD WSF-M22P5-A1	Printed Circuit Boards, PTF, Double Sided, Flexible

Fiat Chrysler Automobiles

Document Number	Title
DC-10614	EMC Performance Requirements–Components
DC-10615	Electrical System Performance Requirements for Electrical and Electronic Components
DC-11224	EMC Performance Requirements–Components
DC-11225	EMC Supplemental Information and Alternative Component Requirements
DC-11223	EMC Performance Requirements–Vehicle

REFERENCES
(GROUPS, PROGRAMS, PUBLICATIONS, & LINKEDIN GROUPS)

AUTOMOTIVE INDUSTRY GROUPS

Auto Alliance
http://www.autoalliance.org

Automotive Industry Action Group
http://www.aiag.org

European Automobile Manufacturers Association
http://www.acea.be

National Automobile Dealers Association
https://www.nada.org

Automotive Council UK
http://www.automotivecouncil.co.uk

Automotive Industries Association of Canada
https://www.aiacanada.com

Center for Automotive Research
http://www.cargroup.org

German Association of the Automotive Industry
https://www.vda.de/en

Motor Trades Association of Australia
http://www.mtaa.com.au

Shanghai Automotive Industry Corporation
https://www.dnb.com/business-directory/company-profiles.shanghai_automotive_industry_corporation_(group).71dd01fd15f78b2262cc38bdbd9433fd.html

PUBLICATIONS

2019 Automotive EMC Guide
The guide is comprised of the latest trends in technology, EMC design, standards, and pre-compliance testing in the automotive space.
https://learn.interferencetechnology.com/2019-automotive-emc-guide/

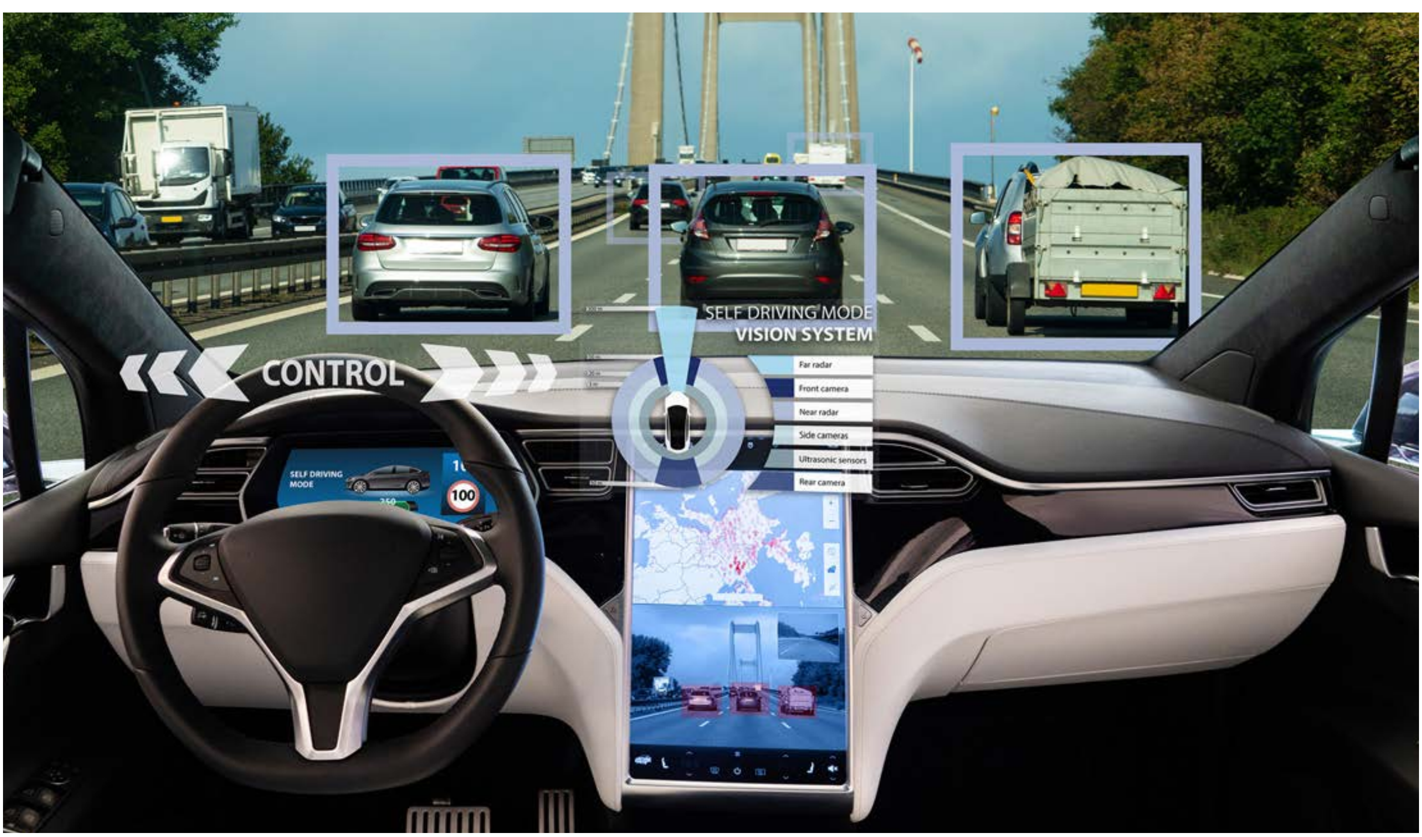
Vehicular Technology Magazine, IEEE
IEEE Vehicular Technology Magazine publishes peer-reviewed articles covering advances in areas of interest to the IEEE Vehicular Technology Society: The theoretical, experimental, application and operational aspects of electrical and electronic engineering relevant to motor vehicles and associated land transportation infrastructure

AUTOMOTIVE INDUSTRY LINKEDIN GROUPS

- Auto OEM Network - World's Largest Automotive Group
- Automotive Industry Professionals Worldwide
- Automotive Management Professionals
- Automotive Industry Professionals
- Automotive OEM Professionals
- Managers of Automotive
- Automotive careers
- Automotive Engineers
- Automotive Electronics and Embedded Software
- The Next Mobility: Automotive & Transportation Industry Innovation
- Automotive PRO Network
- Automotive Infotainment, Telematics & Connectivity
- Automotive Testing
- Automotive Innovation
- Automotive Industry Innovation Group
- ASQ Automotive Division
- Automotive Quality Professionals
- Automotive Systems Engineers
- Center for Automotive Research - CAR
- Automotive Electrical and Electronics Manufacturing
- Automotive Cyber Security
- Automotive active safety / passive safety
- Automotive Electronics Community
- Automotive Sensors and Electronics
- ISO 26262 in Automotive Functional Safety
- Automotive Infotainment Testing
- The Automotive Engineer

AUTOMOTIVE EMC

By Maurizio Di Paolo Emilio, Ph.D



AUTOMOTIVE EMC

INTRODUCTION

The rapid development of the automotive industry and the trend towards autonomous vehicles and ADAS systems continue to drive the need for more sophisticated EMC design and test scenarios for the automotive industry. Vehicle platforms become increasingly much more complex with electronic devices that need a reliable function without impacting security or communication infrastructure.

The increase of electronics in automotive systems has not just foreseen a radical change in control systems with ECUs, but also in the communication, information, security and mobile entertainment systems in vehicles. It is important that all the electronic devices of a vehicle are electromagnetically compatible and do not interfere with the systems outboard.

The new wireless communication paradigms applied to the automotive sector require high performance electronic systems that operate at high bitrates and, therefore, at high frequencies according to the operating environment. Each of these new sub-systems must comply with the electromagnetic compatibility (EMC) standards. Furthermore, the integrity of the signals, the transmitted and processed data streams are critical aspects. Miniaturization of electronic products is a must and, as a consequence, manufacturing tolerance can be no longer neglected. Variations in nominal design parameters cause irregular behaviours that negatively affect the EMC and signal integrity and power (SI / PI) aspects.

SIGNAL INTEGRITY

Historically, engineers have used signal integrity testing (SI) as a key part of design and development of new systems and for maintaining standard qualifications. With today's increasing demand for higher system throughput and reduced latency in cloud computing, customers are increasingly designing low-loss laminate materials with more stringent design specifications and tolerances for impedance control.

The integrity analysis continues to evolve by combining simulation models with instrumentation to include detailed measurements of non-uniform trace structures, vias, packages and connectors. As the PCBs become more complex, the lines between the different scopes of analysis become blurred. The concepts of signal and power integrity are closely related. Power integrity problems in a project can actually appear as signal integrity problems. That's why performing signal integrity analysis is important for creating reliable designs, as well as for understanding and resolving possible problems encountered in the laboratory.

Digital projects traditionally have not been suffered of problems associated with the loss of a transmission line that can have significant consequences on the transmitted data. At low speeds, the frequency response has low influence on the signal. However, as speed increases, high frequency effects take over and even shorter lines can suffer of interferences such as crosstalk and reflections. In this case, the characteristics of a circuit can be determined as a function of parasitic impedances, which become prevalent along a transmission line.

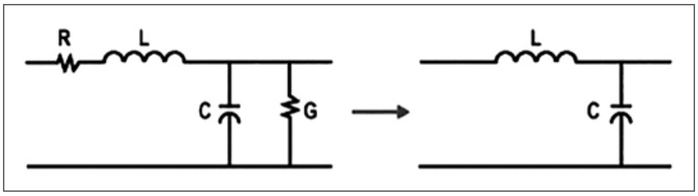


Figure 1: Circuit model of a transmission line (on the left) and approximation to the first order (on the right)

An example of circuit model is shown in *Figure 1*. The impedance plays an important role determining a perfect match of the transmission path of the signal and therefore effects on the quality of the signal. A mismatching between the line, source and load impedances determines a reflection of the signal with consequent energy loss and signal degradation. At high data rates this can cause overshoot of the signal, undershoot and stepped waveforms, which produce signal errors.

The mismatch of impedance can be overcome through the use of circuit schemes with simple parallel (see *Figure 2*) and more complex RC terminations in which a resistor-capacitor network provides a high-pass filter to remove low-frequency effects but passes the high-frequency signal.

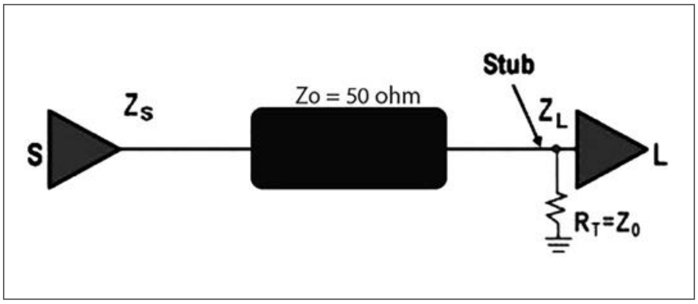


Figure 2: Parallel termination circuit diagram

Losses in the high frequency signal transmission line make difficult for the receiver to interpret the information correctly. The following two causes of losses in a transmission line are due to the transmission medium:

- Dielectric absorption: high frequency signals excite the molecules in the insulation, reducing signal level. Dielectric absorption refers to the PCB material.
- Skin effect: high frequency signal current tends to travel on the conductors with an increase in the self-inductance of the material. The effective reduction of the conductive material causes an increase in resistance and, therefore, the attenuation of the signal (*Figure 3*). The density of alternating current J in a conductor de-

creases exponentially from its value on the surface Js according to depth d from the surface:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\sqrt{\sqrt{1+(\rho\omega\varepsilon)^2}+\rho\omega\varepsilon}$$

Where ρ is the resistivity of the conductor, ω is the angular frequency, μ is the magnetic permeability, ε is the permittivity of the material.

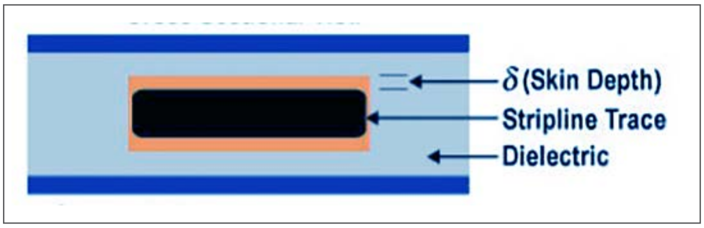


Figure 3: PCB section. The current route is orange. In blue is the ground plane and in celestial is the dielectric of the material. The copper PCB trace is highlighted in black.

CMOS circuits are very popular in many automotive sectors, due to their high speed and very low power dissipation. An ideal CMOS circuit dissipates energy only when it changes state and when the capabilities of the node need to be charged or discharged. In general, a CMOS requires an average of 10 mA and emission limitation techniques are focused on peak voltage and current values rather than average.

The rising current from the power supply on the chips pin is a primary source of emission. By placing a bypass capacitor near each power pin, this problem is limited. Larger capacitors provide strong current peaks, and tend to react badly to high-speed demands. Very small capacitors can react quickly to demand, but their total charge capacity is limited and can quickly run out. The best solution for most circuits is a mix of different sizes of parallel capacitors, perhaps 1-μF and 0.01-μF in parallel.

One area in which automotive designers are interested is in the AM radio band. Most every car is equipped with radios, which has a very sensitive and high gain tuneable amplifier from 500 kHz to 1.5 MHz. Many switching power supplies use switching frequencies within this same band, which leads to problems in automotive applications. As a result, most devices use switching frequencies above this band, often at 2 MHz or higher.

AUTOMOTIVE STANDARD

The automotive industry and the car manufacturers have the aim of satisfying a variety of requirements regarding electromagnetic compatibility (EMC). For example, two requirements must ensure that electronic devices do not emit excessive electromagnetic interference (EMI) or noise and are immune to noise emitted by other systems.

Automotive systems have several receivers installed around the car. The IEC Commission has formulated international standards to protect them. The international standard for this electromagnetic noise is formulated as CISPR 25, and the power supply on board is required to meet this standard (*Figure 4*).

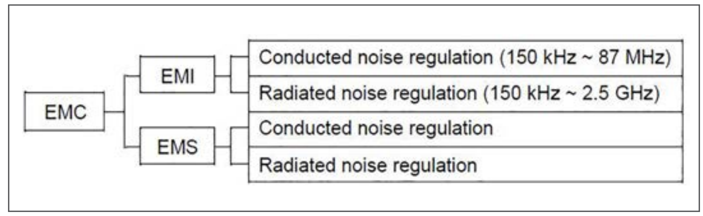


Figure 4: Electromagnetic noise

Automotive standards that relate to electromagnetic compatibility (EMC) are mainly developed by CISPR, ISO and SAE. CISPR and ISO are organizations that develop and maintain standards for international use. The CISPR 25 and ISO 11452-2 standards form the basis of most other standards.

CISPR 25 is a standard with different test methods. It requires that the level of test electromagnetic noise is being performed is at least 6 dB lower than the lowest measured levels. Another standard of testing is the ISO 11452-4 Bulk Current Injection (BCI) to check if a component is negatively affected by the narrow band electromagnetic fields. The test is performed by coupling noise directly in the wiring with a current probe.

CISPR 25 contains limits and procedures for measuring radio interference in the frequency range from 150 kHz to 1,000 MHz. The standard applies to any electronic / electrical component intended for use on vehicles, trailers and devices. CISPR 25 defines the test configuration as shown in *Figure 5* for measuring the noise of the radiation emitted by the apparatus.

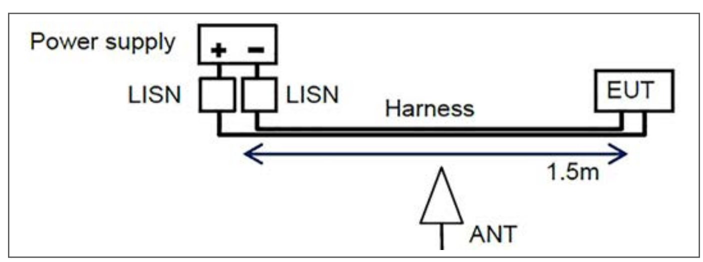


Figure 5: EMI Radiated Noise Test Configuration Example

In the case of irradiated noise measurement of 1 GHz or less, the antenna is placed in the middle of the harness. The wiring current (or voltage) (or LISN) is measured for the conducted noise. The length of the line is different from the test condition for the radiation noise. Therefore, it is important to reduce the noise source level and to prevent noise propagation along the line to reduce EMI noise.

