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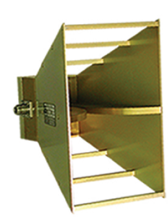
13 Models



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Biconicals
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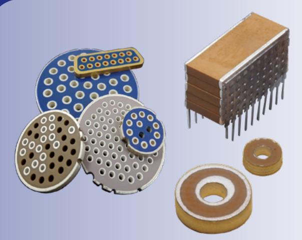

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EMI filter designed and manufactured in the USA with the largest offering of EMI filter capacitor sizes and configurations (cylindrical and rectangular geometries). Solid wall and embedded technologies for commercial and high-performance EMI filter applications.

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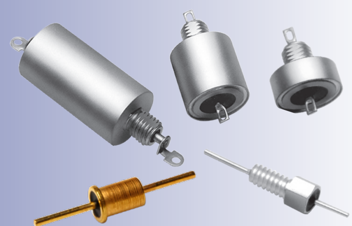

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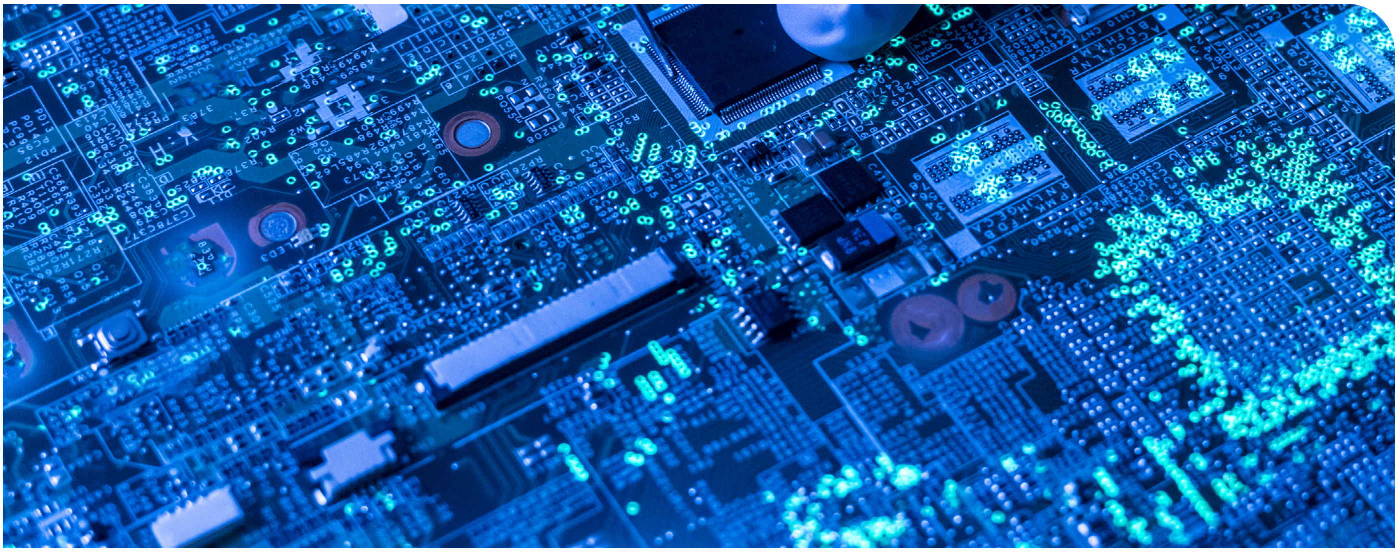

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WELCOME TO ITEM 2022

STEVEN FERGUSON

We have just passed the 50-year milestone of ITEM (Interference Technology Engineers' Master) in 2021 providing the engineering community with insight into the world of Electromagnetic Interference (EMI) and/ Electromagnetic Compatibility (EMC).

Technical articles and reference material combine in this annual, desktop reference guide to guide the reader through issues that challenge the developers and test personnel with innovative and well-established EMI/EMC concepts. Directories provide in-depth listings for services, equipment and materials pertinent to EMI/EMC and the standards lists help you determine what applies to your products.

For many years now, ITEM has covered the related topics of the signal integrity (SI) and power integrity (SIPI), although we may not have referred to these disciplines by these names. This year we are fully recognizing them, as you will see on our cover, and with a new section dedicated to SI, PI and its relationship to EMI.

Major markets and challenges each have a dedicated section:

- EMC Reference Guides
- EMC Fundamentals
- EMC Testing
- EMC in Wireless, 5G, & IoT
- SI, PI & EMI
- Military & Aerospace EMC

As you venture through ITEM 2022, keep in mind that you can help us make it better:

- Share your questions and ask for topics that interest you
- Let us know if any of the information we provide is inaccurate, as we maintain this valued single reference source for the EMI/SI/PI community
- Update your listings in the directories

And by all means, prepare articles to share with the community – you receive an editorial review and you become published.

Enjoy ITEM 2022.


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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 46 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 US Technical Advisory Groups to CISPR SC G and CISPR SC I and as an active member of CISPR SC I and its maintenance teams, CISPR SC I MT7 (CISPR 32 maintenance) and CISPR SC I MT8 (CISPR 35 maintenance). He is also a member of the US TAG for IEC SC77B and the working group preparing the next edition of ANSI C63.4.

Ghery has written 8 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 US, Europe and Asia. Mike is currently on the Board of Directors of the IEEE EMC Society.

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


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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 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, 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 46 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 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 bulgin

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2022 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 kenton@lectrixgroup.com for further supplier contacts.

2022 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
	AH SYSTEMS, INC. t: 818-998-0223 e: sales@ahsystems.com w: www.ahsystems.com	X	X	X													X	X	X			
	ADVANCED TEST EQUIPMENT CORP. (ATEC) t: 800-404-2832 e: galcala@atecorp.com w: www.atecorp.com	X	X		X				X		X			X	X	X	X	X	X	X		
	APITECH t: 888-553-7531 e: sales.eis@apitech.com w: www.apitech.com			X			X			X	X									X	X	
	COILCRAFT t: 800-322-2645 e: sales@coilcraft.com w: www.coilcraft.com						X			X												
	ITG ELECTRONICS t: 914-347-2474 e: sales@ITG-Electronics.com w: www.itg-electronics.com									X												
	KIKUSUI AMERICA, INC. t: 310-214-0000 e: kikusui@kikusuiamerica.com w: www.kikusuiamerica.com	X															X					
	POLYMER SCIENCE, INC. t: 888-533-7004 e: sales@polymerscience.com w: www.polymerscience.com												X	X								
	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 Corp. (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.	https://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		
	APITech	www.apitech.com			X			X			X	X									X	X	
	AR RF/Microwave Instrumentation	www.arworld.us	X	X	X				X									X	X				
B	Beehive Electronics	www.beehive-electronics.com																			X		
	Bulgin	www.bulgin.com				X																	
C	Captor Corporation (EMC Div.)	www.captorcorp.com									X												
	Coilcraft	www.coilcraft.com						X			X												
	Compliance Direction, LLC	www.compliancedirection.com																					
	CPI- Communications & Power Industries (USA)	www.cpii.com/emc	X																				
D	Dassault System Simulia Corp	www.3ds.com/							X														
	Delta Electronics (Americas) Ltd.	www.delta-americas.com									X												
	DLS Electronic Systems, Inc.	www.dlsemc.com					X															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																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
	Fair-Rite Products Corp.	www.fair-rite.com						X							X								
	Fischer Custom Communications	www.fischercc.com																		X			
	Frankonia Solutions	www.frankonia-solutions.com													X	X		X				X	
G	Gauss Instruments	www.gauss-instruments.com								X							X						
	Gowanda Electronics	www.gowanda.com						X															

	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
H	Haefely	www.haefely.com							X									X			X		
	Heilind Electronics, Inc	www.heilind.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			
	Kikusui America, Inc.	www.kikusuiamerica.com/solution/	X															X					
	Krieger Specialty Products	www.kriegerproducts.com														X							
	Kyocera AVX	www.kyocera-avx.com		X	X			X			X												
L	Laird a DuPont Business	www.laird.com									X			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.mbp.it/en/							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	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	Ohmite	www.ohmite.com								X													
	Ophir RF	www.ophirrf.com	X																				
P	Parker Chomerics	www.chomerics.com													X								
	Pearson Electronics	www.pearsonelectronics.com						X															
	Polymer Science, Inc.	www.polymerscience.com												X	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	https://ppmtest.com/																		X			
Q	Quell Corporation	www.eeseal.com			X						X	X									X		

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

TEST LAB DIRECTORY

2022 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 kenton@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																						
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		•	•	•	•	•	•		•	•		•				•		•		
El Dorado Hills	Sanesi Associates	(916) 496-1760		•	•		•	•	•		•										•	

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
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	•		•			•	•		•				•	•						
Redondo Beach	Northrop Grumman Space Tech. Sector www.northropgrumman.com	(310) 812-3162			•	•	•				•		•	•			•	•		•	•	•

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
Riverside	DNB Engineering, Inc. www.dnbenginc.com	(951) 637-2630	•		•		•	•	•	•	•					•						
Sacramento	Northrop-Grumman EM Systems Lab www.northropgrumman.com	(916) 570-4340			•		•		•		•			•						•	•	•
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			•		•	•	•	•	•			•	•	•		•				
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		•	•	•	•	•	•		•			•	•	•			•			
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		•	•		•	•	•		•			•	•					•	•	

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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		•	•		•	•	•		•			•	•			•		•		
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		•	•		•	•	•		•											
Romeoville	Radiometrics Midwest Corp. www.radiomet.com	(815) 293-0772	•		•	•	•	•	•		•	•		•	•			•		•	•	
Roselle	Electri-Flex Company www.electriflex.com	(800) 323-6174																			•	
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			•						•			•	•							•

USA continued

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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																			•	
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	•		•		•	•	•		•				•	•					•	

USA continued

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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	•		•		•	•	•		•			•	•	•				•	•	
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			•		•	•	•		•			•	•	•				•		

USA continued

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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.l3harris.com/	(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			•			•	•	•	•				•	•						
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											•				•				•	
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			•	•						•		•	•			•		•		

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
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			•		•	•			•					•					•	
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	•												•					•		

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
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		•	•		•	•	•		•											
Plano	National Technical Systems www.nts.com	(972) 509-2566	•	•	•	•	•	•	•	•	•	•		•	•			•		•	•	
Plano	Element www.element.com	(469) 304-5255		•	•		•		•		•				•							

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	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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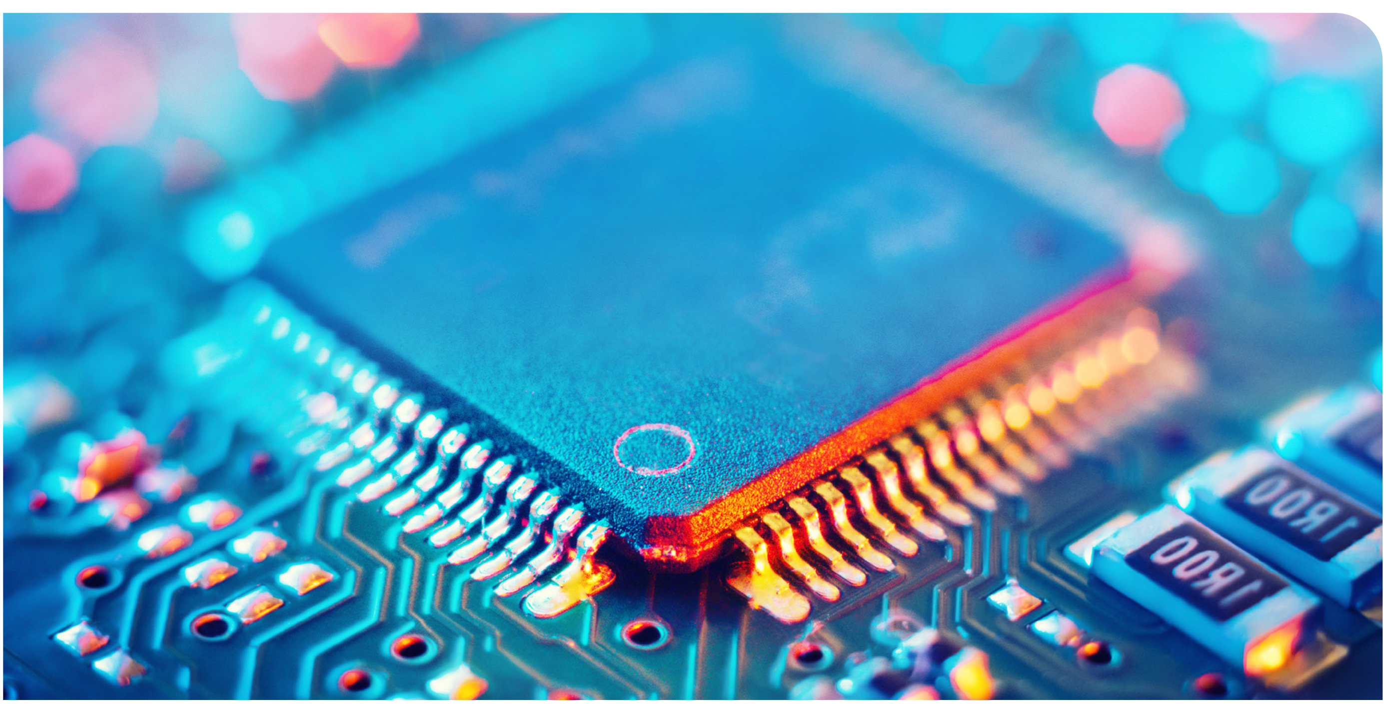
www.compliancedirection.com



2022 CONSOLIDATED STANDARDS

MANY IEC STANDARDS have been adopted by the European Union with and EN designation replacing the IEC while maintaining the same number. In several cases the standard may have been modified. When using an IEC standard, one should check for IEC – EN differences and in both cases check for the current edition.
The standards list adds a category column to help assign the identified standard to a particular type or discipline. Most are self-explanatory, but to avoid confusion the category assignments follow. Often a particular standard could fit in more than one category, so the assignment is simply a judgement call.

- Apparatus – this category is used to group standards for a product or device where it fails to fit in a specific group. For example, a medical device could be a product but it fits into the medical category more closely.
- Auto/Vehicle – standard primarily deals with automotive but includes ship or rail.
- General – primarily deals with definitive or general EM control information.
- Generic – deals with product standards not assigned to a particular group.
- Medical – medical equipment or methods
- MIL/Aero – MIL-STD, Space, Aeronautical equipment, or methods – includes associated design guides.
- Test – primarily deals with test methods
- Wireless – primarily deals with intentional RF emitters or receivers.

Useful websites associated with standards include but not limited to:

ANSI	http://webstore.ansi.org; www.ansi.org; www.c63.org
APLAC	Asia Pacific Laboratory Accreditation Cooperation (APLAC) https://www.apac-accreditation.org/
BSMI	http://www.bsmi.gov.tw/wSite/mp?mp=95
CSA	http://www.cnca.gov.cn/
EN	https://www.en-standard.eu/
FCC	Federal Communications Commission (FCC) www.fcc.gov; Electronic Code of Fderal Regulations https://www.ecfr.gov
FDA	FDA Center for Devices & Radiological Health (CDRH) https://www.fda.gov/MedicalDevices/default.htm
Ford	https://www.fordemc.com
GM	https://global.ihs.com
IC	Industry Canada (Certifications and Standards) http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf06165.html
IEC / CISPR	https://webstore.iec.ch
IEEE	IEEE Standards Association https://standards.ieee.org/
IEEE EMC	IEEE EMC Society Standards Development Committee (SDCOM) https://standards.ieee.org/develop/index.html
ISED	Innovation, Science and Economic Development Canada; https://www.ic.gc.ca/eic/site/icgc.nsf/eng/home
ISO	ISO (International Organization for Standards) http://www.iso.org/iso/home.html
MIL-STD	https://quicksearch.dla.mil/qsSearch.aspx

RTCA	https://www.rtca.org
Russia	Gosstandart (Russia) https://gosstandart.gov.by/en
SAE	SAE EMC Standards Committee www.sae.org
UK EMCIA	Electromagnetic Compatibility Industry Association UK http://www.emcia.org
VCCI	VCCI (Japan, Voluntary Control Council for Interference) http://www.vcci.jp/vcci_e/

Category	Publisher	Number	Title
Apparatus	IEC	60118-13	Electroacoustics - Hearing aids - Part 13: Electromagnetic compatibility (EMC)
Apparatus	IEC	60255-26	Measuring relays and protection equipment - Part 26: Electromagnetic compatibility requirements
Apparatus	IEC	60364-4-44	Low-voltage electrical installations - Part 4-44: Protection for safety - Protection against voltage disturbances and electromagnetic disturbance
Apparatus	IEC	60728-12	Cabled distribution systems for television and sound signals - Part 12: Electromagnetic compatibility of systems IEC (continued)
Apparatus	IEC	60728-2	Cabled distribution systems for television and sound signals - Part 2: Electromagnetic compatibility for equipment
Apparatus	IEC	60870-2-1	Telecontrol equipment and systems - Part 2: Operating conditions - Section 1: Power supply and electromagnetic compatibility
Apparatus	IEC	60974-10	Arc welding equipment - Part 10: Electromagnetic compatibility (EMC) requirements
Apparatus	IEC	61000-3-11	Electromagnetic compatibility (EMC) - Part 3-11: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low voltage supply systems - Equipment with rated current <= 75 A and subject to conditional connection IEC (continued)
Apparatus	IEC	61000-3-12	Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and <=75 A per phase
Apparatus	IEC	61000-3-2	Electromagnetic compatibility (EMC)–Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
Apparatus	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
Apparatus	IEC	61000-3-8	Electromagnetic compatibility (EMC) - Part 3: Limits - Section 8: Signaling on low-voltage electrical installations - Emission levels, frequency bands and electromagnetic disturbance levels
Apparatus	IEC	61326-1	Electrical equipment for measurement, control and laboratory use – EMC requirements – Part 1: General requirements
Apparatus	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
Apparatus	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

Category	Publisher	Number	Title
Apparatus	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
Apparatus	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
Apparatus	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
Apparatus	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
Apparatus	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
Apparatus	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
Apparatus	IEC	61543	Residual current-operated protective devices (RCDs) for household and similar use - Electromagnetic compatibility
Apparatus	IEC	61800-3	Adjustable speed electrical power drive systems - Part 3: EMC requirements and specific test methods
Apparatus	IEC	61967-1	Integrated circuits - Measurement of electromagnetic emissions, 150 kHz to 1 GHz - Part 1: General conditions and definitions
Apparatus	IEC	62040-2	Uninterruptible power systems (UPS) - Part 2: Electromagnetic compatibility EMC) requirements
Apparatus	IEC	62041	Power transformers, power supply units, reactors and similar products - EMC requirements
Apparatus	IEC	62310-2	Static transfer systems (STS) - Part 2: Electromagnetic compatibility (EMC) requirements
Apparatus	IEC	CISPR 11	Industrial, scientific and medical (ISM) radio-frequency equipment - Electromagnetic disturbance characteristics - Limits and methods of measurement
Apparatus	IEC	CISPR 14-1	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
Apparatus	IEC	CISPR 14-2	Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus – Part 2: Immunity – Product family standard
Apparatus	IEC	CISPR 15	Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment
Apparatus	IEC	CISPR 32	Electromagnetic compatibility of multimedia equipment – Emission requirements
Apparatus	IEC	CISPR 35	Electromagnetic compatibility of multimedia equipment - Immunity requirements

Category	Publisher	Number	Title
Apparatus	IEC	TR 61000-3-13	Electromagnetic compatibility (EMC) - Part 3-13: Limits - Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems
Apparatus	IEC	TR 61000-3-14	Electromagnetic compatibility (EMC) - Part 3-14: Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems
Apparatus	IEC	TR 61000-3-15	Electromagnetic compatibility (EMC) - Part 3-15: Limits - Assessment of low frequency electromagnetic immunity and emission requirements for dispersed generation systems in LV network
Apparatus	IEC	TR 61000-3-6	Electromagnetic compatibility (EMC) - Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems - Basic EMC publication
Apparatus	IEC	TR 61000-3-7	Electromagnetic compatibility (EMC) - Part 3: Limits - Section 7: Assessment of emission limits for fluctuating loads in MV and HV power systems - Basic EMC publication
Apparatus	IEC	TS 61000-3-4	Electromagnetic compatibility (EMC) - Part 3-4: Limits - Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A
Apparatus	IEC	TS 61000-3-5	Electromagnetic compatibility (EMC) - Part 3: Limits - Section 5: Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 16 A
Auto/Vehicle	Audi	TL 82466	Electrostatic Discharge
Auto/Vehicle	BMW	600 13.0	Electric- / Electronic components in cars BMW GS 95002 Electromagnetic Compatibility (EMC) Requirements and Tests
Auto/Vehicle	BMW	GS 95003-2	GS 95003-2 Electric- / Electronic assemblies in motor vehicles
Auto/Vehicle	Chrysler	PF 9326	Electrical electronic modules and motors
Auto/vehicle	Diamer Chrysler	DC-10614	EMC Performance Requirements – Components
Auto/vehicle	Diamer Chrysler	DC-10615	Electrical System Performance Requirements for Electrical and Electronic Components
Auto/vehicle	Diamer Chrysler	DC-11223	Performance Requirements -- Vehicle Automotive Electromagnetic Compatibility Standards
Auto/vehicle	Diamer Chrysler	DC-11224	EMC Performance Requirements – Components
Auto/vehicle	Diamer Chrysler	DC-11225	EMC Supplemental Information and Alternative Component Requirements
Auto/Vehicle	Fiat	9.90110	Electric and electronic devices for motor vehicles Freightliner 49-00085 EMC Requirements
Auto/vehicle	FORD	EMC-CS-2009.1	Component EMC Specification. EMC-CS-2009.1
Auto/vehicle	FORD	F-2	Electrical and Electronics System Engineering
Auto/vehicle	FORD	WSF-M22P5-A1	Printed Circuit Boards, PTF, Double Sided, Flexible
Auto/vehicle	GM	GMW3091	General Specification for Vehicles, Electromagnetic Compatibility (EMC)-Engl; Revision H; Supersedes GMI 12559 R and GMI 12559 V
Auto/vehicle	GM	GMW3097	General Specification for Electrical/Electronic Components and Subsystems, Electromagnetic Compatibility-Engl; Revision H; Supersedes GMW12559, GMW3100, GMW12002R AND GMW12002V

Category	Publisher	Number	Title
Auto/vehicle	GM	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
Auto/Vehicle	Honda	3838Z-S5AA-L000	Noise Simulation Test
Auto/Vehicle	Honda	3982Z-SDA-0030	Battery Simulation Test
Auto/Vehicle	Hyundia Kia	ES 39111-00	EMC Requirements
Auto/Vehicle	Hyundia Kia	ES 95400-10	Battery Simulation Tests
Auto/Vehicle	Hyundia Kia	ES 96100-01	EMC Requirements
Auto/vehicle	IEC	60533	Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull
Auto/vehicle	IEC	62236-1	Railway applications - Electromagnetic compatibility - Part 1: General
Auto/vehicle	IEC	62236-2	Railway applications - Electromagnetic compatibility - Part 2: Emission of the whole railway system to the outside world
Auto/vehicle	IEC	62236-3-1	Railway applications - Electromagnetic compatibility - Part 3-1: Rolling stock - Train and complete vehicle
Auto/vehicle	IEC	62236-3-2	Railway applications - Electromagnetic compatibility - Part 3-2: Rolling stock – Apparatus
Auto/vehicle	IEC	62236-4	Railway applications - Electromagnetic compatibility - Part 4: Emission and immunity of the signaling and telecommunications apparatus
Auto/vehicle	IEC	62236-5	Railway applications - Electromagnetic compatibility - Part 5: Emission and immunity of fixed power supply installations and apparatus
Auto/vehicle	IEC	CISPR 12	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers
Auto/vehicle	IEC	CISPR 25	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers
Auto/vehicle	IEC	TR 62482	Electrical installations in ships - Electromagnetic compatibility - Optimizing of cable installations on ships - Testing method of routing distance
Auto/vehicle	ISL	11451-3	Road vehicles -- Electrical disturbances by narrowband radiated electromagnetic energy -- Vehicle test methods -- Part 3: On-board transmitter simulation
Auto/vehicle	ISO	10605	Road vehicles -- Test methods for electrical disturbances from electrostatic discharge
Auto/vehicle	ISO	11451-1	Road vehicles -- Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 1: General principles and terminology
Auto/vehicle	ISO	11451-2	Road vehicles -- Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 2: Off-vehicle radiation sources
Auto/vehicle	ISO	11451-4	Road vehicles -- Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 4: Bulk current injection (BCI)
Auto/Vehicle	ISO	11452-1	Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 1: General principles and terminology

Category	Publisher	Number	Title
Auto/vehicle	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
Auto/Vehicle	ISO	11452-11	Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 11: Reverberation chamber ISO 13766 Earth-moving machinery – Electromagnetic compatibility
Auto/Vehicle	ISO	11452-2	Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 2: Absorber-lined shielded enclosure
Auto/Vehicle	ISO	11452-3	Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 3: Transverse electromagnetic mode (TEM) cell
Auto/vehicle	ISO	11452-4	Road vehicles -- Component test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 4: Bulk current injection (BCI)
Auto/Vehicle	ISO	11452-5	Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 5: Stripline
Auto/vehicle	ISO	11452-7	Road vehicles -- Component test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 7: Direct radio frequency (RF) power injection
Auto/vehicle	ISO	11452-8	Road vehicles -- Component test methods for electrical disturbances from narrowband radiated electromagnetic energy -- Part 8: Immunity to magnetic fields
Auto/vehicle	ISO	7637-1	Road vehicles -- Electrical disturbances from conduction and coupling -- Part 1: Definitions and general considerations
Auto/vehicle	ISO	7637-2	Road vehicles -- Electrical disturbances from conduction and coupling -- Part 2: Electrical transient conduction along supply lines only
Auto/vehicle	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
Auto/vehicle	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
Auto/vehicle	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
Auto/Vehicle	ISO	TS 14907-1	Road transport and traffic telematics -- Electronic fee collection – Test procedures for user and fixed equipment – Part 1: Description of test procedures
Auto/Vehicle	ISO	TS 14907-2	Road transport and traffic telematics – Electronic fee collection -- Test procedures for user and fixed equipment -- Part 2: Conformance test for the onboard unit application interface
Auto/vehicle	ISO	TS 21609	Road vehicles -- (EMC) guidelines for installation of aftermarket radio frequency transmitting equipment
Auto/Vehicle	KVECO	16-2103	EMC Requirements
Auto/Vehicle	Lotus	17.39.01	Lotus Engineering Standard: Electromagnetic Compatibility
Auto/Vehicle	Mack	606GS15	EMC Requirements MAN 3285 EMC Requirements
Auto/Vehicle	Mazda	MES PW 67600	Automobile parts standard (electronic devices)
Auto/Vehicle	Mercedes	A 211 000 42 99	Instruction specification of test method for E/Ecomponents

Category	Publisher	Number	Title
Auto/Vehicle	Mercedes	AV EMV	Electric aggregate and electronics in cars
Auto/Vehicle	Mercedes	MBN 10284-2	EMC requirements and tests of E/E-systems (component test procedures)
Auto/Vehicle	Mercedes	MBN 2200-2	Electric / electronic elements, devices in trucks
Auto/Vehicle	Mitsubishi	ES-X82010	General specification of environment tests on automotive electronic equipment
Auto/Vehicle	Nissan	28400 NDS03	Low frequency surge resistance of electronic parts
Auto/Vehicle	Nissan	28400 NDS04	Burst and Impulse Waveforms
Auto/Vehicle	Nissan	28400 NDS07	Immunity against low frequency surge (induction surge) of electronic parts
Auto/Vehicle	Nissan	28401 NDS02	EMC requirements (instruction concerning vehicle and electrical ...)
Auto/Vehicle	Peugeot	B217110	Load Dump Pulses
Auto/Vehicle	Porsche	AV EMC EN	EMC Requirements
Auto/Vehicle	PSA	B21 7090	EMC Requirements (electric and electronics equipment)
Auto/Vehicle	PSA	B21 7110	EMC requirements (electric and electronics equipment)
Auto/Vehicle	Renault	36.00.400	Physical environment of electrical and electronic equipment
Auto/Vehicle	Renault	36.00.808	EMC requirements (cars and electrical / electronic components)
Auto/vehicle	SAE	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)
Auto/vehicle	SAE	J1113/11	Immunity to Conducted Transients on Power Leads
Auto/vehicle	SAE	J1113/12	Electrical Interference by Conduction and Coupling - Capacitive and Inductive Coupling via Lines Other than Supply Lines
Auto/vehicle	SAE	J1113/13	Electromagnetic Compatibility Measurement Procedure for Vehicle Components - Part 13: Immunity to Electrostatic Discharge
Auto/vehicle	SAE	J1113/2	Electromagnetic Compatibility Measurement Procedures and Limits for Vehicle Components (Except Aircraft)--Conducted Immunity, 15 Hz to 250 kHz--All Leads
Auto/vehicle	SAE	J1113/21	Electromagnetic Compatibility Measurement Procedure for Vehicle Components - Part 21: Immunity to Electromagnetic Fields, 30 MHz to 18 GHz, Absorber-Lined Chamber
Auto/vehicle	SAE	J1113/26	Electromagnetic Compatibility Measurement Procedure for Vehicle Components - Immunity to AC Power Line Electric Fields
Auto/vehicle	SAE	J1113/27	Electromagnetic Compatibility Measurements Procedure for Vehicle Components - Part 27: Immunity to Radiated Electromagnetic Fields - Mode Stir Reverberation Method
Auto/vehicle	SAE	J1113/28	Electromagnetic Compatibility Measurements Procedure for Vehicle Components--Part 28--Immunity to Radiated Electromagnetic Fields--Reverberation Method (Mode Tuning)
Auto/vehicle	SAE	J1113/4	Immunity to Radiated Electromagnetic Fields-Bulk Current Injection (BCI) Method
Auto/vehicle	SAE	J1752/1	Electromagnetic Compatibility Measurement Procedures for Integrated Circuits-Integrated Circuit EMC Measurement Procedures-General and Definition
Auto/vehicle	SAE	J1752/2	Measurement of Radiated Emissions from Integrated Circuits -- Surface Scan Method (Loop Probe Method) 10 MHz to 3 GHz

Category	Publisher	Number	Title
Auto/vehicle	SAE	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)
Auto/vehicle	SAE	J1812	Function Performance Status Classification for EMC Immunity Testing
Auto/vehicle	SAE	J2556	Radiated Emissions (RE) Narrowband Data Analysis--Power Spectral Density (PSD)
Auto/Vehicle	SAE	J2556	Radiated Emissions (RE) Narrowband Data Analysis–Power Spectral Density (PSD)
Auto/vehicle	SAE	J2628	Characterization--Conducted Immunity
Auto/Vehicle	SAE	J2628	Characterization–Conducted Immunity
Auto/vehicle	SAE	J551/15	Vehicle Electromagnetic Immunity--Electrostatic Discharge (ESD)
Auto/vehicle	SAE	J551/16	Electromagnetic Immunity - Off-Vehicle Source (Reverberation Chamber Method) - Part 16 - Immunity to Radiated Electromagnetic Fields
Auto/vehicle	SAE	J551/17	Vehicle Electromagnetic Immunity -- Power Line Magnetic Fields
Auto/vehicle	SAE	J551/5	Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz To 30 MHz
Auto/Vehicle	Scania	TB1400	EMC Requirements
Auto/Vehicle	Scania	TB1700	Load Dump Test
Auto/Vehicle	Smart	DE10005B	EMC requirements (electric aggregate and electronics in cars)
Auto/Vehicle	Toyota	TSC203G	Engineering standard (ABS-TRC computers)
Auto/Vehicle	Toyota	TSC7001G	Engineering standard (electric noise of electronic devices)
Auto/Vehicle	Toyota	TSC7001G-5.1	Power Supply Voltage Characteristic Test
Auto/Vehicle	Toyota	TSC7001G-5.2	Field Decay Test
Auto/Vehicle	Toyota	TSC7001G-5.3	Floating Ground Test
Auto/Vehicle	Toyota	TSC7001G-5.4	Induction Noise Resistance
Auto/Vehicle	Toyota	TSC7001G-5.5.3	Load Dump Test-1
Auto/Vehicle	Toyota	TSC7001G-5.5.4	Load Dump Test-2
Auto/Vehicle	Toyota	TSC7001G-5.5.5	Load Dump Test-3
Auto/Vehicle	Toyota	TSC7001G-5.6	Over Voltage Test
Auto/Vehicle	Toyota	TSC7001G-5.7.3	Ignition Pulse (Battery Waveforms) Test-1
Auto/Vehicle	Toyota	TSC7001G-5.7.4	Ignition Pulse (Battery Waveforms) Test-2
Auto/Vehicle	Toyota	TSC7001G-5.8	Reverse Voltage
Auto/Vehicle	Toyota	TSC7006G-4.4.2	Wide Band-Width Antenna Nearby Test (0.4 to 2 GHz)
Auto/Vehicle	Toyota	TSC7006G-4.4.3	Radio Equipment Antenna nearby Test (28 MHz ...)
Auto/Vehicle	Toyota	TSC7006G-4.4.4	Mobile Phone Antenna Nearby Test (835 MHz ...)
Auto/Vehicle	Toyota	TSC7018G	Static Electricity Test
Auto/Vehicle	Toyota	TSC7025G-5	TEM Cell Test (1 to 400 MHz)
Auto/Vehicle	Toyota	TSC7025G-6	Free Field Immunity Test (20 MHz to 1 GHz AM, 0.8 to 2 GHz PM)
Auto/Vehicle	Toyota	TSC7025G-7	Strip Line Test (20 - 400 MHz)

Category	Publisher	Number	Title
Auto/Vehicle	Toyota	TSC7026G-3.4	Narrow Band Emissions
Auto/Vehicle	Toyota	TSC7203	Voltage Drop / Micro Drops
Auto/Vehicle	Toyota	TSC7508G-3.3.1	Conductive Noise in FM and TV Bands
Auto/Vehicle	Toyota	TSC7508G-3.3.2	Conductive noise in LW, AM and SW Bands
Auto/Vehicle	Toyota	TSC7508G-3.3.3	Radiated Noise in FM and TV Bands
Auto/Vehicle	Toyota	TSC7508G-3.3.4	Radiated Noise in AM, SW, and LW Bands
Auto/Vehicle	Toyota	TXC7315G	Electrostatic Discharge (Gap Method)
Auto/Vehicle	Viston	ES-XU3F-1316-AA	Electronic Component - Subsystem Electromagnetic Compatibility (EMC) Requirements and Test Procedures
Auto/Vehicle	Volvo	N/A	EMC Requirements EMC requirements for 12V and 24V systems
Auto/Vehicle	VW	TL 801 01	Electric and electronic components in cars
Auto/Vehicle	VW	TL 820 66	Conducted Interference
Auto/Vehicle	VW	TL 821 66	EMC requirements of electronic components - bulk current injection (BCI)
Auto/Vehicle	VW	TL 823 66	Coupled Interference on Sensor Cables
Auto/Vehicle	VW	TL 824 66	Immunity Against Electrostatic Discharge
Auto/Vehicle	VW	TL 965	Short-Distance Interference Suppression
General	ANSI	S20.20	ESD Association Standard for the Development of and Electrostatic Discharge Control Program for the Protection of Electronic Parts, Assemblies, and Equipment
General	IEC	60050-161	International Electrotechnical Vocabulary. Chapter 161: Electromagnetic compatibility
General	IEC	60469	Transitions, pulses and related waveforms - Terms, definitions and algorithms
General	IEC	60940	Guidance information on the application of capacitors, resistors, inductors and complete filter units for electromagnetic interference suppression
General	IEC	61000-1-2	Electromagnetic compatibility (EMC) - Part 1-2: General - Methodology for the achievement of the functional safety of electrical and electronic equipment with regard to electromagnetic phenomena
General	IEc	61000-2-10	Electromagnetic compatibility (EMC) - Part 2-10: Environment - Description of HEMP environment - Conducted disturbance
General	IEC	61000-2-11	Electromagnetic compatibility (EMC) - Part 2-11: Environment - Classification of HEMP environments
General	IEC	61000-2-12	Electromagnetic compatibility (EMC) - Part 2-12: Environment - Compatibility levels for low-frequency conducted disturbances and signaling in public medium-voltage power supply systems
General	IEC	61000-2-13	Electromagnetic compatibility (EMC) - Part 2-13: Environment - High-power electromagnetic (HPEM) environments - Radiated and conducted
General	IEC	61000-2-2	Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems
General	IEC	61000-2-4	Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances
General	IEC	61000-2-9	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance. Basic EMC publication

