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A COMPLIANCE HANDBOOK FOR ELECTRICAL AND ELECTRONICS ENGINEERS

2025 ANNUAL REFERENCE GUIDE


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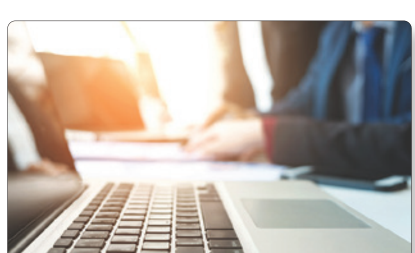
CONTENTS

IN COMPLIANCE
2025 Annual Reference Guide

continued on page 6

CONTENTS

IN COMPLIANCE
2025 Annual Reference Guide



CONTENTS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LETTER From the Editor

Dear In Compliance Community,

For compliance engineers, technical expertise combined with reliable reference materials forms the cornerstone of successful project completion. In an era where technology increasingly supports critical infrastructure, healthcare systems, and emergency communications, your work ensures these systems perform reliably when needed most. Each day brings unique challenges that require both foundational knowledge and current insights into evolving standards and methodologies.

Our 2025 Annual Reference Guide embodies this essential combination of technical depth and practical application. We've carefully selected articles that address the full spectrum of compliance engineering challenges, from EMC testing intricacies to critical product safety requirements. With the rise of high-speed digital interfaces and increasing device complexity, each piece has been chosen for its relevance to your daily work and its enduring value as a technical reference.

Inside these pages, your fellow engineers and industry experts share their knowledge and experience across emerging areas like wireless coexistence testing and multi-device EMC environments. They understand the challenges you face because they face them too. Their articles bridge theoretical foundations with practical applications, delivering comprehensive solutions across industry demands - whether managing complex test scenarios or implementing the latest standards requirements.

We've enhanced this edition with an expanded vendor directory and detailed company profiles to help you connect with the resources you need. As test requirements become more sophisticated and compliance demands more nuanced, having access to the right tools and expertise is crucial. While this special edition serves as your go-to reference, our digital platform at incompliancemag.com offers additional resources to support your work throughout the year.

Thank you for being part of our engineering community. Your dedication to excellence and precision in compliance engineering, especially as our industry adapts to rapid technological change, drives us to maintain the highest standards in delivering reliable technical information to support your important work.

Sincerely,

Lorie Nichols
Editor
In Compliance Magazine

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The EERC™

Electrical Engineering Resource Center

calculator

Antenna Factor and Gain Calculations

offered by A.H. Systems, Inc.

This handy online calculator simplifies antenna measurements by converting between Antenna Factor and Gain parameters. Simply input your frequency (MHz) and either the Antenna Factor or Gain value, and the calculator automatically computes the remaining values. Designed for 50-ohm systems, it's an essential tool for antenna engineers and EMC professionals.

application note

Near and Far Field Measurements with a Vector Network Analyzer

offered by COPPER MOUNTAIN® TECHNOLOGIES

For optimal performance in over-the-air RF systems, antennas must meet specific requirements. Performance parameters like size, wind-loading, environmental ruggedness, transmission pattern, bandwidth, and power handling capability should be considered. Methods of measuring the transmission (or reception) pattern which determines antenna gain with a VNA will be examined in this application note.

https://incompliancemag.com/EERC

IN THIS COMPETITIVE BUSINESS WORLD, EVERY LITTLE THING MAKES A BIG DIFFERENCE.

A.H. Systems, Inc.

When you think of Quality, Reliability, Portability, Fast Delivery, and Customer service, the first name that comes to your mind is A.H. Systems, Inc.

Every engineer wants a good deal. Especially when it comes to purchasing one or more antennas. But what exactly are they paying for? It isn't just getting the cheapest price for the antenna. It's what you get with that antenna that matters. What makes A.H. Systems better than the competition? We provide what really matters. In this competitive business world, every little thing makes a big difference.

QUALITY

A.H. Systems is proud to know it is providing the highest quality products available. Quality problems arising in various areas are to be identified and solved with speed, technical efficiency and economy. We focus our resources, both technical and human, towards the prevention of quality deficiencies to satisfy the organizational goal of "right the first time... every time."

RELIABILITY

We manufacture a complete line of affordable, reliable, individually calibrated EMC Test Antennas, Preamplifiers, Current Probes and Low-Loss, High-Frequency Cables. All Products are available directly from our facility in Chatsworth, CA and through our Distributors and Representatives worldwide. Our products keep on working, which enable us to give a 3-year warranty, the longest in our industry.

PORTABILITY

How many times have you purchased several antennas and then you forget what department has them or where they are? You discover parts are missing and the data is lost. You are now frantic because you have a scheduled deadline for your testing. At A.H. Systems we bring portability to a new level. We specialize in Portable Antenna Kits and provide many models covering the broadband frequency range of 20 Hz to 40 MHz. Excellent performance, compact size and a lightweight package make each Antenna Kit a preferred choice for field-testing. Loss and breakage are virtually eliminated because each component has a specific storage compartment in the carrying case. When testing out in the field or traveling, keep them all in one case. Travel made easy!

FAST DELIVERY

A.H. Systems provides next-day, on-time delivery for a fast turn around schedule to help minimize any down time the customer may be experiencing during testing. We maintain stock of all of our products and to satisfy frantic customers, we have orders shipped the "same-day."

CUSTOMER SERVICE

When you have a problem in the field during testing, you need fast answers to solve your problem. How many times have you called a company to speak to an engineer for a technical problem you are experiencing? And it takes many days to get a call back, let alone the answer to your problems. At A.H. Systems you get great personal service. A live person to talk to! We are here to assist customers with their EMC/EMI testing requirements. We try to solve your problems while you are experiencing them. Even before, during and after the Purchase Order. Our knowledge in EMC testing and antenna design enables us to offer unique solutions to specific customer problems. Not only do we solve your problems, we help you find the right antenna. Talking with our customers and hearing what they have to say enables us to provide better products, services and more options for our customers. Call us. We are here to make your problems, non-problems. For more information about our products visit our website at www.AHSystems.com.

ATEC: Where Quality Test Equipment Meets Reliable Rentals

Advanced Test Equipment Rentals (ATEC) offers over 40 years of experience renting, calibrating, and selling top-of-the-line test equipment to suit any desire. As an ISO 9001 Certified and ISO 17025 Accredited Organization, ATEC can support any Test & Measurement solution at the highest level of quality.

Comprehensive Rental Solutions

Browse through our vast rental inventory, which includes EMC equipment, power supplies, RF equipment and more. We provide customers with a plethora of options to solve even the most granular need.

For instance, if someone needed EMC testing equipment, we offer testing solutions that could perform any of the following test methods:

1. Radiated Immunity: Analyzes how electromagnetic energy can affect a device when it is in its usual environment.
2. Radiated Emissions: Measures the electromagnetic disturbance a device emits.
3. Conducted Immunity: A source will send electromagnetic energy to the DUT via cables or conductor to gauge the DUT's response.
4. Conducted Emissions: Measures the level of internal electromagnetic energy that a DUT may release by using a conductor to connect it to another system.

Serving Multiple Industries

The equipment in our inventory has been used in numerous industries including:

1. Aerospace and Defense: Equipment for avionics, electronic warfare, radar, and military testing to ensure mission-critical reliability in accordance to MIL-STD-461.
2. Automotive: Equipment used for testing components within any vehicle application for both immunity and emissions compliance to standards such as ISO 7637-2.
3. Telecommunications: RF test equipment designed to test 5G, wireless communication, and network infrastructure.
4. Medical: Equipment that validates compliance with medical standards such as IEC 60601-1.
5. Energy: Compliance testing to IEC 61000 standards such as IEC 61000-4-7 and 4-11 for power dips & interrupts and power quality analysis.

Calibration and Service

ATEC's calibration lab offers calibrations traceable to NIST standards, ensuring your equipment performs precisely and accurately. Additionally, we are proudly accredited to ISO 17025:2017 and able to provide high level calibrations for most EMC equipment. Rent or calibrate your equipment at our accredited lab and feel confident in your choice.

Your Test Equipment Resource

Our website contains hundreds of pages to inform readers about products, standards, industries, and more. If you have personalized questions, our knowledgeable sales representatives can help you find the right piece of test or measuring equipment to suit your needs.

Meeting Every Standard

We make sure the equipment you receive meets global standards, such as ISO, IEC, MIL-STD, and ANSI requirements. We stay up to date on meeting the standards that ensure quality rentals, even as they evolve over time.

Why Choose ATEC?

1. Extensive Inventory: Take advantage of our extensive catalog of equipment from leading manufacturers.
2. Flexibility: No need to worry about calibration or long-term commitment. If you rent our equipment, we'll take care of the rest.
3. Reliability: Rest assured; you will receive quality equipment any time you rent with ATEC.
4. Support: Tap into our wealth of test and measurement equipment knowlege to find the best product for you.

Call ATEC today for all your test and measurement equipment solutions!


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UNLOCKING **POSSIBILITIES**

APPLICATIONS OF HIGH POWER SOLID STATE AMPLIFIERS

When it comes to pushing the boundaries of technology and ensuring the reliability of electronic systems, high power solid state amplifiers play a pivotal role in many applications. Here's a glimpse into the diverse realms where these amplifiers are instrumental:

EMC IMMUNITY TESTING

Electromagnetic Compatibility (EMC) testing, immunity testing is performed across the automotive, medical, aeronautic, consumer goods and communications industries ensure that electronic devices can operate properly in the presence of electromagnetic interference (EMI). Amplifiers boost the intensity of electromagnetic fields to the desired level which the device under test (DUT) is exposed.

Typical requirements: *10 KHz-18 GHz (40 GHz) with CW and pulsed power up to 10 kW .*

BCI TEST (BULK CURRENT INJECTION)

Bulk current injection (BCI), where current is injected directly into cables and harness to simulate the EMI (electromagnetic interference) susceptibility a device might encounter with signals applied to power and communication lines. Amplifiers are used in these setups to boost the injected or conducted signals. For this application, amplifiers need to be able to provide the full power from very low impedances to very high impedances since DUT are never 50 Ω.

Typical requirements: *10 KHz-400 MHz with CW power up to 1kW.*

HIRF (High-Intensity Radiated Field) TESTING

HIRF testing involves specific modulation schemes or pulse characteristics to simulate several types of electromagnetic threats. HIRF is a crucial aspect of ensuring the electromagnetic compatibility and safety of electronic systems, particularly in the A & D industry. High-intensity electromagnetic fields are simulated to evaluate how well electronic systems, such as avionics, weapons and other critical components, can withstand and operate within such environments.

Typical requirements: *1-18 GHz with pulsed power up to 1MW and more.*

SCIENTIFIC APPLICATIONS

Scientific applications where precise control and manipulation of electromagnetic signals are necessary such as particle accelerators used in high-energy physics experiments. For these applications, amplifiers often need high linearity and high phase and amplitude stability.

Typical requirements: *very narrow bands amplifiers in the range of 1MHz to 3 GHz, with CW power from a few kW up to a few MW, as well as in pulsed mode.*

COMPONENT TEST

Component test setups with amplifiers generating interference signals, allowing engineers to assess how well communication components can tolerate and reject unwanted signals. This is crucial in ensuring reliability against interference in real-world environments. Filters, duplexers, and other frequency-selective components are tested with the amplifiers generating signals that allow engineers to characterize the performance of these components in terms of IMD, bandwidth, insertion loss, and rejection.

RF components, such as filters, attenuators, and cables are also tested. This involves measuring parameters like gain, noise figure, and distortion to ensure that components meet specifications.

Typical requirements: *In the .5 to 12 GHz segment, with CW power up to 1 kW.*

EW (ELECTRONIC WARFARE) JAMMING AND JAMMING SIMULATION

Electronic warfare systems to amplify the power of jamming signals to disrupting enemy communication and radar systems. Along with electronic countermeasures to amplify signals designed to deceive or neutralize enemy radar and communication systems.

Jamming simulation signals that reproduce the electronic interference and power levels created by hostile forces. Signals are directed toward the system under test to evaluate its ability to operate effectively in the presence of jamming.

Typical requirements: *20 MHz-10 GHz with CW or pulsed power up to a few kW*

EW (ELECTRONIC WARFARE) DESTRUCTION

As with EW jamming and jamming simulation, EW destruction involves generating high power levels to overpower and damage enemy radar and threats as well as assessing the resilience of electronic systems, vehicles, drones, aircraft and missiles to various destruction attack scenarios.

RADAR AND RADAR SIMULATION

Pulse and continuous (CW radar exist but are exceptional) wave amplifiers are used in radar systems helping/ allowing to boost the power of transmitted signals and improve the detection range, accuracy, surveillance and tracking radar enhancing target detection and tracking capabilities.

Radar simulators (versus Operating Radars) are used in laboratory to ensure that electronic devices can operate properly in the presence of electromagnetic interference (EMI). Amplifiers boost the intensity of electromagnetic fields to the desired level which the device under test (DUT) is exposed. (Simply as an EMC test procedure)

Typical requirements: *1-18 GHz with pulsed power from 5 kW up to 1 MW .*

IS YOUR ORGANIZATION PREPARED FOR THE NEW BATTERY CE MARKING REQUIREMENTS?

Batteries have an important role to play in the global push for sustainable power, but without adequate oversight, battery manufacturing can be very harmful to the environment. A new EU Battery Regulation, Regulation (EU) 2023/1542, adopted in July 2023, introduced new battery safety and sustainability rules. It represents a significant change in how battery manufacturers will need to evaluate battery products sold in the EU.

Regulation (EU) 2023/1542 aims primarily to reduce carbon emissions and promote the recyclability of battery materials, with mandates applying to a wide range of battery types. One noteworthy change is the requirement for CE marking on batteries sold in the EU. Although CE marking is already required for most electronics, previous battery directives have not included a CE marking requirement for batteries.

To display a CE mark, a product must meet various health, safety, and environmental standards, and ensuring compliance with these standards is the manufacturer's responsibility. Many manufacturers have their products assessed by a third-party laboratory like Element rather than relying on a self-assessment. Under previous regulations, battery manufacturers had some leeway to make their own decisions about safety testing and assessments, but the requirements of Regulation (EU)2023/1542 are more specific.

Key aspects of this regulation include:

- Battery Categories: It introduces specific categories such as portable, industrial, automotive, electric vehicle (EV), and light means of transport (LMT) batteries, each with distinct requirements.
- CE Marking: Starting August 18, 2024, batteries must have CE markings to indicate compliance with EU standards. In some cases, this process may involve a notified body.
- Battery Passport: Effective February 18, 2027, certain large batteries must be electronically registered with a battery passport containing a QR code and CE marking. Passports provide information about the battery's safety, sustainability, and recyclability.
- Carbon Footprint and Recycled Content: The regulation mandates that batteries' carbon footprints must be calculated, and sets recycled content targets for elements like cobalt, lead, lithium, and nickel, starting from August 18, 2024.
- Removability and Replaceability: Portable batteries should be easily removable and replaceable by end-users, while LMT, EV, and industrial batteries should be replaceable by independent professionals, effective February 18, 2027.
- Safety Testing (SBESS): Specific safety testing requirements for stationary battery energy storage systems (SBESS).
- Due Diligence: Producers must adopt a due diligence policy, establish management systems, assess supply chain risks, and devise strategies to address these risks, effective from August 18, 2025. Third-party verification by a notified body is required.
- Recycling and Material Recovery Targets: The regulation sets efficiency targets for recycling and material recovery for specific elements, applicable from December 31, 2027.
- Information and Labeling: Enhanced labeling requirements include a battery passport, specific product labeling, electronic databases, and second-life data sets to improve information and traceability.
- Shipment of Waste Batteries: The regulation covers the shipment of waste batteries outside the EU.
- Reporting Obligations: Various reporting obligations are introduced, with specific deadlines for implementation phased in from 2024 to 2028.

Because different batteries have different requirements, this regulation will have varying impacts on individual manufacturers. Different aspects of the regulation also have different effective dates or deadlines. A third-party testing partner can help you understand how this and other new regulations will affect you, providing additional certainty that your products are compliant. The experts at Element have the regulatory expertise to help manufacturers evaluate, test, and certify batteries for their intended markets. If you have questions about battery requirements and how they apply to you, reach out today.

element

Synchronized Multiprobe Systems For Reverberation Chambers And Beyond

LUMILOOP GmbH

LUMILOOP GmbH is a German manufacturer of laser-powered electronic sensors. These are used wherever other systems are disturbed by high voltages and currents or electric and magnetic fields: in electromagnetic compatibility (EMC) and high-frequency (HF) measurement environments, near lightning conductors and high-voltage lines, or where there is a risk of explosion.

LUMILOOP's key competence is the optical supply of sensor systems using lasers. In combination with patented opto-electronic components and the patented process for controlling optical power, reliable, safe measuring systems are created.

LUMILOOP combines this Power-over-Fiber (PoF) technology with a state-of-the-art low-power electronic design.

What Is A Reverberation Chamber?

A Reverb is a metallic chamber with reflecting walls. The RF power signal is fed via a transmitting antenna.

To overcome a static field distribution (standing waves), the geometrical properties are changed. Common methods are rotating metal stirrers, a moving rigid wall, or flexible walls made from conductive fabric.

Stirring creates a statistical distribution of field strengths and vectors. Simplified, your DUT gets exposed to “all” field strengths from “all” directions.

Why Is Everyone Talking About It?

Most of the RF power is reflected, so even low power amplifiers can generate high field strength. Reverb chambers offer low investment and operational cost combined with high speed testing.

What’s The Challenge?

The key question is: how much RF power do I need to put in to get the desired electric field strength at my DUT? And how is the target field strength defined if it is changing all the time?

The Traditional Solution

IEC 61000-4-21 describes how to calibrate the empty chamber before testing. The resulting fixed RF power per frequency works as long as the DUT is small and not too reflective. This calibration can easily take one week, and there is still uncertainty about how the DUT influences field distribution.

If you are required to perform this kind of calibration, LUMILOOP will accelerate it dramatically. By running fast hardware-synchronized frequency sweeps on a signal generator, a LSPM RF power meter and an LSProbe electric-field probe, calibration time can go down to 30 minutes!

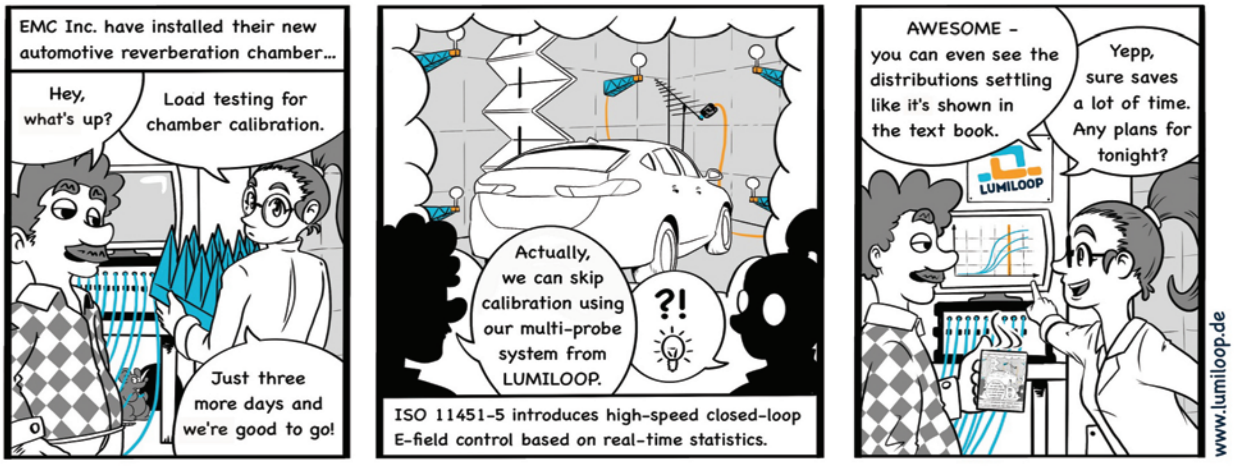
The Modern Solution

ISO11451-5:2023 eliminates the need to calibrate the reverb. It defines real-time closed-loop field strength control, based on statistics from 8 E-field probes. Target field strength is defined by a cumulative distribution function (CDF).

Sounds complicated? LUMILOOP makes this super easy to operate and integrate!

LUMILOOP delivers LSProbe Multiprobe Systems since 2016. ISO11451-5 is based on hardware-synchronized data, collected with several LSProbe systems.

LUMILOOP’s software evaluates standard-compliant statistics for over 8+ probes, with up to 6 antennas and 500 kSample/s each, in real time! It’s as easy as querying one CDF threshold per frequency.



SPECTRUM CONTROL™

Trusted Solutions from the Industry Leader

When it comes to protecting against electromagnetic interference (EMI), Spectrum Control is not just a manufacturer, we are the premier source for EMI troubleshooting, solutions, and compliance. With over five decades of industry leadership, Spectrum Control combines unparalleled engineering expertise, cutting-edge innovation, and advanced manufacturing capabilities to deliver solutions that redefine performance and reliability.

Proven Expertise

Since 1968, Spectrum Control has been at the forefront of EMI filter technology, serving multiple industries with groundbreaking solutions. Our dedicated team of engineers leverages sophisticated simulation tools and exhaustive in-house testing to ensure every product not only meets but exceeds functional and compliance standards.

Innovation that Drives Results

Our commitment to research and development ensures that we stay ahead of the curve. Spectrum Control continues to introduce advanced solutions, such as:

Dual Line EMI Filters: Reducing weight and space by 50%, these filters offer unmatched performance for AC/DC systems.

EMSEC Power Filters: Protecting data with a space-saving design that eliminates conducted EMI emanations.

Power Line Connectors: Compact connectors replace bulky EMI box filters without compromising performance.

Space-Grade EMI Filters: Tailored for military and aerospace applications, using high-grade materials to meet stringent standards.

A Comprehensive, Customizable Portfolio

Whether your EMI challenge lies at the power source, chassis, I/O connection, barrier wall, or PCB, Spectrum Control offers the most extensive product range in the industry. Our portfolio includes glass- and resin-sealed filters, filtered connectors, filter plates, and custom designs to meet your exact needs.

Vertical Integration for Superior Quality and Shorter Delivery Times

Spectrum Control's vertically integrated, U.S.-based manufacturing ensures every critical component, from ceramic substrates to final assemblies, meets the highest quality standards. This approach reduces lead times and enhances reliability, giving our customers a competitive edge.

- To help you minimize risk, reduce total costs, and meet your delivery commitments, rely on our specialized expertise in ceramic component handling and soldering to deliver complete assembled and tested solutions
- We provide fully assembled and tested components, ready for you to install

Trusted by Innovators Worldwide

Leading organizations trust Spectrum Control to solve complex EMI challenges. From off-the-shelf products to fully custom solutions, our engineering-driven approach ensures optimal results for every application.

When you partner with Spectrum Control, you gain a trusted ally committed to delivering innovative, high-performance EMI protection solutions tailored to your specific needs.


EMI PROTECTION
Take Control.
Partner with Spectrum Control to address EMI problems and pass EMC tests
Spectrum Control is the leader in EMI protection, providing innovative EMI/EMC solutions since 1968.
Broad range of filtering products from components to assemblies; from board to panel to chassis
Standard and custom solutions
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Capacitor Impedance Evaluation from S-Parameter Measurements

Part 2: S_{21} Two-Port Shunt and Two-Port Series Methods

By Bogdan Adamczyk, Patrick Cribbins, and Khalil Chame

This is the second of two articles devoted to the topic of capacitance impedance evaluation from the *S* parameter measurements using a network analyzer. The previous article [1] described the impedance measurements and calculations from the S_{11} parameters using the one-port shunt, two-port shunt, and two-port series methods. This article is devoted to the impedance measurements and calculations from the S_{21} parameters using the two-port shunt and two-port series methods.

TWO-PORT SHUNT METHOD

The two-port configuration for a two-terminal DUT is shown in Figure 1.

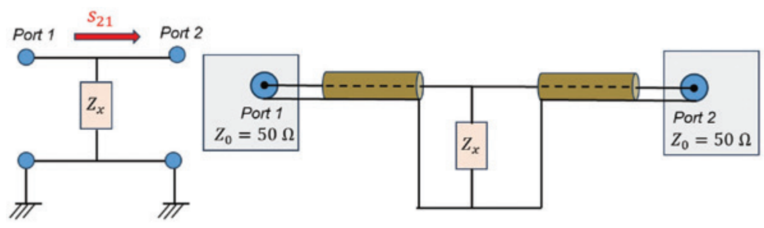

Figure 1: Two-port shunt configuration

Figure 2 shows the transmission line circuit model of this configuration.

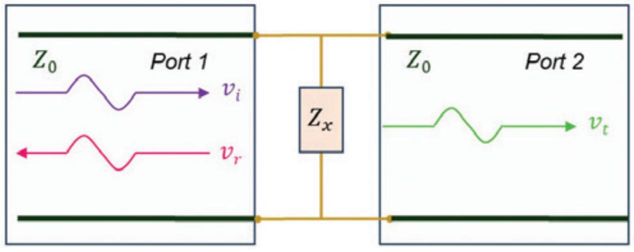

Figure 2: Transmission line circuit model of two-port shunt configuration

The network analyzer sends the incident waves, v_i, (at different frequencies) from Port 1 to Port 2. Between the ports, there is a shunt discontinuity, Z_x. Upon the arrival at the discontinuity, the incident waves get reflected and transmitted.

The reflection coefficient at the discontinuity was derived in [1, Eq. (13)] as

$$\Gamma = -\frac{Z_0}{2Z_x + Z_0} \tag{1}$$

The transmission coefficient at the discontinuity, which is equal to s_{21}, is related to the reflection coefficient by

$$T = 1 + \Gamma \tag{2}$$

Dr. Bogdan Adamczyk is professor and director of the EMC Center at Grand Valley State University (http://www.gvsu.edu/emccenter) where he performs EMC educational research and regularly teaches EM/EMC courses and EMC certificate courses for industry. He is an iNARTE-certified EMC Master Design Engineer. He is the author of two textbooks, "Foundations of Electromagnetic Compatibility with Practical Applications" (Wiley, 2017) and "Principles of Electromagnetic Compatibility: Laboratory Exercises and Lectures" (Wiley, 2024). He has been writing "EMC Concepts Explained" since January 2017. He can be reached at adamczyb@gvsu.edu.

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Thus

$$s_{21} = 1 - \frac{Z_0}{2Z_x+Z_0} \quad (3)$$

or

$$s_{21} = \frac{2Z_x+Z_0-Z_0}{2Z_x+Z_0} \quad (4)$$

leading to, [2],

$$s_{21} = \frac{2Z_x}{2Z_x+Z_0} \quad (5)$$

Eq. (5) is now solved for Z_x in terms of S_{21}.

$$s_{21}(2Z_x + Z_0) = 2Z_x \quad (6)$$

or

$$2Z_x s_{21} + Z_0 s_{21} = 2Z_x \quad (7)$$

$$Z_0 s_{21} = 2Z_x - 2Z_x s_{21} \quad (8)$$

$$Z_0 s_{21} = 2Z_x(1 - s_{21}) \quad (9)$$

resulting in

$$Z_x = Z_0 \frac{s_{21}}{2(1-s_{21})} \quad (10)$$

TWO-PORT SERIES METHOD

The two-port series configuration for a two-terminal DUT is shown in Figure 3.

For this two-port series configuration, we will use the circuit theory (not the transmission line theory) and the two circuit models shown in Figure 4.

Voltage at port 2, V_{L1}, (with $Z_x = 0$, is obtained from the voltage divider as

$$V_{L1} = \frac{Z_0}{Z_0+Z_0} V_G = \frac{V_G}{2} \quad (11)$$

Voltage at port 2, V_{L2}, (with $Zx \neq 0$, is obtained as

$$V_{L2} = \frac{Z_0}{Z_0+Z_x+Z_0} V_G = \frac{Z_0}{2Z_0+Z_x} V_G \quad (12)$$

The s_{21} parameter is determined from

$$s_{21} = \frac{V_{L2}}{V_{L1}} \quad (13)$$

Thus,

$$s_{21} = \frac{\frac{Z_0}{2Z_0+Z_x} V_G}{\frac{V_G}{2}} \quad (14)$$

or

$$s_{21} = \frac{2Z_0}{2Z_0+Z_x} \quad (15)$$

Eq. (15) is now solved for Z_x in terms of S_{21}.

$$s_{21}(Z_x + 2Z_o) = 2Z_0 \quad (16)$$

or

$$Z_x s_{21} + 2Z_0 s_{21} = 2Z_0 \quad (17)$$

$$2Z_0 - 2Z_0 s_{21} = Z_x s_{21} \quad (18)$$

$$Z_x s_{21} = 2Z_0(1 - s_{21}) \quad (19)$$

resulting in

$$Z_x = 2Z_0 \frac{1-s_{21}}{s_{21}} \quad (20)$$

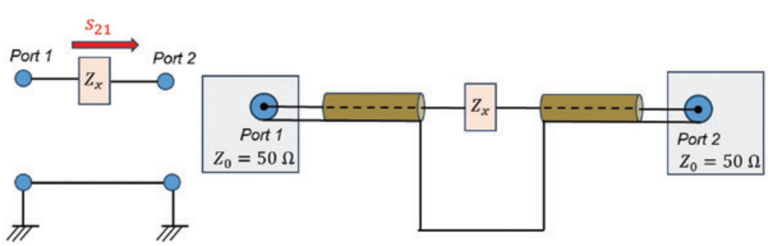

Figure 3: Two-port series configuration

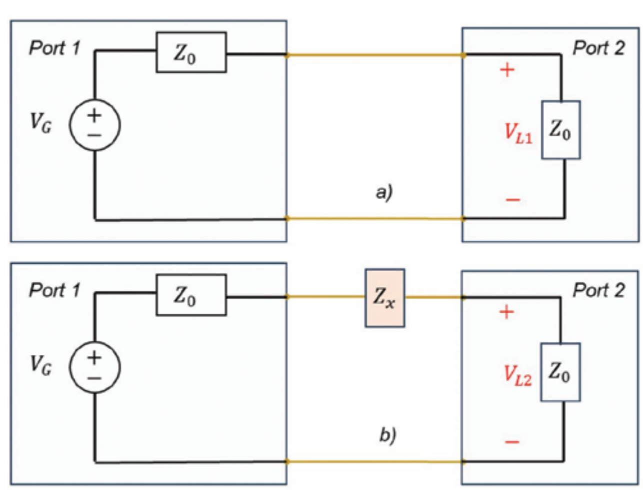

Figure 4: Transmission line circuit models of two-port series configuration: a) $Z_x = 0$, b) $Z_x \neq 0$

IMPEDANCE MEASUREMENT SETUP AND RESULTS

The impedance measurement setup and the PCB boards are shown in Figure 5. The boards were populated with Murata X7R ceramic capacitors, GCM188R71H472KA37, GCM188R71H473KA55, GCM188R71C474KA55, of the values 4.7 nF, 47 nF, and 470 nF, respectively.

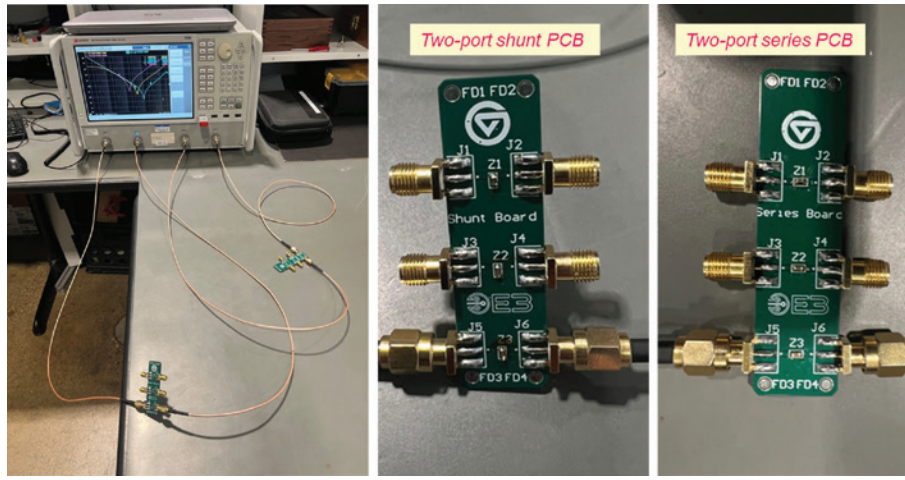

Figure 5: Measurement setup and PCBs

Impedance curves (obtained from the S_{21} parameter measurements) for a 4.7 nF capacitor are shown in Figure 6.

Figure 7 shows the capacitor impedance curve obtained from the Murata Design Support Software "SimSurfing" [4].

The two-port series, two-port shunt, and Murata measurements at 0 dB and self-resonant frequencies for a 4.7 nF capacitor are shown in Table 1.

It is apparent that the two-port shunt measurements, at 0 dB and self-resonant frequencies, are significantly closer to the Murata results, than the two-port series measurements.

Impedance curves for a *47 nF* capacitor are shown in Figure 8.

Figure 9 shows the Murata impedance curve.

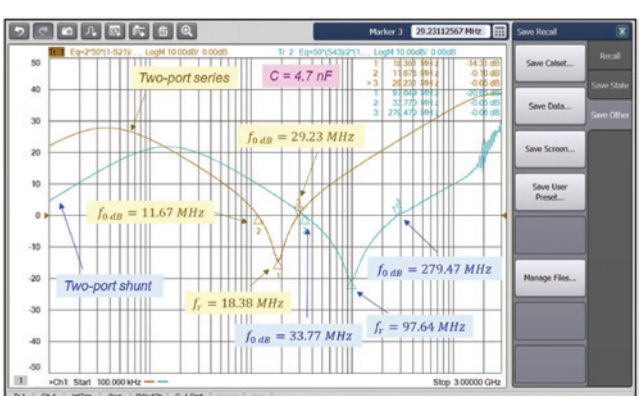

Figure 6: S_{21}-based impedance curves - two-port series (Eq. 20) vs. two-port shunt (Eq. 10)

The two-port series, two-port shunt, and Murata measurements at 0 dB and self-resonant frequencies for a 47 nF capacitor are shown in Table 2.

Again, the two-port shunt measurements, at 0 dB and self-resonant frequencies, are significantly closer to the Murata results than the two-port series measurements.

Impedance curves for a *470 nF* capacitor are shown in Figure 10.

Figure 11 shows the Murata impedance curve.

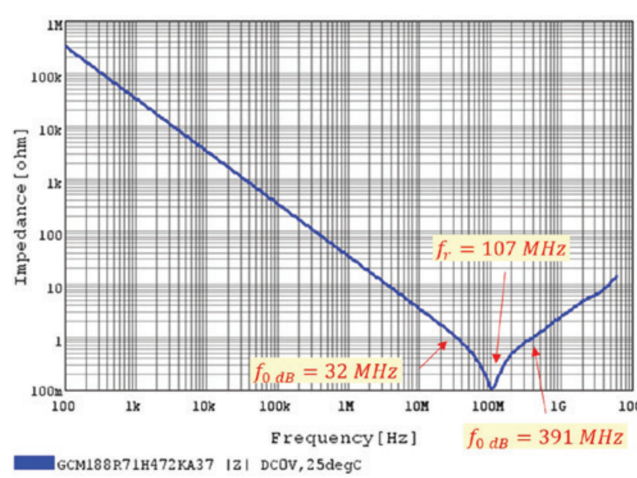

Figure 7: C = 4.7 nF, Murata "SimSurfing" impedance curve

Frequency	Two-port series	Two-port shunt	Murata
1st 0 dB	11.67 MHz	33.77 MHz	32 MHz
Self-Resonant	18.38 MHz	97.64 MHz	107 MHz
2nd 0 dB	29.23 MHz	279.47 MHz	391 MHz

Table 1: C = 4.7 nF, Impedances at 0 dB and resonant frequencies

The two-port series, two-port shunt, and Murata measurements at 0 dB and self-resonant frequencies for a 470 nF capacitor, are shown in Table 3.

Once again, the two-port shunt measurements, at 0 dB and self-resonant frequencies, are significantly closer to the Murata results, than the two-port series measurements.

The overall conclusion is that the two-port shunt method is the most accurate method for the capacitor impedance evaluation from S_{21} parameter measurements.

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1. Bogdan Adamczyk, Patrick Cribbins, and Khalil Chame, "Capacitor Impedance Evaluation from S Parameter Measurements – Part 1: S_{11} One-Port Shunt, Two-Port Shunt, and Two-Port Series Methods," *In Compliance Magazine*, February 2025.
2. Keysight Application Note, *Impedance Measurements of EMC Components with DC Bias Current.*
3. Microwaves & RF Application Note, *Make Accurate Impedance Measurements Using a VNA.*
4. Murata Design Support Software "SimSurfing."

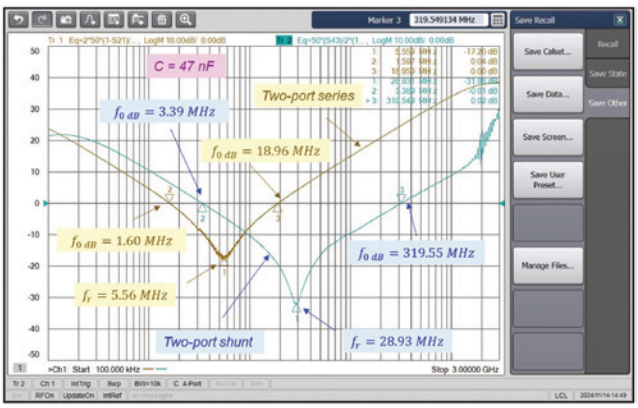


Figure 8: S_{21}-based impedance curves - two-port series (Eq. 20) vs. two-port shunt (Eq. 10)

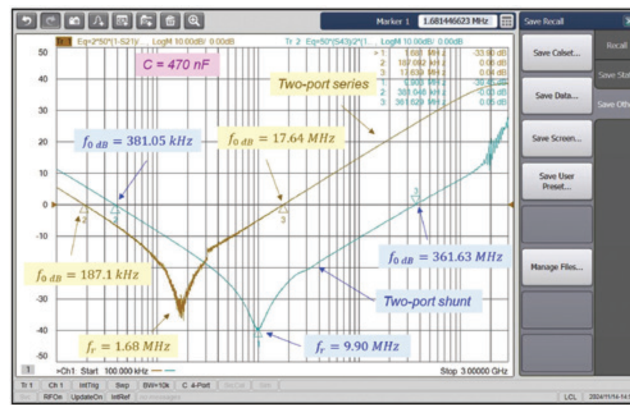


Figure 10: S_{21}-based impedance curves - two-port series (Eq. 20) vs. two-port shunt (Eq. 10)

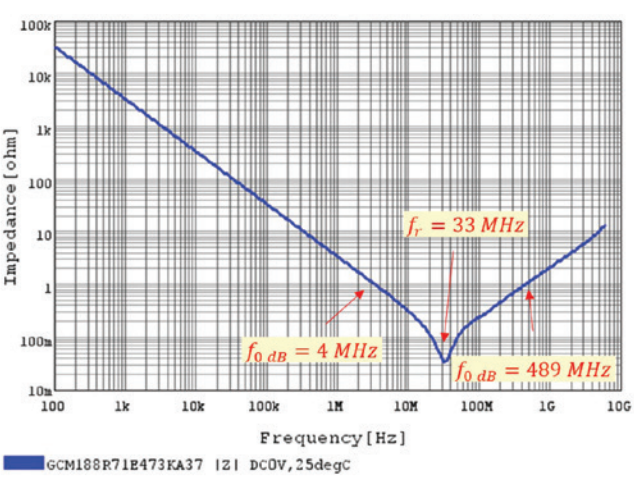


Figure 9: C = 47 nF, Murata "SimSurfing" impedance curve

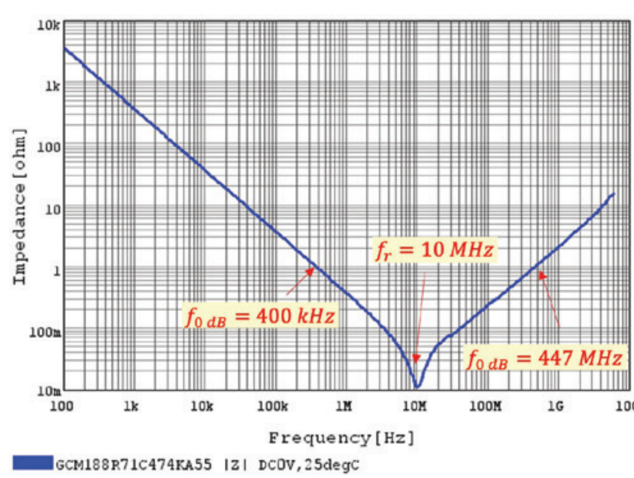


Figure 11: C = 470 nF, Murata "SimSurfing" impedance curve

Frequency	Two-port series	Two-port shunt	Murata
1st 0 dB	1.6 MHz	3.39 MHz	4 MHz
Self-Resonant	5.56 MHz	28.93 MHz	33 MHz
2nd 0 dB	18.96 MHz	319.55 MHz	489 MHz

Table 2: C = 47 nF, Impedances at 0 dB and resonant frequencies

Frequency	Two-port series	Two-port shunt	Murata
1st 0 dB	187.1 kHz	381.05 kHz	400 kHz
Self-Resonant	1.68 MHz	9.90 MHz	10 MHz
2nd 0 dB	17.64 MHz	361.63 MHz	447 MHz

Table 3: C = 470 nF, Impedances at 0 dB and resonant frequencies

Understanding ESD Control

Part 2: ESD Prevention

Dr Jeremy Smallwood on behalf of EOS/ESD Association, Inc.

In Part 1, we looked at charge generation and dissipation and how this leads to specifying a maximum resistance to ground R_g to control electrostatic charge buildup. Charge is stored in the capacitance C and, at the same time, dissipates away through R_g.

In Part 2, we look at the discharge path when electrostatic discharge (ESD) occurs and applying our understanding in ESD controls.

In our simple circuit, the components to the left of the vertical dotted line represent the ESD source capacitance C and its internal resistance Rs. Stored charge in C represents stored energy ready to dump into ESD. Most ESD sources are charged isolated conductors. IEC 61340-5-1 and ANSI/ESD S20.20 consider these to be conductors with resistance R_s less than 10 kΩ and resistance to ground R_g greater than 1000 MΩ. These might be metal or other low resistance items or a charged person.

Now, we will consider what happens when the stored charge can discharge as ESD into an external circuit (to the right of the dashed line) containing a victim ESDS. We have a charged capacitance C, which will discharge through the source series resistance R_s into the external circuit through the device resistance R_d and resistance of the external discharge path (R_{dp}).

For ESD to occur, two criteria must be fulfilled:

- The source capacitance C must have sufficient charge and voltage difference with the ESDS to cause ESD.
- The source must either contact or be close enough to the ESDS for discharge to occur.

If either of these cannot happen, we cannot get potentially damaging ESD. Eliminating either makes a good contribution to preventing ESD risk!

If we connect a low resistance R_g so that little or no voltage is produced on C under normal conditions, we can eliminate the risk of ESD from this source. This is "grounding". The resistance from the item to ground, R_g, can be surprisingly high and still give effective grounding because the charging current is very low. Resistance to ground R_g up to 1000 MΩ is often used. The ground connection is always taken to a common connection ground conductor so that the voltage on all grounded items is the same – this is equipotential bonding. No voltage difference means no possibility of ESD. It is not necessary (but is often desirable) to also connect to physical earth. The equipotential bonding principle would equally work on the space station where no physical ground connection would be possible.

When ESD occurs, current flows through the external circuit and device is limited by the combined resistances of the source, ESDS, and discharge path $R_s + R_d + R_{dp}$. It's worth noting that the energy released into the ESD is dissipated in each resistance according to its resistance value, the largest resistance dissipating the greatest portion of the ESD energy.

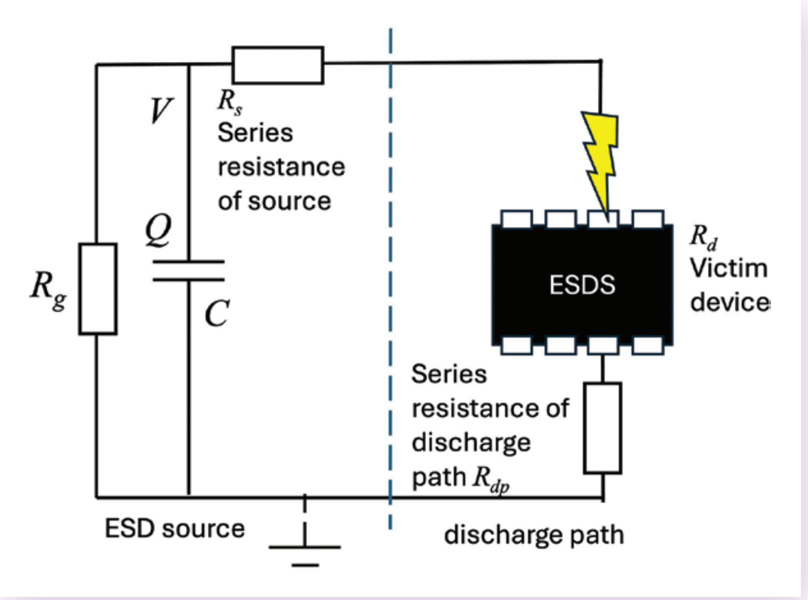
If R_s and R_{dp} are very low resistance (e.g., metal item ESD source and ESDS on a metal tray), the peak ESD current in the discharge can be high, more than tens of amps for a source voltage of even 100 V. ESDS are often susceptible to damage from even short duration high current ESD.

If the ESD source is a person, the source resistance R_s is body resistance and might be of the order 1500 Ω, which would limit the ESD current to around 67 mA for a 100 V source voltage. If we add additional resistance in the discharge path R_{dp}, say 1 MΩ, in a bench mat

Dr. Jeremy Smallwood has worked in electrostatics and ESD control since the late 1980s. He formed Electrostatic Solutions Ltd. in 1998 to provide electrostatics consultancy, training, and R&D services for industry and works with British and IEC standards Committees. His book "The ESD Control Program Handbook" was published by Wiley in 2020.

surface, the peak ESD current could be reduced to about 100 µA, which would be unlikely to give ESD damage.

If R_s and R_{dp} are low resistance compared to the device, all the energy stored in C is dissipated in the device. If they are larger than the resistance of the device, the discharge current is limited, and much of the stored energy is dissipated in these resistances rather than in the device. Resistance in the discharge path has a protective effect. This is particularly true for charged device ESD, where the device itself forms the charged isolated conductor ESD source. A minimum resistance is often specified for a surface which will contact ESDS.