EMC TESTING

When a magnetic field is present, a coil of conductive material can act as an antenna and convert the magnetic field into a current flowing around the wire. The small size of these loops minimizes the inductive effects of these materials. An example of this effect is when there is a differential data signal. A loop can be formed between the transmitter and the receiver with the differential lines. Another common loop is when two subsystems share a circuit, for example a display and an ECU device.

When a high-speed signal is sent through a transmission line and encounters a change in the characteristic impedance, part of the signal is reflected back and the other continues along the electrical path. Then, reflection leads to emissions.

Emissions can be caused by an interruption in the signal track or in the ground plane. For this it is necessary to avoid sharp angles on the signal track. To minimize reflections on components, it's important to use small components such as size 0402 and set the width of the track equal to the width of the 0402 component.

A recurring topic when trying to solve EMI problems is to reduce dv/dt or di/dt where possible. In this context, DC-DC converters may seem completely harmless as switching regulators are much more efficient than other linear solutions. One area in which automotive designers are not interested in creating interference is in the AM radio band. The cars are equipped with AM solutions, which have a very sensitive and high-gain tuneable amplifier from 500 kHz to 1.5 MHz. Most automotive switching supplies use the switching frequencies above this band, often at 2 MHz or higher. If the filter is not sufficient to contain this interference, it can trigger an EMI cycle over the whole circuit.

There are several ways to implement EMI noise reduction countermeasures.

Spread Spectrum Clock Generation (SSCG) is a method by which the energy contained in the small band of a clock source is spread on a larger one in a controlled mode, thus reducing the spectral amplitude of the fundamental and harmonics to reduce the emission radiated by the clock. This is obtained by modulating the clock frequency with unique shapes that allow reaching the peak of reduction of the EMI.

By varying the clock frequency on a band in a controlled mode, the time elapsed from the signal at a certain frequency is reduced, and in this way the concentration of energy at any frequency is reduced. So energy is spread on the band of frequencies that reduce the amplitude of the peak.

SSCG provides a way to reach EMC goals. It is an active solution, preserves the integrity of the clock, and can cover a wide range of frequencies. Compared to traditional methods of using passive components such as ferrite beads, RF coils to suppress EMI, SSCG uses an integrated circuit of active components to reduce the EMI peak using frequency modulation (*Figure 6*).

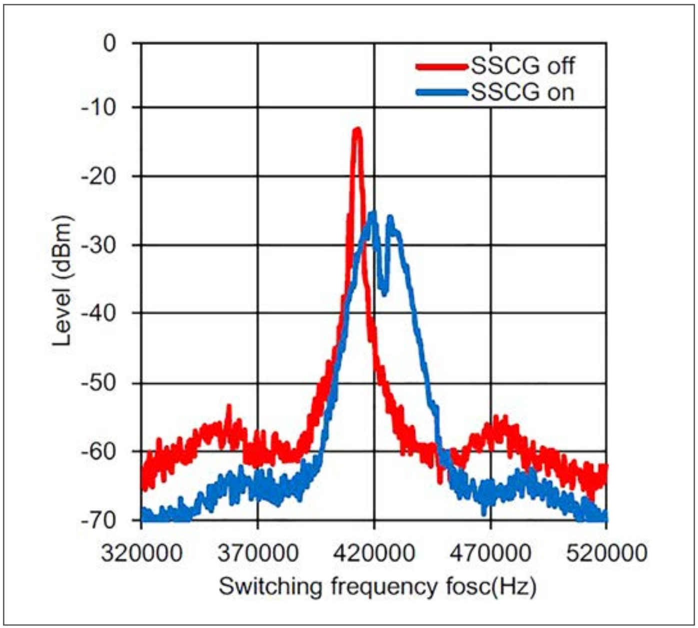


Figure 6: EMI reduction with SSCG

POWER CIRCUITS

Various electronic devices are mounted on vehicles with different power sources. Switching circuits help power management solutions but are essentially noise sources. Where it is not possible to increase the switching frequency is necessary to introduce noise suppression measures.

DC-DC switching solutions for automotive systems have a switching frequency of 2 MHz, with the exception of some devices. Therefore, there is almost no problem in the range of AM radio (from 530 kHz to 1.8 MHz) as it is below 2 MHz, but countermeasures could be requested with values above 2 MHz. In particular, high noise frequency above 30 MHz is the most important since it generates cases of interference such as to interrupt the correct functioning of a system. A diagram of the step-down DC-DC converter is shown in the following *Figure 7*.

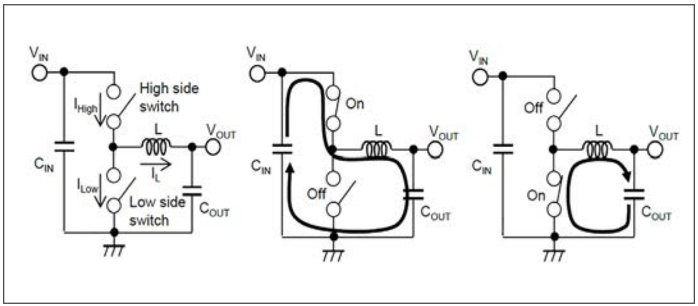


Figure 7: Step-down converter with current loop in various cases depending on the switch position

The parasitic inductance of the loop generates a high frequency voltage and therefore noise. To reduce this high frequency, it is necessary to reduce the parasitic inductance and to improve the switching response speed. Noise suppression measures are not limited to vehicles and can also be used with other industrial equipment (*Figures 8* and *9*).

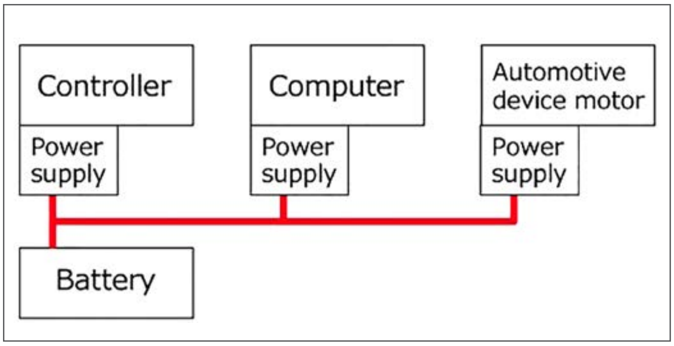


Figure 8: Eutomotive power system

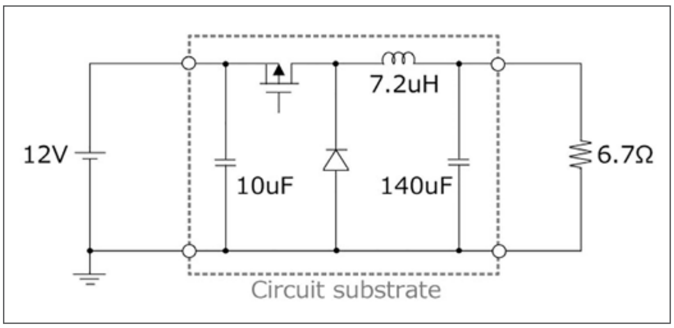


Figure 9: Model of IC DC-DC step-down

Some methods consist of using appropriate shields to suppress noise up to 20 MHz. Or insert a common mode stop coil (CMCC) immediately next to the power connector to suppress noise in common mode at 20 MHz or higher, or, an LPF near the power connector to suppress noise in normal mode at 20 MHz or higher. In *Figure 10* an implementation circuit of what has been described.

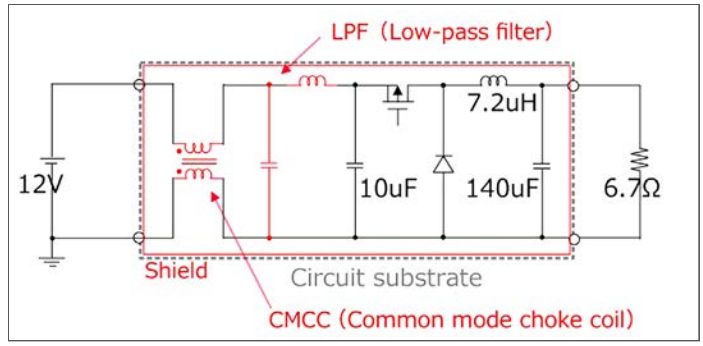


Figure 10: The circuit model of *Figure 9* with noise suppression methods

CONCLUSION

Automobiles rely more on electronics: ADAS systems and self-driving vehicles; in all these there is a growing need to operate without errors without interfering with other systems in the vehicle. Through a selection of the appropriate components, materials and PCB study; engineers are able to design robust systems that enable automotive systems to operate EMI-free reliability.

FIVE STEPS FOR SUCCESSFUL AUTOMOTIVE EMC DESIGN

By Sreevas P. Vasudevan
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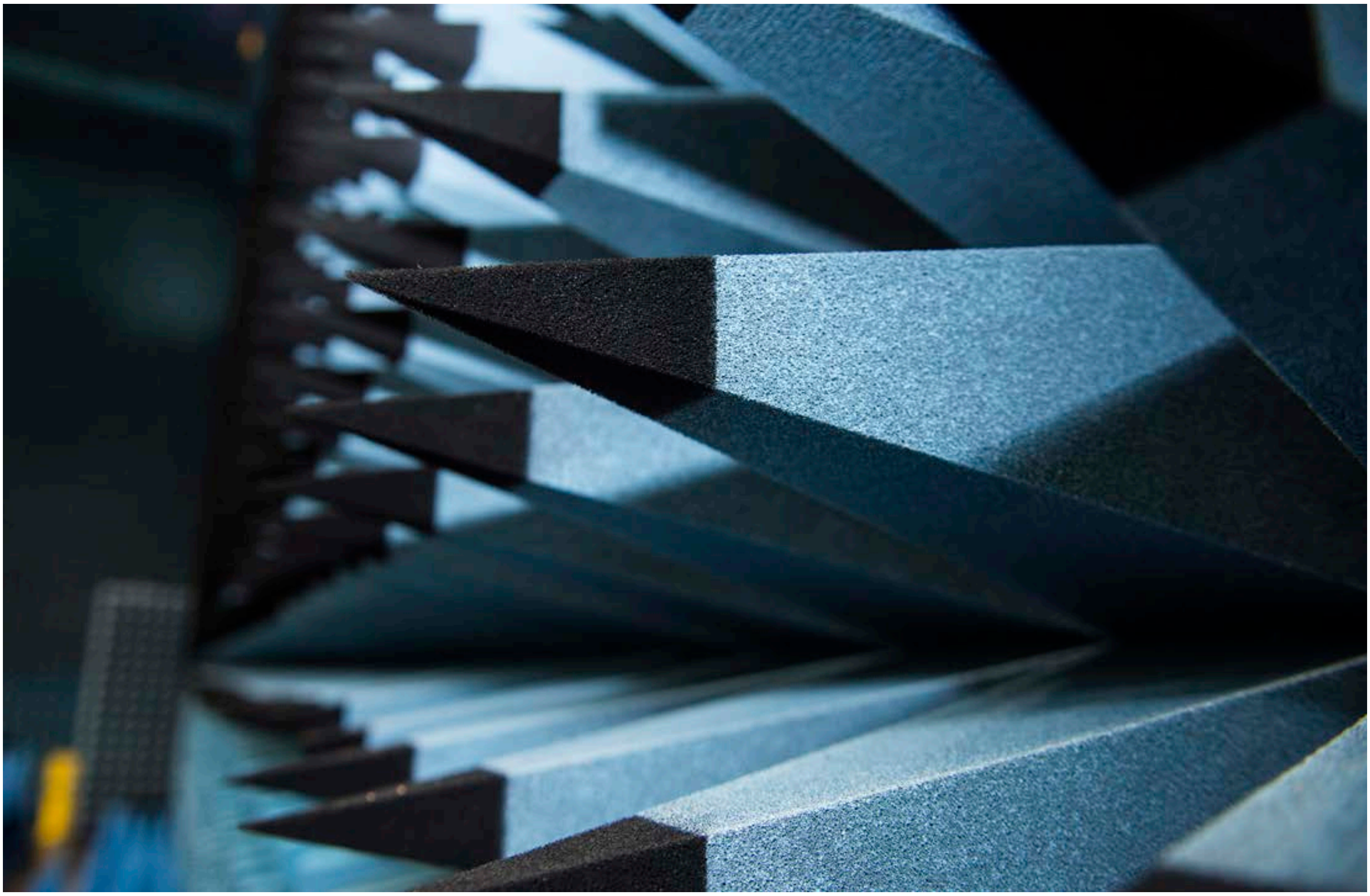
By Praveen S. Mohan
Principal EMI EMC Engineer

EMI/EMC behavior of devices has become a major quality benchmark all over the world. The automotive industry follows several standards and stringent limits. Advancements in technology, customer requirements, along with harsher fuel emissions regulations, have resulted in the need to place more electrical and electronic systems into vehicles. In turn these resulted in the need of using electromagnetic compatible systems in the vehicle to avoid cross coupling between the systems and causing non-compliances or customer dissatisfaction.



FIVE STEPS FOR SUCCESSFUL AUTOMOTIVE EMC DESIGN

What makes automotive EMC special?
Electronic systems in automotive involve in safety critical functions which include engine management, braking control, and airbag deployment, to name a few. Also, the automotive industry has seen a new generation of on board electronics for driver assistance devices and entertainment. Having the mobility of automobile, it can be exposed to different electromagnetic environments, from electromagnetically benign locations to electromagnetically harsh environments like airports with high radar fields.

Almost all automobiles today have sensitive AM/FM/DAB radio receivers (or perhaps even a land mobile VHF/UHF radio), so emissions from digital circuits are one of the biggest EMI problems facing today's designer of vehicular electronics. Most of the time the problem is annoying, but in the case of emergency vehicles (police, fire, ambulance), jamming a radio receiver could be life threatening. As a result, most vehicle manufacturers now require suppressing the offending emissions to extremely low levels.

In short, automotive emission requirements are aimed at protecting on board receivers (CISPR 25) and immunity requirements are very stringent to protect the safety critical on-board devices. Major Original Equipment Manufacturer (OEMs) had come up with their own standards which are more stringent than regulatory requirements. This make it essential for the suppliers to be fine tuning the EMC design best to suit the market.

EMC control–Vehicle level or Electronic Sub Assembly (ESA)
Understanding the fact that all major OEMs use electronics sub assemblies from more than one supplier for integrating in the vehicle, it is required by all major OEMs that the ESA fulfills the emission and immunity requirements. It can un-doubtfully say that making the ESA compliant to respective standards shall increase compliance possibility at the vehicle level testing, but, over the years it is proved that failure at vehicle levels are not completely avoided by making ESA compliant to EMC.

The article aims to provide a brief understanding for suppliers intended to produce products compliant and acceptable to Tier 1 OEMs.

I. UNDERSTAND THE REQUIREMENT
The automotive industry is a good example of responsible 'EMC regulation'. Country specific legal requirements are limited to generic clauses in the form of directives (for Europe) or FCC – Part 15 (United States). In addition to legal requirements, customer-based requirements are established by OEMs. Requirements of Tier 1 OEMs vary with each other in terms of standard followed, test limits and test type. A standardized test specification that cover major OEMs are far from reality even today [R1]. For radiated and conducted emissions of ESA, OEMs use CISPR25 as guideline and for regulatory purpose at vehicle level emission results, CISPR12 is used. For immunity measurements the ISO 11452-series is referenced for ESA and ISO 11451 series is referenced at the vehicle level. These standards apply to vehicles powered by internal combustion engines, as well as hybrid and electric vehicles. Test distances and methods required to validate a product's performance are detailed in these standards. Some of the OEM specific standards, such as standards issued by General Motors, Ford and Fiat Chrysler requirements are available in the public domain. It is of utmost importance that product manufactures (of ESA) shall be aware of the OEMs they are targeting, and the respective levels of emission and immunity to be achieved.