Category	Publisher	Number	Title
General	IEC	61000-5-5	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 5: Specification of protective devices for HEMP conducted disturbance. Basic EMC Publication
General	IEC	61000-5-7	Electromagnetic compatibility (EMC) - Part 5-7: Installation and mitigation guidelines - Degrees of protection provided by enclosures against electromagnetic disturbances (EM code)
General	IEC	61000-5-8	Electromagnetic compatibility (EMC) - Part 5-8: Installation and mitigation guidelines - HEMP protection methods for the distributed infrastructure
General	IEC	61000-5-9	Electromagnetic compatibility (EMC) - Part 5-9: Installation and mitigation guidelines - System-level susceptibility assessments for HEMP and HPEM
General	IEC	62305-1	Protection against lightning - Part 1: General principles
General	IEC	62305-2	Protection against lightning - Part 2: Risk management
General	IEC	62305-3	Protection against lightning - Part 3: Physical damage to structures and life hazard
General	IEC	62305-4	Protection against lightning - Part 4: Electrical and electronic systems within structures
General	IEC	TR 61000-1-1	Electromagnetic compatibility (EMC) - Part 1: General - Section 1: Application and interpretation of fundamental definitions and terms
General	IEC	TR 61000-1-3	Electromagnetic compatibility (EMC) - Part 1-3: General - The effects of high-altitude EMP (HEMP) on civil equipment and systems
General	IEC	TR 61000-1-4	Electromagnetic compatibility (EMC) - Part 1-4: General - Historical rationale for the limitation of power-frequency conducted harmonic current emissions from equipment, in the frequency range up to 2 kHz
General	IEC	TR 61000-1-5	Electromagnetic compatibility (EMC) - Part 1-5: General - High power electromagnetic (HPEM) effects on civil systems
General	IEC	TR 61000-1-6	Electromagnetic compatibility (EMC) - Part 1-6: General - Guide to the assessment of measurement uncertainty
General	IEC	TR 61000-1-7	Electromagnetic compatibility (EMC) - Part 1-7: General - Power factor in single-phase systems under non-sinusoidal conditions
General	IEC	TR 61000-2-1	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 1: Description of the environment - Electromagnetic environment for low-frequency conducted disturbances and signaling in public power supply systems
General	IEC	TR 61000-2-14	Electromagnetic compatibility (EMC) - Part 2-14: Environment - Overvoltages on public electricity distribution networks
General	IEC	TR 61000-2-3	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 3: Description of the environment - Radiated and non network-frequency-related conducted phenomena
General	IEC	TR 61000-2-5	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 5: Classification of electromagnetic environments. Basic EMC publication
General	IEC	TR 61000-2-6	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 6: Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances
General	IEC	TR 61000-2-8	Electromagnetic compatibility (EMC) - Part 2-8: Environment - Voltage dips and short interruptions on public electric power supply systems with statistical measurement results
General	IEC	TR 61000-5-1	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 1: General considerations - Basic EMC publication

Category	Publisher	Number	Title
General	IEC	TR 61000-5-2	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 1: General considerations - Basic EMC publication
General	IEC	TR 61000-5-3	Electromagnetic compatibility (EMC) - Part 5-3: Installation and mitigation guidelines - HEMP protection concepts
General	IEC	TR 61000-5-6	Electromagnetic compatibility (EMC) - Part 5-6: Installation and mitigation guidelines - Mitigation of external EM influences
General	IEC	TR-61000-2-7	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 7: Low frequency magnetic fields in various environments
General	IEC	TS 61000-5-4	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 4: Immunity to HEMP - Specifications for protective devices against HEMP radiated disturbance. Basic EMC Publication
Generic	IEC	61000-6-1	Electromagnetic compatibility (EMC) - Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments
Generic	IEC	61000-6-2	Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity standard for industrial environments
Generic	IEC	61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments
Generic	IEC	61000-6-4	Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
Generic	IEC	61000-6-5	Electromagnetic compatibility (EMC) - Part 6-5: Generic standards - Immunity for power station and substation environments
Generic	IEC	61000-6-6	Electromagnetic compatibility (EMC) - Part 6-6: Generic standards - HEMP immunity for indoor equipment
Generic	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
Medical	IEC	60601-1-1	Safety requirements for medical electrical systems
Medical	IEC	60601-1-10	Requirements for the development of physiologic closed-loop controllers
Medical	IEC	60601-1-11	Medical electrical equipment and medical electrical systems used in the home healthcare environment
Medical	IEC	60601-1-12	Medical electrical equipment and medical electrical systems used in the medical services environment
Medical	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
Medical	IEC	60601-1-3	Radiation protection in diagnostic x-ray equipment
Medical	IEC	60601-1-6	General requirements for basic safety and essential performance – Usability
Medical	IEC	60601-1-8	General requirements for basic safety and essential performance - Alarm systems
Medical	IEC	60601-1-9	Requirements for environmentally conscious design
Medical	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
Medical	IEC	60601-4-2	Medical electrical equipment–Part 4-2: Guidance and interpretation - Electromagnetic immunity: performance of medical electrical equipment and medical electrical systems
Medical	IEC	TR 60601-4-2	Electromagnetic immunity performance

Category	Publisher	Number	Title
Medical	IEC	TR 60601-4-3	Considerations of unaddressed safety aspects in the third edition of IEC 60601-1
Medical	IEC	TR 62354	General testing procedures for medical electrical equipment
Medical	ISO	14708-1	Active implantable medical devices
MIL/Aero	AIAA	S-121	Electromagnetic Compatibility Requirements for Space Equipment and Systems, 2017
MIL/Aero	DoD	ADS-37A-PRF	Electromagnetic Environmental Effects (E3) Performance and Verification Requirements, 28 May 1996 (Army Aviation and Troop Command)
MIL/Aero	DoD	DoDD 4650.01	Policy and Procedures for Management and Use of the Electromagnetic Spectrum, 09 Jan 2009
MIL/Aero	DoD	DoDI 3222.03	DoD Electromagnetic Environmental Effects (E3) Program, Change Notice 2, 10 October 2017.
MIL/Aero	DoD	DoDI 6055.11	Protecting Personnel from Electromagnetic Fields, 19 Aug 2009
MIL/Aero	DoD	DOD-STD-1399-70	Section 070 Part 1 D.C. Magnetic Field Environment, (Notice 1 Validation, 30 Nov 1989)
MIL/Aero	DoD	MIL-HDBK-1195	Radio Frequency Shielded Enclosures, 30 Sep 1988
MIL/Aero	DoD	MIL-HDBK-1857	Grounding, Bonding and Shielding Design Practices, 27 Mar 1998
MIL/Aero	DoD	MIL-HDBK-2036	Preparation of Electronic Equipment Specifications, 1 November 1999
MIL/Aero	DoD	MIL-HDBK-235-1D	Military Operational Electromagnetic Environment Profiles Part 1D General Guidance, 03 April 2018
MIL/Aero	DoD	MIL-HDBK-237D	Electromagnetic Environmental Effects and Spectrum Certification Guidance for the Acquisition Process, 20 May 2005. (Notice 1 Validation 04 April 2013)
MIL/Aero	DoD	MIL-HDBK-240-1	Electromagnetic Environmental Effects to Ordnance Guide Part 1 General Guidance
MIL/Aero	DoD	MIL-HDBK-240-2	Electromagnetic Environmental Effects to Ordnance Guide Part 2 Hazards of Electromagnetic Radiation to Ordnance testing
MIL/Aero	DoD	MIL-HDBK-240-3	Electromagnetic Environmental Effects to Ordnance Guide Part 3 Electrostatic Discharge to Ordnance
MIL/Aero	DoD	MIL-HDBK-240-4	Electromagnetic Environmental Effects to Ordnance Guide Part 4 External Radio Frequency Electromagnetic Environments
MIL/Aero	DoD	MIL-HDBK-240-5	Electromagnetic Environmental Effects to Ordnance Guide Part 5 Lightning Effects to Ordnance (Notice 1 is administrative placeholder)
MIL/Aero	DoD	MIL-HDBK-240-6	Electromagnetic Environmental Effects to Ordnance Guide Part 6 Characterization of the Electromagnetic Environment for HERO
MIL/Aero	DoD	MIL-HDBK-240-7	Electromagnetic Environmental Effects to Ordnance Test Guide Part 7 Hazards of Electromagnetic Radiation to Ordnance Operational Guidance
MIL/Aero	DoD	MIL-HDBK-274A	Electrical Grounding for Aircraft Safety, 14 Nov 2011. (Notice 2 Validation 20 May 2021)
MIL/Aero	DoD	MIL-HDBK-335	Management and Design Guidance Electromagnetic Radiation Hardness for Air Launched Ordnance Systems, Notice 4, 08 Jul 2008. (Notice 5 Cancellation 01 August 2013)
MIL/Aero	DoD	MIL-HDBK-419A	Grounding, Bonding, and Shielding for Electronic Equipment and Facilities, 29 Dec 1987. (Notice 1 Validation 20 February 2014)
MIL/Aero	DoD	MIL-HDBK-454C	General Guidelines for Electronic Equipment
MIL/Aero	DoD	MIL-STD-1275E	Characteristics of 28 Volt DC Power Input to Utilization Equipment in Military Vehicles, 22 March 2013

Category	Publisher	Number	Title
MIL/Aero	DoD	MIL-STD-1310H	Shipboard Bonding, Grounding, and Other Techniques foe Electromagnetic Compatibility, Electeomagnetic Pulse (EMP) Mitigation, and Safety, 17 Sep 2009 (Notice 1 Validation 12 Aug 2014)
MIL/Aero	DoD	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 (Notice 1 Validation 19 Jan 2021)
MIL/Aero	DoD	MIL-STD-1399-300-1	Department of Defense Interface Standard Sectio 300, Part 1 Low Voltage Electric Power, Alternating Current
MIL/Aero	DoD	MIL-STD-1399-300-2	Department of Defense Interface Standard Sectio 300, Part 2 Medium Voltage Electric Power, Alternating Current
MIL/Aero	DoD	MIL-STD-1542B	Electromagnetic Compatibility and Grounding Requirements for Space System Facilities, 15 Nov 1991
MIL/Aero	DoD	MIL-STD-1605A	Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ships), 08 Oct 2009 (Notice 1 Validation 12 Aug 2014)
MIL/Aero	DoD	MIL-STD-188-124B	Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communications-Electronics Facilities and Equipment, 4 April 2013
MIL/Aero	DoD	MIL-STD-220C	Test Method Standard Method of Insertion Loss Measurement, 14 May 2009 (Notice 2 Validation 8 Oct 2019)
MIL/Aero	DoD	MIL-STD-331B	Fuze and Fuze Components, Environmental and Performance Tests for, 31 May, 2017
MIL/Aero	DoD	MIL-STD-449D	Radio Frequency Spectrum Characteristics, Measurement of, 22 Feb 1973 (Notice 2 Validation 4 Apr 2013)
MIL/Aero	DoD	MIL-STD-461G	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 11 Dec 2015
MIL/Aero	DoD	MIL-STD-464D	Electromagnetic Environmental Effects Requirements for Systems, 24 Dec 2020
MIL/Aero	DoD	MIL-STD-704F	Aircraft Electric Power Characteristics, Change Notice 1, 05 December 2016 (Notice 3 Validation 17 Sep 2021).
MIL/Aero	DoD	TOP-01-2-511A	Protecting Personnel from Electromagnetic Fields, 19 Aug 2009
MIL/Aero	DoD	TOP-01-2-620	High-Altitude Electromagnetic Pulse (HEMP) Testing, 10 November 2011
MIL/Aero	DoD	TOP-01-2-622	Vertical Electromagnetic Pulse Testing, 11 September 2009
MIL/Aero	RTCA	DO-160G	Environmental Conditions and Test Procedures for Airborne Equipment (Change 1)
MIL/Aero	RTCA	DO-233	Portable Electronic Devices Carried on Board Aircraft
MIL/Aero	RTCA	DO-235B	Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band
MIL/Aero	RTCA	DO-292	Assessment of Radio Frequency Interference Relevant to the GNSS L5/E5A Frequency Band
MIL/Aero	RTCA	DO-294C	Guidance on Allowing Transmitting Portable Electronic Devices (T-PEDs) on Aircraft
MIL/Aero	RTCA	DO-307A	Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance
MIL/Aero	RTCA	DO-307A	Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance
MIL/Aero	RTCA	DO-357	User Guide Supplement to DO-160
MIL/Aero	RTCA	DO-363	Guidance for the Development of Portable Electronic Devices (PED) Tolerance for Civil Aircraft

Category	Publisher	Number	Title
MIL/Aero	RTCA	DO-364	Minimum Aviation System Performance Standards (MASPS) for Aeronautical Information/ Meteorological Data Link Services
MIL/Aero	SAE	ARP 5583A	Guide to Certification of Aircraft in a High Intensity Radiation (HIRF) Environment
MIL/Aero	SMC	SMC-S-008	Electromagnetic Compatibility Requirements For Space Equipment and Systems, 13 Jun 2008
Test	ANSI	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
Test	IEC	60060-1	International Electrotechnical Vocabulary. Chapter 161: Electromagnetic compatibility
Test	IEC	60060-2	High-voltage test techniques - Part 2: Measuring systems
Test	IEC	60060-3	High-voltage test techniques - Part 3: Definitions and requirements for on-site testing
Test	IEC	61000-4-10	Electromagnetic compatibility (EMC) - Part 4-10: Testing and measurement techniques - Damped oscillatory magnetic field immunity test
Test	IEC	61000-4-11	Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests
Test	IEC	61000-4-12	Electromagnetic compatibility (EMC) - Part 4-12: Testing and measurement techniques - Ring wave immunity test
Test	IEC	61000-4-13	Electromagnetic compatibility (EMC) - Part 4-13: Testing and measurement techniques - Harmonics and interharmonics including mains signaling at a.c. power port, low frequency immunity tests
Test	IEC	61000-4-14	Electromagnetic compatibility (EMC) - Part 4-14: Testing and measurement techniques - Voltage fluctuation immunity test
Test	IEC	61000-4-15	Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 15: Flickermeter - Functional and design specifications
Test	IEC	61000-4-16	Electromagnetic compatibility (EMC) - Part 4-16: Testing and measurement techniques - Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz
Test	IEC	61000-4-17	Electromagnetic compatibility (EMC) - Part 4-17: Testing and measurement techniques - Ripple on d.c. input power port immunity test Electromagnetic compatibility (EMC) - Part 4-17: Testing and measurement techniques - Ripple on d.c. input power port immunity test
Test	IEC	61000-4-18	Electromagnetic compatibility (EMC) - Part 4-17: Testing and measurement techniques - Ripple on d.c. input power port immunity test
Test	IEC	61000-4-19	Electromagnetic compatibility (EMC) - Part 4-19: Testing and measurement techniques - Test for immunity to conducted, differential mode disturbances and signalling in the frequency range 2 kHz to 150 kHz at a.c. power ports
Test	IEC	61000-4-2	Electromagnetic compatibility (EMC)–Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
Test	IEC	61000-4-20	Electromagnetic compatibility (EMC) - Part 4-20: Testing and measurement techniques - Emission and immunity testing in transverse electromagnetic (TEM) waveguides
Test	IEC	61000-4-21	Electromagnetic compatibility (EMC) - Part 4-21: Testing and measurement techniques - Reverberation chamber test methods
Test	IEC	61000-4-22	Electromagnetic compatibility (EMC) - Part 4-22: Testing and measurement techniques - Radiated emissions and immunity measurements in fully anechoic rooms (FARs

Category	Publisher	Number	Title
Test	IEC	61000-4-23	Electromagnetic compatibility (EMC) - Part 4-23: Testing and measurement techniques - Test methods for protective devices for HEMP and other radiated disturbances
Test	IEC	61000-4-24	Electromagnetic compatibility (EMC) - Part 4-24: Testing and measurement techniques - Test methods for protective devices for HEMP conducted disturbance
Test	IEC	61000-4-25	Electromagnetic compatibility (EMC) - Part 4-25: Testing and measurement techniques - HEMP immunity test methods for equipment and systems
Test	IEC	61000-4-27	Electromagnetic compatibility (EMC) - Part 4-25: Testing and measurement techniques - HEMP immunity test methods for equipment and systems
Test	IEC	61000-4-28	Electromagnetic compatibility (EMC) - Part 4-28: Testing and measurement techniques - Variation of power frequency, immunity test
Test	IEC	61000-4-29	Electromagnetic compatibility (EMC) - Part 4-29: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests
Test	IEC	61000-4-3	Electromagnetic compatibility (EMC)–Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
Test	IEC	61000-4-30	Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods
Test	IEC	61000-4-31	Electromagnetic compatibility (EMC) - Part 4-31: Testing and measurement techniques - AC mains ports broadband conducted disturbance immunity test
Test	IEC	61000-4-33	Electromagnetic compatibility (EMC) - Part 4-33: Testing and measurement techniques - Measurement methods for highpower transient parameters
Test	IEC	61000-4-34	Electromagnetic compatibility (EMC) - Part 4-33: Testing and measurement techniques - Measurement methods for highpower transient parameters
Test	IEC	61000-4-36	Electromagnetic compatibility (EMC) - Part 4-36: Testing and measurement techniques - IEMI immunity test methods for equipment and systems
Test	IEC	61000-4-4	Electromagnetic compatibility (EMC)–Part 4-4: Testing and measurement techniques – Electrical fast transient/burst immunity test
Test	IEC	61000-4-5	Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
Test	IEC	61000-4-6	Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields
Test	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
Test	IEC	61000-4-8	Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test
Test	IEC	61000-4-9	Electromagnetic compatibility (EMC) - Part 4-9: Testing and measurement techniques - Impulse magnetic field immunity test
Test	IEC	61340-3-1	Electrostatics - Part 3-1: Methods for simulation of electrostatic effects - Human body model (HBM) electrostatic discharge test waveforms
Test	IEC	62153-10	Metallic communication cable test methods - Part 4-10: Electromagnetic compatibility (EMC) - Transfer impedance and screening attenuation of feed-throughs and electromagnetic gaskets - Double coaxial test method

Category	Publisher	Number	Title
Test	IEC	62153-11	Metallic communication cable test methods - Part 4-11: Electromagnetic compatibility (EMC) - Coupling attenuation or screening attenuation of patch cords, coaxial cable assemblies, pre-connectorized cables - Absorbing clamp method
Test	IEC	62153-12	Metallic communication cable test methods - Part 4-12: Electromagnetic compatibility (EMC) - Coupling attenuation or screening attenuation of connecting hardware - Absorbing clamp method
Test	IEC	62153-13	Metallic communication cable test methods - Part 4-13: Electromagnetic compatibility (EMC) - Coupling attenuation of links and channels (laboratory conditions) - Absorbing clamp method
Test	IEC	62153-14	Metallic communication cable test methods - Part 4-14: Electromagnetic compatibility (EMC) - Coupling attenuation of cable assemblies (Field conditions) absorbing clamp method
Test	IEC	62153-15	Metallic communication cable test methods - Part 4-15: Electromagnetic compatibility (EMC) - Test method for measuring transfer impedance and screening attenuation - or coupling attenuation with triaxial cell
Test	IEC	62153-4	Metallic communication cable test methods - Part 4-0: Electromagnetic compatibility (EMC) - Relationship between surface transfer impedance and screening attenuation, recommended limits
Test	IEC	62153-4-1	Metallic communication cable test methods - Part 4-1: Electromagnetic compatibility (EMC) - Introduction to electromagnetic screening measurements
Test	IEC	62153-4-2	Metallic communication cable test methods - Part 4-2: Electromagnetic compatibility (EMC) - Screening and coupling attenuation - Injection clamp method
Test	IEC	62153-4-3	Metallic communication cable test methods - Part 4-3: Electromagnetic compatibility (EMC) - Surface transfer impedance - Triaxial method
Test	IEC	62153-4-4	Metallic communication cable test methods - Part 4-4: Electromagnetic compatibility (EMC) - Test method for measuring of the screening attenuation as up to and above 3 GHz, triaxial method
Test	IEC	62153-4-5	Metallic communication cables test methods - Part 4-5: Electromagnetic compatibility (EMC) - Coupling or screening attenuation - Absorbing clamp method
Test	IEC	62153-4-6	Metallic communication cable test methods - Part 4-6: Electromagnetic compatibility (EMC) - Surface transfer impedance - Line injection method
Test	IEC	62153-4-7	Metallic communication cable test methods - Part 4-7: Electromagnetic compatibility (EMC) - Test method for measuring of transfer impedance ZT and screening attenuation aS or coupling attenuation aC of connectors and assemblies up to and above 3 GHz - Triaxial tube in tube method
Test	IEC	62153-4-8	Metallic communication cable test methods - Part 4-8: Electromagnetic compatibility (EMC) - Capacitive coupling admittance
Test	IEC	62153-4-9	Metallic communication cable test methods - Part 4-9: Electromagnetic compatibility (EMC) - Coupling attenuation of screened balanced cables, triaxial method
Test	IEC	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
Test	IEC	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

Category	Publisher	Number	Title
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	CISPR 17	Methods of measurement of the suppression characteristics of passive EMC filtering devices
Test	IEC	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
Test	IEC	CISPR TR 16-3	Specification for radio disturbance and immunity measuring apparatus and methods - Part 3: CISPR technical reports
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	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
Test	IEC	CISPR TR 18-1	Radio interference characteristics of overhead power lines and high-voltage equipment - Part 1: Description of phenomena

Category	Publisher	Number	Title
Test	IEC	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
Test	IEC	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
Test	IEC	TR 61000-4-32	Electromagnetic compatibility (EMC) - Part 4-32: Testing and measurement techniques - High-altitude electromagnetic pulse (HEMP) simulator compendium
Test	IEC	TR 61000-4-35	Electromagnetic compatibility (EMC) - Part 4-35: Testing and measurement techniques - HPEM simulator compendium
Test	IEC	TR 61000-4-37	Electromagnetic compatibility (EMC) - Part 4-36: Testing and measurement techniques - IEMI immunity test methods for equipment and systems
Test	IEC	TR 61000-4-38	Electromagnetic compatibility (EMC) - Part 4-38: Testing and measurement techniques - Test, verification and calibration protocol for voltage fluctuation and flicker compliance test systems
Test	IEC	TS 60816	Guide on methods of measurement of short duration transients on low-voltage power and signal lines
Wireless	ETSI EN	300 220	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 25MHz to 1000MHz frequency range with power levels ranging up to 500mW
Wireless	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
Wireless	ETSI EN	300 330	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 9kHz to 25MHz frequency range and inductive loop systems in the 9kHz to 30MHz frequency range
Wireless	ETSI EN	300 440	Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 1GHz to 40GHz frequency range
Wireless	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
Wireless	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 9kHz and 40GHz
Wireless	ETSI EN	301 893	Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering essential requirements
Wireless	ETSI EN	303 413	GPS receivers
Wireless	ETSI EN	303 417	Wireless Power Transfer

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/

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

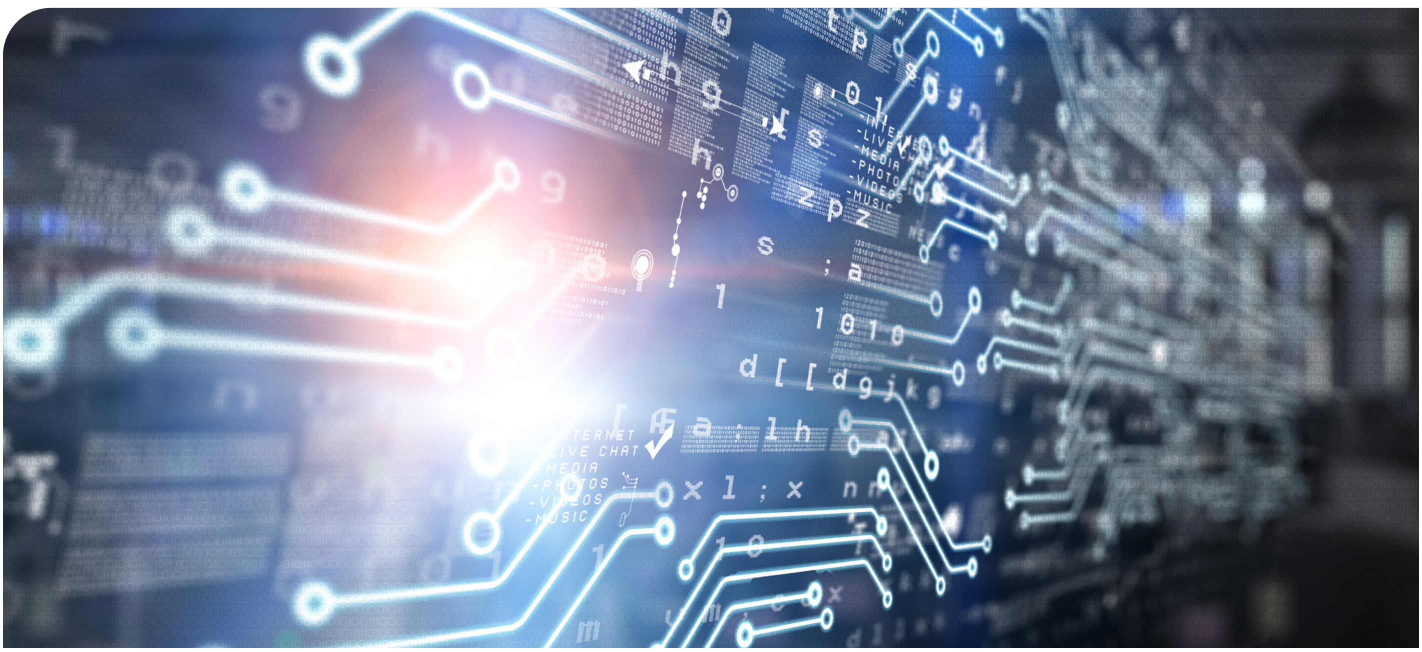
ISO (International Organization for Standards)
http://www.iso.org/iso/home.html

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

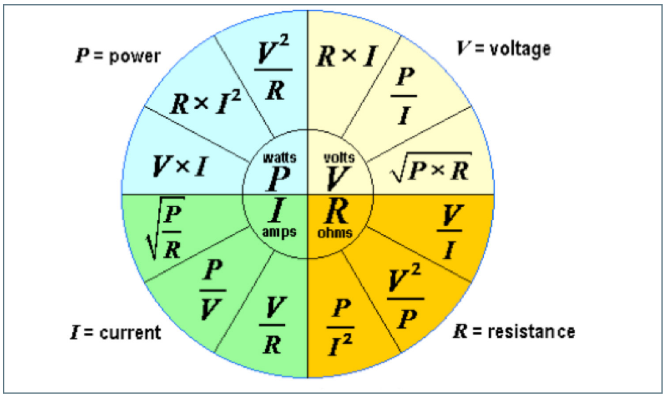
VCCI (Japan, Voluntary Control Council for Interference)
http://www.vcci.jp/vcci_e/



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 Z1,Z2 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

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

REFERENCES & TOOLS

RETURN LOSS, GIVEN VSWR

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

Return Loss, given reflection coefficient (ρ)

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

E-FIELD FROM DIFFERENTIAL-MODE CURRENT

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

ID = differential-mode current in loop (A)

f = frequency (Hz)

L = length of loop (m)

s = spacing of loop (m)

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

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

E-FIELD FROM COMMON-MODE CURRENT

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

IC = common-mode current in wire (A)

f = frequency (Hz)

L = length of wire (m)

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

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, DBMV, DBMA (CONVERSION)

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

Note: For current relationships, substitute A for V

FIELD STRENGTH EQUATIONS

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

DBM TO DBUV CHART

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

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

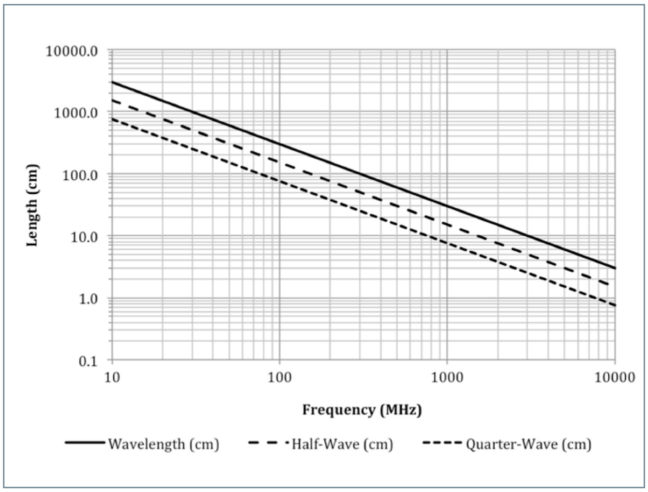
dBm to dBµV, use: dBµV = dBm + 107

REFERENCES & TOOLS

WAVELENGTH EQUATIONS (FREE SPACE)

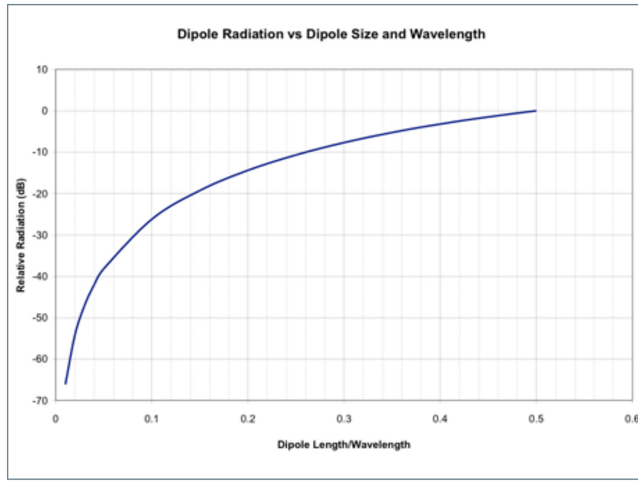
Wavelength(m) = 300/f(MHz)
Half-wavelength(ft.) = 468/f(MHz)

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. 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. Image Source: Bruce Archambeault.

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.

ACRONYMS

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.
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

2021 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/2021-emc-testing-guide/

2021 Automotive EMC Guide
This guide features technical articles, reference materials, and a company directory focused on the EMI challenges that result from today's complex connected automotive systems.
https://learn.interferencetechnology.com/2021-automotive-emc-guide/

2021 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/2021-emc-fundamentals-guide/

2021 IoT, Wireless, 5G EMC Guide
This guide includes content and reference material focused on providing the information required for designing and testing EMI-free wireless devices.
https://learn.interferencetechnology.com/2021-iot-wireless-5g-emc-guide/

2021 Military & Aerospace EMC Guide
This guide provides up-to-date information on a range of mil/aero technologies and EMC standards like MIL-STD-461G and DO-160, ensuring cost-effective design and testing.
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Shielding of Electromagnetic Waves, Theory and Practice
Springer. 2019. Provides efficient ways for design engineers to apply electromagnetic theory in shielding of electrical and electronic equipment.

RECOMMENDED EMC BOOKS, MAGAZINES AND JOURNALS

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

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

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Prentice-Hall, 1993. Practical coverage of high speed digital signals and measurement.

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LINKEDIN GROUPS

Electromagnetic Compatibility Forum

Electromagnetics and Spectrum Engineering Group

EMC - Electromagnetic Compatibility

EMC Experts

EMC Troubleshooters

ESD Experts

Signal & Power Integrity Community

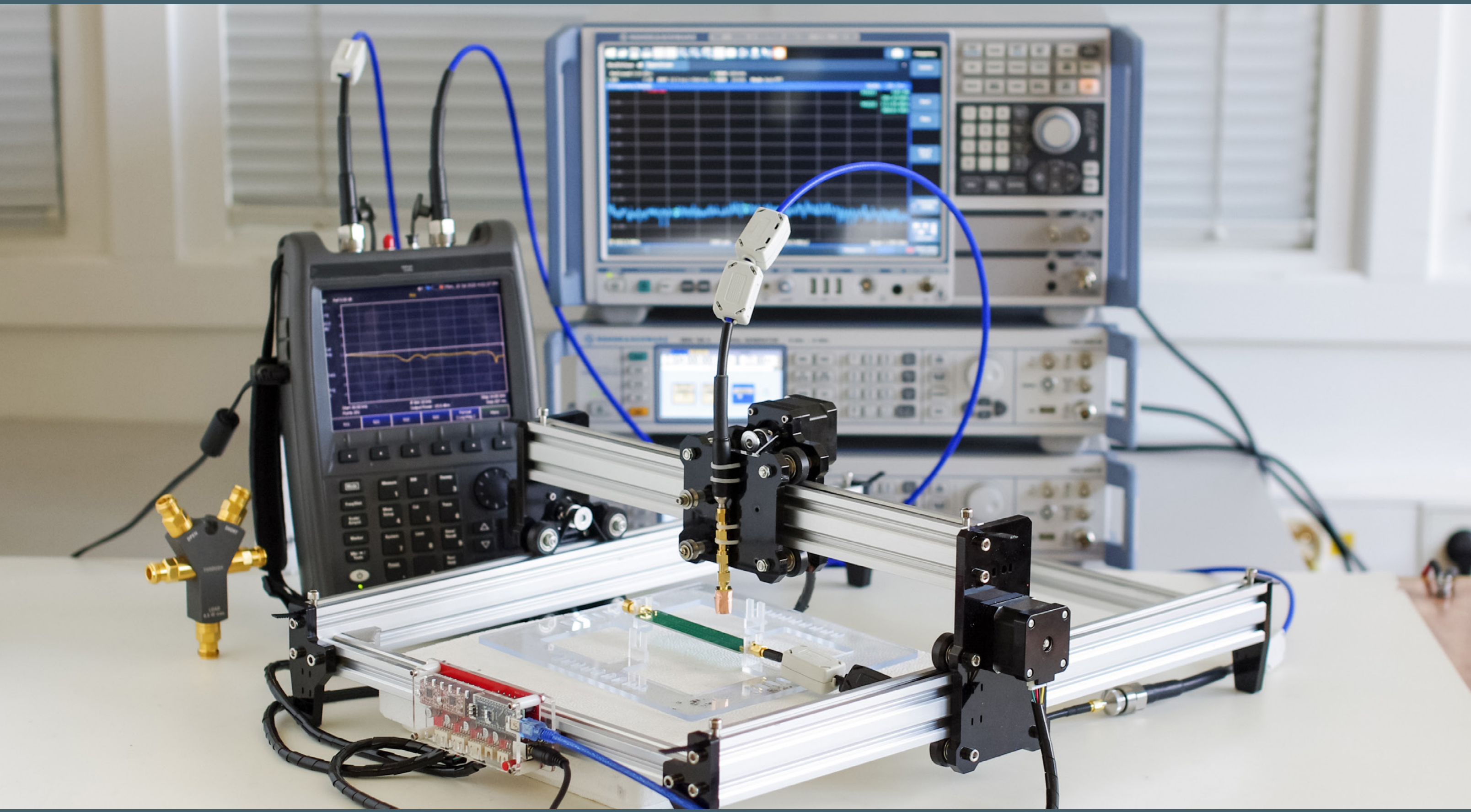
EMI/EMC Testing

IEEE EMC Society

iNARTE

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

EMC FUNDAMENTALS



EMC 101

AR, Souderton, Pennsylvania, USA

The purpose of this document is to give background information to the reader about the basics of EMC (Electromagnetic Compatibility), EMI (Electromagnetic Interference), and how it relates to installations in the real world.

As manufacturers across the world continue to develop, innovate, and expand new technologies and products, one important facet of the design and implementation of these new technologies and products is the compliance to EMC regulations and standards for different economies and countries. Each of the standards define the compliance testing and requirements for product families within specific industries, and typically describe how to test those products.

DEFINITIONS:

EMC – Electromagnetic Compatibility – The ability of a product to operate (compatibility) within different electromagnetic environments.

EMI – Electromagnetic Interference – The amount of electromagnetic emissions (interference), either radiated or conducted, coming from a product.

EUT – Equipment Under Test

CE – Conducted Emissions – A measurement of the interference emitted from a product, typically measured on power input lines or telecommunications ports, with measurements and limits typically expressed in terms of voltage (dBµV) or current (dBµA).