ESD CONTROL IN THE EPA

The principles of ESD control that come out of this discussion are surprisingly simple. Looking around the EPA, we can see many ESD control items designed according to these principles:

- Replace insulators with conductors or static dissipative materials and connect them to common point ground.
- Where possible, ground conductors that might contact the ESDS.
- Always ground personnel who handle ESDS.
- Where necessary, limit voltage differences between isolated conductors and any ESDS that they might contact
- Prevent discharges between ESDS and metal items - Provide resistive contact materials to limit ESD current.

Anything which stands on an ESD control floor may be grounded through it, if designed to do so. Chairs, trolleys, carts, and racks can be grounded through conducting feet or wheels in contact with the floor. Beware that good electrical contact is often prevented by incompatible contacting materials or by dirt buildup.

In the case of personnel, grounding might be done with a wire (wrist strap) connecting the body to ESD earth. Alternatively, make a connection through the ESD control footwear and floor.

Static dissipative bench surfaces provide an intermediate resistance surface that limits the ESD current when a charged ESDS is placed upon the surface. It will also dissipate charge from ESD control tools, tote boxes, or other portable items that are placed upon them, bringing them safely down to zero volts.

ESD control items often act as a system, such as a person grounded through their ESD control footwear and floor. Another case is a hand-held tool. An ordinary tool might have insulating handles, making the metal parts of the tool into isolated conductors that are likely to become charged and a source of ESD. For an ESD control tool, the insulating parts are replaced by static dissipative material, allowing charge to dissipate from the tool to the user's grounded hand. If the user must wear gloves, these must be made of static dissipative material to maintain the ground path from the tool through to the hand.

Understanding how ESD risks arise and can be controlled allows us to focus our resources on developing and implementing an effective ESD control program.

REFERENCES AND FURTHER READING

1. International Electrotechnical Commission, *Electrostatics – Part 5-1: Protection of electronic devices from electrostatic phenomena - General requirements*, IEC 61340-5-1
2. ESD Association, *ESD Association Standard for the Development of an Electrostatic Discharge Control Program for – Protection of Electrical and Electronic Parts, Assemblies and Equipment (excluding Electrically Initiated Explosive Devices)*, ANSI/ESD S20.20-2021.
3. Smallwood J. M., *The ESD Control Program Handbook*, Wiley ISBN 978 1 118 31103-5, 2020.

EMC BENCH NOTES

Troubleshooting with RF Current Probes

By Kenneth Wyatt

In " Interpreting Emissions Using a Near-Field Probe" (February 2025), we showed how to use near-field probes to characterize and interpret dominant harmonic energy sources on PC boards. This time, we'll discuss a more advanced troubleshooting tool for assessing radiated emission issues, the RF current probe. These are most useful for measuring RF common mode harmonic currents on cables.

I suspect most product designers are familiar with the smaller current probes designed for oscilloscopes or digital multimeters (DMMs). These typically have smaller apertures that fit a wire or small cable and generally extend from DC to 100 MHz at best. There are also current probes for electrical measurements with larger apertures that range up to only a few MHz and are really designed for mains frequencies.

RF current probes usually have a hinged aperture that can accept everything from a single wire to large-diameter cables (Figure 1). When their 50Ω port is connected to a spectrum analyzer, you'll observe an RF spectrum similar to that when using a near-field probe. Many manufacturers make these probes, but for this article, we'll use the affordable Tekbox Model TBCP2-30k400 ($679). See Reference 1.

Various harmonic energy sources on your circuit boards or system can couple to attached cables and are the main causes of radiated emissions from products. We'll use the RF current probe to characterize and reduce these coupled RF currents by clamping it around each I/O and power cable (Figure 2). The typical RF current probe is sensitive enough to measure µA of RF current, and only 6 to 8 µA of harmonic current can fail the FCC class B limit.

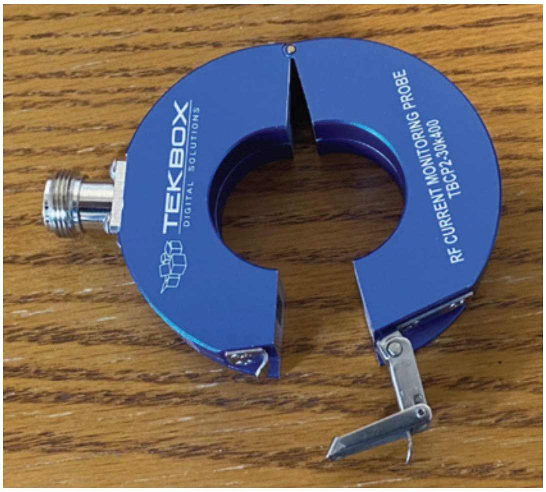


Figure 1: A typical RF current probe from Tekbox with useful frequency range of 30 kHz to 400 MHz (3dB bandwidth).

Figure 2: Using an RF current probe to measure the common mode currents on a USB cable.

Kenneth Wyatt, Sr. EMC Engineer, Wyatt Technical Services LLC, holds degrees in biology and electronic engineering and has worked as a senior EMC engineer for Hewlett-Packard and Agilent Technologies for 21 years. He also worked as a product development engineer for 10 years at various aerospace firms on projects ranging from DC-DC power converters to RF and microwave systems for shipboard and space systems. A prolific author and presenter, he has written or presented topics including RF amplifier design, RF network analysis software, EMC design of products and use of harmonic comb generators for predicting shielding effectiveness. Kenneth is a senior member of the IEEE and a long time member of the EMC Society where he serves as their official photographer. His comprehensive yet practical EMC design, measurement, and troubleshooting seminars have been presented across the U.S., Europe, and Asia.

RF CURRENT PROBE MEASUREMENTS

The RF current probe is merely a current transformer that measures RF currents in the primary (wire or cable to be measured) and couples that to the secondary, which is loaded by the 50Ω input impedance of the spectrum analyzer (Figure 3). This produces a voltage across 50Ω that is usually in terms of dBμV. I usually insert a bit of "bubble wrap" within the probe aperture to keep the wire or cable centered and away from the metal probe case in order to minimize measurement errors.

Because of resonances on cables, I like to slide the RF current probe back and forth on the cable or wire in order to maximize the dominant harmonic or harmonics. Once the harmonic is "peaked up," I tape the probe down to the table to minimize variables while I try different mitigations to reduce cable coupling to the board.

Mitigations could include rerouting internal cables, improving bonding of cable shields to chassis or digital return plane, adding or improving common mode filtering at the I/O or power connectors, shielding energy sources using local shields, etc.

ESTIMATING PASS/FAIL

One important use for the RF current probe is to provide an estimate of passing or failing specific emission test limits. By knowing the current in an I/O or power cable, we can calculate the E-field at the test distance per the standard used. While this won't necessarily be precise, it still gives us a "ballpark" estimate to compare to the test limit at that frequency.

Commercial RF current probes come with a calibration chart of transfer impedance versus frequency (Figure 4). Using Ohms Law, we can use this chart to calculate the measured common mode current in the wire with respect to the voltage measured at the probe output port, assuming a 50Ω system. This is based on work by Dr. Clayton Paul (Reference 2) and further refined by Henry Ott (Reference 3). I also have example calculations in References 4 and 5.

Let's assume we measure one of the dominant harmonics in a cable as 28 dBμV at 120 MHz at the spectrum analyzer. We can also read of a transfer impedance of about 3 dBΩ from the calibration chart in Figure 4.

Using Ohms Law, we can calculate the common mode current (*Icm*) in the cable:

Icm (A) = E (V) / R (Ω)

or, in converting to terms using log identities,

Icm (dBμA) = Vprobe (dBμV) - 3 dBΩ = 28 - 3 = 25 dBμA

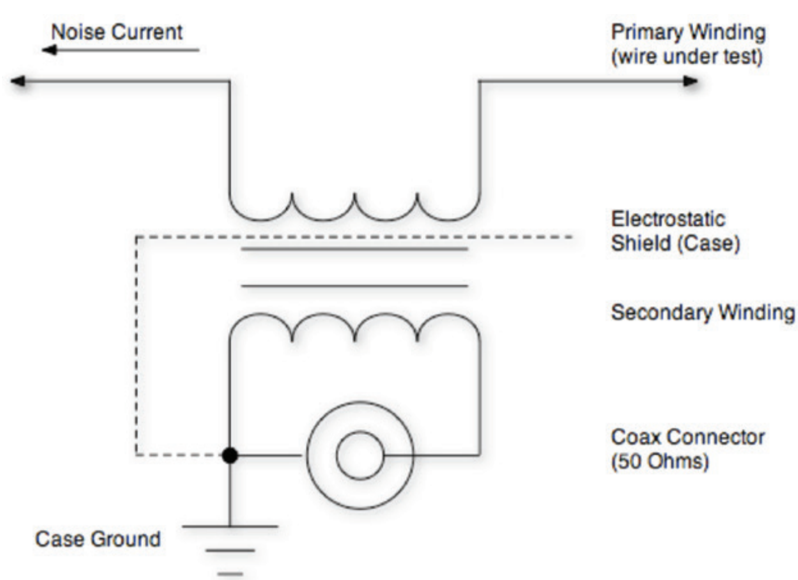


Figure 3: Schematic diagram of a typical RF current probe.

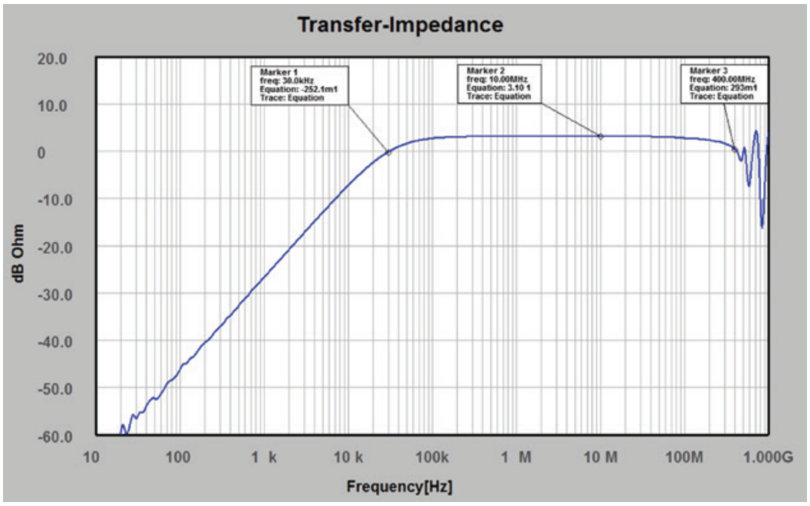


Figure 4: The transfer impedance calibration chart for the Tekbox TBCP2-30k400 RF current probe.

Now using the E-field equation from Paul and Ott:

$$E_c = 1.257 * 10^{-6} \left(\frac{|I_c| f L}{d}\right) = 8.94 * 10^{-4} V/m$$

where,

- E_c is the calculated E-field in V/m due to common-mode current flowing on the cable,
- I_c is the current through the wire or cable (A),
- f is the harmonic frequency being measured (Hz),
- L is the length of the cable in meters and
- d is the measured distance during the compliance testing (usually 3 or 10m).

Converting the measured values to basic units and plugging into the E-field equation, we get 8.94E-4 (V/m). Converting this back to log units, we get 59.03 dBµV/m. Comparing this with the FCC class B limit at 120 MHz (43.5 dBµV/m) indicates we may be over the limit by 15.5 dB.

I developed a simple Excel spreadsheet to streamline all these calculations, which may be downloaded from my Dropbox (Reference 6). Figure 5 shows an example calculation. By entering the specific probe transfer impedance, the frequency of concern, the cable length and test distance (typically 3 or 10m), the E-field in dBµV/m is calculated and may be compared to the appropriate test limit.

SUMMARY

The RF current probe is not only a useful tool for general troubleshooting but may also be used to determine potential passing or failing due to a radiating cable. While they may be a bit pricy, I find the RF current probe is one of my most used tools for troubleshooting emissions. I also have a short video showing how to use these RF current probes (Reference 7).

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1. Tekbox current probes, https://www.tekbox.com/product/tbcp2-32mm-snap-on-rf-current-monitoring-probes
2. Paul, *Introduction to Electromagnetic Compatibility (2nd Edition)*, Wiley Interscience, 2006, pages 518-532.
3. Ott, *Electromagnetic Compatibility Engineering*, Wiley, 2009, pages 690-693.
4. Wyatt, *Workbench Troubleshooting EMC Emissions (Volume 2)*, Amazon.
5. Wyatt, "The RF Current Probe: Theory and Application," *Interference Technology*, https://interferencetechnology.com/the-hf-current-probe-theory-and-application/
6. Wyatt, E-Field Calculator, https://www.dropbox.com/scl/fi/stljvo3398kc1kpu0v05b/E-Field_Calculator_RevF.xlsx?rlkey=32a3asq0v77t5oqfylsyo51c1&dl=0
7. Wyatt, Current Probe Demo https://www.youtube.com/watch?v=OcWiSukx4iA

	A	B	C	D	E	F	G
1	E-Field Calculation from RF Current Probe Reading			Rev. F	Wyatt Technical Services		
2							
3	Assumptions:	The probe transfer impedance is 3 dBΩ (Tekbox TBCP2-30k400 probe).					
4							
5							
6	Purpose:	The purpose of this is to calculate an estimate					
7		of the E-field at a given distance from a wire					
8		or cable, given the frequency, current and length.					
9		The equation is found in Ott's or Paul's textbooks.					
10							
11	Probe Zt:	3	(Leave this at 3 dBΩ for the Tekbox TBCP2-30k400 probe)				
12							
13							
14	ENTER dBµV from F-33-1	28					
15							
16	Calculated dBµA	25	(Equals dBµV - dBΩ)				
17							
18	Converting dBµA to A	1.77828E-05					
19							
20	ENTER Cable Length (m)	1					
21	ENTER Frequency (MHz)	120					
22	ENTER Antenna Dx (m)	3	(Typically 3m or 10m)				
23							
24	Calculated E-Field V/m	8.94E-04					
25							
26	Converting V/m to dBµV/m	59.03	(E-Field in dBµV/m)				
27							
28							

E-Field Calc

Figure 5: A simple Excel spreadsheet can perform all the math required to estimate the E-field in dBµV/m from the measured harmonic current in a wire or cable.

PRACTICAL ENGINEERING

Capacitor Safety Considerations

By Don MacArthur

With over twenty-seven years of experience developing complex measurement devices for use in harsh industrial environments, much of what I know about compliance engineering has been learned the hard way, and I want the readers of In Compliance to learn from my mistakes.

CAPACITOR SAFETY CONSIDERATIONS

In this article, I will cover an issue I have recently witnessed regarding the proper specification of capacitors used in safety applications. Specific manufacturer names are not provided as this is unimportant to this conversation. Below is the specification of the capacitor as stated on its datasheet:

Ceramic AC Capacitors Class X1, 760 VAC/Class Y1, 500 VAC

From the above, notice the datasheet indicates that these capacitors have both X1 and Y1 safety ratings. The datasheet also indicates that both X1 and Y1 ratings have approval from a National Recognized Testing Laboratory (NRTL). The proper NRTL approval of this capacitor (considered a safety critical component) is required to obtain NRTL approval of the end-product in which the capacitor is used.

If this capacitor is used within its ratings and in a location that requires Y1 or line-to-ground isolation, then everything should be good, right? Not so fast.

For this issue, nobody checked the NRTL's online certification directory (here is a link to an example of one such directory: https://productiq.ulprospector.com/en) to confirm both X1 and Y1 ratings for this part were properly listed. Right or wrong, the online directory indicated that the part had approval for only the X1 rating and no indication that it was approved for Y1 applications!

This is an issue because an X1-only rated capacitor cannot be used where a Y1 part is required. Subsequently, when it was time to work on the certification for the end product, this part was flagged as not suitable since it was missing the correct Y1 rating. Not having the correct Y1 rating for this part caused unnecessary churn within the development organization and held up NRTL approval of the end product until it was resolved.

The moral of this story is that if you are involved in product safety for an end-product that involves use of safety-rated capacitors, do not trust what the specifications on the datasheet say if they are related to safety. Early in the development cycle, take the extra step of looking at what is listed on the NRTL's online certification directory. If you are surprised at what you discover, then by checking early, you will have time for a plan B or C. Plan B could be finding an alternate supplier for the part or working with the current supplier to resolve the issue. Plan C could be doing both activities.

In the case that brought about the idea for this post, it turns out that the supplier of the capacitor was able to provide a certificate of compliance from the NRTL in question. The certificate showed that the capacitor had the proper X1 and Y1 safety ratings. The capacitor supplier worked with the NRTL to correct their online directory for this part.

Don MacArthur, The Practical Engineer, is a Guest Contributor to In Compliance Magazine. He has over 30 years of experience in product development, EMC, testing, and product safety compliance. He has developed products for military, commercial, and industrial applications.

MILITARY AND AEROSPACE EMC

Bandwidths Used in Measurements

By Patrick André

The use of bandwidths in EMC measurements is important but often confusing. The term bandwidth can have many meanings which may be unrelated: Receiver bandwidth; Resolution Bandwidth or RBW; Video Bandwidth or VBW; 3 dB or 6 dB Bandwidth; Broadband or narrowband bandwidths.

Receiver bandwidth is the frequency range in which the receiver is designed to function. A spectrum analyzer may be specified to function from 9 kHz to 7.5 GHz, which is its receiver bandwidth. An oscilloscope may have a 500 MHz bandwidth, which would be the upper limit of the useful range.

This is different from Resolution Bandwidth or RBW. RBW is the window size in which the measurement is taken. This RBW window is what is swept across a frequency range being measured. The RBW is typically defined as a 3 dB or 6 dB bandwidth. This means that from the center peak of the detection window to either edge, the signal will drop 3 or 6 dB from the maximum amplitude or center location. The width between these points is the resolution bandwidth.

In Figure 1, the green curve shows a 3 dB bandwidth, while the blue curve shows the 6 dB bandwidth. Since the 3 dB curve drops slower than the 6 dB curve, the total energy under the curve will be higher. For energy distributed over a wider frequency range (not a CW signal), this translates to higher readings from a 3 dB bandwidth than using a 6 dB bandwidth of the same bandwidth value. Most receivers and some higher-end spectrum analyzers have the ability to measure using a 6 dB RBW. Most spectrum analyzers have only a 3 dB RBW.

For military and aerospace measurements, the bandwidths required are defined as 6 dB RBW. 3 dB RBW are allowed, but no correction is allowed for using the wider bandwidth. Therefore, care should be taken to ensure the measurement equipment is using the proper style of bandwidth if there is a choice available.

Since some limit lines are reduced to very low amplitudes at specific frequency ranges, commonly called notches, the ability to measure these very low amplitudes may not be possible without reducing the RBW. This is due to Johnson-Nyquist Noise, also known as thermal noise, which appears as broadband energy. For example, at room temperature (about 300° K), a 1 MHz RBW will measure -114 dBm from a disconnected resistor sitting on a bench. If a measurement at 8 GHz is needed, and the antenna factor is 37 dB/m, we have:

$$-114\ dBm = -7\ dB\mu V$$
$$-7\ dB\mu V + 37 dB/m = 30\ dB\mu V/m$$

This means without considering cable loss, spectrum analyzer noise, instrument noise, or any other sources, and using the required 1 MHz RBW, the minimum noise the system can measure at 8 GHz is 30 dBµV/m even if the equipment is off. However, there have been times when limits of 20 dBµV/m were imposed with a 6 dB margin required, requiring a noise floor of 14 dBµV/m. In other words, your equipment fails when it is off, which does not seem to be the purpose of the test.

A 10 dB improvement in the noise floor can be expected for each reduction of bandwidth of 10 times. Thus, to

Patrick G. André has worked in the EMC field since 1983. His emphasis is on EMC issues specific to the military and aerospace environment, and he works with the RTCA as a member of SC-135 committee. Andre is an iNARTE Certified Engineer and was honored as an iNARTE Certified Master Design Engineer. He is also a senior member of the IEEE EMC Society, the author of several publications, and the coauthor of EMI Troubleshooting Cookbook for Product Designers.

measure 8 GHz with a noise floor of 14 dbµV/m will likely require using a 1 kHz RBW or less, which is a deviation from the standard's required bandwidth by 1000 times. Remember, measuring with the reduced bandwidth must be approved by the procuring activity before it can be used. And remember that signal amplifiers will add their own noise to the system and will amplify that thermal noise along with everything else. Also, using a 1 kHz RBW at 8 GHz is a very slow process, 15 seconds/MHz, and may require a great deal of time to take a proper reading. A scan from 8.0 GHz to 8.5 GHz is over 2 hours. In these cases, it may be wise to consider spot checks at specified frequencies, such as harmonics of known clock frequencies.

Video bandwidths, or VBW, are filters that can be applied to the measured signal. They have the effect of smoothing the appearance of the emissions on the spectrum analyzer, lowering the amplitude in the process. When choosing a VBW equal to or less than the RBW, the filter is being applied. This is not allowed for military and aerospace measurements. Thus, the VBW must be three times wider or greater than the value of the RBW.

Resolution bandwidths are now defined and must be used in their designated frequency range. This was done to help eliminate the need for Broadband and Narrowband emission measurements. Broadband measurements were performed using wider bandwidths, commonly at least 10x the narrowband, and the amplitudes measured were normalized as if using a 1 MHz bandwidth. Assume, for example, a conducted emissions measurement used a 10 kHz bandwidth across some range. The readings were corrected by:

$$Reading\ dB\mu V - 20\log_{10}\frac{10\ kHz}{1\ MHz} = Reading + 40\ dB$$

These measurements were intended to find energy levels across frequencies, especially when dealing with radios and other receivers that are onboard aircraft. Broadband noise could reduce the sensitivity of the communication systems, which is especially important on overseas flights. Some corporate standards still require this measurement; however, most derive their information from the RBW values currently defined in the standards.

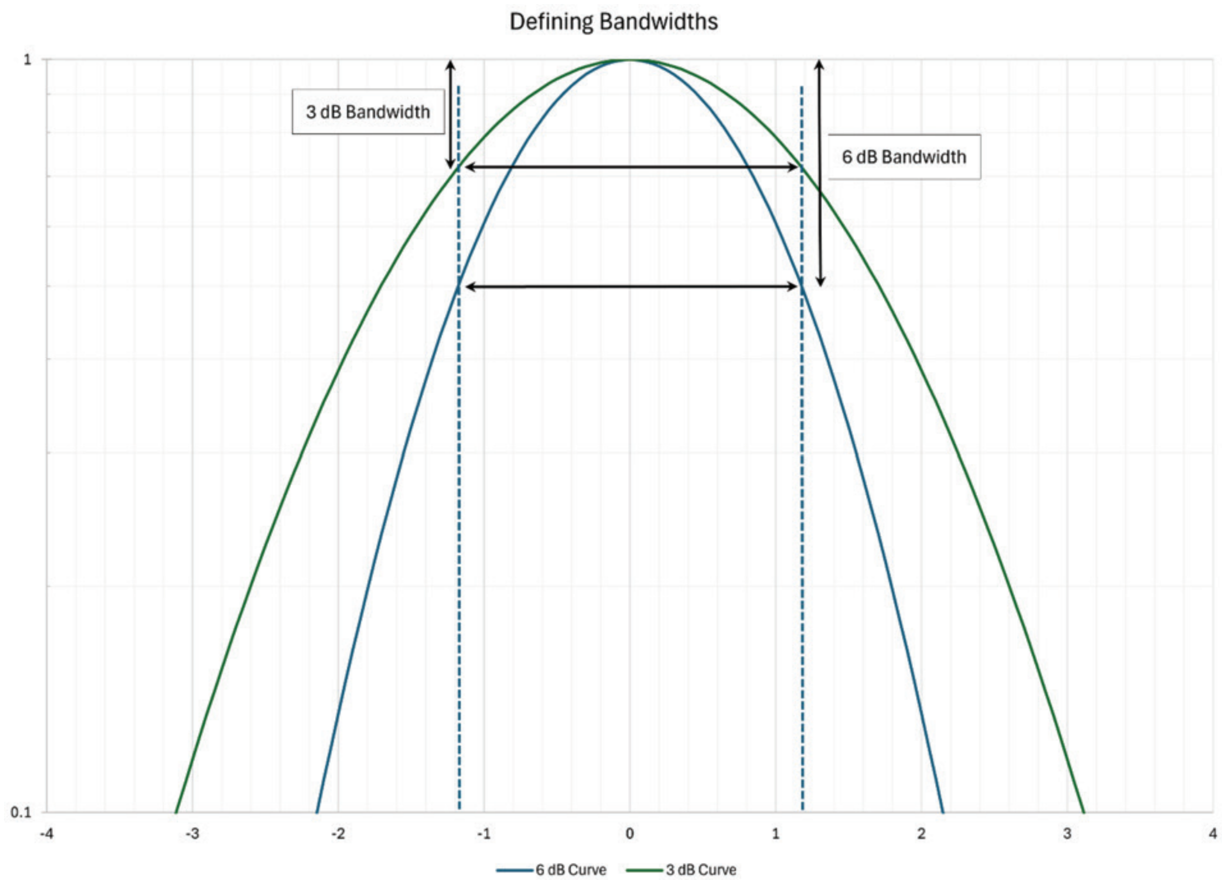


Figure 1: Showing the difference between 3 dB and 6 dB Bandwidths

STANDARDS PRACTICE

Why So Many Immunity/Susceptibility Tests?

By Karen Burnham

This space will do two things: educate people about standards and also use standards to educate people about electromagnetic compatibility (EMC) engineering.

I'd like to start out by discussing the wide variety of immunity standards (known in defense/aerospace as susceptibility standards) that are out there and why we need so many of them. I will focus on defense/aerospace and automotive since those are the areas I'm most familiar with. However, there are similar motivations behind medical standards, such as IEC 60601 and plenty of others. Here, I'll be referring to MIL-STD-461 Rev G and JLR-EMC-CS from Jaguar Land Rover (JLR), both easily available. The JLR standard is broadly representative of those automotive OEMs (original equipment manufacturers, such as Ford or Toyota) impose on module suppliers.

Probably no one's favorite is the standard Radiated Immunity test. This is exemplified by RS103 in MIL-STD-461 for defense/aerospace and JLR RI 114 for automotive. The idea behind this test is for equipment to be immune to its electromagnetic environment. Generally speaking, the main threat to a module will be the RF transmitters co-located on the same platform. Imagine a communication system on an aircraft interfering with an avionics sensor package. That class of threats should be accounted for very explicitly when a program is tailoring its radiated immunity requirements. What's harder to narrowly characterize is the broader array of RF transmitters in the world. While I don't expect to have my electronics interrupted by the local AM radio transmitter, that may change if I drive up to the base of its broadcast tower. Then there are things like aircraft-tracking radar on military platforms like aircraft carriers and in civilian applications at airports. See Figure 1 to compare the levels specified by RS103 and RI 114. The transmitted threats can change significantly over time as different systems are developed, moved, or upgraded. In an example of testing evolving along with consumer technology, the automotive industry adopted radiated immunity testing such as JLR RI 115 that specifically mimics cell phone signals since passengers and drivers can be counted on to put or drop their cell phones in the most inconvenient possible places.

Leaving aside RS101 and 105 from MIL-STD-461 (susceptibility to magnetic fields and EMP, respectively), we can then look at the wide array of conducted immunity tests. IEC-61000-4-2 and derived standards like MIL-STD-461 CS118 and Jaguar Land Rover CI 280 are all meant to address the risk of human ESD to electronics. The JLR standard goes up to ±30 kV for certain units, while CS118 only specifies up to ±15 kV, presumably because the military has more control over how its equipment is used and can train personnel in a way you can't with an average driver.

Karen Burnham is a distinguished expert in Electromagnetic Compatibility (EMC) with nearly three decades of experience across aerospace, defense, and automotive industries. With a BS in Physics and MS in Electrical Engineering, she has led crucial projects for NASA, Dream Chaser spaceship, and Ford Motor Company. Currently serving as Vice President of Standards for the IEEE EMC Society, Burnham brings her extensive expertise to multiple international standards committees. In 2024, she founded EMC United, Inc., where she helps companies prevent and solve EMC challenges. Known for her ability to demystify complex EMC concepts, Burnham is passionate about making EMC both accessible and engaging for hardware designers.

Continuing on, bulk current injection tests such as MIL-STD-461 CS114 and JLR RI 112 represent two threats: lower frequency ranges that are difficult to test via radiated methods due to chamber limitations but easily picked up by long cable runs and also crosstalk between conductors in those long runs.

All units must be immune to the noise carried on shared power buses, such as voltage ripple from power supplies. In MIL-STD-461, that's covered by CS101; in the automotive world, you might look at JLR CI 210. See Figure 2 on page 36 to compare the levels between the two. For a nominally 12 V system, both have max

TABLE XI. RS103 limits.

		LIMIT LEVELS (VOLTS/METER)							
FREQUENCY RANGE / PLATFORM		AIRCRFAFT (EXTERNAL OR SAFETY CRITICAL)	AIRCRAFT INTERNAL	ALL SHIPS (ABOVE DECK & EXPOSED BELOW DECK) AND SUBMARINES (EXTERNAL)*	SHIPS (METALLIC) (BELOW DECKS)	SHIPS (NON-METALLIC) (BELOW DECK)**	SUBMARINE (INTERNAL)	GROUND	SPACE
2 MHz to 30 MHz	A	200	200	200	10	50	5	50	20
	N	200	200	200	10	50	5	10	20
	AF	200	20	-	-	-	-	10	20
30 MHz to 1 GHz	A	200	200	200	10	10	10	50	20
	N	200	200	200	10	10	10	10	20
	AF	200	20	-	-	-	-	10	20
1 GHz to 18 GHz	A	200	200	200	10	10	10	50	20
	N	200	200	200	10	10	10	50	20
	AF	200	60	-	-	-	-	50	20
18 GHz to 40 GHZ	A	200	200	200	10	10	10	50	20
	N	200	60	200	10	10	10	50	20
	AF	200	60	-	-	-	-	50	20

KEY: A= Army
N= Navy
AF= Air Force

* For equipment located external to the pressure hull of a submarine but within the superstructure, use SHIPS (METALLIC) (BELOW DECK)
** For equipment located in the hanger deck of Aircraft Carriers

(a)

Table 10-3: RI 114 Requirements (200-3100 MHz)

Band	Frequency Range (MHz)	Level 1 (V/m)	Level 2 (V/m)	Modulation
4	200-800	50	100	CW, AM 80%
	400-470			Pulsed PRR= 18 Hz, PD= 28 ms
5	800-3000		70	CW, Pulsed PRR= 217 Hz, PD=0.57 ms
6	1200-1400	n/a	300	Pulsed PRR= 300 Hz, PD = 3 μs, with only 50 pulses output every 1 second
7	2700-3100		600	

Note: 600 V/m requirements are only applicable to selected components associated with supplemental restraints system including frontal crash sensors. Contact JLR EMC department for specific applicability

(b)

Figure 1: Comparing radiated susceptibility/immunity levels from (a) MIL-STD-461 and (b) JLR RI 114.

levels of 2 V (126 dBμV), but the automotive standard assumes the noise will get worse with frequency, whereas the defense standard assumes it will go down with frequency.

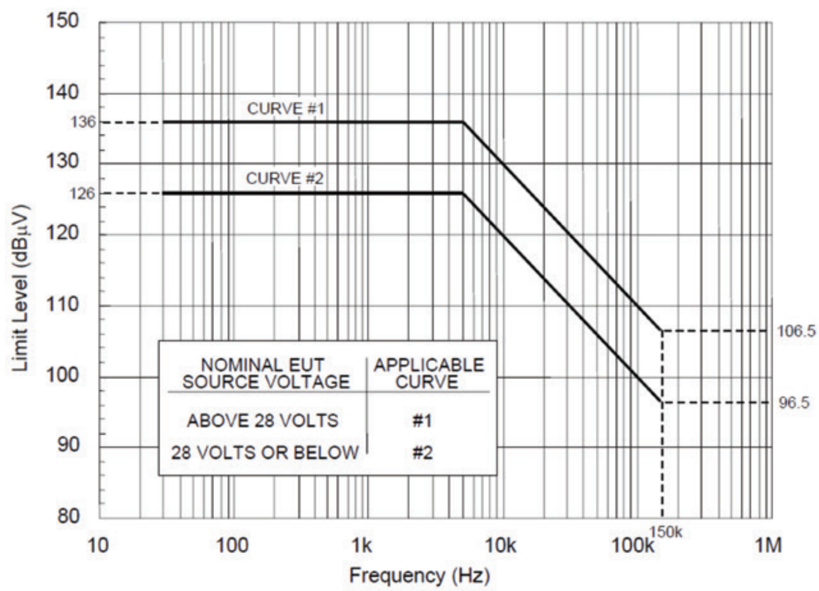
Aside from the susceptibility requirements specifically applied only to RF systems (CS 103/104/105) or large naval vessels (CS109), the remaining MIL-STD-461 tests are largely applicable to threats such as various transients or induced currents produced by direct or nearby lightning strikes or related impulses (CS115/116/117).

The automotive folks have even more on their plate: wire-to-wire coupling when transients are induced by inductive loads switching on and off (JLR RI 130); or when there are continuous disturbances from pulse width modulated, high current modules (JLR RI 150); conducted transients resulting from loads switching on or off, particularly sudden voltage dips or a load dump (JLR CI 220), power cycling in cold start conditions (JLR CI 230); ground voltage offsets due to using chassis as current return (JLR CI 250); and immunity to transient voltage dropouts that can occur for any number of reasons, including the loosening of pins over time and potentially losing connection when going over potholes, for instance (JLR CI 265).

All of which is to say, there are a lot of different ways to disrupt a system using either radiated or conducted electromagnetic energy. Different industries have specific threats that they want to address with their EMC testing requirements based on their operating conditions and platform architecture. Keep in mind that each test represents some real-world condition, even if it's a few steps removed or abstracted. When flowing requirements to your own EUT, give some thought to making sure that each scenario is genuinely applicable and consider making tailoring adjustments to your requirements if they don't make sense.

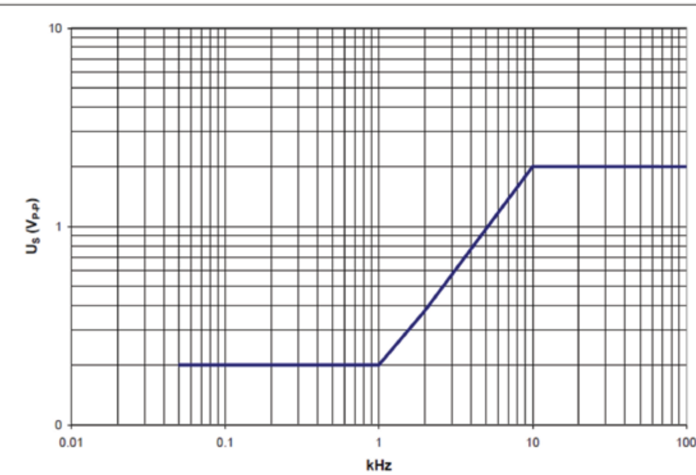
REFERENCES

1. JLR-EMC-CS v1.0 Amendment 4, "Electromagnetic Compatibility Specification for Electrical/Electronic Components and Subsystems" 25-02-2015.
2. MIL-STD-461 Rev G, "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment" 11 December 2015.



(a)

Figure 14-3: CI 210 Requirements



Frequency Range (kHz)	U_S (V_{P-P})	Functional Performance Status		
		Class A	Class B	Class C
0.05 – 1	0.2			
1 – 10	0.2*f*		I	
10 – 100	2			

Note: *f* = frequency in kHz

(b)

Figure 2: Comparing test levels for conducted immunity/susceptibility addressing low-frequency noise from power supplies.

SIGNALS AND SOLUTIONS

Ham Radio? Is That Still "A Thing"?

By Kimball Williams

Someone noticed an Amateur Radio logo I was wearing and asked the question, adding that a relative had been a "Ham" once upon a time, but does "Ham Radio" really still exist because "Didn't cell phones do away with all that?"

That misconception is not unusual and with good reason. For the general public, communication has always focused on reaching out to friends and relatives or for business reasons. Why would anyone go to all the work to set up a radio station and an antenna just to do that?

Of course, that was never the reason for a Ham to set up a station. Ham's use their cell phones just like everyone else. They use their personal radio stations for other reasons. In fact, Amateur Radio stations are licensed by the federal government for specific Services: (Emergency communications, advancing radio technology, radio "art," providing a pool of trained communications experts, and advancing international goodwill.).

Some of those, in fact most, sound serious, and they are. So why is Ham Radio usually spoken of as a hobby? Well…. it is…. sorta. The real genius of Ham Radio is the way each of the FCC Service functions has evolved into its own fun-to-do activity. Let's take the example of Emergency Communications.

Emergency Communications implies the ability to provide communications services when normal infrastructure support (Cell phone/Land line/Residential Electrical power) has all been swept away (Hurricane, Tornado, Earthquake, Landslide, Flood, Forrest Fire, etc.). The Ham needs to set up his/her radio, an independent power source (battery/solar cells/generator, etc.), and a suitable antenna and contact stations outside the "crater," as one of my friends puts it.

In the early days of Ham Radio, amateur radio clubs got together and designated the 4th full weekend in June as "Field Day" when the members would gather for two days of setting up equipment away from their normal station locations and spend 24 straight hours making as many contacts as possible on the bands of their choice. Of course, this also involves the families of the licensed operators, and the entire weekend becomes a social gathering along with the serious side of verifying equipment functionality and developing operator skills. This tradition goes on every year with several hundred radio clubs around the USA, Canada and Mexico taking part.

About 10-12 years ago, a genius Ham in Great Britain began going to local high points with his equipment and making contacts. This became Summits on the AIR or SOTA, which evolved into an ongoing contest among Hams from every country. Not to be outdone, Hams in more vertically challenged countries stepped up and created Parks on the Air or POTA. In this version, Hams visit identified State and Federal parks to set up and exercise their equipment and develop their contacting skills. Now, every day of the year, we find different stations competing with each other to see how many contacts they can make, all under the same conditions that would prevail in an actual emergency. Of course it is fun, but serious fun.

So, if Ham radio is still "a thing," just how many people are really involved in this activity? Currently available numbers indicate that there are more than 700.000 Ham in the USA and over 3,000,000 worldwide!

I think it is safe to say that Ham radio is still alive and well.

kw N8FNC

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Fundamentals of Electromagnetic Compliance

A Practical Overview

By Christopher Hare

Everyone enjoys the advantages of electronic devices and gadgets becoming smaller, lighter, and faster while providing longer battery life and ever-improving processing ability. Smaller devices require smaller electronic components — an advantage in reducing electromagnetic interference (EMI). However, a compact design also means smaller spacing between components, circuit traces, and enclosures, which can lead to increased field interactions, current loops, ground loops, crosstalk, and other potential sources of EMI.

We benefit from the convenience of televisions, cell phones, digital tablets, notebook computers, and IoT devices, all operating at the same time while appliance motors, lights, fans, and HVAC units are operating in the background to keep us comfortable. With multiple electrical and wireless electronic devices operating at the same time, signals must remain reliable in electromagnetically noisy environments.

Christopher Hare is a technical marketing engineer at Coilcraft. He received his Bachelor of Science degree in Physics from Northern Illinois University in 1986 and has been applying his long-developed understanding of physics, engineering, and marketing in various fields ever since. Hare can be reached at tech_support@coilcraft.com.

The rapid growth of the electric vehicle (EV) and hybrid electric vehicle (HEV) market raises new electromagnetic compatibility (EMC) concerns as high-voltage batteries and chargers see increased use. High-voltage and high-frequency automotive electronics, if not properly designed, can lead to EMC compliance headaches. Focusing on design techniques that mitigate EMI will help ensure a low-emissions outcome.

High levels of electromagnetic (EM) noise lead to EMI, which is any undesired electrical disturbance (noise) that interferes with other circuits. Electromagnetic emissions occur when electrical or electronic equipment radiates or conducts EM noise that interferes with other devices. Electromagnetic compatibility is the ability of electronic equipment to function properly without interference from noise sources (immunity/susceptibility) and without causing disturbances to other electronic equipment (emissions).

EMC is verified by testing in accordance with industry standards developed by regulating agencies described later in this discussion. These standards define specific test conditions and limits of noise emissions that may vary by location, application, and operating environment.

NOISE SOURCES

Noise might be of a transient or discontinuous nature, or it might be generated continuously. Potential sources of


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transient or discontinuous conducted emissions include automatic switches, temperature controllers, appliance controllers, other automatic controllers, motor controllers, and any other non-constant or event-driven on/off switching of voltage. Potential sources of continuously conducted emissions include electric motors, unshielded or poorly shielded data lines, switch-mode power converters, and any other constant steady-state switching of voltage. Improperly designed PCBs with power and signal areas too close together or having insufficient filtering can result in transient or steady-state conducted emissions.

MODES OF ELECTRICAL NOISE PROPAGATION

Noise is generally discussed as being either radiated or conducted. The solution to any noise problem requires identifying and understanding the nature of the noise. This can be complicated by the interaction between radiating and conducting modes. After all, any conducted electricity has the potential to generate radiating fields, and likewise, fields can cause electrical signals.

Designing and testing for EMC involves understanding how electric fields (E-fields) and magnetic fields (B-fields) propagate and interact. A fundamental understanding of antenna theory provides insights into how the size and design of electronic components, PCB traces, pads, and grounds relate to various frequencies and their associated wavelengths. Understanding the modes of electrical noise propagation and the methods of testing for EMC leads to design solutions that greatly improve the probability of passing EMC compliance tests in the earliest stages. Failing to design for EMC often results in expensive redesigns and PCB re-spins.

CONDUCTED EMISSIONS

Electrical noise can be transferred to "victim" equipment by field-coupling from source "aggressor" equipment through conducting input lines, cables, connectors, or traces to the equipment circuits. This mode of noise propagation and its effects on power quality are referred to as conducted emissions. Conducted emissions can be conducted directly into the circuit on the input lines, or they can be near-field energy that is capacitively coupled (E-field) or magnetically coupled (B-field) to a circuit unintentionally. Because conducted emissions may involve capacitively- or magnetically-coupled fields, they are essentially reactive (non-radiative) near-field effects that can generally be modeled using lumped resistive, inductive, and capacitive (RLC) elements. Conducted emissions are typically measured in the 150 kHz to 30 MHz frequency range.

DIFFERENTIAL AND COMMON MODE NOISE

Conducted emissions consist of differential mode (DM) currents and common mode (CM) currents. The dominant mode depends on the source of the noise. Differential mode noise currents are superimposed on the intended current that powers the circuit, traveling in a loop from the power source, through the circuit, and returning to ground or the intended source return node for non-grounded circuits.

DM currents include the typically lower-frequency desired fundamental signal and any higher-frequency harmonics. In some circuits, the fundamental frequency plus harmonics make up the desired waveform (AC), such as sine waves, square waves, or triangular waves. In others, the main current is DC, and the AC portion is noise to be filtered out. The cutoff frequency of a low-pass filter inductor, choke, or LC filter must be designed to filter out the high-frequency noise without significantly attenuating the intended signal.

CM currents travel in the same direction through one or more conductors toward a common return point that closes the current loop (e.g., ground). When the return path is not intentional, the CM current may be the result of energy capacitively or magnetically coupled to the common point. Common mode chokes are designed to create high impedance to such CM noise (Figure 1) while presenting low impedance to the desired differential signal.

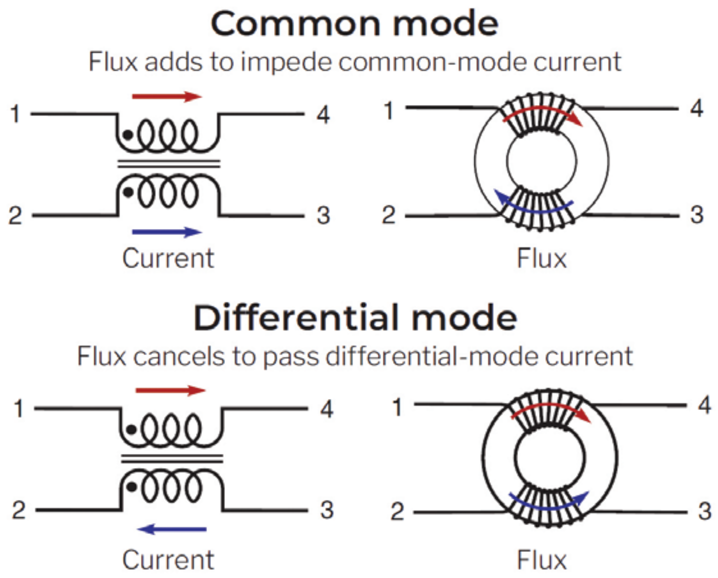

Figure 1: Common mode chokes create high impedance to CM noise (Source-Coilcraft)

RADIATED EMISSIONS

Near-field and far-field are terms associated with antennas. Why mention antennas in an EMC discussion? Unintentional transmitters are circuit elements that unintentionally radiate or scatter radiation. These are, in effect, “antennas” that were not intentionally designed to transmit energy. Unintentional transmitters cause radiated emissions, that is, electromagnetic noise propagated through the air that is received by other parts of the circuit or other devices.

Radiated emissions are essentially far-field at approximately two or more wavelengths distance from the source. The maximum dimension of an optimized antenna is about 1/4 wavelength of the intended signal being transmitted or received. When the size of an unintentional circuit transmitter, such as a PCB trace cable or slot behaving as an antenna, approaches about 4x the wavelength, the transmitted high-frequency energy can be modeled by distributed (transmission line) elements.

Wavelength and frequency have an inverse relationship. Therefore, at higher frequencies in which the corresponding wavelength approaches about 1/4 of the size of the unintended antenna or smaller, radiated emissions can be expected. Consequently, radiated emissions are tested at higher frequencies than conducted emissions, typically in the 30 MHz to 1 GHz range.

Potential sources of radiated emissions include switched wireless devices, IoT devices, radios, switching power supplies, electric motors, digital signal data lines, communications devices, motor drives, and any unshielded or radiating source with ineffective shielding. Some of these are also included as sources of conducted emissions because they can interact both on power cables and data lines as well as via radiation over the air.

EMC COMPLIANCE AGENCIES AND TEST METHODS

Following is a brief overview of EMC compliance agencies, test setups, methods, and standards. It also includes design hints for mitigating EMI and tips for EMC test troubleshooting.

EMC standards define specific test equipment, test set-ups, and pass/fail limits. EMC standards generally set limits on both peak (or quasi-peak) and average emissions levels vs. frequency range for the appropriate classification of the measured device. The equipment designed for measuring these levels is defined within the applicable product standard or within the referenced basic standard. EMC standards are continually under review due to new product types and applications. Therefore, the latest approved standard should be applied in any EMC test plan.