Vehicle Level		Electronic Sub-Assembly	
Emission Standards	CISPR 12, EN 55012	Emission Standards	CISPR 25, EN 55025
Immunity Standards	ISO 11451-2 (Radiated Immunity)	Immunity Standards	ISO 11452-2 (Radiated Immunity)
	ISO 11451-3 (On Board Transmitter Immunity)		ISO 11452-3 (TEM Cell Method)
	ISO 11451-4 (BCI Method)		ISO 11452-4 (BCI Method)
	ISO 10605 (ESD)		ISO 11452-5 (Stripline)
			ISO 11452-7 (Direct RF Power Injection)
			ISO 11452-9 (Portable transmitter)
			ISO 10605 (ESD)

Table 1: Automotive EMC Standards Overview

II. INCLUDE EMC IN DESIGN
It is often observed that EMC is taken into consideration at the final phase of the project, either after experiencing a compliance failure or at final sample stage. EMC design from the earliest stages of the project leads to easy implementation and cost-effective design approaches. When designing an electronic circuit, it is necessary to take several precautions to ensure that its EMC performance requirements can be achieved. Methods that can address EMC during the design are optimized as:

- Component selection and frequency selection
- PCB design for minimum radiation
- Cabing & Shielding

A. Component selection and frequency selection
For many automotive electronic systems, the embedded microcontroller is the only high-speed source of EMI on the board. If one can confine the selection of the component

having lower emission profile and higher immunity performance, the EMC performance can be improved. Always ask for EMC compliance data for microcontrollers or passives used in the design. A detailed view EMC performance graphs will help to identify the advantages and shortcomings of the components. Preparing a 'frequency table' (such as shown in *Table 2*) that list out the fundamental frequency and the dominant harmonics associated with each component would be a handy tool for better understanding of the circuit for design. Better design shall use frequencies that will not interfere constructively.

IC Reference	Radiated Emission Level	Radaiated Immunity Level	Fundamental Frequency	Harmonic Frequency (1st, 3rd, 5th , 7th, 9th , 11th)	EMC Remarks

Table 2: Component selection-Frequency check

B. PCB design for minimum radiation

Clocks & Harmonics: The primary sources of emissions from microcontroller based automotive systems are the clocks and other highly repetitive signals. A non-sinusoidal periodic waveform is composed of a fundamental frequency plus harmonic frequencies. The harmonics of these signals result in discrete narrowband signals that are typically within the VHF and UHF radio ranges. These harmonics are easily radiated by cables, wiring and printed circuit boards. The amplitude of square wave harmonics in digital systems decreases at the slowest rate (20 dB/decade) as frequency increases, and therefore are a rich sources of high frequency harmonics. Any conductor will act as an efficient antenna when it's physical dimensions exceed a (1/20) fraction of a wavelength. This shows that for a 300 MHz signal, a PCB trace of 5 cm can act as antenna. The design shall take care in avoiding PCB trace length comparable to the wavelength of the signal carried through it.

Spread Spectrum Clocking (SSC): Radiated emissions are typically confined in a narrow band centered around clock frequency harmonics. By uniformly distributing the radiation over a band of a few MHz, regulatory measurement levels (in a 120 kHz bandwidth at frequencies below 1 GHz and in a 1 MHz bandwidth at frequencies above 1 GHz) will be reduced up to 8 dB [R2].

Current Loop: Another key source of emissions is current flow. As processor speeds increase, the current requirement of the processor increases. Current flowing through a loop generates a magnetic field, which is proportional to the area of the loop. Loop area is defined as trace length times the distance to the ground plane. As signals change logic states, an electric field is generated from the voltage transition. Thus, radiation occurs because of this current loop and the voltage transition. The following *Equation (1)* shows the relationship of current, its loop area, and the frequency to EMI (E-field): Since the distance to the ground plane is fixed due to board stack up requirements, minimizing trace length on the board layout is key to decreasing emissions.

$$\text{EMI (V/m)} = k\, I A f^2 \qquad (1)$$

Where:
k = constant of proportionality
I = current (A)
A = loop area (m^2)
f = frequency (MHz)

Decouple Power Line: Whenever a digital circuit switches, it also consumes current at the switching rate. These pulses of power current will radiate as effectively as pulses of signal current. These switching peak currents cause more radiation since the power levels are usually much higher than those on an individual signal line. For devices with multiple power and ground pins, each pair of pins should be decoupled.

High frequency capacitors in the 0.01–0.1 μf range should be installed as close as possible to the device VCC. Also, high frequency capacitors (0.001 μf typical) shall be placed on the input and outputs of all on-board voltage regulators. This will protect these devices against high levels of RF energy and will also help suppress VHF parasitic oscillations from these devices. Keep the capacitors close to the devices, with very short leads.

C. Cabing & Shielding

Radio Frequency Immunity: The design method for better immunity to radio frequency is to avoid unwanted energy reaching vulnerable circuits. This requires high frequency filtering on cables (both power and I/O) which act as antennas and a careful circuit layout and circuit decoupling. To prevent coupling, noise carrying cables shall be placed away from chassis seams. Ferrite beads can be used to attenuate common mode noise on I/O cables. Provide adequate grounding for all cables. Both ends of cables shall be grounded to chassis ground.

The system case acts as shield and reduces EMI by containing EMI radiation. Effectiveness of the shield depends on the material used and the discontinuities in the case. Cable and module shielding are effective but are not popular in vehicular designs due to the costs.

III. REVIEW FOR EMC GUIDELINES

In the above section multiple EMC design methods are mentioned, it is important to suitably select the best possible methods based on the design considerations and cost impact. For better implementation, EMC design reviews shall be conducted at the sample stage. Introduction of front loading enables us to confirm the EMC design effect from the first prototype step and to reduce time for EMC improvement countermeasure at later stages. EMC review, hand in hand with design stage, helps to have a robust EMC design by ensuring major EMC checks are in place.

Structure of EMC design review–The EMC design review shall include the hardware circuit designer, PCB designer, mechanical designer, software designer and persons responsible for cable / interfaces. A detailed check for–Hardware selection, PCB guideline implementations, cable / interface connections must be performed at each review and the potential EMC challenges shall be noted.

- EMC design review can look for answers to important question like,
- How severe are the EMC challenges for the circuit under design?
- What should be the focus of the EMC design–PCB or at interface cables.
- Is shielding of cables/critical circuits a possible solution?
- Do we need an EMC simulation for a cost-effective implementation?
- A facility for EMC pre-compliance is available or can be developed.

IV. PLAN FOR PRE-COMPLIANCE

Performing pre-compliance EMC testing avoids the risk of product failure and eliminates costly re-testing after design. EMC troubleshooting using near field probes for emission measurement are common nowadays, but for automotive device where the emission requirements are too stringent and immunity levels are too high, an exposure to actual test levels and setups is necessary to understand any pitfalls in design before final compliance testing.

There are organizations having in-house equipment capable for automotive emission and immunity measurement, and these organization benefit from easy access and quick fix to EMC threats during design stage itself.

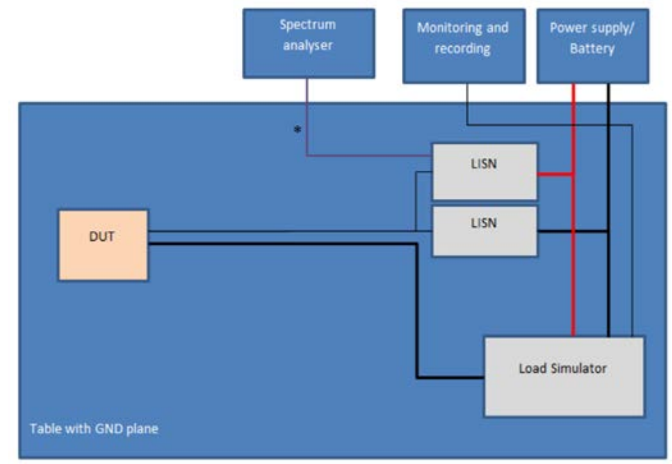
A. Common mode current measurement:

Measuring common-mode currents from cables can give an estimate of the radiated emission values, as radiated emission from cable is directly proportional to the common-mode current in that cable. We can use below equation to find out the amount of E-field emission.

$$E = \frac{12.6 \times 10^{-7}(f \times l \times Icm)}{r}$$

Where E is the e-field strength in uV/m, Icm is in micro amps, f is in MHz, r (distance from Antenna) & l (Length of the harness) are in meters. Common mode current can be measured with a high frequency clamp-on current probe and a spectrum analyzer/EMI Receiver.

A generic test setup for emission measurement for automotive devices using a LISN, current probe, and spectrum analyzer/EMI receiver is shown below.



* Connect current probe to spectrum analyser for Current probe measurement and clamp it to harness.

Figure 1: Conducted emission test setup.

B. 1 m Radiated Emission test

Radiated emission testing can be performed as part of pre-compliance measurement with proper calibrated antennas if we can control or reduce the reflection of the emitted field. This can be achieved by keeping the DUT away from reflective surfaces. A lot of trial and error measurement may be required to build this setup in an internal lab. Small broadband antennas are the best choice for 1m EMC testing. A bi-conical antenna (30–200 MHz) and a small log periodic antenna (200–1,000 MHz) are suitable for this kind of measurement. Active antennas are the other option for this kind of test. The antenna needs to be placed 1 m from the DUT. Connect the antenna to a spectrum analyzer and take measurements. A reference measurement with an approved lab can give a bench mark for the internal pre-compliance measurement. However at least a 6 dB correction factor may be required with respect to an approved lab. Cost effective pre-compliance for radiated emissions can be made by the "Golden Product method" [R4] where the correction factors for the environment and equipment of pre-compliance measurement can be identified by comparing with a Golden sample whose radiated emissions behavior is already available from a test lab.

C. Pre-compliance Immunity testing

Measuring radiated immunity for automotive products without an anechoic chamber will be difficult to do as the fields are very high and it can interfere with the system around and with licensed radio services. Alternative ways to do this are to use hand held radio transmitters and place close to the device under test to check if these can cause any performance degradations. The BCI (ISO 11452-4) test in a small shielded room or shielded box can be used for understanding the immunity performance of the device up to 1 GHz [R3]. This is relatively less expensive than a fully installed antenna measurement.

With these methods, immunity performance of the product at different electromagnetic field levels can be observed and the product can be taken to an approved facility for further investigation and compliance testing.

D. ESD testing

ESD tests can be done in an internal lab with an ESD generator. Various models of ESD generators are available and these can be set up in an internal lab without much space and cost impact. Care should be taken to monitor the temperature and humidity of the area during the test time, as these environmental factors have impact on the static discharge.

V. SYSTEM INTEGRATION

Vehicle manufacturers are required to gain EMC approval for all vehicles. The electronic sub-assemblies, components and separate technical units are operated in full functionality for approval testing. Vehicles must not have electromagnetic emissions above the limits and must be immune to interference levels stated in the appropriate standards. Even though OEMs use sub-assemblies that have sufficient EMC robustness when tested individually, there exist a high chance that electromagnetic robustness for emission and immunity can be affected when different functional modules are integrated. These can be due to sharing of a common power supply or sharing a common communication network.

Inter-system radiated emissions and immunity of ESAs within the vehicle can be improved by proper positioning of the ESA in the vehicle. It is observed that for conventional automobiles with internal combustion engines, EMC sensitive equipment are positioned away from engine section where high power and high frequency switching noise are high. CAN, LIN, and FlexRay are major communication networks. When devices are connected to a shared bus network, electromagnetic noise can be controlled by proper impedance matching design.

VI. CONCLUSION

Much advancement is happening in the automotive industry. As automotive systems are more and more occupied with electronic systems and subassemblies, EMI/EMC measurements became crucial for market certification and safety. It is required that automotive suppliers are positioned well in advance for EMC achievement. The above explained the key stages of a successful EMC achievement. Time for required for product development can be reduced if we only had a harmonized method of testing worldwide and with different OEMs. One day, methods and procedures might be unified for test execution that everyone can adopt. For now, by following a common EMC requirement and include EMC in the design strategy, a robust EMC design can more likely be achieved.

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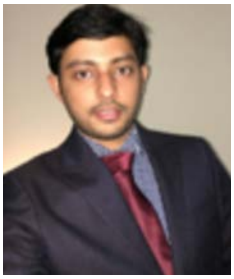
AUTHOR BIOGRAPHY



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Mr. Praveen Mohandas is an EMC engineer with 13 years of experience in EMC design, development and validation. Praveen holds a bachelor’s degree in Electronics and Communications and has hands-on experience in the field of EMC design, debugging and validations. He also has in-depth knowledge of EMC standards, legal requirements and various OEM requirements along with vehicle level EMC design reviews and validation process. Mr. Praveen is currently working in UK as a Principal Product Development Engineer in the field of EMC for Electric vehicle products. Praveen holds a patent, “ESD capacitor identification tool”, registered under Indian Patent office. He can be reached at sm.praveen93@gmail.com

USING AN OSCILLOSCOPE TO VERIFY EMC TESTS FOR AUTOMOTIVE ELECTRONICS

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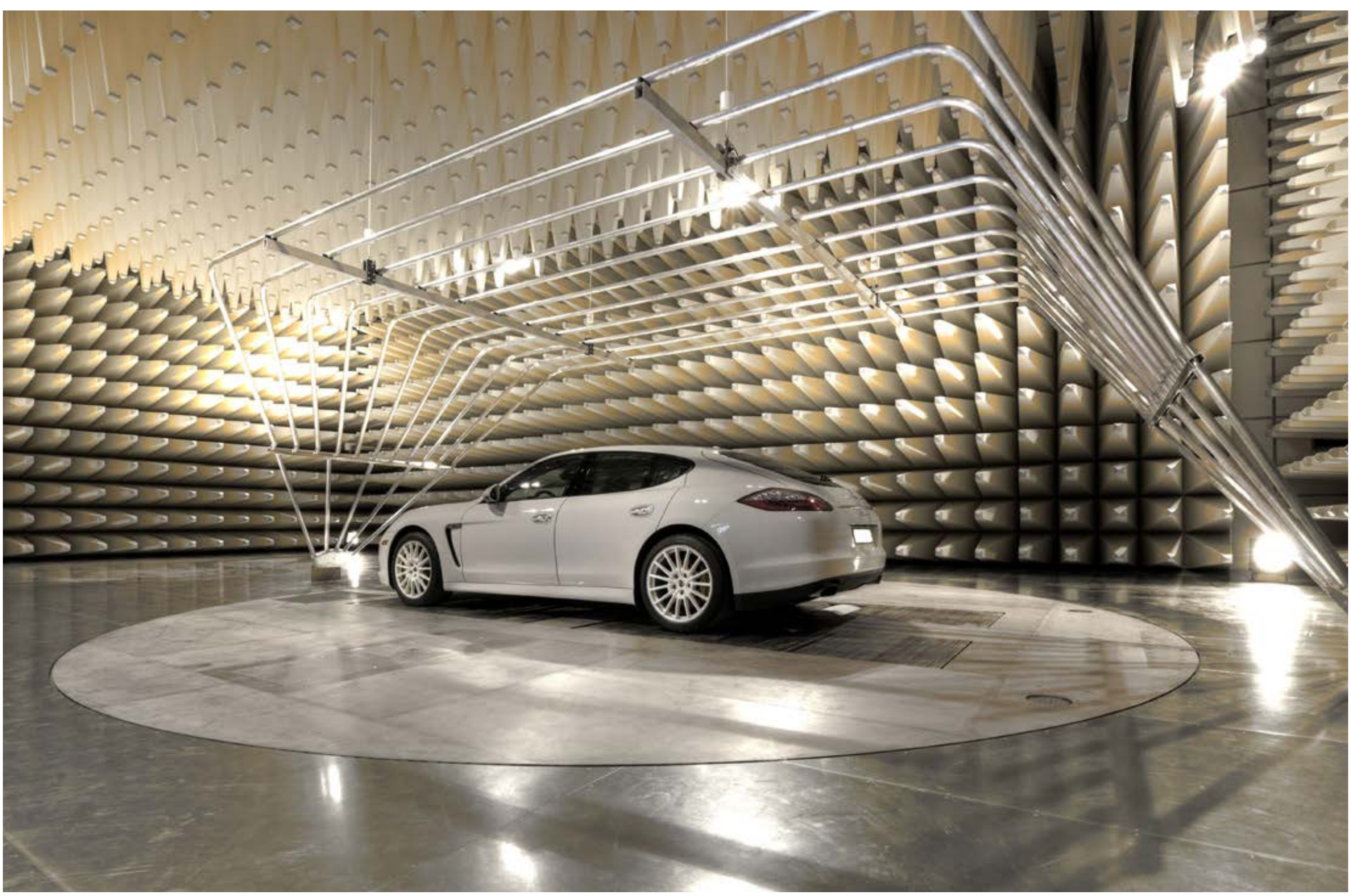
Consumer demand for more entertainment, safety, and communication options within automobiles has significantly increased both the density of electronic components and the number of on-board wired and wireless signals. The result: an ever-expanding range of signals contained within the same car-sized fixed space.