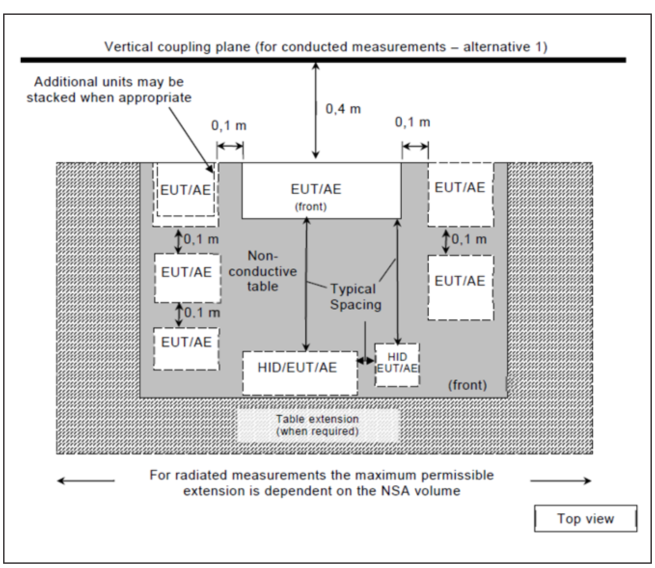


Figure 1: CISPR 32 Conducted Emissions Test Setup

RE – Radiated Emissions – A measurement of the over-the-air interference emitted from a product, from both the enclosure (often called the enclosure-port) or the cabling. Limits typically expressed in terms of Volts per meter (dBµV/m) for electric field, or Amperes per meter (dBµA/m).

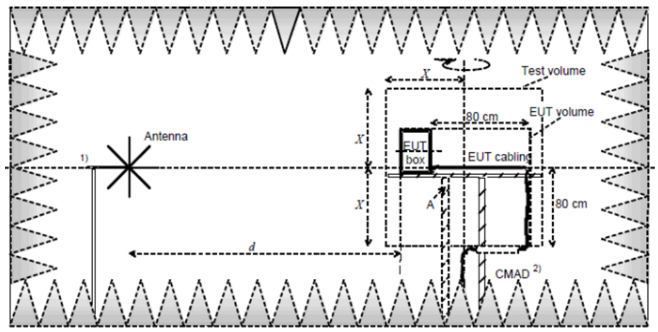


Figure 2: CISPR Radiated Emissions Test Setup

CS or CI – Conducted Susceptibility or Conducted Immunity – The application of a test signal, often imparted onto interfacing cables to EUTs via BCI, CND, EM Clamp, or other means, to observe that the EUT operates acceptably throughout the application of the test.

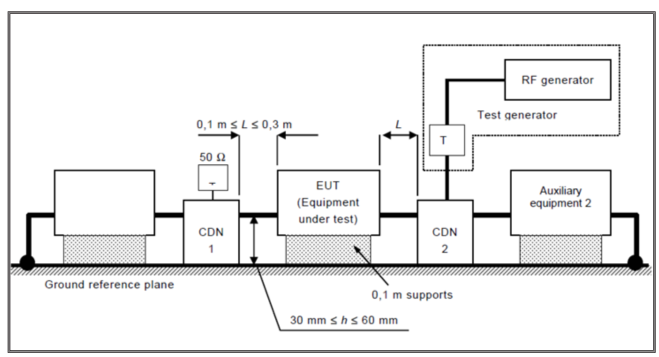


Figure 3: Conducted Immunity or Susceptibility Test Setup

RS or RI – Radiated Susceptibility or Radiated Immunity – The application of a test signal, applied with a test antenna over-the-air, to observe that the EUT operates acceptably throughout the application of the test.

Test Method – The specific test performed. Each test method typically has its own title, such as CS114, RE102, or IEC 61000-4-6, but will fall within the categories of CE, RE, CI, or RI.

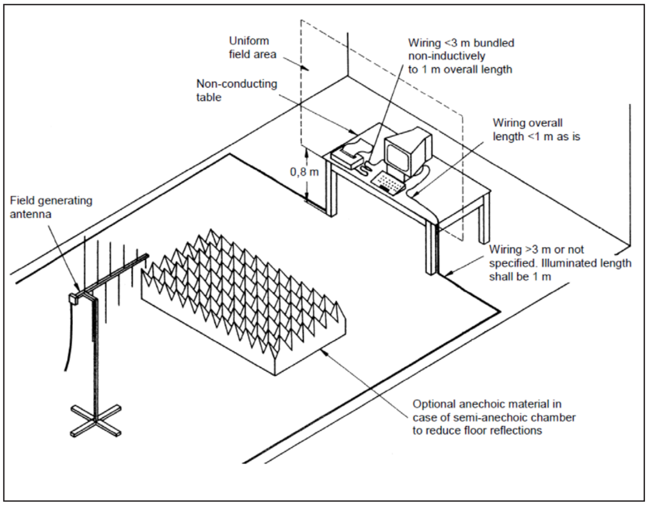


Figure 4: Radiated Immunity or Susceptibility Test Setup

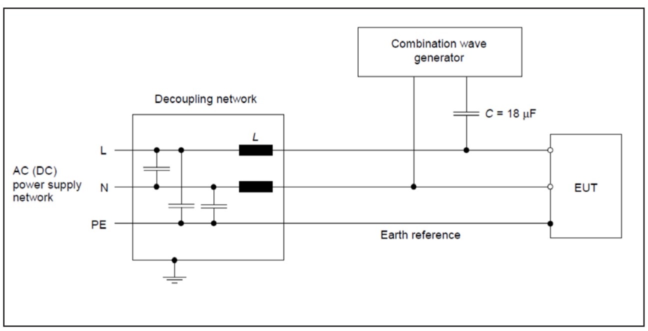


Figure 5: Transient Testing per IEC 61000-4-5, Surge Immunity, Test Setup

Test Standard – A document which defines the requirements, compliance criteria, and limits for a particular product family or industry. For a closer look at test standards, refer to Amplifier Research Application Note #67, EMC Standards Overview. The above definitions of CE, RE, CI, and RI describe the four (4) types of compliance tests performed for pieces of equipment. Within each category, there are two basic phenomena: Continuous and Transient Phenomena.

WHAT'S THE DIFFERENCE BETWEEN CONTINUOUS AND TRANSIENT IN THE WORLD OF EMC TESTING?

Continuous test methods typically involve testing within a defined frequency range (for example, 150 kHz to 80 MHz for Conducted Immunity and 80 MHz to 6 GHz for Radiated Immunity). The purpose of testing for continuous phenomena is to ensure that a device or product will operate as intended when a signal is ever-present within its installed environment, or, conversely, not emit a continuous signal that will interfere with other devices environment. For example, a product should always continue to operate when placed within a wireless transmitter's vicinity, be it Bluetooth, Wi-Fi, or an RFID reader.

Transient test methods involve testing which simulates phenomena in the real world that are not always present, such as electrostatic discharge (simulating an electrostatically charged human body touching the EUT), surge (simulating a lightning strike of the installed building or location), and electrical-fast transients (simulating load switching of relays). The waveforms defined by the transient test methods are specific to rise time, duration, repetition rate, and source impedance.

During transient testing, an EUT upset or malfunction may be permitted, provided it can return to the previous state or operating mode without user intervention. The compliance criteria for this is dependent on the test standard being tested.

WHAT'S THE PURPOSE OF EMC TESTING AND COMPLIANCE?

First, there are the legal issues. If regulatory requirements aren't met, then a manufacturer cannot legally sell the product in the country of intention. If a product is sold that doesn't meet the requirements, the product will likely be removed from the marketplace, fines may be imposed on the manufacturer, and prison time for owners and employees of the manufacturer is a possibility.

Second, EMC testing can and will reveal potential design flaws within a product, where the manufacturer can make a product better, and not just do the bare minimum to meet the requirements. This can alleviate the need for costly recalls and design changes.

WHAT'S THE MOST IMPORTANT ASPECT OF EMC TESTING AND COMPLIANCE?

EMC is a vast and complex worldwide industry which involves regulatory requirements, different economies, documentation, laboratories, equipment manufacturers, test standards, and test methods. There's one word that nearly every aspect comes back to, which is the most important word in the EMC dictionary:

IMPEDANCE

Impedance, or resistance, is where the applied limit, test level, waveform, and EUT response is derived. Impedance of a cable will define the amount of RF current that is imparted into an EUT, and the impedance of the shield of the cable will define how much of that RF current is shunted to ground. The impedance of an antenna will define its effectivity as a radiator, and the impedance of a ground connection, whether it be a shield, a ground strap, or a ground wire, will help define its effectiveness in either shielding for emissions or shunting RF current to ground.

OKAY, SO NOW I THINK HAVE THE BASIC UNDERSTANDING OF WHAT EMC IS, BUT NOW WHAT DO I DO?

Let's say that your company has a product that utilizes digital electronics. Depending on where you intend to sell that product, you'll need to meet regulatory requirements to ensure that the product isn't going to interfere with other products, or that other products aren't going to interfere with it. In the United States, the FCC is the government authority that enforces regulations, and the only thing that the US regulates is emissions. For most products, the regulatory requirements are found in Title 47 of the Federal Register under Part 15. If you need to sell into Europe, then you'll need to investigate testing under the EMC Directive (2014/30/EU) for compliance.

I HAVE A PRODUCT THAT I WANT TO SELL IN BOTH THE US AND IN EUROPE. WHAT'S MY NEXT STEP?

You'll have to have your product tested, of course. A testing laboratory should be able to help you define what your requirements are, depending on your product type and where you plan on selling it. Once you have the requirements defined, it's time to get to the test laboratory.

A test laboratory's services can be used in a few different ways. If you need to see how close you are to compliance, book some evaluation time to run through a few different tests to see where your product stands. Typically, evaluation of the radiated and conducted emissions as well as radiated immunity test methods is where many manufacturers start.

Many companies/manufacturers develop their own in-house testing laboratories to streamline the test phase of product development. This option enables a manufacturer to mitigate problems as they arise, and not be at the mercy of a test lab schedule.

Depending on which test laboratory you choose, or if you're using an internal or captive laboratory, some regulatory or approving bodies require the test laboratory to be accredited to ISO 17025 before compliance can be declared.

If you've done some pre-compliance testing, which can be done on an engineering bench with a small amount of equipment, and are ready for the full-bore test program, contact the test lab for a quotation to test the product for compliance. Once you have a test date, you're all set.

CONCLUSION

The above gives a very basic description of EMC, what it is, and why it's important. The end goal is to ensure that products in the marketplace do not interfere with each other and are immune to interference from other products (within reason). If you have additional questions or need guidance for your requirements, do not hesitate to contact AR's applications engineers at 800-933-8181.

REFERENCES

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5 STEPS TO SELECTING THE RIGHT RF POWER AMPLIFIER

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You need an RF power amplifier. You have measured the power of your signal and it is not enough. You may even have decided on a power level in Watts that you think will meet your needs. Are you ready to shop for an amplifier of that wattage? With so many variations in price, size, and efficiency for amplifiers that are all rated at the same number of Watts many RF amplifier purchasers are unhappy with their selection. Some of the unfortunate results of amplifier selection by Watts include: unacceptable distortion or interference, insufficient gain, premature amplifier failure, and wasted money. Following these 5 steps will help you avoid these mistakes.

Step 1 - Know Your Signal Step 2 – Do the Math
Step 3 - Window Shopping
Step 4 - Compare Apples to Apples
Step 5 – Shopping for Bells and Whistles

STEP 1 – KNOW YOUR SIGNAL

You need to know 2 things about your signal: what type of modulation is on the signal and the actual Peak power of your signal to be amplified. Knowing the modulation is the most important as it defines broad variations in amplifiers that will provide acceptable performance. Knowing the Peak power of your signal will allow you calculate your gain and/or power requirements, as shown in later steps.

SIGNAL MODULATION AND POWER- CW, SSB, FM, AND PM ARE EASY

To avoid distortion, amplifiers need to be able to faithfully process your signal's peak power. No matter what the modulation type is, you need to know the Peak power.

Fortunately, for many modulation types Average power is the same as Peak power: CW, SSB (single tone and voice), FM, and Phase Modulation all have Average equal to Peak power. The power in these RF carriers is relatively easy to measure with an Average power meter, a Spectrum Analyzer, or an RF Wattmeter. Many RF amplifiers are rated for CW power, so that spec will apply for SSB (single tone and voice), FM, and Phase Modulated signals as well. For SSB, since the carrier is suppressed, the significant power is all in the sideband carrier.

WATCH OUT FOR AM MODULATION

AM Peak power depends on the percentage of modulation, but you may need to allow for 100% modulation, which creates signal peaks of 4x the un-modulated carrier, or +6dB. That means that you would need a 400W amp to faithfully AM modulate a 100W CW signal. If you have less power available, or "headroom", your amplifier will be operating in compression, which will distort the signal by "clipping" or cutting off the peaks of the waveform. Although some distortion may by tolerable for speech communication, since AM communications are subject to a variety of other impairments, you should specify your RF amplifier to produce the minimum AM distortion possible. AM voice communications usually use modulation depth in the range of 60-80%. Specifying performance at 90% modulation will provide a safe margin for most AM communications.

AM Peak Power (dBm) = CW Power (dBm) + 6db (100% modulation)
AM Peak Power (Watts) = CW Power (Watts) x 4 (100% modulation)

A 100W amplifier will begin to clip a 100W carrier as soon as any AM modulation is applied. Clipping is a form of distortion that causes more problems than just reducing signal "readability". Clipping also causes increased harmonic products in the form of carriers of substantial power, which can cause interference far off-frequency.

AM average power is not the same as CW average power, as it varies with the modulation depth. The average power increases with modulation depth. For sine wave modulation, the relationship is as follows:

Modulation Index (M) = Modulation Depth / 100
AM Average Power Increase = $(1 + M^2 / 2)$
AM Average Power Increase in dB = $10 \log_{10} (1 + M^2 / 2)$

Example: For a 100 WCW with 70% Modulation:
AM Average Power Increase = $(1 + 0.70^2 / 2)$
AM Average Power Increase = (1 + .245)
AM Average Power Increase (ratio) = 1.245

AM Average Power Increase in dB = 10 log10 (1 + M2 / 2)
(Continued from the example above)
AM Average Power Increase dB = $10 \log_{10} (1.245)$
AM Average Power Increase dB = 0.95

To calculate the Peak power required when you know your AM Modulation Depth or Index:

AM Peak Power (Watts) = $(M + 1)^2$ x CW Power

Example: For a 3WCW signal with 80% Modulation Depth:
Peak Power (W) = $(0.8 + 1)^2$ x 3 WCW
Peak Power (W) = $(1.8)^2$ x 3 WCW
Peak Power = 9.72 Watts

Example: For a 100 WCW signal with 90% Modulation Depth:
Peak Power (W) = $(0.9 + 1)^2$ x 100 WCW
Peak Power (W) = $(1.9)^2$ x 100 WCW
Peak Power = 361 Watts

MULTI-TONE OR MULTI-CARRIER SIGNALS CAN BE A BIG SURPRISE

If your signal has multiple discrete carriers it will require more power to faithfully amplify than you probably think.

You cannot simply add the individual powers. The Peak power required for 100% fidelity is equal to the individual carrier Peak power times the square of the number of carriers. That is because the Peak Power is equal to E^2 /R. In this formula R is the load, so the voltages across the load must be squared. That means if you have two carriers with a Peak Power of 1W each, it will require a 4W amplifier to avoid signal compression. If you have 10 carriers with 1W Peak Power each it will take a 100W class A amplifier to avoid compression! That may be overkill for your application, as your modulation may not require such very low distortion.

For a multicarrier signal with equal amplitude carriers: Peak Power (Watts) = (number of carriers)2 x Peak Power (W) of a single signal

If your signal contains carriers with varying power levels or modulation types, you can't go wrong by taking the square of the number or carriers and multiplying it by the highest single Peak Power signal expected.

Once you calculate the Peak Power you need, the surprisingly high wattage may force you to consider economizing. Before you begin dropping the Peak Power wattage number and shop for lower power amplifiers, bump the amplifier class down to from A to AB. That will provide your required Peak Power number with typically a modest amount of distortion and higher efficiency at lower cost per Watt.

COMPLEX MODULATION PEAK POWER IS A LITTLE MORE COMPLEX

If your signal is modulated by complex (simultaneous phase and amplitude) modulation you will need to resort to specialized means of measurement. If you have a peak power meter, and you are sure no other significant contributions to the signal power are present, it should provide a valid peak measurement. Checking with a spectrum analyzer is always prudent to be sure of what a broadband power sensor is "seeing". Lacking a peak power meter, a spectrum analyzer that has a peak detector may be used. Lastly, try a peak search marker on a sample detector trace set to the Max Hold function.

You can estimate Peak Power from an Average power measurement based on your signal format Peak-to-Average ratio (PAR) or Crest Factor. For example, 64QAM has a PAR value of about 3.7dB. PAR actually uses the RMS value, not average, so add 1.5dB to the average power to get RMS power. For a 64QAM signal with 0 dBm average power:

0dBm average + 1.5dB ≅ 1.5dBm RMS
1.5dBm RMS + 3.7dB PAR ≅ 5.2dBm Peak

Modulation Format	Approx. PAR (dB) Without CFR	Approx. PAR (dB) With CFR
64QAM	3.7	N/A
8VSB	6.5-8.1	4-6
W-CDMA (DL)	10.6	2.2-6.5
WIMAX/OFDM/WLAN	12-13	6-7

These higher PAR levels translate to higher power being needed in an amplifier. That can be seen as inefficiency, as the heavy lifting is being done at lower power levels, or as a reasonable cost of increasing the density of the data. Crest Factor Reduction (CFR) schemes that pre-clip the signal can reduce the PAR for some types of modulation, but even so, complex modulated signals will still degrade slowly over a wide power range as the signal peaks are increasingly clipped in the amplifier (see **fig. 1**). This causes progressively increasing digital errors and also pushes energy into adjacent channels, creating "noise". It is important to remember that PAR for complex-waveform signals can vary with the data payload sent, so try to test your system with a worst-case data set. Pseudo-noise (PN) data produced by a signal generator may not represent your worst- case signal.

SO WHAT IF THE AMPLIFIER RUNS OUT OF HEADROOM?

Running an amplifier out of the linear range doesn't just mean you get less power out. It can create big problems:

1. **You can damage the amplifier.** Power amps typically specify a P_1 level to represent a safe power output level (see **Step 4** for a brief discussion about P_1). It is good practice to make sure your Peak signal levels stay under the P_1 level to avoid over-driving the amplifier. Some of the excess power that can not be translated into the output waveform can appear on the output transistors as heat. Typical destructive levels for these expensive devices are about P_6 or P_7, only 5-6 dB above P_1. Add attenuation to the amplifier input as necessary to keep under P_1 levels. Many AR Modular RF amplifier designs offer over-drive protection in the form of an Automatic Limiter Circuit (ALC) to prevent accidental over-drive levels. Amplifiers employing newer Gallium-Nitride (GaN) devices are more damage-resistant than the LDMOS devices that preceded them.

2. **You can ruin your signal.** As your signal peaks cannot be reproduced with the same gain as the lower level signals, they are distorted. This can mean the amplifier is useless at your desired power level, and must be used with lower gain or drive levels and less power out. In general, you must adjust the input level to reduce the output power, or get a bigger amp. Many AR Modular RF models offer wide-range gain controls that help with fixed power levels.

3. **You can make other problems.** The power that is missing from your distorted signal is appearing somewhere else- as interference out of your frequency channel or as harmonics way off-frequency. Complex-modulated signals can create interference in adjacent channels. Harmonics are especially a problem with broadband amplifiers that amplify the 2nd or 3rd harmonic of the lower frequencies covered. Since no input filters can be employed, a conservative design with lots of headroom is needed. Output filters can fix harmonics but can dissipate a lot of heat at high power, and need to be well designed mechanically to be able to transfer the heat to a sink.

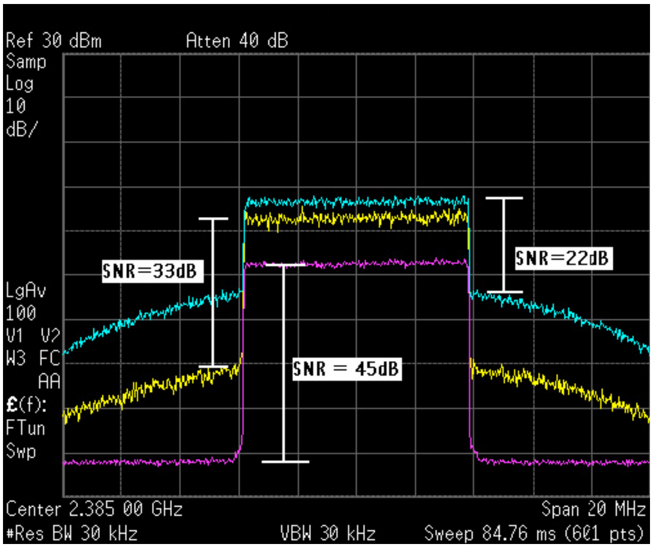


Fig.1

Figure 1 shows an OFDM signal degrading in an amplifier as the Peak power approaches and crosses over the P_1 compression point. The lowest trace is an uncompressed signal with better than a 45dB signal-to-noise ratio (SNR). The middle Trace 2 shows the input signal 10dB higher than for Trace 1, with signal peaks just touching the P_1 point. While the gain across the data channel has increased by 10dB, Intermodulation distortion has created "shoulders" of noise, reducing the SNR to 33dB. Increasing the drive by only 5dB in Trace 3 shows that the power in the adjacent channels has increased by 16dB, and SNR has been reduced to about 22dB. Your specific application will determine what level of SNR is required or can be tolerated.

COMPLEX MODULATION NEEDS MORE HEADROOM BUT HOW MUCH?

As shown, complex-modulation formats exhibit high Peak powers compared to their Average power. With Crest Factor reduction (CFR) schemes, digital and amplifier linearization techniques, and the variables of the signal payload, the effective PAR and range of acceptable non-linearity is wide. Most digital formats can suffer modest to moderate distortion and remain usable. For example, absent other distortion, WLAN modulation can still provide acceptable performance when Peak power is limited to an amplifier's P_1 power point (see **Step 4** for an explanation of P_1).

OFDM modulation with a PAR of 12 may allow a Peak power de-rating of as much as 6 dB from Peak. De-rating the input power to allow the amp to meet the Peak power requirements is commonly referred to as "back off" and is expressed in dB. Even de- rating by 6dB leaves the Peak power still 6dB over average, and that must allowed for by either backing off the CW P_1 point by 6dB or by adding 6dB of headroom to the output power rating of the amp. Your specific application must determine the effective PAR value you apply to the average power of your signal when calculating the Peak power, but Peak power will always be significantly more than average power. Using an effective PAR, or "back off" of 6-7dB should provide a useful working number.

PULSE MODULATION

Measuring pulse Peak power can be done easily with a Peak power meter regardless of pulse width. You can also calculate Peak power by dividing Average Power by the duty cycle of the pulse modulation.

Duty Cycle (dB) = 10 log(duty cycle ratio)

Example: For a pulsed RF train with an Average power of 0dBm and a duty cycle of 15%:

0dBm + 10 log(0.15) = 8.24dBm Peak

Try to use representative pulse trains or a worst-case scenario to obtain Peak values that will allow enough headroom for your pulse peaks.

STEP 2 – DO THE MATH – DO YOU NEED GAIN OR POWER NUMBERS?

Your application determines either the signal level you want your amplifier to produce (in Watts or dBm) or the amount of gain you require. If you require a specific signal level, the difference between that power level and the peak power of your signal is the minimum degree of amplification, or gain, you require. If you have a specific gain requirement then your signal peak power added to the gain will provide the minimum power out necessary for the amplifier to produce.

Power Out (dBm) – Peak Power In (dBm) = Gain (dB) Required

For example, you may know the Peak Envelope Power (PEP) required to provide a specific Effective Radiated

Power (ERP) at an antenna. In that case, for a signal with a Peak power of +10dBm and a desired PEP of 50 Watts:

dBm = 10 log(milliwatts)

10 log(50,000 mW) = +47 dBm

+47dBm PEP - 10dBm Peak = +37dB Gain @ 50W Peak Output (+10 dBm Input)

Many RF amplifiers with have different power input specifications, but 0 dBm is fairly common. In the example above, to avoid over-driving the amplifier, it may be necessary to add 10 dB attenuation to the RF amplifier input to reduce the input power to 0 dBm. In that case the example looks like this:

+47dBm PEP - 10dBm Peak + 10 dB Attenuation = +47dB Gain (0 dBm Input)

If you know the Gain required but not the Wattage necessary to provide it, add the Peak power to the gain, and convert the sum to Watts:

Peak power (dBm) + Gain (dB) = Peak power out (dBm)

Power (Watts) = antilog10(dBm/10)

For example, you have a Peak signal power of +3dBm and require a Gain of 40dB to obtain a final peak power level of +43dBm to drive a larger power amplifier. Remember to add 3dB to the Gain to compensate for the 3 dB attenuator to bring the input level to 0dBm:

0dBm Peak + 40dB Gain + 3dB Attenuation = +43dBm = 20 Watts Peak

If your signal level is below 0dBm, you can search for amplifiers with higher gain that will produce the desired power level in **Step 3**. To determine the maximum Input Power level for an amplifier, subtract Gain from the CW P_1 power out:

Peak power out dB – Gain dB = Peak Input level

For example, to find the Peak input level for a 20W amp with 48dB gain:

20W = +43dBm
+43dBm – 48dB = -5dBm

STEP 3 – WINDOW SHOPPING- SELECT BY TYPE, FREQUENCY, AND POWER

This step is where you can begin to pre-select amplifiers that might meet your requirements. Here is where CW and Pulse amps will diverge. The other big break point for selection is whether you are shopping for a "module", or a system. A module is usually a smaller unit that comes with or without a heat sink, and usually without any controls or indicators, designed to be integrated into an assembly. A full system is self- contained, complete with chassis, cooling, AC-DC power supplies, front-panel and remote controls and indicators.

As amplifiers are usually designed over more frequency ranges than power levels, it can save time to first screen a vendor's lists by Power Out, then by frequency, then by Gain.

REMEMBER, CHEAP SPECS WILL SHRINK IN THE WASH- SHOP FOR A SIZE LARGER

At this early stage of the process it is essential to make your initial selection based on a wider range of advertised powers and frequencies than you think you need. Print out the data sheets for any potential candidates for further scrutiny in **Step 4**. As you zoom into the specs you will find that the band edges may not perform as well as you might wish, or the power specs quoted are overly optimistic. You might need to get an amplifier with wider coverage to improve flatness across your frequency band, or pick a slightly more powerful amplifier than the rating specified to get a reasonable margin of gain or power. You may also find that another spec will invalidate otherwise attractive features, like poor Harmonic specs from an amplifier being pushed a little too hard.

STEP 4 – COMPARING APPLES TO APPLES

Here is where you need to look closely at the specs. Depending on the amplifiers you have selected so far, you need to make an educated choice which amps will actually provide the gain and power for your application. The important thing to accomplish at this step is to make sure you are comparing "apples to apples" or in this case Usable Watts to Usable Watts.

SIGNAL LINEARITY AND USABLE WATTS

All amplifiers will compress at some level. So this discussion will short-cut past the relative virtues of amplifier Classes of Operation so frequently seen in amplifier literature. Either an amplifier is Class A or it is not. If it is, the amplifier may be relied on to provide superior performance in terms of fidelity, low distortion, and immunity to VSWR over the entire linear power range.

AR Modular RF can provide Class A RF power amplifiers that exhibit the highest signal linearity for the most demanding applications, like the **KAW2180**, a 100W minimum dual-band Class A amplifier that operates from 0.01-1000 MHz. All other types of RF amplifier (usually

Class AB) will provide some more distortion in exchange for efficiency, and may require some spec-diving to figure out how many linear watts you will really get.

RF power amplifier ratings can be expressed in many kinds of Watts: Average, P_1, CW, Peak, ALC Watts, even Peak-to-Peak (P-P). You job here is to "normalize" all the results to a common and meaningful value, like P_1 Watts, so a direct comparison can be made.

P_1 POWER VS. SATURATED POWER

All amplifiers exhibit gain compression at higher operating levels, meaning the gain (not the level) decreases as input power rises. The output level at which the power has deviated from true linearity by 1dB is typically specified as the P_1 point. Even Class A amplifiers have a P_1 point. The P_1 power level is the most useful reference to output power as it can be measured directly and accurately and indicates the practical power limit that may be safely and conservatively employed. Beyond the P_1 point, as input power increases, compression also increases until the departure from linear gain is -3dB, or one-half the power out that occurs at lower powers. This is known as the Saturation level or P_3. This not generally regarded as a usable or safe power level. The P_1 level is typically about 2dB below the P_3 saturated power level.

Saturated Power P3 – 2dB = Usable Power P1

For example, for an amp specified at 100W out P3 saturated power, the actual "usable" power, or P1 level, is found:

100W P_3 – 2dB = +50dBm P_3 – 2dB = +48dBm P_1 = antilog$_{10}$(4.8) = 63 Watts P_1

Modulation usually requires some of linearization to be effective when using power levels above P_1. Your job here is to look through all the specs of amplifiers that have "made the cut" so far, and make sure that for any amp specified in Watts, or anything other than P_1 watts, you find the P_1 level specification. If you don't, you may discover that the rated power is the saturation level. AR Modular RF typically specifies a minimum power level below P_1 as the rated power out. See if any amp specifications provide you with a margin, and when you look at P_1 power levels, include that margin in your comparison.

GAIN- TOO MUCH OF A GOOD THING?

Make sure you are checking the gain of the amplifiers that can provide the power out you want, and referencing it to your signal level. The designed input power level may be too far from your signal level. You don't want to have add a preamplifier or use excessive attenuation, but it is not unusual have to add a small amount of attenuation on the input. Pick an amplifier that provides enough margin that you can add a pad on the input in case you find it is necessary later to reduce the power out of the amplifier. Variable Gain is a useful feature for setting system levels.

CONVERTING CW TO AM MODULATION SPECS

As stated before, AM Peak power is 4x CW power or +6dB. Use the P1 level for CW watts to calculate AM power. Divide CW-rated power by 4 (or subtract 6dB) to estimate available AM Power. If the specs say something like "100W CW, AM, FM, PM, SSB", it does not mean you may modulate a 100W carrier with 100% AM. You should be able to modulate 25W with 100% AM. With an under-powered amp, your only alternative available to produce low-distortion AM is to reduce the RF "drive" to the amp until the un-modulated carrier is 25% of the linear output (-6 dB), drastically reducing the output power. This is an especially poor outcome if the original power spec was for saturated power, as the result is decreased by another 37%.

CW P_1 Watts ÷ 4 = AM Peak Watts

For P_1 in dB:

CW P_1 dB – 6dB = AM Peak Watts

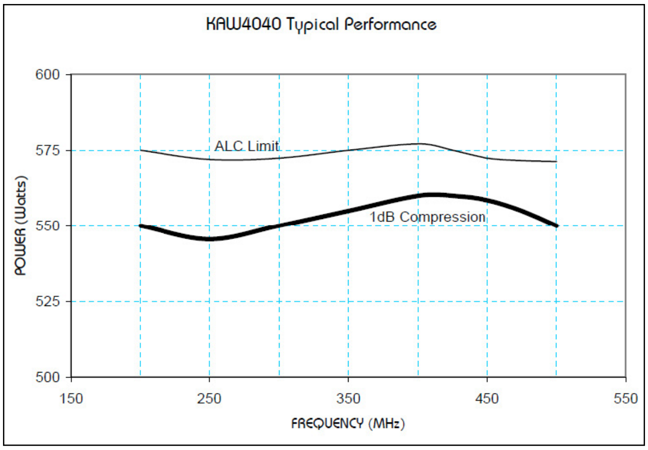
FLATNESS AND ALC POWER LEVELS

Most RF amplifiers specify Flatness. In general, the wider the frequency coverage, the looser the Flatness spec becomes. Flatness is a good indication of the relative quality of broadband design quality. Flatter amps are easier to use as the gain is more predictable.

Automatic Level Control (ALC) is a feature mainly used for CW modulation. RF power amplifiers with ALC will usually specify an ALC Power level in addition to P_1 Watts. The main function of ALC is to provide overdrive protection to the device at the output of the amplifier. For CW signals the ALC level defines the maximum RF level available from the amplifier, regardless of drive level. ALC can help protect the amplifier from over-drive, and can also provide improved Flatness, especially for CW signals. An adjustable ALC can allow you to vary the ALC level below the P_1 point. ALC is a "friendly" limiter, creating much lower distortion than P_1. The ALC function will need to be slowed or disabled for non-CW modulated signals, or serious distortion will result. Amplifiers with ALC Fast/Slow selection can enable some limited ALC functionality for non-CW signals, but it will be less responsive. For amplifiers with variable Gain, reducing the gain below the ALC Limit will also reduce Flatness as the gain lowers.

RF PULSE AMPLIFIERS – A DIFFERENT WORLD

Pulse amplifiers are a separate breed of RF amplifier. Pulse amplifiers are rated in Peak Watts and are commonly



run at saturated power levels, where compression makes no difference to the modulation fidelity. Pulse-specific amp designs come in two types depending on the pulse modulation method. The first, Pulse Gated amplifiers can have a CW signal applied to the input and an external gating signal is applied to the amp to produce the pulsed output. Alternatively, a pulse train is applied to the amp input and the gating is used to quiet the amp between pulses. The non-Gating type has design features specifically for preserving the shape of pulsed signals with fast rise-times. A CW rated amp can also pass pulses, but the highest pulse fidelity is obtained by design features not usually contained in a CW amp. If your main requirement is for pulse performance, select from pulse amps with the correct Peak power rating.

HARMONIC DISTORTION – TROUBLE IS JUST AN OCTAVE AWAY

Having worked your way down to a short list of amps that will meet your P_1 , gain and frequency requirements, you need to pick an amplifier with low Harmonic levels, as compared to other like designs. Harmonics are a relative indicator of amplifier design quality and stress. Harmonic distortion is measured in dBc, or the power level as compared to the output carrier power. Harmonic specs vary widely, from relatively high levels in the low teens, like -13 dBc, to much lower levels like -60 dBc or less. The higher power range of numbers is usually associated with broader-band amplifiers that can not employ a filter at a harmonic frequency as it is in the gain passband. Out of the gain passband, filters can knock harmonics way down, but a filter following a high power amplifier can get really hot, depending on the energy absorbed, and that heat can lead to a short filter life. For narrower amps with a bandwidth less than an octave wide, a better scheme is to reduce them with a conservative design and then a cooler-running filter, if needed. Make sure when comparing harmonics specs you understand any big differences as they can be the result of completely different types of amplifiers. If you require the absolute minimum of harmonic distortion, use a Class A amplifier.

WIDE-BAND OR BAND-SWITCHED – AUTOMATIC OR MANUAL TRANSMISSION?

Finally, make sure how your wide-band operating frequencies are provided, either by "band-switching" or by a true, single broad-band design. Some frequencies just can not be effectively amplified by the same design if they are too far apart. If you can switch from one band to another (by switching from one amplifier to another) you may be able to get improved Gain, Flatness and Harmonic distortion performance for less cost.

STEP 5 – SHOP FOR FEATURES – THE "BELLS AND WHISTLES"

When you have worked your way this far you should have a short list of the available amplifiers in the power and frequency range that have a good chance of meeting your needs. Within this selection you can shop for the accessory functions that will make your amplifier more usable, like blanking, remote controls, variable Gain control, VSWR tolerance, efficiency or power consumption, size, other kinds of protection, interfaces, and finally cost.

Some intangible factors can make a big difference to your long-term happiness with your final selection. Chief among these is robustness of design, which appears as a gain or power margin above the rated power, which will equate to longer life with fewer problems. Other factors include the vendor's willingness to adapt a design for your specific needs, a long-term commitment to service by the vendor, and responsive customer support.

ABOUT IMPEDANCE MISMATCH TOLERANCE

You may feel some important factors have been left out of this selection process, like load impedance variability. The truth is no one knows what happens with random VSWR. Almost anything is possible, even gain. The main thing is you want to avoid damaging the amplifier. Remember, reflected power has done its work, and whether it is an antenna or another amplifier, the important thing is to present the signal accurately to the load at as close to the right level as you can, and survive whatever returns. AR Modular RF is known for RF power amplifiers that can withstand nearly infinite mismatch conditions, like the **KAW4040**, a 200-500 MHz amplifier rated for 500W CW (minimum), with P1 well above the 500W level, and full VSWR protection.