Figure 2 shows the test limits for FCC Part 15 (radio frequency devices) Subpart B radiated emissions limits for frequencies greater than 1 GHz for average measured values at 3 m and 10 m distances. Figure 3 shows the same for measured quasi-peak values.

Quasi-peak measurements apply a weighting factor based on the repetition frequency of the spectral components of the signal. Even if the emission is over a test limit when measured with peak detection, it can pass if the quasi-peak level is below the limit. For this standard, one must meet the limits for both average and quasi-peak measurements. Quasi-peak measurements require more time than peak measurements. If initial (faster) peak measurements pass, they will pass quasi-peak testing, and the slower quasi-peak test is not needed.

Basic EMC publications include definitions of terms and specific test set-ups and equipment requirements, such as those for line impedance stabilization networks (LISN) that stabilize the impedance of the source and provide isolation of the test equipment and circuit under test. EMC product standards and EMC product family standards refer to specific products and categories of products, while generic EMC standards apply where specific product or family categories do not exist. Product, product family, and generic EMC standards reference the more fundamental basic EMC standards.

Selecting appropriate EMC standards can be confusing, requiring a clear indication of the product category and markets, whether local, international, or both. Consulting an accredited EMC test laboratory can save much time and effort in determining the appropriate test standards and requirements for general or specific products and applications.

The following are the major EMC regulation agencies and examples of some of their basic product, product family, and generic standards currently in effect.

Major U.S. and Global EMC Regulating Agencies

The major regulating agencies that publish EMC standards include:

- FCC — Federal Communications Commission (USA / North America): Products designed for North American markets are generally tested to the basic compliance limits of the Federal Communications Commission (FCC) Part 15.
- IEC — International Electrotechnical Commission (International)
- CISPR — Comité International Spécial des Perturbations Radioélectriques (International): CISPR is part of the IEC.

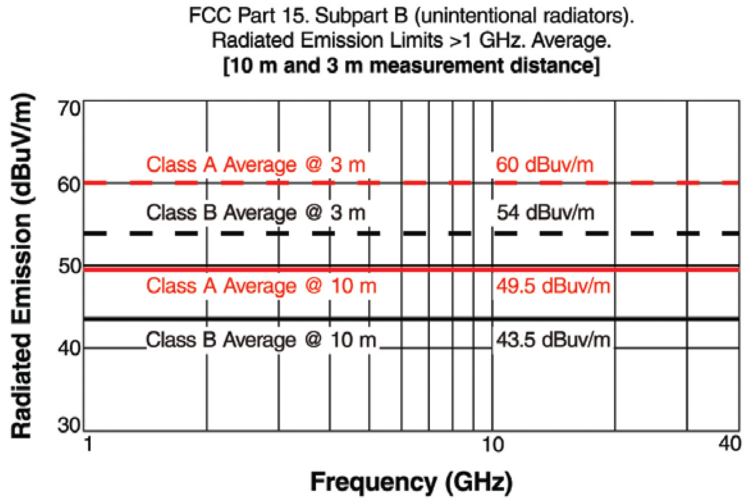

Figure 2: FCC Part 15, Subpart B, Radiation Emissions Limits > 1GHz - Average

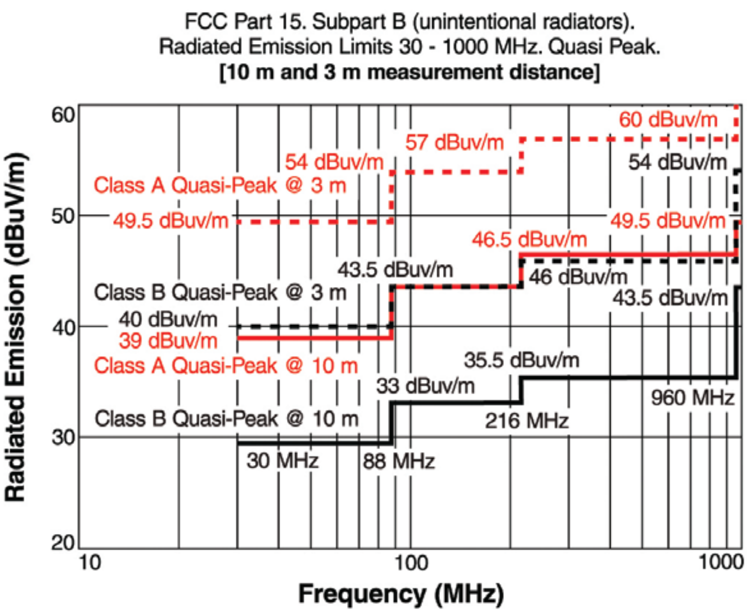

Figure 3: FCC Part 15, Subpart B, Radiation Emissions Limits 30 – 1000 MHz – Quasi-Peak

Basic EMC Standards

The major basic EMC standards cover a wide range of devices and include:

- FCC Title 47 Part 15 — *Radio Frequency Devices* is a basic standard in the U.S. Under this standard, Class A digital devices are generally marketed for use in commercial, industrial, or business environments. Class B digital devices are generally marketed for residential environments but can include commercial, industrial, or business environments. Class B requirements are more stringent. Therefore, Class B devices can be used in Class A environments.
- IEC 61000 Series, Parts 1, 2, 4, 5, 6, and 9 define basic terminology, test and measurement methods, and installation and EMI mitigation guidelines.
- IEC 61000-3—The European (international) Standard for all electrical and electronic equipment that is connected to the public mains up to and including 16 A max.
- CISPR 16 — Defines measuring apparatus and methods for radio disturbance and immunity testing from 9 kHz to 1 GHz.

Product EMC Standards

Product EMC standards apply to specific products, such as electric vehicle conductive charging systems, power electronic converter systems, cables and connectors, or medical electrical equipment.

Examples of product-specific EMC standards include:

- IEC 61851-21 — *Electric vehicle conductive charging system – Part 21: Electric vehicle requirements for conductive connection to an AC/DC supply*
- IEC 62477-1 — *Safety requirements for power electronic converter systems and equipment – Part 1: General*
- IEC 61726 — *Cable assemblies, cables, connectors and passive microwave components – Screening attenuation measurement by the reverberation chamber method*
- IEC 60601-1-2 — *Medical electrical equipment – Part 1-2: General requirements for basic safety and essential performance – Collateral standard: Electromagnetic compatibility – Requirements and tests*

PRODUCT FAMILY EMC STANDARDS

Product family EMC standards apply to wider general product categories, such as vehicles, information technology equipment, and industrial, scientific, and medical equipment.

Generic EMC standards are grouped as either residential, commercial and light industrial, or industrial. Industrial includes higher-power industrial and scientific and medical equipment. When a specific EMC standard does not exist for new products, a simplified generic EMC standard may be invoked.

Examples of product CISPR EMC standards include:

- CISPR 25 — *Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers*. This is the go-to standard for automotive applications.
- CISPR 22 — *Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement – High frequency conducted emissions standard*
- CISPR 11 — *Industrial, scientific and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement – High frequency conducted emissions standard*
- CISPR 15 — *Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment*

Generic EMC Standards

Generic EMC standards are grouped as either residential, commercial and light industrial, or industrial. Industrial includes higher-power industrial and scientific and medical equipment. When a specific EMC standard does not exist for new products, a simplified generic EMC standard may be invoked. As with other product standards, they may refer to basic EMC standards for specific test methods.

Generic EMC standards examples include:

- IEC 61000-6-3 — Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments
- IEC 61000-6-4 — Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments

Designing to Mitigate EMI

Because higher-frequency harmonics are considered noise in conducted emissions testing, low-pass filters are purposely designed into electronic equipment to reduce this high-frequency noise to below the defined limits of the conducted emissions test. Series inductors and capacitors between line and neutral lines, such as X-caps between the power and neutral lines, are employed to reduce the high-frequency DM currents. Common mode chokes and Y-caps between the lines and chassis ground are used to reduce the CM noise.

When the source includes significant conducted noise, as with switching power supplies, additional elements may be needed to create higher-order LC filters that further reduce the DM and CM noise. Some good news is that the use of small surface mount (leadless) components reduces connection inductance and the length of traces that may contribute to higher EMI.

DESIGN HINTS FOR PASSING EMC PRE-COMPLIANCE AND COMPLIANCE TESTS

1. These design hints for passing EMC pre-compliance and compliance testing do not comprise an exhaustive list. However, following these guidelines will help ensure minimal generation of EMI.
2. Minimize the length of circuit traces to avoid making unintentional emitters/antennas. This is listed as #1 because it is most critical in preventing EMI. Minimizing trace length decreases the total stored reactive energy of the trace and reduces ringing due to parasitic inductance. This is especially critical in switched power converters.
3. Consider EMC in the earliest stages of the design process. It can save considerable time and help prevent time-consuming PCB redesigns.
4. Use simulation programs to design and simulate noise filters and use real measurements to verify them. Even accurate models may not fully capture some important parasitic interactions.
5. Use magnetically shielded inductors to minimize B field coupling unless your design requires purposeful interaction with the inductor field (e.g., NFMI or RFID). Magnetic shielding is created by surrounding the inductor with a high-permeability, low-reluctance material (e.g., ferrite), creating a “closed” magnetic path. The purpose of magnetic shielding is to reduce

the amount of magnetic flux generated outside the inductor, in turn reducing the likelihood of radiating energy to nearby components or circuit board traces, causing electromagnetic interference.

6. Avoid electrically conducting (metal) materials directly above, next to, or below inductors or high-frequency switches (e.g., switched power converters). When this can't be avoided, use raised inductors to increase the distance between the inductor and the conductors below.
7. Place the start winding of inductors closest to the high dv/dt side of switches.
8. Maintain spacing between components, generally 1.5x the largest x-y dimension.
9. Avoid or slow down sharp rising-edge and falling-edge waveforms (slew rate control). This can lead to reduced efficiency, so there are trade-offs and a balance must be struck.
10. Route clock lines and other high-speed traces away from power sources.
11. Avoid running high-speed lines across gaps in return lines.
12. Consider ground loops or return paths of reference planes as potential EMI sources.
13. Avoid discontinuous signal return paths, e.g., gaps in ground planes.
14. Utilize filtering or shielding to block coupling paths from energy sources.
15. Engage filter reference designs with proven performance and save design time.
16. A single pole (L or C) filter provides -20 dB/decade of frequency filtering. A two-pole (LC) filter has a more rapid attenuation rate of -40 dB/decade. A three-pole filter (e.g., LCL) gives -60 dB/decade attenuation. Therefore, a sharp cutoff frequency requires a high-order filter.
17. Consider spread-spectrum control methods to spread noise energy to lower levels over a range of frequencies.
18. Slope compensation requires a certain level of ripple current to maintain stability. If the ripple is too high, it can cause EMI. When using slope compensation, check that the ripple current is not a source of EMI.

EMC FILTER SIMULATIONS

Computer programs for designing noise filters speed up the design and analysis phase of electronic product development. Free programs are useful for designing and verifying the performance of LC filters. Physics-based three-dimensional EM (3D EM) simulation programs that use more advanced computational solver methods, such as FEM, FDTD, and MoM, are higher-priced and require more advanced knowledge. However, these advanced solver programs provide more geometry- and materials-related insights when attempting to understand EM field interactions.

COST-FREE PASSIVE COMPONENT FILTER SIMULATION PROGRAMS

There are no-cost programs available to help engineers design and simulate lumped-element filters and their effects on circuit behavior. It typically takes much less time to model and simulate a proposed circuit than to build and test the physical circuit, especially when performing "What if?" analyses that involve many iterations. Thus, SPICE-based and other circuit design and synthesis simulation programs provide fast insights while saving time in the initial stages of design and analysis.

3D ELECTROMAGNETIC SIMULATIONS

The major advanced 3-dimensional electromagnetic (3D EM) programs for simulating printed circuit boards (PCBs), electronic components, and circuits include Ansys - HFSS, AWR Axiem/Analyst, CST Studio Simulia, and Cadence Clarity. These programs use physical models that include materials and geometry details and advanced computational techniques for a better understanding of the effects of materials and spacings at various operating conditions.

PRE-COMPLIANCE TESTING

Even the best design simulations can miss unanticipated field or wave interactions. Intertek Testing Services NA, Inc., an accredited EMC test lab, has found that about 50% of EMC tests fail on the first try (note 5). Some failures may be unavoidable, but many are due to preventable design oversights, such as failure to apply EMC principles or to simulate predictable interactions between circuit components. Pre-compliance testing allows engineers to pre-verify EMC standard compliance so that no such surprises delay the release of a product due to necessary re-designs. When un-predicted EM noise is made visible by pre-compliance testing, there are methods that can be employed to identify the source and remediate the problem.

TIPS FOR EMC TEST TROUBLESHOOTING

1. Use E-field and B-field probes to locate sources of EMI on a PCB.
2. If inductors or capacitors are suspected, rotate inductors by 180 degrees and place nearby inductors

and capacitors 90 degrees to each other. If available, replace inductors that have side terminations with bottom-terminated inductors.

3. Use a spectrum analyzer to determine the frequency range and amplitude of noise sources.
4. Set the resolution bandwidth of the spectrum analyzer to that specified in the applicable emission standard.
5. Slower voltage rise times create higher-order harmonics of lower magnitude, and faster rise times lead to higher-magnitude, higher-order harmonics.
6. Lower duty cycle leads to lower-magnitude, higher-order harmonics, and higher duty cycle leads to higher-magnitude, higher-order harmonics.
7. Determine whether the noise is DM or CM. If the noise is suspected to be CM, select a CM choke for the offending frequencies. If the noise is reduced, the noise is CM (unless the choke is a combination choke). If the noise is not reduced, it is more likely DM noise.
8. If changing EMI filter components does not change the EMC test results, this points to a possible PCB layout issue.
9. A combination of too many circuit elements can lead to resonances that amplify unwanted harmonics. In such cases, removing a component, such as a capacitor, may improve EMC test results. This may seem counterintuitive. However, sometimes more is not better.
10. Is ringing in your switched mode power supply switching edges causing EMI? Use a simulation program to design an RC snubber circuit to reduce the ringing. Higher resistance dampens the ringing but can affect efficiency, so use simulation to optimize the trade-offs.
11. If the source issue is a strong E-field, a metal "Faraday cage" shield connected to ground provides a closed field path that shunts noise to ground.
12. Wrap thin copper completely around a noisy transformer and connect the copper to ground to create a Faraday cage shield.
13. Use copper tape in closed loops to create prototype shielding. Test with and without the shielding to determine whether it is needed.
14. Review the design hints above for additional insights into possible solutions.

CONCLUSION

The continual increased use of electronics and electrical products has led to an environment filled with many signal and noise sources over a wide range of frequencies. Understanding how fields interact to create intentional and unintended transmitters and receivers and applying EMI mitigation techniques when designing and testing can lead to positive outcomes in electromagnetic compliance testing.

DEFINITIONS AND TERMINOLOGY

CISPR — Comité International Spécial des Perturbations Radioélectriques

Common mode current (noise) involves currents flowing in the same direction to circuit ground at higher frequencies. It is also called asymmetrical or longitudinal current.

Conducted emissions are unintentionally conducted, capacitively coupled (E-field), or magnetically coupled (B-field) to the circuit. They are typically measured in the 150 kHz to 30 MHz frequency range.

Crosstalk occurs when a high-frequency (e.g., clock) signal couples into nearby analog circuits.

Differential mode (normal) noise involves currents flowing in opposite directions at lower frequencies, also called symmetrical or transverse current.

Electromagnetic (EM) field — A field of force that consists of both electric and magnetic components, resulting from the motion of an electric charge and containing a definite amount of electromagnetic energy.

Electromagnetic (EM) noise, a.k.a. electrical noise, is any unwanted electrical disturbance, not necessarily in the audible frequency range (audible noise).

EM emissions occur when equipment radiates or conducts electromagnetic noise.

EM immunity is the ability of the equipment to withstand outside sources of EM noise without adversely affecting functionality.

EM susceptibility is the sensitivity of equipment to function within an environment of EM noise.

An *aggressor* is equipment that emits EM noise. Aggressors conduct or radiate EM emissions.

A *victim* is equipment that is adversely affected by EM noise. Victims are susceptible to EM emissions.

EMC is *electromagnetic compatibility*. EMC is verified by testing to industry global and local standards.

EMI is *electromagnetic interference*. If EMI exists at a level that exceeds the applicable EMC testing standards, the equipment is not EMC-compliant.

Far-field — Involving a distance from the source in which the distributed element models are needed for high-accuracy far-field simulations. The transition from near-field to far-field exists at about 1/6 the wavelength of the signal (or noise).

FCC — Federal Communications Commission (U.S.)

FCC Title 47 Part 15 — Radio Frequency Devices is a basic EMC standard in the U.S. applicable to electromagnetic energy at any frequency in the radio frequency (RF) spectrum between 9 kHz and 3 GHz.

FDTD — Finite difference time domain - A powerful method of solving Maxwell's equations directly without requiring physical approximations.

FEM — Finite element method - An advanced method of numerically solving differential equations that, for example, define physical relationships over a geometric space.

IEC — International Electrotechnical Commission Intentional transmitters (antennas) purposely transmit EM waves for wireless charging and communications.

LISN — Line impedance stabilization network - Pi filter networks that stabilize the impedance of the test source and provide isolation of the test equipment and circuit under test.

MoM — Method of moments - Efficient full-wave numerical technique for solving open-boundary electromagnetic problems.

Near-field — Involving capacitively-coupled E fields or magnetically-coupled B fields. Lumped element models can be sufficient for near-field simulations.

Radiated emissions are the result of unintentional current loop paths that radiate EM noise from the circuit. They are typically measured in the 30 MHz to 1 GHz frequency range.

SMPS — Switched mode power supply (switching converter).

Unintentional radiator — A device that intentionally generates radio frequency energy for use within the device or that sends radio frequency signals by conduction to associated equipment via connecting wiring but which is not intended to emit RF energy by radiation or induction.

Unintentional transmitters unintentionally transmit EM waves as noise. The FCC defines this as an "incidental radiator" - A device that generates radio frequency energy during the course of its operation, although the device is not intentionally designed to generate or emit radio frequency energy.

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Understanding the New Capabilities and Regulatory Compliance Testing Requirements for Wi-Fi 6E & 7

Reduce Time To Market and Visits to Testing Labs for New Wi-Fi Products

By William Koerner

Wireless connectivity has had such an impact on how we conduct our daily lives. With the wires removed, we are suddenly able to be connected to almost anyone, anywhere and anytime. According to a report released by IDC Research, 3.8 billion Wi-Fi devices were shipped in 2023.

Over the last few years, the number and complexity of Wi-Fi standards has grown. The United States (U.S.) opened up the 6 GHz band, while the European Union (EU) opened up about half of the 6 GHz bands for Wi-Fi 6E and now Wi-Fi 7. Although the Wi-Fi 7 standard has yet to be formally adopted, manufacturers have already released Wi-Fi 7 products. Each new standard offers more: more bandwidth, more data transfer options, and more capability.

However, one of the final steps to introducing new wireless products to the market is regulatory approval. And with each wireless standard, the regulatory requirements get more challenging. Focusing primarily on the U.S. and EU, this article will review the changes introduced by each wireless standard and discuss the measurement challenges in achieving regulatory approval.

OVERVIEW OF SUBSTANTIAL CHANGES TO WI-FI STANDARDS

Wi-Fi 6E

The Institute of Electrical and Electronics Engineers (IEEE) formally released the 802.11ax standard in 2021. This version of the standard focused on establishing a higher efficiency (HE) physical layer. Thus, it is also referred to as the HE standard and commercially known as Wi-Fi 6. Wi-Fi 6E is also the 802.11ax standard but extended (E) for use in the 6 GHz band, where allowed.

Table 1 on page 50 shows the significant changes introduced with the 802.11ax standard and their impact on the radio interface.

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EXODUS ADVANCED COMMUNICATIONS

Feature	Description	Impact
160 Max Channel Bandwidth	Ability to transmit in a 160 MHz Channel Bandwidth.	Allows for more devices to transmit at the same time, and higher data rates.
OFDMA	Modulation format that allows for assign Resource Units (RUs) to associated stations.	Lower contention overhead, increase efficiency of spectrum usage.
MU-MIMO	Multi-user MIMO, allows the AP to simultaneously receive and transmit to multiple stations.	Simultaneous transmit/receive allows for even more efficient use of spectrum and lower latency.
1024 QAM	10 bits per symbol	Higher data rate, up to 1201 Mb/sec theoretically
Preamble Puncturing	Multiple RUs allow for ability to control each RU transmission, turn certain RUs off to address interference.	Efficient use of spectrum, no need to switch operating channels to address interference.

Table 1: New features introduced in 802.11ax

160 MHz Bandwidth

Perhaps the first thing most will notice is the wider bandwidth. This allows for the use of 160 MHz, or 80+80 MHz noncontiguous channel bandwidths in the 5 or 6 GHz frequency bands. This allows for more data to be transmitted compared to the previous 80 MHz. This is optional but most likely standard for these devices.

Orthogonal Frequency Division Multiple Access (OFMDA)

An extension to the OFDM that was already available, this system allows for sharing of the channel with multiple clients simultaneously. This is a mandatory feature for both the down link (DL) and up link (UL) and allows for a more efficient use of the spectrum.

Multiple User – Multiple Input Multiple Output

This feature, along with OFDMA, allows for up to eight spatial streams and simultaneous transmissions to each client. This feature potentially allows for continuous transmission and reception to multiple clients at the same time. The Down Link (DL) MU-MIMO is mandatory, and Up Link (UL) MU-MIMO is optional.

1024 Quadrature Amplitude Modulation (QAM)

1024 QAM is an extension of the modulation technique used for the previous standard, 802.11ac. This means that the I/Q constellation has 1024 points in its constellation and allows for transmitting 10 bits per symbol, allowing for higher data rates over previous standards.

Preamble Puncturing

This is an optional feature for Wi-Fi 6, and I am not aware of any commercial products that have enabled this feature. This feature is used with OFDMA to allow transmissions to be stopped in certain subcarriers, mostly as a way to avoid interference from other signals (noise or other transmitters). This allows the devices to continue transmitting in the same channel but avoiding parts of the channel while the interference is present.

Feature	Description	Impact
320 Max Channel Bandwidth	Ability to transmit in a 320 MHz Channel Bandwidth.	Allows for more devices to transmit at the same time, and higher data rates.
4096 QAM	12 bits per symbol	Higher data rate, up to 2882 Mb/sec theoretically
Multi-Link Operation (MLO)	Ability to simultaneously send and receive to associated stations and to APs using different frequency bands and operating channels.	Simultaneous transmit/receive allows for even more efficient use of spectrum and lower latency.
Bandwidth Reduction	Multiple RUs allows for the ability to transmit and receive in non-standard bandwidths; contiguous and non-contiguous 320/160 + 160 MHz and 240/160+80 MHz bandwidths	Can be used for Low Power indoor devices to mitigate contention based protocol/incumbent interference. Allows for 240 MHz bandwidth channel in the 5 GHz band.
Preamble Puncturing	Multiple RUs allow for ability to control each RU transmission, turn certain RUs off to address interference. Mandatory to be considered a Wi-Fi 7 Certified device.	Efficient use of spectrum, no need to switch operating channels to address interference.

Table 2: New features added for 802.11be

Wi-Fi 7

Wi-Fi 7 is the commercial name given to the IEEE Standard of 802.11be. Its main design goal is to achieve extremely high throughput (EHT). This standard has not been formalized by the IEEE, but Wi-Fi 7 products have been available, at least in the U.S., for at least six months. However, those early products will not have all of the new features defined for this standard.

Table 2 shows the significant features added for 802.11be and its impact on the radio interface.

320 MHz Bandwidth

This is optional for both the 5 and 6 GHz band but typically the first feature to be implemented due to the increase in potential data rates. It is even possible to implement a 240 MHz bandwidth as well. I know of one commercial AP that is using a 240 MHz channel in the 5 GHz band.

4096 QAM

4096 QAM allows for 4,096 points in the constellation, as compared to 1,024 for Wi-Fi 6. This equates to 12 bits per symbol, compared to 10 for Wi-Fi 6. Thus, again, higher data rates, theoretically up to 2882 Mbits/sec.

Multi-Link Operation (MLO)

MLO allows sending/receiving packets concurrently on multiple channels which can be either in the same band or different bands. It is designed to provide:

- High spectrum efficiency
- Low latency
- Load balancing
- High reliability

Bandwidth Reduction (Dynamic Bandwidth)

With the adaptive connections possible with Wi-Fi 7, it is possible to reduce the bandwidth of the current operating channel. This could be for either avoiding interference in part of the channel, or a way to optimize the use of the network when only part of a nominal channel is available. This allows the devices to stay on the same channel instead of either stopping transmissions or having to find a free channel. This is not the same as preamble puncturing.

Preamble Puncturing

While optional for Wi-Fi 6, it is mandatory for Wi-Fi 7 certified devices. This allows the devices to notch out, or puncture, part of the original channel to avoid interference and keep transmitting on the current channel. While the overall data rate may reduce, it prevents the devices from having to vacate the whole channel and move to another channel.

6 GHz Band – Wide Open Spaces… With Rules…

On April 23, 2020, the U.S Federal Communications Commission (FCC):

> *"…adopted the rules that make the 1,200 MHz of spectrum in the 6 GHz band (5.925 – 7.125 GHz) available for unlicensed use…*
>
> *"The 6 GHz band is currently populated by, among others, microwave services that are used to support utilities, public safety, and wireless backhaul. Unlicensed devices will share this spectrum with incumbent licensed services under rules crafted to protect those licensed services and enable both unlicensed and licensed operations to thrive throughout the band…"*

On June 17, 2021, the European Commission:

> *"…adopted a Decision harmonising the use of the 6 GHz band for wireless networks across the EU, which will support a growing number of devices, online applications and innovative services that require larger bandwidth and faster speeds…*
>
> *"…The harmonisation decision will make 480 MHz of additional spectrum available in the 6 GHz band. It will almost double the amount of available spectrum, adding to the 538.5 MHz available in the 2.4 GHz and the 5 GHz bands…*
>
> *"…Member States shall make this frequency band available for the implementation of Wi-Fi by 1 December 2021…"*

So, while devices will be able to use the new spectrum for free, there are still regulations with which to comply to avoid interfering with those who have paid to use the spectrum.

Applicable Regulations

FCC

The FCC is responsible for setting the rules and specifications for devices that use the spectrum in the U.S.. Those specifications are found in the Code of Federal Regulations (CFR). The following sections contain the rules and specifications for the different frequency bands in the U.S.:

1. Part 15 Subpart C Intentional Radiators - 15.247 Operation with the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz – for the 2.4 GHz band; and
2. Part 15 Subpart E Unlicensed National Information Infrastructure (U-NII) Devices - 15.407 General technical requirements – for the 5 and 6 GHz bands.

The test requirements, or guidance documents, are part of the FCC's Knowledge DataBase (KDB), and describe how to make the required measurements, or refer to other standards for complete measurement procedures, typically ANSI 63.10. The following KDB documents apply for the 2.4, 5, and 6 GHz bands:

1. KDB 558074 D01 Meas Guidance v05r02 – Measurement Guidance for the 2.4 GHz band;
2. KDB 905462 D02 UNII DFS Compliance Procedures New Rules v02 – Dynamic Frequency Selection for the 5 GHz band;
3. KDB 789033 D02 General UNII Test Procedures New Rules v02r01 – Measurement Guidance for the 5 GHz band;
4. KDB 987594 D02 U-NII 6 GHz EMC Measurement v03 – Measurement Guidance for the 6 GHz band; and
5. KDB 987594 D05 AFC DUT Test Harness Testing v01r01

The FCC regulates the use of the 6 GHz band for unlicensed devices through the use of equipment classes and has different specifications and rules for each class. Figures 1 and 2 show the current and just updated equipment classes for use in the 6 GHz Band (found in KDB 987594 D01 U-NII 6GHz General Requirements v03.)

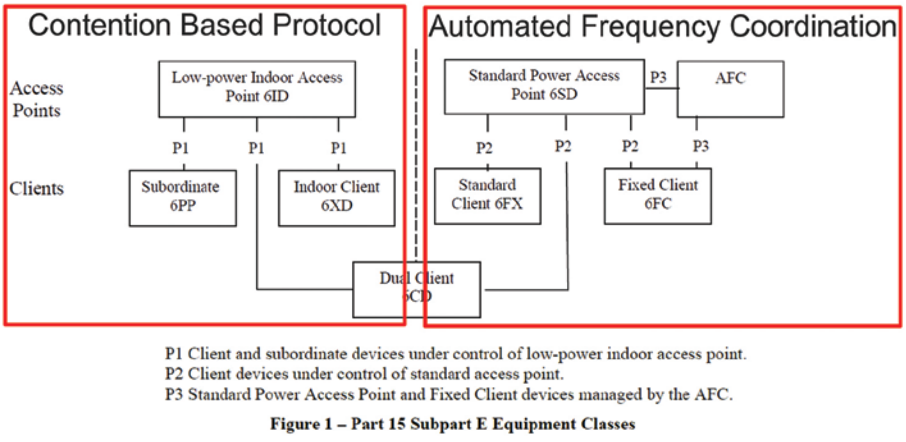
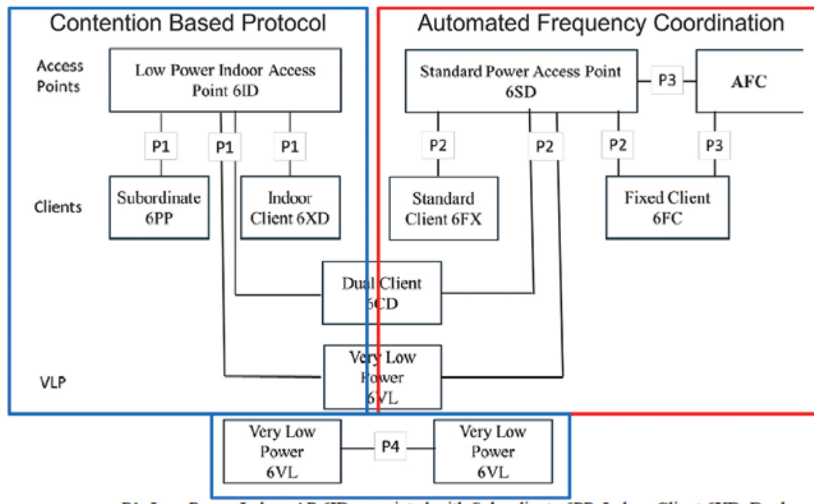


Figure 1: Current FCC Subpart E equipment classes with test requirements

The devices on the left side are part of the low power indoor (LPI) devices and are managed by a contention-based protocol (CBP). This protocol requires devices to monitor the operating channel, and if an incumbent signal is detected anywhere in the channel, it must stop transmitting in that channel until the incumbent stops transmitting.

The devices on the right side were recently authorized for use by the FCC (August 2023). These devices must be associated with a standard power (SP) access point (AP) and are managed by an automated frequency coordination (AFC) system. These devices are typically designed for outdoor use and thus must ensure they are not transmitting on frequencies that are known to be used by incumbents in the immediate area.



- P1: Low Power Indoor AP 6ID associated with Subordinate 6PP, Indoor Client 6XD, Dual Client 6XD or Very Low Power 6VL.
- P2: Standard Power Access Point 6SD Associated with Standard Client 6FX, Dual Client 6XD, Very Low Power 6VL or Fixed Client 6FC managed by the AFC
- P3: Standard Power Access Point 6SD and Fixed Client 6FC managed by the AFC.
- P4: Very Low Power 6VL as peer-to-peer or P2P

Figure 2: Approved FCC Subpart E equipment classes, including VLP devices, with test requirements

Figure 2 shows the recently approved (October 2024) equipment classes that now include very low power (VLP) devices. These devices may be connected to an access point or operate in a peer-peer association (think augmented reality (AR), etc.). Note that VLP devices that are in a peer-peer association are not required to be managed by an AFC system unless they are also connected to an SP AP. VLP devices can be used either indoors (LPI environment) or outdoors (SP environment) and must implement a CBP and Transmit Power Control (TPC) functionality. With the recently published Third Rule and Order, the FCC also allows these devices to use the whole 6 GHz band (5925 – 7125 MHz).

EU

The European Commission determines the directives for radio devices (known as the Radio Equipment Directive, or RED). Article 3(2) of the RED states that:

> *"2. Radio equipment shall be so constructed that it both effectively uses and supports the efficient use of radio spectrum in order to avoid harmful interference."*

The specifications to meet those requirements are defined by the European Telecommunications Standards Institute (ETSI). The following ETSI documents are applicable for the 2.4, 5, and 6 GHz bands in the EU:

1. EN 300 328 V2.2.2 – covers the harmonized standards for the 2.4 GHz band;
2. EN 301 893 V2.1.1 – covers the harmonized standards for the 5 GHz band, including DFS; and
3. EN 303 687 V1.0.0 – covers the harmonized standards for the 6 GHz band.

The EU manages the use of the 6 GHz through the harmonized standard EN 303 687. Developed by ETSI, this standard manages the interaction of the unlicensed and incumbent signals through the following methods:

1. Restricted equipment classes – Similar to the FCC approach, ETSI only allows two types of equipment classes for use in the 6 GHz band:
2. Low power indoor (LPI): Similar concept as the FCC, limited power and for indoor use only; and
3. Very low power (VLP): Right now, this is for narrowband restricted devices. Currently, no AFC system is in use in the EU.
4. No channels above 6425 MHz – Rather than worry about interference in the upper half of the spectrum, the use of unlicensed devices is not allowed.
5. Adaptivity interference testing – This method has been in use for many years, and for all frequency bands. ETSI has a more restrictive approach to devices managing incumbents and is similar to CBP in that devices must stop transmitting while incumbents are transmitting.
6. Punctured channel masks – For those devices employing channel or preamble puncturing, there are very well-defined emission masks for the punctured sub-channels as part of the harmonized standard.

Regulatory Testing Impact

Wi-Fi 6E

Table 3 lists the regulatory testing impact of the changes introduced with the Wi-Fi 6E standards.

Changes	Regulatory Test Impact	FCC	ETSI
160 MHz Channel Band-width	Additional Transmitter Tests	Y	Y
	Additional DFS Tests	Y	N
Open up 6 GHz Band for use	All of 6 GHz Band?	Y	N
	New Receiver Test	Y	N
	Device Classifications	YY	Y
	Automated Frequency Coordination (AFC)	Y	N
Channel Puncturing	Additional DFS Tests	Y	N
	Tx Masks for Punctured Channel	Y/N	Y
New Modulation Format	Additional Tests?	Y	Y

Table 3: Regulatory testing impacts for Wi-Fi 6E

160 MHz Bandwidth

1. Adding a new bandwidth will require additional transmitter tests for both the FCC and ETSI. These tests are required for each operating mode of a device, which includes the channel bandwidth, and for each frequency band with the new bandwidth.
2. The additional bandwidth will add DFS tests for the FCC. The FCC requires that several of the tests be conducted for each channel bandwidth (KDB 905462). For ETSI, the focus is on testing, potentially, the lowest and highest bandwidth, so this is not adding any additional testing.

6 GHz Band

1. As mentioned earlier, the FCC opened up the whole 6 GHz band, allowing for 60-20 MHz channels, and seven (7) 160 MHz channels. More channels mean more testing, as tests are typically on the low, mid, and high channels of the band. For the EU, there are only three (3) 160 MHz channels available.
2. The FCC added a new receiver test for LPI devices, contention-based protocol. Any device that is associated with an LPI AP must employ a CBP system. VLP devices must also employ a CBP system even if they are not connected to an LPI AP. ETSI has always had a receiver-based detection system, so this does not add any new receiver tests.
3. As discussed above, both the FCC and ETSI manage the 6 GHz band by defined classes of equipment. Each device will have specific maximum output power limits and interference management techniques.
4. The FCC has added the AFC requirement for standard power devices, those that would typically be used outside. This relies on a requirement for the AP to request frequency and power limits based on its geolocation. All devices connected to that AP must also adhere to the frequency and power limits dictated by the AP. ETSI currently does not employ an AFC system.

Preamble (Channel) Puncturing

1. If the feature is employed in Wi-Fi 6E, it can be used in the 5 GHz band to avoid interference with detected radar signals (DFS Requirement). This will require additional tests for the punctured channel. It is unclear if ETSI requires additional tests for DFS for punctured channels in the 5 GHz band.
2. No new Tx masks are required for the FCC for the 6 GHz band. There are Tx mask requirements for the 5 GHz band. ETSI currently has Tx masks specified for punctured channels in both the 5 & 6 GHz bands.

New Modulation Format

It is currently unclear if this will add new testing, but both the FCC and ETSI require that the devices be tested under the worst-case conditions. It is also unclear if the higher-density QAM modulation will represent a worst-case condition, but it will have to be investigated as part of pre-compliance testing to determine its impact.

Wi-Fi 7

Table 4 lists the regulatory testing impact of the changes introduced with the Wi-Fi 7 standards.

Changes	Regulatory Test Impact	FCC	ETSI
320/240 MHz Bandwidth	TX Tests	Y	N
	Additional DFS Tests	Y	N
	Additional Receiver Tests	Y	N
Adds Preamble Puncturing	Additional DFS Tests	Y	?
	Additional AFC Tests	Y	N
	Tx Masks for Punctured Channel	N	Y
Adds Multi-Link Operation (MLO)	Additional Spurious Emission/PSD Tests	?	?
Adds New Modulation Format	Additional Tests?	Y	Y

Table 4: Wi-Fi 7 regulatory testing impacts for Wi-Fi 7

320/240 MHz Bandwidth

1. Similar to the requirement for Wi-Fi 6E, adding a new bandwidth will require additional testing for the FCC for all operating modes for transmitter tests. ETSI does not currently support bandwidths greater than 160 MHz.
2. The possibility of using a 240 MHz bandwidth in the 5 GHz bandwidth will add additional DFS testing for the FCC only. ETSI currently does not support bandwidths wider than 160 MHz.
3. Similar to the requirement for Wi-Fi 6E, the FCC added CBP tests for LPI and VLP devices in the 6 GHz band. ETSI already has receiver tests, so there are no additional tests required.

Preamble Puncturing

1. Similar to the requirement for Wi-Fi 6E, the use of preamble, or channel, puncturing in the 5 GHz band will require additional DFS tests for the FCC only. ETSI supports preamble puncturing, but it is unclear if additional tests would be required to satisfy DFS requirements.
2. The FCC will have new tests for the AFC functionality for punctured channels for devices that are either a SP AP or connected through a SP AP. ETSI currently does not support an AFC system.
3. The FCC does require a spectral emission mask for the 6 GHz band but does not require different masks due to preamble puncturing. It does, however, require a Tx emissions mask for punctured channels in the 5 GHz band. ETSI has already defined spectral emission masks for punctured channels in the 5 and 6 GHz bands.

Multi-Link Operations (MLO)

This feature allows a Wi-Fi 7 device to transmit on more than one channel or frequency band at one time. This change may or should require additional testing. The FCC states that it is recommended to verify that a device, when transmitting in different bands, does not exceed the spurious emission requirements, or if transmitting in the same band, that the total power spectral density (PSD) does not exceed the limits. I have seen several test reports where the test lab indicates that they have looked at the MLO operation and saw nothing of concern. It is unclear if there is a similar requirement from ETSI on this topic as well.

New Modulation Format

It is currently unclear whether this will add new testing, but both the FCC and ETSI require that the devices be tested under the worst-case conditions. It is also unclear if the higher-density QAM modulation will represent a worst-case condition, but it will have to be investigated as part of pre-compliance testing to determine its impact.

REGULATORY MEASUREMENT CHALLENGES

FCC

Contention Based Protocol (CBP)

CBP was implemented as part of the requirements for LPI (and now VLP) devices that are operating in the 6 GHz bands. The overall requirement is that, if there is an incumbent signal detected by a device at a level of -62 dBm or lower anywhere in the channel, the device must stop transmitting completely in that channel until the incumbent is no longer detected.

For Wi-Fi 7, it is possible for paired devices to use bandwidth reduction, that is, reduce the bandwidth of the

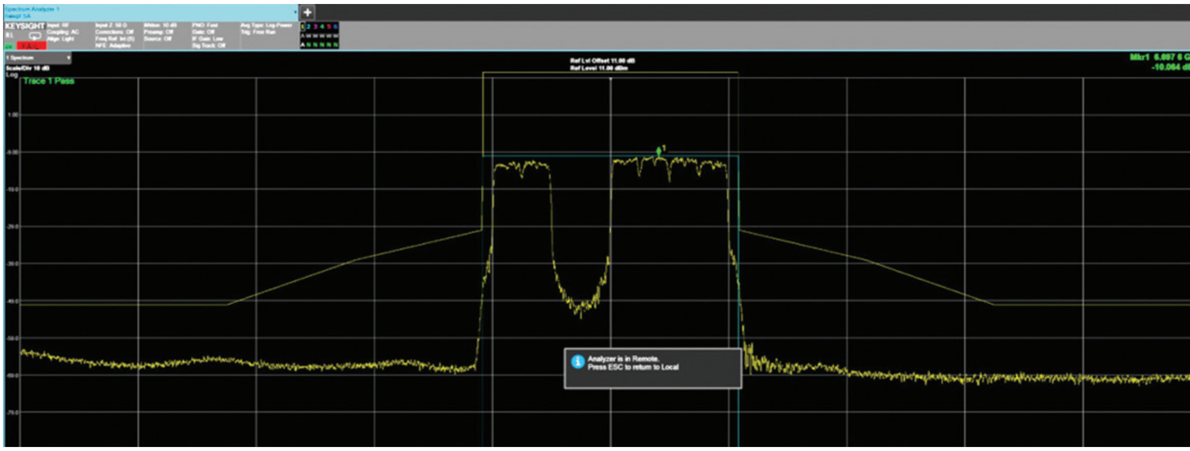


Figure 3: Example of FCC punctured channel emission mask result generated from testing software[1]

operating channel to avoid the incumbent signal. If your devices support that, you would be required to perform the CBP test in this scenario. This will require a tuned measurement on the sub-channel where the incumbent was detected.

The FCC has not provided any guidance for addressing this issue, so we advise consulting with an FCC-authorized Telecommunications Certification Body (TCB) for final review and approval. However, a suggested measurement procedure would likely include the following steps:

1. Set the center frequency of the spectrum analyzer to the center of the sub-channel where the incumbent was detected
2. Set frequency span to zero span
3. Ensure that the resolution bandwidth (RBW) is not too wide to detect the signal from the remaining channel and
4. Use the existing CBP measurement procedure for 90% detection probability.

It is important to note that preamble puncturing <u>*cannot*</u> *be used to circumvent CBP requirements.*

Preamble Puncturing – Emission Masks

<u>*6 GHz Band*</u>

At the October 2023 TCB Workshop, the FCC summarized the results of discussions between industry and the FCC on the subject of emission mask requirements for punctured channels in the 6 GHz band. After lengthy discussions and review, the FCC stated (and included in KDB 987594) that if channel puncturing is used in the 6 GHz Band:

1. For standard power devices, the emission mask of a channel that has employed channel puncturing and the emission mask requirements are the same as those for the whole operating channel. The device, however, must comply with all AFC requirements; that is, the power level within the punctured sub-channel must be at or below the power that the AFC systems would permit across the whole sub-channel.
2. For low power indoor devices, channel puncturing is not permitted, as CBP must be used if incumbents are detected anywhere inside the operating channel.

Figure 3 shows an example of using industry-available testing software to make such a measurement.

Note that the emissions mask is the mask for the whole 160 MHz channel and no changes for the punctured sub-channel.

<u>*5 GHz Band*</u>

The 5 GHz band represents a different challenge for emission masks for the 5 GHz band. Currently, there are no in-band emission mask requirements for the 5 GHz band. But the FCC made a change to address when channel puncturing is used to avoid an incumbent/radar signal in the 5 GHz band. From KDB 789033 D02:

> *"When a 20 MHz portion is punctured the remaining emissions do not bleed into the notched channel, i.e., 26 dB or 99% bandwidth is contained outside of the notched band."*

Currently, there is no defined measurement procedure for this. So, once again, we recommend consulting with a TCB for review and approval. However, from the wording, it appears that the following could be a reasonable engineering best guess for a procedure:

1. Measure emissions or 99% bandwidth of both sides of puncture
2. Verify that the bandwidth upper frequency of left sub-channel is not greater than the center frequency of sub-channel – 10 MHz and
3. Verify that the bandwidth lower frequency of the right sub-channel is not greater than the center frequency of sub-channel + 10 MHz.

Figure 4: Example of a 5 GHz punctured channel FCC emission mask measurement[2]

4. Use the existing channel move and close time measurement procedure.

Figure 5 shows an example of what that punctured signal might look like.

Figure 4 shows an example of this type of measurement procedure where the fifth-20 MHz sub-channel of a 160 MHz channel was punctured, and just the lower remaining channels are shown.

Preamble Puncturing – DFS Requirements

Another other requirement added by the FCC for channel puncturing and DFS Testing is:

Figure 5: DFS channel move and close time FCC requirements for punctured 5 GHz channel

> *"For purposes of DFS testing, verify channel closing and move times are met when one and two 20 MHz channels are punctured."*

In this scenario, you will be required to test for puncturing in at least 2-20 MHz sub-channels with an injected radar signal. Currently, it only requires a measurement of the channel close and moving time and be within the specifications of the existing DFS test. This will require a tuned measurement on the punctured sub-channels instead of monitoring the whole operating channel.

Once again, there is no current measurement guidance on how to do this, so the following is a reasonable engineering best guess for a procedure:

1. Set the center frequency of the spectrum analyzer to center of channel ("sub-channel") where radar was detected
2. Set frequency span to zero span
3. Ensure RBW is not too wide to detect signal from remaining transmission and

AFC – 6 GHz LPI

In KDB 987594, the FCC indicates that the Wi-Fi Alliance (WFA) AFC Test Harness is to be used to verify the requirements for SP APs and devices controlled by an SP AP. The test harness emulates an AFC system to request information from the equipment under test (EUT) and return the requested frequency/channel and power (PSD) limits. RF test equipment is required to monitor the frequency and power of the EUT to then verify it does not exceed the defined limits.

The test harness is only available through the Wi-Fi Alliance. It does have the ability to incorporate RF test equipment but is limited to whatever drivers have been developed by test equipment vendors. Many companies (including mine) have yet to develop drivers for incorporation into the test harness and are reviewing the requirements for integrating its drivers into the test harness. But keep in mind that a test report generated by the test harness is required in order to be accepted by the FCC.