USING AN OSCILLOSCOPE TO VERIFY EMC TESTS FOR AUTOMOTIVE ELECTRONICS

It's important for electronic components used within automobiles to be robust and to function correctly in a real-world environment increasingly filled with electromagnetic (EM) waves originating from cell phones, Bluetooth headsets, satellite radio, AM/FM radio, wireless internet, radar, and countless other potential sources of electromagnetic interference (EMI). Ensuring robustness means meeting rigorous EMI immunity standards within a controlled environment. Electronic control units (ECUs) under test typically must comply with strict ISO (International Organization for Standardization) guidelines and with requirements negotiated between the automobile manufacturer and the ECU component supplier.

As an example of typical frequencies and field strengths seen during testing, consider the radiated RF immunity test described in ISO/IEC 61000-4-21. The test utilizes a reverberant chamber containing a mechanical-mode tuner. When a sufficient number of tuner positions have been obtained at a given test frequency, the tuner produces a statistically uniform field within the useable volume of the chamber with test frequencies ranging from 0.4 to 3 GHz and field strengths as high as 200 V/m (CW and AM) and 600 V/m (radar pulses). Field strengths in such test environments are too high, both for electronic test equipment to monitor the signals, and for test personnel to be safely within the reverberent chamber. Thus, measurement instruments and test personnel remain outside of the sealed chamber. Fiber-optic transmitter and receiver units and fiber optic cables transport the signal from the ECU inside of the chamber to the test equipment outside of the chamber.

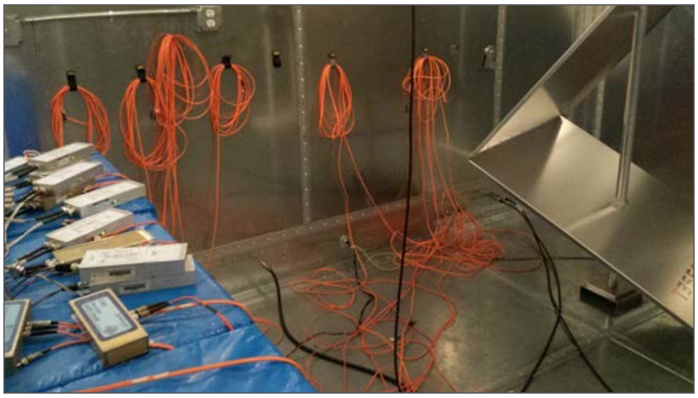


Figure 1: Reverberant chamber equipped with a mode tuner (right) and fiber optic transmitters (left). Note that the ECU and antennas were present also, but are not shown in this photo.

Figure 1 shows a real-world test configuration for deviation detection in immunity testing, photographed from inside the sealed chamber (while the transmitting antenna was powered off). Note that the mode tuner is shown to the right of the chamber. The left side of the chamber has CAN bus fiber-optic transmitters placed on a foam bench having a relative permittivity of <1.4 and located within the usable volume of the reverberant chamber. The fiber-optic transmitters optically convert the output signals from the ECU under test. The signals are transported through the chamber by means of RF-hardened fiber-optic cables that exit the chamber near the floorboard via waveguides.

In addition to immunity to EMI, automotive electronic components are designed to have a certain level of immunity to ESD. Test levels for ESD immunity range from 2 kV to 25 kV. Voltage is typically applied in steps until it reaches an established limit. Before an ESD simulator is applied to the ECU under test, it must first be calibrated using an oscilloscope. *Figure 2* shows an ESD simulator gun applying a contact discharge into a current shunt target that is connected to the oscilloscope's 50 Ω DC-coupled input via a double-shielded cable and inline attenuators.

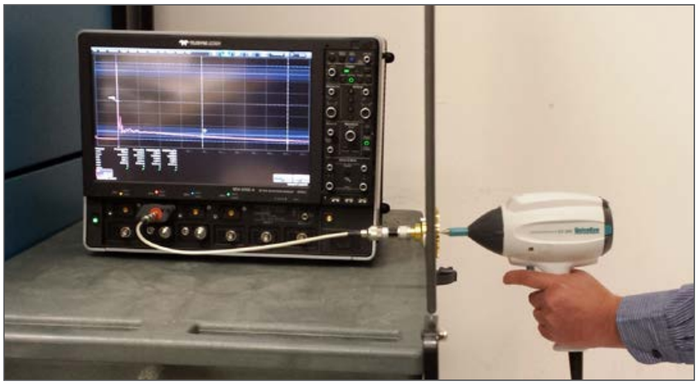


Figure 2: An ESD gun discharges into a current shunt target. The resulting pulse waveform is captured and measured with an oscilloscope.

Verifying the ESD simulator includes characterizing the discharge pulse waveform. The second edition of ISO 10605 identifies rise time, first peak current, current at t1, and current at t2 as the parameters of interest. The values of t1 and t2 vary with the value of R and C in a given RC network for the purpose of verifying its time constant. An oscilloscope rapidly and automatically characterizes each of these measurement parameters.

Another important measurement requirement for automotive electronics is the Electrical Fast Transient (EFT), a phenomenon in which current flow is instantaneously interrupted, resulting in arcing between contacts. Common causes for EFT can include relay-contact bounce, opening and closing of circuit breakers, switching of inductive loads, and powering down equipment. Breakdown of the air gap between electrical contacts often triggers a rapid burst of EFT pulses. The sudden sequence of energy bursts from EFT pulses can couple into nearby electrical paths, risking digital signal corruption of automotive electronic systems and ensuing potential malfunctions. Therefore, electronic products must be tested to ensure safe operation in the presence of EFT events.

Figure 3 depicts a series of EFT bursts acquired as segments using an oscilloscope's sequential capture mode. Note that the long gap time between bursts has been removed by the process of sequential capture, leaving only the desired burst waveform within the acquisition.

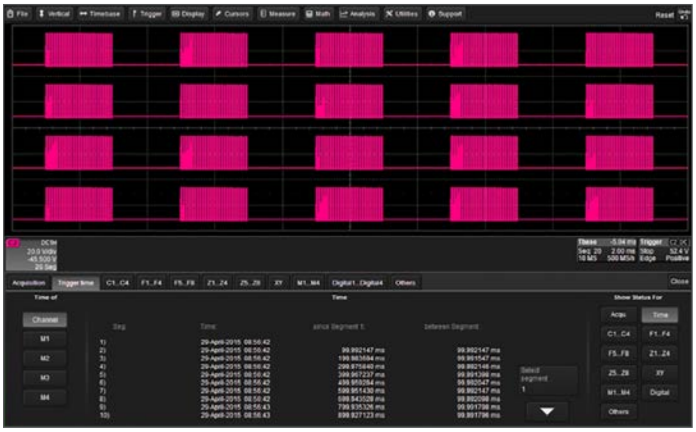


Figure 3: EFT bursts acquired as segments and time stamped

In contrast, *Figure 4* shows EFT pulses, rather than bursts, acquired as segments.

Potentially tens of thousands of individual pulses could be acquired. Note that the time scaling for sequential burst capture here is 2 ms per division (corresponding to a 20-ms time capture window), while the time scaling for sequential pulse capture is 100 ns per division (corresponding to a 1-ms time capture window).

Figure 4: EFT pulses acquired and time stamped as segments

The intersegment time stamps in EFT burst capture mode shows an inter-burst timing of approximately 100 ms between bursts, while the intersegment time stamps in EFT pulse capture mode shows an inter-pulse timing of approximately 100 ms between pulses. The time scaling between the two captures differs by a factor of 1000x, highlighting the contrast between the characterizations of either individual EFT pulses or EFT bursts.

A final consideration is voltage drop and interruption testing. To verify that devices will operate properly in the presence of a voltage supply interruption, electronics must be tested for voltage dips (defined as a sudden reduction in voltage followed by recovery to the original voltage), short interruptions (defined as a complete absence of supply voltage for a short period of time followed by a recovery to the original voltage), and voltage variations (defined as gradual changes of the supply voltage to a higher or lower voltage value than the rated voltage).

To ensure that the signal generator outputs the intended conditions to simulate these effects, the signal generator waveform characteristics must be validated with an oscilloscope before connecting the generator to the electronic units under test.

Figure 5 shows an example (abbreviated) waveform from the standard ISO 16750-2. This waveform shape is used to verify the reset behavior of devices with reset functionality (such as microcontrollers) at different voltage drops. Note that the waveform begins at 13.55 V. In the first dip, the voltage level drops approximately 10.6% to 12.12 V where it dwells for 105 ms, then the level returns to its original 13.55-V battery level. One half second later, the second dip lowers the voltage level 21.2% to 10.68 V, where it dwells for 105 ms before returning to the original 13.55 V. This process of decrementing the voltage-dip level and returning to source voltage continues at fixed intervals until the level reaches zero volts.

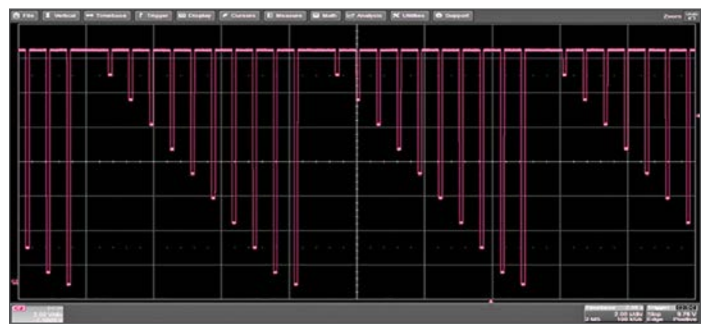


Figure 5: Signal used for testing below-battery voltage levels.

Testing the time duration and voltage level reduction of each dip is a time-consuming and error-prone task when relying on a live operator to measure using cursors from a single waveform capture. Not only do cursors rely on the operator's hand-eye coordination, but they are also specified to yield a 2% measurement inaccuracy. In addition, significant time is lost as an operator manually places each cursor at the correct time and voltage level. Lastly, the results will cover only a single acquisition, which by definition does not provide statistical significance.

Figure 6 shows a measurement method that resolves each of the problems listed above. With this method, we use a negative going runt trigger to isolate a specific dip level. A runt trigger is a hardware trigger selection in which the waveform must first pass through one threshold, but not cross through a second threshold, to meet the trigger criteria. By selecting the runt polarity to be negative going, the trigger circuit isolates a voltage dip, which meets the criteria. Because the trigger circuit can lock onto this specific dip level each time it occurs, the oscilloscope rapidly accumulates measurement statistics. In *Figure 6*, the trigger circuit has locked onto the first dip. With display persistence turned on, one can see that the first dip is the only dip acquired by the oscilloscope (*Figure 6*, right, pink). A histogram further displays quantified results with statistical significance. In this case, the histogram plots the distribution of pulse width along the X-axis, with the number of occurrences of each width displayed on the Y-axis (*Figure 2*, right, blue). Statistics showing measurement results are tallied in the measurement parameter table (*Figure 6*, right, bottom).

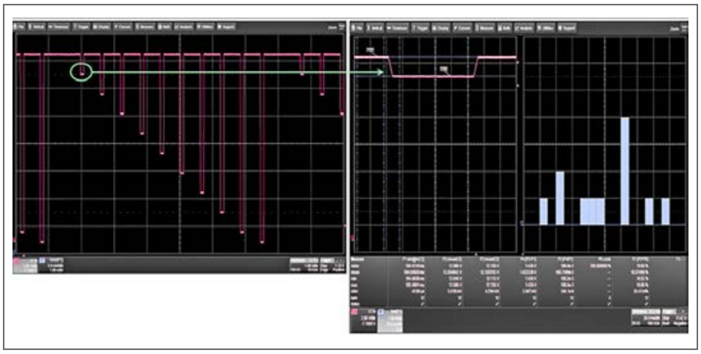


Figure 6: Runt trigger, measurement parameters and histogram quantify the first dip both in terms of voltage and percent

Automotive EMI and ESD testing involves many forms of testing. Oscilloscopes are well equipped to perform the rapid parametric measurements required for EMC immunity testing as well as calibration of an ESD simulation simulator. Using a fast-segmented acquisition mode, both electrical fast transient pulses and bursts can be captured and characterized. New techniques have been developed for validating the setup for voltage drop tests, providing rapid and accurate characterization.

Note: Photographs and images used in this article appear courtesy of Hitachi Automotive Systems, Farmington Hills, MI (an ISO-accredited lab).

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MILITARY + AEROSPACE

MILITARY & AEROSPACE EMC EQUIPMENT MANUFACTURERS

Introduction

The following chart is a quick reference guide of test equipment and includes everything you'll need from the bare minimum required for key evaluation testing, probing, and troubleshooting, to setting up a full in-house precompliance or full compliance test lab for military and aerospace testing. The list includes amplifiers, antennas, current probes, ESD simulators, LISNs, near field probes, RF signal generators, spectrum analyzers, EMI receivers, and TEM cells. Equipment rental companies are also listed. The products listed can help you evaluate radiated and conducted emissions, radiated and conducted immunity, and a host of other immunity tests, such as the new ESD test for MIL-STD-461G.

EMC Equipment Manufacturers		Type of Product/Service															
Manufacturer	Contact Information - URL	Amplifiers	Antennas	Conducted Immunity	Current Probes	EMC Filters	EMC Testing	ESD Simulators	LISNs	Near Field Probes	Pre-Compliance Test	Radiated Immunity	Rental Companies	RF Signal Generators	Software	Spectrum Analyzers/EMI Receivers	TEM Cells
A.H. Systems	www.ahsystems.com	X	X		X						X						
Aaronia AG	www.aaronia.com	X	X								X					X	
Advanced Test Equipment Rentals	www.atecorp.com	X	X	X	X			X	X	X	X	X	X	X		X	X
ALTAIR	www.altair.com														X		
AR RF/Microwave Instrumentation	www.arworld.us	X	X	X					X		X	X		X	X	X	
Anritsu	www.anritsu.com		X								X			X		X	
Electro Rent	www.electrorent.com	X		X				X	X		X	X	X	X		X	
EM Test	www.emtest.com/home.php			X							X						X
EMC Partner	www.emc-partner.com			X				X									
Empower RF Systems	www.empowerrf.com	X										X					
Fischer Custom Communications	www.fischercc.com				X				X	X	X						
Gauss Instruments	www.gauss-instruments.com/en/															X	
Haefley-Hippotronics	www.haefely-hipotronics.com			X				X									
HV Technologies, Inc.	www.hvtechnologies.com	X	X	X								X		X		X	
Instrument Rental Labs	www.testequip.com	X		X				X	X		X	X	X	X		X	
Instruments For Industry (IFI)	www.ifi.com	X		X								X					
ITG Electronics	www.itg-electronics.com					X											
Keysight Technologies	www.keysight.com/main/home.jspx?cc=US&lc=eng								X	X	X			X	X	X	
Microlease	www.microlease.com/us/home	X		X				X	X		X	X	X	X		X	
Milmega	www.milmega.co.uk	X		X								X					
Narda/PMM	www.narda-sts.it/narda/default_en.asp	X	X	X					X		X	X				X	
Noiseken	www.noiseken.com			X				X			X						
Ophir RF	www.ophirrf.com	X		X													
Pearson Electronics	www.pearsonelectronics.com				X												
PPM Test	www.ppmtest.com		X								X	X			X	X	
R&B Laboratory	www.rblaboratory.com						X										
Rigol Technologies	www.rigolna.com	X			X					X	X			X	X	X	
Rohde & Schwarz	www.rohde-schwarz.com/us/home_48230.html	X	X	X	X				X	X	X	X		X	X	X	
Siglent Technologies	www.siglentamerica.com									X	X			X	X	X	
Signal Hound	www.signalhound.com				X					X	X			X	X	X	
Solar Electronics	www.solar-emc.com	X	X		X		X	X		X					X		
TekBox Technologies	www.tekbox.net	X							X	X	X				X		X
Tektronix	www.tek.com									X	X				X	X	
Teseq	www.teseq.com/en/index.php	X		X	X			X			X	X					X
Test Equity	www.testequity.com/leasing/	X		X				X	X		X	X	X	X		X	
Thermo Keytek	www.thermofisher.com/us/en/home.html			X				X						X			
Thurlby Thandar (AIM-TTi)	www.aimtti.us										X			X		X	
Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X		X	X				X	
TPI	www.rf-consultant.com										X			X			
Transient Specialists	www.transientspecialists.com			X								X					X
TRSRenTelCo	www.trsrentelco.com/categories/spectrum-analyzers/emc-test-equipment	X	X	X					X		X	X	X	X		X	
Vectawave Technology	www.vectawave.com	X															
Windfreak Technologies	www.windfreaktech.com										X			X			