At this point, you may find no amplifier is a perfect fit for you. AR Modular RF would like to speak with you about your requirements. We routinely produce quality custom amplifier modules and systems and can modify our existing designs to meet your needs. AR Modular RF fabricates all our amplifiers in Bothell, Washington, where the company has attained the reputation for making and supporting the finest RF Power amplifiers for almost 4 decades.

EMI PRE-COMPLIANCE TESTING

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INTRODUCTION

This article describes how I perform pre-compliance testing for the top four EMI issues I constantly run into; conducted emissions, radiated emissions, radiated immunity, and electrostatic discharge. Of these, the last three are the most prevalent issues, with radiated emissions typically being the biggest compliance challenge during certification testing. If your product or system (EUT) has adequate power and I/O port filtering, conducted emissions and the other power line-related immunity tests are not usually an issue.

You might consider assembling your own EMI troubleshooting kit. For your convenience, I've developed a list of recommended equipment useful for troubleshooting EMI. The download link is listed in Reference 1.

AMBIENT TRANSMITTERS

One problem you'll run into immediately when testing conducted or radiated emissions outside of a shielded room, is the number of ambient signals from sources like FM and TV broadcast transmitters, cellular telephone, and two-way radio. This is especially an issue when using external antennas. I'll usually run a baseline plot on the analyzer using "Max Hold" mode to build up a composite ambient plot. Then, I'll activate additional traces for the actual measurements. For example, I often have at least two plots or traces on the screen; the ambient baseline and the actual pre-compliance measurement.

Fortunately, there are three ways around this:

1. In most cases, you'll observe a range of product emissions in a harmonic relationship. Very often, these harmonics are created from the same source and if one, or more, are masked by ambient signals, then working on the others that are more visible will generally bring the whole batch down, as well.

2. In some cases there will be a critical harmonic masked by an ambient transmitter. A good example is a 100 MHz harmonic hidden underneath a large FM broadcast station at 99.9 MHz. In this case, I'll try reducing the resolution bandwidth from 100 or 120 kHz down to as little as 1 kHz, or less. This often "filters out" the modulation from the FM station, allowing you to observe the hidden harmonic. This also presumes the harmonic is an unmodulated continuous wave (CW) signal. Just be sure reducing the RBW doesn't also reduce the harmonic amplitude. If your harmonic is modulated, this may not work and you may have to move to a quieter measurement site.

3. Move your pre-compliance testing well away from urban transmitters (easier said than done these days).

Another caution when using spectrum analyzers is that strong nearby transmitters can affect the amplitude accuracy of the measured signals, as well as create mixing products that appear to be harmonics, but are really combinations of the transmitter frequency and mixer circuit in the analyzer. You may need to use an external bandpass filter at the desired harmonic frequency to reduce the affect of the external transmitter. An example would be an FM broadcast band "stop band" filter.

Although more expensive, an EMI receiver with tuned preselection would be more useful than a normal spectrum analyzer in high RF environments. Suppliers, such as Keysight Technologies or Rohde & Schwarz, make EMI receivers. All these techniques to deal with ambient signals are described more fully in *Reference 2*.

CONDUCTED EMISSIONS

This is usually not an issue given adequate power line filtering, however, many low-cost power supplies lack good filtering. Some "no name" brands have no filtering at all! The conducted emissions test is easy to run and only requires a line impedance stabilization network, or LISN (basically an impedance match from the power line to 50 Ohms). *Figure 1* shows a typical LISN.

Figure 1: A typical line impedance stabilization network, or LISN.

I prefer setting the vertical units from the default dBm to dBμV, so the displayed numbers are positive. Then adjust the Reference Level for even increments along the vertical axis. This is also the same unit used in the test limits of the EMI standard. I also like to set the horizontal scale from linear to log (if possible), so frequencies are easier to read out.

Set up your spectrum analyzer as follows:

1. Frequency 150 kHz to 30 MHz

2. Resolution bandwidth = 9 kHz, per the standard, or 10 kHz is close enough

3. Preamp = Off
4. Set the vertical units to dBµV
5. Adjust the Reference Level so the highest harmonics are displayed and the vertical scale is reading in even 10 dB increments
6. Use average detection initially and CISPR detection on any peaks later
7. Internal attenuation — start with 20 to 30 dB at first and adjust for best display and no analyzer overload.

Obtain a Line Impedance Stabilization Network (LISN) and position it between the product or system under test and the spectrum analyzer. Note the sequence of connection below!

***CAUTION**: It's often important to power up the EUT prior to connecting the LISN to the analyzer. This is because large transients can occur at power-up and may potentially destroy the sensitive input stage of the analyzer. Note that the TekBox LISN has built-in transient protection. Not all do…you've been warned!*

Ideally, you'll want to set up the test according to CISPR 11 or 32 (depending on the type product, ISM or ITE). See Figure 2 for an example. The LISN is bonded to the ground plane and the EUT is placed on a table 80 cm high.

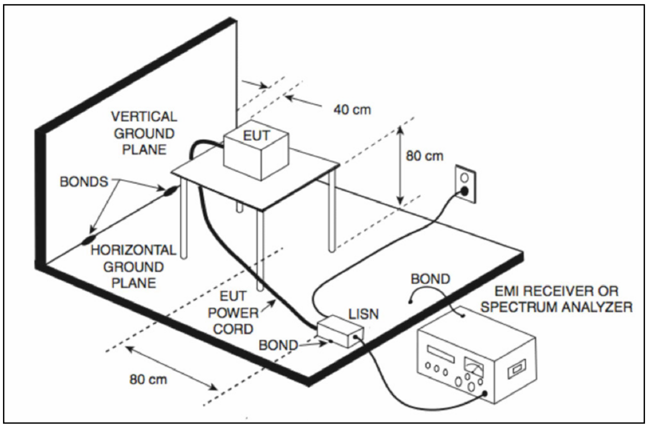


Figure 2: The suggested test set up for conducted emissions.

Power up the EUT and then connect the 50-Ohm output port of the LISN to the analyzer. Note the harmonics are usually very high at the lower frequencies and taper off towards 30 MHz. Be sure these higher harmonics don't overdrive the analyzer. Add additional internal attenuation, if required.

By comparing the average detected peaks (or quasi peak, if your analyzer offers this option) with the appropriate FCC or CISPR limits, you'll be able to tell whether the EUT is passing or failing prior to formal compliance testing. Refer to the References section for FCC and CISPR conducted emission limits in dBµV.

RADIATED EMISSIONS

This is normally the highest risk test and most prone to fail compliance testing. Therefore, setting up this test in-house should be a priority. Performing an accurate pre-compliance test for radiated emissions requires a calibrated EMI antenna positioned either 3m or 10m away from the product under test. This way, you'll be able to compare the emissions with actual test limits. These antennas can range in price from $1,000 to $6,000 USD.

The test should be set up in any area large enough and far away from other equipment that could interfere with the testing. Sometimes a parking lot is used. I've more often used a large conference room (*Figure 3*).

Figure 3: An example of a 3m pre-compliance test set up in a large conference room. Note the DIY turntable for helping maximize emissions.

I prefer setting the vertical units from the default dBm to dBµV, so the displayed numbers are positive. Then adjust the Reference Level for even increments of 10 along the vertical axis. This is also the same unit used in the test limits of the EMI standards and also used in the equation below for calculating the E-field level. I also like to set the horizontal scale from linear to log (if possible), so frequencies are easier to read out.

Set up your spectrum analyzer as follows:

1. Frequency 10 to 500 MHz
2. Resolution bandwidth = 120 kHz, per the standard, or 100 kHz is close enough

3. Preamp = On (or use an external 20 dB preamp if the analyzer lacks this). This may not be required if the harmonic emissions are observable without it.

4. Set the vertical units to dBµV

5. Adjust the Reference Level so the highest harmonics are displayed and the vertical scale is reading in even 10 dB increments

6. Use positive peak detection

7. Set the internal attenuation = zero

You can calculate the E-field (dBµV/m) at a given measurement distance (typically 3m or 10m) by recording the dBµV reading of the spectrum analyzer and factoring in the coax loss, external preamp gain (if used), any external attenuator (if used), and antenna factor (from the antenna calibration provided by the manufacturer). This calculation can then be compared directly with the 3m or 10m radiated emissions test limits using the formula:

E-field (dBµV/m) = SpecAnalyzer (dBµV) – PreampGain (dB) + CoaxLoss (dB) + AttenuatorLoss (dB) + AntFactor (dB)

Refer to the References section for FCC and CISPR radiated emission limits in dBµV/m.

RADIATED IMMUNITY

Most radiated immunity tests are performed from 80 to 1000 MHz (or, in some cases, as high as 2.7 GHz). Common test levels are 3 or 10 V/m. Military or automotive products can go as high as 50 to 200 V/m, depending on the operational environment. The commercial standard for most products is IEC 61000-4-3, whose test setup is quite involved and relatively expensive, in that it requires lots of test equipment and a semi-anechoic chamber designed for a uniform E-field at the EUT position. However, using some simple techniques, you can identify resolve most issues quickly on the work bench.

Handheld Radio — For radiated immunity, we generally start outside the EUT and use license-free handheld transmitters, such as the Family Radio Service (FRS) walkie-talkies (or equivalent) to determine areas of weakness. By holding these low power radios close to the product or system under test, you can often force a failure (*Figure 4*).

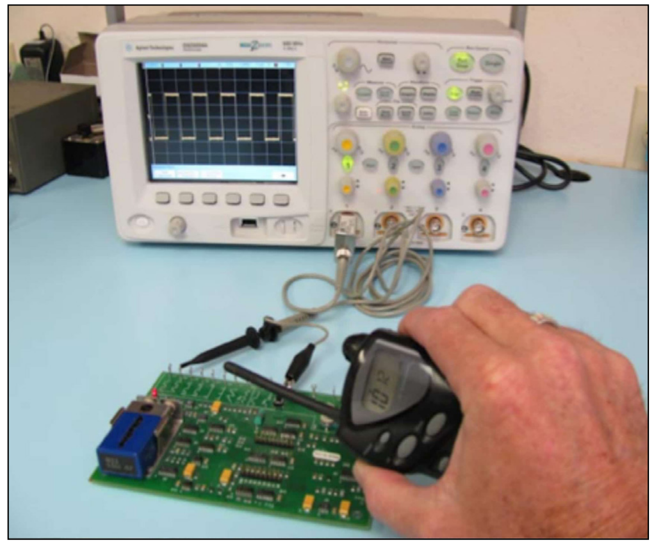


Figure 4: Using a license-free transmitter to force a failure.

Hold the transmit button down and run the radio antenna all around the EUT. This should include all cables, seams, display ports, etc.

RF Generator — It's very common that only certain frequency bands are susceptible and sometimes the fixed frequency handheld radios are not effective. In that case, I use an adjustable RF generator with attached large size H-field probe and probe all around at known failing frequencies. It also helps to probe the internal cables and PC board to determine areas of sensitivity. For smaller products, as in Figure 5, try using the smaller H-field probes for best physical resolution.

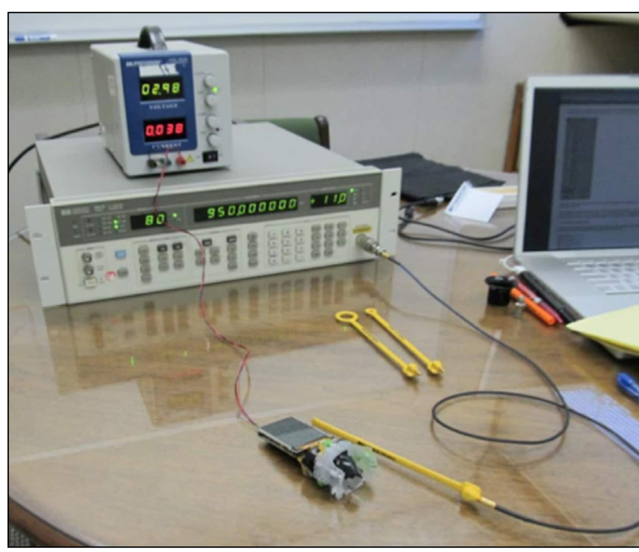


Figure 5: Using an RF generator and H-field probe to determine areas of sensitivity.

In place of the larger lab-quality RF generators, I also use a smaller USB-controlled RF synthesizer, such as the Windfreak SynthNV (or equivalent) with the near field probe. The SynthNV is USB-controlled and can produce up to +19 dBm RF power from 34 MHz to 4.4 GHz. This also fits into my EMI troubleshooting kit nicely. See *Figure 6*. You'll find a list of recommended generators in *Reference 1*.

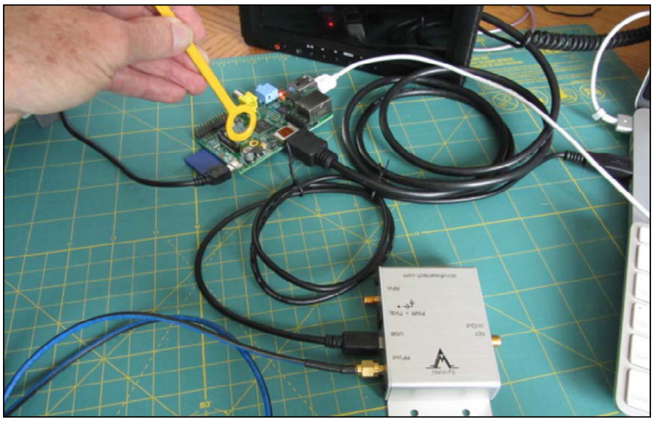


Figure 6: Using a small synthesized RF generator to produce intense RF fields around the probe tip.

ELECTROSTATIC DISCHARGE

Electrostatic discharge testing is best performed using a test setup as described in the IEC 61000-4-2 standard. This requires a test table and ground planes of certain dimensions. The EUT is placed in the middle of the test table. I usually suggest replacing floor tiles with copper or aluminum 4 x 8-foot sheets, which will fit right into the spaces of the existing tiles (*Figure 7*).

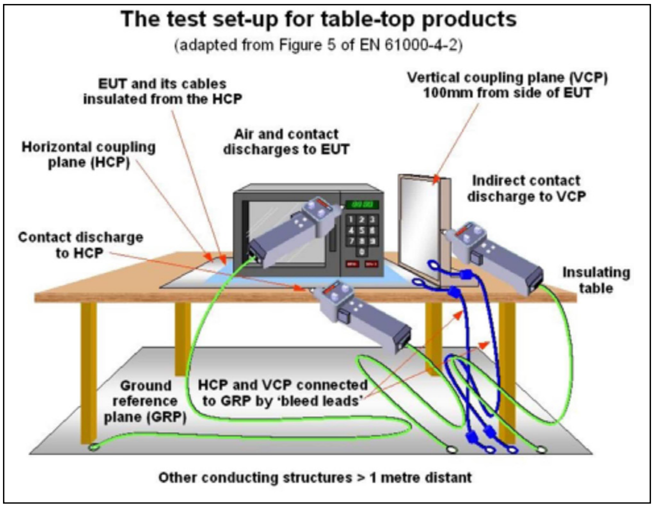


Figure 7: The ESD test setup according to IEC 6100-4-2. Image Source: Keith Armstrong.

Testing requires an ESD simulator, which is available from a number of sources. See *Reference 1*. I use the older KeyTek MiniZap (Figure 8), which is relatively small and can be adjustable to +/- 15 kV. There are several other suitable (and newer) designs.

ESD testing is rather complex as far as identifying the test points, but basically, there are two tests — air discharge and contact discharge. Use air discharge for all points where an operator could touch the outside of the EUT. Use contact discharge for all exposed metal where an operator could touch and discharge into. Test both positive and negative polarities. Most commercial tests require 4 kV contact discharge and 8 kV air discharge.

Figure 8 – A typical ESD simulator with air and contact discharge tips. It can produce up to +/- 15 kV.

The test setup also includes horizontal and vertical coupling planes. Use the contact discharge tip into the coupling planes. These planes need a high-impedance discharge path to earth. See the IEC 61000-4-2 standard for details and exact test procedures.

SUMMARY

By developing your own EMI pre-compliance tests, you'll save time and money by moving the testing process in-house, rather than scheduling time and the related cost and scheduling delays by depending on commercial test labs.

Most of the high-risk EMI tests are easily performed with low-cost equipment. The cost savings by performing troubleshooting at you own facility can mount up to hundreds of thousands of dollars and weeks or months of product delays.

REFERENCES

1. Recommended list of EMI troubleshooting equipment – http://www. emc-seminars.com/EMI_Troubleshooting_Equipment_List-Wyatt.pdf

2. André and Wyatt, EMI Troubleshooting Cookbook for Product Designers, SciTech, 2014.

EMI FILTERING 101: UNDERSTANDING THE BASICS

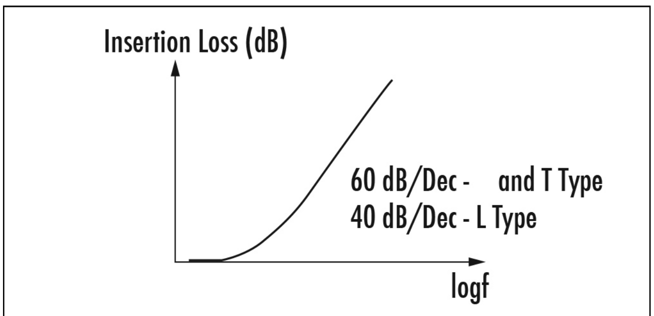
David Armitage
Manager of Engineering, Schaffner EMC, Inc.

INTRODUCTION

To start at the very beginning, what is an *electrical filter*? An electrical filter can be passive, active, analog, or digital. It is a device usually composed of discrete components which can be placed between circuits, networks, or equipment/ systems to either emphasize, de-emphasize or control the frequency components of a desired or undesired signal. The term “signal” can be a communication or power type signal. Filters accept an electrical signal at its input and deliver a different or modified signal at its output depending upon the filters internal configuration. The general term filter, of course, can also be used for a device on control and signal type lines. However for this article, we will focus on the AC/Mains EMI (**E**lectro**M**agnetic **I**nterference) power type filter.

FILTER CLASSIFICATIONS

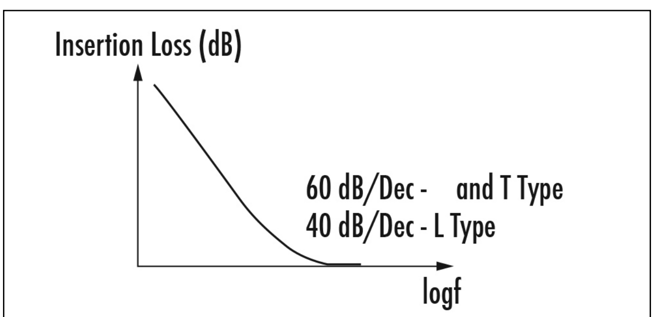
There are four basic types or classification of general filters. They are:



1. Low Pass

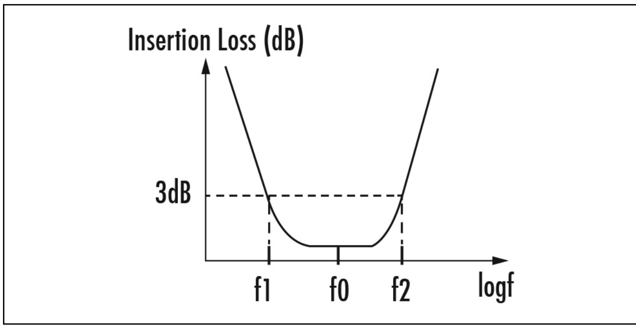
Rejects undesired RF energy above a desired cut-off frequency, passing frequencies below this point with little or no insertion loss.

AC line filters are typically of the low pass variety.



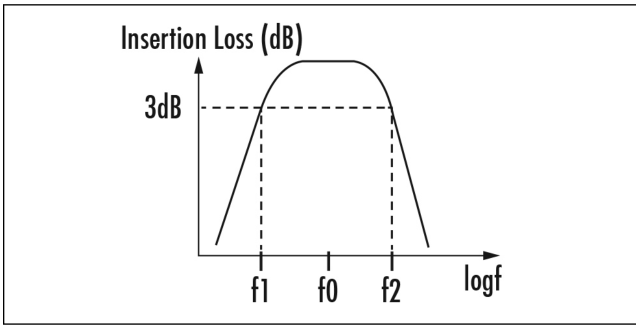
2. High Pass

Rejects undesired RF energy below a desired cut-off frequency, passing frequencies above this point with little or no insertion loss.



3. Band Pass

Passes a range of desired frequencies with little or no in sertion loss, rejecting frequencies outside this specific range.



4. Band Reject

Rejects a range of frequencies within a particular frequency band of operation while passing all other frequencies outside this band.

WHY DO WE NEED EMI FILTERS?

One reason is that regulatory agency requirements dictate that conducted and radiated emissions be constrained below specified limits, but the unit must also pass immunity/ transient requirements. Designers often forget that an EMI filter can assist in meeting immunity and fast transients requirements and radiated emissions as well. Even for military/aerospace equipment, they must be protected from failure due to EMI noise and security requirements may call for filters to protect classified data. Contractual requirements imply or specify filters.

Essentially, an AC power or mains EMI filter is a low pass filter that blocks the flow of “noise” while passing the desired input which can be DC or 50/60/400 Hertz power frequency. An ideal EMI filter will reduce the amplitude of all frequency signals greater than the filter cut-off frequency. The cut-off frequency is the frequency between the signal’s passband and the reject bands at 3 dB attenuation below the acceptance line. The measure of a filter’s ability to reduce a given signal level is insertion loss or attenuation. A power line or mains EMI filter is placed at the power entry point of the equipment that it is being installed into to prevent noise from exiting **or** entering the equipment.

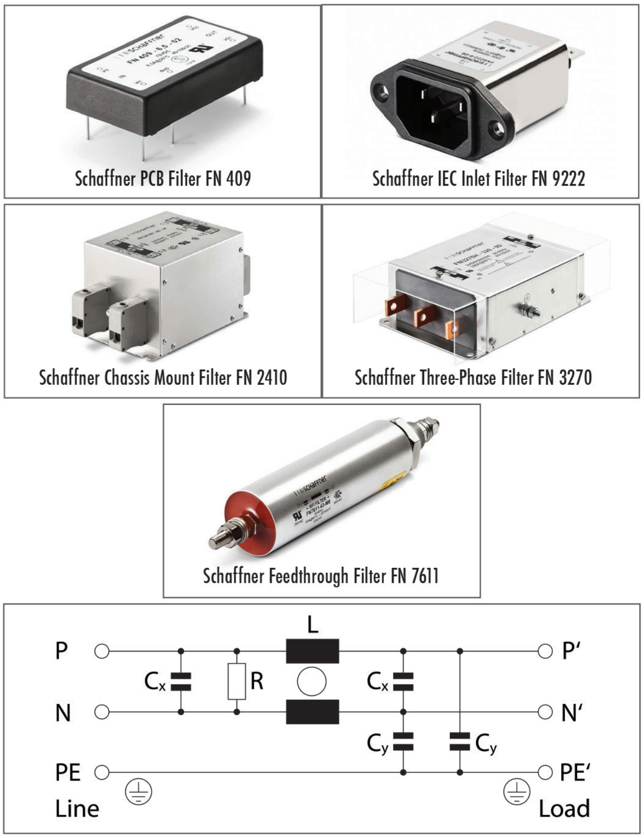


Figure 1. Examples of Various Filter Packages and a Typical Filter Configuration (Courtesy of Schaffner Company)

FILTER CONFIGURATIONS

Essentially, an EMI filter is made up of two basic types of components–capacitors and inductors. The simplest type is called a first-order filter consisting of just a single reactive component. Capacitors shunt noise current away from a load while inductors block or reduce the noise. Generally, these single component filters are not very useful as their attenuation only increases at a rate of 6 dB/octave or 20 dB/decade.

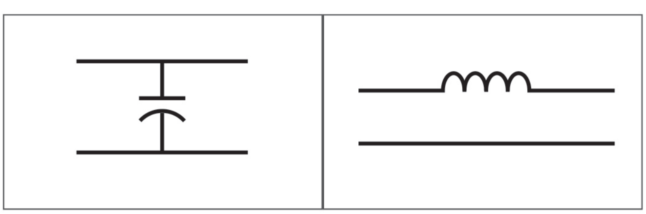


Figure 2. First Order Filters

To achieve greater attenuation, a second or higher-order filter as shown in Figure 3 consisting of two reactive components or more is required. The value of the inductive or capacitive components is determined by the impedance of the source, load and the highest frequency to be passed (i.e. cutoff frequency). This two-element filter is sometimes referred to as an "L" filter. Filter resonances and ringing must be considered, and involves a design characteristic called damping factor which describes gain and the time response of the filter.

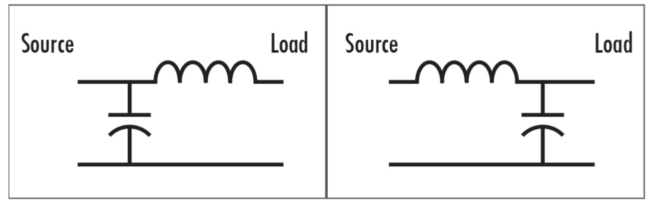


Figure 3. Second Order Filters

A third-order filter, of course, consists of three or more reactive elements as shown in Figure 4. These types of filters are sometimes referred to as "pi (π)" or "T" filters. The disadvantage of a larger filter is that physical size increases. The third-order filter is among the most popular topologies of filters used.

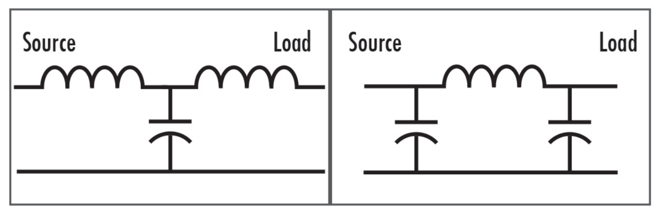


Figure 4. Third Order Filters

HOW TO DETERMINE WHICH CONFIGURATION TO USE

IMPEDANCE MISMATCH

Two different circuit configurations exist for the higher order filters in Figures 3 and 4. One aspect of filter design is impedance mismatch. So, which one should the designer use. If the designer has access to computer simulation software, then it can be used to determine the best configuration. However, if a simulation program is not available, then there is a simple "rule of thumb" that can be used to assist the designer. The first filter element nearest the source, or load end, should be selected to provide the highest possible mismatch at EMI frequencies. Typically, this means that if the source or load impedance is low (<100 Ohms), then the first filter element should be an inductive component. Conversely, if the source or load impedance is high (>100 Ohms), the first filter element should be capacitive. This provides the designer an extremely efficient design with the least number of stages or components. Refer to *Figure 5* as a quick, handy guide.

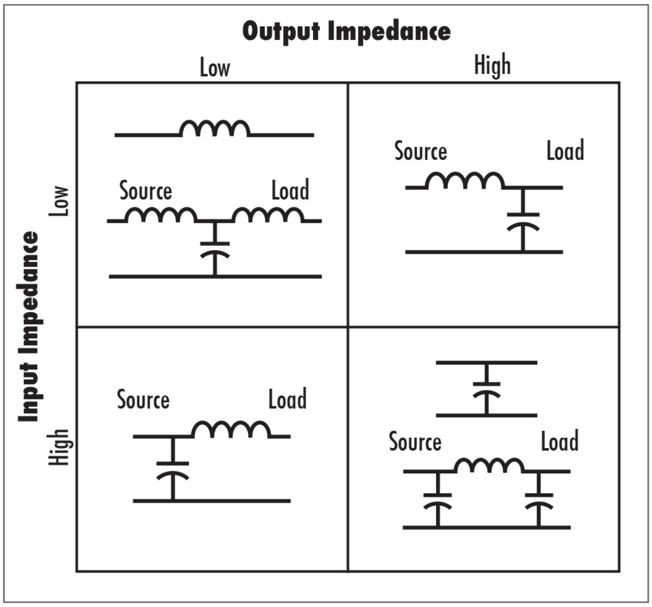


Figure 5. Handy Reference Chart for Impedance Mismatch (Reference 3)

COMMON-MODE CURRENTS VERSUS DIFFERENTIAL-MODE CURRENTS

Filters are not only for conducted emissions, but also help in meeting radiated emissions levels by controlling what propagate from the mains power cable and also helps in immunity issues like induced RF (Radio Frequency) signals and transients like electrical fast transients (EFT). In all circuits both common-mode (CM) and differential-mode (DM) currents are present. There is a significant difference between the two. Given a pair of transmission lines and a return path, one or the other mode will exist, usually both. Differential-mode signals carry data or a signal of interest (information). Common-mode is an undesired side effect from differential-mode transmission and is most troublesome for EMC.

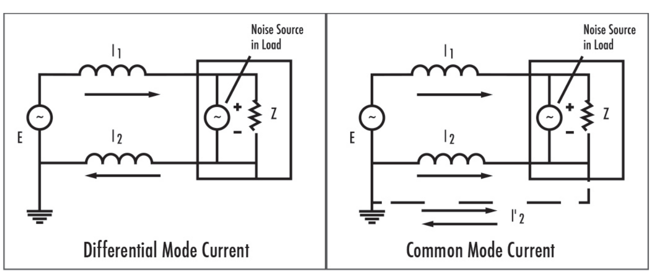


Figure 6. Common Mode and Differential Mode Current Flow (Reference 3)

When using simulation software to predict emissions, differential-mode analysis is usually the form of analysis used. It is impossible to predict radiated emissions based solely on differential-mode (transmission-line) currents. Common-mode currents are the primary source of EMI. If only calculating differential-mode currents, one can severely under-predict anticipated radiated emissions since numerous factors and parasitic parameters are involved in the creation of common-mode currents from differential- mode voltage sources. These parameters usually cannot be easily anticipated and are present in the formation of power surges in the power and return planes during edge switching times.

Differential-mode current is the component of RF energy present on both the signal and return paths that is equal and opposite of each other. If a 180° phase shift is established precisely, RF differential-mode currents will be canceled. Common-mode effects may however, be developed because of ground bounce and power plane fluctuation caused by components drawing current from a power distribution network.

Using differential-mode signaling, a device sends out current that is received by a load. An equal value of return current must be present. These two currents, traveling in opposite directions, represent standard differential-mode operation. Differential-mode filtering involves placing capacitors between lines and/or an inductor in series with either the high or low side of the line. Reference *Figure 7.*

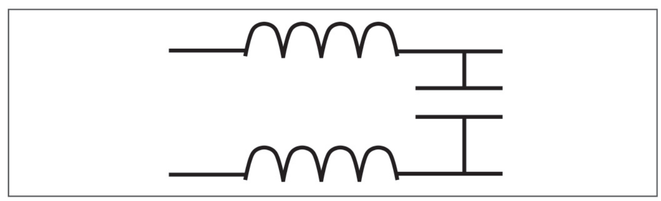


Figure 7. Differential Mode Filtering

Common-mode current is the component of RF energy that is present on both signal and return paths, often in common phase to each other. The measured RF field due to common- mode currents will be the sum of the currents that exist in both the signal and return trace. This summation could be substantial. Common-mode currents are generated by any imbalance in the circuit. Radiated emissions are the result of such imbalance.

Common-mode filtering involves capacitors to ground and/or a common mode inductor in series with both side of the line or lines. A common-mode inductor does not affect differential- mode currents except for whatever imperfect coupling exists (i.e., leakage inductance). It is best to split the inductor evenly on both sides of the transmission line to maintain balance in the circuit. This is important for both common-mode and common-mode rejection ratio of the circuit. Mutual inductance will maximize the impedance to common-mode noise. Reference *Figure 8.*

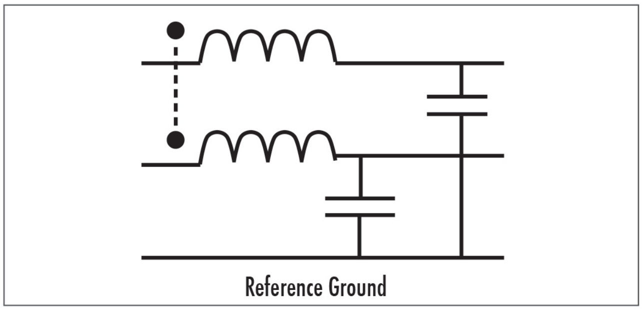


Figure 8. Common Mode Filtering

Because these are two different noise current modes of propagation, it is important to determine which type of noise current exists so that proper filtering can be implemented for maximum efficiency and cost. This is important for both common-mode and common-mode rejection ratio of the circuit. One can see that most typical filter configurations contains both common mode and differential mode filtering as shown in Figure 6.

LAYOUT HINTS

We will discuss the advantages and disadvantages of open printed circuit board (PCB) constructed filters versus filters in a metal can shield. There are two types of noise coupling (radiated and conducted). Radiated and conducted noise has a tendency for mutual transformation through a wire or trace by a process termed crosstalk. Crosstalk is observed where there are many wires or traces located in close proximity. Therefore, even if conducted noise is only a problem at one location, you cannot completely ignore the possibility of radiated coupling to another location. So, if a filter circuit is incorporated on a printed circuit board, then proper design and layout techniques must be done such as avoiding routing of traces parallel to each other, providing sufficient separation between traces to minimize inductive coupling or routing adjacent layers (microstrip or stripline) orthogonally to each other to prevent noise coupling between traces. See *Figure 9*. However, with the use of a metal shield, crosstalk/ radiated noise coupling crosstalk is controlled.

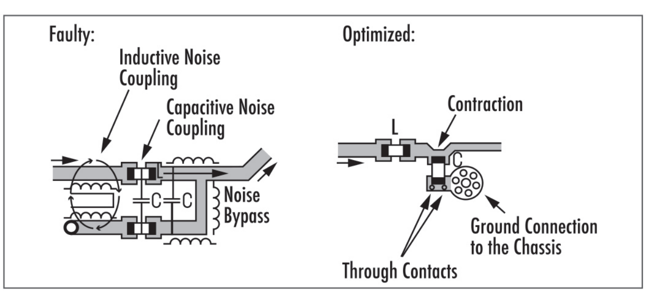


Figure 9. Proper Layout avoids parasitic couplings, which reduce filter performance (Figure, courtesy Würth Electronik)

Other things to consider are the high frequency parasitic and resonance effects. Real inductors and capacitors fall short in performance when compared to theoretical models. Some of this is due to the actual inductor and capacitor elements themselves (e.g. lead inductance, winding capacitance, resistance effects, etc.) while others are caused by the circuit board layout, packaging or wiring. Changing to a different EMI filter can affect the radiated emission characteristic because of these parasitic and resonance effects. So, when you change from a filter that passes testing, one must re-test not only for conducted emissions, but also re-test for radiated emission as the high frequency effects may not be the same between the two filters especially since most commercial filters are never tested beyond 30 MHz.

The filter should be placed directly at the exit point of the wire from the product. Good effective separation is essential. The separation prevents coupling of noise back into the input wires circumventing and nullifying the effects of the filter. This would be an excellent choice for an AC inlet mounted EMI filter or "power entry module (filter)".

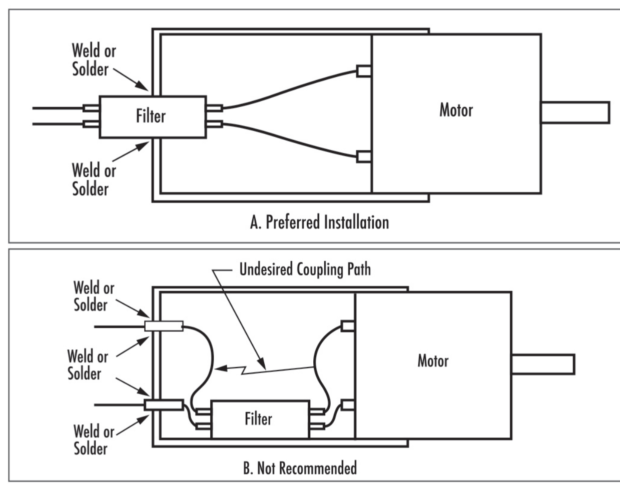


Figure 10. Lead Isolation (Reference 4)

To go along with the above item, avoid improper lead routing. Do not bundle or physically cross filter input and output wires. Again, with the leads physically crossing each other, it nullifies the effectiveness of the filter due crosstalk between wires as was discussed earlier.