ETSI

Preamble Puncturing – Emission Masks

ETSI has much more stringent emission mask requirements for any 6 GHz channel that employs preamble puncturing to notch out part of the channel. Figure 6 shows an example (taken from Annex D of EN 303 687) of the mask where the third-20 MHz channel of an 80 MHz channel is punctured.

Figure 7 shows an example of using testing software to make a measurement on a punctured channel where two-20 MHz channels are punctured and the applicable emission mask taken from EN 303 687.

SUMMARY

As a summary of the additional requirements due to the implementation of Wi-Fi 6E and Wi-Fi 7:

FCC

1. No preamble puncture is allowed for indoor devices using the 6 GHz band to avoid CBP; however, bandwidth reduction (dynamic bandwidth) is allowed.
2. Preamble puncturing is allowed in the 5 GHz band to avoid interfering with local radars.
3. Unknown emission mask requirements for the punctured channel in the 5 GHz band, other than comparing the 26 dB or 99% bandwidth to the punctured sub-channel.
4. Outdoor devices under the control of a standard power AP must also meet the requirements of an AFC system.

ETSI

1. It is unclear if there are additional requirements or if preamble puncturing is allowed for DFS capabilities in the 5 GHz band. It is possible to use a Notified Body to review and approve measurement techniques.
2. Preamble puncturing is available in the 6 GHz band and uses procedures in EN 303 687.
3. ETSI currently does not support bandwidths greater than 160 MHz. The next version of EN 303 687 addresses this but is not expected to be formalized anytime soon.
4. Finally, it is possible to submit measurement procedures and results to Notified Bodies for approval of the capabilities described above. Several commercial products have been approved for Wi-Fi 7 use in the EU.

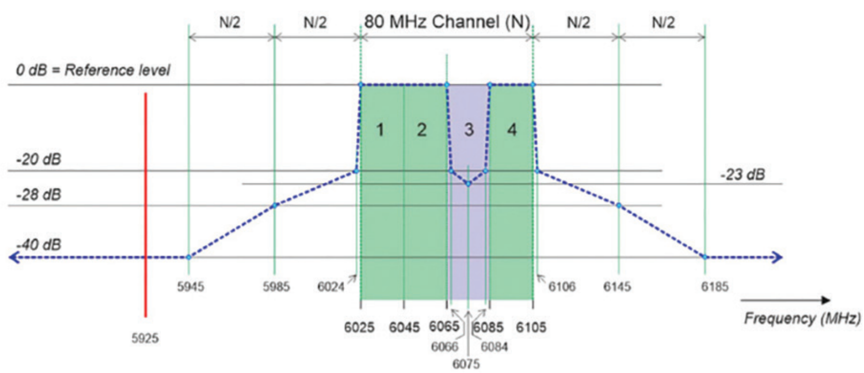


Figure E.3: Example 3

Figure 6: ETSI punctured channel emission mask - 6 GHz

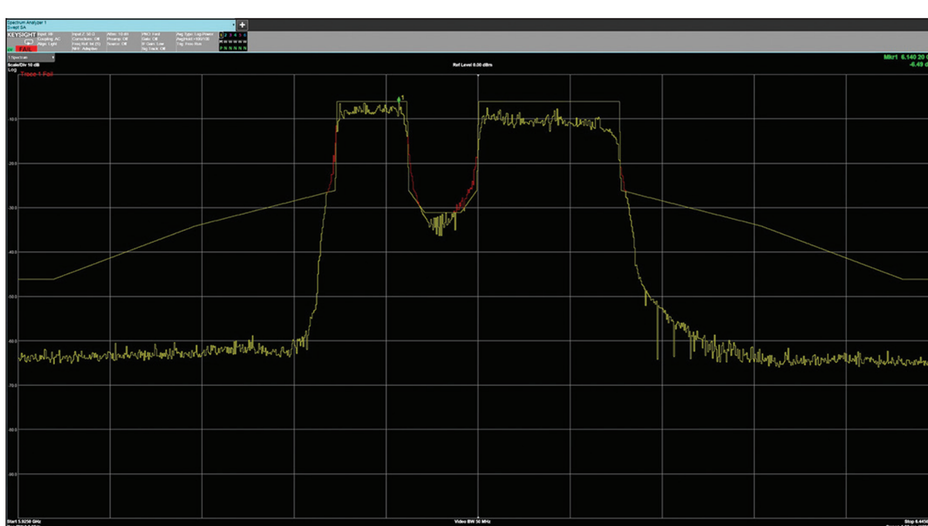


Figure 7: ETSI punctured channel emission mask measurement[3]

With each new wireless standard, the regulatory requirements tend to get a bit more complicated, as do the measurement requirements as well. Because of this, many larger device manufacturers have taken to performing exhaustive pre-compliance testing before sending the device to the test lab for final testing. This can result in increasing time to market as multiple trips to the test lab can be quite time-consuming. It is also an excellent way to quickly verify if changes to firmware/hardware cause an unexpected change in the regulatory testing results.

ENDNOTES

1. Test results were generated using Keysight XA5002A FCC Regulatory Testing Software
2. Test results were generated using Keysight XA5002A FCC Regulatory Testing Software
3. Test results were generated using Keysight XA5001A ETSI Regulatory Testing Software

The Importance of ANSI C63.27 in Wireless Coexistence Testing for Connected Medical Devices

Understanding How Radios Affect Medical Device Compliance

By David Schaefer

Communication has advanced at an unbelievable pace in the 150 years between the Pony Express and the advent of the internet. The shelf life of information has drastically decreased, from weeks to seconds, and the distance we are willing to travel for information has shrunk to virtually nothing. We demand instantaneous access to a massive range of data, no matter where we may be in the world. Companies are spending billions of dollars for faster access to information, and consumers spend more each year on faster devices. Cellular carriers, aware of this trend, have shifted from voice-only networks to data-centric services and are relying more heavily on spectrum sharing.

The first recognizable iteration of Wi-Fi launched in 1999. Prior to 2008, about two billion Bluetooth devices were sold prior. But, in 2022 alone, 4.9 billion Bluetooth devices were shipped in the span of a single year. There are now Wi-Fi access points in planes, dog collars with GPS, and toothbrushes with Bluetooth connectivity. Radio devices are everywhere, and there are more users, more devices, and greater saturation of frequency bands.

Beyond the proliferation of the devices themselves, multiple radio technologies are also being combined into single devices. Many cell phones now have seven different radio technologies, including: 1) Bluetooth, 2) Wi-Fi, 3) global navigation satellite system (GNSS), 4) wireless power transfer, 5) nearfield communication, 6) ultra-wideband for location sensing, and of course 7) 4G or 5G cellular radio.

The radio spectrum is a valuable and finite resource that needs to be shared across all applications, so efficient spectrum utilization is critical as well as a growing focus of regulators. New technologies such as smart antenna systems and orthogonal frequency-division multiplexing (OFDM) are being developed to try to optimize the use of the frequency spectrum. Optimizations such as cognitive radio, which is programmed to select the least congested nearby channels to try to minimize interference, are mandated by trade groups such as the Wi-Fi Alliance and regulatory bodies including the U.S. Federal Communications Commission (FCC) and the European Commission are following suit.

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Connected medical devices monitor patient health and make crucial health information accessible when it is needed. Such devices are often instrumental in saving lives, but they rely on proper operation in their electromagnetic environment.

WIRELESS COEXISTENCE RISKS AND CHALLENGES FOR MEDICAL DEVICES

Connected medical devices monitor patient health and make crucial health information accessible when it is needed. Such devices are often instrumental in saving lives, but they rely on proper operation in their electromagnetic environment. Unfortunately, thousands of incidents of electromagnetic interference (EMI) occur in healthcare every year.

The U.S. Food and Drug Administration (FDA) has a database called MAUDE (Manufacturer and User Facility Device Experience) that tracks medical device malfunctions. It currently contains more than 250,000 reports of issues related to electromagnetic compatibility (EMC). Between 2010 and 2019, there were more than 170 reports of deaths attributable to EMC, electrostatic discharge (ESD), or wireless malfunctions.

Because of the way in which the reports are compiled and recorded, it is not possible to determine how many of these incidents are specifically related to wireless coexistence, but these figures obviously raise concerns about the adequacy of wireless device testing and how such risks can be reduced or eliminated.

HOW MEDICAL TECHNOLOGIES USE RADIO BANDS

Manufacturers are increasingly relying on wireless technologies for functions that are critical to patient well-being, using a variety of radio technologies and frequency bands. Some of these are exclusive to medical devices, but many are shared with other applications or entities. Examples include:

- Inductive radio, which is typically below 200 kHz
- Medical Implant Communication Service (MICS) and Medical Device Radiocommunication Service (MedRadio) 401-406 MHz
- Medical micropower network (MMN) devices in 400 MHz bands
- Industrial, scientific, and medical (ISM) bands are various specific bands shared by medical devices, industrial devices, and various scientific devices, with the most commonly used bands being 13.56 MHz and 2.4 GHz.
- Medical body area networks (MBANs) are adjacent to the 2.4 gigahertz ISM band and allow multiple sensors on a patient's body to communicate with a control unit.
- Wireless Medical Telemetry Service (WMTS) is a safe, proprietary band also used for sensors, like MBANs, but is typically limited to critical care in healthcare facilities.

Medical micropower networks (MMNs) are a subset of MedRadio specifically for implanted nerve stimulators. Thanks to extensive negotiations with the military and the FCC, MMN bands can only be used for these implantable nerve stimulators.

Some bands used by medical technologies are not exclusive to such devices. For example, Wi-Fi is ubiquitous in medical facilities. Most facilities use a secure network to transmit patient data both within the facility and to other medical facilities. MRI, X-ray, and other screening or diagnostic devices may transmit images or data through the secure Wi-Fi network, and it can also be used for tracking patient or staff movements through the facility.

Off-the-shelf technologies like Wi-Fi have both pros and cons: widespread use of Wi-Fi makes interoperability easier, and using a tried and tested technology like Wi-Fi in a new medical device reduces development time. However, Wi-Fi technologies have generally poor product support, can quickly become obsolete due to consumer technology churn, and operate on very crowded bands (2.4 and 5 GHz).

The use of Bluetooth is also becoming more widespread in healthcare. In fact, there is a new use case called the Bluetooth Health Device Profile that has been specifically developed for use in transferring medical data. Common current uses for Bluetooth include inventory tracking, sensors, and glucose monitoring. An emerging application uses 2.4 GHz Bluetooth to send a wake-up signal to an implant, and the implant then uses inductive or MedRadio to transfer data. Additionally, ZigBee, a mesh networking protocol, is used for real-time monitoring systems, similar to MBANs.

Radio frequency identification (RFID) technology is also widely used in medical facilities. It covers multiple unlicensed bands and is primarily used for tracking everything from million-dollar pieces of equipment to single doses of drugs.

Cellular technology in medical applications faces similar hurdles to Wi-Fi. It is used for data transfer, step counters, and even in some diagnostic imaging. The high-bandwidth capabilities of 5G are also prompting more explorations of its use in medicine, such as in remote robotic surgery or in ambulances connected directly and continuously with a hospital.

A critical advantage for all these technologies, and a large part of the reason they are now so in demand, is wireless mobility. Healthcare providers and patients need to be able to move freely, whether across the world or simply from one room to another, without losing access to their data. These applications of radio technologies are not only convenient but can lead to better health outcomes due to faster communication and fewer geographic barriers to accessing the best possible care.

REDUCING THE RISK OF INTERFERENCE THROUGH COEXISTENCE TESTING

Radios also pose a special challenge as medical device manufacturers must use wireless communication in a crowded spectrum. The more users there are on a single band, the greater the risk of interference. There are now billions of Wi-Fi, Bluetooth, and cellular devices in use, with still more added every day. Device manufacturers must manage risks and work proactively to prevent interference with their products. Interference may be inconvenient for consumer products, but it has potentially much more serious consequences for medical devices.

Unfortunately, although risks to the proper operation of safety-critical devices have been widely acknowledged, methods for quantifying those risks have been varied and not comprehensive. This lack of information highlights the importance of widespread wireless coexistence testing for medical devices.

So, let's take a step back to answer an important question. How is coexistence testing different from normal EMC testing?

Electromagnetic compatibility (EMC) is the ability of electronic systems to function acceptably in their

> Historically, some testing laboratories have performed coexistence testing by purchasing off-the-shelf radios and operating them in a shielded room in proximity to the equipment under test (EUT). However, this type of testing has limitations.

electromagnetic environment. Essentially, EMC testing evaluates whether a product will work in the field despite potential interference. Coexistence testing can be thought of as a subset of EMC testing specifically for radio products that demonstrates whether the presence of in-band or out-of-band radios have any impact on functional wireless performance, basic safety, or essential performance.

It is a common misconception that standard EMC tests developed by the International Electrotechnical Commission (IEC) are sufficient to evaluate the risk of interference from nearby wireless sources. However, the specific exclusion bands that are part of most standards eliminate the assessment of in-band interference and with standard EMC testing, there is no way to quantify the risk of interference from other users of the same frequency band, such as other nearby wireless medical devices. As such, EMC testing in accordance with the technical requirements of familiar standards will not directly address coexistence for the radio.

In the EU, the Radio Equipment Directive (RED) cites several standards with requirements similar to coexistence testing, but they are not comprehensive. Tests such as receiver blocking, adjacent channel selectivity, and adaptivity are similar to coexistence tests, but they use continuous wave (CW) or additive white Gaussian noise instead of a representative real-world signal. Additionally, these tests focus only on radio performance, not host performance. When a radio is incorporated into a host, such as a medical device, it may change the radio performance in a way that is not addressed by these tests.

Another factor to consider is that in-band interference is more likely to emerge as a problem for devices that operate in the same band over a long period. Wireless products in a healthcare environment, like a hospital, are likely to be operating simultaneously for very long periods of time.

In 2007, the FDA issued a guidance document that included consideration of coexistence for wireless devices. This FDA guidance document recommended a risk analysis, which is a key part of any medical device evaluation for compliance. Although this document was a recommendation when first published, the FDA now requires an evaluation of coexistence for nearly every product that implements wireless technology. Today, it is a growing area of interest for the FDA, and medical device manufacturers are facing questions during the product review and approval process of whether coexistence has been adequately evaluated through risk analysis or testing.

HOW COEXISTENCE TESTING IS PERFORMED

Historically, some testing laboratories have performed coexistence testing by purchasing off-the-shelf radios and operating them in a shielded room in proximity to the equipment under test (EUT). However, this type of testing has limitations. Some devices, like cell phones, will jump between multiple bands while in use, and there is no way for the technicians conducting these tests to control what band or bands these off-the-shelf devices are using during the test. This means that repeatability is, in some cases, impossible.

Furthermore, the results of the tests can only be applied reliably to the exact off-the-shelf devices used in testing and are not necessarily applicable to other types of devices that use similar radio technology. This also presents an unknown level of risk whenever new radio devices enter the market.

Currently, the recommended testing approach is to thoroughly test and ensure device compatibility in the intended electromagnetic environment using the following steps:

- Perform a risk analysis to determine failure modes and thresholds for wireless communications that occur due to interference, using medical device standards relevant to application and geography.
- Satisfy the requirements for ANSI C63.27 for co-channel interference, adjacent channel interference, and adjacent band interference.
- Supplement with additional testing as new technologies enter the market and new threats emerge.

C63.27 provides the methods for evaluating devices, specifies test plan requirements, and offers guidance on how risk analysis and the results can be used to estimate the likelihood of coexistence.

WHAT IS ANSI C63.27?

ANSI is the American National Standards Institute, a U.S.-based standards development organization, and C63 is a standards development committee focused on EMC and radio testing. The standard C63.27, *American National Standard for Evaluation of Wireless Coexistence,* was first published in 2017 and provides a method for evaluating device coexistence with a focus on mitigating risk. The second edition of C63.27 was released in 2021 with a few significant changes.

C63.27 provides the methods for evaluating devices, specifies test plan requirements, and offers guidance on how risk analysis and the results can be used to estimate the likelihood of coexistence. It is a generalized test method for any wireless product, but the primary focus of its use has been in connection with the evaluation of medical devices.

The standard does not provide pass/fail parameters because they will be specific to each radio and application. Instead, it provides testing guidance and indicates how to evaluate the risk presented by interference from other radios. This will be based on key performance indicators (KPIs) for the functional wireless performance (FWP) – essentially, a combination of monitoring radio performance and how it relates to overall device performance. For example, a KPI might be a bit error rate, while the FWP is a function of the EUT that depends on a wireless link and will be affected if the bit error rate drops. The 2021 edition of C63.27 requires a determination of whether the EUT passed or failed based on its FWP, while the 2017 edition only required reporting of results.

The overall methods in the standard apply to any type of radio, but the standard is intended to test the performance of the end device as a whole, not just the radio modules within the device. The same radio module can be used in either a medical device or an entertainment device, but the functionality, failure thresholds, and potential errors will differ significantly in these different applications.

While C63.27 provides generalized methods for testing coexistence, it currently only contains guidance for a limited number of technologies and frequency bands (Bluetooth, Wifi, and digital enhanced cordless telecommunications (DECT)). The methods described can be used for any radio, and with the FDA's increased scrutiny of wireless in medical devices, device manufacturers should investigate testing to C63.27 for any radio in their product.

The standard contains three potential levels for evaluating a device. Tier three is the least rigorous, testing the fewest signals and providing only very general insight into devices in which potential performance errors are undesirable but will not cause serious consequences. Tier one is the most rigorous and is used for devices where the absence of coexistence can cause unacceptable consequences.

TEST SETUP UNDER C63.27

The setup for testing contains three items – the EUT, a companion device communicating with the EUT, and an interference source. Four test methods are described in C63.27. The choice of the test method is up to the user of the standard and should be chosen in partnership with your chosen test laboratory. The four methods are:

- *Conducted (wired) method:* Performed by using a mixer to combine the intended and unintended signals and connecting to the antenna port or the EUT. This excludes the antenna itself from testing and is the most repeatable but least realistic test method.
- *Multi Chamber method:* The EUT and the equipment generating signals are each placed in separate chambers to control how the equipment under test is exposed to the signals.
- *Radiated-anechoic method:* Places the EUT in a chamber with both intended and unintended signal emitters. This creates an environment that does not necessarily replicate the deployed environment but removes environmental variables that would decrease repeatability.
- *Radiated open lab method:* This method involves no chambers or shields and usually attempts to replicate the deployed environment. This testing may be affected by ambient signals and limits the interfering signal to those legally allowed by spectrum regulators.

With a well-designed test plan, test data will help determine crucial coexistence parameters for the device and form the basis for proper risk analysis.

Not all medical products containing a radio necessarily need to be tested in accordance with the requirements of C63.27 but a risk analysis does need to be conducted to evaluate potential effects and failure modes. AAMI TIR69:2017 is a technical information report that offers a process to assess and categorize the risks associated with the wireless functions of a medical device. If the risk assessment shows that the device's wireless technology presents no significant risk, the manufacturer can choose not to test for wireless coexistence. However, many manufacturers choose to do so anyway. C63.27 provides a more comprehensive risk assessment to wireless threats.

CREATING A WIRELESS COEXISTENCE TEST PLAN

ANSI C63.27 specifies that, prior to testing, the manufacturer must create a test plan that includes key performance indicators, the intended functional wireless performance, and how these factors will be monitored. The manufacturer will need to provide information that includes the test methods to be used, the intended signals for the device, and the interfering signals to be tested.

A common misconception is that the testing laboratory will make these decisions. Yes, testing labs can help discuss test needs and provide guidance but manufacturers are ultimately responsible for the development of the risk analysis and for identifying what needs to be monitored during testing.

To determine appropriate coexistence parameters, manufacturers must have a good understanding of what radiofrequency signals may interfere with their device based on when, where, and how the device will be used. Because there are a finite number of frequencies, different methods have been devised so that the same frequencies can be used in multiple ways:

- FDMA stands for frequency-division multiple access. An example of this is FM radio. The FM band is split into multiple channels that can be used simultaneously, but one channel cannot be used by two stations at the same time and in the same location.
- TDMA stands for time-division multiple access. This means that different radios use the same frequency band but at different times to avoid interference – essentially, taking turns.
- CDMA stands for code-division multiple access. CDMA uses transmitter coding and spread spectrum techniques to allow multiple transmitters to share channels and bands.

The goal of coexistence testing is to determine if a given device, considering its output power, can reliably operate in its intended frequency band without interference either from within the same band or from adjacent bands. There are three primary values that testing will focus on:

- Maximum separation distance between interference and EUT
- Maximum duty cycle of interfering signals
- Maximum frequency separation of signals in the adjacent channel/band

Interference can come in multiple forms:

- *Adjacent channel or adjacent band interference:* When two channels are close to each other, there can be overlap between them, decreasing the overall signal quality in both bands.
- *Co-channel interference:* When two different transmitters using the same channel can be picked up by the same device, creating crosstalk.
- *Harmonic interference:* Out-of-band transmitters can sometimes cause a harmonic signal to show up in a different band.

With a well-designed test plan, test data will help determine crucial coexistence parameters for the device and form the basis for proper risk analysis. Manufacturers will be able to evaluate both the point at which the equipment's key performance indicators begin to degrade and at what point the equipment becomes nonfunctional. These values can be used to calculate minimum signal strength, the minimum separation distance from other transmitters, and other technical and safety parameters.

EXPERT OBSERVATIONS FROM THE TESTING LAB

Many medical devices use off-the-shelf Bluetooth, cellular, and Wi-Fi technologies. Fortunately, these well-established technologies already have certain protections against interference, like cognitive radio, It's important that manufacturers and their testing partners be familiar with the updated version of ANSI C63.27 when creating their test plans.

built in. This reduces some risks that need to be tested for custom-built radios. Manufacturers can make some modifications to off-the-shelf radio modules or systems to improve their performance in medical devices, such as changing frequency bands, adjusting radio sensitivity, or improving antenna performance, but off-the-shelf technology typically can't be significantly modified. Even so, any results from testing can be used to benchmark future module purchases, as well as adjust the radio parameters.

Cellular technology has the added advantage of higher transmit power, more frequency bands, and frequency division duplexing, that is, where transmitting and receiving are on separate channels. These features can help prevent unintended signals from affecting the intended signal.

For purpose-built radios, manufacturers must include some sort of collision avoidance programming. Manufacturers must also be mindful of the firmware or software controlling the radio. In testing, we have found firmware in Bluetooth or Wi-Fi devices that unintentionally negates the cognitive radio functions or the collision avoidance functions, reducing the device's resistance to interference.

THE FUTURE OF WIRELESS COEXISTENCE

As previously noted, the second edition of ANSI was published in 2021. The primary changes included in this edition offer further clarification on the interfering signal parameters and additional testing for LTE-LAA equipment. The requirements for the test of Tier one devices have also been updated with additional tests now required for that category. This version of the standard also includes a new Annex F, which lays out parameters for estimating the likelihood of coexistence. This is an important component of risk management.

It's important that manufacturers and their testing partners be familiar with the updated version of this standard when creating their test plans. A working group has been formed to release a corrigendum covering some minor fixes to the 2021 edition with an expected publication date of Q1 of 2025. After publication of the corrigendum, work will begin on the third edition.

Future editions of the standard will likely address some limitations in the current edition. For example, the output power of the interfering signal or intended signals could be varied over time to simulate movement around a facility, reflections, or channel utilization. The duty cycle of these signals could also be increased or decreased during testing.

As new technologies develop and the use of radio bands changes, the devices that rely on these technologies will also need to undergo coexistence testing. The FCC has opened the 6 GHz band for unlicensed use, and there are now many 5G bands in use. Other new bands are being opened for different applications, and the use of radios in medical facilities continues to grow.

With the rapid pace of technological development, the ever-changing regulations surrounding radio devices, and the high stakes associated with medical technologies, manufacturers must fully understand the requirements and best practices associated with their products and must have a reliable, well-informed, and communicative testing partner to guide them through the testing process.

Complying With the EU's EMC Directive Without 3rd Party Testing

A Guide to Alternative Self-Declaration Compliance Paths

By Keith Armstrong

A common path to achieving compliance to the European Union's (EU's) EMC Directive 2014/30/EU (which I shall call the EMCD here) takes many manufacturers down the route of utilizing a third-party EMC test laboratory to obtain EMC test reports for their products. This process was detailed in the article "IT Server Hardware Compliance, Part 1," which appeared in the December 2023 issue of *In Compliance Magazine* [1].

However, it is important to understand that the EMCD *contains no legal requirements for performing any EMC laboratory tests*. This was equally true for the original EMCD, 89/336/EEC, and its 2nd Edition, 2004/108/EC.

Manufacturers are required to affix the CE marking to their products, and to do that, they must first have created and signed an EU EMC Declaration of Conformity (DoC), which is based on the evidence of EMCD compliance contained within a Technical Documentation File (TDF).

As I will show later, there are two routes to declaring EMC compliance (sometimes called conformity to the EMCD), and it is the manufacturer's choice whether his DoC relies entirely on all relevant harmonized standards (the "Standards Route") or uses just a few or none of the relevant harmonized standards (the "EMC Assessment Route").

Either way, a DoC is effectively a legal statement by a manufacturer that "if my product was tested to these harmonized standards, it would probably pass."

CE-marking plus a DoC is a requirement for crossing customs borders into and within the EU. For the official "chapter and verse" on this, see my January 2024 blog "No tests are required for CE-marking to the EMCD[1]."

How a manufacturer obtains sufficient confidence to make this legal declaration is entirely up to that manufacturer

1. Available at https://www.emcstandards.co.uk/no-tests-are-required-for-ce-marking-to-the-emc.

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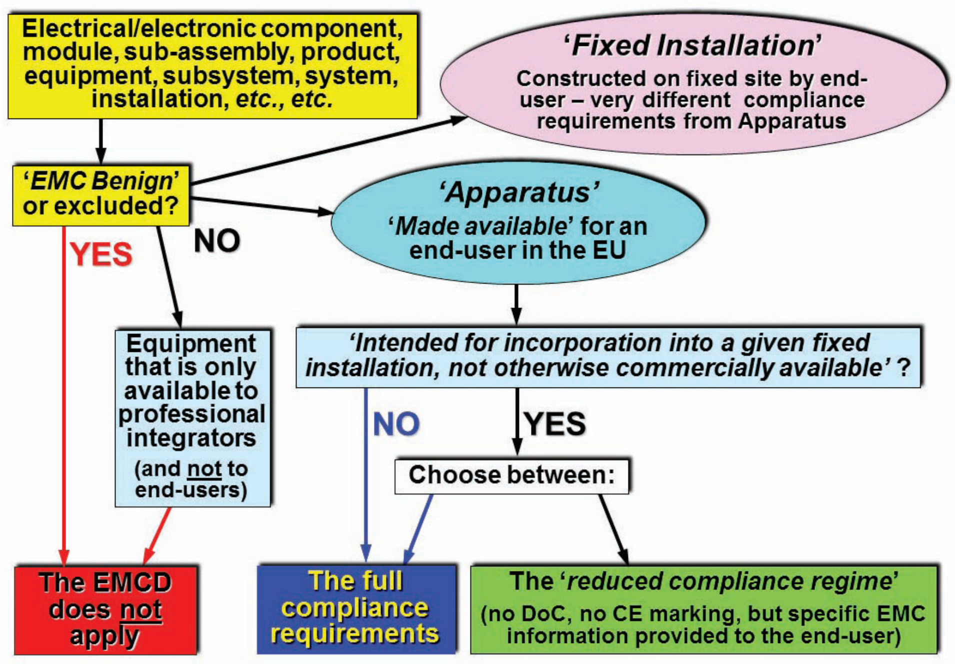

Figure 1: Applying the EMC Directive

and should be documented in the TDF. But compliance with the EMCD certainly does not require any test reports from third-party EMC test labs. This makes it possible for manufacturers of electronic products to save time and money by testing in their own EMC labs.

This also makes it possible for individual entrepreneurs who might be working out of their garages (like Mr. Hewlett and Mr. Packard!) to sell their products in the EU without the high costs associated with EMC testing to standards. In fact, the same is true for most of the so-called CE Marking Directives – third-party testing is only a legal requirement in a very few EU Directives, and only when dealing with especially dangerous products, such as certain kinds of medical equipment, machinery such as chainsaws, bandsaws, etc.

I have often heard the EU's single market described in the United States (U.S.) as "Fortress Europe," when the exact opposite has always been true. The EU's single market does not present any significant barriers of cost or delay to any equipment from anyone, anywhere in the world.

APPLYING THE EMC DIRECTIVE

OK, that's enough background. Let's get into the details!

To see how it is that manufacturers can comply with the EMCD [2] without third-party testing, even without any testing at all, we need to understand how the EMCD works. When we understand this, we will also understand that even passing third-party laboratory tests to all relevant EU-harmonized EMC standards might not, on its own, ensure compliance with the EMCD.

The EMCD applies to both *apparatus* and *fixed installations*, with special legal meanings for both of these otherwise commonplace terms. Figure 1 shows that apparatus is treated very differently from fixed installations.

Apparatus is any electrical/electronic item that could cause or suffer EMI *and* which is "made available for an end-user in the EU" for the first time (see later). It is important to understand that the EMCD applies to every individual unit of manufacture (e.g., individually serial numbered items), and Chapter 2.2 in [4] and Chapters 1.2 and 3.2.2 in [5] provide much more detail on this.

The EMCD also has a special category of apparatus "… intended for incorporation into a given fixed installation, and not otherwise commercially available" (which most of us would call *custom*, *bespoke*, or *one-off* equipment), which can avoid having to be CE marked for EMC, although it then has to comply with other EMC activities.

Inherently benign equipment is excluded from the EMCD's scope, and the official guide [5] contains a list of what is currently considered to be EMC benign. As a general rule, inherently benign equipment never contains any operational semiconductors (rectifiers, transistors, ICs, etc.) or thermionic valves, or makes sparks.

Equipment that is only made available for the exclusive use of professional integrators in the construction of their own products and which is not made available for end-users (even by distribution) is also excluded from the scope of the EMCD. However, such equipment will almost certainly have to be CE marked for compliance with an EU safety directive, such as the Low Voltage Equipment Directive (the LVD) [6], Machinery Directive [7], etc. This is one reason why a manufacturer should never assume EMC compliance when purchasing a CE-marked third-party product for incorporation into another product, system, or installation.

I have seen many large projects suffer greatly from main contractors making two big errors regarding EMC:

1. Mistakenly assuming that every item of equipment that carries a CE marking must perforce comply with the EMCD. This article describes three ways in which this assumption can be wrong, all of which are shown in Figure 1.
   a. When the equipment is *inherently benign*;
   b. When the equipment is only supplied to professional integrators, whether it is manufactured in volume or custom-designed (e.g., as a subcontract); or
   c. When the equipment is custom-made for a particular end-user's fixed installation
2. Mistakenly assuming that an EMC-compliant final system merely needs EMC compliance for its constituent parts, often mistakenly called the CE + CE = CE approach (see later).

Also exempt from the EMCD are: a) radio amateur equipment that is not commercially available; b) aeronautical equipment covered by Regulation 216/2008; c) "custom-built evaluation kits destined for professionals to be used solely at research and development facilities;" and d) equipment covered by the Radio Equipment Directive (2014/53/EU), typically referred to as the RED[2].

2. See https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/radio-equipment-directive-red_en

For any equipment that has one or more functions that use radio wave communications or propagation (even simple broadcast receivers), the RED has very important implications for complying with the EMCD [2] and the LVD [6]. (See a video of my presentation at the 2020 IEEE EMC+SIPI Symposium, "Who's Afraid of the Big Bad RED," available at https://vimeo.com/469763677.)

Equipment that has EMC aspects addressed in specific product Directives (e.g., medical devices, automotive, etc.) is only exempt from the EMCD to the extent covered by those other Directives. Unfortunately, this is widely misunderstood to mean they are totally exempt from the EMCD.

Apparatus that must comply with the EMCD when made available for an end-user in the EU may be advertised or exhibited before it is EMC compliant, as long as it is clearly marked as being non-compliant with the EMCD, and, as not (yet) being available to end-users in the EU.

EMC CONFORMITY OF APPARATUS

The EMCD requires all apparatus to:

1. Comply with the Essential Requirements
2. Undergo a conformity assessment procedure
3. Have a TDF prepared and readily available for inspection by enforcement officials
4. Be supplied with specified User Information
5. Have a signed EC Declaration of Conformity
6. Carry the CE marking

Items 1-5 in the above list must be complete before the CE marking is applied (item 6).

All of the items 1-6 must be complete before the apparatus is "made available" for the first time in the EU (see 2.2 and 2.3 in [4]). It is important to note that being made available for the first time in the EU does not only mean new products. Used or second-hand products that are brought into the EU are also covered and have to comply with the EMCD, no matter how old or how large they are.

As already mentioned, there is an exclusion to compliance with the EMCD for apparatus intended for incorporation into a given fixed installation and not otherwise commercially available (see later).

THE PROTECTION REQUIREMENTS

The Essential Requirements (Clause 1 of Annex I in [2]) state the essential legal requirements for compliance with the EMCD, using simple terminology in the (probably vain) hope that this will make it difficult for lawyers to interpret them in ways other than what was intended:

> *"Equipment shall be so designed and manufactured, having regard to the state of the art, as to ensure that:*
>
> *(a) the electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended;*
>
> *(b) it has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use."*

Who would ever want their products not to comply with these Essential Requirements? The costs of dealing with the resulting complaints (and the loss of possible future sales) would eat into the financial bottom line, making a manufacturer less profitable.

So, even if there was no EMCD, the Essential Requirements above should still be applied to help reduce financial risks.

CONFORMITY ASSESSMENT IN GENERAL

Conformity assessment is specified in Annex II of [2] and requires an EMC Assessment that results in a TDF that demonstrates how it is that a product can claim compliance with the Essential Requirements. A TDF should cover all operational modes and all intended use configurations, and the amount of verification work required can be reduced by first identifying the worst-case combinations of configuration and operational mode, i.e., the ones that would cause the highest emissions or are the most susceptible to interference.

As I said earlier, there are two routes to conformity with the EMCD:

1. The Standards Route, which uses harmonized EMC standards; and
2. The EMC Assessment Route, which can use any standards or none.

CONFORMITY ASSESSMENT BY USING HARMONIZED STANDARDS

When following the Standards Route, the product's DoC must list all of the relevant harmonized EMC test standards that apply to the product, which can be found on the official listing website at [8]. This route to EMC conformity requires that all these harmonized standards are correctly applied. But what does "correctly applied" actually mean?

Clearly, one way is to have a third-party test lab perform all of the tests exactly as described in the relevant standards, with the EMC test reports forming the bulk of the TDF. If the test lab is accredited by a national accreditation body to perform a particular test, there is more confidence that the test will be done correctly. Unfortunately, my experience (and that of many others) is that not all national accreditation bodies are equal.

Third-party testing has been very well described in [1], so I don't need to go into it here.

Some manufacturers (and not only the larger ones) have their own full-compliance EMC testing labs, and some of them even have some/all of their testing labs accredited for most of their tests – but not all, so make sure to check with them if accredited tests are what you want. These labs are generally best used just as if they were third-party labs.

(Interestingly, in-house testing labs located in the same building as the design teams can pay back their original investment much more quickly than the usual business case predicts. I have seen one such lab achieve full payback in four months!)

However, as stated early on in this article, using the services of a third-party accredited testing lab to correctly apply a harmonized standard to test exactly to the standard is <u>not</u> the only option when following the Standards Route.

The "correct application" of a harmonized standard actually means that a manufacturer has done enough homework to have sufficient confidence that if the product was fully tested in an EMC laboratory that was accredited to test to that standard – it should pass.

Let's be perfectly clear on this. "Correct application" does not mean that the product has actually been tested to that standard but only that, if it were tested at some future time, it would probably pass.

The EMCD leaves manufacturers totally free to decide on the amount and quality of EMC testing they do themselves - or have done for them - to have sufficient confidence to sign their DoC when using the Standards Route.

(It is important to understand that there are no absolute guarantees in the world of EMC, even with fully accredited third-party testing. A product that passes in one testing lab can fail when tested in another lab, even though nothing has changed in the product and the exact same cables are used with it. Some manufacturers take advantage of this by always using test labs that they find are more likely to give them a pass result!)

Here are four examples of when laboratory testing might not be required to correctly apply a harmonized radiated emissions standard such as EN 55022:

A. When the product emits a certain amount of radio frequency (RF) power spread in a particular way over a particular frequency spectrum, and calculations/simulations show that, if this emitted power was measured according to the relevant EMC test standard, it would be almost certain to pass (even when taking measurement uncertainty into account). For examples of this approach, see [9] [10] and [11].

B. When the product is housed in a well-shielded and well-filtered enclosure that has been proven by shielding effectiveness testing and/or simulation to provide more than sufficient RF attenuation to ensure that, if

Even when full testing is done in a lab that is accredited for that test, and passed, it might not ensure compliance with the Essential Requirements in real-life operation. This is, of course, what really matters for compliance with the EMCD and also (more importantly) for financial success.

its emitted RF power was measured according to the relevant EMC test standard, it is certain to pass (even when taking measurement uncertainty into account).

Many manufacturers purchase well-shielded/filtered overall enclosures, then ruin them with modifications, completely wasting their high cost (see Chapter 5 of [12]). So an expert assessment is usually required to have sufficient confidence in the final assembly.

C. When a product fails in a test lab and a simple modification applied by hand makes it pass, and the same modification is applied on production units, there can be sufficient confidence that, if a new production sample was retested, it would pass.

In this context, "the same modification" means physically and dimensionally the same – for example, an additional shield bond made with a screw-fixing is not the same for EMC as an additional bond made in a different place or made in the same place with a braid strap or piece of green/yellow wire instead of a screw.

D. When a product has passed an equivalent or tougher radiated emissions test and has not been changed (either in its hardware, software, or components).

A typical example is a product that has passed MIL-STD 461 radiated emissions tests, which set lower emissions limits than the relevant harmonized test standard (see [13]).

4.3 in [5] provides very good guidance on EMC assessment, and makes it clear that the EMCD contains no legal requirements for testing.

Unfortunately, even when full testing is done in a lab that is accredited for that test, and passed, it might not ensure compliance with the Essential Requirements in real-life operation. This is, of course, what really matters for compliance with the EMCD and also (more importantly) for financial success. This is because no harmonized test standards cover all of the EM disturbances that could occur in real life. Also, it is because the tests have been specifically developed to ensure repeatability in testing, which can often mean they are simply not representative of real-life EM disturbances.

Also, given the inevitably slow pace of international standardization, most published standards are behind the times. For example, none of the harmonized immunity standards cover the very close proximity of cellphones, e-book readers, Wi-Fi transmitters, RFID transmitters (including active RFID tags), etc., even though such proximity is now a normal "… electromagnetic disturbance to be expected in its intended use…".

Immunity to the near-fields (see [14]) that can be created by portable RF transmitters in very close proximity is arguably now a necessity for legal compliance with the Essential Requirements, even though not tested by any harmonized standards.

"Big deal," you might say, "but I don't want to spend any more on legal compliance than I have to!" OK, but think for a minute about what I said earlier in the section on Essential Requirements. If products don't comply with them, they are less likely to be financially successful. If they have big problems with EMC in real life, they could even do irreparable damage to a manufacturer's brand image and future profitability. Some companies have actually been bankrupted by real-life EMC problems.

The real reason we need to achieve EMC compliance is to have products that work well enough in real life and don't upset customers. Achieving this is important to help control financial risks, and so what if we have to produce a few pages of legal documentation for EU sales, when it merely covers EMC work we have already done?

For these reasons, when following the Standards Route, in addition to correctly applying all relevant harmonized standards, I always recommend performing a full EMC assessment as detailed below, then doing whatever else it takes to ensure conformity with the Essential Requirements. This can sometimes be as quick and easy as a check for emissions or immunity using a homemade near-field probe with a low-cost spectrum analyzer [15].

Please note that, when following the Standards Route, the DoC should not state that the product has been tested to the listed harmonized standards and has passed those tests (unless they have been, of course!). Generally, it is better for the DoC to say something like, "The following standards have been applied…".

CONFORMITY ASSESSMENT BY NOT USING HARMONIZED STANDARDS

The EMC Assessment Route is the other route to EMC conformity permitted by the EMCD. When following this path, a manufacturer declares the EMC conformity of his apparatus directly with the Essential Requirements of the EMCD, using just some of the relevant harmonized standards, or just some parts of some harmonized standards, or even ignoring all harmonized standards completely. The EMC Assessment Route must follow a specified technical methodology to ensure that the Essential Requirements are met.

According to [5], the EMC Assessment Route is usually more appropriate than the Standards Route in the following situations:

- Where the Essential Requirements are not entirely covered by the application of the harmonized standards that are relevant for the product;
- Where the apparatus uses technologies incompatible with, or not yet taken into account by, any harmonized standards;
- The manufacturer uses test facilities not yet covered by harmonized standards;
- The manufacturer prefers to apply other standards or specifications (even in-house specifications) that are not harmonized under the EMC Directive; or
- The apparatus is physically too large to be tested in the type of facility specified by a relevant harmonized standard, or where "in-situ" testing is necessary (e.g., for systems or installations that are first assembled on the end-user's site) and is not adequately covered by a harmonized standard.

Of course, a manufacturer may choose to follow the EMC Assessment Route simply to save time and money, which is often the case for start-up companies that cannot afford the cost of laboratory testing.

This alternative conformity route is essentially the old TCF route under the first EMC Directive (89/336/EEC), but with the significant difference that now there is no legal requirement for any TDFs to be assessed by a third party (see Notified Bodies, later).

Non-harmonized methods of demonstrating conformity with the Essential Requirements, which may be able to be used, either singly or in suitable combinations, as part of an EMC Assessment Route, include (but are not limited to):

1. Non-EU-harmonized but published EMC test standards (e.g., FCC, military, automotive, national, etc.);
2. In-situ/on-site EMC tests [16];
3. EMC tests or checks developed by the manufacturer that are not compliant with the harmonized test methods listed in [8]. These are often called "pre-compliance" EMC tests and can vary from full-compliance tests that are just done a little more quickly than they should be, to near-field probing and a variety of other low-cost methods e.g., those described in [15], which might bear little resemblance to harmonized tests;
4. Calculations (e.g. [9] [10] [11]);
5. Validated computer simulations;
6. Comparisons with known EMCD-compliant products made by the same manufacturer, which use the same technologies, devices, and construction methods. (But beware. Hardware and software technologies, and devices, change very rapidly. And so do their EMC characteristics!)

The EMC Assessment Route's technical methodology includes (but is not limited to):

A. Assessing the EM environment(s) normally expected at the user(s) location(s), taking into account (see [17]):
   i. The likely proximity to sensitive equipment that the product's emissions could interfere with;
   ii. The likely EM "threats" that could interfere with the product, plus the degradation of functional performance that the user will accept when it is interfered with.

B. Create the EMC specifications for the product. To help make life easier, these often use modified versions of harmonized standards, basic IEC test methods (see [1]), other EMC standards (automotive, military, aerospace, etc.), and/or guidance for systems and installations such as [12] [18] [19] or some of the many references they contain.

C. Verify and/or validate the product's design against the EMC specifications. Verification and validation techniques include, but are not limited to, EMC testing.

Constructing systems only from items that are CE-marked, and mistakenly assuming that this alone takes care of the EMC compliance of the overall system or installation, is often (mistakenly) called the CE + CE = CE approach. I say "mistakenly" because it simply doesn't work!

THE 3RD EDITION OF THE EMCD, 2014-30-EC, APPLIES FROM 20 APRIL 2016

All of the technical compliance issues discussed in this article, and in [1], were previously published in *In Compliance* Magazine in December 2014 (see [20]) and are unaffected by the third edition of the EMCD [2]. The changes in [2] are more to do with adapting the existing EMCD to the EU's New Legislative Framework (NLF, see [4]).

The changes wrought by the NLF are mostly concerned with extending legal compliance requirements to all economic operators through whose hands EMCD-compliant products pass, including the manufacturer of the products (obviously), appointed agents, distributors, importers, etc.

CE + CE DOES NOT EQUAL CE

Constructing systems only from items that are CE-marked, and mistakenly assuming that this alone takes care of the EMC compliance of the overall system or installation, is often (mistakenly) called the CE + CE = CE approach. I say "mistakenly" because it simply doesn't work!

This incorrect approach is very widely used by system integrators, installers, and major contractors. However, it is easy to show that, technically and/or legally, this approach should never be relied upon, and Chapter 1.2.2 in the official guide [5] contains a specific warning against using it. More detailed information on this is given in Chapter 1.5 of [12], Chapter 2.3.4 of [18], and Chapter 2.3.3 of [19].

Note that the so-called CE + CE = CE approach is also incorrect technically and/or legally for most, if not all other, EU Directives, including [6] and [7].

CONCLUSION AND ADDITIONAL INFORMATION

There's a great deal more I could write on complying with the EMCD, but I've covered the main issue of how to comply without using laboratory testing and wandered off into some related issues as well.

To find out more about related issues, here are some sources of free information:

- Employing Notified Bodies (see [21]);
- Creating and maintaining the TDF (Technical Documentation File) (see [21]);
- The EU EMC DoC (Declaration of Conformity) (see [21]);
- Correctly affixing the CE Marking (see [21]);
- The EMC information legally required to be provided with each apparatus (see [21]);
- Maintaining EMC compliance in serial or batch manufacture (see [21]);
- Maintaining EMC compliance when the harmonized standards change (see [21]);
- EMC compliance of custom-designed "apparatus intended for incorporation into a given fixed installation, and not otherwise commercially available" (see Chapter 2.5 of [18]); and
- EMC compliance of "Fixed Installations" (see [18]).

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Emerging Standards and Regulations for Medical Devices

Understanding Requirements Within the IEC 60601-1 Series of Standards

By Vik Chandna

In response to rapid technological advancements in the medical device field, regulatory bodies like the U.S. Food and Drug Administration (FDA) and Health Canada are actively working to ensure that applicable standards are in place that thoroughly account for these innovations.

The first edition of IEC 60601-1, titled "Medical electrical equipment - Part 1: General requirements for safety," was published in 1977. This standard laid down the basic fundamentals for the safety of medical electrical equipment (ME equipment) and established a framework for subsequent editions and amendments.

Since its initial publication, IEC 60601-1 has undergone several updates to reflect advances in technology, changes in regulatory requirements, and improvements in safety assessments for medical devices. The current edition of IEC 60601-1 is Edition 3.2 and is internationally recognized and accepted by regulatory authorities worldwide.

Vik Chandna is the Director of Product Safety at Megalab Group and has over 22 years of experience in the regulatory field working with standards such as IEC 60601-1, IEC 61010-1, and IEC 62368-1. For more information, contact Chandna at vchandna@megalabinc.com.