REFERENCES

(ARTICLE LINKS, DIRECTORIES, CONFERENCES, & LINKEDIN GROUPS)

LINKS TO LONGER ARTICLES

"MIL-STD-461G – The Compleat Review"
https://interferencetechnology.com/mil-std-461g-compleat-review/

"Selecting the Proper EMI Filter Circuit For Military and Defense Applications"
https://interferencetechnology.com/selecting-proper-emi-filter-circuit-military-defense-applications/

"Why is there AIR (In MIL-STD-461G)?"
https://interferencetechnology.com/air-mil-std-461g/

"Overview of the DO-160 standard"
https://interferencetechnology.com/overview-of-the-do-160-standard/

"Design for DO-160 pin injection for indirect lightning"
https://interferencetechnology.com/design-for-do-160-pin-injection-for-indirect-lightning/

"DO-160 cable bundle testing for indirect lightning"
https://interferencetechnology.com/do-160-critical-sections-cable-bundle-for-indirect-lightning/

PUBLICATIONS

2019 Military & Aerospace EMC Guide
Curated specifically for engineers working in the EMC field—as well as the manufacturers and suppliers of components, test equipment, and services for those engineers.
https://learn.interferencetechnology.com/2019-military-and-aerospace-emc-guide/

CONFERENCE DIRECTORIES

AFCEA Events:
www.afcea.org/site/

ASCE Events:
https://www.asce.org/aerospace-engineering/aerospace-conferences-and-events/

ASD Events:
https://www.asdevents.com/aerospace-defence

Aviation Week Event Calendar:
www.events.aviationweek.com/current/Public/Enter.aspx

Defense Conferences:
www.defenseconference.com/

Global Edge (MSU):
https://globaledge.msu.edu/industries/aerospace-and-defense/events/

IEEE AESS Events:
www.ieee-aess.org/conferences/home

Jane's Events:
www.janes.com/events

LINKEDIN GROUPS

- Aerospace and Defense Subcontractor and Suppliers
- Aerospace and Security and Defence Technology and Business (Defence spelled correctly)
- Defense and Aerospace
- EMP Defense Council
- High Intensity RF (HIRF) Professionals
- Radio, Microwave, Satellite, and Optical Communications
- RF/Microwave Aerospace and Defense Applications
- RF and Microwave Community

TABLE OF NEW EQUIPMENT ALLOWED/REQUIRED IN MIL-STD-461G

Tony Keys
EMC Analytical Services

Ken Javor
EMC Compliance

The following table was compiled by Ken Javor, of EMC Compliance. The updated changes to MIL-STD-461G require some new equipment. One of these changes allows the use of time domain EMI receivers, which will help speed up the testing, due to their fast FFT-based signal acquisition. Following is a list of some specific changes and equipment requirements:

CS101 *(Conducted Susceptibility, Power Leads)–There is now a requirement to measure induced AC power line ripple. This requires a new "*power ripple detector", which is a specially designed isolation transformer that matches the power line to 50 ohms.

CS114 *(Conducted Susceptibility, Bulk Cable Injection)–This injection probe test now requires the use of a current probe calibration fixture to validate the test level* during pre-calibration.

CS117 *(Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads)–Thi*s is a new test added to MIL-STD-461G and requires a lightning transient simulator.

CS118 *(Conducted Susceptibility, Personnel Borne Electrostatic Discharge)–This* is a new test added to MIL-STD-461G and requires a standard electrostatic discharge simulator.

RS103 *(Radiated Susceptibility, Electric Field)–This test requires an E-field antenna that can go down to 2 MHz.*

Table of New Equipment Required for Latest Updates to MIL-STD-461G			
Requirement	Equipment Type	Vendor(s)	Websites
General	Time Domain EMI receivers*	Amplifier Research Gauss Instruments Keysight	http://www.arworld.us/html/dsp-receiver-multistar.asp http://www.gauss-instruments.com/en/products/tdemi http://www.keysight.com/en/pdx-x201870-pn-N9038A/mxe-emi-receiver-3-hz-to-44-ghz?cc=UG&lc=eng
CS101	Frequency domain ripple monitoring transducer* High-voltage differential probe, 100 MHz, 1k V(RMS) Digital Oscilloscopes (200 MHz - 4 GHZ, 5/10 GSa/s)	Pearson Electronics Rohde & Schwarz Rohde & Schwarz Rohde & Schwarz	https://www.pearsonelectronics.com/news/225-mil-std-461g-cs101-simplified https://www.rohde-schwarz.com/us/product/rtzd01-productstartpage_63493-34629.html https://www.rohde-schwarz.com/us/product/rto-productstartpage_63493-10790.html or https://www.rohde-schwarz.com/vn/product/rte-productstartpage_63493-54848.html
CS114	Current probe calibration fixture	Solar Electronics	http://www.solar-emc.com/RFI-EMI.html (scroll to bottom of page)
CS117	Indirect lightning test systems	Solar Electronics	http://www.solar-emc.com/2654-2.html
CS118	ESD gun	EMC Partner EM Test LISUN Group Noiseken TESEQ	https://www.emc-partner.com/products/immunity/esd/esd-generator http://www.emtest.com/products/productGroups/ESD_generators.php http://www.lisungroup.com/product-id-318.html http://www.noiseken.com/modules/products/index.php?cat_id=1 http://www.teseq.com/product-categories/esd-simulators.php
RS103	1 – 18 GHz electric field probe (most test facilities already have one)	Amplifier Research ETS/Lindgren NARDA	http://www.arworld.us/html/field-analyzers-field-monitoring.asp http://www.ets-lindgren.com/EMCProbes http://www.narda-sts.us/products_highfreq_bband.php

* Specified as acceptable for use, but not required.

MILITARY RELATED DOCUMENTS AND STANDARDS

The following references are not intended to be all inclusive, but rather a representation of available sources of additional information and point of contacts.

Document Number	Title
MIL-HDBK-235-1C	Military Operational Electromagnetic Environment Profiles Part 1C General Guidance, 1 Oct 2010.
MIL-HDBK-237D	Electromagnetic Environmental Effects and Spectrum Certification Guidance for the Acquisition Process, 20 May 2005.
MIL-HDBK-240A	Hazards of Electromagnetic Radiation to Ordnance (HERO) Test Guide, 10 Mar 2011.
MIL-HDBK-263B	Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices), 31 Jul 1994.
MIL-HDBK-274A	Electrical Grounding for Aircraft Safety, 14 Nov 2011.
MIL-HDBK-335	Management and Design Guidance Electromagnetic Radiation Hardness for Air Launched Ordnance Systems, Notice 4, 08 Jul 2008.
MIL-HDBK-419A	Grounding, Bonding, and Shielding for Electronic Equipment and Facilities, 29 Dec 1987.
MIL-HDBK-454B	General Guidelines for Electronic Equipment, 15 Apr 2007.
MIL-HDBK-1004-6	Lightning Protection, 30 May 1988.
MIL-HDBK-1195	Radio Frequency Shielded Enclosures, 30 Sep 1988.
MIL-HDBK-1512	Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods, 30 Sep 1997.
MIL-HDBK-1857	Grounding, Bonding and Shielding Design Practices, 27 Mar 1998.
MIL-STD-188-124B	Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communications-Electronics Facilities and Equipment, 18 Dec 2000.
MIL-STD-188-125-1	High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C41 Facilities Performing Critical, Time-Urgent Missions Part 1 Fixed Facilities, 17 Jul 1998.
MIL-STD-220C	Test Method Standard Method of Insertion Loss Measurement, 14 May 2009.
MIL-STD-331C	Fuze and Fuze Components, Environmental and Performance Tests for, 22 Jun 2009.
MIL-STD-449D	Radio Frequency Spectrum Characteristics, Measurement of, 22 Feb 1973.
MIL-STD-461F	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 10 Dec 2007.
MIL-STD-461G	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 11 Dec 2015.
MIL-STD-464C	Electromagnetic Environmental Effects Requirements for Systems, 01 Dec 2010.
MIL-STD-704F	Aircraft Electric Power Characteristics, 12 Mar 2004.
MIL-STD-1275E	Characteristics of 28 Volt DC Input Power to Utilization Equipment in Military Vehicles, 22 March 2013 (MIL-STD-1275F expected in 2020)
MIL-STD-1310H	Standard Practice for Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility Electromagnetic Pulse (EMP) Mitigation and Safety, 17 Sep 2009.
MIL-STD-1377	Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding Hazards of EM Radiation to Ordnance; Measurement of, 20 Aug 1971.
MIL-STD-1399	Section 300 Part 2 Medium Voltage Electric Power, Alternating Current 25 September 2018.

MIL-STD-1542B	Electromagnetic Compatibility and Grounding Requirements for Space System Facilities, 15 Nov 1991. MIL-STD-1605 Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ships), 08 Oct 2009.
MIL-STD-1686C	Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices). 25 Oct 1995.
ADS-37A-PRF	Electromagnetic Environmental Effects (E3) Performance and Verification Requirements, 28 May 1996.
DOD-STD-1399	Section 070 Part 1 D.C. Magnetic Field Environment, Notice 1, 30 Nov 1989.
DoDI 3222.03	DoD Electromagnetic Environmental Effects (E3) Program, 24 Aug 2014.
DoDD 4650.01	Policy and Procedures for Management and Use of the Electromagnetic Spectrum, 09 Jan 2009.
DoDI 6055.11	Protecting Personnel from Electromagnetic Fields, 19 Aug 2009.

AEROSPACE STANDARDS

AIAA STANDARDS

http://www.aiaa.org/default.aspx

Document Number	Title
S-121-2009	Electromagnetic Compatibility Requirements for Space Equipment and Systems

RTCA STANDARDS

www.rtca.org/

Document Number	Title
DO-160G	Environmental Conditions and Test Procedures for Airborne Equipment
DO-160G Change 1	Environmental Conditions and Test Procedures for Airborne Equipment
DO-233	Portable Electronic Devices Carried on Board Aircraft
DO-235B	Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band
DO-292	Assessment of Radio Frequency Interference Relevant to the GNSS L5/E5A Frequency Band
DO-294C	Guidance on Allowing Transmitting Portable Electronic Devices (T-PEDs) on Aircraft
DO-307	Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance
DO-357	User Guide: Supplement to DO-160G
DO-363	Guidance for the Development of Portable Electronic Devices (PED) Tolerance for Civil Aircraft
DO-364	Minimum Aviation System Performance Standards (MASPS) for Aeronautical Information/ Meteorological Data Link Services
DO-363	Guidance for the Development of Portable Electronic Devices (PED) Tolerance for Civil Aircraft
DO-307A	Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance

SAE STANDARDS

www.sae.org/

Document Number	Title
ARP 5583A	Guide to Certification of Aircraft in a High Intensity Radiation (HIRF) Environment

SUMMARY OF MILITARY AND AEROSPACE EMC TESTS

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Introduction

Military and aerospace EMC tests cover a wide range of products. While the standards, including limits and test methods may differ, all EMC test standards have a few things in common. The most basic are the limits for emissions and the types and levels of susceptibility testing.

Emissions tests (and their associated limits) are put in place for military and aerospace equipment primarily to protect other systems from interference. These other systems may or may not include radio equipment. Examples abound showing the effect of inadequate EMC design. The Interference Technology 2016 Military EMC Guide *(Reference 1) provides three such examples on page 11.*

SUMMARY OF MILITARY AND AEROSPACE EMC TESTS

While many military and aerospace EMC issues may be addressed by operational changes, testing is still required to find weaknesses.

Military and aerospace EMC testing is performed at the system and subsystem levels. MIL-STD-464C provides requirements at the system or platform level. The latest version, MIL-STD-461G, provides requirements at the equipment or subsystem level. *Reference 1* provides details on both of the standards, but this article will highlight some key tests, particularly as they relate to MIL-STD-461G.

Ratio	Description
CE101	Conducted Emissions, Audio Frequency Currents, Power Leads
CE102	Conducted Emissions, Radio Frequency Potentials, Power Leads
CE106	Conducted Emissions, Antenna Port
CS101	Conducted Susceptibility, Power Leads
CS103	Conducted Susceptibility, Antenna Port, Intermodulation
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation
CS109	Conducted Susceptibility, Structure Current
CS114	Conducted Susceptibility, Bulk Cable Injection
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads
CS117	Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads
CS118	Conducted Susceptibility, Personnel Borne Electrostatic Discharge
RE101	Radiated Emissions, Magnetic Field
RE102	Radiated Emissions, Electric Field
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs
RS101	Radiated Susceptibility, Magnetic Field
RS103	Radiated Susceptibility, Electric Field
RS105	Radiated Susceptibility, Transient Electromagnetic Field

Table 1: MIL-STD-461G Emission and susceptibility requirements

MIL-STD-461G divides test requirements into four basic types. Conducted Emissions (CE), Conducted Susceptibility (CS), Radiated Emissions (RE) and Radiated Susceptibility (RS). There are a number of tests in each category and the following table, taken from MIL-STD-461G Table IV, shows these test methods.

A brief description of each these tests will be provided below. These are summarized from a more detailed introduction to MIL-STD-461G, which is found in the *References 1, 2,* and *3*. Keep in mind that a complete copy of MIL-STD-461G is 280 pages, so any information here is brief and the standard must be read and understood. A copy of MIL-STD-461G may be obtained free. See *Reference 4*.

CE101 Conducted Emissions, Audio Frequency Currents, Power Leads. CE101 is applicable from 30 Hz to 10 kHz for leads that obtain power from sources that are not part of the EUT. There is no requirement on output leads from power sources. Emission levels are determined by measuring the current present on each power lead. There is different intent behind this test based on the usage of equipment and the military service involved. The specific limits are based on application, input voltage, frequency, power, and current.

CE102 Conducted Emissions, Radio Frequency Potentials, Power Leads. CE102 is applicable from 10 kHz to 10 MHz for leads that obtain power from sources that are not part of the EUT. There is no requirement on output leads from power sources. The lower frequency portion is to ensure EUT does not corrupt the power quality (allowable voltage distortion) on platform power buses. Voltage distortion is the basis for power quality so CE102 limit is in terms of voltage. The emission levels are determined by measuring voltage present at the output port of the LISN. Unlike CE101, CE102 limits are based on voltage. The basic limit is relaxed for increasing source voltages, but independent of current. Failure to meet the CE102 limits can often be traced to switching regulators and their harmonics.

CE106 Conducted Emissions, Antenna Port. CE106 is applicable from as low as 10 kHz to as high as 40 GHz (depending on the operating frequency) for antenna terminals of transmitters, receivers, and amplifiers and is designed to protect receivers on and off the platform from being degraded by antenna radiation from the EUT. CE106 is not applicable for permanently mounted antennas.

CS101 Conducted Susceptibility, Power Leads. CS101 is applicable from 30 Hz to 150 kHz for equipment and subsystem AC and DC power input leads. For DC powered equipment, CS101 is required over the entire 30 Hz to 150 kHz range. For AC powered equipment, CS101 is only required from the second harmonic of the equipment power frequency (120 Hz for 60 Hz equipment) to 150 kHz. In general, CS101 is not required for AC powered equipment when the current draw is greater than 30 amps per phase. The exception is when the equipment operates at 150 kHz or less and has an operating sensitivity of 1 µV or better.

The intent is to ensure that performance is not degraded from ripple voltages on power source waveforms.

CS103, CS104 and CS105 Conducted Susceptibility, Antenna Port, Intermodulation, Rejection of Undesired Signals and Cross-Modulation. This series of receiver front-end tests include test methods for Intermodulation (CS103), Rejection of Undesired Signals (CS104) and Cross Modulation (CS105). They were designed for traditional tunable super-heterodyne type radio receivers. Due to the wide diversity of radio frequency subsystem designs being developed, the applicability of this type of requirement and appropriate limits need to be determined for each procurement. Also, requirements need to be specified that are consistent with the signal processing characteristics of the subsystem and the particular test procedures to be used to verify the requirement.