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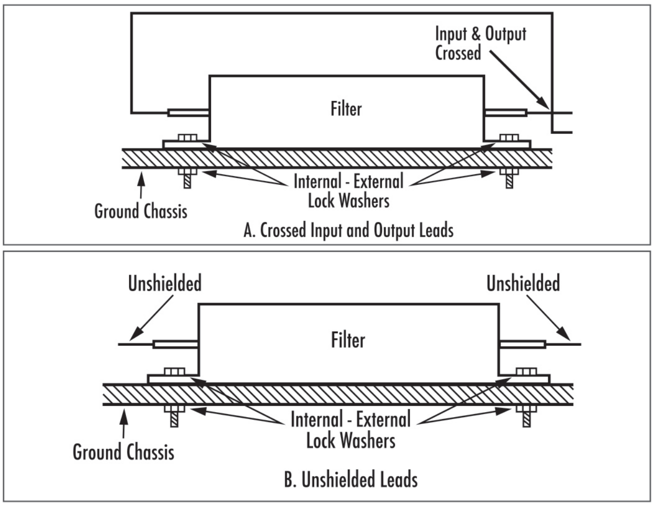

Figure 11. Separation of Input and Output Leads (Reference 4)

Provide a low impedance ground for the filter. It is imperative that the EMI filter mounting surface be clean and unpainted (e.g. conductive surface). Good filter grounding is an important factor for common mode filtering performance of the filter. A poor filter bond limits the filtering to chassis by adding series impedance, thus changing resonance effects and filtering capability of the common mode capacitors. See *Figure 12*.

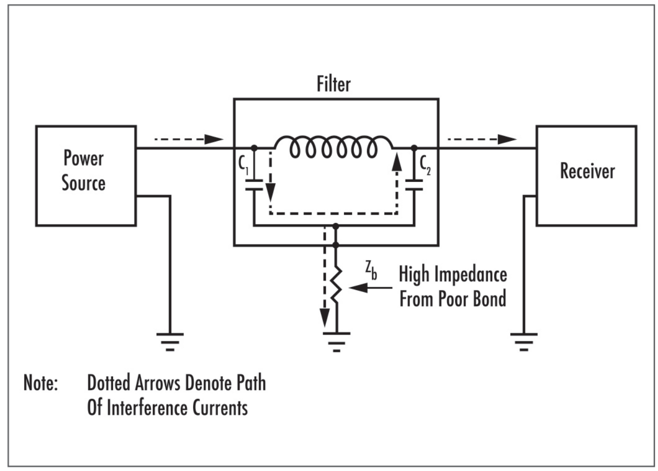

Figure 12. Effect of Poor Filter Bonding (Reference 4)

FINAL THOUGHT

Commercial filters are available for various applications with different insertion loss. There are other features to consider like Earth leakage, ambient temperature and over load characteristics. Before going to the test lab, procure different filter configurations from a commercial filter company to have on hand during testing. If the original one doesn't pass, then change over to an alternate one. Having them on hand will shorten the development time and save on test lab cost due to multiple revisits.

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EMC FOCUS—POWER SUPPLIES

RECOM Power GmbH

Electromagnetic Interference (EMI) is always a potential problem with switched-mode power supplies, both AC-DC and DC-DC converters. Modern designs can perform well for emissions and immunity but external connections must still be correct for best performance. Sometimes, extra filtering is necessary to meet specific application requirements. However, incorrect filter designs can actually make EMI worse. This article gives some guidelines for achieving the best conducted EMI performance from AC-DC and DC-DC converters including when using external filters.

Electromagnetic Compatibility (EMC) of equipment is a term covering conducted and radiated emissions, susceptibility to conducted voltage disturbances and radiated fields, and immunity to Electrostatic Discharge (ESD). Distortion of AC line current by AC-DC converters is also included. In Europe, the EMC directive 2014/30/EU mandates that end-equipment meets harmonised standards. In this article we look at conducted emissions from switched-mode AC-DC and DC-DC converters and how performance can be affected by filter components.

HIGH EFFICIENCY CAN RESULT IN HIGH NOISE

Engineers are familiar with the benefits of switched-mode converters - high efficiency with small size and weight, but many will also have struggled with the electrical noise they produce. Modern converter designs have however improved with better components and topologies that have inherently low noise, such as resonant types. Techniques such as 'frequency dithering' also help by reducing the energy of emissions in a given measurement bandwidth. The origin of the noise is the fast switching of semiconductors, with waveform rise and fall times measured in nanoseconds, necessary for high efficiency. The high dV/dt and di/dt levels though cannot be completely contained within the converter and can appear as voltage or current noise 'spikes', conducted along input or output lines. From Fourier analysis, the envelope of emissions from a generic switching waveform is shown in Figure 1, illustrating that as rise/fall time Tr, Tf decreases, the bandwidth of emissions increases with an overall amplitude affected by the duty cycle of the waveform Ton/Tp [1].

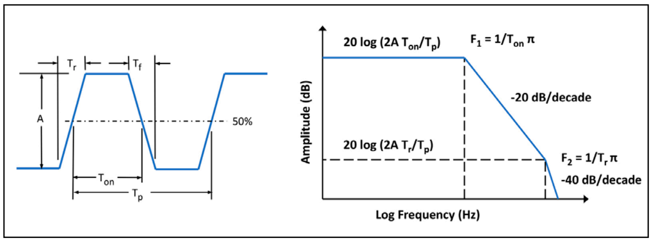

Figure1: Envelope of emissions from a switching waveform

NOISE COMPONENTS

Conducted noise is of two types, Differential Mode (DM) and Common Mode (CM), which are usually present together at some level. DM noise is measured as a voltage between a power line and its return. CM noise is measured between both power lines and system ground and is normally recorded as a voltage across a defined impedance. This is because power converters tend to operate as a current source for CM noise at high frequencies. Figure 2 shows the two types diagrammatically.

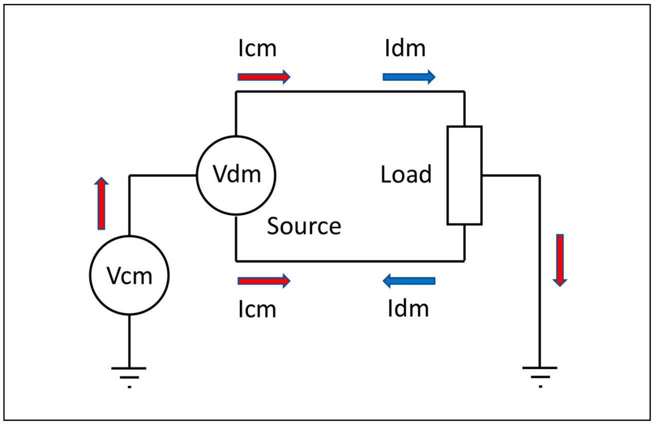

Figure 2: Types of noise that can be present

DM noise is easily measured with an oscilloscope or analyser but CM requires use of a standard termination network, a Line Impedance Stabilisation Network (LISN). This includes the defined termination impedance and filtering necessary to isolate any effect from the upstream power source. The LISN is defined by CISPR standards, typically CISPR 22 for IT equipment, and is intended for AC-DC converter noise measurements but is often also used with DC-DCs. The LISN outputs a weighted combination of DM and CM noise so that even with no CM noise present, half of the amplitude of the DM noise is seen. This means that attenuation of both DM and CM noise types is necessary to meet the limit lines of CISPR 22 standard and its derivative EN 55022.

DC-DC CONVERTER INPUT FILTERS

There is no common standard for noise emissions from DC-DC converters as they are normally embedded in systems which overall must meet EMC regulations. Board-mount DC-DC manufacturers incorporate at least a parallel input capacitor in the product package and the resulting noise levels are often perfectly acceptable. Occasionally lower levels are needed in the application and the manufacturer will typically recommend an L-C filter added externally to reduce DM noise, L and C1 in Figure 3.

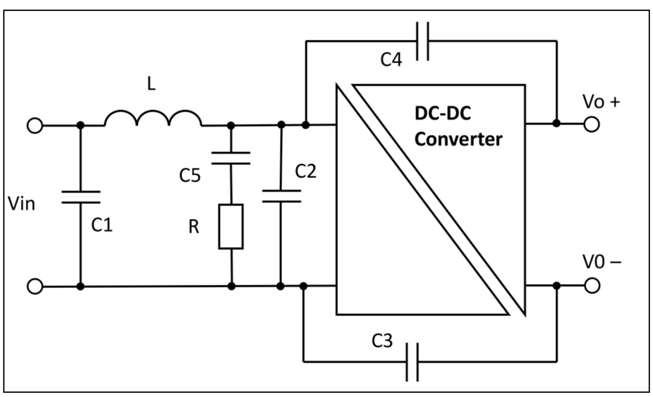

Figure 3: Filter components around a DC-DC converter

It might be tempting to add large value components thinking that this will give lowest noise but this can be counterproductive: large inductance values can have high resistance, producing voltage drop and power dissipation. Magnetic saturation with high inductance can be a problem and self-resonance may be low resulting in ringing and potential overvoltage at the DC-DC input. The effect can even make the measured noise spectrum worse. Figure 4 shows the noise of a sample converter with no filter, just L and C1 fitted and then with C2 added, giving higher spectrum peaks.

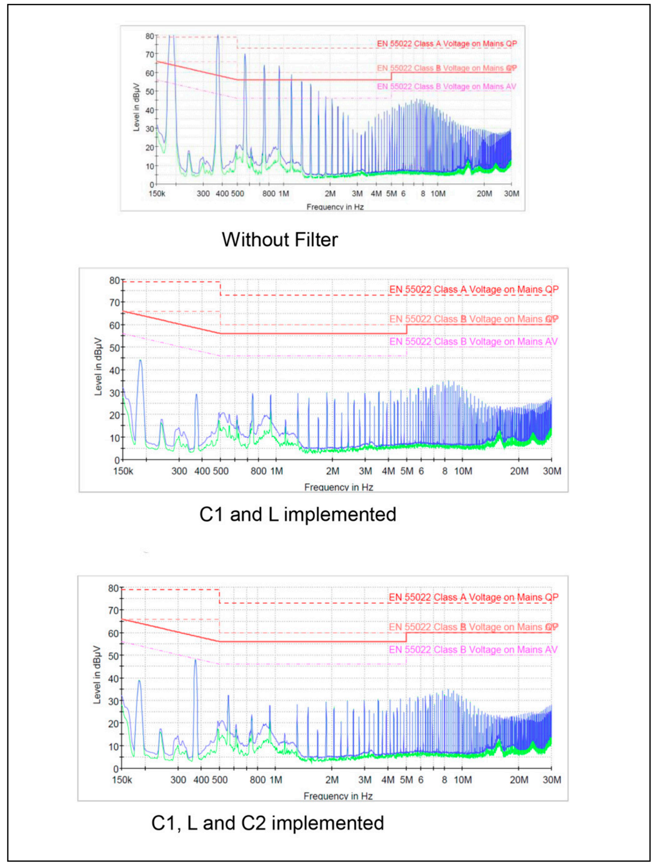

Figure 4: Extra filter components can actually make EMI worse

Another problem that can occur is instability of the converter control loop. This occurs when the output impedance of the filter, at its resonant frequency, is close to the input impedance of the DC-DC (which is incrementally negative - input current goes down as input voltage goes up). Middlebrook [2] investigated the effect and concluded that the output impedance of the input filter must be much less than the input impedance of the converter. This can be achieved with an extra damping circuit R and C5 in Figure 3. C5 is >>5 x C2, which may be internal to the DC-DC and R is = SQRT(L/C2). Alternatively, a lossy electrolytic capacitor has a similar effect but its capacitance and loss resistance are not as well controlled.

CM noise is often not an issue with DC-DC converters as both input and output may be grounded. If the input is floating, capacitors C3 and C4 can be added to reduce CM noise levels. However, there may be a limit to the capacitance allowable if the converter is forming part of a safety barrier to high voltage AC. C3 and C4 values will then set the maximum AC leakage current that can flow and must be 'Y' safety types with the right transient voltage rating. In the extreme, two capacitors may be needed in series for the most sensitive applications such as patient-connect medical in case one capacitor fails short.

In some applications, voltage transient suppression may be needed at the DC-DC converter input. Some standards for transient levels are established, for example in the automotive and rail industries, but in other application areas the levels are not well defined. A recent euronorn, EN IEC 61204-3:2018 'Low voltage switch mode power supplies -Part 3: Electromagnetic Compatibility', is not widely accepted yet but does define some overvoltages for different application categories of DC-DC converters.

AC-DC CONVERTER INPUT FILTERS

Actually, the situation with AC-DC converters is simpler. For high power products, there is usually a direct connection to AC mains. The converter therefore must meet the EMC directive so will have a filter fitted internally, suitable for the intended application; industrial, IT, medical, test equipment etc. However, there is a large market for board-mounted AC-DC converters that connect to AC mains through internal tracks and wiring. The converter will often have internal filtering for the highest EMC emissions standards, (Class B) such as the RECOM RAC20-K series but sometimes products are offered meeting the lower, class A limit line. This is a cost saving and may be sufficient, especially if the converter is supplied from AC which is already filtered elsewhere in the system. Manufacturers will suggest external filter components which will enable these parts to meet the class B limit, typically an 'X' rated capacitor across the AC line and 'Y' capacitors from both AC lines to ground. The RECOM RAC03-GA series is an example.

For these components to be effective, they should be placed very close to the converter with a direct, low impedance connection to ground. Remember that there are limits to values allowed: the 'X' capacitor for example must discharge to a safe voltage typically within one second after disconnection of the AC mains and may need a parallel discharge resistor, suitably rated. As mentioned for DC-DC converters, the 'Y' capacitors must not allow a dangerous leakage current to flow if the system ground becomes disconnected. The maximum current allowed can be as low as 10µA for the most sensitive medical applications, limiting capacitor values to around 100pF. Other applications allow much higher leakage currents, 3.5mA for example in IT areas, allowing higher 'Y' capacitor values.

System EMC performance cannot be easily predicted from the performance of individual components so compliant board-mount AC-DC converters, for example, cannot guarantee a system 'pass'. However, manufacturers such as RECOM [3] with their wide range of system and board-mount power supply products offer the use of their in-house EMC test facilities to help their customers with pre-compliance equipment testing.

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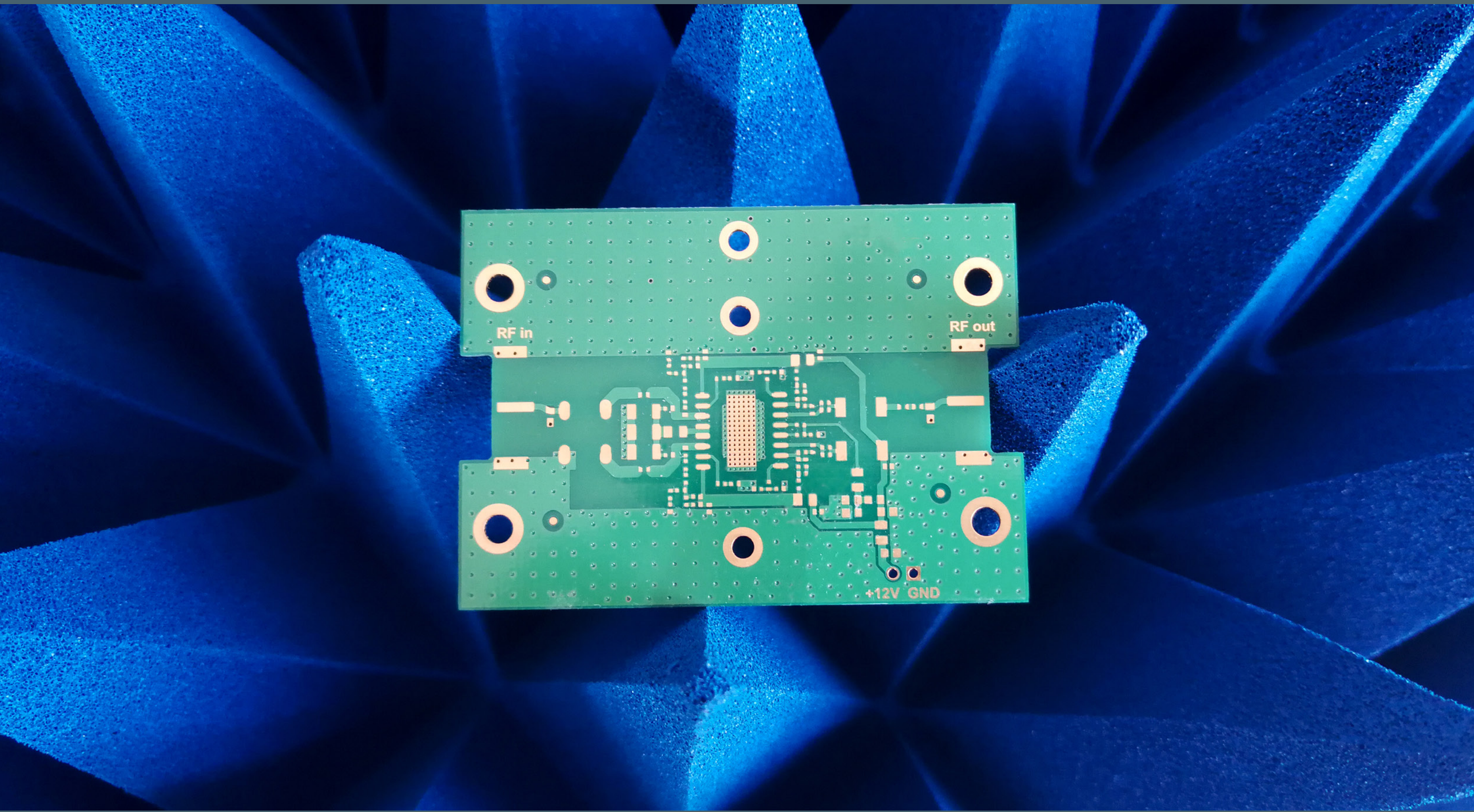
3. www.recom-power.com

EMC TESTING



EMC EQUIPMENT MANUFACTURERS SUPPLIER MATRIX

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. 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 Supplier Matrix		Type of Product/Service												
Manufacturer	Contact Information - URL	Antennas	Amplifiers	Near Field Probes	Current Probes	Spectrum Analyzers/EMI Receivers	ESD Simulators	LISNs	Radiated Immunity	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/category/emc-compliance-esd-rfi-emi.aspx	X	X			X	X	X	X	X	X		X	X
AR RF/Microwave Instrumentation	www.arworld.us	X	X			X		X	X	X	X			X
Anritsu	www.anritsu.com					X					X			X
BHD Test and Measurement	www.bhdtm.com		X			X	X	X	X	X	X		X	X
Compliance Worldwide	www.complianceworldwide.com								X	X	X			
CPI	www.cpii.com	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					
Exodus Advanced Communications	www.exoduscomm.com		X											
F2 Laboratories	www.f2labs.com								X	X	X			
Gauss Instruments	www.gauss-instruments.com/en/					X								
Instruments For Industry (IFI)	www.ifi.com		X						X	X				
Kent Electronics	www.wa5vjb.com	X												

EMC Equipment Manufacturers Supplier Matrix		Type of Product/Service												
Manufacturer	Contact Information - URL	Antennas	Amplifiers	Near Field Probes	Current Probes	Spectrum Analyzers/EMI Receivers	ESD Simulators	LISNs	Radiated Immunity	Conducted Immunity	Pre-Compliance Test	TEM Cells	Rental Companies	RF Signal Generators
Keysight Technologies	www.keysight.com/main/home.jspx?cc=US&lc=eng			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/	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			
R&K Company Limited	www.rk-microwave.com		X											
Rigol Technologies	www.rigolna.com			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
Siglent Technologies	www.siglentamerica.com			X		X					X			X
Signal Hound	www.signalhound.com			X		X					X			X
Solar Electronics	www.solar-emc.com	X			X		X	X		X				
TekBox Technologies	www.tekbox.com		X	X				X			X	X		
Tektronix	www.tek.com			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				
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
Transient Specialists	www.transientspecialists.com								X	X		X		
TRSRenTelCo	www.trs-rentelco.com/SubCategory/EMC_Test_Equipment.aspx	X	X			X		X	X	X	X		X	X
Vectawave Technology	www.vectawave.com		X											
Windfreak Technologies	www.windfreaktech.com													X

EMC TEST EQUIPMENT SELECTION AND SIZING

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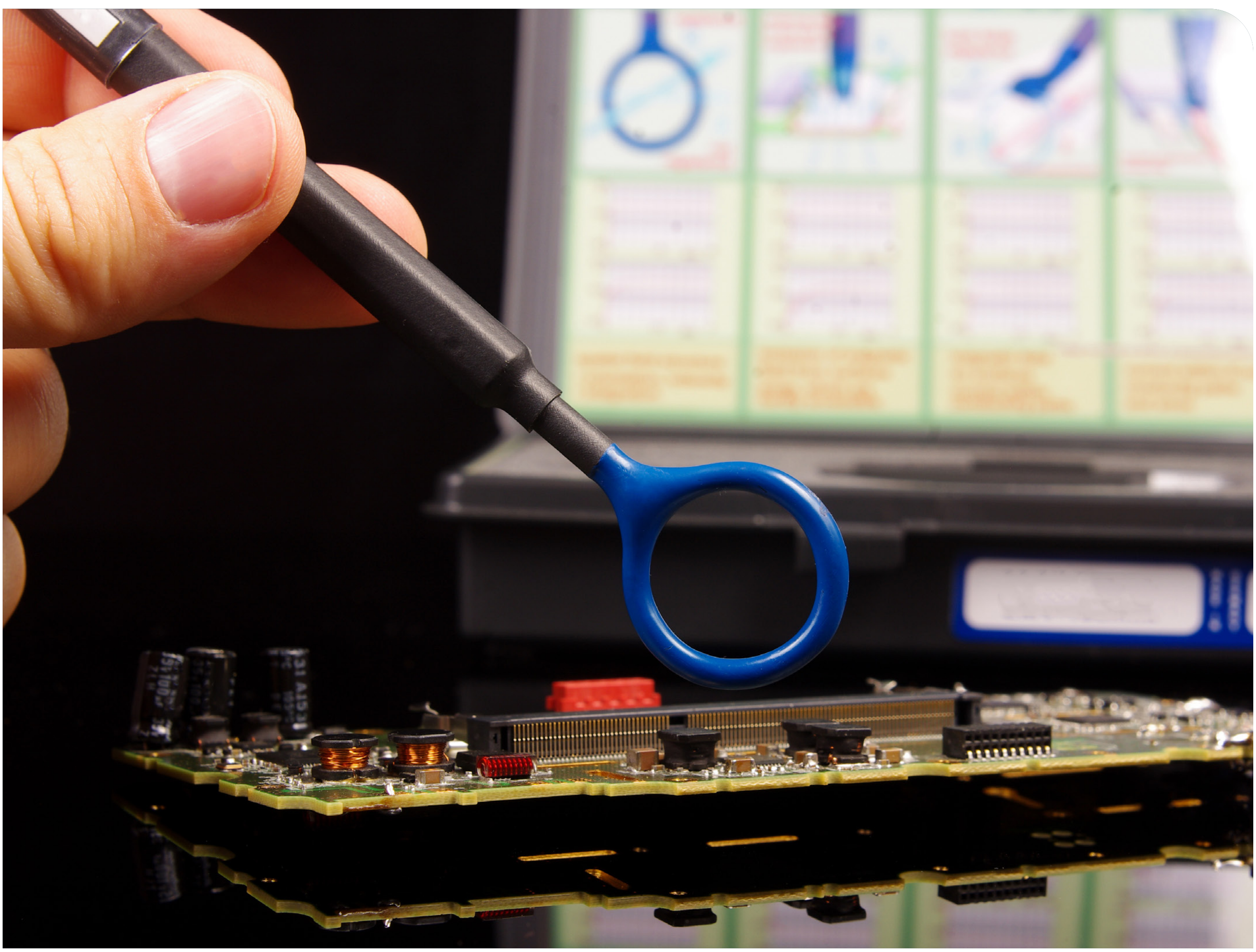
Explosive growth in technologies like portable electronics, Internet of Things (IoT) devices, and autonomous vehicles has led to a world full of electromagnetic interference. Efficient EMC testing is more critical than ever, and is dependent on high-quality test equipment. Historically, not a lot of education has been provided on the careful considerations needed for determining and selecting the proper quality test equipment demanded for this testing. This paper walks through the important considerations for selecting test equipment, specifically for EMC testing.



INTRODUCTION

Electromagnetic compatibility (EMC) testing has been around for decades and will continue as long as there are electronic devices in use. What has become apparent, is that the need for EMC testing has continued to grow nearly exponentially throughout its existence. Test environments and requirements across all industries continue to evolve at a rapid pace. While this rapid growth certainly drives the need for new and additional test equipment to accommodate new requirements, the growth also drives the need for educated and experienced EMC engineers and test personnel.

The problem is that this growth tends to outpace available EMC resources. It is not uncommon to see engineers and technicians with little or no EMC test experience thrust into positions that even a seasoned EMC engineer could have difficulty with. Again, formal EMC education is not always readily available to some organizations and test programs often don't have the available time for someone to get up to speed. That said, this paper is intended to examine the thought process behind selecting and sizing appropriate test equipment when the need arises. There are numerous types of EMC testing, which require numerous types of test equipment. Significant amounts of time could be spent on each one of these tests, but in the interest of brevity, we will focus the efforts of this paper on radiated immunity (RI) and RF conducted immunity (CI).

DEFINING TEST REQUIREMENTS

The first step in selecting the proper equipment for RI and CI testing is to understand the requirements of the test itself. Across all industries, RI and CI testing share a lot of commonalities. However, when you dive into the respective test standards, you begin to realize that there are, in fact, some significant differences. An example of these differences for RI can be seen in Table 1. This table is not intended to be comprehensive; however, it does identify some of the key differences between some of the more common test standards in today's electronics marketplace.

To the uninitiated, some of these differences may not seem that drastic. For example, looking at the cost of an amplifier needed for 200 V/m testing at a 1 meter test distance versus the cost of an amplifier for 200 V/m testing at 2 meters, one might change their mind. Another example involves required modulations. Sizing equipment for a 10 V/m MIL-STD-461 RS103 system may not be sufficient to use for a 10 V/m IEC 61000-4-3 system. The reason is that IEC 61000-4-3 requires a 1 kHz, 80% amplitude modulated signal. This type of modulation increases the overall amplitude of the signal, if not adjusted as in the case of other standards. Therefore, this test would need to be calibrated at 18 V/m, rather than just 10 V/m. This brings up another key difference between these two test standards. IEC uses what's termed a 'substitution method' of testing, where the intended field must be calibrated prior to running a test. In this case, field probes are not used during test. Conversely, MIL-STD-461 allows the use of field probes to actively measure the field during testing, negating the need for calibration.

Again, these are examples and the list could go on and on. The important takeaway here is to ensure that the test requirements are fully realized and understood prior to investigating test equipment. Purchasing the wrong test equipment can prove to be a costly mistake in terms of lost test time and overall expenditures.

Table 1 – Example Differences Between Common RI Standards

Radiated Immunity	Frequency	Test Level	Modulation	Distance	Leveling Method
IEC 61000-4-3 ed 3.0 2006	80MHz-6GHz, product and usage dependent.	1-30V/m, and Special.	1kHz AM, 80% Calibrate CW at 1.8x target field level.	3m recommended; 1m minimum	substitution
MIL-STD-461, RS103 components and subsystems	30MHz-18GHz required 2MHz-40GHz optional extended	5 - 200V/m, application dependent	1kHz 50% duty PM	1m, or greater	closed loop
DO-160G Section 20.5 (Anechoic Chamber Method) 2010	100MHz-18GHz	1-490 V/m CW, 150-7200V/m Pulse; Category and freq dependent	CW, and Pulse	1m, or greater. Allows <1m at high freqs if far-field	substitution
ISO 11451-2:2015 Fourth edition Road vehicles vehicle test methods, Off-vehicle external radiation sources	10kHz - 18GHz	user defined; 20-100V/m typical, frequency and Test Level Category dependent; or Custom	CW 10kHz - 18GHz AM 1kHz 80% 10kHz - 800MHz PM 577us, 4600us period 800MHz - 1.2GHz PM 577us, 4600us period 1.4GHz - 2.7GHz PM 3us, 3333 us period 1.2GHz - 1.4GHz PM 3us, 3333 us period 2.7GHz - 18GHz Peak Conservation/Constant Peak	no part of radiating antenna closer than 0.5m; antenna phase center ≥2m horizontally from reference point.	substitution
ISO 11452-2 3rd edition Jan 2019; component test	80MHz - 18GHz	user defined; 25-100V/m typical, frequency and Test Level Category dependent; or Custom	CW 80MHz - 18GHz AM 1kHz 80% 80MHz - 800MHz PM 577us, 4600us period 800MHz - 18GHz Peak Conservation/Constant Peak	1m	substitution

Table 1: Example Differences Between Common RI Standards.

COMPONENT CATEGORY CONSIDERATIONS

Once you are clear on what your test requirements are, you can start considering your options for test equipment. As a matter of staying organized, we will break down equipment according to various categories here.

A. AMPLIFIERS

The foundation for proper amplifier selection is in understanding critical amplifier specifications. Amplifiers have a broad spectrum of specification parameters. Each of these parameters certainly has relevance for various applications, however, there are a few key parameters to keep in mind relating to EMC testing.

First, let's look at power. When looking at an amplifier spec sheet, you may see various definitions of power like rated power, Psat, P1dB, and so on. Figure 1 shows an example of the various power levels of a 500 watt (rated power) amplifier.

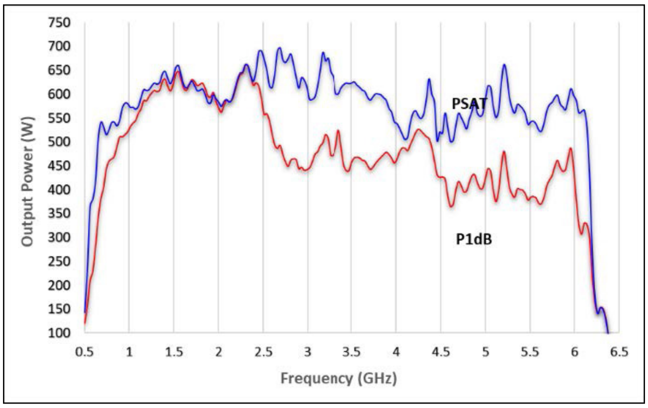


Figure 1: Various Power Ratings of a 500 Watt Amplifier

P1dB refers to the amp's 1 dB compression point. This is the power level where, theoretically, a 10 dB increase in input power produces a 9 dB increase in output power. Effectively, the P1dB power is the top end of the amplifier's linear region. Beyond the P1dB point, the amplifier will go further into compression. What this means to an EMC engineer, is that up to the P1dB point, the amplifier will operate within its linear region. This is important when testing to standards that have linearity requirements. For example, IEC 61000-4-3, the test method used for testing most commercial electronic products in today's marketplace has a specific test as part of its calibration routine to verify that the amplifier used is operating in its linear region. If the amp is not, the test system fails calibration and cannot be used. If this is the test method you're designing your system around, it would be wise to size your amplifiers according to their P1dB specification.

Psat is a common nomenclature for saturated power. Here, the amplifier is outside of its linear region, and an increase in input power will have no increase in output power. As we just discussed, Psat would not be the best choice for sizing an amplifier if you're testing commercial products. However, many other test standards do not have such stringent linearity requirements. Standards like MIL-STD-461, DO-160, and ISO 11451/11452 for the military, aviation, and automotive industries respectively, fall into this category. In these cases, it would be acceptable to size an amplifier according to its Psat.

The last power definition we'll touch on is rated power. The most important thing to remember about rated power is that there is no 'textbook' definition for rated power. It is a manufacturer-specific definition. One manufacturer may consider their rated power to be Psat, another may use P1dB, and another may use an entirely different definition. A 1,000 watt amplifier from Company A is not necessarily the same as a 1,000 watt amplifier from Company B. The point is, when looking at the rated power of an amplifier, it's extremely important to understand the manufacturer's definition of rated power.

Regardless of the definition of power you're considering, it is always important to add margin onto what you think you need. In EMC testing, there are always unknowns. Poorly matched transducers, chamber loading/reflections, poor cables, and many more factors can result in the need for more power than expected.

Another important amplifier parameter to consider is amplifier harmonics. Harmonics are unwanted signals occurring at multiples of the fundamental frequency, and are an inherent type of distortion to all amplifiers. In EMC testing, it's important to limit this type of distortion for two key reasons (among others). One being the repeatability of a test. RI and CI tests are swept in frequency and equipment under test (EUTs) are tested at a single frequency at a time, unless you are testing using multi-tone methodology. If an EUT fails and there is a great amount of harmonic distortion, it may not be clear whether the EUT failed as a result of the incident fundamental frequency or from one of its harmonics. A second reason is due to the prevalence of broadband measurement equipment. In most cases, EMC tests utilize broadband power meters to measure amplifier power and broadband field probes to measure the generated electric field. These types of devices are not frequency-selective and therefore cannot differentiate between a fundamental and harmonic signal. Additionally, if the EUT is a broadband device it may also fail as a result of the total spectrum power, including the fundamental and harmonics, rather than failing from any single signal.

Lastly, we'll briefly discuss mismatch tolerance. Mismatch tolerance is the ability of an amplifier to handle unmatched loads, and thus varying amounts of reflected power. In EMC applications, especially at lower frequencies, transducers (antennas/clamps/etc.) can be a very poor match to 50 Ohms (typical nominal output impedance of RF amplifiers). Field reflections/standing waves can cause significant reflected power as well. During test, it is important to continue to deliver forward power as well as protect the amp from reflected power damage.

B. ANTENNAS

Similar to amplifiers, antennas have many specification parameters, and certain parameters are more relevant in relation to EMC testing. When choosing equipment for radiated immunity, proper antenna selection is critical. Selecting the wrong antenna could mean limited exposure areas, insufficient fields, and other problems.

The first, and possibly most important, parameter to consider is the measured field strength of an antenna. This is empirical data of electric field strength produced by a given input power. This is highly useful for determining amp/antenna combinations for target immunity field strengths. Again, it's very important to size the amp with margin (6 dB is good target, 3 dB minimum) as non-free space conditions can contribute considerable loss (not just cables!). Measured data can be scaled for other power inputs. Also, the measured field is typically lowest at the lowest operable frequency, corresponding to the lowest antenna gain. Keep in mind that test distance greatly affects field strength. Figures 2 and 3 show the measured field strength of a horn antenna at both 1 meter and 3 meter test distances. The difference caused by gain is apparent.

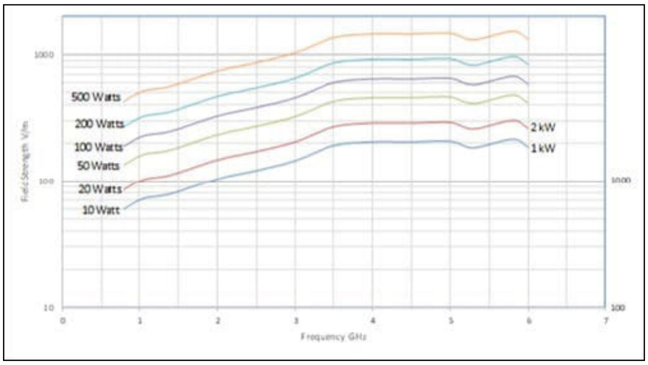


Figure 2: Measured Field Strength at 1 Meter.

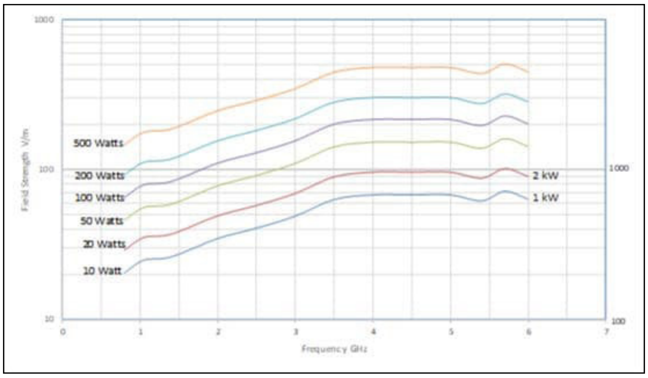


Figure 3: Measured Field Strength at 3 Meters.

In general, the more power that is put into an antenna, the more field is generated. However, there is no antenna that can handle infinite power. Input power is often limited by the power handling of the RF connector on the antenna, but there are other factors that can limit the power further. Some antenna manufacturers will specify just a single power level for power handling. This, unfortunately, is ambiguous. Input power ratings really vary over frequency with power rating typically decreasing as frequency increases. Figure 4 shows the power handling of the same antenna represented in Figures 2 and 3.