KEEPING UP WITH INNOVATION

The landscape of the medical technology (MedTech) industry has undergone significant transformation in recent years, driven largely by advances in technology and a shift towards innovation and entrepreneurship.

Several key trends are contributing to this evolution:

- *Integration of advanced technologies:* Medical device manufacturers are increasingly incorporating cutting-edge technologies such as artificial intelligence (AI), machine learning, home healthcare, robotics, and wearable technologies into their products. These technologies enhance the capabilities and functionalities of medical devices, leading to more accurate diagnoses, personalized treatments, and improved efficiency in patient diagnostics and treatments.

- *Rise of startup companies:* The once high barriers to entry in the MedTech industry have been significantly reduced in recent years, fostering the formation of an increasing number of startup companies focused on developing innovative medical devices. These startups often have strong cross-functional teams involved in the development processes, allowing them to bring products to market more quickly and more efficiently than larger, established companies. In addition, innovation hubs,


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incubators, and accelerators are further supporting the formation and growth of startup companies by providing funding, resources, and mentorship.

- *Focus on user-centered design:* Previous usability studies show a growing emphasis on designing and developing medical devices that improve the user experience for both healthcare providers and patients. This involves understanding the needs and preferences of these users and designing devices that align with these factors and are easy to use.

Overall, the MedTech industry is experiencing a period of rapid innovation and disruption, driven by technological advances, entrepreneurial spirit, and a growing focus on improving healthcare outcomes. This trend is expected to continue as new technologies emerge and the demand for innovative medical devices grows.

However, while innovation is flourishing in the MedTech industry, startups and small companies face regulatory challenges in bringing their products to market. Navigating complex regulatory pathways and obtaining approvals from certification and regulatory bodies such as UL, CSA, the FDA, and Health Canada to affirm compliance with the applicable safety standards are significant hurdles for MedTech startups.

Fortunately, emerging regulatory frameworks and initiatives aimed at streamlining the regulatory process for innovative medical devices are helping to address some of these challenges.

COMMON STANDARDS

The following standards are crucial for ensuring the safety and effectiveness of medical electrical equipment (ME equipment):

Standard	Description
IEC 60601-1-8:2006/AMD2:2020	Collateral Standard: General requirements, tests and guidance for alarm systems in medical electrical equipment and medical electrical systems
IEC 60601-1-11:2015/AMD1:2020	Collateral Standard: Requirements for medical electrical equipment and medical electrical systems used in the home healthcare environment
IEC 60601-1-12:2014/AMD1:2020	Collateral Standard: Requirements for medical electrical equipment and medical electrical systems intended for use in the emergency medical services environment
IEC 60601-2-2:2017/AMD1:2023	Particular requirements for the basic safety and essential performance of high frequency surgical equipment and high frequency surgical accessories
IEC 60601-2-3:2012/AMD2:2022	Particular requirements for the basic safety and essential performance of short-wave therapy equipment
IEC 60601-2-10:2012/AMD2:2023	Particular requirements for the basic safety and essential performance of nerve and muscle stimulators
IEC 60601-2-18:2009	Particular requirements for the basic safety and essential performance of endoscopic equipment
IEC 60601-2-22:2019	Particular requirements for basic safety and essential performance of surgical, cosmetic, therapeutic and diagnostic laser equipment
IEC 60601-2-33:2022	Particular requirements for the basic safety and essential performance of magnetic resonance equipment for medical diagnosis
IEC 60601-2-35:2020	Particular requirements for the basic safety and essential performance of heating devices using blankets, pads and mattresses and intended for heating in medical use
IEC 60601-2-40:2016	Particular requirements for the basic safety and essential performance of electromyographs and evoked response equipment
IEC 60601-2-52:2009/AMD1:2015	Particular requirements for the basic safety and essential performance of medical beds
IEC 80601-2-60:2019	Particular requirements for the basic safety and essential performance of dental equipment
IEC 80601-2-78:2019	Particular Requirements for Basic Safety and Essential Performance of Medical Robots for Rehabilitation, Assessment, Compensation or Alleviation

Table 1: Example of 60601-1 series of Collateral and Particular Standards [2]

- ***IEC 60601-1: Medical electrical equipment – Part 1: General requirements for basic safety and essential performance***

  Key aspects covered in IEC 60601-1 include:

  - *Basic safety principles:* This standard outlines the fundamental framework for ensuring that the construction and design of the ME equipment conforms with the constructional requirements of the standard. Conformity is further validated by conducting basic safety testing such as electrical isolation measurements, protective earthing, leakage currents, and temperature measurements to ensure the safe operation of ME equipment.
  - *Essential performance requirements:* IEC 60601-1, in conjunction with the manufacturer's requirements, specifies essential performance criteria that ME equipment must meet to ensure its intended function and effectiveness in diagnosing, treating, or monitoring patients' health conditions.

- ***ISO 14971: Application of risk management to medical devices*** **[3]**

  This standard emphasizes the importance of risk management throughout the lifecycle of ME equipment, from design and development to manufacturing, installation, and use. It requires manufacturers to identify, assess, and mitigate potential risks associated with their devices.

These standards provide comprehensive guidelines for manufacturers to apply during the design, development, and testing phases of product development. In addition, the IEC 60601-1 series of standards are further categorized by the specific type of ME equipment and its intended use. These specific standards provide detailed requirements and guidance tailored to different categories of ME equipment.

The standards are further broken down into the following types:

- *Particular Standards:* Numbered 60601-2-X/80601-2-X, these standards define the requirements for specific types of ME equipment or specific measurements built into products. Particular standards may modify, replace, or delete requirements contained in the general standard and collateral standards as appropriate for the particular ME equipment under consideration, and may add other basic safety and essential performance requirements [1].
- *Collateral Standards:* Numbered 60601-1-X, these standards supplement and define the requirements for certain aspects of safety and performance, e.g., electromagnetic disturbances (IEC 60601-1-2), home healthcare (IEC 60601-1-11), and alarm systems (IEC 60601-1-8). Collateral standards complement the requirements contained in the general standard [1]

As of April 2024, there are approximately 78 particular standards and seven collateral standards in the IEC 60601-1 series of standards applicable to various types of ME equipment. Table 1 provides a sampling of some of these standards.

Unlike medical devices used in professional environments such as hospitals and clinics, ME equipment used in the home is intended to be operated by non-professionals and even patients. These and other types of lay operators are users with limited knowledge and training in operating the device.

STANDARDS ADDRESSING EMERGING ISSUES

Home Healthcare

As devices have become smaller in size and with the improved internet/network infrastructure, hospitals and the medical industry are expanding the use of certain ME equipment in environments outside of healthcare facilities, including the home healthcare environment. This effort is being driven by the following factors:

- *Patient convenience:* Home healthcare allows patients to receive medical care in the comfort of their own homes, eliminating the need for frequent visits to hospitals or clinics. This is particularly beneficial for patients with disability or mobility issues.
- *Cost-effectiveness:* Home healthcare can be more cost-effective than traditional hospital-based care since it reduces the need for outpatient visits and stays.
- *Technological advancements:* The miniaturization of medical devices has made it possible to develop smaller, portable devices that can be used at home without compromising functionality or accuracy. For example, devices like portable ultrasound machines, wearable monitors, and home dialysis machines are becoming increasingly common.
- *Remote monitoring and telemedicine:* With the improved internet and network infrastructure in residential properties over the past decade, remote monitoring of patients' vital signs and health status is feasible. Healthcare providers have the ability to monitor patients' conditions in real time and, when necessary, intervene, even from a distance.

Telemedicine platforms also enable virtual consultations between patients and healthcare providers, further facilitating home-based care.

The expanded use of ME equipment in the home healthcare environment led to the publication of IEC 60601-1-11, "General requirements for basic safety and essential performance – Collateral Standard: Requirements for medical electrical equipment and medical electrical systems used in the home healthcare environment." This collateral standard took the IEC 60601-1 General standard one step further in taking into consideration a number of key issues, as detailed in the sections that follow.

Medical Equipment Used by a Lay Operator

Unlike medical devices used in professional environments such as hospitals and clinics, ME equipment used in the home is intended to be operated by non-professionals and even patients. These and other types of lay operators are users with limited knowledge and training in operating the device.

To address these concerns, IEC 60601-1-11 references an additional collateral standard, IEC 60601-1-6, "General requirements for basic safety and essential performance - Collateral standard: Usability." This usability standard ensures that the ME equipment for home use is simple to use and feature-intuitive, with user-friendly interfaces to accommodate individuals with limited medical knowledge or training. This involves providing non-complex accompanying documents, clear instructions, visual aids, and minimalistic designs to facilitate ease of use.

Device Classification

IEC 60601-1-11 mandates that ME equipment in the home healthcare environment be categorized as a Class II (non-grounded) device, meaning equipment or a device that is only internally powered. The electrical ground found in home healthcare environments is frequently considered to be unreliable when compared to hospitals and other professional healthcare environments. For this reason, pluggable Class I devices (grounded ME equipment) are not permitted.

Figure 1: Protective earth (grounded) equipment not permitted

Class II devices are also known as double-insulated devices. They are designed to provide an extra layer of electrical protection by incorporating two levels of isolation (commonly referred to as double or reinforced insulation) between mains to operator/patient accessible circuits. This design approach is essential in environments where grounding may be unreliable.

Internally Powered Devices

Battery-operated ME equipment and devices offer an additional level of safety by eliminating the need for direct connection to mains supply receptacle. This reduces the risk of shock hazards caused by voltage fluctuations, faulty wiring, or other issues commonly encountered in residential settings. Moreover, battery-operated devices enhance portability and flexibility, allowing users to use the devices in various locations without being tethered to a wall receptacle.

Patient Connections

One crucial aspect of the IEC 60601-1-11 standard is the classification of applied parts, which are parts of the ME equipment that come (or can come) into direct contact with the patient. These applied parts are categorized based on their levels of isolation, patient leakage currents, and their level of protection against the risk of electrical shock under normal and fault conditions.

In the context of the IEC 60601-1 standard, there are three types of applied parts:

- *Type B applied parts:* These are applied parts that offer the lowest level of protection against electrical shock and patient leakage current. They are typically found in medical devices intended for use in professional healthcare settings, where electrical grounding is reliable and stringent safety measures can be enforced. However, in the home healthcare environment, where electrical grounding may be less reliable, the use of Type B applied parts is restricted due to the higher risk they pose under fault conditions.

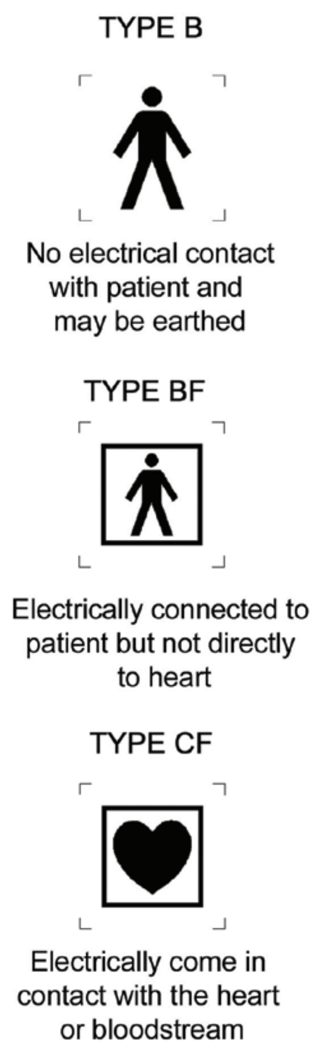

Figure 2: The three types of applied parts within the 60601-1 series of standards [1]

- *Type BF and CF applied parts:* These applied parts provide a higher level of isolation compared to Type B applied parts. Type BF (body floating) applied parts are designed for use in direct contact with the patient's body, offering a higher degree of protection against patient leakage current. Type CF (cardiac floating) applied parts provide an even greater level of isolation, specifically for devices used in close proximity to the heart or other critical areas.

By restricting the use of Type B applied parts and requiring the use of Type BF or CF applied parts in home healthcare devices, IEC 60601-1-11 mitigates the risk of electrical shock and patient harm in home healthcare environments where the electrical source may be less predictable.

Environmental Conditions

- *Operating temperature range:* The operating environment within the home is not as controlled as what is typically found in a professional environment such as a hospital. Therefore, IEC 60601-1-11 stipulates that ME equipment intended for use in the home healthcare environment shall be operable within an expanded temperature range of +5 to +40 degrees Celsius.
- *Water ingress protection:* Coinciding with the previously discussed requirements for the home environment, IEC 60601-1-11 also requires that ME equipment used in the home healthcare environment conform with the requirements of an IPX1 or IPX2 (transit-operable, hand-held, and body-worn) rating:
  - *IPX1 rating:* An IPX1 rating for a device is classified as the lowest level of protection against liquid penetration. This test involves dripping water vertically onto the ME surface. The ME equipment is placed onto a turntable rotating at one round per minute and under a drip box proving a flow of water of one millimeter per minute for a duration of 10 minutes. Upon completion of the test, the testing lab identifies any water penetration within the device that could cause a failure of basic safety and/or essential performance requirements.
  - *IPX2 rating:* Similar to IPX1, the IPX2 test involves dripping water vertically onto the ME surface. The ME equipment is placed onto a turntable rotating at one

round per minute and under a drip box providing a flow of water of three millimeters per minute. The test duration is also 10 minutes, but the unit is tested in four 2.5-minute test sections each with a 15-degree tilt. Similar to the IPX1 test, the ME equipment is then evaluated for any water penetration that could compromise basic safety and/or essential performance.

- *Mechanical shock/vibration*: Unlike a professional healthcare facility, the home healthcare environment is not as controlled and additional rough handling test criteria shall be taken into consideration. For this reason, IEC 60601-1-11 includes selected vibration and shock tests to evaluate how ME equipment responds to these conditions during normal use.

  The test criteria for the shock and vibration tests are selected based on the environment and classification of device (i.e., hand-held, portable, mobile, body-worn, and transit-operable.

  Table 2 outlines the severity level of the mechanical tests based on the ME equipment classification.

Artificial Intelligence

Autonomous artificial intelligence (AI) is a branch of AI in which systems and tools are advanced enough to act with limited human oversight and involvement. The actions an autonomous AI system can perform range from automating basic repetitive tasks and data analysis to decision making.

Medical device manufacturers are taking this technology into account by implementing advanced sensors, cameras with vision, and software algorithms with AI. Since this technology is still in its early stages, IEC TC62 has been working on the development of a first edition of a new standard, IEC 63450 [2], which will address the technical verification and validation processes applicable to AI-enabled medical devices. IEC 63450 is currently scheduled for publication in mid-2025. [2]

As AI-enabled ME equipment relies heavily on software, medical device manufacturers should also consider applying the requirements of IEC 62304, which defines the life cycle requirements for software within ME equipment. The processes, activities, and tasks described in this standard establish a common framework for medical device software life cycle processes.

The IEC 62304 standard defines three safety classes for medical device software as follows:

- Class A: No injury or damage to health is possible
- Class B: Injury is possible, but not serious
- Class C: Death or serious injury is possible

If ME equipment contains software, regulatory bodies such as the FDA and Health Canada will look for evidence of compliance with the requirements of IEC 62304.

Cybersecurity

With manufacturers now including network capability in ME equipment (technologies such as LTE/5G, WiFi, Bluetooth, or physical LAN connection), there comes a need to ensure that devices are protected against cybersecurity threats. Cybersecurity incidents can render ME equipment and the networks within the hospital environment inoperable, resulting in the delay and disruption of patient care.

Table A.3 – Qualitative assessment of HOME HEALTHCARE ENVIRONMENT ME EQUIPMENT subjected to shock and vibration

	Non-TRANSIT-OPERABLE use				TRANSIT-OPERABLE use [a]			
	MOBILE	PORTABLE	HAND-HELD	BODY-WORN	MOBILE	PORTABLE	HAND-HELD	BODY-WORN
Vibration	1	1	1	1	2	2	2	1
Shock	1	1	1	1	2	2	3	2
Drop	1	1	3	2	2	2	3	3
Mechanical strength 0=no test, 1=least severe or 7M1[b], 2=moderately severe or 7M2, 3=most severe or 7M3								

[a] TRANSIT-OPERABLE use includes use outdoors, use in automobiles and use in or attached to wheelchairs.

[b] The 7Mx designations are described in IEC 60721-3-7:1995 [5] and IEC TR 60721-4-7:2001 [7].

Table 2: Qualitative assessment of home healthcare environment ME equipment subject to shock and vibration (Table A.3 from IEC 60601-1-11 [5])

> The IEC has approximately 12 active working groups involved in the development of the 4th edition of the standards, each of which is involved in separate aspects of the standard's revision.

Under Section 524B(a) of the FD&C Act, which came into effect in March 2023 [6], the FDA can refuse to consider premarket submissions submitted on or after October 1, 2023, if the premarket submission does not provide documentation that supports claims of compliance with the requirements of Section 524B. The requirements include:

- Having a plan to monitor, identify, and address, as appropriate and in a reasonable time, post-market cybersecurity vulnerabilities and exploits, including coordinated vulnerability disclosure and related procedures,
- Designing, developing, and maintaining processes and procedures to provide a reasonable assurance that the device and related systems are cyber secure, and make available post-market updates and patches to the device and related systems, and
- Providing a software bill of materials (SBOM) detailing commercial, open-source, and off-the-shelf software components.

Manufacturers should plan ahead and take these requirements into consideration well in advance of their regulatory submissions.

THE FUTURE OF IEC 60601-1

During the IEC TC62/SC62A meetings in Seoul, South Korea, in September 2023, there was a general consensus between the National Committees (NCs) to move forward with efforts to develop a 4th edition of IEC 60601-1. [7] The IEC has approximately 12 active working groups involved in the development of the 4th edition of the standards, each of which is involved in separate aspects of the standard's revision. No firm date has been set for the publication of the 4th edition of IEC 60601-1, but most experts expect that a draft of the revised standard will be available for review and comment by mid-2025.

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Filter Designs for Switched Power Converters Part 1: Overview

Understanding the Power Converter and Its System Requirements for Good EMC Practice

By Dr. Min Zhang

I have always wanted to write articles on filter design. Needless to say, the subject alone can easily spawn a book. This is because, in the world of electronics, we have power filters, transformers, low-frequency filters, digital circuit filters, and analog circuit filters. Each design requires its unique and dedicated filter design principles. Additionally, we have different requirements, and it is fair to say that most commercially available filters are designed to meet certain EMC specifications. Hence, they are most likely designed to work efficiently with the test setup, particularly the line impedance stabilization network (LISN) for conducted emission tests.

Given the numerous points to consider, capturing everything in one article is nearly impossible. My favorite books and articles on this subject are listed in the reference section [1]-[3], and I encourage readers to explore them.

This series of articles focuses primarily on power filters for switched-mode power converters and similar applications. By defining this boundary, I am concentrating on conducted emissions (from 9 kHz to 110 MHz) and radiated emissions (from 30 MHz to 1 GHz). Although most power supplies also need to meet transient protection requirements, we will not cover transient protectors in this series. Topics related to harmonics, as well as digital and analog circuit filter design, are beyond the scope of this series. When referring to switched power converters and similar applications, I mean power converters such as AC-DC, DC-DC, DC-AC, and motor drive applications.

We want to discuss filter design in this specific field because we now live in an era where we aim to electrify everything for the good purpose of making a more sustainable future. In this article, which is Part 1 of the series, I will provide an overview of the filter design principles for switched conversion applications.

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UNDERSTANDING THE EMC & EMI REQUIREMENTS

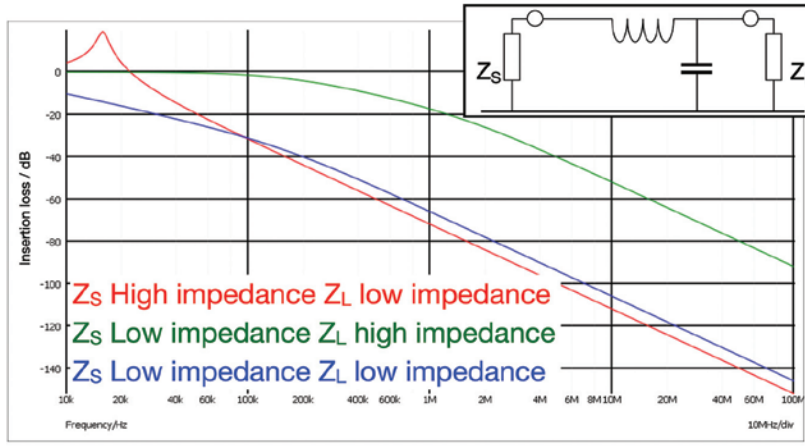


Figure 1: The effectiveness of the filter configuration (such as this simple L-C low pass filter) depends on the impedances seen at either end of the filter network.

First, let us distinguish between the concepts of EMC and EMI requirements. When we refer to EMC (electromagnetic compatibility), we mean meeting the electromagnetic compatibility requirements. This entails demonstrating control over electromagnetic interference (EMI) by adhering to the emission limits defined by the specific standard relevant to your product application. For instance, if you are designing a power supply for an aircraft, the conducted emission limit defined in RTCA DO-160 is very different from the limits for a commercial application (CISPR/FCC Class B limit). The LISNs used in these two applications differ as well [4], which means you need to understand your source-load impedance to effectively design the filter.

Most of my work involves helping clients meet these EMC requirements, whether they are the stringent military specifications or the relatively easier industrial emission standards. However, engineers sometimes face unique challenges. For example, a client in the semiconductor manufacturing industry required an extremely EM-quiet environment for their machines to operate accurately. This meant they needed to control the electromagnetic interference (EMI) based on their own system requirements. In this scenario, there is no LISN per se, as the power supply design depends solely on their specific system. Consequently, the system's impedance is unlikely to match a 5 or 50 µH LISN [5].

Although the requirements differ, they all aim to achieve one end goal: operating the product with controlled EM noise to avoid interfering with other equipment and preventing nuisance issues within the product/system itself.

UNDERSTANDING THE SWITCHED POWER CONVERTER OPERATION

This area is crucial. An EMC engineer with little or no knowledge of switching converters cannot effectively solve the challenging EMI issues caused by these converters. Similarly, design engineers with advanced knowledge of complex switching schemes but lacking an understanding of EM theory (particularly the concept of energy in space) will struggle to control emissions.

I highlight this because I experienced it first-hand. During my PhD research on sophisticated switching schemes, I lacked EM knowledge. It was only years later, after understanding EM theory, that I could view the problem from a different perspective. Many EMC engineers likely have similar stories.

It's unrealistic to expect EMC engineers to possess the same level of knowledge of power converters as power electronics design engineers. EMC engineers have their own disciplines, including testing skills and simulations. However, a basic understanding of power converter fundamentals is always useful.

In my view, the two essential circuits that engineers need to understand are the buck converter and the flyback converter. Why? The buck converter represents the most basic DC-DC step-down converter, widely used in power conversions. Understanding the buck converter helps in understanding other applications, such as boost converters, which are essentially the mirror image of buck converters (as shown in Figure 2 (a) vs (b)).

As shown in Figure 2, most motor drive applications, whether DC brushed motors or brushless DC motors (single-phase or three-phase), are essentially made of buck converters. For instance, three-phase brushless DC motors use hardware that is essentially three synchronous buck converters, regardless of the control method (sinusoidal pulse width modulation (PWM), space vector modulation (SVM), field orientated control (FOC), etc.). Similarly, the concepts of hot loop and switch nodes in the buck converter apply to motor drive applications. The hot loop areas and the switch nodes are highlighted in Figure 2. The hot loop area is defined as the loop area where the worst di/dt current circulates, indicating a high level of magnetic field (near field). This highlights

So why flyback converters? The biggest disadvantage of a buck converter is that it is not isolated, meaning it does not provide safety isolation. For many applications, system safety requirements necessitate an isolation transformer.

the importance of reducing this area. The switch node is defined as the worst dv/dt voltage node in the circuit, indicating a high level of changing electric field. This underscores the importance of minimizing capacitance coupling nearby.

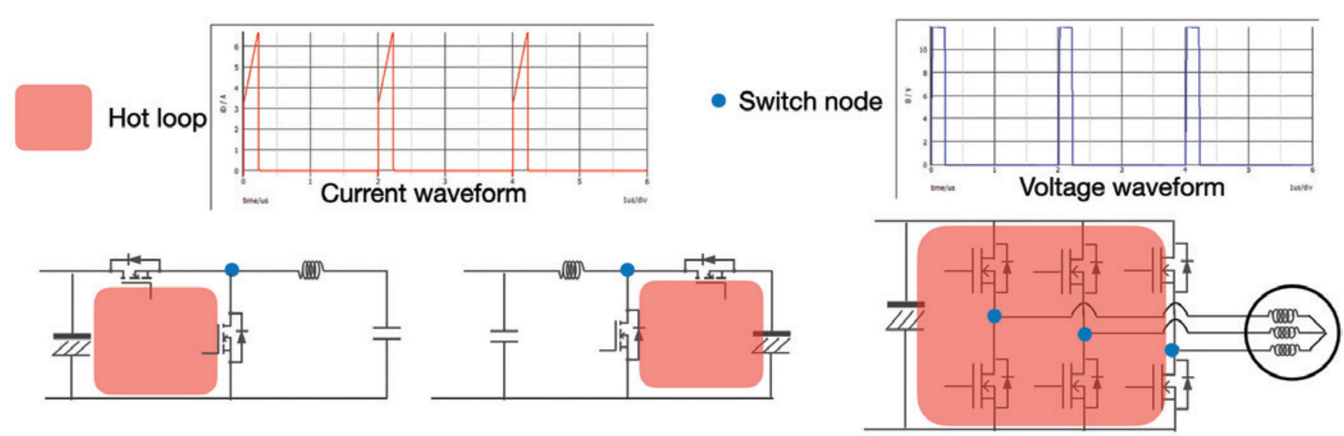
We will discuss the details of how buck converters work and their EMI characteristics in later articles. So why flyback converters? The biggest disadvantage of a buck converter is that it is not isolated, meaning it does not provide safety isolation. For many applications, system safety requirements necessitate an isolation transformer. Typically, for power levels under 150W, a flyback converter is preferred due to its good balance of efficiency, size, and cost (owing to the small number of components). Such converters are popular in designs like mobile phone and laptop chargers. Therefore, understanding the operation of flyback converters is essential.

Understanding flyback converters helps in understanding other circuits like forward converters. Flyback converters are popular in the power range under 150W. When power requirements increase, we often see topologies such as phase-shift full bridge (PSFB), dual-active-bridge (DAB), LLC, etc. However, the principles of these higher power converters are not far from those of a flyback converter.

Isolated flyback converters are more complex due to their requirement for a transformer. It is worth noting that, unlike the ideal transformer, current does not flow simultaneously in both windings of the flyback transformer but rather functions as an inductor with two windings; a more descriptive name should be "two winding inductor" [6]. In most applications, since the flyback transformer stores energy, an air gap is needed. During power conversion, energy moves from the input bulk capacitor to the transformer's air gap and then to the output capacitor.

The presence of the transformer introduces additional considerations. From an EMC perspective, the first is leakage inductance. The leakage inductance of the transformer forms an L-C resonance circuit with the parasitic capacitance of the switching device, causing overshoot and ringing. This is why a snubber circuit is often needed for the converter. This is illustrated in Figure 3 on page 90.

Another consideration is the parasitic capacitance of the transformer, which includes the primary side, the secondary side, and, most importantly, the capacitance between the primary and secondary sides. This determines the common mode current path of the converter, making it standard practice to place



(a) A simplified synchronous Buck (b) A simplified synchronous Boost (c) A simplified 3-phase motor drive

Figure 2: (a) Simplified diagram of a synchronous buck converter, (b) simplified diagram of a boost converter, and (c) a three-phase motor drive consisting of three synchronous buck converters.

Figure 3: Snubber circuit for flyback converters

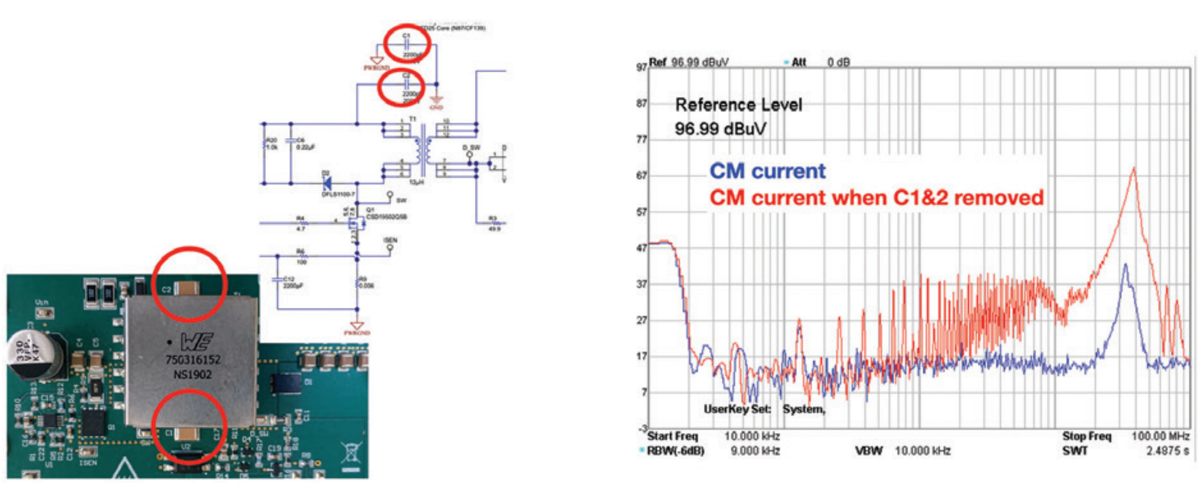
capacitors between the primary and secondary sides of the transformer. I haven't seen many articles discussing how to characterize and test the parasitics of a flyback converter transformer, so we will discuss this in greater detail in subsequent articles.

Both buck and flyback converters generate broadband noise, which is often a significant noise culprit in electronic systems. The concept and consequence of broadband noise is well explained in [7]. In terms of noise profiles, the two circuits discussed above are very similar.

UNDERSTANDING THE BASICS OF FILTER PRINCIPLES

Now that you understand the converter circuits and are familiar with the system EMC/EMI requirements, you are ready to design a filter. Filters (except for active filters, which require a microcontroller) are made of passive components, which are relatively simple, such as inductors (L), capacitors (C), and resistors (R). You also have transient protection devices, such as MOVs, TVS diodes, etc. Therefore, filter design might seem easy at first glance. The basic filter design flow is as follows:

1. *Understand your circuit's noise profile:* This can be achieved through benchtop tests and/or SPICE simulations.
2. *Determine the required dB reduction (attenuation):* Based on the results, identify how much attenuation is needed across the frequency range.
3. *Select the L, C, and R components:* Choose components to meet the required reduction, often determined by the filter's cut-off frequency.
4. *Perform a simulation:* Verify that the noise is reduced (e.g., by 60 dB) through simulation.
5. *Implement the filter:* Build the filter based on your design.



Capacitors across the two sides of the transformer

Conducted Emission Current Probe Measurement Results

Figure 4: Putting capacitors across the transformer can reduce the common mode noise, but one needs to be cautious of the leakage current requirement.

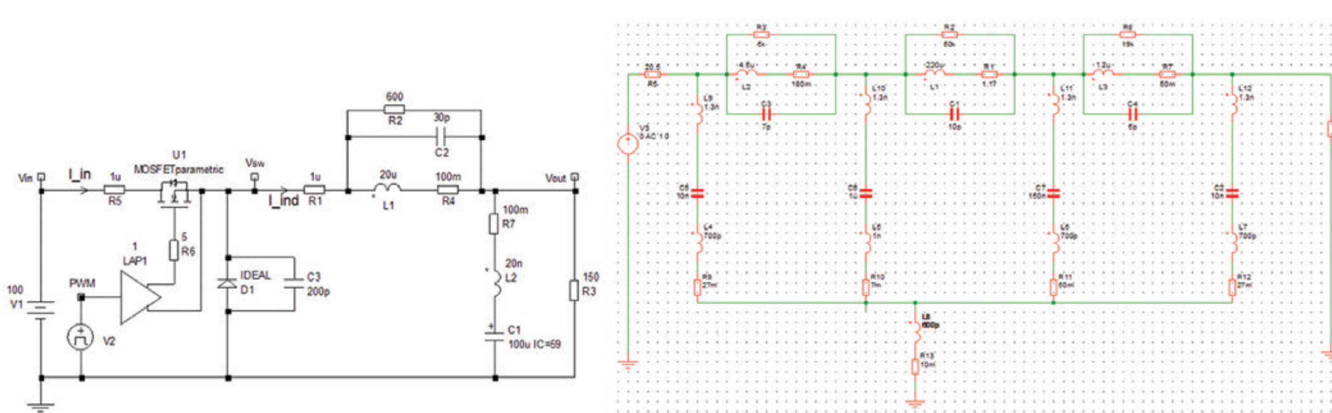
Engineers sometimes buy an off-the-shelf part and hope it will magically eliminate all noise. In other cases, they simply add some inductors and capacitors without proper calculation.

6. *Measure the performance:* Test the filter and observe the results. Often, the actual performance may not match your expectations.

This is a common scenario I observe in my fieldwork. Engineers sometimes buy an off-the-shelf part and hope it will magically eliminate all noise. In other cases, they simply add some inductors and capacitors without proper calculation. But let's say you followed Steps 1-5—why might the results still be unsatisfactory?

We will discuss this in greater detail later, but at a top level, here are common areas that engineers often overlook:

1. *Simulation model detail:* Does the model capture all parasitics, such as leakage inductance of transformers and parasitic capacitance of switching devices (Figure 5(a))?
2. *Inclusion of a LISN circuit:* Does the simulation include a LISN circuit? Often, design engineers who are not EMC specialists may overlook this.
3. *Parasitic capacitance to test ground:* Does the simulation model include parasitic capacitance between the circuit and the test ground plane? This is crucial for determining the common mode current path.
4. *Differential and common mode noise separation:* Has the engineer clearly separated the noise types into differential and common modes?
5. *Realistic component models:* When building L-C-R filter circuits, have the parasitics of the L, C, and R components been considered? Engineers should use a more realistic passive component model based on the impedance curves provided by manufacturers (as shown in Figure 5 (b))
6. *Filter damping:* Is the filter dampened? High-Q (resonant) filters can worsen the situation.
7. *Filter connection to the board:* Has the connection of the filter, for example, capacitors to RF reference, been well considered? The "ground" connection is equally important. (I always try to avoid using "ground," so we will discuss this in future articles).
8. *Filter layout:* Is the layout of the filter well-considered? Could the magnetics in the filter couple noise to nearby circuitry?
9. *Saturation and DC offset:* What is the current RMS value going through the magnetics? What is the DC voltage offset on the capacitors?
10. *And more:* The list can go on.



(a) A more realistic buck converter model

(b) A more realistic filter model

Figure 5: (a) a more realistic simulation circuit of a buck converter, including key parasitics, (b) a more realistic filter circuit (differential mode only).

When I started as a power electronics engineer 20 years ago, IGBTs were the go-to devices for medium voltage power conversion and motor drive applications. MOSFETs dominated lower voltage applications.

Given these considerations, review your approach—are there any missing elements? Additionally, as mentioned earlier, engineers need to understand their source and load impedance (as shown in Figure 1). The performance of a filter heavily depends on these parameters. When a LISN defines the impedance, it's straightforward. Most commercial off-the-shelf manufacturers design filters based on a defined LISN impedance.

KEEPING UP WITH TECHNOLOGY PACE

When I started as a power electronics engineer 20 years ago, IGBTs were the go-to devices for medium voltage power conversion and motor drive applications. MOSFETs dominated lower voltage applications. By the early 2010s, advancements in technology had reduced the R_{DS}(on) (on-resistance) of MOSFETs to a few milliohms, enabling higher efficiency and smaller form factor products. Of course, in terms of EMC/EMI challenges, we had to deal with tail currents related to IGBTs, reverse recovery charge issues with MOSFETs, and fine-tuning dead time for applications using both devices. Nonetheless, we managed. The switching speeds of MOSFETs increased, but never to a level that was hard to manage.

However, things have changed with the development of wide bandgap devices such as GaN and SiC semiconductors. I write extensively on this subject, which readers can find in [8]. These advancements have had a significant impact on switching speeds, specifically the rise and fall times, creating substantial EMI challenges.

One trend I have observed is that, in the past, conducted emissions associated with switched converters were mainly differential mode below a few MHz, while common mode noise dominated the spectrum above a few MHz. This pattern no longer holds with wide bandgap devices. Due to their extremely fast switching, common mode noise now dominates even in the low-frequency range. This is not limited to high voltage, high power systems, as demonstrated in [9]. For example, in much smaller power applications like a GaN-based charger (active clamp flyback converter), common mode noise dominates the low-frequency range, as shown in Figure 6.

This is the trend of technology. As more advanced devices emerge in the future, our knowledge in suppressing the associated noise must also evolve.

OTHER CHALLENGES

As I was writing this article, I realized I was gradually stepping into power converter design territory. I don't want to step on power electronics engineers' toes, but there are many considerations when designing a power converter. Designing a filter with a specific cut-off frequency is not always straightforward; a power converter filter must work with the converter control loop.

To simplify for EMC engineers who don't design power converters: a control loop, often consisting of a feedback loop (typically a voltage loop) and/or a feedforward

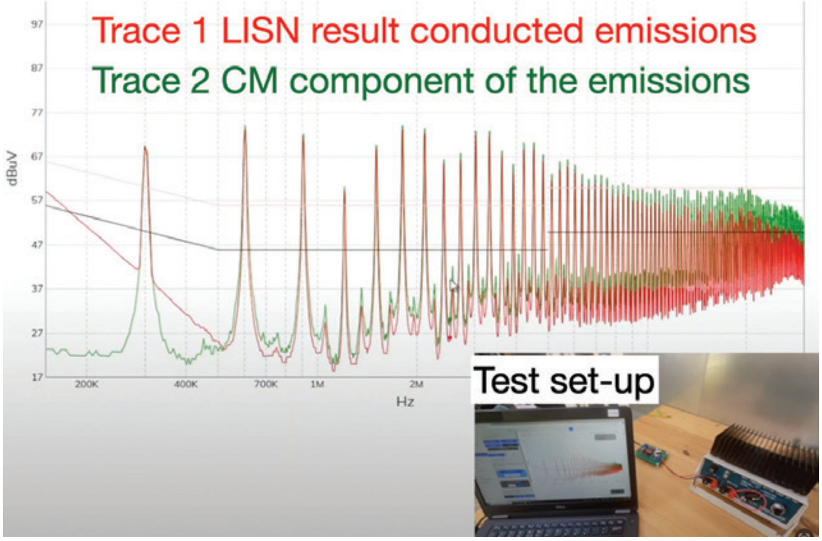


Figure 6: Conducted emissions of an active-clamp flyback converter, the common mode components dominate the noise spectrum
(See a video demonstration at https://youtu.be/70xhHsDk_M4?si=pf3p_q_63UCQEuAC)

There are switching schemes that can reduce the switching events for power converters, such as discontinuous space vector modulation schemes (typically employed in three-phase power applications and motor drives).

loop (often a current loop), is designed to stabilize the circuit so the power converter can supply well-regulated power under various load conditions. These loops ensure stable operation even with step changes in load. Power electronics engineers design the loop based on the power converter circuit's transfer function together with the filter transfer function.

A simple controller may have a proportional-integral design (what we call a PI controller). The proportional and integral gains (Kp and Ki) need to consider the filter transfer function to achieve the desired gain margin and phase margin. This means the cut-off frequency of the filter needs to be adjusted. Therefore, the filter's transfer function affects the loop design. It doesn't necessarily deteriorate the loop design, but it does make the design more challenging, requiring compromises, as with all engineering tasks.

As usual, a filter design must also meet size, weight, and, perhaps most importantly, cost requirements.

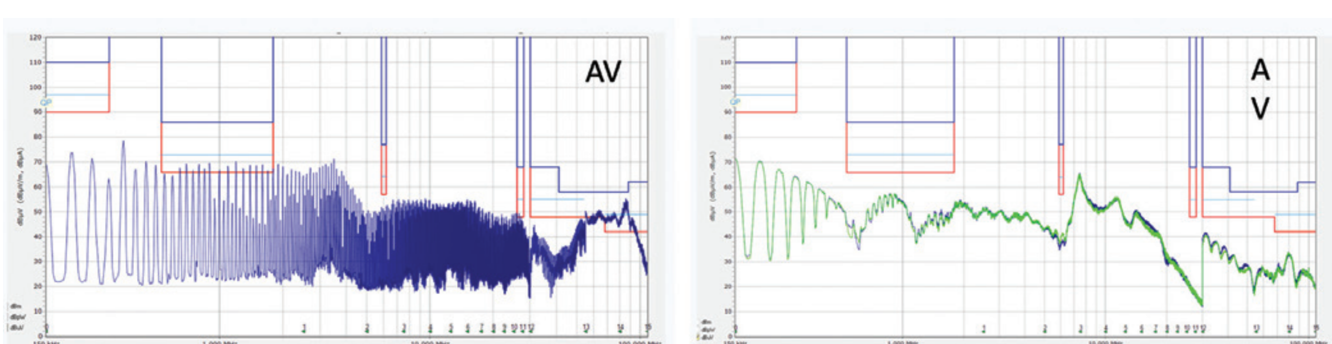
SWITCHING SCHEMES AND SPREAD SPECTRUM CONTROL

There are switching schemes that can reduce the switching events for power converters, such as discontinuous space vector modulation schemes (typically employed in three-phase power applications and motor drives). Other schemes aim to reduce the common mode voltage by cleverly selecting the switching vectors (again, a subset of space vector modulations). Such switching schemes can also be employed in multi-level converters. One can simply search the keywords, and there are abundant resources in the IEEE database.

Having spent four years developing such switching schemes myself, I have mixed feelings about them. On an academic level, the idea is certainly sound. However, I have rarely seen such schemes used in industrial applications for various reasons. Perhaps the benefit of using a complicated switching scheme is compromised when it comes to real-life engineering. The complexity of implementing such schemes (not so much in computing power, but in ease of implementation for engineers) is also a reason why they are not popular.

Spread spectrum can be implemented even in the simplest converter topology (such as a buck converter). The idea of not using a fixed switching frequency spreads the energy out, resulting in reduced signal measured in any one bandwidth. It should be noted that such techniques can either result in low-frequency noise improvement or high-frequency noise suppression, sometimes both, depending on the software schemes that engineers employ.

Figure 7 demonstrates the conducted emission improvement a spread spectrum technique can achieve on a dual active bridge-based DC-DC converter.



(a) Normal switching (b) Spread spectrum

Figure 7: The effect of spread spectrum switching scheme on a dual active bridge converter (Source: Lyra Electronics, the author worked with Lyra on this project.)

Reference [10] demonstrates the high-frequency (radiated emission) improvement by utilizing the spread spectrum scheme. However, as it was rightly pointed out in [7], such techniques are fine for passing the EMC test, but when it comes to protecting a real-life victim, such as a broadcast television, the spread spectrum technique can still potentially cause TVI. I also agree with the argument stated in [7], where the author suggests that with FFT or time-domain type receivers, we should perhaps revisit the emission tests (which always measure the noise with a fixed bandwidth).

IS ACTIVE FILTER TECHNOLOGY GOING TO TAKE OFF?

I am a practical engineer who works almost entirely with industrial partners, so my approach to solving EMI noise is very practical. However, I have also spent my fair share of years in academia, keeping my ears open for potential technological breakthroughs. I have always had a great interest in active filters.

In the past, active filters were primarily used to counter low-frequency magnetic fields [11]. One could also say that the power factor correction technique, widely used in AC-DC applications, is also a form of active filter. Attempts were made to address higher frequency spectra (both conducted and radiated regions), but they never gained traction. In the year 2023, Texas Instruments introduced active filter solutions for both single and three-phase industrial applications [12], detailed in [13]. We are still waiting for more case studies on this chip, and I personally plan to work with it to assess its potential.

Other techniques are also available, forming part of my ongoing research, which I hope to share with the audience in the near future. In conclusion, I believe active filters will eventually find their market, given the advancements in technology.

SUMMARY

In this first part of our series on filter designs for switched power converters, we've laid the groundwork by exploring the essential aspects of EMC and EMI requirements, the operation of switched power converters, and the fundamental principles of filter design. Understanding these core concepts is crucial for effectively managing emissions and ensuring compliance with regulatory standards. By delving into both the buck and flyback converter circuits, we highlighted their significance in power conversion and the common challenges faced in their design.

As technology continues to evolve with advancements like wide bandgap semiconductors, staying abreast of these changes is vital. Future articles will build on this foundation, offering deeper insights into specific design strategies and practical solutions for overcoming EMI challenges in switched power converter applications.

As technology continues to evolve with advancements like wide bandgap semiconductors, staying abreast of these changes is vital. Future articles will build on this foundation, offering deeper insights into specific design strategies and practical solutions for overcoming EMI challenges in switched power converter applications.

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EMI Shielding and Thermal Interface Considerations for Commercial and Defense Drone Technology

Utilizing Advanced Materials to Ensure High Performance and High Reliability for UAVs

By Sierra Meloan and Ben Nudelman

Aerial drones are rapidly becoming integral to modern society, dominating headlines in combat tactics and finding widespread use across various industries. From 2020 to 2030, the global drone market is anticipated to grow at a compound annual growth rate (CAGR) of 20%, with much of this expansion taking place in the segments of logistic drones, enterprise drones, and defense drones.

Advancements in drone technology accelerate the need to meet strict demands of lightweighting, electronics thermal management, and electromagnetic interference (EMI) shielding to ensure uncompromised signal integrity.

TYPES OF DRONES AND THEIR GROWING APPLICATIONS

Before we talk about some engineering solutions to thermal management and EMI shielding challenges, let's explore the scope of drones we'll cover in this article. When we say drones, we're referring to unmanned aerial vehicles (UAVs), which are aircraft that are meant to be operated remotely or without a human pilot on board. And while many of the examples we give will refer to drone applications, it's important to note that the products we discuss can and are used in other drone-adjacent remote or aerial applications. This includes commercial aircraft, defense aircraft, electric aircraft, and even ground-based drone defense technology.

Drones come in nearly every shape, size, and price range. They can be as small as a bumblebee or as large as a small passenger jet, and they can cost anywhere from $10 to hundreds of millions of dollars. Their propulsion systems can be electric motors, gas-powered heat engines, and even jet engines, while propeller types include fixed wing and rotary wing. And, while vertical takeoff and landing (VTOL) and short takeoff and landing (STOL) are not exclusive features of drones, they are common in many types of commercial and defense drones.