CS109 Conducted Susceptibility, Structure Current. CS109 is a highly specialized test applicable from 60 Hz to 100 kHz for very sensitive Navy shipboard equipment (1 µV or better) such as tuned receivers operating over the frequency range of the test. Handheld equipment is exempt from CS109. The intent is to ensure that equipment does not respond to magnetic fields caused by currents flowing in platform structure. The limit is derived from operational problems due to current conducted on equipment cabinets and laboratory measurements of response characteristics of selected receivers.

CS114 Conducted Susceptibility, Bulk Cable Injection. CS114 is applicable from 10 kHz to 200 MHz for all electrical cables interfacing with the EUT enclosures.

CS115 Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation. CS115 is applicable to all electrical cables interfacing with EUT enclosures. The primary concern is to protect equipment from fast rise and fall time transients that may be present due to platform switching operations and external transient environments such as lightning and electromagnetic pulse.

CS116 Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads. CS116 is applicable to electrical cables interfacing with each EUT enclosure and also on each power lead. The concept is to simulate electrical current and voltage waveforms occurring in platforms from excitation of natural resonances with a control damped sine waveform.

CS117 Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads. CS117 is one of two new test methods added to MIL-STD-461G. CS117 is applicable to safety-critical equipment interfacing cables and also on each power lead. Applicability for surface ship equipment is limited to equipment located above deck or which includes interconnecting cables, which are routed above deck. The concept is to address the equipment-level indirect effects of lightning as outlined in MIL-STD-464 and it is not intended to address direct effects or nearby lightning strikes.

CS118 Conducted Susceptibility, Personnel Borne Electrostatic Discharge. CS118 is applicable to electrical, electronic, and electromechanical subsystems and equipment that have a man-machine interface. It should be noted that CS118 is not applicable to ordnance items. The concept is to simulate ESD caused by human contact and test points are chosen based on most likely human contact locations. Multiple test locations are based on points and surfaces which are easily accessible to operators during normal operations. Typical test points would be keyboard areas, switches, knobs, indicators, and connector shells as well as on each surface of the EUT.

RE101 Radiated Emissions, Magnetic Field. RE101 is applicable from 30 Hz to 100 kHz and is used to identify radiated emissions from equipment and subsystem enclosures, including electrical cable interfaces. RE101 is a specialized requirement, intended to control magnetic fields for applications where equipment is present in the installation, which is potentially sensitive to magnetic induction at lower frequencies.

RE102 Radiated Emissions, Electric Field. RE102 is applicable from 10 kHz to 18 GHz and is used to identify radiated emissions from the EUT and associated cables. It is intended to protect sensitive receivers from interference coupled through the antennas associated with the receiver.

RE103 Radiated Emissions, Antenna Spurious and Harmonic Outputs. RE103 may be used as an alternative for CE106 when testing transmitters with their intended antennas. CE106 should be used whenever possible. However, for systems using active antenna or when the antenna is not removable or the transmit power is too high, RE103 should be invoked. RE103 is applicable and essentially identical to CE106 for transmitters in the transmit mode in terms of frequency ranges and amplitude limits. The frequency range of test is based on the EUT operating frequency.

RS101 Radiated Susceptibility, Magnetic Field RS101 is a specialized test applicable from 30 Hz to 100 kHz for Army and Navy ground equipment having a minesweeping or mine detection capability, for Navy ships and submarines, that have an operating frequency of 100 kHz or less and an operating sensitivity of 1 µV or better (such as 0.5 µV), for Navy aircraft equipment installed on ASW capable aircraft, and external equipment on aircraft that are capable of being launched by electromagnetic launch systems. The requirement is not applicable for electromagnetic coupling via antennas. RS101 is intended to ensure that performance of equipment susceptible to low frequency magnetic fields is not degraded.

RS103 Radiated Susceptibility, Electric Field. RS103 is applicable from 2 MHz to 18 GHz in general, but the upper frequency can be as high as 40 GHz if specified by the procuring agency. It is applicable to both the EUT enclosures and EUT associated cabling. The primary concern is to ensure that equipment will operate without degradation in the presence of electromagnetic fields generated by antenna transmissions both onboard and external to the platform. The limits are platform dependent and are based on levels expected to be encountered during the service life of the equipment. It should be noted that RS103 may not necessarily be the worst case environment to which the equipment may be exposed.

RS105 Radiated Susceptibility, Transient Electromagnetic Field. RS105 is intended to demonstrate the ability of the EUT to withstand the fast rise time, free-field transient environment of EMP. RS105 applies for equipment enclosures which are directly exposed to the incident field outside of the platform structure or for equipment inside poorly shielded or unshielded platforms and the electrical interface cabling should be protected in shielded conduit.

Not all tests are required for each type of device or intended use environment. MIL-STD-461G provides a matrix in Table V showing how these tests are used based on the intended use of the device.

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Type of Product/Service																		
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS109	CS114	CS115	CS116	CS117	CS118	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	L	S	L	A	S	A	L	S	A	A	L	L	A	L
Submarines	A	A	L	A	S	L	S	L	A	S	L	S	S	A	A	L	L	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S		A	A	A	L	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S		A	A	A	L	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S		A	A	A	L	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S		A	A	A	L	A		A	L		A	
Ground Army		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	
Ground Navy		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	L
Ground, Air Force		A	L	A	S	S	S		A	A	A		A		A	L		A	

Legend:
A: Applicable (in green)
L: Limited as specified in the individual sections of this standard. (in yellow)
S: Procuring activity must specify in procurement documentation. (in red)

Table 2: MIL-STD-461G Requirement matrix

Again, the reader is referred to *References 1* through *3* for more details, or to MIL-STD-461G for the details of the standard (*Reference 4*). This guide also provides a list of standards that apply to various military equipment.

A popular and common aerospace EMC requirement required by the FAA for commercial aircraft is RTCA/DO-160, Environmental Conditions and Test Procedures for Airborne Equipment. The latest version is RTCA/DO-160 G, published on December 8, 2010, with Change 1 published on December 16, 2015. DO-160 covers far more than just EMC issues, but the EMC subjects covered include input power conducted emissions and susceptibility, transients, drop-outs and hold-up; voltage spikes to determine whether equipment can withstand the effects of voltage spikes arriving at the equipment on its power leads, either AC or DC; audio frequency conducted susceptibility to determine whether the equipment will accept frequency components of a magnitude normally expected when the equipment is installed in the A/C; induced signal susceptibility to determine whether the equipment interconnect circuit configuration will accept a level of induced voltages caused by the installation environment; RF emissions and susceptibility; lightning susceptibility; and electrostatic discharge susceptibility.

This document can be purchased from RTCA on their website (*Reference 5*). A manufacturer producing products subject to the requirements in RTCA/DO-160 should obtain a copy and ensure they have a complete understanding of the content of the document and that any laboratory testing to it is properly accredited.

Examples of differences in test equipment between commercial and military standards.

There are differences in test equipment used compared with commercial EMC tests. Some examples are provided below.

Where 50 µH LISNs are universally required for commercial EMC tests, there are specific cases for CE01 and CE02 tests where a 5 µH LISN is called out. Limits for CE101 tests are provided in dBµA. LISNs are only used for line impedance stabilization. The measurements are taken with current probes. Limits for CE102, on the other hand, are given in dBµV and measurements are taken in much the same way as for commercial standards with the receiver connected to the RF output port of one of the LISNs and the other RF output port(s) terminated in 50 Ohms. It should be noted that MIL-STD-461G calls out a 20 dB pad on the output of the LISN to protect the receiver from transients. This is not a requirement in the commercial standards, but is worth considering when setting up a laboratory for commercial testing, as well.

Military EMC standards, such as MIL-STD-461G will require the use of different antennas for radiated emissions testing. Commercial equipment standards, such as CISPR 32 and ANSI C63.4, require the use of linearly polarized antennas and do not contain requirements for magnetic field testing.

MIL-STD-461G, RE101, requires the use of a 13.3 cm loop sensor, not required in the commercial standards. A receiver capable of tuning from 30 Hz to 100 kHz is needed.

MIL-STD-461G, RE102, requires testing of radiated emissions to as low as 10 kHz. From 10 kHz to 30 MHz a 104 cm (41 inch) rod antenna is used. This frequency range is not covered in CISPR 32 or the FCC Rules for radiated emissions. Thus, the antenna and receiver requirements are different. From 30 MHz to 200 MHz a biconical antenna is used, also commonly used in commercial testing. From 200 MHz to 1 GHz a double ridge horn antenna is called out in 461G. This is different than the tuned dipole or log periodic dipole array antennas used for commercial testing.

The test procedures are also different for radiated emissions testing, requiring different laboratory set-ups and test facility types. No turntable is needed for MIL-STD-461G, nor is an antenna mast capable of moving the antenna over a range of heights.

MIL-STD-461G, RS103, can require significantly higher field intensities for radiated susceptibility testing. Where CISPR 35 requires 3 V/m from 80 MHz to 1 GHz and at a few discrete frequencies up to 5 GHz (with the option of testing a few discrete frequencies at up to 30 V/m), MIL-STD-461G requires testing from 20 V/m to as high as 200 V/m over the range of 2 MHz to 40 GHz for certain equipment. Additional test equipment (signal generators, amplifiers, antennas, etc.) is required over that needed for commercial testing.

Each test in MIL-STD-461G requires its own unique test equipment. Some may be useable for commercial testing, others may not. If testing to MIL-STD-461G, ensure that the equipment is proper for the tests being performed. A detailed understanding of the requirements in MIL-STD-461G is required to ensure that the proper equipment is being used and the laboratory is following the appropriate processes.

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1. 2016 Military EMC Guide, *Interference Technology*
2. Ken Javor, MIL-STD-461G: The "Compleat" Review, *Interference Technology*, April 2016
3. Ken Javor, Why Is There AIR (in MIL-STD-461G)?, *Interference Technology*, April 2016
4. MIL-STD-461G, December 2015, Defense Acquisition System
5. RTCA/DO-160G, RTCA, December 2010.

SELECTING THE PROPER EMI FILTER CIRCUIT FOR MILITARY AND DEFENSE APPLICATIONS

David Stanis

Introduction

Insertion loss, the term used to express a filter's ability to reduce or attenuate unwanted signals, has traditionally been measured in a 50 ohm source and 50 ohm load impedance condition, as standardized in MIL-STD-220.

In this matched 50 ohm impedance condition, various types of filter circuit configurations, single capacitor, "L's", "PI's", and "T's", will exhibit the same response for that given circuit regardless of the relationship between the input, output, and RF signal source.

SELECTING THE PROPER EMI FILTER CIRCUIT FOR MILITARY AND DEFENSE APPLICATIONS

MIL-STD-220 insertion loss tests are well defined, universal, and are excellent for monitoring filter manufacturing consistencies. However, the results can be misleading when it comes to selecting the proper filter circuit that must function in a complex impedance setting.

Passive inductive and capacitive filters are impedance sensitive devices by nature and therefore source and load conditions must be taken into consideration when selecting a filter circuit.

This is particularly true, and becomes more pronounced, when you consider that most EMI line filters are not matched filter networks. That is to say the ideal design value of the individual components that make up the network have been modified, or intentionally mismatched, in order to accommodate operating line voltages, operating line currents, and reasonable packaging schemes.

In most cases the ideal inductor for a given response has been greatly reduced in value to accommodate the operating current and reduce the DCR; therefore the capacitors have to be increased in value to achieve the required insertion loss.

This intentional mismatch, which is widely practiced throughout the industry, only affects the very low frequencies by introducing ripple in the pass-band and has little, if any, negative effect in the reject band.

CIRCUIT CONFIGURATIONS

EMI line filters are passive devices and their effect are bidirectional. They are all low-pass brute force networks, passing DC and power line frequencies with very low losses while attenuating the unwanted signals at higher frequencies.

They do not differentiate between EMI generated inside or outside the subsystem or system. They are equally effective in reducing EMI emissions as well as protecting a device from unwanted EMI entering via the power lines.

Each additional element improves the slope of the insertion loss curve. That is, the reject-band will be reached must faster with each section, or element, added. Increasing or decreasing the individual elements values does not change the slope of the curve but does affect the cutoff frequency.

More importantly, when the source and load impedance of the circuit changes, the slope of the insertion loss curve also changes. A “PI” circuit type filter, for example, is best suited when the source and load impedances are of similar values and relatively high. As these impedances become lower, the insertion loss for the “PI” filter also becomes lower. The reverse is true for “T” circuits.

If the circuit impedances varies with frequency, as most circuits do, then it is advantageous to use multiple element filters such as a “PI” or “T” circuit. In the case of a “PI” circuit that exhibits maximum or load impedance is reduced the filter still has two active elements. For all practical purposes it becomes an “L” circuit.

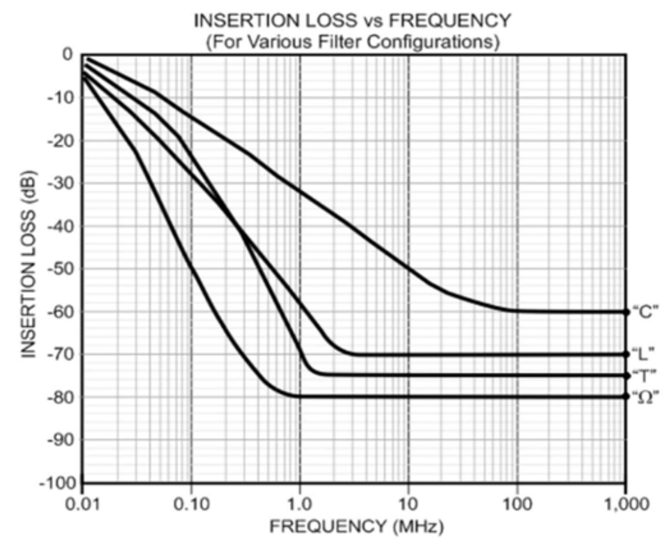

Figure 1

Additionally, the amount of filtering achievable is limited by the inductance (ESL) and resistance (ESR) in the capacitor and the parasitic capacitance in the inductors. The results are that the insertion loss curves “levels off” at approximately 80 to 90 dB.

The following is a brief description of the most popular types of EMI Filter circuits and their application. It should be pointed out that these are only general guidelines due to the fact that most impedance conditions and EMI profiles are dynamic, complex, and change with frequency.

- **Feedthrough Capacitor**–A single element shunt feedthrough capacitor has attenuation characteristics that increases at a rate of 20 dB per decade (10 dB at 10 kHz, 30 dB at 100 kHz). A feedthrough capacitor filter is usually the best choice for filtering lines that exhibit very high source and load impedances.
- **L-Circuit Filter**–A two element network consisting of a series inductive component connected to a shunt feedthrough capacitor. This type of filter network has attenuation characteristics that increases at a rate of 40 dB per decade (20 dB at 100 kHz, 60 dB at 1MHz). An “L” circuit filter is best suited for filtering lines when the source and load impedances exhibit large differences. For most applications this type of network provides the greatest performance when the inductor is facing the lower of the two impedances.
- **PI-Circuit Filter**–This is a three element filter consisting of two shunt feedthrough capacitors with a series inductive component connected between them. This three element filter has attenuation characteristics that increases at a rate of 60 dB per decade (20 dB at 15

kHz, 80 dB at 150 kHz). A "PI" circuit filter is usually the best choice when high levels of attenuation are required and when the source and load impedances are of similar values and relatively high.

- **T-Circuit Filter**–This also is a three element filter consisting of two inductive components with a single shunt feedthrough capacitors connected between them. Like the "PI" circuit filter, this device has attenuation characteristics that also increase at a rate of 60 dB per decade (20 dB at 15 kHz, 80 dB at 150 kHz). A "T" circuit filter is the best choice when high levels of attenuation are required and when the source and load impedances are of similar values and relatively low.
- **Double Circuits**–Double "L's," double "PI's", and double "T's" consisting of four and five elements are best suited when extremely high levels of attenuation are required. Double "L's" have a theoretical attenuation of 80 dB per decade, while double "PI's" and double "T's" have a theoretical attenuation of 100 dB per decade. The source and load impedance conditions that apply to the single circuit devices apply to the double circuit filters.

The following table summarizes the various source and load impedance settings and the proper filter circuit for that condition.

Table 1

High Impedance	Circuit	Load Impedance
High	"C"	High
Low*	"L"	High
High	"L"	Low*
High	"Pi"	High
Low	"T"	Low
High / Low	"Double"	High / Low

*The inductor facing the lower of the two impedances

MISMATCHING

As previously stated, most EMI line filters are intentionally mismatched for ease in manufacturing. A typical example of this industry wide practice is a cylindrical style filter.