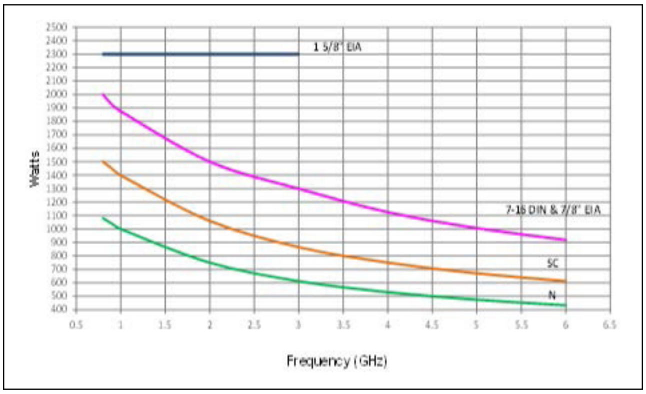


Figure 4: Antenna Power Handling.

When a single value is presented, this can sometimes be misconstrued as the maximum power rating over the full band. If this isn't made clear, it can be very easy to input this power level at a higher frequency and cause damage to the antenna. It should also be noted that these power levels are almost always defined as continuous or average power. Some immunity applications require high field strength pulsed tests. In these cases, large amounts of power are applied to the antenna but in very short durations and duty cycles. In these scenarios, the average power is very low, and therefore the antenna can handle much higher 'peak' power. Peak power handling of antenna is less well defined as voltage breakdown becomes the primary failure mechanism, and there are difficulties in characterizing this type of failure.

C. MEASUREMENT EQUIPMENT

The last equipment category we'll touch on is measurement equipment. The most common types of measurement equipment used in immunity testing are RF power meters and electric field probes. Typically, both of these types of devices are broadband measurement devices, measuring RMS power or electric field of continuous wave (CW) signals. As we discussed before, this can present problems when harmonics or other unwanted signals are present, as these signals would contribute to the measured power or field. This is why it's so important to limit harmonics and other unwanted signals. If frequency-selective measurements are desired, a receive antenna would need to be used along with a spectrum analyzer or EMI receiver. However, it should be noted that this method is typically not allowed in most test standards.

Another inherent problem of these devices is their ability, or rather inability, to accurately measure modulated signals. The majority of test standards require some type of modulation to be applied to the test signal. Traditional RF power meters and electric field probes are only capable of measuring CW signals, so either the test must first be calibrated without modulation applied, or the intented test signal must first be generated as a CW signal, then modulation applied. Either way, extra steps are involved. The adjective 'traditional' was used intentionally, as technologies are evolving, and some new RF power meters and electric field probes have the capability of measuring modulated signals. While these types of devices are gaining traction, the bulk of test standards are still written around the use of their traditional average measurement counterparts.

SUMMARY

As you can see, there are many factors to consider when selecting equipment for EMC testing. It's important to fully understand the multitude of requirements and specifications of not only the equipment itself, but the standards documents that dictate the tests. Of these equipment parameters, many are typically presented for a given piece of equipment, but not all parameters may be relevant to your particular application. With an in-depth knowledge of these parameters, it can be much easier to select the proper equipment for EMC testing applications.

HOW TO PREPARE YOUR PRODUCT AND YOURSELF FOR EMC TESTING

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INTRODUCTION

Your product has EMC requirements. You have to test it to demonstrate compliance with those requirements. How do you prepare for the test? How do you prepare your product for the test? These are two different areas that need preparation before you go to the lab. Let's look at them, one at a time.

HOW DO YOU PREPARE FOR THE TEST?

First, you need to understand what you need to gather before going to the lab. A step before that is that you must select a lab to perform the tests. Then, you need to know what information the lab will need prior to the tests in order to allow them to properly test your product and write a test report. Some labsº may require a written test plan before performing the tests, and the contents of the test plan will aid them by gathering information needed for the test reports.

How do you select a lab? First, you need to know what will be required of the laboratory in order for its results to be acceptable in the countries in which you wish to sell your product. Not all labs are acceptable everywhere in the world. The requirements for a lab to be accepted in various parts of the world is beyond the scope of this article, but you should ensure that the lab's results and reports will be acceptable. Some parts of the world have no restrictions on what lab you may use, others may require that the lab be accredited for testing in their country. When in doubt, ask to see proof.

Secondly, mere possession of accreditation is not, in and of itself, evidence that the lab truly does quality work. You should become educated on the requirements around the world and perform your own inspections of the candidate laboratories. Some labs will welcome your visit, others might not. You will have to decide what level of comfort is adequate for your company. If you don't have the expertise in-house you might consider hiring a consultant to evaluate the laboratory or laboratories you are considering.

Once you have settled on a laboratory to perform the tests, find out from the lab what information they need you to provide. Later we'll talk about the information that a laboratory must include in the test report, and you will see that much of it comes from you. Know what information is needed and have it available when you go to the lab. Part of you laboratory selection process should include asking about lead time requirements. Are they so busy that they can't fit in the number of days you will need for the tests until 6 months from now? And you need to ship in 1 month? That is important information. Few things upset management more than being told that they can't start shipping product (and receiving money) until a few months after they had planned. Your fault or not, you will be blamed, so make sure you understand your company's schedule requirements and what the laboratory can deliver.

Also, talk to the lab and have a good idea how long the tests will take and then when they can deliver a test report for your review. Talk to your marketing people to see when they plan on announcing this product and start shipping it. You don't want to be the bottleneck that stops the process. Have these discussions early (both with the lab and with your own people) and keep the information up to date. Ensure that you keep your management informed of the status and any delays that you see coming.

HOW DO YOU PREPARE THE PRODUCT FOR THE TEST?

First, design the product with EMC in mind. Provide guidance to the development team early and often on design features that they should include to increase their chances of passing the first time. Review the designs to make sure that obvious mistakes are not included in the product design. Perform preliminary development tests when possible to catch mistakes and failures early, when they can more easily be fixed.

Once the product is designed and debugged, make sure that all necessary hardware and software is available for the test. The hardware that you will need to provide to the laboratory may be more than just the box you are testing. What about peripheral devices? Are they common items that the laboratory might already have in their possession? Or are they special items that only you might have? You might also ensure that all subassemblies are installed correctly and that all chassis and enclosure fasteners are tight. What about the cables connecting the various parts of the system? Are specially designed cables necessary?

A classic example to consider is if your product includes an HDMI interface. If your product depends on properly shielded cables, with the shields properly terminated, cables that simply meet the HDMI cable specification may not be adequate. The HDMI specification does not address the termination of the outer shield of the cable and many HDMI compliant cables do not have this outer shield terminated or terminated properly. They meet the HDMI specification, but are not typically adequate from an EMC perspective. Does your product need the shield terminated? Make sure the cables used for the test (and sold with your product) have the shields terminated correctly.

If any software is required in order for your product to be exercised as required by the EMC standard to which it is being tested make sure you pack that software with the product, or pre-install it and test it to make sure it works. Remember that the clock is running when you arrive at the lab and you don't want to be paying their hourly rate to troubleshoot you product to make it work, or waste time running back to your company to get software you forgot.

Also, it's wise to bring the following items: product documentation, installation manual, user manual, extra tools – especially specialized ones required to remove covers or cables, etc., backup copies of software, a backup laptop, backup hardware in case of product failure (especially important for potentially destructive tests like ESD), extra cables, troubleshooting items like ferrite chokes, copper tape, and aluminum foil.

WHAT INFORMATION MIGHT YOU NEED TO PROVIDE TO THE LAB?

The laboratory is going to write a test report (or reports) for you at the completion of the tests (assuming the product passed, writing a full report for a product that fails is a waste of time and your money). ISO/IEC Guide 17025:2005 provides a list of items that must be included in the test report and regulatory agencies add their own requirements. Let's look at the items that ISO/IEC 17025 requires:

Articles 5.10.2 and 5.10.3 of ISO/IEC 17025 list a number of required items to be included. These are;

- 5.10.2a – The report is labeled with a title, such as "Test Report"
- 5.10.2b – The name and address of the laboratory used for the measurement
- 5.10.2c – Unique identifier of the report on each page and a clear identification of the end of the report
- 5.10.2d – Name and address of the client
- 5.10.2e – Test methods clearly identified
- 5.10.2f –
    - Description of the condition of the EUT
    - Clear and unambiguous identification of the EUT on the cover or first page of the report. All applicable model numbers and manufacturer's trade names are to be listed here
- 5.10.2g – Date(s) of the test shall be identified
- 5.10.2h – reference to the sampling plan and procedures used by the lab (not typically needed in an EMC test report)
- 5.10.2i – test results with units of measurement
- 5.10.2j – name(s), function(s) and signature(s) of person(s) authorizing the test report
- 5.10.2k – a statement to the effect that the results relate only to the items tested
- 5.10.2 Note 1 – hard copies of test reports should include the page number and total number of pages
- 5.10.2 Note 2 – a statement that the test report shall not be reproduced except in full, without written approval of the lab.
- 5.10.3.1a – deviations from, additions to, or exclusions from the test methods, and information on specific test conditions, such as environmental conditions
    - Temperature, humidity, barometric pressure
    - Operating voltage and frequency
- 5.10.3.1b – a statement of compliance/non-compliance with requirements and/or specifications
- 5.10.3.1c – a statement on the estimated uncertainty of measurement
- 5.10.3.1d – where appropriate and needed, opinions and interpretations
- 5.10.3.1e – additional information which may be required by specific methods, customers or groups of customers

In the United States, the Federal Communications Commission (FCC) has some additional requirements. These will vary depending on the type of approval process used for the product

DEVICES AUTHORIZED UNDER VERIFICATION

- 47 CFR 2.955(a)(3)
    i. Indicate the actual date all testing was performed (see also 17025 5.10.2g)
    ii. State the name of the test laboratory, company, or individual performing the verification testing. (see also 17025 5.10.2b)
    iii. Contain a description of how the device was actually tested, identifying the measurement procedure and test equipment that was used (see also 17025 5.10.2e)

iv. Contain a description of the equipment under test (EUT) and support equipment connected to, or installed within, the EUT (see also 17025 5.10.2f)
v. Identify the EUT and support equipment by trade name and model number and, if appropriate, by FCC Identifier and serial number
vi. Indicate the types and lengths of connecting cables used and how they were arranged or moved during testing
vii. Contain at least two drawings or photographs showing the test set-up for the highest line conducted emission and showing the test set-up for the highest radiated emission. These drawings or photographs must show enough detail to confirm other information contained in the test report. Any photographs used must be focused originals without glare or dark spots and must clearly show the test configuration used
viii. List all modifications, if any, made to the EUT by the testing company or individual to achieve compliance with the regulations in this chapter
ix. Include all of the data required to show compliance with the appropriate regulations in this chapter (see also 17025 5.10.2i)
x. Contain, on the test report, the signature of the individual responsible for testing the product along with the name and signature of an official of the responsible party, as designated in §2.909

DEVICES AUTHORIZED UNDER CERTIFICATION

- 47 CFR 2.1033(b)
  i. The full name and mailing address of the manufacturer of the device and the applicant for certification (see also 17025 5.10.2d)
  ii. FCC identifier
  iii. A copy of the installation and operating instructions to be furnished the user. A draft copy of the instructions may be submitted if the actual document is not available. The actual document shall be furnished to the FCC when it becomes available
  iv. A brief description of the circuit functions of the device along with a statement describing how the device operates. This statement should contain a description of the ground system and antenna, if any, used with the device
  v. A block diagram showing the frequency of all oscillators in the device. The signal path and frequency shall be indicated at each block. The tuning range(s) and intermediate frequency(ies) shall be indicated at each block. A schematic diagram is also required for intentional radiators
  vi. A report of measurements showing compliance with the pertinent FCC technical requirements. This report shall identify the test procedure used (e.g., specify the FCC test procedure, or industry test procedure that was used), the date the measurements were made, the location where the measurements were made, and the device that was tested (model and serial number, if available). The report shall include sample calculations showing how the measurement results were converted for comparison with the technical requirements
  vii. A sufficient number of photographs to clearly show the exterior appearance, the construction, the component placement on the chassis, and the chassis assembly. The exterior views shall show the overall appearance, the antenna used with the device (if any), the controls available to the user, and the required identification label in sufficient detail so that the name and FCC identifier can be read. In lieu of a photograph of the label, a sample label (or facsimile thereof) may be submitted together with a sketch showing where this label will be placed on the equipment. Photographs shall be of size A4 (21 cm x 29.7 cm) or 8 x 10 inches (20.3 cm x 25.4 cm). Smaller photographs may be submitted provided they are sharp and clear, show the necessary detail, and are mounted on A4 (21 cm x 29.7 cm) or 8.5 x 11 inch (21.6 cm x 27.9 cm) paper. A sample label or facsimile together with the sketch showing the placement of this label shall be on the same size paper
  viii. If the equipment for which certification is being sought must be tested with peripheral or accessory devices connected or installed, a brief description of those peripherals or accessories. The peripheral or accessory devices shall be unmodified, commercially available equipment

DEVICES AUTHORIZED UNDER DECLARATION OF CONFORMITY

- 47 CFR 2.1075(a)(3)
  i. The actual date or dates testing was performed
  ii. The name of the test laboratory, company, or individual performing the testing. The Commission may request additional information regarding the test site, the test equipment or the qualifications of the company or individual performing the tests
  iii. A description of how the device was actually tested, identifying the measurement procedure and test equipment that was used
  iv. A description of the equipment under test (EUT) and support equipment connected to, or installed within, the EUT
  v. The identification of the EUT and support equipment by trade name and model number and, if appropriate, by FCC Identifier and serial number
  vi. The types and lengths of connecting cables used and how they were arranged or moved during testing
  vii. At least two photographs showing the test set-up for the highest line conducted emission and showing the test set-up for the highest radiated emis-

sion. These photographs must be focused originals which show enough detail to confirm other information contained in the test report

viii. A description of any modifications made to the EUT by the testing company or individual to achieve compliance with the regulations

ix. All of the data required to show compliance with the appropriate regulations

x. The signature of the individual responsible for testing the product along with the name and signature of an official of the responsible party, as designated in §2.909

xi. A copy of the compliance information, as described in §2.1077, required to be provided with the equipment

In Taiwan, the Bureau of Standards, Metrology and Inspection (BSMI) has a few of their own requirements for report content.

- If testing with different numbers of cables connected to multiple samples of a given I/O port type is performed, data for each number of cables used shall be provided to show that the addition of the final cable did not increase emissions by more than 2 dB.
- A statement that the final test results represent the worst case, along with a listing of the configuration variations that were investigated to determine the worst case.
- Clear photographs of the test setup providing sufficient detail to duplicate the test results. Each test setup must be documented.
    - 6 exterior pictures of a system EUT for class A equipment
    - 6 exterior and 6 interior pictures of a system EUT for class B equipment.
    - Pictures required for the power supply and internal boards. Board photos required of both sides with sufficient detail to identify EMC critical parts.
    - Minimum photo size is 4 by 6 inches
- List of removable EMI suppression components in the product.
- List of key EMI generation components (clock generators and distribution parts)
- Block diagram of the EUT showing the clock distribution
- BSMI cover sheet containing the following information:
    - Product Name. This shall be the same name as provided on shipping and final sales packaging
    - Applicant (Intel for our products)
    - Description of nameplate mains characteristics
    - Logo or Brand
    - Model Number or Type. Detailed model number(s)
    - Test Result. Passed. State class A or class B
    - Original Signature. Electronic signatures are acceptable if the report and all supporting documentation is submitted on a CD-ROM

The following items may be specific to one regulator, but should be provided in the report:

- List of accreditations, approvals, listings, etc held by the laboratory. Include identification numbers if applicable.
- If multiple model numbers are covered by the report, provide a description and evidence of differences reviewed by the laboratory.
- Name and signature of the person taking the data. Needed for each set of data in the report.
- List all test equipment used during the tests.
    - Test equipment type
    - Manufacturer
    - Model number
    - Serial number
    - Calibration date and calibration due date
- Details of applicable regulatory compliance labels showing label details and location on the product.
- List of all components of the EUT system. Include internal components such as power supplies, motherboards, hard disk drives, floppy disk drives, CD-ROM drives and add-in cards.
    - Equipment type
    - Manufacturer
    - Model number
    - Serial number
- List of all cables
    - Length
    - Type (shielded, unshielded, coax, etc)
    - Devices interconnected with the cable
- EUT exercise/stimulation software used
- Any required user warning statements.

As you can see, preparation for testing a product to EMC requirements is an intensive process. You will need to go through this list of information and make sure that any of it that must be provided to the laboratory is identified and provided in a format that is useful to the laboratory.

Talk to them in advance and make sure that you have everything they need, in a format that they can use. The time (and money) that you save is your own (or your employers).

SUMMARY OF COMMERCIAL EMC TESTS

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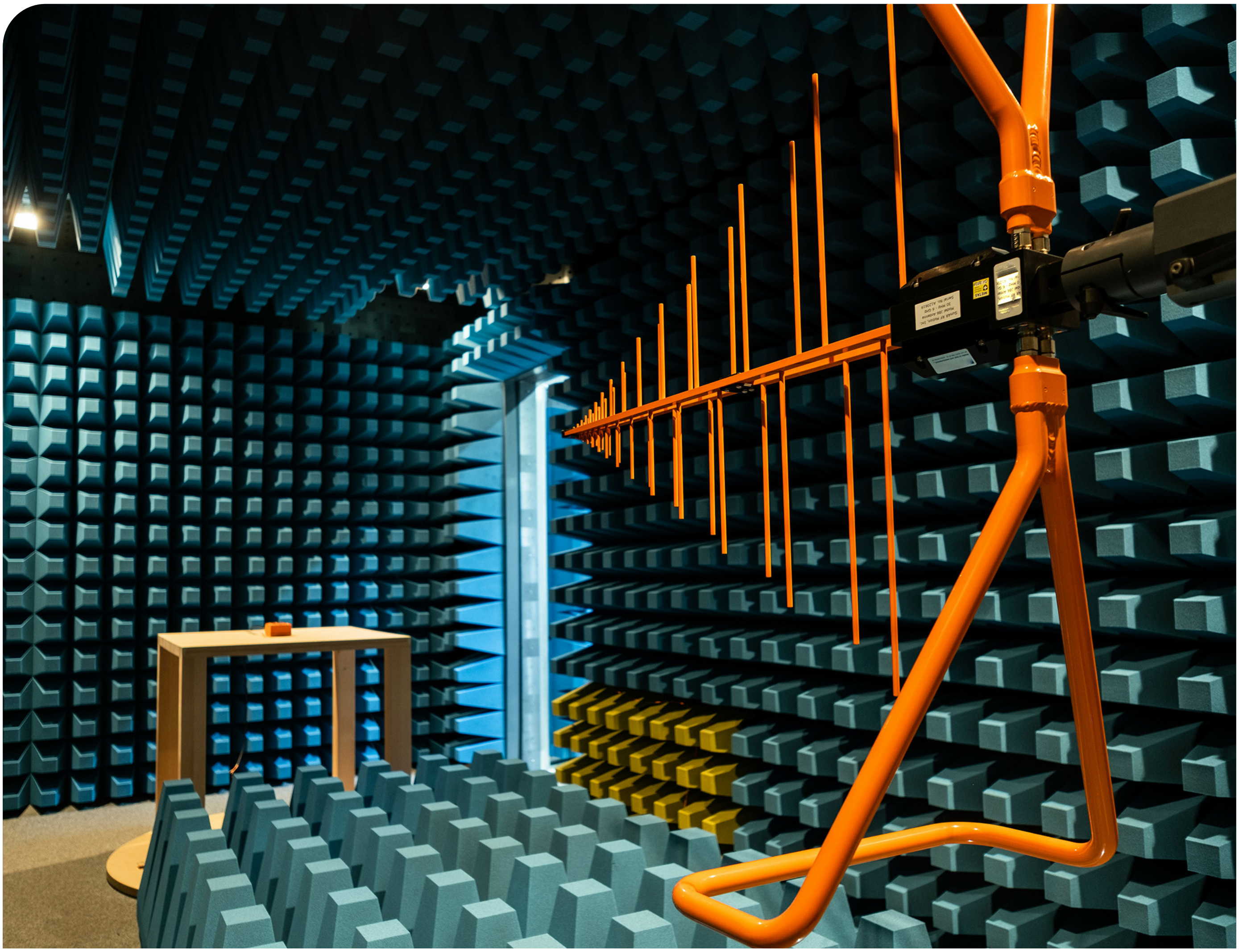
INTRODUCTION

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.

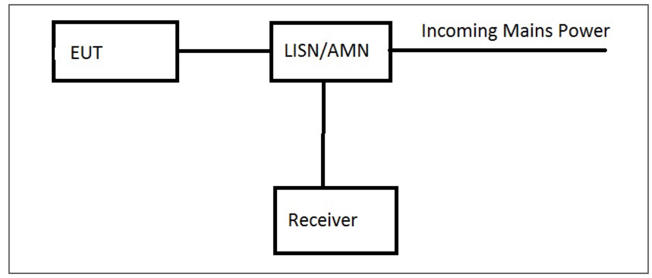


Figure 1 – Generalized test setup for conducted emissions using a line impedance stabilization network (LISN).

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, California. 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, California 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*.

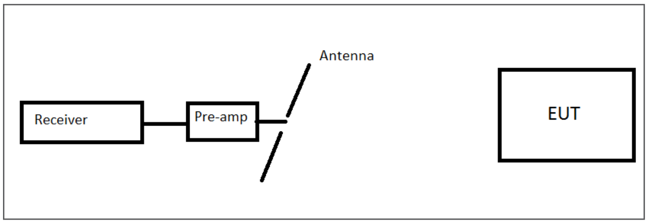


Figure 3 – General test setup for radiated emissions testing.

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).

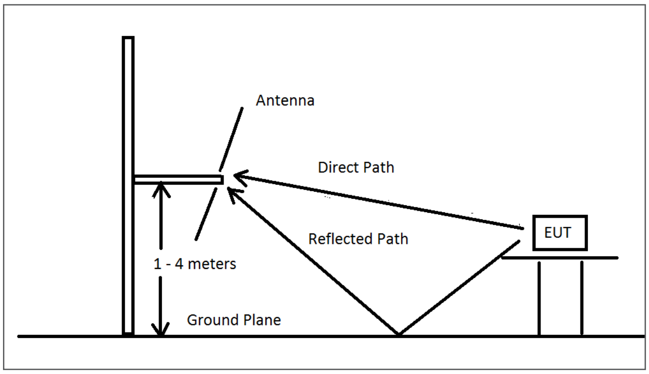


Figure 4 – Diagram showing the direct and reflected waves. The antenna height is adjusted to maximize the measurement.

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 24 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.

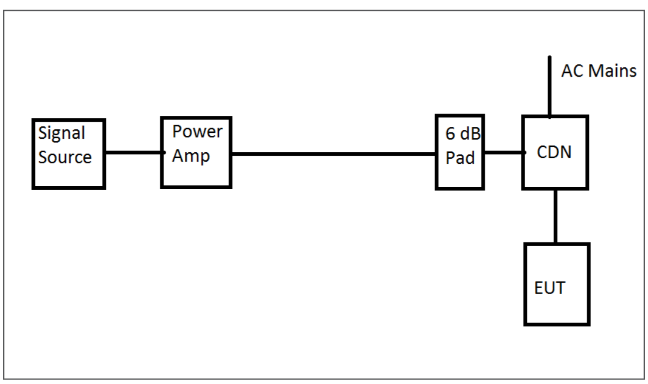


Figure 5 – Typical test setup for the conducted immunity test.

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 24 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 24) 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 24 (and 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.

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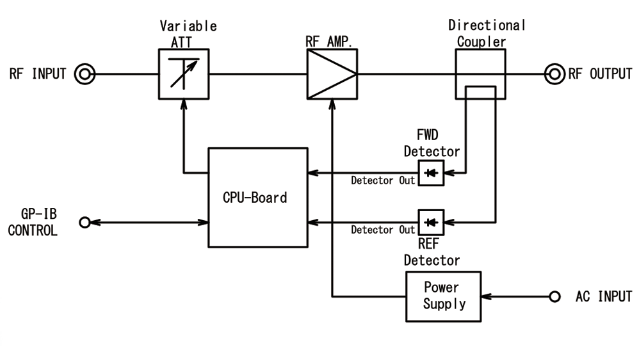
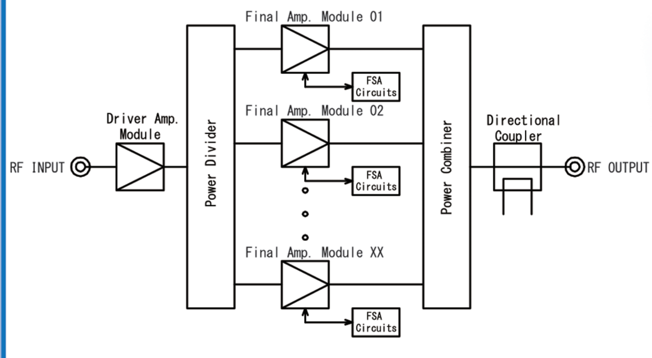
The novel FSA design provides reverse power protection over a wide impedance range and extended period of time without shutdown or severe output limitations. Many amplifier manufacturers make similar claims. But the new FS amplifier design, which leverages over 40 years of R&K RF design experience, delivers the highest reliability and performance of any impedance tolerant amplifier on the market. Contact your local sales representative or R&K to learn more!

Conventional Amplifier



FS Amplifier



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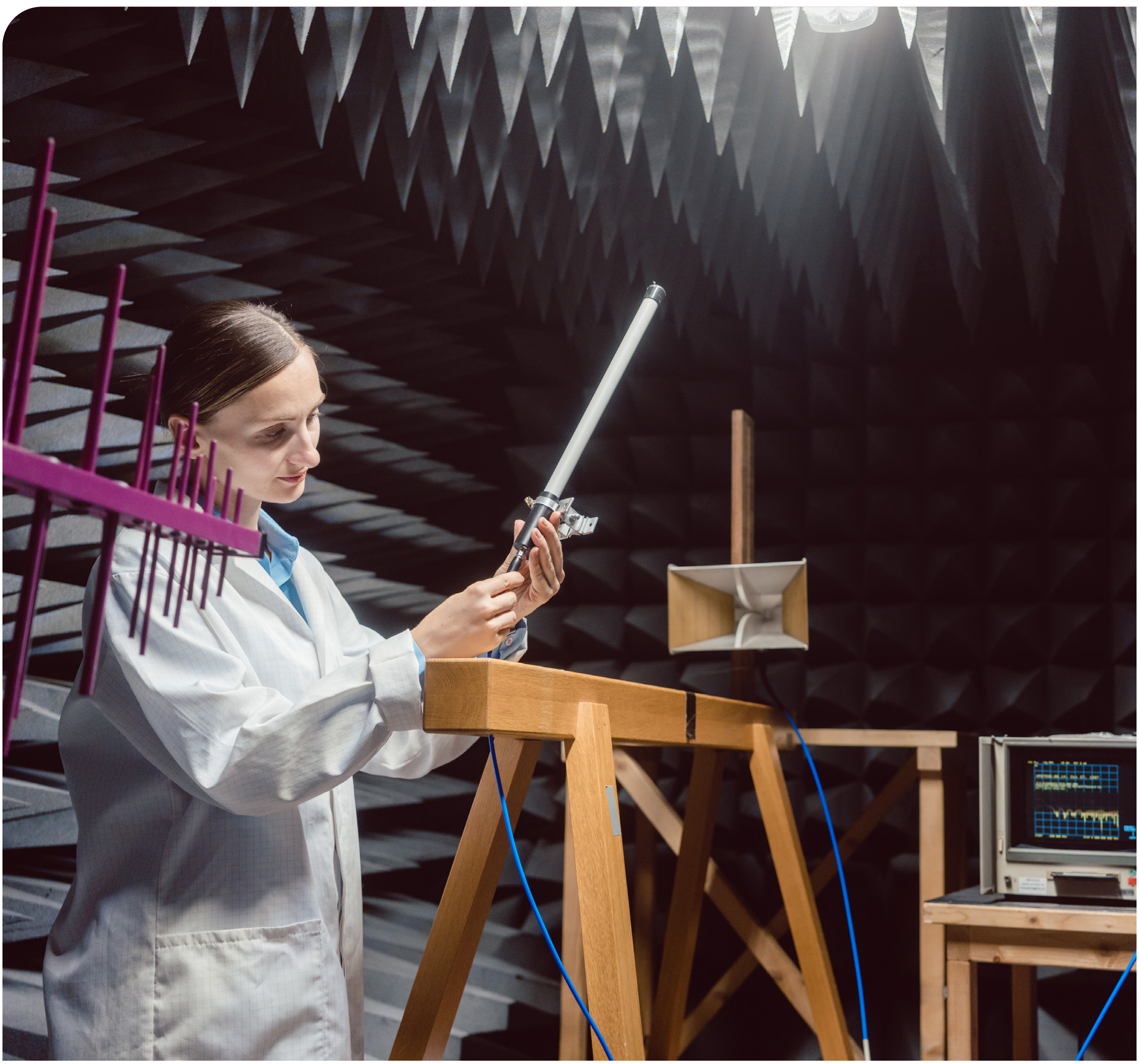
A SIMPLE GUIDE TO ANTENNA SELECTION

A.H. Systems, Inc.



Selecting an antenna for testing can sometimes be straightforward but often requires some specific consideration. One aspect in antenna selection is knowing the intended test frequencies and then selecting a matching antenna.

Not all antennas are created equal, and when it comes to frequency different antenna styles perform better at some frequencies and not at others. Some special considerations are sometimes required in antenna design typically at very high and very low frequencies. Take an antenna for a low frequency in the kHz range. A single wavelength at this range is on the order of miles long. Even a ¼ wavelength antenna at kHz frequencies is impractical at around 10,000 ft long. To get a better understanding of wavelength size and frequency, a frequency and wavelength calculator is helpful.

Low frequency radio signals tend to act more like low frequency audio, traveling through and around objects in non-directional ways. On the other hand, elements for high frequency antennas on the order of GHz can be very small, but signals tend to propagate in very directional ways more like light, but also won't go around or through objects. Because of this, low frequency signals are naturally more omnidirectional and high frequency ones are more directional. Attempting to make directional low frequency antennas or omnidirectional high frequency ones can be challenging.

Other antenna design factors such as bandwidth are frequency-dependent as well. High frequencies require more precise length elements, making it more difficult to construct a wide bandwidth high frequency antenna, but some designs manage to achieve this.

ACTIVE AND PASSIVE

Receiving and transmitting RF signals, while related, have some different antenna requirements. Reception picks up very small signals and delivers them to the receiver, requiring a well-tuned sensitive antenna. To aid with weak signals, some antennas or receivers employ active circuitry that amplifies the incoming signal. The amplifiers are better located near to or on the antenna to reduce the chance of it amplifying the noise as well, but ideally will boost weak signals. When used with a transceiver, these amplifiers need to be switched in and out since they do not handle transmit power. They are designed so they are connected during reception, but bypassed during transmission.

BEAMWIDTH AND ANTENNA GAIN

Another factor in antenna selection is beamwidth, or the gain of the signal versus how directional it is. Directional antennas have a narrow beamwidth in the shape of a lobe in the intended direction, while omnidirectional antennas have a more spherical propagation. Other antennas — such as doughnutshaped ones — have some directionality. In this case, the signal does not propagate up or down much but does cover 360° on a single plane. An antenna beamwidth coverage calculator can be helpful for determining beamwidth requirements.

FREQUENCY RANGE

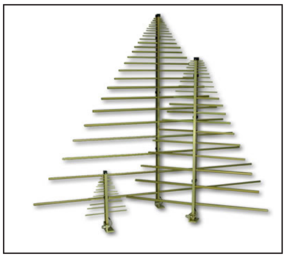
Antennas have different frequencies they are tuned for, in addition to the bandwidth or range or frequencies they can cover. Horn antennas and similar designs have a relatively narrow bandwidth while others such as a log periodic in comparison are very wide. Choosing an antenna with a wider bandwidth will also impact its other characteristics. If only a narrow test frequency is needed, it is preferable to have an antenna designed solely for that range.

LOOP ANTENNAS

For low frequencies below 30 MHz, loop antennas are ideal for magnetic field strength measurements. These consist of a typically circular loop or coil; the size and number of turns of the loop impacts the frequency the antenna works on. Without any matching network, loop antennas are resonant such that the circumference is a single wavelength of the desired frequency. They can be adjusted with a matching network to be anywhere from 10% of the size up to full size wavelength.

Loop antennas are convenient to use due to their small size relative to their frequency. For magnetic field testing at low frequencies, loop antennas produce a voltage for a given field strength, making them easy to use. They are less ideal for higher frequencies due to their size and response characteristics.

MONOPOLES



Monopoles can be used in many frequency ranges depending on their size, but like other antennas get larger at lower frequencies. Matching networks used with monopoles allow them to work over a wider range. Monopoles are constructed of a ground plane that is typically around 1/4 wavelength and a single radiating/reception element in the middle of the ground plane and perpendicular to it. Monopoles are good for measuring the electric field in testing.

LOG PERIODIC AND HYBRID ANTENNAS

Log Periodic AntennasThe log periodic antenna is another broadband antenna that is much more directional and handles higher frequencies than other similar designs. They are constructed of multiple elements that become progressively smaller toward the tip of the antenna. These antennas are a good choice for both emission and immunity testing and can be used for both reception and transmission.

The hybrid or biological antenna design is a mix of a log periodic and a bow tie type design as a reflector. This antenna design has a wideband response, making it a good choice for testing a wide range of frequencies without having to switch antennas. It can be used for immunity and other compliance testing with repeatable results.

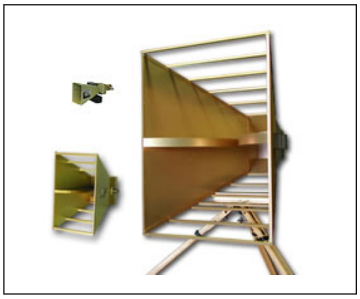
DIPOLES

The dipole is a simple design and is considered somewhat of a standard when it comes to antennas. Its design consists of two equal length of tuned elements in line with each other but opposite in direction. The elements on a dipole are typically tuned to ¼ wavelength such that the total length is ½ wavelength. The dipole is simple but also an effective antenna with a radiation pattern that covers a 360° doughnut-like pattern when vertically polarized. When horizontally polarized, the same doughnut pattern makes them bidirectional. Shorter dipoles can also be constructed with matching network components. The dipole does not have a very wide bandwidth and while still useful it is less desirable for testing a wide range of frequencies as it requires adjustments or multiple antennas for different test frequencies.

BICONICAL ANTENNAS

Biconical antennas are a modified type of dipole where the two elements form a roughly conical shape. This change allows them to have a wider bandwidth versus a regular dipole. The cones used on these are rarely solid and are often made of multiple elements, making them easier to fold or transport. Their broadband nature allows quick testing without having to adjust or change the antenna. They are linearly polarized and typically work in frequency from 20 MHz to 300 MHz, but when designed for it, they can work as high as 18 GHz.

HORNS



Horn AntennasAt frequencies around 1 GHz and higher, a horn antenna becomes a practical choice. Horns are too large for sub-1 GHz use but they work well for high frequencies. Horn antennas are very directional both for receiving and transmitting so they can both pick up weak signals and transmit a strong signal to a device. This makes them a good choice for both immunity and emission testing.

Above 1 GHz a horn is still a good choice and they get physically smaller and more directional as frequency increases. Horns work well up to 40 GHz and above, but the addition of a pre-amplifier for reception is a good addition to improve the dynamic range of the antenna.

CONCLUSION

Selecting the right antenna for a situation can sometimes seem confusing when considering all the necessary criteria. Frequency is a paramount consideration and often the starting point for a design. To help get past the confusion, contact an expert in the field. A.H. Systems carries a line of antennas for all kinds of testing situations and can help best fit your application or need.

WIRELESS / 5G / IOT

WIRELESS & 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 Equipment								
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
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 Equipment								
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/bc-121-5.php							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
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
Signal Hound	www.signalhound.com			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 GROUPS & ORGANIZATIONS

MAJOR WIRELESS 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

WIRELESS 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 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.

WIRELESS GROUPS & ORGANIZATIONS

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
(GROUPS, WEBSITES, BOOKS, FORMULAS & TABLES)

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.
http://mwrf.com/test-measurement-analyzers/measure-interference-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

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
(GROUPS, WEBSITES, BOOKS, FORMULAS & TABLES)

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
1000	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

THE VITAL ROLE OF SIMULATION FOR VIRTUAL EMI AND EMC TEST ENVIRONMENTS

Jiyoun Munn
Technical Product Manager, Comsol, Inc.