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The Genesys AC Pro models include the added functionality of AC+DC output, analog input for Real-Time control with low latency, and the option for frequencies up to 5kHz.

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- Clear and responsive color touch screen, offering easy access to the many features and functions through an intuitive menu structure.
- Wide selection of interfaces is standard with IVI/LabView drivers and Virtual Control Panel (GUI) included.
- IEC, marine and avionics test standards available.

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Commercial drones are used for non-defense or non-military applications, such as for recreational or industrial purposes. You've likely seen drone footage used for the latest Hollywood blockbuster or in a nature documentary or even experienced drone light displays at sporting events or holiday celebrations. Commercial applications have driven a 25% CAGR in drone usage over the last decade.

From an industrial standpoint, drones are used in a variety of applications. Drones offer improved vision and sensors for agriculture and forestry surveying as well as wildlife tracking. Contractors and civil engineering firms are using drones to inspect difficult-to-reach or dangerous locations such as infrastructure and construction sites. Some drone manufacturing companies are marketing their technology for public safety, touting their benefits for fire inspection, police operation, search and rescue, and even crowd control.

And we can't forget about logistics drones that are used for delivery and fulfillment. Around the world, we're seeing more and more small-scale trials with delivery drones for packages. Drones also play a vital role in getting critical equipment and supplies like medicine to remote locations that may otherwise be difficult to reach. Drones are playing a major part in our lives, even if they aren't always visible or obvious. From Washington to Botswana, from Detroit to Japan, from Hollywood to India, drones are being used for all kinds of purposes and making headlines every day.

DIFFERENCES BETWEEN COMMERCIAL AND DEFENSE DRONES

While some of the technology utilized for EMI shielding and thermal interface materials is common to both defense and commercial applications, there are some notable differences between these classes of drones.

Many defense drones have a high degree of autonomy as well as interoperability, meaning they need to be able to communicate with other military systems. Commercial drones have varying levels of autonomy and interoperability, and it's important to note that those requirements tend to be much more application-specific. For example, a light show is one situation where perfectly synchronized drones that operate autonomously and in communication with the base terminal and the surrounding drones would be required.

Longevity and reliability often vary as well. Defense drones are expected to operate with minimal maintenance for years or decades. They must work continuously for hours or days at a time while potentially carrying hundreds or thousands of pounds of payload equipment and flying at lightning-fast speeds.

On the other hand, commercial drones often have relatively light payloads, if any at all, and use lower-power propulsion systems to operate for shorter periods. Most commercial drones don't have a mission-critical reliability need, except for those utilized for public safety and rescue operations. Recreational drones may need more frequent battery changes and repairs to motors or propellers.

The security and regulatory requirements around each drone type are different as well. Commercial drones are usually only required to meet some U.S. Federal Aviation Administration (FAA) restrictions around flight locations and heights, as well as U.S. Federal Communications Commission (FCC) regulations around wireless communication. The requirements for defense drones are much more strict. Defense drones must meet many military standards, such as MIL-STD-461 for EMI shielding of electronics, in order to provide resistance against interception, jamming, and cyber threats.

When we refer to the advanced technology within drones, we are not only referring to their propulsion and communication modules but also their advanced sensors. Lidar, radar, laser, and ultrasonic sensors are used for collision avoidance and precision positioning when paired with location control GPS sensors and stabilization or orientation modules. Advanced flight analytics, such as time of flight sensors, can give operators details about how the drone is performing relative to environmental conditions and can be used to enhance future flights.

Additional sensors are needed if the drone is meant to do a specific job, such as videography or imaging. Cameras, chemical detection, thermal sensors, and hyperspectral sensors are just a few examples. It's important to note that some of this technology can also collect data internally, process the inputs, and respond automatically or communicate in real-time to the operator. Drones do a tremendous amount of data processing, which is the primary reason they need high levels of EMI shielding and thermal management.

EMI SHIELDING SOLUTIONS FOR DRONE APPLICATIONS

Now that we've provided a brief introduction to drone technologies and requirements, let's dive into how one can shield drones from radiated susceptibility as well as radiated emissions.

An important note is that all devices have different needs for EMI shielding to make sure that nearby electronics are not impacting their performance. The right combination of EMI shielding and thermal interface materials will vary by device and application to provide device-level or component-level protection from unwanted electromagnetic radiation.

Conductive Elastomer Gaskets

One of the most commonly used and versatile solutions for system-level EMI shielding is a conductive elastomer gasket. Conductive elastomers consist of a base polymer such as silicone, fluorosilicone or an ethylene propylene diene monomer (EPDM) that gives the material its flexibility and structure. This base polymer is then embedded with metallic particles such as silver-plated aluminum, nickel-plated aluminum, silver-plated copper, nickel-plated graphite, and others that give the gasket its electrically conductive properties.

The specific particles and binders each lend themselves to different benefits based on the design requirements. For example, fluorosilicones will be used where the gasket may come into contact with harsh chemicals or washdown fluids. A silver-plated aluminum particle will provide very high conductivity, shielding, and galvanic corrosion resistance against aluminum substrates that are exposed to moisture and salt bog.

Conductive elastomers can be extruded into a gasket that sits in a groove or molded into a flat sheet and then die-cut into very intricate shapes, such as those that would be suitable for a connector for grounding. They can provide the advantage of being an EMI shield as well as an environmental seal, cutting down on the number of seals or gaskets required. They can also be developed as co-extruded parts where there is a durable non-conductive gasket permanently bonded to a conductive gasket for an even higher level of galvanic corrosion resistance.

While most shielding products are used at the enclosure level, precision-stamped metal shield cans are used to shield components at the board level and give individual component-level attenuation. Board shields come in an infinite number of shapes and sizes with all kinds of board mating styles and precision features.

Conductive elastomers can also come in form-in-place formats where a very thin bead of conductive gasketing is robotically applied onto a thin wall for cavity-to-cavity isolation and precise shielding within electronic enclosures.

Conductive Heat-Shrinkable Polyolefin Tubing

One product that has seen particular use in drone applications is an electrically conductive heat-shrinkable polyolefin tubing. The tubing and boots get their conductivity courtesy of a flexible conductive coating filled with either silver or silver-plated copper particles. The tubing has a 2:1 shrink rate, the same as standard shrink tubing, but it offers significant weight reduction compared to braided cable shielding or shielding cable wrap while giving the added benefit of water sealing.

Conductive Coatings and Sealants

Electrically conductive coatings are often applied via airbrushing onto metal or plastic substrates to provide EMI shielding, an intentional ground path, or a corrosion-resistant and conductive surface for mating against conductive elastomer gaskets. Conductive sealant and gap fillers are applied using a caulking gun directly from the packaging tube or unique applicator and are used as gap fillers at the seams of conductive enclosures. Sealants and conductive gap fillers are designed to be painted, sanded, or smoothed so they can provide the optimal surface finish and then integrated with other sealing or esthetic components of an airframe. Some things to consider when working with materials are working life, times, and masking or fixturing for accurate application.

Conductive Plastics

Injection-molded conductive plastic parts are made from engineered polymers that incorporate a conductive powder or fiber into the pellet blend. The pellets are then molded into complex shapes that provide the physical benefits of plastics while adding the advantages of an electrically conductive housing. Conductive plastic parts have a lower density than aluminum for when light weighting is important and provide significant time and cost savings of having to machine metal housings or covers for electronics protection. The final part can incorporate embedded hardware such as captive fasteners and minimize secondary manufacturing practices while holding similar tolerances as machined parts.

Overall, the advantages of using conductive plastics are weight reduction, RF absorption, corrosion resistance, good shielding effectiveness, and suitability for harsh environments. These plastics are ideal for moderate to high volumes, and while they do provide many benefits, some considerations are the initial cost for the injection molding tooling, upfront design time, minimum wall thickness, fluid exposure, and the color options that are available.

Conductive Foam Gaskets

Conductive fabric-over-foam and conductive foam solution applications were developed mainly for high-volume, cost-sensitive, low-compression force applications like consumer electronic devices. The foams used in these gaskets are often urethane or silicone, where higher temperature limits of up to 125°C are required. Conductive fibers or fabrics are used to provide electrical continuity and shielding ability. These materials are often used as a grounding gasket on board-level shields or as a connector gasket that's needed to provide low contact resistance.

There are many advantages to using these gaskets, and one important one is that they are soft with a very low compression force. Additionally, they are lightweight and low density, typically low cost, and work well as a dust seal. Hundreds of standard parts and profiles are available, and tooling for custom parts is a relatively inexpensive option compared to other solutions. One drawback is that foam-based gaskets are typically not recommended for water or moisture sealing.

Board-Level Shielding

While most shielding products are used at the enclosure level, precision-stamped metal shield cans are used to

shield components at the board level and give individual component-level attenuation. Board shields come in an infinite number of shapes and sizes with all kinds of board mating styles and precision features. RF broadband absorbers can be added to the shields to give extra RF absorption.

The pros of board shields are that they're low cost and highly customizable with a lot of design options, and they can be integrated into automated assemblies. Additionally, they can be made of several materials and packaged in tape and reel formats, as well as assembled by pick-and-place machines. Aluminum is an increasingly common material for precision board shielding as it has the added benefit of excellent thermal conductivity, serving as a shield and a heat sink. While the upfront tooling cost is a drawback, the low unit cost can certainly make up for that over the course of a high-volume program.

THERMAL INTERFACE MATERIALS FOR DRONE APPLICATIONS

Thermal Gap Filler Pads

Thermal gap filler pads or, simply, gap pads are designed to be soft to reduce component stress when creating an interface between heat-generating components and heat-dissipating surfaces. This conformability helps with vibration dampening and gives the gap pads a large compression range to take up assembly or manufacturing tolerances.

Nearly all gap pads are NASA E595 outgassing certified, meaning they're approved for use in vacuum, space, and high-altitude applications. Gap pads are traditionally manufactured in sheets and can be cut into any shape or size. While common thicknesses range from 0.25 mm up to about 5.0 mm, gap pads can be made in much larger thicknesses as well. One of the advantages of gap pads is their ease of application, as they can simply be peeled off a protective liner and applied onto a heat sink or electronic component.

Thermal Gels

Thermal gels, also known as dispensable gap filler gels, are one-component, fully-cured dispensable thermal interface materials. A single-component material is advantageous because it requires no mixing or additional curing after dispensing onto a substrate. Thermal gels have very different physical properties from those of gap pads, providing some added benefits. These materials can be easily dispensed to meet various tolerance ranges or gap heights without requiring an additional part number in your bill of materials.

While gap pads have a typical minimum thickness of about 0.010" or 0.25 mm, gels can be dispensed in bond lines as thin as about 0.002" or 50 microns and up to well over half an inch on the thicker side. This means significantly increased thermal performance at thinner bond lines as the material can wet out and make effective contact between surfaces. Other benefits include very low compression forces, even lower than those of the already soft gap pads, thus reducing the force on underlying components. They also tend to have a lower density than pads, further reducing weight.

MEETING THE NEEDS OF DRONE APPLICATIONS

As you can see, there are many tools available to ensure heat management and EMI shielding for drones, and many more innovations are on the horizon. Current advancements are focused on higher thermal conductivity, higher flow rate, lower compression force, and higher reliability products to keep up with the needs of higher power connectivity equipment. This includes silicone and non-silicone solutions for gap pads and gels, as well as additions to thermal grease, phase change material, and even two-component material product families.

On the EMI shielding side, current research is directed toward new elastomer solutions, such as unique form-and-place materials and RF-absorbing solutions. The industry is not only developing new products but ensuring that these products are augmented with supporting information, such as high-frequency shielding data up to 115 GHz for EMI shielding products and environmental reliability data. Enhanced reliability testing capabilities aim to better align with customer requirements so that products perform reliably and consistently over the entire lifetime of the device.

Finally, remember that there are easy steps to reduce significant weight and ensure reliability in any environment. Lightweighting products such as conductive heat string tubing and plastics can provide up to 75 percent weight reduction while maintaining an important level of EMI shielding and RF absorption. Conductive foams and some thermal gels allow you to take advantage of light weight solutions while providing grounding or excellent heat transfer, respectively. These are all important considerations to keep drones flying safely and reliably.

Preventing Liability from Foreign-Made Products

How to Protect Yourself When Selling Foreign Products

By Kenneth Ross

A quick look through recent 2024 recall notices posted on the website of the U.S. Consumer Product Safety Commission (CPSC) reveals that a majority of recalled products were manufactured in China.[1] And a recent analysis of 1st quarter 2024 recalls by Sedgwick Brand Protection reveals the following products with the highest number of recalls – sports and recreation, children's products, electronics, toys, and home appliances.[2] Most of these products are manufactured in China or other locations in Asia.

The Hong Kong Trade Development Council (HKTDC) analyzed recalls in 2021 and had the following conclusions:

> *According to information collected from the CPSC consumer product recall database, there were 155 recalls involving nearly 36 million units during January-August 2021 that either violated mandatory standards or presented a substantial risk to the public.*
>
> *Imported products accounted for approximately 85.8 percent of the recalls issued (133) and about 89.1 percent of the total number of units recalled (31.8 million) during the first eight months of the year, while U.S. products accounted for 16.1 percent of the recalls issued (25) and approximately 10.9 percent of the total number of units recalled (3.9 million).*
>
> *Mainland China remains the supplier with the largest number of recalls and recalled units, with its products having been involved in eighty-six recalls affecting some 28.4 million units during January-August 2021 (four of these recalls were shared with products from other locations). Mexico ranks third in terms of the total number of recalls behind mainland China and the U.S., with nine recalls involving 87,759 units during January-August 2021, while Vietnam and Taiwan rank fourth each with eight recalls affecting some 1.5 million units and India ranks sixth with seven recalls affecting about 146,400 units.*

Kenneth Ross is a Senior Contributor to In Compliance Magazine, and a former partner and now Of Counsel to Bowman and Brooke LLP. He provides legal and practical advice to manufacturers and other product sellers in all areas of product safety, regulatory compliance, and product liability prevention, including risk assessment, design, warnings and instructions, safety management, litigation management, post-sale duties, recalls, dealing with the CPSC, contracts, and document management. Ross can be reached at 952-210-2212 or at kenrossesq@gmail.com. Ross' other articles can be accessed at https://incompliancemag.com/author/kennethross.

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Despite this risk, U.S. manufacturers and retailers will continue to buy all kinds of raw materials, component parts, and finished products from China and elsewhere. And these numbers will continue to increase as long as there is no backlash from consumers.

And an analysis of 2023 recalls by Don Mays revealed that "four of the top five recalls citing injuries were for small appliances, all of which were manufactured in China." Mays also said:

> *Most of the products named in recalls were manufactured in China. This indicates that robust supply chain controls and adequate risk management procedures may be missing from importing companies' product safety programs. Relying on foreign manufacturers requires an extra level of due diligence to ensure problems won't be encountered once the products get to the US market.*[3]

Given this reality, there are a number of issues that manufacturers and product sellers have to face when trying to prevent future product safety and product liability problems caused by foreign-made products.

WHERE TO BUY PRODUCTS OR COMPONENTS

The first issue is whether it is advisable to buy safety-critical products, component parts, or raw materials from China or any other country with a less sophisticated and less robust safety and quality system. Usually, U.S. manufacturers or product sellers do not buy from foreign sources to buy better-quality products. Rather, they hope to achieve an acceptable level of quality and safety at a lower price.

So, given the increased risks and increased costs of dealing with foreign manufacturers, especially those companies not known for producing high-quality products, can you save enough money by buying from foreign manufacturers to justify the risk? You can spend most or all of your profits on one product liability case or recall if the foreign supplier does not take care of the entire cost, including administrative costs for your employees. And this cost does not include damage to the U.S. manufacturer's or retailer's reputation in the marketplace.

Despite this risk, U.S. manufacturers and retailers will continue to buy all kinds of raw materials, component parts, and finished products from China and elsewhere. And these numbers will continue to increase as long as there is no backlash from consumers. In that case, U.S. manufacturers need to be prepared to provide assurances to their immediate customers (i.e., retailers) and the ultimate customer about the safety and quality of these products.

In addition, U.S. manufacturers and retailers need to take extra precautions to minimize the risk to an acceptable level and to be prepared to convince government agencies and consumers that its products are safe. So let us examine some well-known prevention techniques and see what else can and should be done when foreign-made products are imported into the U.S.

CONTRACTS AND INSURANCE

U.S. manufacturers and retailers should have more detailed contracts and specifications when dealing with foreign suppliers. Most contracts and specifications for U.S. and foreign suppliers are inadequate when dealing with some safety issues, such as recalls and defending product liability lawsuits. Since a U.S. based supplier usually can be sued in all states in the U.S., it is a bit easier to deal with issues that are not in the contract and to get the attention of domestic suppliers if something bad happens.

With foreign manufacturers who have no assets or employees in the U.S., and therefore possibly no U.S. jurisdiction in which they can be sued, it is harder to enforce contracts in general and certainly harder to deal with issues not explicitly set forth in the contract.

Some of the issues that could be included in such contracts and specifications involve required certifications or other safety and quality testing, documentation that must be sent to the U.S. in English to support the certifications and testing, confirmation of the foreign manufacturer's understanding of U.S. safety regulatory issues, and clear terms that address when they must tell you about a post-sale safety or quality issue.

You should be sure to include in the contract remedy and damage provisions that are acceptable to you. For example, you may not want the foreign manufacturer to disclaim consequential damages or to argue that repair or replacement is the only remedy. This is especially true for component parts, where the additional costs of repair, replacement, or refund can be enormous. In addition, do you expect the foreign manufacturer to pay for all costs of a recall? If so, be sure it is clearly set forth in the contract.

Of course, the foreign manufacturer should indemnify you and hold you harmless in the event of a product liability claim or lawsuit. However, do you really want them defending the case, or do you want it clear that you control the defense or at least are able to participate in it, even if their insurance applies? Their insurance company should be U.S.-based and financially capable of responding in the future. And you should require a relatively low self-insured retention. Last, it would be good to get the foreign manufacturer's insurance company to pay for your attorneys to help defend the case.

You should think about how you are going to enforce this contract if necessary. Will you have to sue in China? Or will they agree to jurisdiction in the U.S.? And is the foreign company financially capable of paying for any recall or any deductible in an insured matter? If the company goes bankrupt or closes its doors, the insurance premium is not paid and there is no one other than the U.S. manufacturer to pay for the recall. Maybe the foreign manufacturer should be required to post some type of bond with provisions for when the U.S. manufacturer can access the proceeds of the bond.

And the foreign manufacturer needs to agree to cooperate with the U.S. manufacturer in all respects during production, during any product liability case, and during any government inquiry. They need to timely provide documents in English and provide personnel who can explain in a U.S. court of law or in a deposition why their product was reasonably safe.

It is true that many foreign companies will not agree to these contractual and insurance provisions. In that case, the U.S. company must either decide to take the risk, especially if the component is safety-critical, or must increase its review and analysis of the safety and quality of the purchased products so that they meet the requirements of the U.S. company.

See "Manufacturing in China: Minimizing Your Risks by Doing Things Right"[4] by China law expert Dan Harris for a further discussion of contracting issues with the Chinese.

DESIGN PROCEDURES

Safety and quality procedures for foreign manufacturers should not be any different than those applicable to U.S.-based manufacturers. However, it is more important that you know what the foreign manufacturer is doing and how they are documenting the results.

- Some additional questions to consider asking foreign manufacturers include:
- Do they do a hazard analysis, a failure mode and effects analysis, a design review? Do they document these procedures? Do they train their personnel in how to do them? What level of safety is acceptable? Is it up to the foreign manufacturer to decide on levels of safety or do they need your approval for the final design?
- Do they get certifications from respected testing agencies? Do they give these agencies all the necessary information? Are they possibly supplying misleading or incomplete information that potentially jeopardizes the certifications? Is it possible that these certification agencies are inappropriately or incorrectly certifying the

product as a result of bribes or incompetence? Should these certifications be done in the U.S. or Canada?

- Should the foreign company just comply with regulations and standards, or should they exceed them? Who decides that and who decides on how much safer the product must be?
- How do you know that the foreign manufacturer continues to comply with the design approved by the certifying agency? Do you confirm compliance on a periodic basis?

MANUFACTURING ISSUES

What type of quality testing do they do – full, partial, random? What do they consider a product that meets specifications? Do they believe that "close enough" is acceptable? Is that acceptable to you?

Should you do full, partial, or random incoming inspection testing of the product or component part? Do you confirm that the foreign manufacturer has not changed the raw material in the part or product they sell you after you or the certifying agency has approved? There are many horror stories of changes made in material or manufacturing processes after approval.

Should you have full-time people at the plant in the foreign country monitoring their manufacturing and quality control processes? Or how often should you visit their facilities, and should the visit be unannounced?

WARNINGS AND INSTRUCTIONS

Do you review and "approve" the warnings and instructions provided by the foreign manufacturer? Do you require them to utilize the services of a competent native English speaker to draft the warnings and instructions? Do you require them to retain a competent U.S.-based attorney to provide advice on the legal adequacy and defensibility of the warnings and instructions?

The U.S.-based manufacturer should not generally undertake the rewriting of the warnings and instructions of a supplier, U.S. or foreign. Doing that makes them more potentially liable. It is better to require the foreign manufacturer to utilize competent people to assist them. They know their products best and should be required to provide you with a component part or finished product that is safe in its design, manufacture, and warnings and instructions.

POST-SALE ISSUES

The foreign manufacturer needs to have competent personnel in-house to receive and evaluate post-sale safety and quality issues. They have to agree to allow you to review this information if it is appropriate. And there should be some agreement on when it is appropriate.

For example, if a Chinese manufacturer sells the same component to ten manufacturers and has a problem with products sold to one or more of those manufacturers, it should be required to tell you about the problems, even if you have not had any with their component. The goal is for you to be able to prevent problems before they happen.

Certainly, you need to be notified immediately if the component part has been inserted into a product made by another manufacturer and has been recalled or repaired anywhere in the world because of a problem with that component. And you should be sure that the supplier's personnel or their advisors are familiar with the U.S. government reporting responsibilities and know what to tell you and when.

The foreign manufacturer's design and manufacturing processes should enable them to narrow the potential universe of problem products so as to allow you to correct or retrieve only those products that need to be dealt with. This includes traceability and marking procedures that are appropriate for the risk level of the particular product.

DEFENDING THE PRODUCT

U.S. manufacturers do not want to be in a position in which their only defense is blaming a foreign supplier. This is especially true if the manufacturer is not in the courtroom with you.

So, while you are evaluating who to do business with and what procedures you want them to adhere to, also consider how they will appear in court if they have to defend the adequacy of their part or product. Are the people who would testify sincere and knowledgeable, and can they speak well (preferably in English)? Do they have documents that have been written carefully and that correctly present what they did to produce a safe and quality product? Will your witnesses be able to understand and use these documents to defend the adequacy of the product or part?

For an informative discussion of these and other risk mitigation techniques when dealing with China-based manufacturers, see the blog "Reducing Your Product Liability Risks from Overseas Products" by Dan Harris.[5] Also, see a webinar presented by this author and Dan Harris on these topics.[6]

CONCLUSION

All of the techniques and concerns mentioned in this article are also important for U.S.-based suppliers. However, given the location of manufacturers who are producing products with problems, it is even more important to go the extra mile with foreign suppliers.

Ultimately, the manufacturer or product seller gets to make a business decision on whom to buy from and what to require them to do. Since it may well be impossible to find a foreign manufacturer that is willing to do all of the things detailed in this article, the company will need to decide what preventive techniques are priorities and when or if the lack of a technique is a deal breaker. In that way, U.S.-based companies will be better prepared to make a rational business decision and assume a future risk that they deem acceptable.

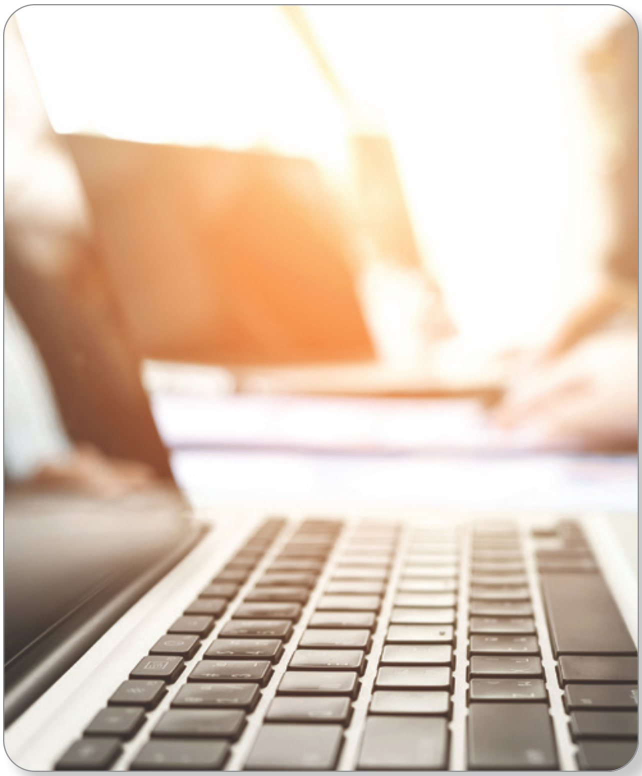
ENDNOTES

1. https://business.cpsc.gov/Recalls/rrcpsc.aspx
2. https://www.sedgwick.com/brandprotection
3. https://productsafetyinsights.com/publications
4. https://harris-sliwoski.com/chinalawblog/manufacturing-in-china-minimizing-your-risks-by-doing-things-right (December 26, 2023)
5. https://harris-sliwoski.com/chinalawblog/reducing-your-product-liability-risks-from-overseas-products (September 6, 2023)
6. "Product Sourcing & Contracting Overseas to Reduce Product Liability and Product Safety Risks," https://www.productsafetyprofessionals.org/webinar-archive (March 20, 2024)

Laboratory Automation with PyVISA

Applying Python and PyVISA to Automated Testing

By Dr. Zachary Nosker



Python has become a widely used programming language in the area of electronic test automation, especially when used with the PyVISA library. While the fundamental principles of lab automation have been around for a long time (i.e., the SCPI protocol), Python and PyVISA have made it easy to get started quickly with test automation. Once data has been collected, Python also has a plethora of data analysis tools (pandas, scipy, scikit, etc.) that are useful in analyzing data.

In this article, I will introduce how to interface with instruments using Python/PyVISA and give a practical example of measuring power supply efficiency. Finally, I will introduce how to plot gathered efficiency data directly in Python.

SCPI PROTOCOL

The Standard Commands for Programmable Instruments (SCPI) is a definition layer on top of the IEEE 488.2-1987 standard for instrument communication. While SCPI was originally meant for IEEE 488.1 (GPIB connections), this has expanded to include RS-232, Ethernet, USB, and several others. SCPI commands are sent in ASCII format and received as a string of ASCII text. Here is an example of a simple SCPI transaction:

Host query: `*IDN?`

Device reply: `Siglent Technologies,SDL1020X-E,SDLxxxxx xxxxxx,1.1.1.21R2\n`

SCPI defines a number of generic commands like `MEASure` and `CONFigure`, which can be used to read data from or configure parameters on test equipment.

VISA Specification

Unfortunately for the SCPI standard, different operating systems, interfaces, and devices meant that the early days of SCPI required different libraries for each device and bus system. In order to alleviate this pain, the Virtual Instrument Software Architecture (VISA) specification was created to seamlessly work with all devices and bus systems.

PYTHON AND PYVISA

Even with the VISA specification in place, it has traditionally been challenging to interface a host computer to measurement devices without expensive/cumbersome software and hardware. With these drawbacks in mind, the PyVISA library was created to simplify instrument communication and make lab automation more efficient.

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Python itself is a free, interpreted programming language that can be used with any modern operating system. Since this is an interpreted (and not compiled) language, Python can generally be “installed” on any system, even where the user does not have admin/root access. While the syntax of Python can take some getting used to (spaces are used as delimiters instead of ; or other characters), it is a very widely used language with many libraries, examples, and code snippets available.

PyVISA works as a front end to the VISA library and simplifies the process of communicating with instruments. PyVISA is officially tested against National Instruments’ VISA and Keysight IO Library Suite and can be used with hardware adapters from National Instruments, Keysight, and many others.

To get started, here is a simple program that queries what instruments are visible to PyVISA on my computer. In the below code snippet, I am using National Instruments VISA on a 64-bit Windows computer running Python 3.11.5 and PyVISA 1.13.0

In [2]:

```
import pyvisa
instruments = pyvisa.ResourceManager().list_
resources()
instruments
```

Out[2]:

```
('USB0::0xF4EC::0x1621::SDL13GCQ6R0772::INSTR',
 'USB0::0x2A8D::0x3402::MY61003767::INSTR',
 'GPIB0::12::INSTR',
 'GPIB0::22::INSTR')
```

This output shows there are four instruments connected to my computer, two connected by USB and two by GPIB. Now we can create an object for each instrument and query what it is. Note that all instruments will reply to the special `*IDN?` Command:

In [5]:

```
for i in instruments:
    inst = pyvisa.ResourceManager().open_
resource(i)
    print(i,inst.query('*IDN?'))

USB0::0xF4EC::0x1621::SDL13GCQ6R0772::INSTR Siglent
Technologies,SDL1020X-E,SDL13GCQ6R0772,1.1.1.21R2

USB0::0x2A8D::0x3402::MY61003767::INSTR Keysight Techn
ologies,E36234A,MY61003767,1.0.4-1.0.3-1.00

GPIB0::12::INSTR HEWLETT-PACKARD,34401A,0,7-5-2

GPIB0::22::INSTR HEWLETT-PACKARD,34401A,0,11-5-2
```

From the query, you can see I have a Keysight power supply (E35234A) and a Siglent power supply (SDL1020X-E). For the following example, I am using the Siglent power supply only to read the input and output voltages of the device under test (DUT).

MEASURING EFFICIENCY

For a power supply, efficiency is the measure of how much power you get out per unit of power put in. Since $P = VI$, this can be written as:

$$\eta = \frac{P_o}{P_{in}} = \frac{v_O \times i_O}{v_I \times i_I}$$

As this equation gives a fraction less than 1, it is customary to multiply by 100 and express efficiency as a percentage.

POWER SUPPLY SETUP

For the following test, I am using a 720 W adjustable DC-DC power supply from DROK (shown in Figure 1). For the purpose of this example efficiency test, I am using a constant input voltage of 25 V with a fixed output of 12 V. Note there is a large fan near the North side of the board which turns on when the power supply is under heavy load. We will see the effects of this fan in the full efficiency characteristic.

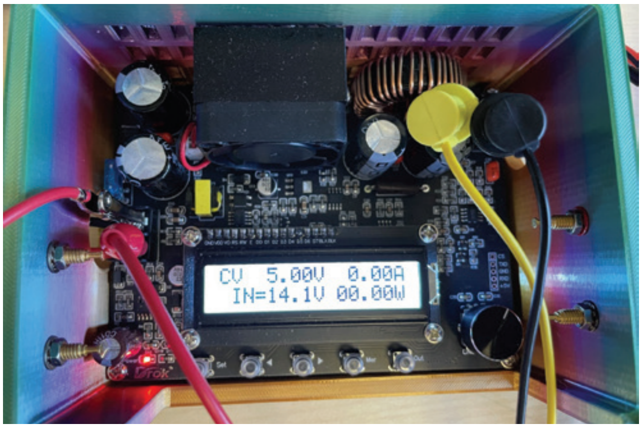

Figure 1: Drok 720 W Adjustable DC Power Supply

PRACTICAL EFFICIENCY MEASUREMENTS¶

In order to measure the efficiency of a DC-DC power supply, we must apply a source voltage v_s and a load current i_{LOAD}. The voltage source is a DC voltage and the load current is an electronic load running in the constant current mode. We step up the load current and measure the efficiency at various load points to create a full plot showing the efficiency characteristic of the power supply.

Since each measurement requires four values (input voltage, input current, output voltage, and output current), we need sufficient equipment to read all these parameters. In practice, it is beneficial to measure the input and output voltage on separate meters as close to the DUT as possible.

For current measurements, reading the current directly from the voltage source (for input current) and the electronic load (for output current) are generally close enough when using modern, calibrated equipment.

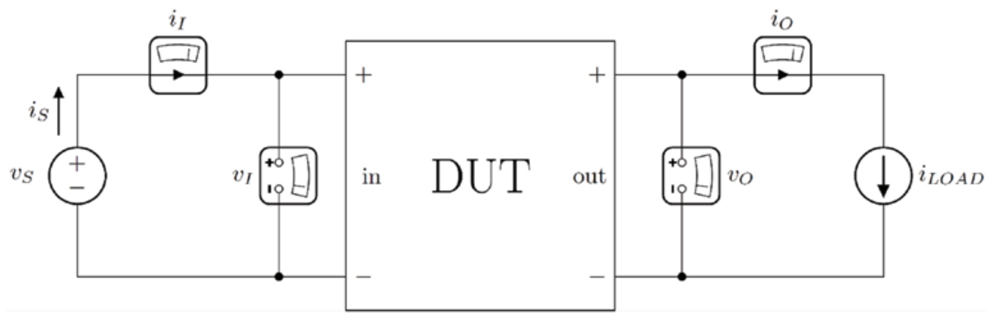

Figure 2: Practical instrumentation of power supply for efficiency measurements

Instrument Objects for Efficient Data Collection

We can use the tools available in Python to create an object for each piece of equipment and create a standard list of methods that our instruments will use. As an example, we can make a read_v() method for all of our instrument objects to read the voltage value. At the top level, we just see the method instrument.read_v(), but this actually maps to the specific SCPI commands for our instrument and returns data that Python can read.

For this test, we will need four instrument objects, though the voltage measurements will be instances of the same object with different addresses (same meter, different GPIB address).

In [6]:

```
#Basic object for Keysight E36200 series power supply
#Note that channel must be specified
class keysight_E36200(object):

    def __init__(self, visa_address, **kwargs):
        self.pyvisa = pyvisa.ResourceManager().
open_resource(visa_address)
        #
        #Setup some things
        #
        self.__channel = int(kwargs['channel'])

        #check if this is the correct device

    def set_v(self, voltage):
        self.pyvisa.write('VOLT {0:G}, (@{1})'.
format(voltage,self.__channel))

    def set_i(self, current):
        self.pyvisa.write('CURR {0:G}, (@{1})'.
format(current,self.__channel))

    def read_v(self):
        return float( self.pyvisa.query('MEAS:VOLT? (@
{0})'.format(self.__channel)) )

    def read_i(self):
        return float( self.pyvisa.query('MEAS:CURR? (@
{0})'.format(self.__channel)) )

    def output_enable(self):
        self.pyvisa.write('OUTP 1, (@{0})'.
format(self.__channel))

    def output_disable(self):
        self.pyvisa.write('OUTP 0, (@{0})'.
format(self.__channel))
```

In [7]:

```
class SDL1000X(object):

    def __init__(self, visa_address):
        self.pyvisa = pyvisa.ResourceManager().
open_resource(visa_address)
        #
        #Setup some things
        #

    def read_v(self):
        return float(self.pyvisa.
query('MEASure:VOLTage:DC?'))

    def read_i(self):
        return float(self.pyvisa.
query('MEASure:CURRent:DC?'))

    def set_i(self, current):
        self.pyvisa.write(':SOURce:CURRent:LEVel:IMMe
diate {0:f}'.format(current))

    def output_enable(self):
        self.pyvisa.write(':SOURce:INPut:STATe ON')

    def output_disable(self):
        self.pyvisa.write(':SOURce:INPut:STATe OFF')
```

In [8]:

```
class hp34401(object):

    def __init__(self, visa_address):
        self.pyvisa = pyvisa.ResourceManager().
open_resource(visa_address)

    def read_v(self, average=1):
        #start from v=0, add values and average as
needed
        v = 0.0
        self.pyvisa.write("CONFigure:VOLTage:DC")

        for x in range(average):
            v += float(self.pyvisa.query("READ?"))

        voltage = v / average

        return voltage
```

We also need to import a few libraries which will be helpful for this test:

In [9]:

```
import time
import numpy as np
import pandas as pd
```

Then, create an object for each instrument with a descriptive name:

In [10]:

```
inst_load = SDL1000X('USB0::0xF4EC::0x1621::SDL13GCQ6R
0772::INSTR')
inst_supply = keysight_E36200('USB0::0x2A8D::0x3402:
:MY61003767::INSTR',channel=1)
inst_vin_sense = hp34401('GPIB0::12::INSTR')
inst_vo_sense = hp34401('GPIB0::22::INSTR')
```

We now have objects for the four instruments we are using to measure efficiency, and each instrument has high-level methods with descriptive names. Note again that the actual SCPI commands sent to each object are very different, but the intended data (like measuring current) returns the appropriate data for Python.

Calibrate Input Voltage

The wire connecting from the power supply to the DUT has a finite impedance, and when the input current increases (due to increasing load current), the input voltage seen at the input of the DUT will decrease. In order to compensate for this effect, we can directly measure the voltage right at the DUT and increase/decrease the supply voltage to stay within a certain bound (in this case, 10mV).

In [11]:

```
def calibrate_vin(supply, sense, v_target):

    v_meas = sense.read_v()
    v_diff = v_meas - v_target
#Keep input to within 10mV
    while abs(v_diff) > 0.01:
        supply.set_v(supply.read_v() - v_diff/1.5)
        time.sleep(1)

        v_meas = sense.read_v()

        v_diff = v_meas - v_target
```

Cooldown¶

When using the calibration function above and at very high load currents, it is possible that the input voltage will be so high that it could electrically overstress (EOS) the device we are testing. To avoid this, we can create a simple “cooldown” loop that decreases the load and lowers the supply voltage slowly down to a safe voltage:

In [12]:

```
def cooldown(v_final,steps):
    #Read current and voltage right now
    v_now = inst_supply.read_v()
    i_now = inst_load.read_i()

    #Determine step size
    v_step = (v_now - v_final)/steps
    i_step = i_now/steps

    #Reduce by step sizes
    i_now -= i_step
    v_now -= v_step

    for s in range(steps):
        inst_supply.set_v(v_now)
        inst_load.set_i(i_now)
        i_now -= i_step
        v_now -= v_step
        time.sleep(1)
    #Disable when current is 0 and voltage is at
target
    inst_load.output_disable()
    inst_supply.output_disable()
```

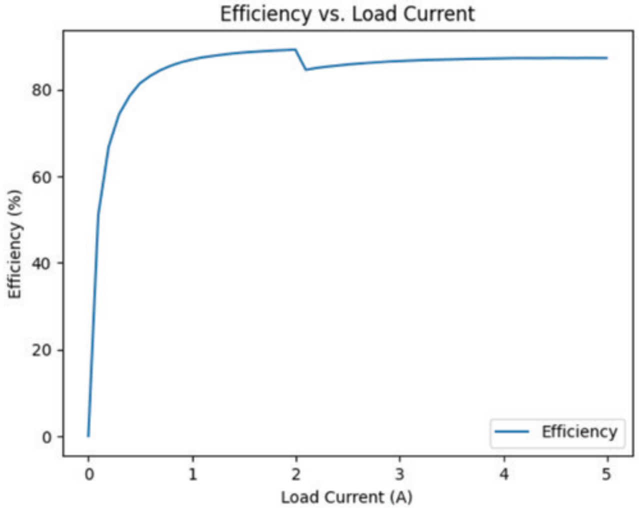

Figure 3: Python plot of efficiency vs. load current

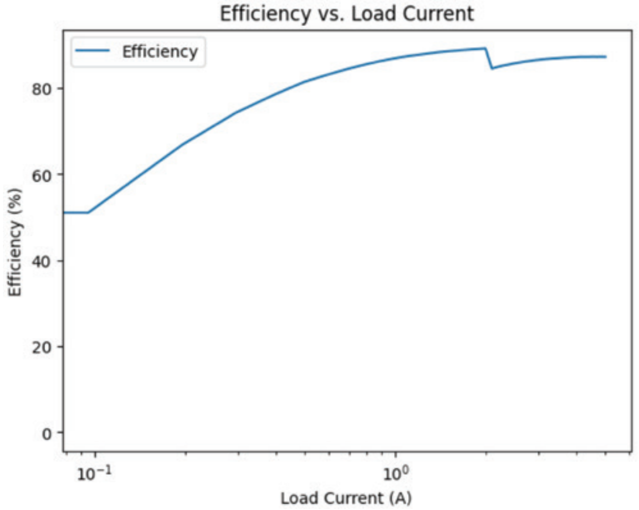

Figure 4: Plot of efficiency vs. load current with a logarithmic X axis

Initial Setup¶

Next, we need to set up the loads point we will use for our test and set the remaining parameters. All test data will be stored in a Pandas DataFrame object which will be useful for plotting and exporting to .csv later on.

In [13]:

```
load _ currents = np.linspace(0,5,51) #100mA steps
#load _ currents = np.logspa
ce(-2,0.6989700043360189,100)

supply _ voltage = 25

inst _ supply.set _ v(supply _ voltage)
inst _ supply.output _ enable()
time.sleep(1)

inst _ load.set _ i(0)
inst _ load.output _ enable()

input("Press ENTER when ready\n")

row _ counter = 0

column _ labels = ['Vin _ set','Iload _ set','Vin','Iin','
Vout','Iout','Efficiency']
all _ data = pd.DataFrame(columns=column _ labels)
```

Loop Through Currents¶

The main loop works as follows:

1. Set the next load current value on the electronic load;
2. Wait for the current to stabilize;
3. Calibrate the input voltage (right at the DUT) to keep this close to the supply voltage value;
4. Read all meters and calculate efficiency;
5. Store all read data as a new row in the all_ data DataFrame; and
6. Increment the row counter and continue to the next load value.

In [14]:

```
for lc in load _ currents:
    inst _ load.set _ i(lc)
    time.sleep(1)
    calibrate _ vin(inst _ supply, inst _ vin _ sense,
supply _ voltage)

    data = [supply _ voltage,
    lc,
    inst _ vin _ sense.read _ v(),
    inst _ supply.read _ i(),
    inst _ vo _ sense.read _ v(),
    inst _ load.read _ i()]

    efficiency = (100* data[4] * data[5]) / (data[2] *
data[3])
    data.append(efficiency)

    #print(*data, sep=",")
    all _ data.loc[row _ counter] = data

    row _ counter += 1
```

Cooldown and Save Data¶

Once the loop is complete, cooldown in 10 steps and save the all_data DataFrame to a .csv file (with a timestamp that guarantees all data files are unique):

In [15]:

```
cooldown(supply _ voltage,10)

timestamp = time.strftime("%Y.%m.%d.%H.%M.%S")

all _ data.to _ csv('.\\data\\Efficiency _ '+timestamp+'.csv')
```

Plot data inline¶

Since the entire all_data DataFrame still exists in memory, we can easily plot this using matplotlib:

In [22]:

```
%matplotlib inline
import matplotlib.pyplot as plt
```

In [31]:

```
all _ data.plot(x='Iout',y='Efficiency')
plt.title('Efficiency vs. Load Current')
plt.xlabel('Load Current (A)')
plt.ylabel('Efficiency (%)')
plt.show()
```

Note that there is a large dip in efficiency when the load current is near 2 A. This is the point where the fan on the DC-DC converter turns on and causes a noticeable kink in the efficiency characteristic.

Plot With Log X Axis¶

Similarly, we can change the X axis to logarithmic scale, which tends to show a smooth curve when plotting efficiency:

In [37]:

```
fig, axs = plt.subplots(1)
all _ data.plot(ax=axs,x='Iout',y='Efficiency')
plt.title('Efficiency vs. Load Current')
plt.xlabel('Load Current (A)')
axs.set _ xscale('log')
plt.ylabel('Efficiency (%)')
plt.show()
```

SUMMARY

Using Python and the PyVISA library, we have created instrument objects and a simple program to tabulate the efficiency of a DC power supply. We have also used the plotting tools in Python to create graphs of efficiency for this test.

With the basic program in place, it is possible to modify this program to add features, including:

- Loop through different input voltages;
- Change the tested currents;
- Save plot data as image or pdf files; and
- Save data as a Word document or PowerPoint slides.

Vulnerabilities of LTE and LTE-Advanced Communications

Ensuring Proper Communication in Environments with High Interference

By Naseef Mahmud

Demand for high-volume data streams in the current market for modern wireless communication systems is growing at a fast pace. In order to keep up with the trend to higher throughput requirements within unchanged bandwidth limitations, long-term evolution (LTE) technology has become a popular solution for replacing the transfer of data over 2G/3G communication networks. Although 5G is gaining ground in big cities and throughout the developed world, LTE is still the primary cellular standard in most countries around the globe. The popularity of LTE is driven in large part by the low cost and high performance it delivers. LTE can potentially reach a raw bit rate of 300 Mbps in the downlink channel using advanced MIMO configurations. Further, voice over LTE (VoLTE) enables voice transmissions.

Another major advantage of LTE is that 2G and 3G services are being switched off in many parts of the developed world. As a result, the default fallback system for emergency scenarios is the 4G LTE network.

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Other than providing the standard of choice for commercial networks, LTE is also often used to broadcast emergency information in times of natural disasters and national crisis situations.

However, LTE has some vulnerabilities that are a matter of concern since it is possible to completely take down an LTE network or at least partially block communication networks intentionally or unintentionally. Some defined LTE bands are prone to coexistence issues with the S-band radar frequencies, such as those used by air traffic control (ATC) and air traffic surveillance (ATS) radars that scan the horizon up to 500 km range. In addition, at the lower end of the frequency spectrum, LTE has coexistence issues at the ultra high frequency (UHF) bands.

A clear understanding of LTE technology and its vulnerabilities is especially important for commercial, civil-governmental, and defense applications. This article highlights areas of greatest susceptibility to interference and jamming of the LTE network and possible counter-measures and also explores coexistence issues. Our goal is to provide a solid foundation for the use of LTE technology for devices used in commercial, civil-governmental, and military applications.

JAMMING TECHNIQUES

Wireless communication systems are not deployed in an ideal environment. The channels are subject to unwanted interference from other services operating in the adjacent frequency bands. There are also cases of jamming attempts on the network. This causes the performance of the network to degrade. In this section, we'll discuss conventional jamming techniques as well as certain new, smarter, and more power-efficient jamming techniques.

Barrage Jamming

Barrage jamming (BJ) is the most basic jamming technique. This is highly effective when there is no prior knowledge of the network. The entire spectrum of the target signal is jammed by transmitting band-limited noise to the system. This means the signal-to-noise ratio (SNR) decreases over the entire bandwidth. BJ is the most inefficient method of jamming. It requires a lot of power but is taken as a baseline for comparing the efficiency of other forms of jamming and their corresponding effectiveness. More information on BJ analysis can be found in [2]. Figure 1 on page 116 presents the spectrum for a BJ attack.