The military specifications for this particular filter are:

Operating Voltage: 70 VDC
Operating Current: 5 ADC
Circuit Configuration: "PI"
DC Resistance: .015 ohms maximum
Case Diameter: .410 inches maximum

Full Load Insertion Loss per MIL-STD-220 (50 ohms):

150 kHz: 16 dB
300 kHz: 38 dB
1 MHz: 75 dB
10 MHz: 80 dB
100 MHz: 80 dB

Based on a source and load impedance of 50 ohms, MIL-STD-220, a properly designed Butterworth filter (a filter network that has a maximum flat pass-band with average cutoff frequency to reject-band ratio), would produce the following element values in order to satisfy the minimum insertion loss requirements:

C_1 = .0769 µfd
L_2 = 385 µHy
C_3 = .0769 µfd

The theoretical MIL-STD-220 insertion for a "PI" filter of these values is as indicated below:

150 kHz: 33 dB
300 kHz: 51 dB
1 MHz: 83 dB
10 MHz: >100 dB
100 MHz: >100 dB

The capacitance values for C1 and C3, .0769 µfd, are acceptable for a 70 VDC rated filter and are easily manufactured. However, L2 must be 385 µHy in order to satisfy the insertion loss requirements

In order to achieve 385 µHy at 5 ADC, allow for core saturation (the change in incremental permeability of the core material with DC bias), and comply with the .015 DC resistance requirement, the diameter of the inductor would be in excess of 2.0 inches. This inductor would obviously not fit a case with an outside diameter of .410 inches.

By simply reducing the inductor to a realistic value and increasing the value of C1 and C3, we can achieve the required insertion loss in the reject-band with a design that can easily be manufactured. The typical values for this application would be:

C_1 = .70 µfd
L_2 = 5 µHy
C_3 = .7 µfd

The theoretical MIL-STD-220 insertion for this modified filter is:

150 kHz: 25 dB
300 kHz: 50 dB
1 MHz: 83 dB
10 MHz: >100 dB
100 MHz: >100 dB

As previously stated, this practice of intentionally mismatching the element values will introduce a substantial amount of ripple, as much as 10 to 20 dB, in the pass-band. However, at frequencies below 1 KHz, the response is normally flat to within ± 1 dB.

Figure 2 depicts the MIL-STD-220 insertion loss characteristics for the ideal filter network and the modified design as compared to the specification requirements.

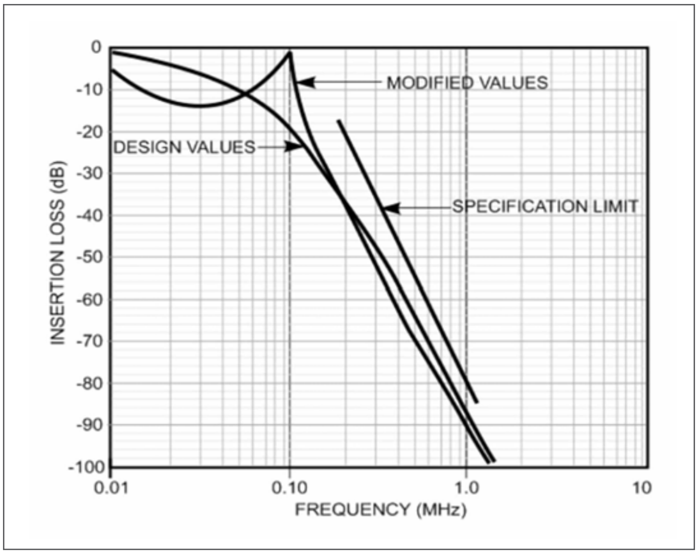

Figure 2

MIL-STD-220 INSERTION LOSS VERSES MIL-STD-461 EMI TESTING

The majority of EMI filters are employed in order to cause system compliance to one of various military or commercial EMI/EMC specifications.

The most widely references military EMI/EMC specification is Military Specification MIL-STD-461 (462,463). This document specifies the allowable amount of conducted and radiated emissions that a subsystem or system can generate.

Conducted emissions is interference that is present, or ‘conducted’ on primary power lines (AC or DC) and/or signal lines as detected by a current probe or other means.

Radiated emissions is interference, both ‘E” and “H” fields, that is being transmitted or radiated from the total system as detected by a receiving antenna.

In addition, MIL-STD-461 also delineates a series of tests that subject the device under test to various types of conducted and radiated interference to determine the survivability of the device when exposed to a harsh EMI environment. This series of tests is referred to as conducted and radiated susceptibility.

Conducted emission requirements and test methods are referred to as “CE”. The numbers that follow refer to the applicable frequency range and whether it pertains to input power lines or signal lines. (i.e., CE03 establishes test methods and maximum allowable interference that can be present on AC and DC power lines over the frequency range of 15 kHz to 50 MHz.)

Similarly, “CS” stands for Conducted Susceptibility, “RE” for Radiated Emission, and “RS” for Radiated Susceptibility.
As previously stated, EMI filters being bidirectional devices not only help to reduce the amount of conducted emissions generated within, but also protect the system from unwanted interference entering via the power lines and signal lines.

To some degree EMI filters also help to reduce the radiated interference. This is due to the fact that the power lines and signal lines can act as ‘transmitting antennas’ if too much EMI is present. However, the majority of radiated problems are system configuration related (i.e., improper grounding, shielding, lack of EMI gaskets, the choice of materials in the case of “H” fields, etc.).

The EMI profiles, and impedance, of any device is very complex and will change drastically over a given frequency range. It’s this phenomenon that makes selecting an EMI filter based solely on 50 ohm insertion loss data difficult.

Figure 3 compares the theoretical MIL-STD-220 50 ohm insertion loss of a “PI” filter and a “L” filter comprised of the following components.

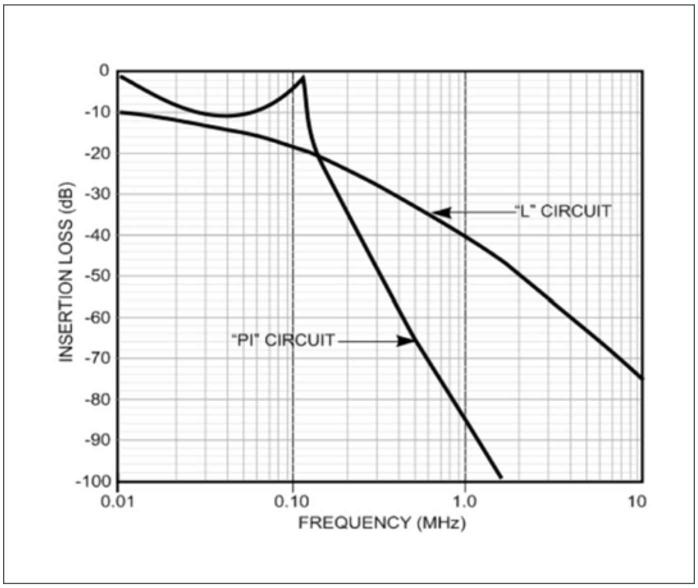

Figure 3

“PI” Circuit:

C_1 = .70 μfd
L_2 = 5 μHy
C_3 = .70 μfd

“L” Circuit:

C_1 = .70 μfd
L_2 = 5 μHy

Looking at this comparison, and if size was not an issue, one would have a tendency to choose the “PI” circuit over the “L” circuit based on performance. At 1 MHz the “PI” circuit provides 80+ dB of insertion loss where the “L” circuit only provides 40+ dB.

However, MIL-STD-461 conducted emission tests are not performance under 50 ohm source and load conditions.

Figure 4 illustrates a typical MIL-STD-461 conducted emissions test configuration.

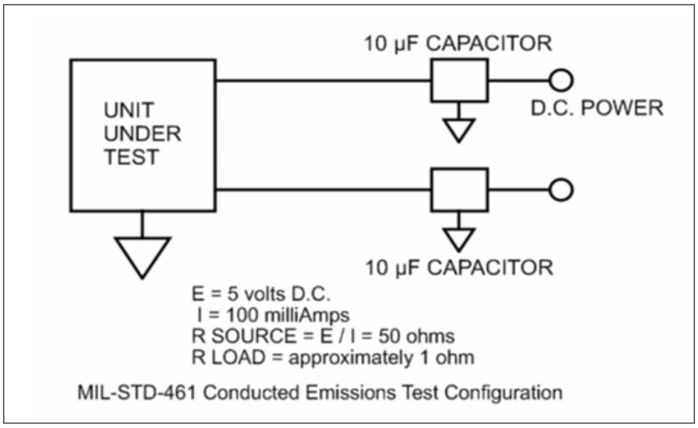

Figure 4

Not knowing the EMI source impedance (the device under test), we will assume ohms law. In this case 50 ohms. We don't know what the load impedance is, however, due to the 10 µfd line stabilization capacitors (required by MIL-STD-461 as part of the test configuration), we can assume it is low compared to the source impedance. In this case, we will theorize 1 ohm.

In this more realistic setting, 50 ohm source and 1 ohm load, the "L" circuit performs almost as well as the "PI" circuit as illustrated in Figure 5. By slightly increasing the values of C1 and L2 in the "L" circuit, a response identical to the "PI" circuit can be achieved.

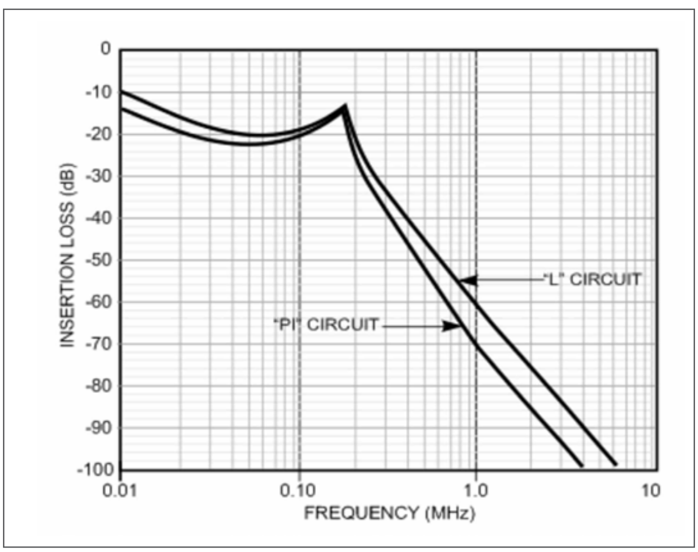

Figure 5

In the above example we were only concerned with EMI emanating from the test sample. If we were also concerned about protecting against unwanted interference entering the device then a "T" circuit would be the filter of choice. In essence, by using a "T" circuit we have two "L" circuits with the inductor facing the lower impedance.

If the "T" circuit consisted of L1 facing the unit under test and, L3 facing the load with C2 in the middle, then for conduced emissions the "L" circuit is comprised of C2 and L3. For conducted susceptibility, if we assume the unit under test to be the lower of the two impedances, the "L" circuit is comprised of C2 and L1. In both instances the secondary inductor will provide some additional filtering. However, its contribution is relatively small compared to the other two components.

There are an infinite number of source and load impedance combinations for signal line applications where the 10 µfd line stabilization capacitors are not required as part of the test configuration. For these situations the theoretical insertion loss can be calculated by varying RS and RL in the equations.

Although the circuits that we have been discussing only address common mode (interference which is present as a common potential between ground and all power lines) EMI, the same philosophies apply when selecting differential mode (interference which is present as a potential between individual power lines) EMI filtering elements commonly found in multicircuit filter assemblies, or "Black Box".

CONCLUSION

Selecting the proper EMI filter circuit is not a difficult task provided, that as a minimum, the following parameters are taken into consideration:

- The EMI source impedance
- The EMI load impedance
- The EMI propagation mode (common mode, differential mode, or both)
- Conducted emission requirements
- Conducted susceptibility requirements

Other considerations that are not readily apparent are the effects caused by mismatching; performance at full load; and the inability to achieve the theoretical insertion loss due to the inductance (ESL) and resistance (ESR) in the capacitor, and the parasitic capacitance in the inductors.

OVERVIEW OF THE DO-160 STANDARD

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Introduction

In aerospace, there is one standard that always seems to be popping up, DO-160. Aircraft suppliers are often complying with aviation authorities' regulations by testing their product to DO-160.

DO-160 is a standard that was published by the industry group Radio Technical Commission for Aeronautics known as RTCA. RTCA is not a government regulation, however the FAA, EASA, and others will often cited RTCA/DO-160 as a means of compliance for certification. In fact, it is the de facto standard in aerospace environmental testing.

DO-160 includes both environmental plus EMC, but in this article, we'll provide an overview of just the EMC-related sections. In later blogs, we'll go through each section, describing the tests in more detail, along with specific challenges for each.

So what is in RTCA/DO-160?

OVERVIEW OF THE DO-160 STANDARD

DO-160 ENVIRONMENTAL TESTING

The first thing to note is that DO-160 is test procedure. It is not a requirement. It is not a handbook. Sure, it gives some guidance of what testing is applicable but at its core is the need for companies to standardize testing categories, methods, and procedures.

With this standardization, aerospace suppliers can produce products that more easily get certified on multiple aircraft.

For example, if Bombardier, Embraer, and Boeing all have different testing needs then a supplier needs to understand all three testing requirements. In addition, the testing facilities that test to these standards will also have to read and comply with all the different procedures.

With the advent and adoption of RTCA/DO-160, airlines, suppliers, testing facilities, and airlines all benefit from the standardization of testing.

- Airlines are not required to maintain test standards, methods, and procedures
- Suppliers can produce products that comply with multiple aircraft platforms
- Test Facilities become more efficient and familiar with one set of testing
- Airlines recognize test pedigrees from a common standard

So, what does DO-160 look like?

RTCA/DO-160 TOC

- Sect 1–Purpose and Applicability
- Sect 2–Definitions of Terms
- Sect 3–Conditions of Tests
- Sect 4–Temperature and Altitude
- Sect 5–Temperature Variation
- Sect 6–Humidity
- Sect 7–Operational Shocks and Crash Safety
- Sect 8–Vibration
- Sect 9–Explosion Proofness
- Sect 10–Waterproofness
- Sect 11–Fluids Susceptibility
- Sect 12–Sand and Dust
- Sect 13–Fungus Resistance
- Sect 14–Salt Spray
- Sect 15–Magnetic Effect
- Sect 16–Power Input
- Sect 17–Voltage Spike
- Sect 18–Audio Frequency Conducted Susceptibility (Power Inputs)
- Sect 19–Induced Signal Susceptibility
- Sect 20.0–Radio Frequency Susceptibility (Radiated and Conducted)
- Sect 21.0–Emission of Radio Frequency Energy
- Sect 22.0–Lightning Induced Transient Susceptibility
- Sect 23.0–Lightning Direct Effects
- Sect 24.0–Icing
- Sect 25.0–Electrostatic Discharge
- Sect 26.0–Fire, Flammability
- Appendix A–Environmental Test Identification
- Appendix B–Membership
- Appendix C–Change Coordinators

After that quick preview, let's take a look at each EMC related section.

RTCA/DO-160 EMC SECTIONS

Section 15.0–Magnetic Effect

Technically Magnetic Effect is part of EMC, just barely. This test measures your equipment's effect on critical flight sensor like a compass.

The goal is to determine where your product can be located, relative to these aircraft sensors. There is rarely an issue with the test results from Magnetic Effect.

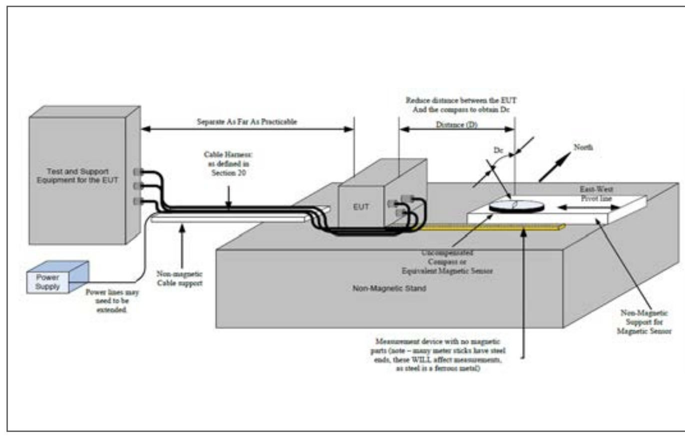

Figure 1: DO-160 Figure 15-1 Test Installation and Procedure

Section 16.0–Power Input

Power input is the longest section of the standard stretching almost 70 pages. The tests are run depending on your products power source (i.e. 28VDC, 115VAC, 270VDC.)