THE VIRTUAL ROLE OF SIMULATION FOR VIRTUAL EMI AND EMC TEST ENVIRONMENTS

Before deploying microwave and millimeter-wave devices and systems within 5G, the Internet of Things (IoT), and high-speed wireless communication, it is essential to predict their performance. This need has increased the demand for virtual test platforms through simulation software.

High carrier and system bus frequencies are necessary for high-data-rate communication between multiple devices present in such systems. However, increased operational frequencies may induce undesirable and troublesome electromagnetic compatibility (EMC) and electromagnetic interference (EMI) issues, especially when communication is congested. Moreover, the impact from other physics is no longer negligible in mmWave devices. Multiphysics phenomena, such as structural deformation caused by heat expansion, need to be a part of the design consideration as well. Fortunately, a wide range of EMC and EMI scenarios can be virtually emulated and tested without having to elaborately adapt test configurations to real-world environments.

Using electromagnetics simulation software for evaluating device functionality reduces time and costs during the development and production cycle. Virtual evaluations can be performed prior to fabrication, test, and manufacture, and are an important component in reliable quality control processes.

The goal of simulation is to describe the real world as closely as possible on the computer by using proven physics equations. Ideally, the numerical model is used to mimic multiple physical phenomena representing a great variety of operational conditions, which is hard to realize in a lab environment. Accurately analyzing real-world designs and conditions comes at a cost. The more complex the analysis, the more computational resources are needed. Therefore, engineering judgment is used for excluding unnecessary parts from the analysis and for configuring the simulation settings to ensure efficient computations.

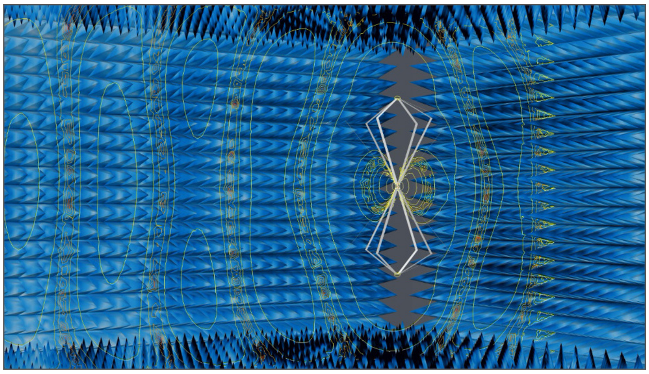


Figure 1: Contour plot of the logarithmic field distribution of a biconical antenna in a fully anechoic chamber.

When evaluating EMI and EMC performance of radiating devices, test engineers often perform measurements in a fully anechoic chamber. Simulation tools are used to set up a numerical environment that can reproduce such tests virtually (*Figure 1*) by using, for example, the finite element method (FEM). For instance, the pyramidal absorbers that are attached to the anechoic chamber walls contain lossy conductive carbon particles. The absorbers attenuate the incident electromagnetic waves gradually with only small amounts of unwanted reflections. For efficiency, instead of modeling the full-sized wall of absorbers, the simulation uses only a single pyramidal unit cell with periodic boundary conditions (*Figure 2*). This is an efficient way of estimating the performance of the complete set of absorbers to make sure the reflectivity is at a minimum. Even if the model consists of just a single unit cell, the periodic boundary conditions make it equivalent to an infinite array of pyramidal absorbers. The effective homogeneous material properties obtained from the unit cell simulation are then used for the entire anechoic chamber wall.

To validate the virtual version of the anechoic chamber, a wideband biconical antenna is placed inside the anechoic chamber. The performance of the antenna (for example, far-field radiation patterns and S-parameters) is computed to validate that there is no degradation of performance due to the incomplete absorber characterization.

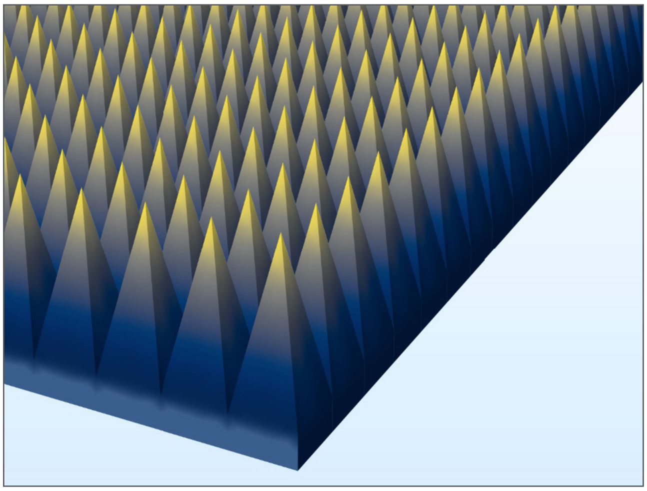


Figure 2: Microwave absorber simulation using Floquet periodic boundary conditions.

Although the real-world representation of the antenna inside the fully anechoic chamber in the simulation is visually quite appealing, as shown in *Figure 1*, its computational cost is unnecessarily high. The simulation can be made much faster and more efficient in terms of memory usage by using a numerical technique that is equivalent to the anechoic chamber walls. Such techniques involve using perfectly matched layer (PML) and absorbing boundary condition features. To efficiently study the near and far fields and other antenna parameters, it is sufficient to place the same biconical antenna in a much smaller surrounding air domain enclosed by a perfectly matched layer (*Figure 3*).

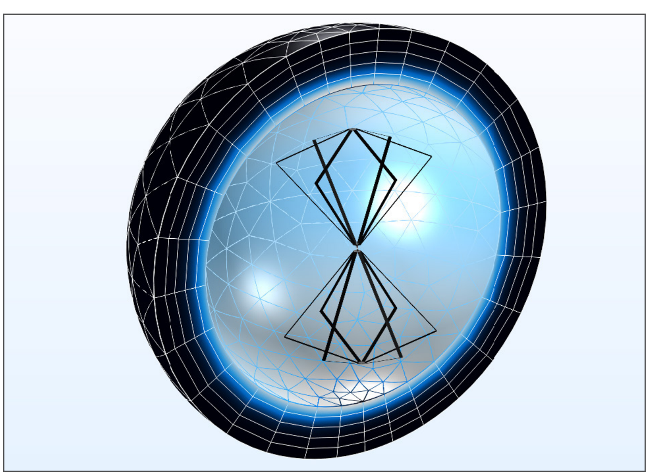


Figure 3: Biconical antenna enclosed by a PML. The PML at the front is removed from view to show the interior.

In order to simulate a large system efficiently, it is crucial to choose proper numerical boundary conditions. In addition, eliminating design details that are deemed to have negligible impact on the results, and just keeping the relevant components, can make further efficiency gains. By using PMLs, a large system can be simulated and not limited to just device-level modeling.

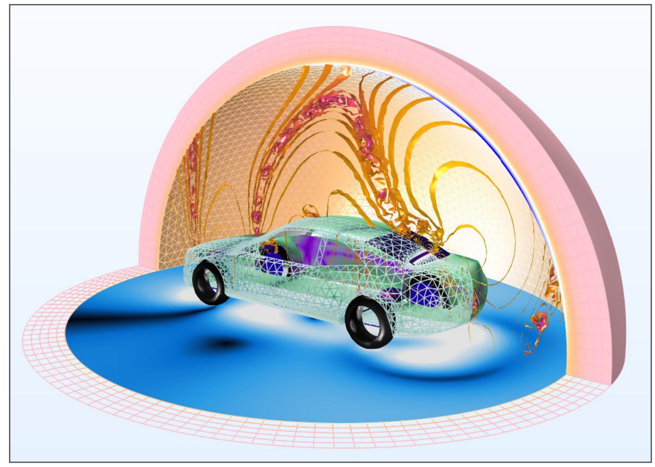


Figure 4: Impact on cable harness by the radiation from the rear windshield in the FM radio frequency band.

In *Figure 4*, the electric field transmitted from a fictitious radiating device on the rear windshield of a car is studied to see the radiated emission effect over the cable harness inside. The PML covers the upper half-space, absorbs all outgoing waves, and ensures that reflected waves do not bounce back onto the car. Meanwhile, the bottom ground and the car body generate reflection and multipath fading effects on the cable harness. The electromagnetic waves coupled to the cable are a source for unwanted conducted emission as well. In a real car system, it would be hard to access and relocate the source and victims for the EMI/EMC test. However, by using simulation, it is possible to analyze arbitrary configurations. In this way, by not being limited by physical testing, engineers can produce more robust system designs.

By using simulation, one can estimate the actual performance of devices for IoT applications when they are deployed in a real environment. IoT devices may be placed in a living room, a garage, or other spaces in a house. The electrical size of the problem in terms of the number of spanned wavelengths can easily exceed what can be addressed by so-called full-wave numerical methods. Full-wave methods include the finite element method (FEM), the finite difference time domain (FDTD) method, and the method of moments (MoM). There are alternative computational electromagnetics approaches available for approximating the performance of IoT devices without sacrificing too much accuracy. In addition, such approximate methods can produce useful results while still using limited computational resources. One such approach is the method of ray tracing. *Figure 5* shows multiscale simulation capabilities when ray tracing is employed together with FEM. The part of the simulation that uses FEM analyzes a small simulation domain surrounding the antenna of a wireless router that includes a truncated surrounding air domain. Rays are launched from the antenna location, and their initial strength is proportional to the directional intensity of the 3D far-field radiation pattern of the antenna. The antenna coverage inside a media room (*Figure 5*) can be approximated quickly without long simulation times or excessive memory usage. This multiscale electromagnetics modeling technique is a great alternative for overcoming the limitations of traditional computation methods for large EMI and EMC problems.

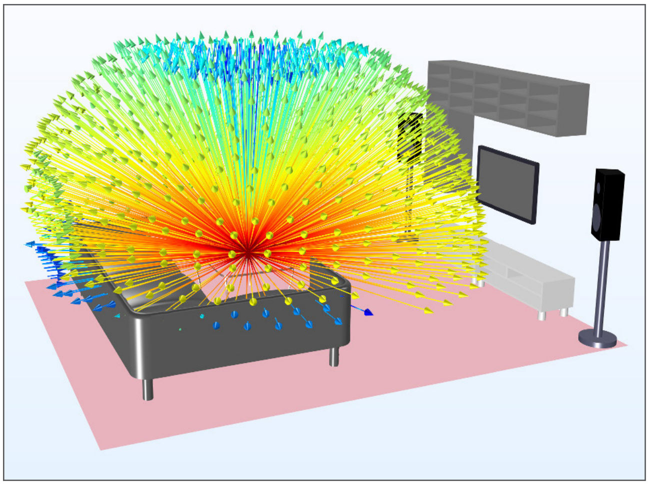


Figure 5: Multiscale electromagnetics simulation example. It combines the conventional finite element method for antenna analysis and ray tracing for describing indoor communication.

Simply combining existing computational methods can overcome the limitations of traditional numerical analysis. Two such situations are when you need to produce wideband results with high-frequency resolution, or when you need to analyze signal integrity and time-domain reflectometry (TDR) for a large device. Such simulations can be very time consuming. However, in both cases, the computational performance can be greatly boosted by conducting a fast Fourier transform (FFT), either from the time domain to the frequency domain or the other way around. For example, you can first perform a transient analysis and then run a time-to-frequency FFT to achieve a wideband S-parameter and far-field calculation in the frequency domain. Alternatively, you can first perform a frequency sweep and then run a frequency-to-time FFT for a time-domain bandpass impulse response. This is useful for time-domain reflectometry analysis, such as identifying a defective part of a transmission line, which results in impedance mismatch and signal quality degradation.

Simulation provides virtual analysis platforms for a wide range of test scenarios. However, learning how to use electromagnetics simulation software may not be the best use of time for everyone in an organization. Limited training and access to simulation software may restrict usage of electromagnetics simulation tools to a small set of expert users. Completed numerical EMI and EMC test models may frequently need new input parameters in order to adjust to a real-world test environment's variations. The need for updating boundary conditions, mesh, and postprocessing settings outside of the simulation group can cause unexpected delays in the development cycle. The good news is that simulation software has evolved to accommodate specialists who are not dedicated simulation engineers. The simulation models can be converted to easy-to-use apps (*Figure 6*). An app has a straightforward, specialized user interface (UI) and can be shared with colleagues and customers through existing web browsers or as a standalone executable file. Such standalone apps do not require purchasing extra software licenses and can run regardless of the operating system. A large number of people involved in EMI test projects can easily access the virtual test kit provided by an app and optimize the product without learning how to use the software behind the curtain.

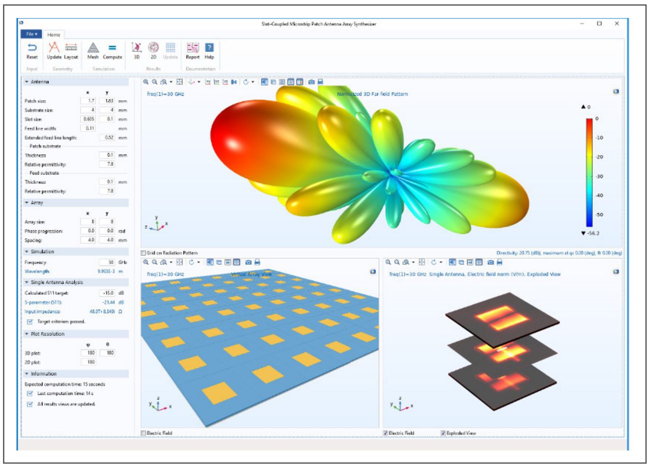


Figure 6: Simulation app for quickly estimating the far-field pattern of a phased array antenna using a full-wave single antenna simulation and array factor.

The variety of simulation tools that support multiple numerical methods within electromagnetics helps engineers and researchers not only to design conventional devices, such as filters, couplers, antennas, and waveguide structures, but also to test EMI and EMC problems in applications for 5G, IoT, and wireless communication. Conventional electromagnetics analyses can be extended to include multiple physical effects using multiphysics simulation. The simulation software industry is also evolving to meet the demands of the fast-paced market for emerging high-speed communication technologies and help more people benefit from simulation.

TELECOMMUNICATION TESTING ON RELEVANT RF COMPONENTS

AR RF/Microwave Instrumentation

The telecom industry has undergone rapid development in the past several decades. Digital communications methods have advanced, requiring increased bandwidth and frequency coverage. This advancement has complicated an RF measurement system's capability to accurately characterize system components. The 3rd Generation Partnership Project (3GPP) provides modern broadband mobile communication guidance. This development is chronicled in the evolutionary steps known as 2G, 3G, 4G, and now to the 5G stage currently being launched. A review of how the air interface layer changed through this evolution will help explain how measurement systems often need to be upgraded to meet the new performance criteria.

1.0 2ND GENERATION

2G modulation was the early format to move from analog modulation to digital modulation schemes. And building off of analog bandwidth and frequency coverage, the only thing to be added within the measurement system was time domain considerations to match the modulations transmitter gating.

2.0 3RD GENERATION

3G represented a significant advancement in digital communication. Military developments in spread spectrum technology spun off into the commercial space leading to Code Division Multiple Access (CDMA) and the higher data rate wideband CDMA (WCDMA) shown in Figure 1. As shown in Figure 2, this scheme used a Pseudorandom number waveform (PN) and quadrature modulation that required more bandwidth than the previous 2G channels. Additionally, the orthogonal modulation used has extensive peak power excursions, seen in Figure 3.

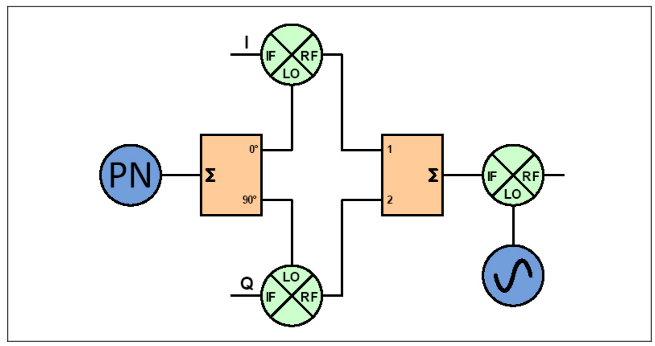


Figure 1: CDMA Transmitter Fundamentals Block Diagram

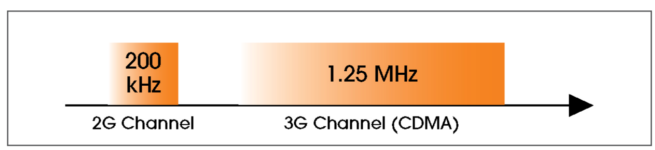


Figure 2: 2G vs. 3G Channel Bandwidth

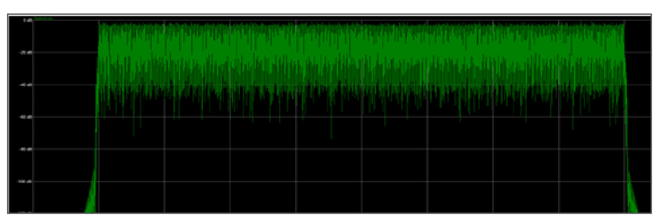


Figure 3: Power/Frequency Spectrum of an Orthogonal Modulated Carrier

3G RF measurement systems could no longer use traditional CW techniques used for many decades as these cannot accurately represent wideband orthogonal modulation. Consequently, significant investment was required in both signal generation and signal analysis. Vector signal generators are required along with signal analyzers capable of demodulation and spectral measurements such as Adjacent Channel Power (ACP), Spectral Emissions Mask (SEM), and Error Vector Magnitude (EVM), as seen in Figure 4. * Due to a demand for more spectrum for broadband mobile communication, moving to 3G increased the spectrum from 450 MHz to 6 GHz.

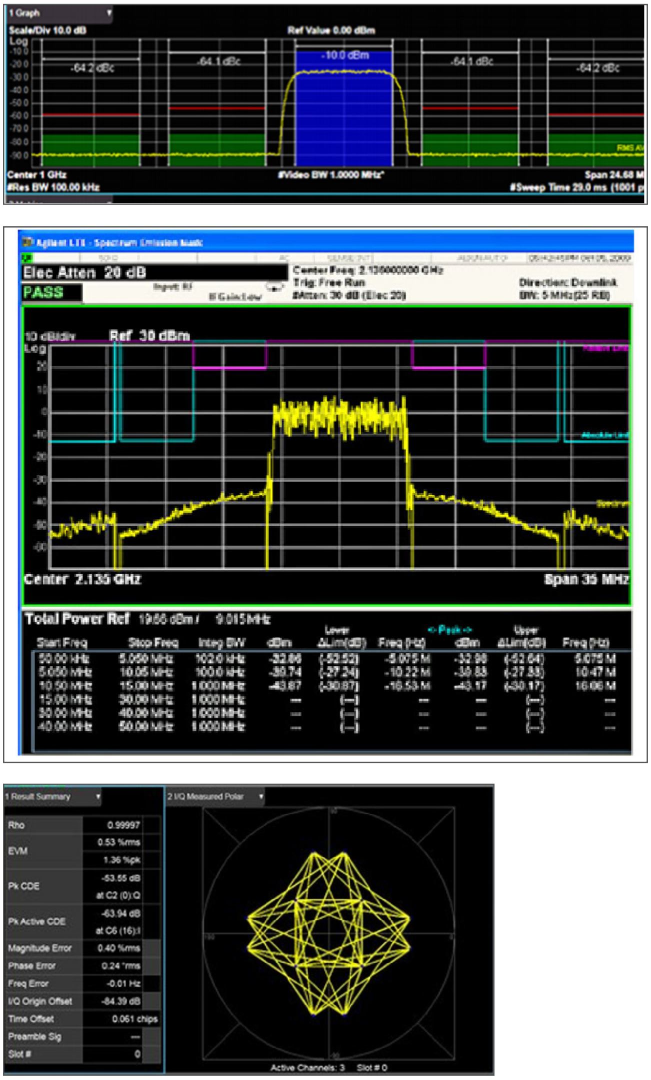


Figure 4: 3G Measurements

** Concurrent with 3G development were advances in fixed wireless technology commonly called WIFI/WLAN. This also uses orthogonal modulation and uses the s*

An example of a 3G RF measurement system is shown in Figure 5. This type of setup is used to characterize the RF components in the 3G radio head. It consists of a multichannel power supply for active devices, a signal generator capable of vector modulation, and a spectrum analyzer. Network analyzers may also be capable of 3G modulation/analysis and S-Parameter measurement.

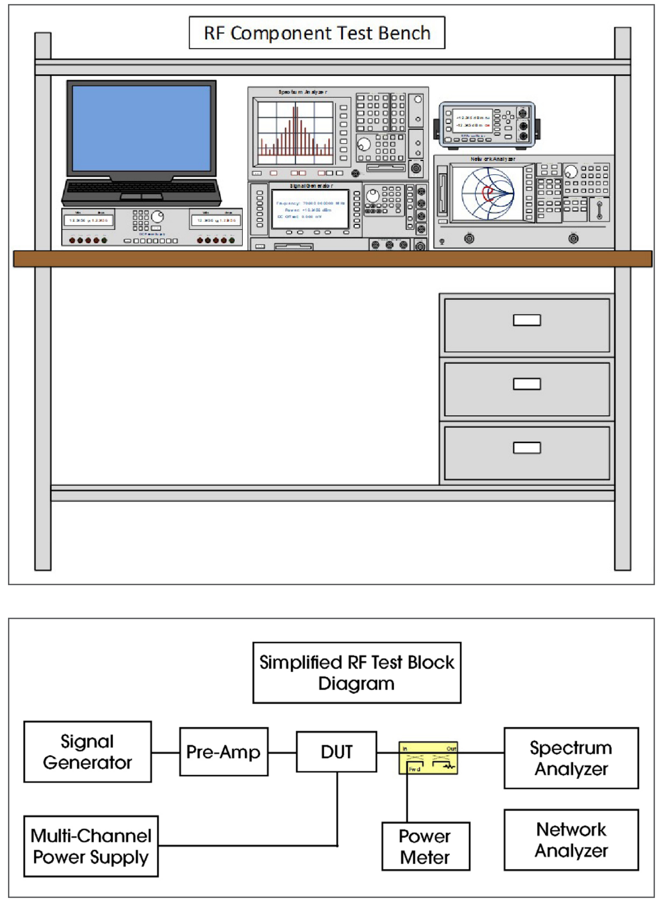


Figure 5: 3G Measurement System

The **signal generator** is a significant upgrade from 2G capable models. These Vector Signal Generators (VSG) employ arbitrary waveform generation (ARB) and I/Q modulation capability. The ARB sample rate determines the bandwidth potential, which must exceed the channel bandwidth of the desired 3G signal, which is a maximum of 5 MHz. Due to the very high peak to average power excursions of 3G modulation, the linear output power of the signal generator is often limited. A pre-amplifier is required to provide nondistorted signals to the Device Under Test (DUT).

For the **pre-amplifier**, a Class A amplifier is the best choice. Its frequency range should be broad enough to cover the entire 3G spectrum and be able to provide the additional non-distorted signal required by the DUT. Since DUT failures may present a very high mismatch, the amplifier should be ruggedized to 100% return power

The **power supply** is used for active device bias, which is a simple but vital part of the RF test bench. Current sense lines must be employed to compensate for voltage drops on high current devices. Overvoltage limiting is desired to protect the DUT from overvoltage transients.

The **DUT**, if active, should use bypass capacitance on the test circuit board, which will supply surge current energy for RF bursts and peak-to-peak power excursions. For precise efficiency calculations, a directional coupler and power meter are used to determine the exact power at the output of the DUT calculations.

In addition to covering the 3G frequency + harmonics, the **spectrum analyzer** may be configured for predefined measurements based on 3GPP specification. If EVM is measured, a vector demodulation option is required.

3.0 4TH GENERATION

4G, otherwise known as Long Term Evolution (LTE), increases channel bandwidth to 20 MHz per channel and can include 5 contiguous channels to 100 MHz total bandwidth. Figure 6. The RF test bench remains much the same, with the exception that the VSG must increase ARB bandwidth to greater than 100 MHz.

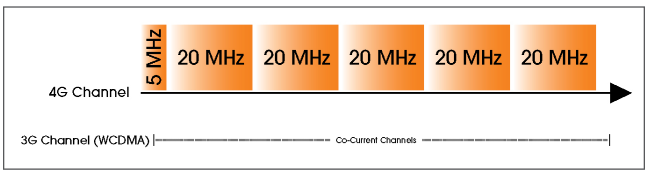


Figure 6: 3G vs. 4G Channel Bandwidth

4.0 5TH GENERATION

5G is a paradigm in mobile communications. More than a simple evolution, this generation introduces new protocols and is called New Radio (NR). Significant increases in bandwidth and latency are keystones for this new standard. Overcrowding in the current 3GPP spectrum designated as Frequency Range 1 (FR1) and bandwidth requirements has pushed the upper-frequency range (FR2) to 24.25 – 52.600 GHz, as shown in Figure 6. FR1 measurement systems will overlap 4G system capability. However, the move to FR2 with a bandwidth up to 400 MHz will require significant investment in new measurement systems capable of those high frequencies. Test equipment manufacturers are developing test equipment and methods to alleviate the considerable cost of a new test bench. These methods may include a box solution capable of making all the RF measurements, including saturation, Intermodulation Distortion (IMD), and S-Parameters. RF cables and connectors must be low loss and length minimized. On-chip antennas will require an Over the Air (OTA) test chamber, seen in Figure 7.

3GPP Frequency Designation	Frequency Range
FR1	410 - 7125 MHz
FR2	24.2 - 52.6 GHz

Figure 7: 5G Frequency Spectrum

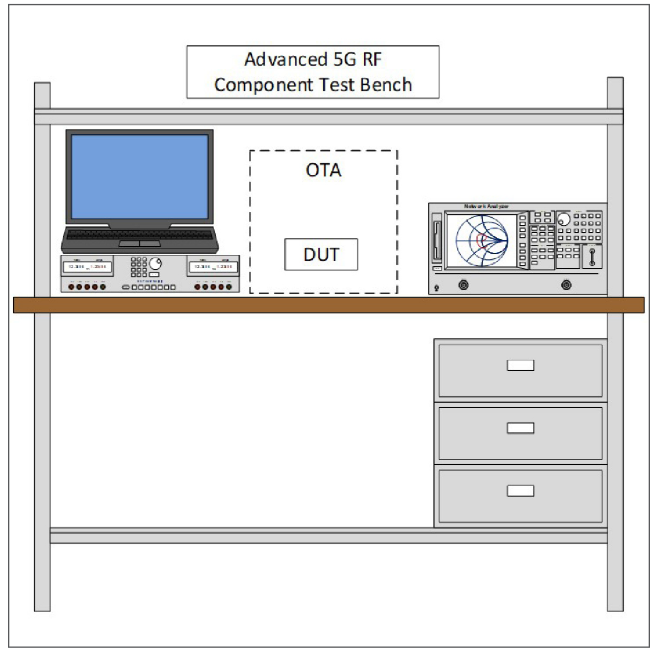


Figure 8: 5G RF Test Bench

CONCLUSION

The history of evolving wireless communications has shown a continuing need to upgrade measurement systems. As we continue to evolve within the telecom industry, and it is expected that this requirement will continue. The frequency spectrum and bandwidth will only increase. Test specifications will mandate additional changes to required test equipment. Capital investment in new equipment should be expected to keep up with the ever-changing demand for more data bandwidth.

THE INTERNET OF THINGS, WIRELESS AND SECURITY

Mike Violette
Washington Laboratories/American Certification Body

SUMMARY

This article gives an overview of international and domestic efforts to protect our connected world. These efforts will be ongoing in perpetuity as the world becomes more complex, more risky and increasing exposed to many varieties of threats.

ACROSS THE POND

The European Union (and UK) are actively addressing the security of wireless devices, as outlined under the Radio Equipment Directive (RED). The Directive, one of many that affects electronics devices, has a specific provision that is going to be enacted in the near very near future. Manufacturers and test labs (and Notified Bodies) need to be prepared to manage an important clause in the RED.

The need is obvious: in our connected world, more Internet of Things (IoT) devices are being hooked up to networks, other devices and critical infrastructure. They are increasingly vulnerable to attacks from many corners of the internet. For instance, in our work, nearly every device has a wireless feature implementing all manner of IEEE 802.11 standards for WiFi, Bluetooth, as well as other applications for radar, sensing and other uses of the electromagnetic spectrum.

The May 10, 2021 hacking of the Colonial Pipeline by bad actors, especially during these turbulent and fraught times, made the US Federal Government to issue an emergency declaration. This, coupled with work done by others in the industry point to the fragile nature of our infrastructure where penetration into networks is nothing new.

Many other alarming examples exist across the world and across cyber-verse. In April of 2021 *The New Yorker*[1] published an amazing exposé of North Korea's state-sponsored hacking and blackmailing operations that squeeze billions of dollars from banks, corporations and other institutions—representing a significant contribution to the country's coffers. In an ongoing effort, the North Korean government recruits talented programmers and then gives them intense training runs targeted campaigns of extortion, often under severe duress to the programmers that include threats to families and close ones if the programmers don't deliver.

So there is much discussion in many industries of the ways to secure the networks. In the US, the National Institute of Standards and Technology (NIST) has developed a Cybersecurity Framework that provides guidance to organizations (both at the Federal and Private Industry level) with "standards, guidelines and best practices to manage cybersecurity risk.2 These are not mandated, at the present, with some exceptions for Federal Government purchasing guidelines, witness the prohibition of acquisition of products from certain companies that have been implicated in IP theft or other breaches of trust.

Add Wireless to the mix, and the cracks in the wall of security get wider.

At the present, the European Union is implementing security measures for wireless devices. There have been provisions in the RED for security

The full legalese of the Article that addresses security is embedded here: RE Directive. Without repeating the full text of the Article, the key elements that industry is (already) considering are under the following Articles:

Article 3.1

- (a) Health and safety
- (b) EMC

Article 3.2 Radio spectrum efficiency

Article 3. Radio equipment within certain categories or classes shall be so constructed that it complies with the following essential requirements:
(a)-(c): Inter-compatibility/functionality provisions

Until now, most of the work on radio devices looked at the above provisions as it relates to device compliance to the above Articles 3.1 and 3.2(a)-(c).

It's starting to get a little interesting with the following provisions under Article 3.3(d)(e) and (f), here:

Article 3.3 (d): *radio equipment does not harm the network or its functioning nor misuse network resources, thereby causing an unacceptable degradation of service;*

Article 3.3 (e): *radio equipment incorporates safeguards to ensure that the personal data and privacy of the user and of the subscriber are protected;*

and

Article 3.3 (f): *radio equipment supports certain features ensuring protection from fraud;*

The above clauses are commonly-viewed as the "cybersecurity clauses" and there is further guidance from the EU forthcoming.

As yet, there are no harmonized standards that have been published to guide evaluations of devices. This leaves the interpretation of these requirements with the Notified Bodies (and others).

However, on 12 January 2022, the EU Com published the Delegated Regulation implementing EU RED Art 3.3 d), e), f) covering Cyber Security.

The legal date is comes into effect is 1 August 2023 with compliance by manufacturers by 1 August 2023 with the pre-amble to the document stating:

"Whereas:

1. *Protection of the network or its functioning from harm, protection of personal data and privacy of the user and of the subscriber and protection from fraud are elements that support protection against cybersecurity risks.*

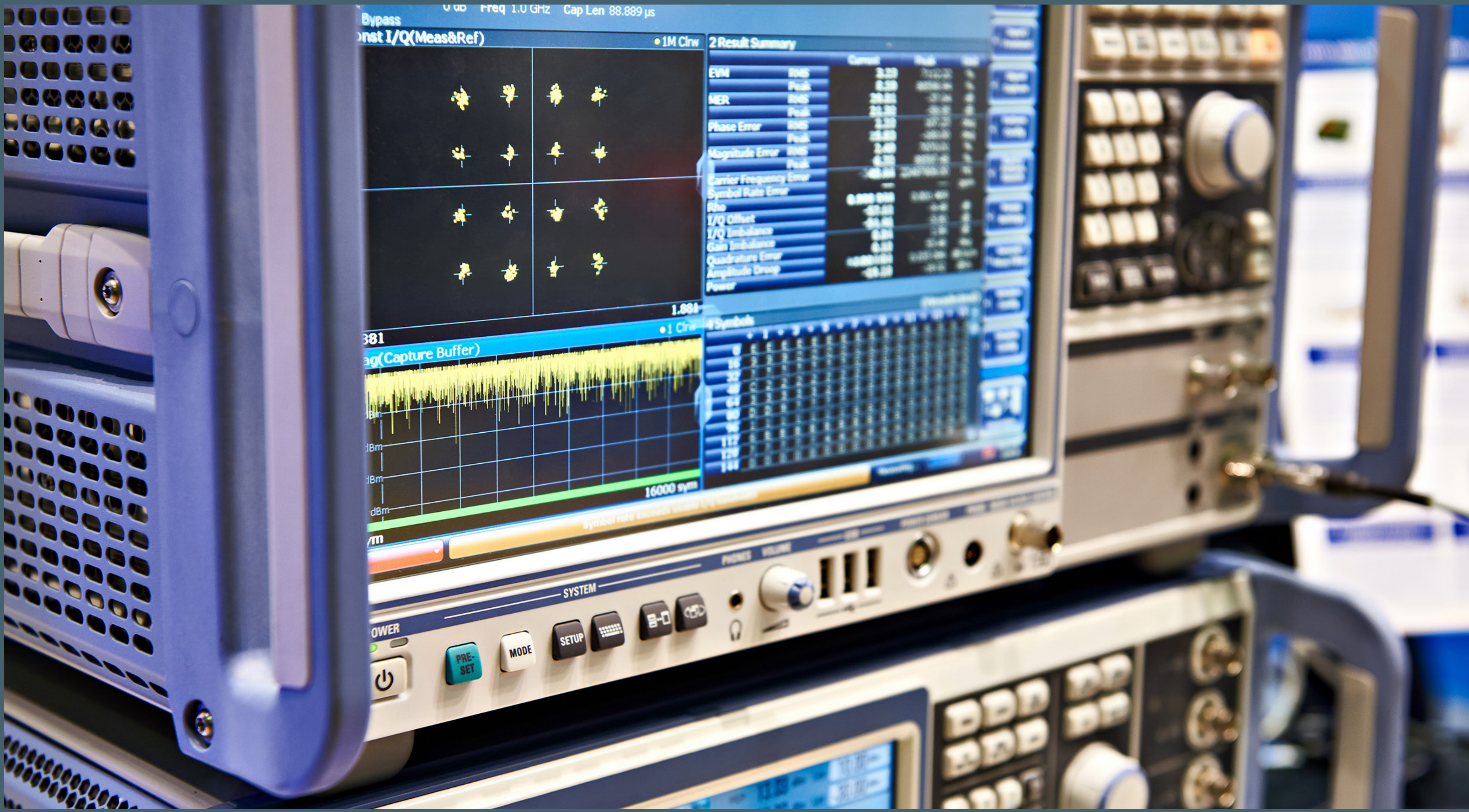
The regulation specifies that harmonized ENs should be published by 12 June 2023. Full implementation is specified to be before the end of 2024, with some phase-out periods of products already in the pipeline.

Not to exclude other important clauses, they must be mentioned. Notably there is much discussion about Article 3.3(g) that covers access to emergency services (911 in the US, 112 in Europe) and Article 3.3(i) which protects users with disabilities. Finally, Article 3.3(j) which mandates controls on software loaded onto devices that may otherwise compromise the compliance (this Article could be construed as to having cyber-implications as devices are increasingly connected to the Cloud for performance and functional updates and could be compromised in some way).

It must be noted that, like all the European Directives, there are broad performance requirements in these Articles and clauses. It is up to the standards bodies to develop criteria and procedures for these assessments and at the present time, the standards and protocols for assessment of "Cyber-resilience" are largely lacking. This should change soon as schemes get rolled out by the accreditation bodies, specifiers (such as customers and governments) and others in the industry.

The bad guys are busy. The compliance community has a large role in evaluation and helping manufacturers select effective and reasonable protections.