Partial Band Jamming

Partial band jamming (PBJ) is a technique in which a certain portion of the entire system bandwidth is targeted and jammed by transmitting additive white Gaussian noise (AWGN) over this specific bandwidth. When the power of the jamming signal is constant, the effectiveness of the jamming depends directly on the fraction of the jamming bandwidth and the signal bandwidth. More information on PBJ can be found in [1,2]. In Figure 1, the part of the spectrum affected by PBJ can be seen.

Single-Tone Jamming

In single-tone jamming (STJ), a single high-powered impulse of AWGN noise is transmitted to jam only a certain band of interest. In the LTE downlink, only single subcarriers can be jammed using the STJ technique.

Figure 1 shows the effect of STJ on the spectrum. STJ can also be considered as a special case of PBJ. A more analytical investigation of the STJ can be found in [2]. In STJ, the knowledge of the target system's carrier frequency is required in order to jam the target signal.

Multi-Tone Jamming

Multi-tone jamming (MTJ) is another form of PBJ. Unlike STJ, multiple, equally powered noises are transmitted in order to take down multiple frequency subcarriers within the LTE bands. An MTJ attack is highly effective when there is a power limitation on the transmit side. This means that if there is a strict limitation on the transmit power, an increase in the number of transmitted tones will decrease the power associated with the individual transmitted jamming tones. A detailed analysis of the effect of MTJ on orthogonal frequency-division multiplexing (OFDM) can be found in [3].

Figure 1 shows an illustration of an MTJ attack on the spectrum. In MTJ, knowledge of the target system's carrier frequency is required.

Asynchronous Off-Tone Jamming

There are two types of asynchronous off-tone jamming (AOTJ). The first type is called single off-tone jamming, and the second is a multiple off-tone jamming attack. The operational concept of this technique is to transmit asynchronous off-tones that are not perfectly periodic or that have an offset at the sampling frequencies. As a result, the energy gets smeared from the true frequency into the adjacent frequency bins, thus creating inter-channel interference (ICI) of the OFDM signal at the receiver [1].

Also, the side lobes of the signal (sync function) are not aligned with the OFDM subcarriers because frequency offset can have non-zero components at the sampling period that can be a source of ICI. One advantage of AOTJ is that the jamming signal does not need frequency matching with the target signal or any channel state information (CSI). AOTJ demonstrates superior performance compared to BJ, STJ, and MTJ. An example of the two types of AOTJ can be seen in Figure 1.

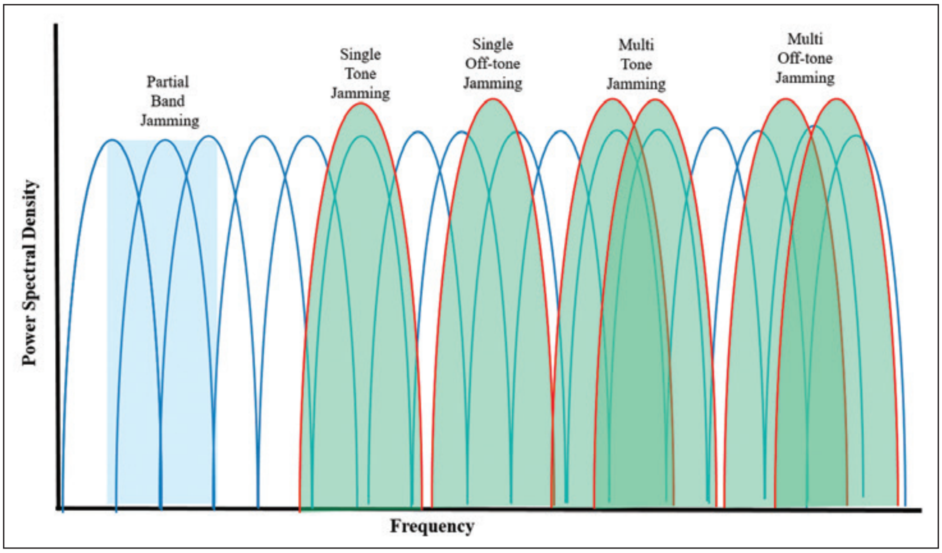

Figure 1: Different jamming attacks on LTE downlink [1]

Pilot Tone Jamming and Pilot Tone Nulling

In pilot tone jamming, the jammer must be perfectly synchronized with the target signal. This is done through the observation of communications between all the parties involved in the network. For example, a vector jammer signal Zi is equal to 0 (Zi = 0) for non-pilot sub-carriers and qi (Zi = qi) for the pilot tones, which is an independent and identically distributed AWGN [4]. If this AWGN sequence is coherently transmitted on all pilots simultaneously, then the noise is not averaged out for linear combinations.

In case of pilot tone nulling, it is also important to know the channel. The transmitter transmits a signal which is channel-corrected and π-radian phase shifted of the pilot tone. This causes the original pilot tone to cancel out and thus degrades the performance of the network.

COEXISTENCE WITH OTHER SERVICES

Coexistence of LTE and S-Band Radar

Air traffic control (ATC) radar, military air traffic surveillance (ATS) radar, and meteorological radar operate in the S-band frequency range. In fact, 4G communication systems (such as LTE) also operate in the same frequencies. The testing and measurement of their coexistence is absolutely essential as performance degradation of mobile devices and networks has been proven.

Table 1 lists the LTE frequency bands for frequency division duplex (FDD) and time division duplex (TDD) modes of operation. Bands 1, 4, 7, 10, 22, 23, and 30 are fairly close to any operational S-Band radar system.

LTE base stations (eNodeB) may be disturbed through radar systems. Depending on the ATC or ATS radar system, a power of up to 7000 MW EIRP is transmitted. The blocking requirements of the LTE base stations (BS) and user equipment (UE) must also comply with these

Operating Band	Centre Frequency of Interfering Signal [MHz]	Interfering Signal mean power [dBm]	Wanted Signal mean power [dBm]	Interfering signal centre frequency minimum frequency offset from the channel edge of the wanted signal [MHz]	Type of Interfering Signal
1-7, 9-11, 13-14, 18,19,21, 24, 33-43	$(F_{UL\_low}-20)$ to $(F_{UL\_high}+20)$	-35	$P_{REFSENS}$ +6dB*	See table 7.6-2	See table 7.6-2
	1 to $(F_{UL\_low}-20)$ $(F_{UL\_high}+20)$ to 12750	-15	$P_{REFSENS}$ +6dB*	—	CW carrier

Table 1: Blocking performance requirement for wide area BS [5]

E-UTRA band	Parameter	Units	Frequency			
			range 1	range 2	range 3	range 4
	$P_{Interferer}$	dBm	-44	-30	-15	-15
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43	$F_{Interferer}$ (CW)	MHz	F_{DL_low} -15 to F_{DL_low} -60	F_{DL_low} -60 to F_{DL_low} -85	F_{DL_low} -85 to 1 MHz	-
			F_{DL_high} +15 to F_{DL_high} + 60	F_{DL_high} +60 to F_{DL_high} +85	F_{DL_high} +85 to +12750 MHz	-
2, 5, 12, 17	$F_{Interferer}$	MHz	-	-	-	F_{UL_low} - F_{UL_high}
Note: For the UE which supports both Band 11 and Band 21 the out of blocking is FFS.						

Table 2: Out-of-band blocking parameters [5]

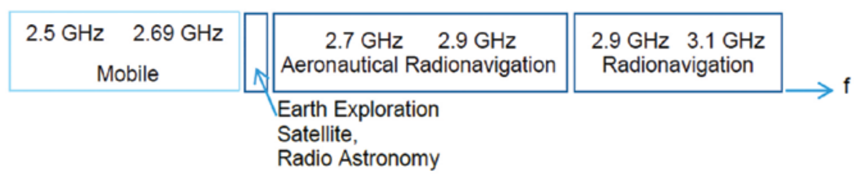

Figure 2: International Telecommunication Union Radio (ITUR) regulations in the band of 2.5 GHz to 3.1 GHz [7]

figures by considering the distance of the BS or UE. TS36.141 defines the blocking performance requirement for wide area BS as described in Table 1.

The UE may even be closer to a radar system. According to [5], out-of-band blocking parameters are defined as shown in Table 2.

In 3GPP TS36.521-1 [5], the test purpose of "TC 7.6.2 Out-of-band blocking" is described as "unwanted CW [continuous wave] interfering signal falling more than 15 MHz below or above the UE receive band, at which a given average throughput shall meet or exceed the requirement…". Under minimum conformance requirements, the throughput is mentioned to be "≥95% of the maximum throughput of the reference measurement channel."

As shown in several measurements, disturbance of LTE networks occurs through S-band radar, such as degradation of performance due to lower throughput indicated by an increasing block error rate (BLER). Throughput reduction is unlikely but not a major drawback. However, spectral efficiency, power reduction, and costs are of significant importance for any mobile network operator. Therefore, disturbance through other signals is of great interest.

Unlike mobile communications, radar is not defined by a global specification. Thus, many different systems applying different waveforms, frequencies, and bandwidths are deployed and operate nearly autonomously to detect the desired kind of target. For a radar engineer, bandwidth is also one of the key parameters when defining the radar system, as bandwidth defines range resolution. Depending on the radar, bandwidth can range from nearly zero (just a carrier frequency, CW radar) to measure radial velocity up to several GHz for high-resolution range measurements (e.g., ultra-wideband radar [UWB]).

The 2.7 GHz to 2.9 GHz frequency band is primarily allocated to aeronautical radio navigation, i.e., ground-based fixed and transportable radar platforms for meteorological purposes and aeronautical radio navigation services. The operating frequencies of these radars are assumed to be uniformly distributed throughout the S-band [6].

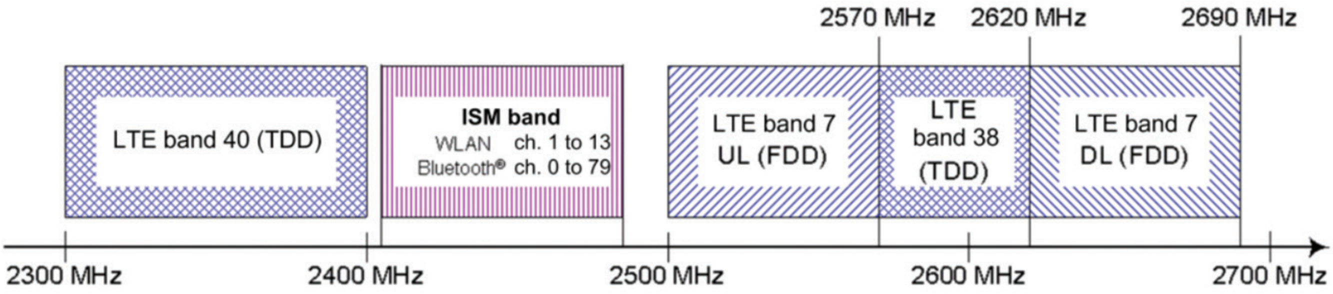

Figure 3: The 2.4 GHz ISM band and adjacent LTE bands

The two frequency bands for mobile communication and aeronautical radio navigation are very closely located, so the coexistence problem also needs special attention.

The application note 1MA211 [6] describes a more detailed investigation of the coexistence problem. The application note also discusses the potential issues concerning S-band radar systems and LTE signals from base stations/mobile devices operating in close range to the signal. It addresses frequency allocation of these systems, explains the performance degradation or malfunction that can be expected, and describes test and measurement solutions for interference testing of radar and LTE networks in detail.

Coexistence with LTE in Critical Environments

In critical environments such as hospitals, it is also important to ensure the coexistence of LTE with other wireless transmissions. The radio frequency (RF) environment of hospitals is very crowded, with many potential sources of interference, including wireless patient monitoring devices, wireless biosensors, smart TVs, etc. In addition, medical staff, patients, and guests in this environment typically introduce additional transmitters into the mix, such as smartwatches, smartphones, and wireless headphones. As a result, WLAN, Bluetooth®, and other mobile standards such as LTE or 5G are simultaneously in operation in a single environment. Therefore, network operators and manufacturers from both the mobile radio and the medical sector have a vital interest in preventing potential interference by performing in-depth testing of their products.

WLAN and Bluetooth® radio communication services operate in the license-free ISM4 band and have a high density of devices in most urban and sub-urban operating environments. LTE band 40 lies very close to the lower end of the ISM band, and LTE band 7 follows, albeit with somewhat more separation at its upper end (see Figure 3).

In addition, 5G new radio (NR) technology's use of its Frequency Range 1 (also widely known in the industry as FR1, 410 MHz to 7125 MHz) overlaps with the LTE frequency spectrum and may even share some of the same band numbers. 5G uses these frequencies for ultra-reliable low latency communications required for telemedicine applications.

LTE also operates in the frequency bands that are already available for existing 3G networks. Moreover, additional ranges are available for use, such as the 2.5 GHz to 2.7 GHz band (Europe/Asia) and the 700 MHz band (USA). LTE bands 5, 12, 13, 14, 17, 19, and 20 overlap with digital TV bands and should be checked for vulnerabilities where digital TV services are still in service. In this coexistence scenario, the digital TV transmitter may act as an interferer on the cellular system LTE. Depending on the spectrum situation, the LTE base station receiver or the LTE terminal receiver could be impacted. If the LTE system and the digital TV system are operated in different frequency bands, this coexistence scenario will never be a co-channel scenario. A more detailed discussion on the issue can be found in [8].

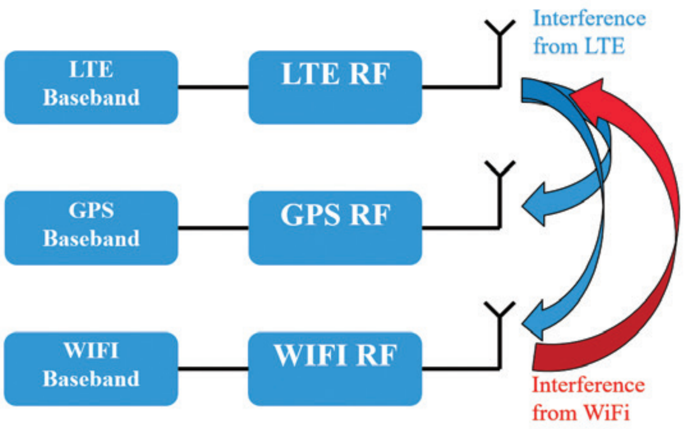

Figure 4: Coexistence interference in a user device supporting LTE, GPS, and Wi-Fi

In-Device Interference and Coexistence

With the ever-growing usage of various wireless technologies and services, user equipment is typically designed with multiple radio transceivers designed to operate in accordance with standards such as LTE, Wi-Fi, Bluetooth, and global navigation satellite systems (GNSS) simultaneously. This means that in-device coexistence interference becomes a matter of concern due to the extreme proximity of multiple transceivers or different antennas coupling with each other within the same device and that can potentially act as interferers.

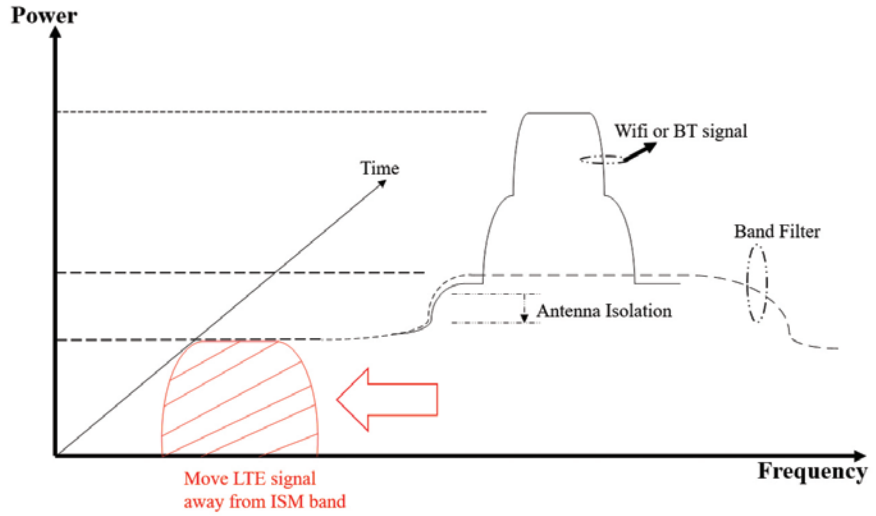

Figure 5: Moving LTE signal away from ISM ban

The extreme proximity of co-located radios due to the small form factor of user equipment and the scarcity of spectrum are the main points that account for this problem. When these radio technologies within the same equipment are working on adjacent frequencies or sub-harmonic frequencies, interference power due to out-of-band emissions from a transmitter of one radio may be much higher than the signal strength of the desired signal for a receiver of a collocated radio. This situation is known as in-device coexistence interference.

Figure 4 shows one situation where user equipment supports multiple standards. The LTE signals undergo interference between different co-located radio transceivers. The Wi-Fi does not interfere with GPS but interferes with Bands 7 and 41 of LTE.

MITIGATION TECHNIQUES

As discussed in the previous section, there are various jamming techniques, as well as unwanted interference that play a role in the degradation of the performance of the LTE communication system. This is important to know when looking at civil-governmental systems as well as military communication systems, which must be robust in both circumstantial and hostile jamming scenarios. Therefore, keeping all the discussed techniques in mind, a few schemes already exist or offer themselves for jamming mitigation.

Jamming Mitigation

One of the most basic ways of mitigating unwanted interference is to rely on RF techniques, such as sufficient filtering or isolation. Unfortunately, the current state-of-the-art filter technology cannot provide sufficient interference rejection, making finding better mitigation schemes necessary.

Certain interference and jamming mitigation schemes such as frequency division multiplexing (FDM) based solutions, time division multiplexing (TDM) based solutions, transmit power control solutions, and frequency hopping solutions are extremely popular.

FDM-Based Solution

The basic idea is to shift LTE or ISM signals away from an interfering band via the frequency domain. This can be done by performing inter-frequency handover within E-UTRAN or removing secondary cells (SCells) from the set of serving cells as shown in Figure 5.

TDM-Based Solution

The basic idea behind TMD-based solutions is shown in Figure 6. This solution relies on avoiding the overlapping of signal transmission in the time domain. In LTE, a discontinuous reception (DRX) mechanism can provide TDM patterns for the scheduling of LTE transmissions.

Transmit Power Control Solution

This solution relies on reducing the power of the transmitting signal (LTE or ISM) to mitigate interference on the other receivers. Figure 7 shows a graphical depiction of the solution. Reducing the transmit power also means a reduction in the size of the coverage area.

Furthermore, in some cases, the UE can autonomously deny ISM transmission in order to protect important LTE signaling (e.g., radio resource control [RRC] connection configuration).

Frequency Hopping (FH) Solution

Frequency hopping (FH) solutions are widely used to mitigate the effects of hostile jamming. FH is mainly limited by the collision effect, and the spectral efficiency of the FH system is extremely low. In order to develop the spectral efficiency of the FH systems, a space-time coded collision-free frequency hopping scheme based on the OFDM framework and a secure subcarrier assignment algorithm can be used in which each user hops to a different set of subcarriers in a pseudo-random manner at the beginning of each new symbol period and at each symbol period. Different users always transmit on non-overlapping sets of subcarriers, thus making the FH scheme collision-free.

Frequency hopping has also been considered in cases where there is significant additional available bandwidth for use. However, it is difficult to overcome the impact of active jamming, especially when jammers acquire the inherent properties of media access control (MAC) layer protocols. There is a mitigation scheme known as the subcarrier-level radio agility. This is based on the concept that jamming signals will likely experience varying levels of fading on different OFDM subcarriers. As a result, some subcarriers may not be significantly affected by the malicious power emission. As long as a transceiver pair is made aware of which subcarriers these are, they can be temporarily used for legitimate packet transmissions.

Thus, a framework is created that allows a transceiver pair to exchange information about these unaffected subcarriers in the available spectrum, where the jamming signal experiences significant fading. Once such subcarriers are identified, the maximum allowable

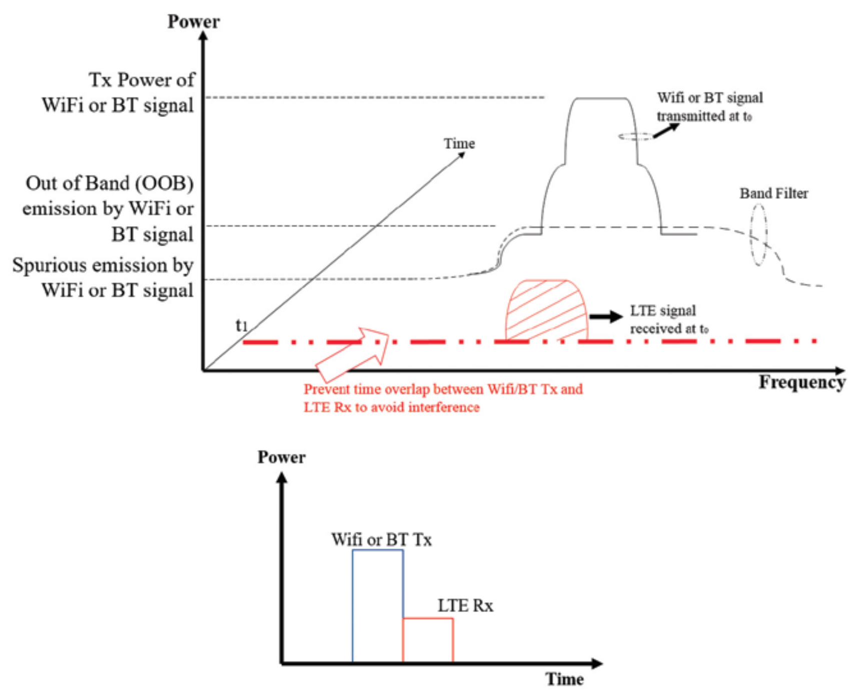

Figure 6: Time division multiplexing for co-existence interference avoidance

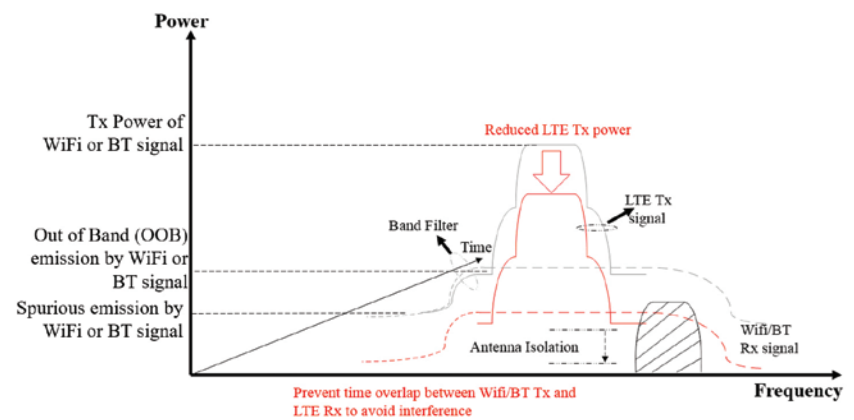

Figure 7: LTE power control for co-existence interference mitigation

transmit power is assigned to these channels. These channels are then used for packet transmissions to increase the probability of successful packet delivery, thereby increasing the long-term throughput (while being actively jammed).

Coexistence Problem Mitigation Techniques

Different approaches can mitigate disturbances on radar and 4G base stations. One approach is to reduce transmit power at the base station and radar. Also, increasing frequency separation or distance between the two services is a potential solution. However, these two approaches reduce the maximum range of the radar and coverage of the base station, and frequency selection may be impossible due to technical restrictions. One approach to mitigate the problem is to avoid letting mobile service base station antennas point toward the S-Band radar. Also, the improvement of receiver selectivity, filtering of transmitter signals, and reduction of unwanted spurious emissions on both sides allows coexistence.

The latter choice is the most straightforward mitigation measure, both at the radar and base station side. Receiver saturation can be avoided through inter-modulation, and a blocking filter can be placed on the radar's receiver before the low noise amplifier (LNA). At the base station side, a filter can be placed on the transmitter close to the antenna to suppress the out-of-band LTE emissions in the spurious domain. Furthermore, a revision of the ETSI 3GPP technical specifications TS 136.101 (for user equipment) and TS 136.104 (for base stations) is recommended. Currently, these standards impose flexible power levels for spurious emissions in non-protected bands, while these levels are much more stringent in the protected bands. Because the S-band (and the L-band) are used for security and safety services, a more stringent maximum power level for spurious emissions should be defined.

In any case, the test and measurement of radar, LTE base stations, and user equipment is necessary to confirm spectral emission masks and prove robustness against other co-existing signals [6]. Off-the-shelf test & measurement equipment and dedicated test systems to characterize susceptibility to interference and jamming exist and can aid in the development of more robust communication equipment or in designing more efficient targeted jamming scenarios.

INTEGRATION OF 4G LTE WITH TACTICAL NETWORK

Advanced communication technology is a key component of military success. The integration of the 4G LTE network allows the dissemination of secured mission command data, imagery, streaming video, and voice transmission between dismounted soldiers and command centers. The availability of real-time, complete situational awareness of the surrounding area gives combat soldiers a clear advantage. Military mobile communications must keep up with the innovations in the commercial space. LTE offers lower latency, faster speeds, and a more efficient architecture than the latest wireless military network technology when it comes to two-way communication.

Mobilization of a military 4G LTE network can be done by installing the base stations on a moving vehicle or an unmanned aerial vehicle (UAV, commonly referred to as drones) overhead or even on satellites operating at UHF (300 MHz – 3 GHz). Streaming video feeds from various individual endpoints and UAV cameras can be safely transmitted on this 4G network. Depending on the frequency band, LTE service is supported for terminals moving at up to 350 km/h (220 mph) or 500 km/h (310 mph).

4G LTE makes it possible for the military to set up beyond-line-of-sight radio communication at a low cost. The low frequency bands (i.e., 700 MHz) make it possible for deployment in rural areas as the signal travels further and provides better in-building coverage. This means fewer base stations are required to serve the same area. On the other hand, with 700 MHz in urban areas, there is a higher possibility of running into capacity issues, as there are more users per cell. Typically, higher frequencies (such as 2.6 GHz) are used for small cells (micro, pico, femto, etc.) to increase system capacity in hotspot areas. Users are handed over to these cells to free up resources on the macro cell. It's basically an overlay to the macro layer, which typically uses lower frequencies to provide wide-area coverage.

With 3GPP Release 12, two essential features were added to the LTE standard. First, there is device-to-device (D2D) communication. Here, two or more devices can directly communicate with each other, using uplink spectrum (FDD mode) at certain periodically occurring moments in time or uplink subframes (TDD mode). This feature is defined for in-coverage scenarios, where a base station still serves these devices, and out-of-coverage scenarios, where no network is available. Second, there is group communication on top of D2D, which, for instance, enables these devices to establish voice communication throughout the group using the D2D functionality.

With Release 13, the standard has been enhanced even further to support, for instance, mission-critical push-to-talk (MCPTT) services utilized by all types of terminals, ranging from popular smartphones to ruggedized devices. These and other features and applications are of interest in the case of public safety. When an emergency, disaster, or any unexpected event occurs, communication infrastructure is particularly important and plays a vital role. In many instances, the terrestrial communication infrastructure, especially core network functionality, can be seriously compromised and fail to ensure reliable communication for rescue teams. In times like these, the isolated EUTRAN operations, also part of Release 13, might be an interesting and effective solution to the problem. This feature enables the local routing of the communication (i.e., via base station only) when the interface to the core network is harmed or unavailable.

All-in-all, the features incorporated with Release 12 and 13 make LTE an interesting candidate for tactical communications as the underlying technology for next generation battlefield communications.

CONCLUSION

This article is intended to point out vulnerabilities of LTE and LTE-Advanced. We've discussed a number of commonly used jamming techniques as well as more recently developed "smart" approaches, such as barrage jamming, partial band jamming, single-tone jamming, multi-tone jamming, asynchronous off-tone jamming, and pilot tone jamming and nulling. Even though every jamming scheme has its own advantages and disadvantages, asynchronous off-tone jamming has shown to be more efficient in terms of figure of merit than the other schemes.

This article has also reviewed unwanted interference and jamming mitigation schemes. We've offered a few solutions, including frequency division multiplexing-based solutions, time division multiplexing-based solutions, transmit power control-based solutions, and the popular frequency hopping-based solution.

We've also addressed the coexistence issue of LTE with S-band frequencies and in critical environments such as hospitals. The coexistence issue of LTE and S-band frequency is extremely critical and requires constant attention because air traffic control radars and air traffic surveillance radars operate in the S-band. A coupling of the LTE transmitted power in the receiver of a radar may cause a rise in the noise floor and result in a failure to detect an object in the sky.

We have identified the vulnerabilities of the technology and shared strategies and techniques to address them. It goes without mentioning that user equipment and the eNodeB need to be more robust in design. Both are used in security-relevant applications and should be designed to be "self-aware" of interference and jamming cases and programmed to take action to maintain un-degraded communication.

Testing and measurement are key components in all steps of the development and maintenance process of LTE and LTE-Advanced systems and devices, ensuring proper communication even in environments with high interference.

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Do Measurements Validate Simulations?

Or Do Simulations Validate Measurements?

By Dr. Bruce Archambeault

I expect the title of this article might raise a few eyebrows! It is very common for people doing simulations to make a measurement of a similar set up to validate the simulation. This is a reasonable precaution since modern simulation tools will give a very accurate answer to whatever question it is asked. The real issue is did the tool user understand the problem well enough to capture the important features, and did the user understand the tool well enough to use it correctly.

However, we usually do not expect a measurement to be validated. After all, measurements are a great emotional comfort! I have seen many test laboratories claim measurement uncertainty in the 1.5 to 2 dB range. However, whenever I ask an experienced EMC test person how well they might expect to correlate between two different laboratories, I often get a response that anything better than 8 dB is ok, and certainly, I have never been told that better than 6 dB is expected! This tells me what the "real" laboratory accuracy is. And this is when all the equipment is functioning to specification.

When we look at a typical EMC chamber, we all know and accept that the chamber effects can be +/- 4 dB from the theoretical. This alone could account for 6 dB or more difference between laboratories! When we add the difference between different antenna's response to the nearness of the metal chamber floor as it travels up/down the antenna mast (which can be as much as 4 dB), the potential for site-to-site variation continues to climb. Then we have an antenna factor that was probably measured in a different test environment than where we use it, cable loss, receiver accuracy, etc. So maybe when a simulation is not validated in the test laboratory, we should simply try another test laboratory? (I am NOT recommending this practice! But I think you see my point.)

Obviously it would be cost prohibitive to improve all the things in the previous paragraph so the site-to-site repeatability is reduced to 1-2 dB. However, I do think we should be careful to understand exactly how accurate the measurements are and not place too much credibility in the numbers resulting from such measurements.

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Again, all the above assumes the equipment is operating correctly. I recently heard a story where a salesman was demonstrating a comb generator source to a potential customer in their chamber. The receiver measured fine over a portion of the total frequency range. However, there was one band where there were no comb harmonics! It turned out that the receiver had a broken band, and the operators were not aware of it and had been using the receiver with the broken band on product measurements for a while. I have also heard many stories of how a cable from the antenna had a broken connector without operators realizing it. This points to the importance of having (and using) a test artifact on a regular basis.

Usually, benchtop measurements are better controlled with fewer chances for error (although the examples above could also happen in a benchtop setting). However, these measurements often introduce other, more subtle issues. Many years ago, I wanted to make measurements of the impedance between power and ground-reference planes on a printed circuit board (PCB) in order to validate some simulations of the same PCB. The measurements were very different than the simulation results, and this was because the measurement VNA had 50-ohm ports. I had not loaded my simulation ports with 50 ohms. (Why would anyone ever put 50 ohms between power and ground reference?). Once I modified the simulation to include the loading, the simulation and measurements agreed very well. This was a clear example where the measurement changed the thing I was trying to measure!

Of course, the story is not completely one-sided. Simulations can have subtle issues that can cause errors. Years ago, I was involved in a project at IBM where we wanted to know the impedance of vias transitioning through 250 mil thick PCB up to 50-60 GHz. Test equipment, probing techniques, and de-embedding probe effects were not as advanced as they are now. So a group of five engineers teamed up to do simulations on the via structure using five different simulation techniques since it is commonly accepted that if very different simulation techniques give the same result, it is likely the correct result.

The simulation techniques we used included the Method of Moments, the Partial Element Equivalent Circuit technique, two different Finite-Difference Time-Domain tools, and the Finite Element Method. Figure 1 shows the initial results. Since the goal was to have data up to 50-60 GHz, the agreement above 10 GHz is not good.

Some careful analysis discovered that the various techniques/engineers all made assumptions about the geometry that made sense to them individually but were slightly different from each of the others. First, it is important to understand that no simulation technique uses round objects, even if the software tool displays a round object. The round object must be converted to rectangular or triangular objects in order for the solution software to properly grid the object. Users should always check the gridding to see that this conversion has been done correctly.

In the above instance, one of the engineers converted the round via, via pad, and via keep out to a square that would fit inside the round object. Another converted the round to a square where the round fit inside the square. Another engineer made the area of the round the same as the area of the square. Once these differences were understood, and the models modified so that all were using the same dimensions, then the simulations all agreed very well. The main point is that each engineer, being very experienced in modeling/simulation, made assumptions that seemed reasonable. The tools gave very accurate answers to the models, but the models were not 100 percent correct!

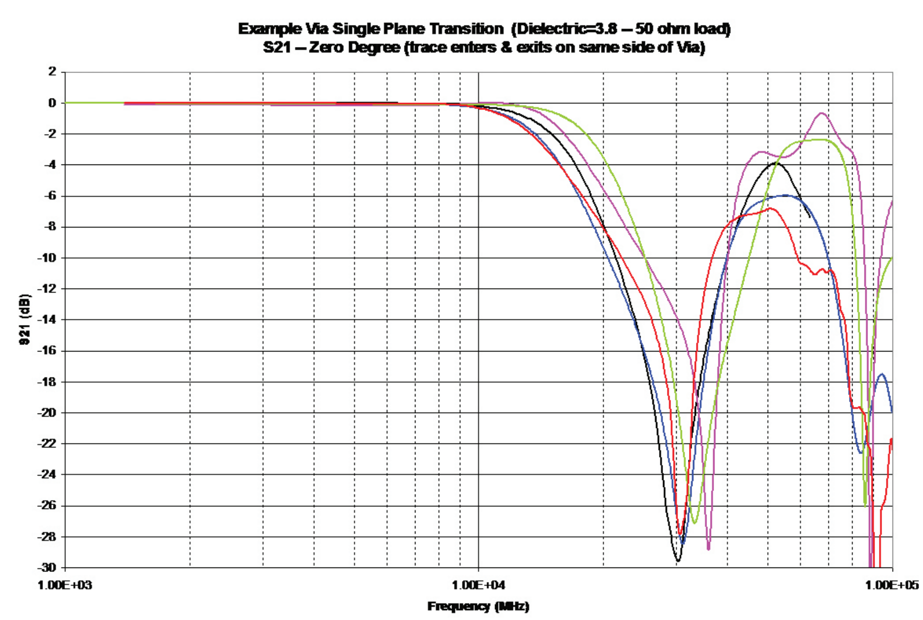

Figure 1: Initial Via Model Results

Another common issue with simulation tools are the source and load ports. A 'lumped' port is basically a port that connects at a point. Figure 2 shows an example of a simple microstrip trace using a lumped port. While this is fine for some applications, the current that is spread across the width of the trace must neck down to all flow through the point connection. This will increase the inductance of the connection by increasing the current density in that region. Figure 3 shows an example of this effect.

This increase in inductance can be avoided when a number of ports are used in parallel, often called a 'face' port. The impedance must be adjusted to provide the correct desired impedance, with many in parallel.

The other commonly used port is a 'wave' port. This type of port is often used to drive or load a transmission line in a printed circuit board model because, when used properly, it will automatically ensure the EM modes are correct. One important point is that the circumference of the wave port is a perfect electrical conductor (PEC). This will connect any metal object that touches the edges of the port. For example, if a stripline is intended to be modeled, and the upper reference is considered a power plane, and the lower reference a ground-reference plane, then the two planes would not physically be connected, but the wave port would force them to be connected.

Another potential issue with wave ports is their size. Users must ensure that they are large enough to allow the correct modes to be created. Figure 5 shows two examples of a PCB with a wave port. Figure 5a shows a small wave port, while Figure 5b shows a larger wave port. Figure 6 shows the electric field with the small wave port. Note that the fields are strongest between the microstrip and the wall of the wave port (PEC), and this is not correct. Figure 7 shows the correct fields are created when the wave port is larger.

CONCLUSION

There are many ways to make errors, both with measurements and with simulations. Engineers should constantly double-check themselves and not assume that either gives the correct answer. Measurements are often considered the "gospel" but while they can be considered "real world," they will often change the thing they are trying to measure. Understanding how the measurement devices work and where issues can be created is extremely important to make sure that the results are correct.

On the other hand, simulations will usually not change the thing they are try to measure, but subtle issues can creep

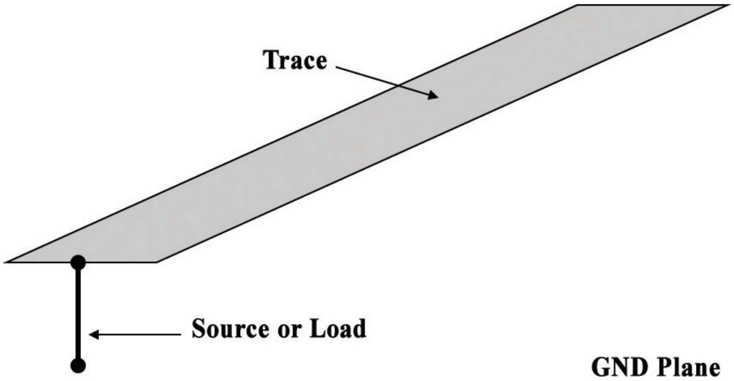

Figure 2: Lumped Port on Simple Microstrip Model

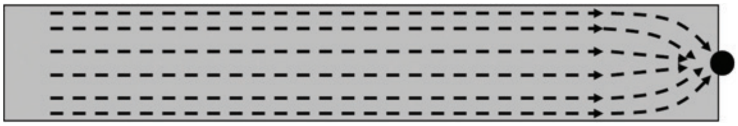

Figure 3: Current across the trace width must narrow to the single point of contact

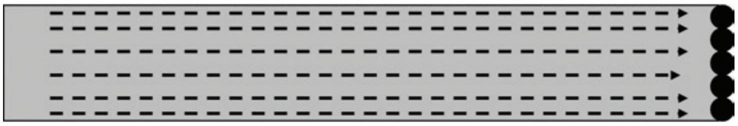

Figure 4: Current does not narrow when a number of ports are used in parallel

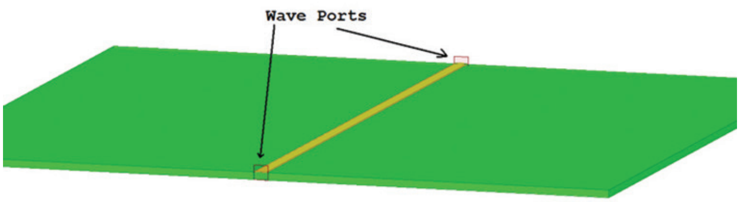

Figure 5a: Small wave port

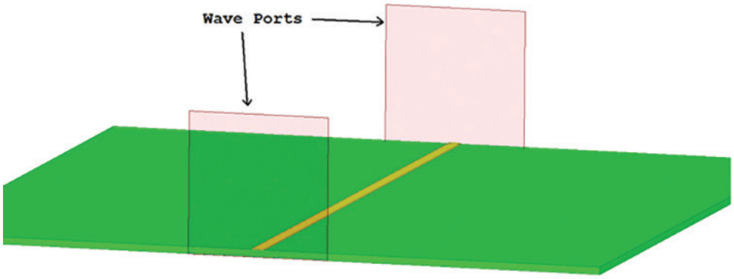

Figure 5b: Large Wave port

in the model, yielding incorrect results. These simulation tools are extremely powerful, and should be a tool in the engineer's tool box, but they cannot be used as simply as a screwdriver! Training on the simulation technique to understand its strength and its weaknesses is vital.

The bottom line? Question everything.

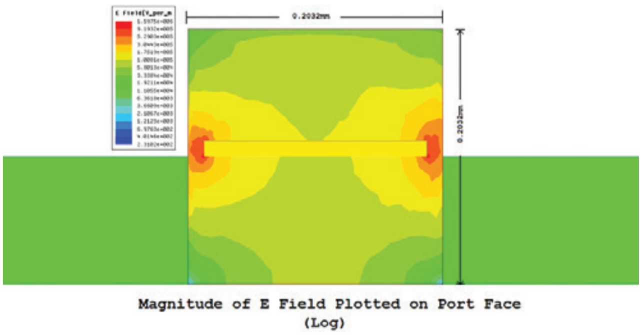

Figure 6: Incorrect electric fields due to too close PEC walls of wave port

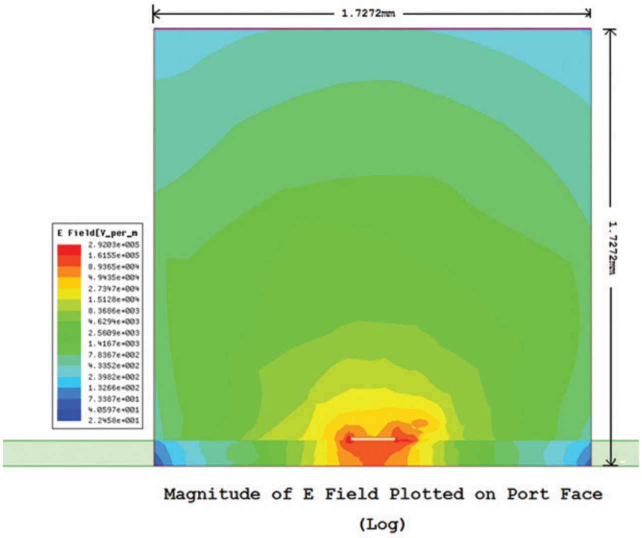

Figure 7: Correct electric field modes for microstrip trace

Methods and Effects of Magnetic Pulses on the Magnetoreception of Birds

Exploring Magnetic Sensing Mechanisms in Avian Navigation

By Jose Martin Hernandez Piña and Jeremiah Szántó

The Earth's magnetic field is a dipole that acts like a large magnet, with its poles relatively near to the geographic (rotational) poles. Although the magnetic north pole is really in the geographic south position and vice versa, the magnetic north pole is typically referred to as the end of the dipole closest to the geographic north pole, and the magnetic south pole is similarly referred to as the end of the dipole closest to the geographic south pole. The geomagnetic field lines of force leave the magnetic South through Antarctica, circle the Earth, and re-enter through the magnetic North's surface, through the Arctic pole, creating vectors of these ascending lines of force in the Southern Hemisphere and descending lines of force in the Northern Hemisphere, which are parallel to the earth's surface at the equator.

As one moves closer to the equator, the strength of the lines of force steadily declines, reaching maximum values of around 60,000 nT at the poles and around 30,000 nT at the Equator [1]. These characteristics make the magnetic field a very reliable and omnipresent source of information, in which the magnetic vector (the vector between the line of force of the magnetic field and the line of force of gravity) provides directional information that the bird can use as a "compass." Further, the spatial distribution of other factors, such as intensity or inclination, can be components of the "map," providing information on the geographic position of the bird as they vary between the poles and the equator. [2, 3].

METHODS OF MAGNETIC SENSING IN BIRDS

Although it is not completely understood how migratory birds are capable of sensing the orientation and intensity of the geomagnetic vector field generated by the Earth, behavioral experiments indicate that they

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use a combination of sensing methods and that the combination of these senses provides migratory birds with the ability to successfully migrate [4]. Referred to as the avian magnetic compass, migratory birds determine their position and direction with two separate measurements, which consist of inclination (or deviation) from the magnetic field lines for determining orientation with the poles and magnetic field intensity for determining direction [4]. The two primary methods of detecting inclination and intensity are the radical pair mechanism and the magnetite hypothesis.

Radical Pair Mechanism

A likely mechanism for an axial magnetic compass in migratory birds, the radical pair mechanism relies on unpaired electrons with parallel (T) and antiparallel (S) spins [5]. Sets of unpaired electrons result in differing chemical properties based on what spin combination the set has. This, in turn, alters the reaction rate and yield of chemical processes that occur. A weak external magnetic field can modify the relative alignment of the electrons, thereby altering the reaction rate and yield, and is dependent on the intensity and the orientation of the external field.

For migratory birds, this process usually occurs on the surface of certain cell membranes. The direction of the external field lines produces arrays of protein oriented in the same direction, and the varying density of the synthesized protein enables the bird to determine the orientation of the field lines [5].

In order to produce these radicals, cryptochrome photoreceptors located in the eyes of the bird use photons from external light, such as the sun [4]. Behavior experiments determined that the photoreceptors and the bird's ability to navigate are impacted by the wavelength of perceived light. Further, short wavelengths of light from UV to about 560nm were necessary for radial pair production [4]. Tests that involved birds in total darkness displayed a 90-degree shift in the preferred direction, which suggested that the radical pair sensing mechanism was not activated. Instead, a separate magnetic sensing mechanism behaves as a backup [5]. Although it is uncertain what the backup mechanism is, it likely relies on the magnetite-based magnetoreception mechanism.

Magnetite Hypothesis

The biomineralization of magnetite in animals that migrate, such as certain birds and fish, leads to the hypothesis that the ferrous ferrite may play a role in magnetoreception [5]. Crystals of magnetite roughly 50nm in size are attached to mechanoreceptors within specific cells and behave as small compass needles within the cells of the bird or fish. The torque produced by the crystal under an external magnetic field triggers the receptor, thereby providing a method of sensing the field. This behavior has also been studied in magnetotactic bacteria, which orient themselves with external magnetic fields [5].

Studies conducted on homing pigeons have determined that magnetite-containing dendrites are located at six locations on the upper beak. Clusters of the dendrites have been found to deform under weak magnetic fields, producing a torsion on the dendrite. We hypothesize that this torque behaves in the same manner as the radical pairs, and provides a complementary sensing method for magnetic fields [5].