The tests in the section range from normal, abnormal and emergency operating voltages to voltage surges. It also can measure to AC harmonics, current inrush and power factor. This section encompasses all things about your power input lines.

Categories for AC equipment are sorted by the expected frequency range. For example, category A(CF)–is for power sources that stay at the center frequency, 400Hz. A(NF) is for Narrow Frequency (360 to 650 Hz) and A(WF) is for Wide Frequency (360 to 800 Hz.)

DC categories are "A" for sources with DC supplied from transformer-rectifier units, "B" for sources with significant battery capacitance, "D" 270 VDC equipment and "Z" sources without constant battery capacitance.

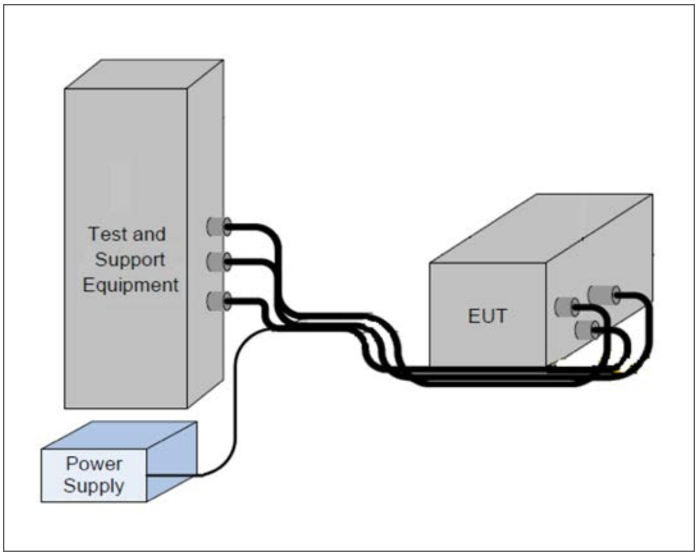

Figure 2: DO-160 Figure 16-1 Generic Test Setup Example

Section 17.0–Voltage Spike

Voltage Spike determines whether your product can tolerate the voltage spikes arriving at the unit's power leads (AC or DC). The main adverse effects to be anticipated are permanent damage, component failure, insulation breakdown, susceptibility degradation, or changes in equipment performance.

Voltage Spike is separated in two categories, category "A" applying a 600 V spike or category "B" applying a 200 V spike or twice the line voltage (whichever is less).

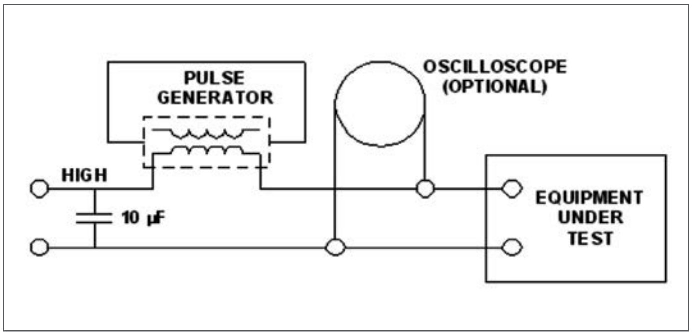

Figure 3: DO-160 Figure 17-2 Voltage Spike Test Setup, DC or single-phase AC

Section 18.0–Audio Frequency Conducted Susceptibility (Power Inputs)

Audio Frequency determines whether your unit will tolerate frequency components normally seen during operation of the aircraft. These frequency components are typically harmonics of the power source fundamental frequency.

The categories for Audio Frequency mirror that or power input. They include R(CF), R(NF), or R(WF) for AC power sources and R, B, or Z for DC sources. Cat K(CF), K(NF), or K(WF) may also be required for AC systems with higher distortion levels.

The test applies distortion to the primary power through an audio transformer.

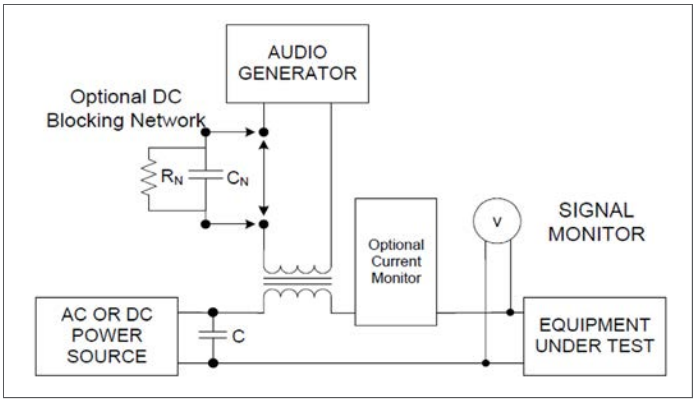

Figure 4: DO-160 Figure 18-1 Test Setup for Audio Frequency Conducted Susceptibility Test (For AC and DC Power Lines, Differential Mode)

Section 19.0–Induced Signal Susceptibility

Inducted signal susceptibility includes five tests that determine the effect of interfering signals related to the power frequency harmonics, audio frequency signals, and electrical transients created by other systems. The test simulates noise generated on other interconnecting bundles that are routed in close proximity to your unit's wire harness on the aircraft.

The categories include B, A, Z, and C which include increasing levels of susceptibility. The most severe test of five tests involves a switching relay chattering noise on to closely wrapped wires.

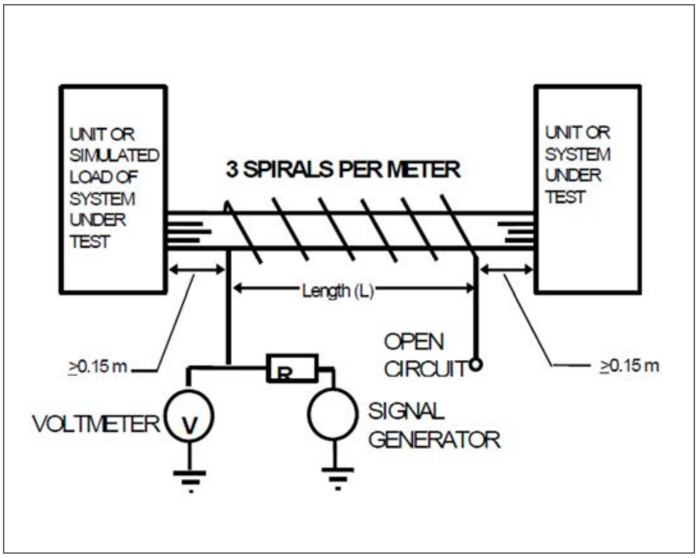

Figure 5: DO-160 Figure 19-4 Audio Frequency Electric Field Susceptibility Test Setup

Section 20.0–Radio Frequency Susceptibility (Radiated and Conducted)

Radio Frequency Susceptibility's purpose is to determine whether your product will operate within when the unit and its cable are exposed to a RF field. RF susceptibility is actually two tests; Radiated and Conducted Susceptibility, often referred to as RS and CS respectively. RF noises is applied to the EUT in continuous wave, square wave, and pulsed modulation modes.

Both tests ensure the products uninterrupted operation when it is installed in the aircraft. The section's categories includes a designator for the CS level first and the RS level second (i.e. "YG".)

Radiated Susceptibility uses an anechoic chamber and an antenna to blast the product with RF whereas Conducted Susceptibility uses an injection clamp in induce the noise onto the EUT's I/O cable.

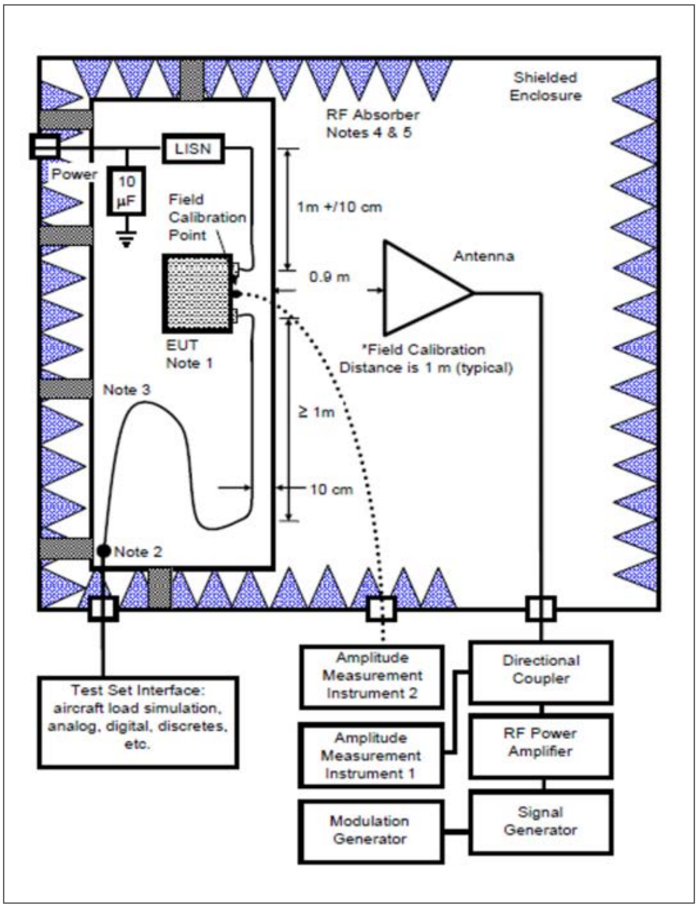

Figure 6: DO-160 Figure 20-2 Radiated Susceptibility Test Setup

Section 21.0–Emission of Radio Frequency Energy
Radiated and Conducted Emissions is your typical emissions testing for aerospace products. Just like section 20.0, this section is broken into two tests; radiated and conducted.

The purpose of Emission of Radio Frequency Energy is to put an upper limit on the amount of RF energy your equipment can emit on the airplane. This will ensure proper integration and operation of the aircraft.

The categories include varying levels of acceptable emissions based on the location of the equipment. Consideration is also given by the aircraft manufacturer to the nature of the product being designed.

A typical setup for the conducted emissions portion is shown below.

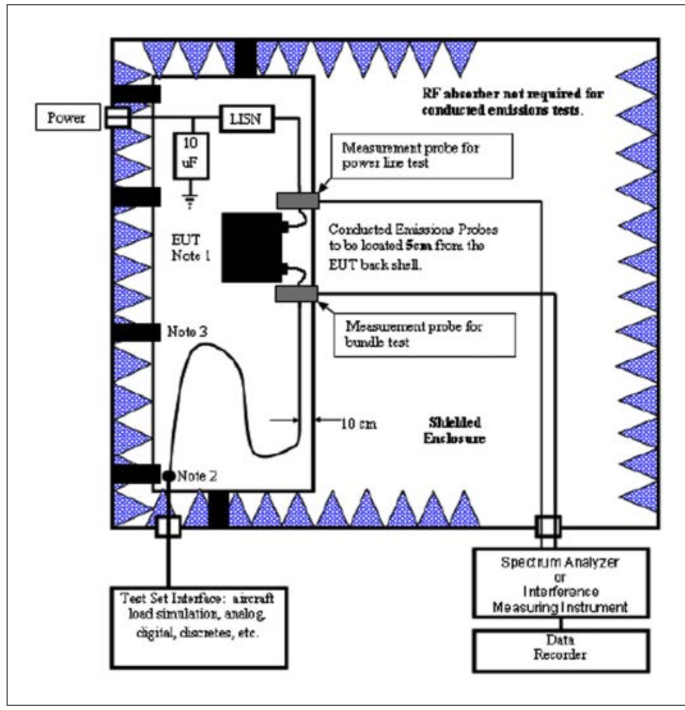

Figure 7: DO-160 Figure 21-6 Typical Setup for Conducted RF Interference Test

Section 22.0–Lightning Induced Transient Susceptibility
Lightning Induced Transient Susceptibility is intended to simulate lightning events striking the airplane and coupling onto your product's interconnecting cables.

This section, sometimes referred to as indirect lightning, is severe in nature, often driving hundreds or thousands of amps into a single pin of your unit's connector.

The section is broken into three separate parts; pin injection, induced cable bundle strikes, and multiple burst testing. Pin injection looks for hard failures in your product after the strike where as cable bundle and multiple burst often requires your unit to operate while the event is occurring. Each test includes different waveforms that have durations as long as 500 µs. Levels 1–5 increase in severity, topping out at 3,200 volts and 5,000 amps. This section is often the hardest to pass.

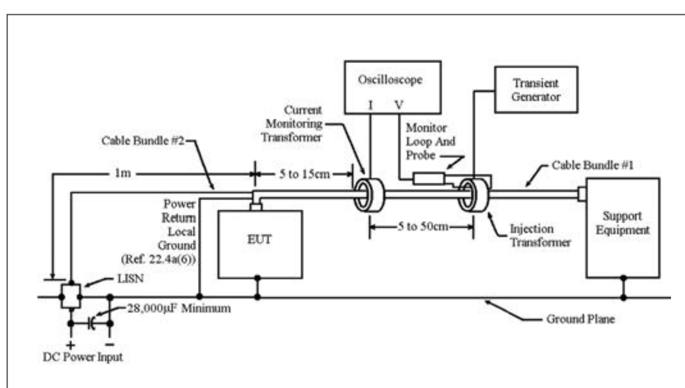

Figure 8: DO-160 Figure 22-17 Typical Cable Induction Test Setup

Section 23.0–Lightning Direct Effects
Direct Effects, contrary to indirect lightning, tests products that may be directly struck by lightning. This is limited to products that will be mounted on the exterior aircraft. The section includes a high voltage strike test and a high current test. The equipment is often not expected to survive but must not cause any unsafe condition to the aircraft.

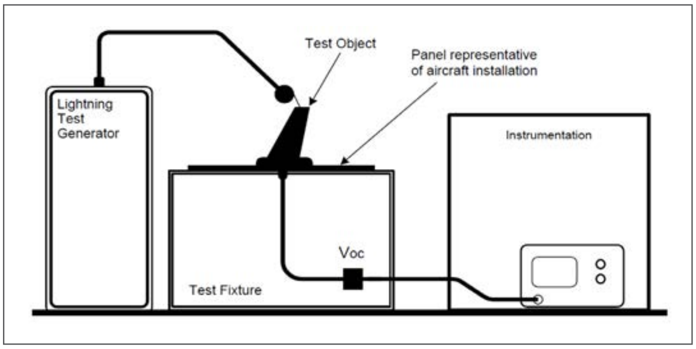

Figure 9: DO-160 Figure 23-10 – Typical Installation for Measurements of Injected Transients

Section 25.0–Electrostatic Discharge
Electrostatic Discharge or ESD is a test to ensure your products reliance to static charges. This section test relates to airborne equipment which may be involved in static electricity discharges from human contact. It is applicable for all products that are accessible during normal operation or maintenance of the aircraft. Though no applicable to connector pins, aircraft manufacturers often require it.

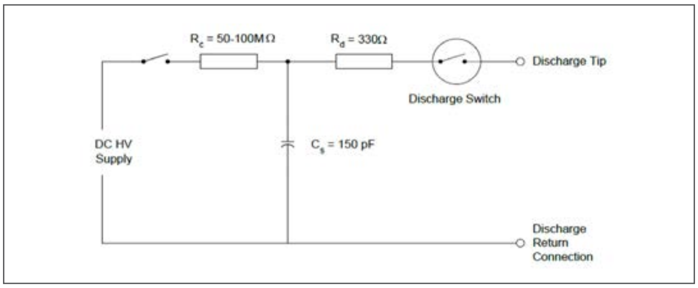

Figure 10: DO-160 Figure 25-2 Simplified Diagram of the ESD Generator

SUMMARY

The EMC sections of DO-160 thoroughly tests your products ability to survive and operate in normal and abnormal conditions seen on an aircraft. Passing this 500-page standard is not easy. Understanding the test and how it is applied to your design is critical.

I have written extensively at www.aerospacepal.com including a DO-160 video to help users understand. Please also continue to read my blog on *Interference Technology* as I dive deeper into the sections listed above.

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