EMI, SI & PI


Bypass
Freq 1.0 GHz
Cap Len 88.889 µs
2 Result Summary
16000 sym
SYSTEM
SETUP
MODE
PRE-SET

TOP THREE EMI AND POWER INTEGRITY PROBLEMS WITH ON-BOARD DC-DC CONVERTERS AND LDO REGULATORS

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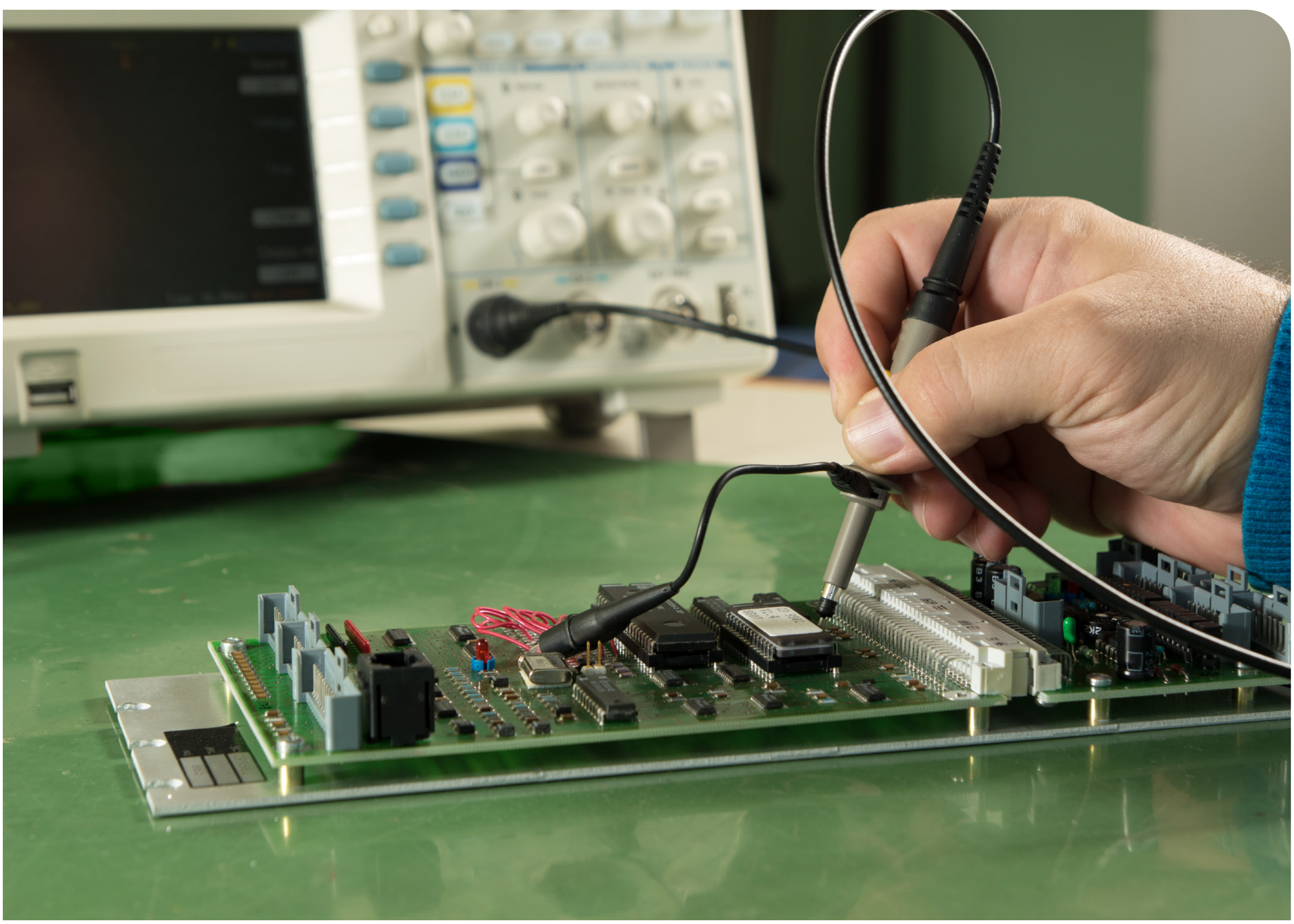
Modern devices are continuing a long-term trend of squeezing more electronics into smaller packages, while also increasing system performance, data rates and operating efficiency. Higher efficiencies are often achieved by implementing faster silicon MOSFETs or even faster eGaN FETs while size is reduced by increasing switching frequencies and replacing aluminum and tantalum capacitors with smaller ceramic devices. One result of this trend is that there is greater interaction between the disciplines of EMI, signal integrity (SI) and power integrity (PI).



TOP THREE EMI AND POWER INTEGRITY PROBLEMS WITH ON-BOARD DC-DC CONVERTERS AND LDO REGULATORS

INTRODUCTION

EMI is a measure of the electromagnetic emissions produced by the high-speed current and voltage signals the system creates. Power integrity is a measure of the power quality at the device that being powered. This means that the power supply voltages must be maintained within the allowable operating voltage range of high-speed devices.

Devices, such as modems, reference clocks and low noise amplifiers (LNAs) are all sensitive to noise on the power rails, which results in timing jitter, spurious responses reduced data channel eye openings, and degraded signal-to-noise ratio (SNR). This too, is a measure of power integrity.

The power supply itself is a noise source and the noise sources generated by the power supply must be kept from propagating through the system.

This article discusses the three most common causes of EMI and power integrity issues while providing tips for how to avoid or minimizes them in your design,

1. **Ringing** on switched waveforms causes broad resonant peaks in the emission spectrum.
2. **DC-DC converters generate noise** at the switching frequency, and because of high speed switching devices, can generate broadband switching harmonics well into the GHz.
3. **Power plane resonance** in DC-DC converter or LDO regulators due to high-Q capacitors resonating with power planes.

RINGING AND RADIATED EMISSIONS

Any ringing on the switched waveform (fairly common) can lead to broadband resonances in the resulting RF spectrum. Resonant frequencies resulting from DC-DC converters or low dropout (LDO) linear regulators can be as low as a few kHz while resonance due to the PDN with switching devices, such as MOSFET's can be in hundreds of MHz or higher.

The harmonic energy resulting from this switching is "captured" by the PDN and device resonances, evident as ringing in the time domain. The current and voltage of this ringing produces EMI. The magnitudes of the ringing and EMI are related to the quality factor (Q) and characteristic impedance of the resonance and the harmonic energy produced by the switching.

As an example, the switching waveform on a DC-DC buck converter demo board was measured with a Rohde & Schwarz RTE 1104 oscilloscope and Rohde & Schwarz RT-ZS20 1.5 GHz active probe (*Figure 1*).

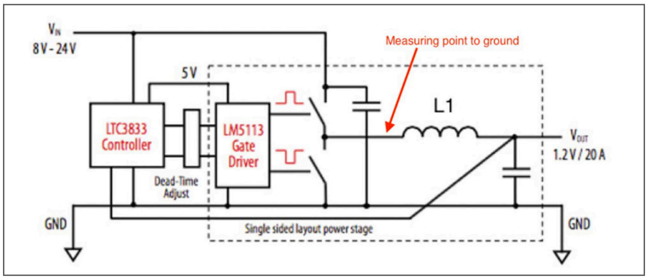


Figure 1. Diagram showing the measuring point at the switch device junction (on the left side of L1) to ground return.

There was a very large ringing superimposed on the switched waveform of 216 MHz. This can be seen clearly in *Figure 2*.

A Fischer Custom Communications F-33-1 current probe was used to measure both the input power cable common mode current (violet trace) and output load differential mode current (aqua trace). See *Figure 3*. Note the broad resonant peaks at 216 MHz (*marker 1*) and the second harmonic at 438 MHz (*marker 2*).

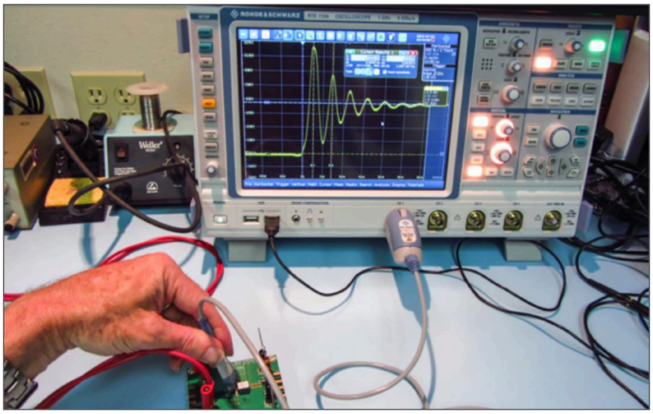


Figure 2. Measuring the rise time and ringing on a DC-DC converter. Notice to strong ringing at 216 MHz.

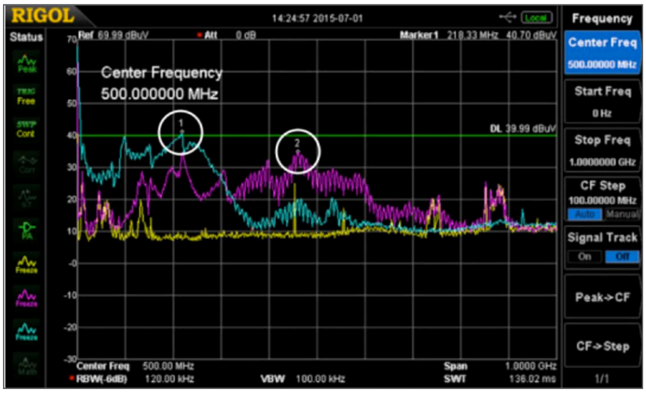


Figure 3. Resulting resonances from the 216 MHz ring frequency (marker 1) and second harmonic at 438 MHz (marker 2).

Remediation Tips - There are several ways to improve the design to minimize the resonances, ringing and therefore EMI. Since the energy is related to the switching frequency, rise time of the switching, characteristic impedance, and Q of the resonances, these factors are also the paths to mitigation.

- Slower edges will degrade operating efficiency but reduce high frequency energy
- Careful PCB design and capacitor selection will minimize the characteristic impedance and Q
- Keep traces short and wide and dielectrics thin.
- Keep all the switching circuitry on one side of the board, preferably with a thin dielectric to the respective ground return plane.
- Use of a snubber circuit, damping of resonances using controlled ESR capacitors, or redesign of the inductor for lower leakage inductance.

For additional detail on measuring ringing refer to *Reference 1*.

FAST EDGES CREATE BROADBAND NOISE AT GHZ FREQUENCIES

Today's on-board DC-DC converters use switching frequencies as high as 3 MHz. This is an advantage because it allows for physically smaller inductor and filter components, as well as increased efficiency. However, the fast edge speeds create broadband harmonic energy. The bandwidth of this harmonic energy is related to the voltage and current rise time. A 1ns edge speed can produce harmonic energy up to 3 GHz, or more.

These broadband harmonics are the cause of radiated emissions failures and also can affect the receiver sensitivity of any on-board telephone modems or other wireless systems, such as GPS. *Figure 4* shows how a typical DC-DC converter circuit can be characterized using an H-field probe connected to a spectrum analyzer.

It's also possible to connect the probe to an oscilloscope and hold it near each DC-DC converter to get some idea of the ringing, if any, without disturbing the circuit.

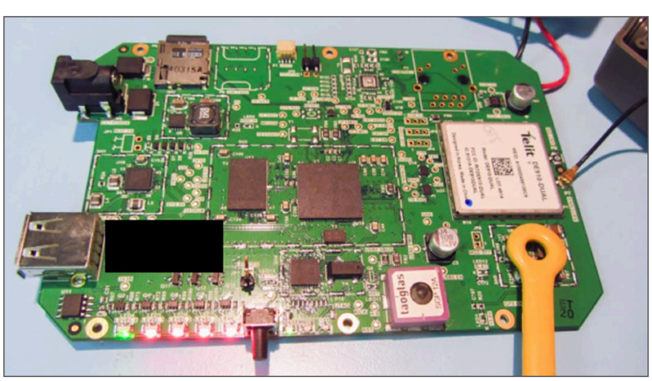


Figure 4. Probing DC-DC converter noise sources on a typical wireless device.

Figure 5 shows the resulting measurement of a couple DC-DC converters. The yellow trace is the ambient noise floor of the measurement system and is always a good idea to record for reference. The aqua and violet traces are the two converter measurements. Note that both produce broadband noise currents out to 1 GHz, with the convertor in violet out to beyond 1.5 GHz. Note the violet trace is 20 to 50 dB higher than the ambient noise floor.

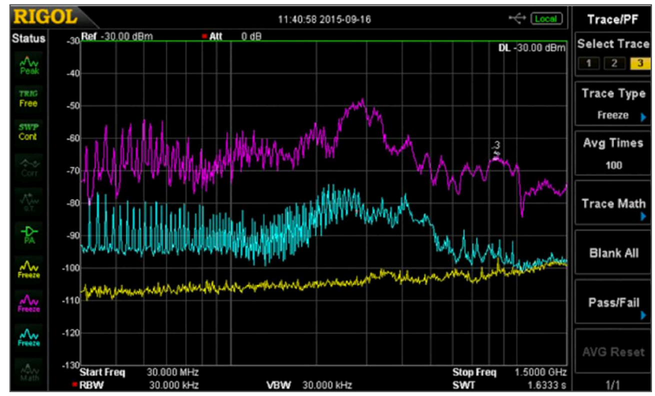


Figure 5 - In this example, we're looking from 30 MHz to 1.5 GHz to generally characterize the spectral emissions profile of a couple of on-board DC-DC converters. Both will potentially cause interference to mobile phone bands in the 700 to 950 MHz region. The one with the violet trace is over 30 dB above the ambient noise level in the mobile phone band.

Remediation Tips – To reduce the risk of self-interference to on-board mobile phone modems and wireless systems, the product design must start off with EMC in mind and with no corners cut.

This will consist of:

- A near perfect PC board layout
- Filtering of DC-DC converters
- Filtering of any high frequency device
- Filtering of the radio module
- Local shielding around high noise areas
- Possibly shielding the entire product
- Proper antenna placement

The PC board layout is critical and is where most of your effort should reside. An eight or ten layer stack-up will provide the most flexibility in segregating the power supply, analog, digital, and radio sections and provide multiple ground return planes, which may be stitched together around the board edge to form a Faraday cage. Care must be taken to avoid return current contamination between sections – especially in the ground return planes. For wireless products, the power plane for the radio modem section should be isolated (except via a narrow bridge) from the digital power plane. All traces to this isolated plane should pass over the bridge connecting the two. This can provide up to 40 dB of isolation between the digital circuitry and radio.

It is vital that the power and ground return planes be on adjacent layers and ideally 3-4 mils apart at the most. This will provide the best high frequency bypassing. All signal layers should be adjacent to at least one solid ground return plane. Clock, or other high-speed traces, should avoid passing through vias and should not change reference planes.

Power supply sections should be well isolated from sensitive analog or radio circuitry (including antennas). Be aware of primary and secondary current loops and their return currents. These return currents should not share the same return plane paths as digital, analog, or radio circuits. Remember that high frequency return currents want to return to the source directly under the source trace.

For more details on resolving DC-DC converter noise issues with wireless radio modems, refer to *Reference 2.*

PC BOARD PLANE RESONANCE AND THE EFFECT ON RADIATED EMISSIONS

Noise propagation in a simple system can be represented by three elements, the voltage regulator, the printed circuit board planes with decoupling capacitors (PDN) and the device being powered (load).

Each of these three elements is comprised of resistive, inductive and capacitive terms. Even "noise free" low dropout (LDO) regulators can be highly inductive (*Reference 3*). The resistive, inductive and capacitive terms can resonate amplifying the noise signals created by the power supply and the load as they travel across the PDN creating EMI. The harmonics of the switching frequency and the switch ringing discussed earlier excite these PDN resonances (*Reference 4*). As stated previously this noise can degrade and interfere with on-board wireless modems, as well as resulting radiated and conducted emissions.

A short video helps explain the basic principles of PDN design (*Reference 5*). The radiated EMI of a LTC3880 DC-DC converter measured near the input plane using an H-field probe is seen in *Figure 6*.

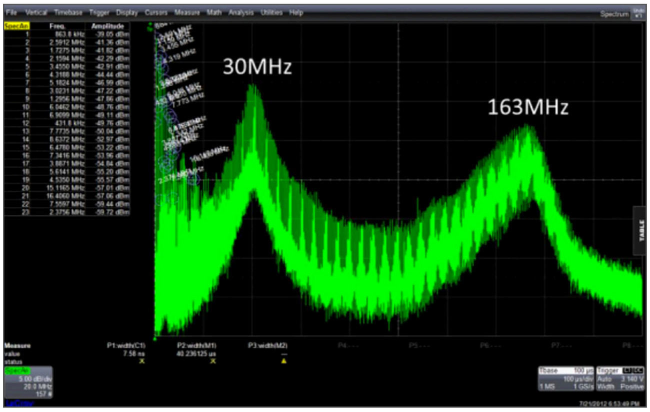


Figure 6. Spectrum analyzer display showing the 30 MHz and 160 MHz resonances detected near the input power connections of a DC-DC converter.

The 163 MHz is attributed to the ringing of the switches as seen in *Figure 7*. This ringing is caused by the inductance of the upper MOSFET bond wires, pins and circuit board planes, ringing with the lower MOSFET and PC board capacitance.

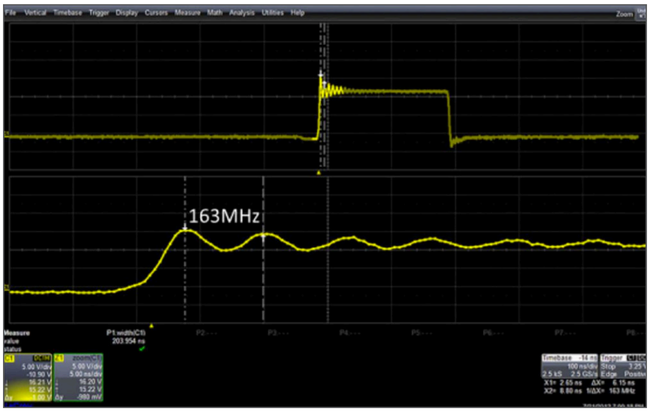


Figure 7. The 163 MHz EMI is easily explained by the ringing at the switch device, as discussed earlier.

The input ceramic decoupling capacitor resonates at approximately 30 MHz, as seen in *Figure 8* and results in the large 30 MHz EMI signature.

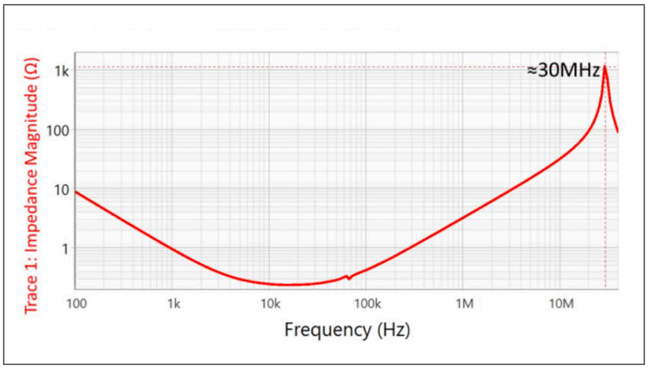


Figure 8. The larger 30 MHz emission is identified as a printed circuit board resonance using an H-field probe and confirmed by a 1-port reflection impedance measurement at the input capacitor.

The input power plane section of the DC-DC converter (measured in *Figure 6*) is shown in *Figure 9* with schematic representations of the component, PC board and external connections.

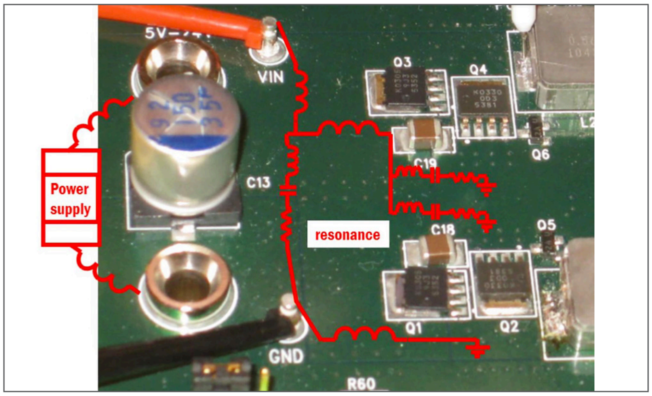


Figure 9. The power plane section of the DC-DC converter (measured in Figure 6) with schematic representations of the component, PC board and external connections.

A very simple simulation example can be used to illustrate these impedance resonance effects. Consider a simple DC-DC converter as shown in *Figure 10*.

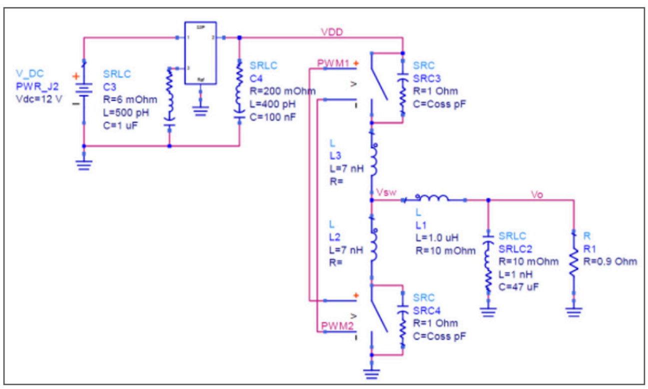


Figure 10. A simple DC-DC converter for illustration of plane resonance EMI. The "FET" switches include lead inductance and drain capacitance (Coss). A small PC board and two ceramic capacitors are included.

Designers frequently place the FET switches on one side of the board with power entry on the opposite side of the PC board. The small PC board plane used in this example has power entry through a pair of pins and no interconnect inductance is added to connect power to the PC board. A large 47 µF ceramic capacitor is placed on the top side of the PC board, while a smaller, 0.1 µF ceramic capacitor is placed very close to the FET switches on the bottom side of the PC board. Two parallel vias connect power and ground from the top side of the PC board to the bottom side as seen in *Figure 11*.

The simple model is used to simulate the harmonic current in the input connector, which is directly related to conducted and radiated emissions. Two simulations are performed; one with low ESR ceramic capacitors and the other with a lower Q controlled ESR ceramic replacing the 0.1 µF capacitor close to the FET switches. Both simulations are shown together in *Figure 12*.

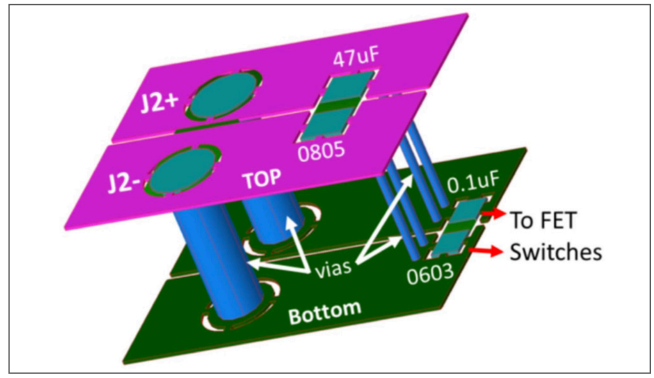


Figure 11. The large round pins on the left are the input power connector, J2. The larger capacitor on the top side is an 0805 sized 47 µF and the smaller capacitor on the bottom side is an 0603 sized 0.1 µF.

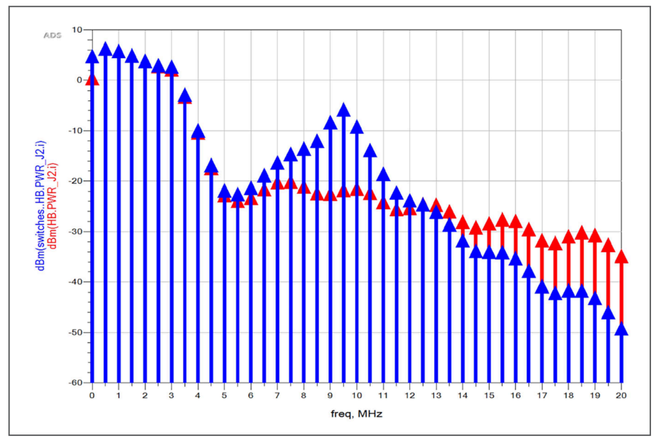


Figure 12. Spectral simulation of the input power lead shows the high Q ceramic (10 mΩ blue) has a clear peak near 10 MHz that is eliminated using a controlled ESR ceramic (200 mΩ red)

The simulated impedance, measured at the smaller capacitor in *Figure 13* shows the corresponding plane resonance with a clear 10 MHz peak using the high Q ceramic capacitor (blue) and the peak is eliminated using the controller ESR ceramic capacitor (red).

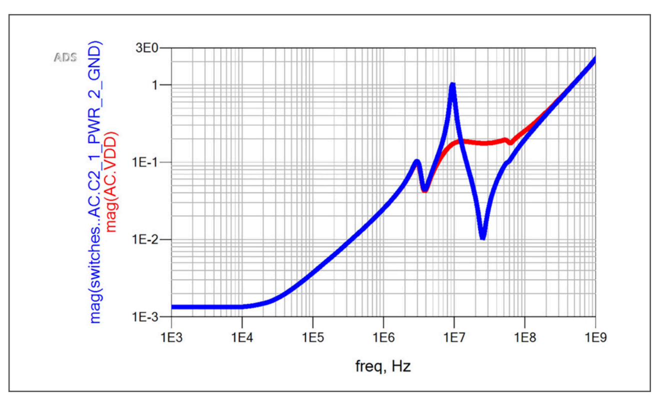


Figure 13. The simulated impedance at the 0.1 uF capacitor using high Q ceramic (10 mΩ blue) and a controlled ESR ceramic (200 mΩ red)

Remediation Tips – To minimize PDN resonances, the complete system of voltage regulator, PDN and the load need to be carefully balanced. Damping resistance must be included to eliminate or minimize the existence or Q of resonances. This will consist of:

- Short, wide power planes
- Keep the layout as small as possible to minimize inductance
- Thinner PC board dielectric layers, closer to the surface
- Incorporate EM simulation to identify and minimize PDN resonances
- Keep capacitors on one side of the PC board to the extent possible
- Low-Q or ESR controlled capacitors reduce Q
- Choose voltage regulators and output capacitors for good control loop stability
- Don’t place cutouts or holes in ground plane layers below the power plane
- Ferrite beads are a very common cause of PDN resonances
- Be aware of inductive interconnects bringing power to the system.

Printed circuit board design and decoupling is critical and “rules-of-thumb” generally don’t work well in high speed circuits. The design of the circuit board and capacitor decoupling always involves trade-offs, but the impacts on resonances need to be weighed carefully. A multi-frequency harmonic comb generator can be extremely helpful for quickly identifying PDN resonances (*Reference 3*).

SUMMARY

As you can see, designing DC-DC converters, LDOs, and PDNs with today’s high-speed technology nearly always requires careful circuit design, adequate filtering, simulation of the PDN, very careful circuit board layout, and use of controlled-ESR filter capacitors. Poor designs can result in:

- Ringing in power supply switches (or other fast-edged digital switching) resulting in associated radiated or conducted emissions resonant peaks at the ring frequency and harmonics.
- High frequency broadband noise well beyond 1 GHz, resulting in self-interference to radio modems.
- Poor stability and resonances in un-damped power distribution networks, leading to instability, spectral resonances, and associated radiated and conducted emissions.

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MILITARY & AEROSPACE EMC

SELECTING THE PROPER EMI FILTER CIRCUIT FOR MILITARY AND DEFENSE APPLICATIONS

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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.

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.

INTRODUCTION

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 CONFIGURATION

EMI line filers 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. 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.

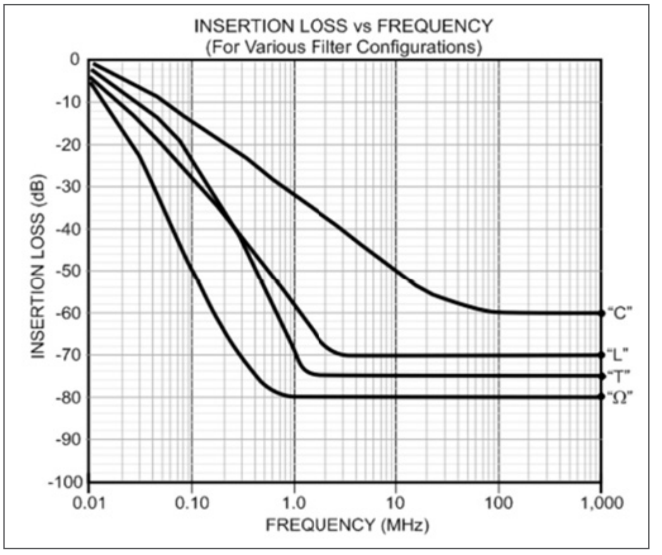

Figure 1. Insertion Loss vs Frequency Curves

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.

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 filer 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	300 kHz	1 MHz	10 MHz	100 MHz
16 dB	38 dB	75 dB	80 dB	80 dB

Based on a source and load impedance of 50 ohms, MILSTD-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:

C1 = .0769 µfd

L2 = 385 µHy

C3 = .0769 µfd

The theoretical MIL-STD-220 insertion for a "PI" filter of these values is as indicated below:

150 kHz	300 kHz	1 MHz	10 MHz	100 MHz
33 dB	51 dB	83 dB	>100 dB	>100 dB

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

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:

C1 = .70 µfd

L2 = 5 µHy

C3 = .7 µfd

The theoretical MIL-STD-220 insertion for this modified filter is:

150 kHz	300 kHz	1 MHz	10 MHz	100 MHz
25 dB	50 dB	83 dB	>100 dB	>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 passband. 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.

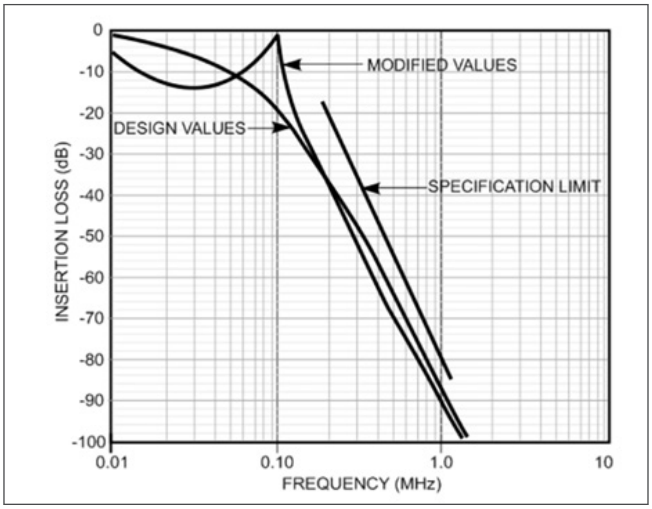

Figure 2. MIL-STD-220 insertion loss characteristics for ideal filter network and modified design compared to specification requirements.

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 filers 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.).

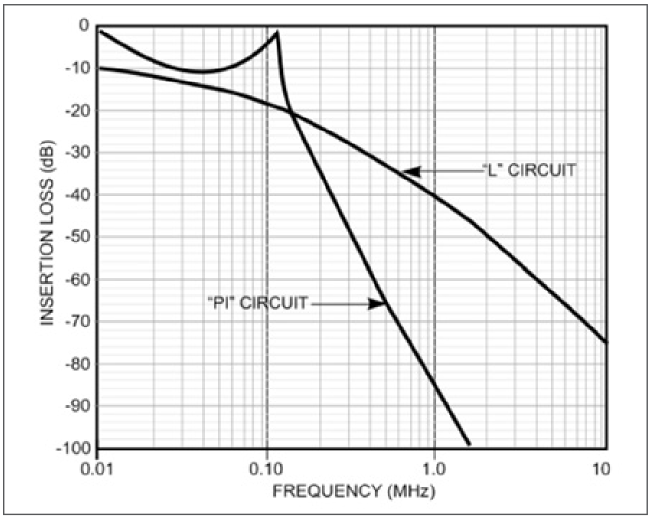

Figure 3. comparison of theoretical MIL-STD-220 50 ohm insertion loss of a "PI" filter and a "L" filter

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.

"PI" Circuit:

C1 = .70 µfd

L2 = 5 µHy

C3 = .70 µfd

"L" Circuit:

C1 = .70 µfd

L2 = 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.

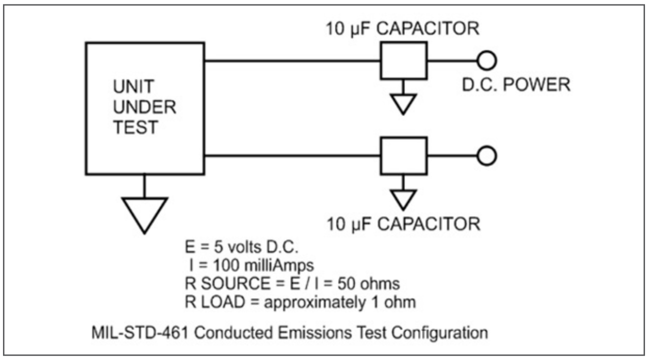

Figure 4. MIL-STD-461 Conducted Emissions Test Configuration

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.

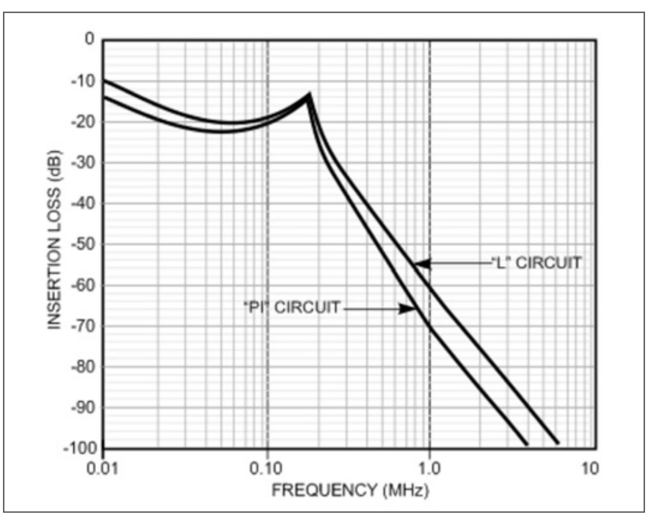

Figure 5. Performance of "L" and "PI" circuits for 50 ohm source and 1 ohm load

In the previous 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.

For more information about EMI Filters and Filter Connectors, please contact:

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Email: mmacbrair@wems.com

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/

CONFERENCE DIRECTORIES

AFCEA Events:
www.afcea.org/site/

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

ASD Events:
https://www.asdevents.com/shopcontent.asp?type=aero-space_defence

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

Defense Conferences:
www.defenseconference.com/

Global Edge (MSU):
www.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
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- RF/Microwave Aerospace and Defense Applications
- RF and Microwave Community

WHAT IS MIL-STD-461?

Quell Corporation

WHAT IS MIL-STD-461?

MIL-STD-461 has been the DoD standard for Electromagnetic Compatibility (EMC) qualification testing for many years, and has become the basis for many industrial and commercial applications. The standard has evolved since the initial issue was released more than 50 years ago, with many changes to the specific requirements and tests. Technology advances and issues with compatibility have spurred updates to the standard. The main goal, however, has been to provide a reasonable assurance that equipment's unintentional emission limits are managed, and that the devices are not vulnerable to interference from natural and machine-made electronic signals and noise.

MIL-STD-464 provides the system level requirements. This system document points to MIL-STD-461 as the standard for qualifying individual subsystems and equipment. The system requirements may impose tailored MIL-STD-461 requirements for the subsystem qualification to support a specific application. This indicates that MIL-STD-461 requirements support generic usage for equipment that serve most cases, and tailoring applies to unique cases. Even as a generic type of standard, many variances to support wide-spread applications are included.

The evolvement of MIL-STD-461 includes some significant milestones that the product developers have faced and how changes have affected their approach to designing control measures. Although MIL-STD-461 is a test standard, the requirements drive many design parameters to obtain compatibility.

Documentation has always been a key element of EMC test and evaluation programs. Three specific documents are identified in MIL-STD-461G under the umbrella of Data Item Descriptions (DIDs) as applicable to the EMC qualification.

Configuration Management is a key to standardization, as described in MIL-STD-461 for various applications. However, tailoring may be preferred where the test configuration conforms to the actual installation if the device is used for a specific purpose. Documentation of the test configuration should support being able to re-create the initial test.

The standard includes 19 test and evaluation methods that document the various test parameters, plus general requirements to document many of the test parameters.

These methods are:

- 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

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.

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 4 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	

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 usable 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*
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