MAGNETIC PULSE GENERATION WITH HELMHOLTZ COIL

In order to further investigate the behavior and functionality of magnetoreception in birds (or other animals), the application of magnetic pulses with specific direction and intensity are used to study how

Figure 1: An example of a Helmholtz coil two-system for uniform magnetic field creation

Despite this risk, U.S. manufacturers and retailers will continue to buy all kinds of raw materials, component parts, and finished products from China and elsewhere. And these numbers will continue to increase as long as there is no backlash from consumers.

the bird's flight behavior is affected. The application of magnetic shielding techniques may be used to block Earth's existing magnetic field. But in order to generate a uniform magnetic field with specified direction and intensity, the application of a Helmholtz coil (see Figure 1) is employed [6].

Two coils placed in parallel along the same axis can produce a relatively uniform magnetic field between the coils, This configuration is known as a Helmholtz coil, named after the German physicist Hermann von Helmholtz. Three pairs of Helmholtz coils can be configured on the X, Y, and Z axis, allowing for complete control of the magnetic field in the center of the configuration.

A configuration of a 3D Helmholtz coil system enables the ability to cancel Earth's magnetic field, as well as produce a static, rotating, or alternating field [6].

EFFECTS OF MAGNETIC PULSES ON BIRDS

The application of 500mT pulses for a few seconds on passerine migrants (bird) initially produces a shift in orientation during flight [5]. As expected, by 4 to 10 days after the treatment, the passerine migrants that had experienced the pulses had recovered their normal orientation and returned to their expected migration path. Another important note made in the experiment was that young birds that had not yet migrated were not affected by the pulse treatment. The shift in orientation due to magnetic pulses indicates that there is involvement with magnetic material for migratory and targeted-location flight [5].

A similar experiment was conducted on homing pigeons [5]. It was determined that pigeons treated with pulses deviated from the untreated control group path, a deviation that became more substantial as the distance between home and the release point was increased. Overall, this indicated that the magnetic pulses would affect the internal avian compass but left the navigation map relatively unaffected, as the pigeons were still capable of returning home.

CONCLUSION

The magnetic orienting mechanism in birds has been discovered to be a two-step system. First, utilizing the information offered by variables of the terrestrial magnetic field, such as strength or tilt, the map allows them to calculate their geographical position, and the compass allows them to decide the direction to follow. It is also known that birds have an intrinsic sense of magnetoreception. It is the primary foundation, along with the internal circadian clock, for establishing the many navigation systems through intricate learning processes. All of this comes together to produce an adult bird's entire navigation system.

The following are two hypothesized magnetoreception models: By converting the strength of the Earth's magnetic field into mechanical force within specialized cells, magnetoreception based on magnetite particles housed in the upper part of the beak function as chains of magnetite particles that interact with the Earth's magnetic field and provide directional information and even geographic position to the birds.

Chemical magnetoreception based on a radical pair model, in which a molecule is energized by the absorption of a photon, produces an electron and forms a pair of radicals, which affects the speed of singlet-triplet interconversion depending on the alignment with the Earth's magnetic field.

Because both magnetoreception models are hypothetical, the current understanding of magnetoreception models is insufficient to identify the magnetoreception model employed. Although a clear picture of how information from the magnetic compass is interpreted is beginning to appear, our present understanding of magnetoreception is constantly evolving.

There are still a lot of questions concerning magnetoreception and how data is processed from these receptors to the brain. Advances in behavior, anatomy, and physiology will aid in the discovery and identification of magnetic reception structures in the future.

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Hardening the Power System from HEMP and IEMI

A Cost-Effective Plan to Harden Existing Facilities

Dr. William A. Radasky, Ph.D, P.E.

This article provides an extension of my article in the June 2021 issue of *In Compliance Magazine*, describing the different ways to protect power system electronics in high-voltage power control houses found in HV substations [1]. The intention here is to provide a specific plan to start to harden power grids against the fields produced by high-altitude electromagnetic pulse (HEMP) and intentional electromagnetic interference (IEMI). In addition, we will discuss the differences in protecting power company substation control houses and control centers and even power generation stations against these threats. Finally, there will be a discussion of the approach to protect the high voltage transformers (V ≥ 100 kV) against the late-time portion (E3) of the HEMP, which also will provide protection against an extreme geomagnetic storm if it were to occur.

While the worst-case levels of the early-time (E1) HEMP environment have not changed, this is not the case for the late-time (E3) HEMP environment, due to the work of the U.S. EMP Commission [2]. The worst-case level of E3 HEMP has doubled, and the IEC is in the process of increasing the worst-case level in IEC 61000-2-9 Ed.2 draft [3]. While this increase is significant, the same new draft version of IEC 61000-2-9 also discusses the fact that the worst-case E1 HEMP field occupies a very limited portion of the ground exposure. And, when considering that there are over 9000 high voltage substations in the U.S., they all cannot be illuminated at the worst-case E1 peak HEMP level with a single high-altitude burst. Also given the costs of hardening a large number of buildings, there have been discussions in the IEC and in other standards organizations considering resilience aspects to reduce the cost burden of protection [4].

Figure 1 presents the draft versions of the worst-case HEMP time waveforms, including the new version of E3 HEMP. In the standard, the actual "incident" E3 magnetic field is provided, along with the method to compute the electric field depending on the earth's deep conductivity. This accounts for the substantial variation of

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ground conductivities in many places of the world including the U.S. In the new standard, it is not assumed that the E3 HEMP electric field is the same everywhere and, in many places, could be more than a factor of 10 lower.

As this article will also discuss the additional protection needed for IEMI, Figure 2 describes the most recent presentation of the relationship of the electromagnetic fields in the frequency domain that can cause IEMI relative to E1 HEMP, lightning electromagnetic pulse and also standard levels of EM fields associated with EMC [1].

This article first discusses (in Section 2) the basic problem of hardening a large number of critical buildings to protect their electronics and then looks at the various options for protection. The issue of replacing existing buildings is also discussed. The role for high-level EM protection, such as recommended in MIL-STD-188-125-1, is also mentioned.

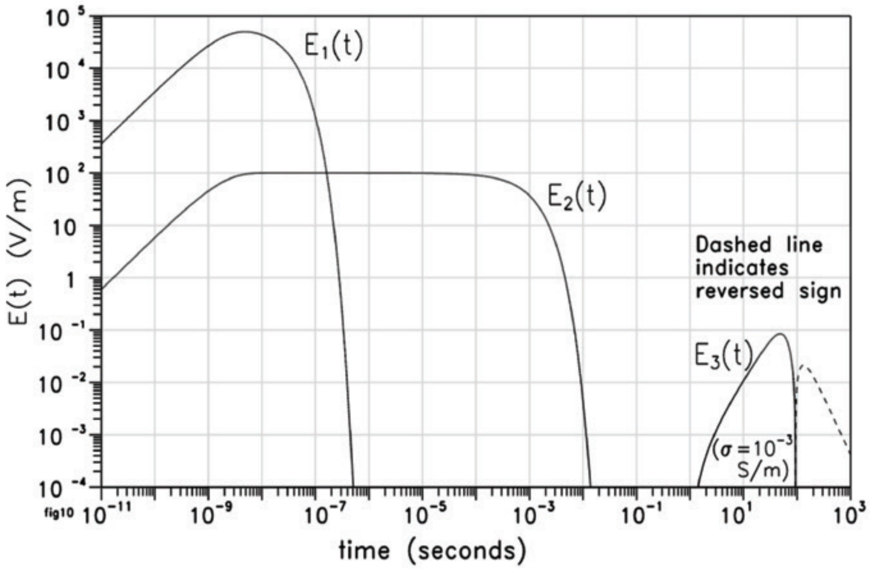

Figure 1: Worst-case HEMP waveforms in IEC 61000-2-9 CDV [3]

Section 3 of this article discusses the method to determine the level of hardening of buildings depending on the EMC requirements that are necessary to operate normally. Also, the variability of the incident environments is discussed along with the idea of considering resiliency.

Section 4 presents the best hardening approach for existing buildings for E1 HEMP and IEMI, while Section 5 discusses the best approach for protecting the large transformers that can be affected by E3 HEMP. Section 6 describes the rationale for developing a hardening program over time. Section 7 provides a summary and recommendations.

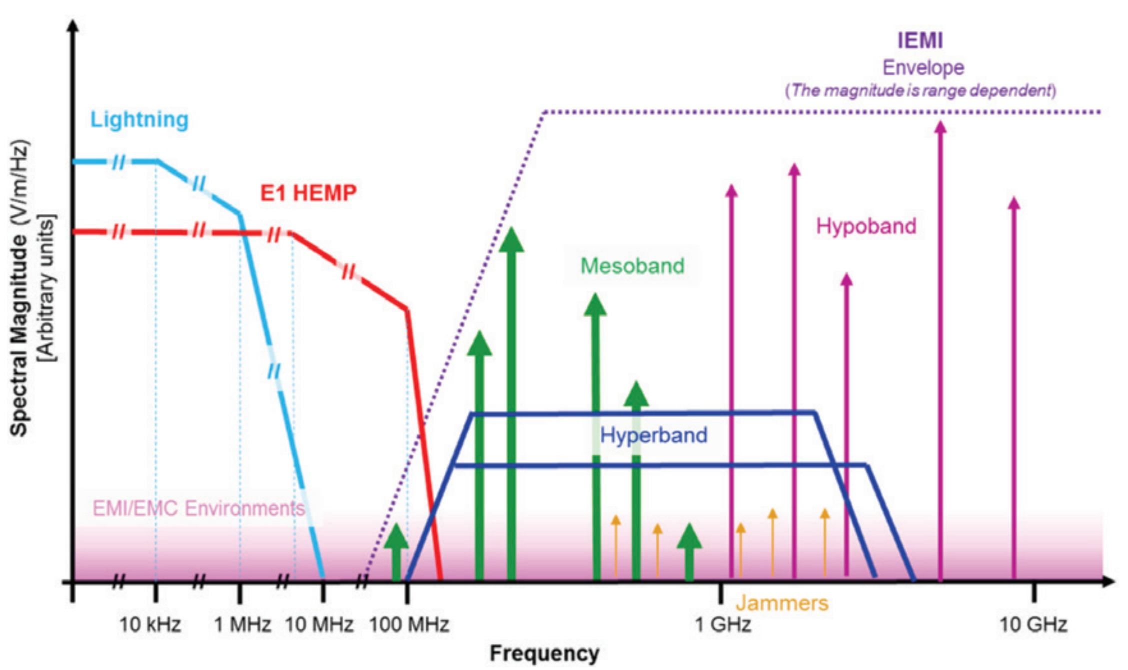

Figure 2: Comparison of the fields producing IEMI with the worst-case E1 HEMP, the nearby fields of a cloud-to-ground lightning strike, and the radiated environments considered in studies of EMC [1]

It should be noted that due to the extremely large amount of material to be covered here, this article will rely strongly on references to provide the details, as we cannot cover all of the hardening techniques in a single article. Most of the references are IEC standards or peer-reviewed publications from the IEEE EMC Society.

DEALING WITH IMPROVING EM HARDNESS OF EXISTING BUILDINGS

As mentioned in the introduction, most large power companies in the U.S. and worldwide have several hundred (or more) high-voltage substations connected to a control center. They also have an even larger number of distribution substations, although each of them controls much less power than a single high-voltage substation. The problem in terms of protecting substation control houses is that the threats of HEMP and IEMI are high impact, low probability (HILP) threats (HEMP has not occurred anywhere in the world since the 1962 tests by the U.S. and the Soviet Union – although the capability to detonate a high altitude burst clearly exists today).

As is clear to consumers over the past 5 years, it seems that the rates one pays for electricity are increasing, and power companies are not in a position to spend even more money on their existing infrastructure, when they are planning for increases in their overall grids due to shifts toward electrical cars and renewable power sources.

The best solution is to improve the hardness of the existing buildings by upgrading the protection of the best existing buildings, and to use this design for new substation control buildings, if needed. In addition, due to the criticality of particular substations (depending on their location and their service area), some of the existing buildings can be upgraded over time. For substation control houses, what should be the approach to evaluate methods to upgrade the hardening to HEMP and IEMI? Let us examine Figure 3, which describes the basic substation control house and the ways that EM fields and conducted transients can penetrate the building.

Beginning with a metal substation building, one can see in Figure 3 that there are many ways that EM fields and currents can penetrate the building and then reach the electronics inside (not shown). The best approach is to evaluate the control houses by testing their shielding effectiveness with emphasis on those recently built. The reason for considering recently built buildings is that one would like to emphasize those using current construction techniques from local vendors. The best test method is to use the signals from radio stations in the AM, FM, Digital TV, and cellular bands to measure the fields outside and inside the building. This allows the electronics to continue operating, as there is no new field being transmitted. This method is fully described in IEC 61000-4-23 [5] and is very quick to apply.

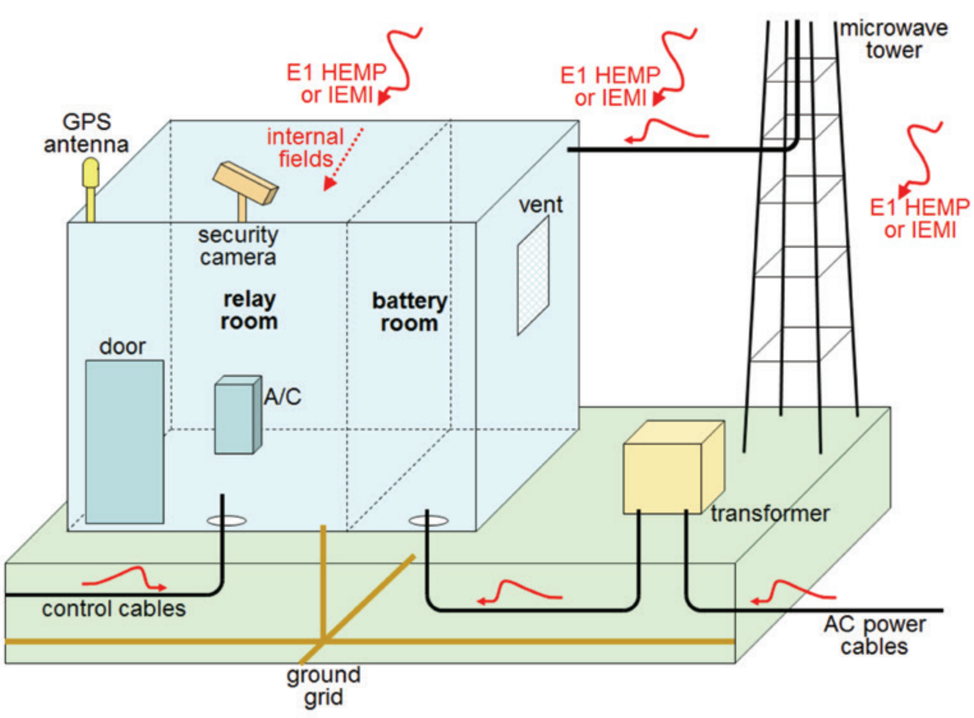

Figure 3: A general example of a typical metal control house showing the ways that E1 HEMP and IEMI environments could penetrate the building (note that internal wiring is not shown)

One of the special characteristics of a high-voltage control house with modern solid-state electronics inside is that the electronics must survive the daily electromagnetic disturbances typical from the switching transients in the high-voltage yard.

Once one finds the best building for a power company, then the next step is to evaluate the many possible EM leaking points, as are clearly observed in Figure 3. Using normal EMC protection techniques, one can improve the grounding and shielding of cable entries, shield windows with wire grids, provide gaskets for the doors, provide filters for the power entry, etc. [6]. The goal is not to protect all penetrations, but rather to determine which penetrations should be improved on a cost-effective basis. Once the best set of protection is installed, then testing should be performed again to ensure that the building achieves its recommended level of protection. While this approach will consider different types of building designs in the U.S., as there are over 150 major power companies in the U.S., there may be fewer or even one company operating a national power grid in European or Asian countries, which will make this process more efficient. Also, in the U.S. there are companies that make control house buildings in a factory that are transported for installation. In this case, there could be efficiency in the building evaluation process.

FACTORS THAT CAN REDUCE THE REQUIRED SHIELDING EFFECTIVENESS FOR SOME BUILDINGS

One of the special characteristics of a high-voltage control house with modern solid-state electronics inside is that the electronics must survive the daily electromagnetic disturbances typical from the switching transients in the high-voltage yard. Because of this, the IEC has published a special set of EMC immunity requirements for electronic equipment in high-voltage substations and power stations [7].

While there are requirements for radiated and conducted environments in this standard, those that are most severe are those of the conducted environments, which include the electric fast transient (EFT) test as described in IEC 61000-4-4 [8]. This voltage pulse has a 5 ns rise time and a 50 ns pulse width. The typical coupled E1 HEMP voltage for an above-ground conductor, such as a microwave cable, GPS, or camera cable, has a 10/100 ns pulse shape. The typical common mode requirement for the EFT is a peak of 4 kV for the electronics in a control house, while the expected transient for a buried yard cable is ~20 kV. So only a modest level of E1 HEMP protection is needed for the incoming yard cables. For a building shield of 30 dB, the worst-case internal E1 HEMP field would be ~1.7 kV/m. The coupled levels of conducted transients to internal cables will be lower than the 4 kV EMC immunity level. Unfortunately, some existing concrete substation buildings have been tested to shielding levels as low as 6 dB, which would allow fields that are too high into the building.

While the 30 dB level of shielding (along with POE protection) appears adequate for high-voltage power control houses, the situation is different for control centers. Each power company typically has 1 main control center for their high voltage substations, and a backup control center in case there is a failure at their main control center. The control center typically has communications and computer rooms, and digital displays to connect to all of their substation buildings to provide real-time information to ~4 operators.

While most of the power system operates with computer control, there are times when a particular substation loses communications, or there is a natural event such as a fire, lightning, or a fault that impacts the operation of the grid. These control centers are important to ensure that each grid operates efficiently and to prevent a blackout. The significant aspect of the control centers is that the electronics are not designed to tolerate high levels of EM noise as are those in a substation control house. Typical electronics are usually required only to have a “residential” level of immunity from EM disturbances, which could be as low as 0.5 kV for the EFT immunity test or up to a factor of 8 below the 4 kV requirement for substation electronics. This means that a control center needs approximately 50 dB of shielding effectiveness to protect its electronics.

In the recent past within the U.S., 3 separate new control centers have been built to protect against HEMP. Due to the relatively high level of shielding required, a decision was made in all 3 cases to use the military standard, MIL-STD-188-125-1 [9], with some modifications to correct for aspects of the standard that are not cost-effective [10]. During the construction of the first new HEMP control center in Houston in 2013, the A&E firm developing the construction plans evaluated the additional cost of an 80 dB HEMP shielded building vs. "normal" construction to be approximately 4%. This is consistent with cost studies performed in the past for the U.S. military for highly shielded buildings. It should be noted, however, that the cost of building a highly shielded building when the levels of required shielding are not high, is not cost-effective.

A third category to be considered are the power plants generating electricity. Of course, there are many different types of power plants from thermal (including nuclear), to solar panels, to wind turbines, to turbines at dams. In most cases, the large power plants need to convert turbine medium voltages to high voltages for transmission to population centers, and thus require a power substation; renewable plants also need a substation to coordinate the final AC power flow to the correct voltages and the proper phasing with the existing AC network. Therefore, the protection levels and approach required are the same as the high voltage substation control houses.

Clearly, those power plants that produce a significant amount of power for a particular company should be considered as a protection priority from the threats of HEMP and IEMI. It is also noted that power plants are often not owned by the power company operating the power network, introducing another difficulty in the hardening process.

One factor mentioned at the beginning of this article is the fact that the HEMP standards generally specify the worst-case HEMP environments for two reasons. This provides a reasonable upper bound of the fields that could be produced, but it also avoids the variability of the fields that could be produced based on the height of the burst, the location of the burst, the yield of the weapon, the weapon design, and for E3 HEMP the deep ground conductivity under the burst.

One presumes that if an attack is planned, the attacker would try to maximize the field levels. Of course, even if this is done, one cannot maximize the fields over the entire footprint of the exposure. For E1 HEMP the fields toward the edge of the exposure region can be lower than the worst case by factors of 2 to 10, and the maximum field exposure area is typically less than 10% of the total area exposed. For the E3 HEMP the fields typically fall to 10% or less at the edge of the exposure, and if the deep ground conductivity is high, all of the fields will be smaller than the worst case. This means that only a few substations will see the maximum fields.

There are other factors to consider, including the orientation of power lines, which affect the coupling of E1 HEMP. Based on the polarization of the E1 HEMP fields for the center of the U.S., E-W oriented cables will pick up more than 10 times the peak current and voltage than will N-S cables (in the air or buried) [11]. These are important aspects of the HEMP variability, and one should consider the advantage of using lower levels of fields based on these variations.

The last point of consideration is that all of the discussion thus far has been to evaluate the best way of adding protection to a "partially" shielded building. It is possible that in some cases, if an outage can be accepted for some limited time, then a plan to accept electronic upsets, and limited damage to electronics might be acceptable. This could be achieved by having replacement electronics available in the building that are not connected to power or data and which are placed in a modestly shield cabinet inside the building.

This approach could be used for buildings that are not as critical to the overall operation of the power grid, although a criticality study would need to be performed. In the U.S., power companies have been asked by the North American Electric Reliability Corporation (NERC) to determine their nine most important assets, and to consider them to develop protection plans against different threats (but not necessarily HEMP and IEMI).

RECOMMENDED APPROACH FOR PROTECTING BUILDINGS – HEMP AND IEMI

As mentioned earlier in this article, the best approach for substation control houses is to evaluate the construction techniques of recently built houses with a preference for metal buildings. A shielding effectiveness measurement campaign should be developed to identify the best existing buildings in the network. As indicated earlier, the use of radio communications signals is a very efficient way of testing an operating control house, as the radio signals are already occurring, and they are usually far enough away to be considered to create a plane wave incident field. This method has been evaluated in peer-reviewed journal articles and is presented as a testing option in IEC 61000-4-23 [5].

Once this process is accomplished, then the best building (or two) should have between 20 and 30 dB of shielding effectiveness across the E1 HEMP spectrum (1 – 100 MHz). From past experience, the priority for improving the protection of the building is usually first determined by any above-ground penetrations of the shield without complete bonding and grounding. These are usually cable entries for GPS antennas, microwave cables, camera cables, A/C mounting, windows without EM mesh, and door gaskets. If the yard cables penetrate the building walls and not the floor, this is a major leakage path to be considered for improvement.

The best way to minimize the repairs and their cost is to perform the improvements while making measurements, usually with temporary copper tape, to determine the most important leakage points. In any event, after the repairs are made, it is important to remeasure the shielding effectiveness of the building with the EMC repairs completed. For buildings manufactured in a factory and then shipped, the measurements should be made before and after shipping to determine the impact of the shipping process.

As mentioned earlier, this process works well when the target protection level is 30 dB but does not work well (on a cost-benefit basis) for a control center building for the reasons mentioned earlier, which needs on the order of 50 dB. It is very difficult (and costly) to raise the shielding effectiveness of a 20 dB building to 50 dB by making repairs. Therefore, it is recommended that the MIL-STD-188-125-1 approach be used, which is also presented in IEC 61000-6-6 [12], with consideration of reducing some of the unnecessary costs and correcting the errors in the standard [10]. It is also recommended that the newest version of the MIL-STD-188-125-1A [13} not be used because it is not published for public use and has not been peer-reviewed by commercial technical organizations (IEEE, CIGRE). It is recommended only for certain military projects.

If particular power system buildings are to be considered for HEMP and IEMI protection, then the power substation at the power plant can apply the control house procedure mentioned above. If there is a local control center building for the plant, then it should also be considered for protection, but at the higher level of 50 dB. Typically, a control center room for a power plant is much smaller than a control center room for a power company's entire grid, so it may be possible to build a shielded room for this purpose at a lower cost than for an entire building.

While the emphasis in this section has been on the E1 HEMP, the IEMI has some differences to consider, although they are not usually very costly. First, the IEMI threat in the frequency domain is typically found between 100 MHz and 10 GHz. It is noted that in IEC 61000-2-13 [14], there are narrowband threats that are defined but also wider bandwidth threats (even single fast pulses, like JOLT [15]. The main difference with IEMI is that the threat comes from a local antenna outside the fence. The fields fall off rapidly from the antenna, and a solid metallic fence can cause the attacker to move further away to "fire" their threat over the fence. While normally substation electronics are in a building that is not close to the outside fence, there have been cases where they are close to the fence. These cases are clearly those where a new building needs to be built away from the fence to prevent very high IEMI fields from exposing the equipment.

When IEMI is considered in addition to the E1 HEMP, one factor to consider immediately is that the window meshes must be designed for higher frequency fields. E1 HEMP requires about a 4-inch mesh, while IEMI requires a mesh of a few cm [16]. Fortunately, there are commercially made meshes for a frequency of 18 GHz, which can be used for the IEMI threat. Of course, if the windows are not needed, they should be replaced with metal, eliminating the need for meshes.

Another point, in general, is that the cable penetration grounding is not as critical for IEMI, as the IEMI fields do not couple or propagate as well on external metallic cables as from E1 HEMP fields due to their frequency range. On the other hand, significant cracks in the shield allow more penetration of fields at higher frequencies. If the IEMI is important to a particular building due to close public access, then it is important that the building be tested at higher frequencies using cellular radio signals to ensure that important apertures are well sealed.

Finally, there are IEMI field detectors that are being made today [4], and these could be used to determine if an attack is underway. The placement of these detectors is important to ensure that the main attack scenarios are covered and that any alerts for an attack are evaluated against the possibility of false alarms.

RECOMMENDED APPROACH FOR PROTECTING LARGE TRANSFORMERS

While this article has dealt mainly with the high-frequency threats of E1 HEMP and IEMI on electronics that control the power grids, the late-time E3 HEMP is a serious threat to the large transformers that are the key part of the power transmission network. While high voltage (HV) transformers are defined to operate at V > 100 kV, most modern transmission systems operate at 400 kV (Europe) or 500 kV (U.S.). In China and India, new HV transformers are being built to operate at 1 MV to efficiently move power.

The process of coupling E3 HEMP fields and also geomagnetic storm fields into the power network is complex; there is an IEEE paper [17] that explains the entire process and a recent CIGRE Technical Brochure that reviews the worldwide measured geomagnetic fields from 1989 to 2018 [18]. It is noted that the E3 HEMP threat and the typical CME geomagnetic storm are very similar disturbances and couple to power grids and cause transformer difficulties in similar ways. Fortunately, there are modeling techniques that can evaluate power grids, which are essentially very large antennas, to determine where (which transformers) the largest currents will occur given an E3 HEMP or a large geomagnetic storm. This modeling process is not difficult and will identify those transformers at the highest level of risk.

Of course, it is prudent to validate the modeling technique used, and even a small geomagnetic storm from the recent past can be used for that purpose. It is useful to add geomagnetically induced current (GIC) monitors on transformer neutral cables to perform the validation. It is noted that the CIGRE TB 780 does provide information on how to install GIC sensors on transformers [18].

If the modeling process indicates a significant number of important transformers are at risk, the next step is to add additional GIC monitors on these transformers to observe the response of these particular transformers relative to others in the network. Over time, one should be able to confirm that these transformers will carry a significant portion of the GIC current. It is noted that transformers at the edge of the grid and transformers in regions of the earth where the deep ground conductivity is low are most at risk.

Once the utility is concerned that a particular transformer is at risk, and it supplies a significant amount of power to the overall network, then protection needs to be considered. The main cost-effective treatment is to add a neutral resistor [19]. One of our customers did this, and it reduced the induced current in the transformer by about a factor of 2, as indicated by a GIC measurement made during a significant geomagnetic storm in the early 2000s. The second treatment is a neutral capacitor, but it must be protected against power faults and lightning surges with a bypass arrester. Otherwise, the capacitor will be damaged. The problem with the capacitor is that, with bypass protection, they are expensive, so on a cost-effective basis, the neutral resistor seems to be the better approach.

In terms of resilience, another approach is to have backup transformers at the critical substations where high levels of GIC may occur. While it is typical for power companies to purchase a few large transformers in advance, the selected transformers are based normally on the age of the transformers. In this case, the placement of the transformers should be based on the probability of a high GIC and the importance of the substation to the overall operation of the grid. As noted by the EMP Commission in 2008 [20], if one waits for large transformers to be damaged during an E3 HEMP event, the delivery time could be many years, especially if a large number of transformers were damaged during one event.

PERFORM PROTECTION OVER TIME, NOT ALL AT ONCE

One of the questions that always occurs when the subject of HEMP and the power grid is discussed is why do we not protect the grid immediately? It is true that, as indicated in this article, we do know how to do the job. The problem is the cost will be very high due to the large number of high voltage substation control houses in the U.S. (~9000) and many more worldwide, and the number of experts available to perform the work is not large.

This is why the idea of evaluating buildings, which already exist, and hardening them on a cost-effective basis to achieve a sufficient level of protection is the best way to develop a prototype approach that can be used in the future, as power grids expand. This can be done separately by each power company. If these projects, including cost information, could be openly published as the work is completed, this would be a significant help to smaller power companies. It is possible that some national prototypes could be developed.

In the same way, the protection of power control centers requires higher levels of shielding, but it would be beneficial if those adapting the MIL-STD-188-125 approach to commercial applications as described by the IEC could publish their results so cost savings could also be shared across the industry.

Finally, the development of a group of backup power transformers at substations where the transformers are at significant risk from E3 HEMP is something that can be done over time and would only modify the procedures that are already embraced by the power industry. The main feature would be to determine the transformers at significant risk, along with other factors already considered by power companies.

SUMMARY AND RECOMMENDATIONS

The main recommendation of this article is to start the process of upgrading high voltage substation control houses to E1 HEMP and IEMI to protect the electronics inside by evaluating their best metal buildings for their shielding effectiveness and using the typical EMC hardening techniques to improve the shielding levels to at least 30 dB. Testing is needed to ensure the work is done on a cost-effective basis, and rapid test methods are recommended.

The main recommendation of this article is to start the process of upgrading high voltage substation control houses to E1 HEMP and IEMI to protect the electronics inside by evaluating their best metal buildings for their shielding effectiveness and using the typical EMC hardening techniques to improve the shielding levels to at least 30 dB.

In a similar fashion, control center buildings need to be protected to ~50 dB due to the susceptibility of the type of electronics found inside, and this level is not amenable to reaching from a starting point of ~20 dB. This means the basic high shielded building approach should be used, but the MIL-STD-188-125-1 needs to be adapted and those adaptations published so it can be used on a commercial basis. The IEC has started that process by indicating areas where the military standard is not cost-effective, but more work is needed.

The consideration of the IEMI threat in addition to E1 HEMP is important, and while the threat does not cover a large area at one time (unless there is a coordinated attack), the IEMI threat is much more probable than a HEMP attack. The features of an IEMI attack are well understood, and many of those features are discussed in this article. The main factors are to ensure that an IEMI attacker cannot get close to the electronics, and to consider upgrading the substation fences to reduce the fields incident on the electronics. In terms of EM protection, the most important add-on for IEMI is to ensure that a fine metal mesh is used to cover windows.

The final aspect of this article is that the method of protecting the large power transformers that are very expensive and take many years to replace is straightforward. Validated analysis methods exist and can be used to determine which transformers are most at risk. Adding GIC sensors to those transformers and evaluating their measurements during future geomagnetic storms can confirm the potential vulnerability of particular transformers. In terms of protection, the neutral resistor appears to be the most cost-effective in that it can substantially reduce the currents that will flow in a particular transformer. A resilience approach includes providing backup transformers at the substations where transformers that are at risk are located.

As one who has worked directly for more than 20 power companies worldwide on this problem for over 20 years, I am trying to develop an industry-wide approach to cost-effectively protect power grids throughout the world. In addition, I have worked directly with IEC SC77C as the Chair for 25 years in the past and as an expert in writing and updating existing standards to be more accurate and cost-effective. This is too big of a job for a small group of experts to perform, and we need to develop techniques that can be used and replicated easily.

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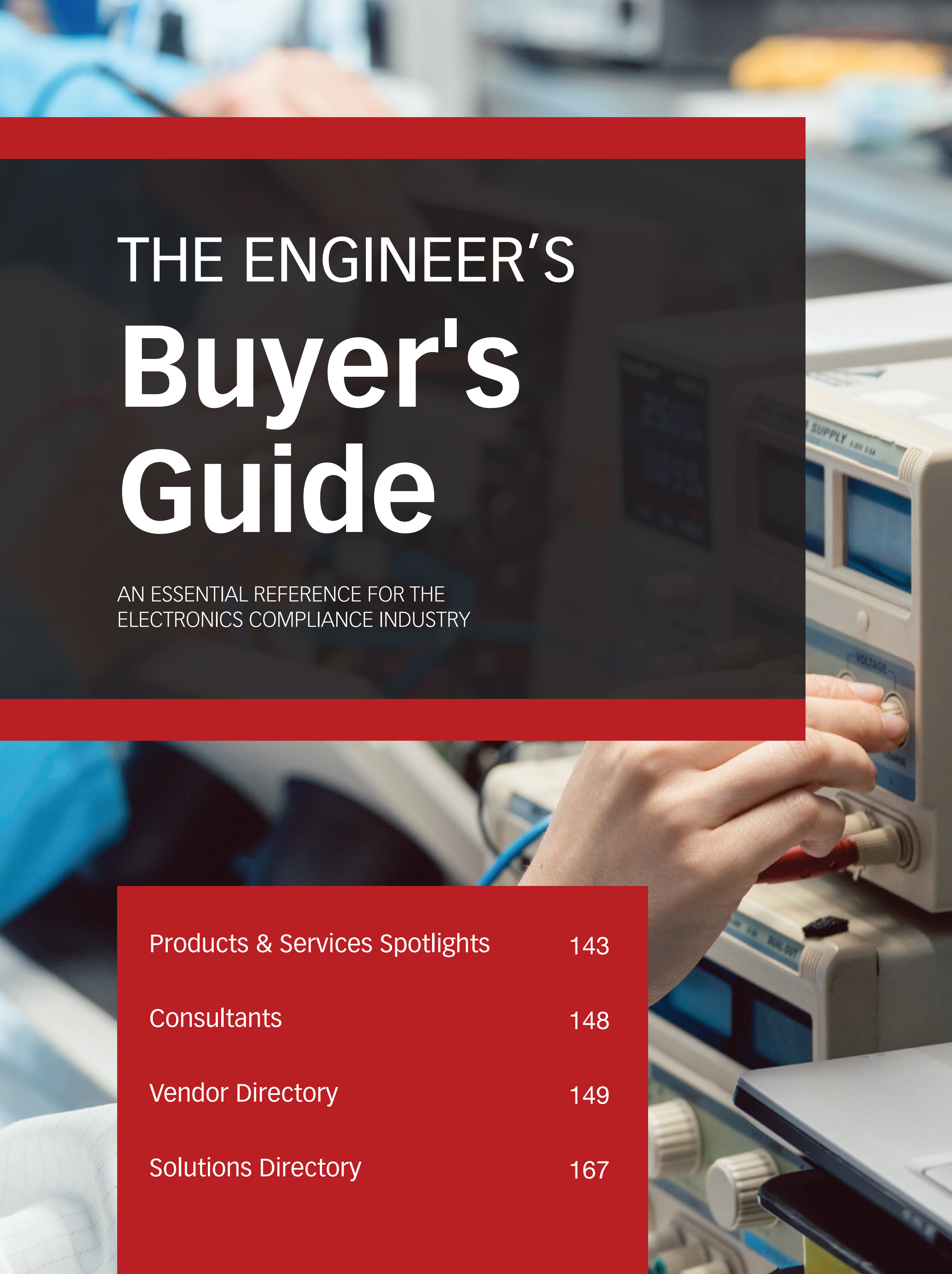

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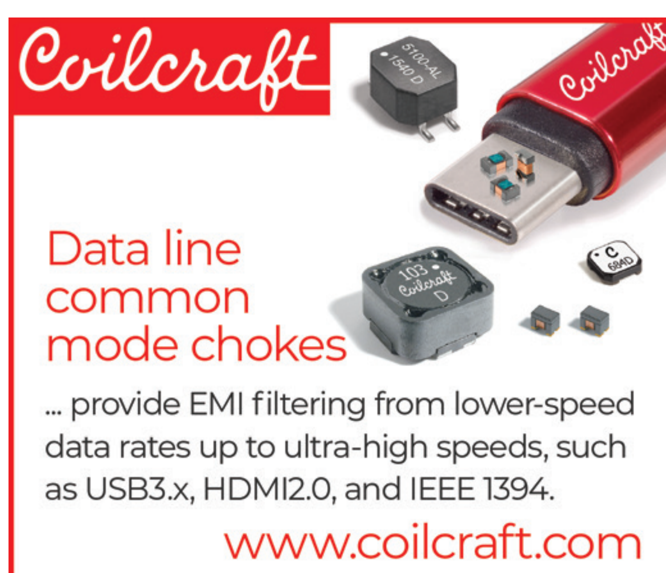

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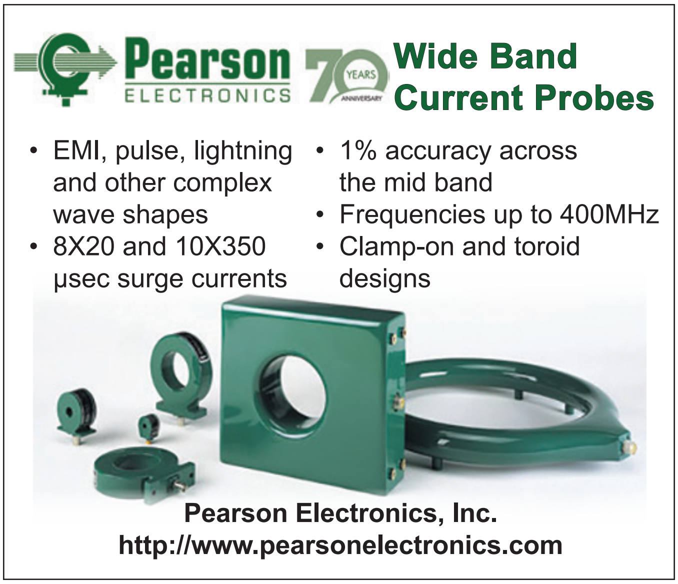
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Merus Power
Nokia, Finland | http://www.meruspower.fi

Metal Textiles Corporation
Edison, NJ USA | http://www.metexcorp.com

METZ CONNECT
Tinton Falls, NJ USA | http://www.metz-connect.com/us

MFG Tray (Molded Fiber Glass) Company

6175 US Highway 6
Linesville, PA 16424 USA
tel: (800) 458-6090
mfgtraysales@moldedfiberglass.com
https://www.mfgtray.com

The MFG Tray Company are pioneers in the material handling industry. MFG Tray, like other divisions of Molded Fiber Glass Companies, have found great success applying the unique properties of reinforced composites to offer solutions in various industries. MFG Tray's Fibrestat ESD product line encompasses a variety of trays, containers and specialty products molded from high-strength, glass-reinforced composites that are specifically formulated to dissipate electrostatic discharge and to safely and effectively convey, accumulate and store static-sensitive parts and assemblies. The high conductivity, low electrical resistance of MFG Tray's composite materials is a permanent property ensuring the safe transfer of electrostatic discharge away from sensitive microprocessors, assemblies, loaded circuit boards and other electronic components for the life of the tray or containers.

MH&W International Corportion
Mahwah, NJ USA http://www.mhw-intl.com

Michigan Scientific Corp.
Milford Township, MI USA http://www.michsci.com

Micom Laboratories Inc
Dorval, QC Canada https://www.micomlab.com

MiCOM Labs
Pleasanton, CA USA http://www.micomlabs.com

Microwave Vision Group
Kennesaw, GA USA https://www.mvg-world.com

montena technology sa
Rossens, Switzerland https://www.montena.com/system/home

Montrose Compliance Services, Inc.
Santa Clara, CA USA http://www.montrosecompliance.com

MPB Measuring Instruments
Rome, Italy http://www.gruppompb.uk.com

MPE Ltd
Liverpool, Merseyside UK http://www.mpe.co.uk

The MuShield Company, Inc.
Londonderry, NH USA http://www.mushield.com

Narda STS, USA
Hauppauge, NY USA http://www.narda-sts.us

National Institute for Aviation Research
Wichita, KS USA http://www.niar.wichita.edu/researchlabs/eme.asp

Nemko
Lysaker, Norway https://www.nemko.com

NetSPI
Minneapolis, MN USA http://www.netspi.com

Nexperia Semiconductor
Farmington Hills, MI USA https://www.nexperia.com

NexTek, Inc.
North Billerica, MA USA http://nextek.com

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info@jabar.nolato.com
https://www.nolato.com/jabar

Nolato Jabar LLC is a U.S. manufacturer and fabricator of EMI shielding, thermal interface, and commercial silicone sealing and damping solutions.

Our Jabar® MIL-SPEC EMI shielding and thermal interface products provide integrity and quality for performance-critical defense, aerospace and telecommunication applications. Products include M83528 particle-filled elastomers, wire oriented in silicone, elastomer-filled metallic sheeting, and shielding vents.

Our non-conductive sealing and damping silicone products are used in both commercial and non-commercial applications and are available in either solid or sponge materials.

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NRD LLC
Grand Island, NY USA http://www.nrdllc.com

NSI-MI Technologies
Suwanee, GA USA http://www.nsi-mi.com

Oak-Mitsui Technologies
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Okaya Electric America, Inc.
Valparaiso, IN USA http://www.okaya.com

Omni Controls
Tampa, FL USA http://www.omnicontrols.com

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Santa Cruz, CA USA http://www.onfilter.com

OnRule
Santa Clara, CA USA http://www.onrule.com

OPHIR RF/Ophir EMC
Los Angeles, CA USA http://www.ophirrf.com

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Easton, PA USA http://www.orbel.com

Orbis Compliance LLC
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Packaging Compliance Labs
Kentwood, MI USA https://pkgcompliance.com

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PAVONE Technologies
New Delhi, Delhi India http://pavonetech.in

PC Squared Consultants
Bentonville, AR USA https://www.consumerproductcompliance.com

PCE Instruments
Hamble-le-Rice, Southampton UK http://www.pce-instruments.com

Pearson Electronics, Inc
Palo Alto, CA USA http://www.pearsonelectronics.com

Pendulum Instruments
Redwood City, CA USA https://pendulum-instruments.com

The Photonics Group
West Chester, OH USA https://thephotonicsgroup.com

Pickering Interfaces
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Polyonics
Westmoreland, NH USA http://www.polyonics.com

PPG Aerospace Cuming-Lehman Chambers
Chambersburg, PA USA http://www.cuminglehman.com

PPG Engineered Materials
Wallingford, CT USA https://www.dexmet.com/applications/emi-shielding

Prana
Malemort sur Corrèze, France http://www.prana-rd.com

Preen AC Power Corp.
Irvine, CA USA http://www.preenpower.com

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Orange, CA USA https://www.premieremc.com

Premium Packaging
Girraween, NSW Australia https://premiumpackaging.com.au

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Bensenville, IL USA http://www.productsafetyinc.com

Protective Industrial Polymers
North Ridgeville, OH USA http://www.protectpoly.com

Purdue Engineering Professional Education
West Lafayette, IN USA https://engineering.purdue.edu/online

QAI Laboratories
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Quanta Laboratories
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Quell Corporation
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Reliant EMC LLC

Menlo Park, CA USA https://www.reliantemc.com

Remcom

State College, PA USA http://www.remcom.com

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Ronkonkoma, NY USA http://www.retlif.com

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Northbrook, IL USA http://www.saftgard.com

Safe Engineering Services & Technologies

Laval, QC Canada http://www.sestech.com

Sanwood Environmental Chambers Co., Ltd

Dongguan City, Guangdong Province China http://www.climatic-chambers.com.tw

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Manorville, NY USA http://www.sasindustries.com

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Edison, NJ USA https://schaffner.com

Schlegel Electronic Materials

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Irvine, CA USA http://www.sealscience.com

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Canandaigua, NY USA http://www.select-fabricators.com

SF Cable

Hayward, CA USA https://www.sfcable.com

SGS

Suwanee, GA USA — https://www.sgs.com/en/our-services/connectivity-and-products/connectivity

Siglent Technologies North America

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Signal Hound

La Center, WA USA — http://www.signalhound.com

SILENT Solutions LLC

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Slayson

San Diego, CA USA — https://slayson.com

Solar Electronics Co.

North Hollywood, CA USA — http://www.solar-emc.com

Southwest Research Institute

San Antonio, TX USA — http://www.swri.org

Spectrum Control

Fairview, PA USA — http://www.spectrumcontrol.com

Spectrum EMC, LLC

Sierra Vista, AZ USA — http://www.spectrumemc.com

Spes Development Co

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Spira Manufacturing Corporation

San Fernando, CA USA — http://www.spira-emi.com

Sprinkler Innovations

Seabrook, NH USA — http://www.sprinklerinnovations.com

Static Solutions, Inc.

Hudson, MA USA — https://staticsolutions.com

StaticStop ESD Flooring

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https://www.staticstop.com

StaticStop manufactures a full line of ESD/Static Control Flooring, including an adhesive-free interlocking flooring that can be used over bad subfloors and installed directly on top of existing floors without any disruption to operations. We offer the most comprehensive line of ESD flooring solutions available, including installation and maintenance options to provide the right product at the best price for any application.

StaticWorx, Inc.

Williston, VT USA — https://staticworx.com

SteppIR Communication Systems

Bellevue, WA USA — http://www.steppir.com

Suzhou 3ctest Electronic Co., Ltd.

No. 99 E'meishan Road, SND
Suzhou, Jiangsu, 215153, China
tel: +86-512-68077192
https://www.3c-test.com

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SW Safety Solutions

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Bloomfield, CT USA — http://www.swift-textile.com

Syntakt Packaging Integration

Spokane, WA USA — https://syntaktsystems.com

TDK Electronics

Iselin, NJ USA — http://www.epcos.com

TDK-Lambda Americas

Neptune, NJ — https://www.us.lambda.tdk.com

TDK RF Solutions

1101 Cypress Creek Road
Cedar Park, TX 78613 USA
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https://www.tdkrfsolutions.tdk.com

TDK RF Solutions is a world leader in the design, development & manufacture of technical solutions for the EMC testing and Antenna measurement industries. We offer a complete range of solutions including automated test systems, anechoic chambers, RF absorber, antennas, software, RF filters, and a wide range of test products & accessories. We call it Total System Technology®, and it means TDK RF Solutions is your best choice of partner for proven solutions & services. If you are in the market for a complete turnkey solution or looking to expand your test capabilities with a new antenna, contact us to see what TDK can do for you.

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Tech-Etch
Plymouth, MA USA — http://www.tech-etch.com

Techmaster Electronics
Vista, CA USA — https://techmaster.us

Technical Safety Services
Berkeley, CA USA — http://techsafety.com/services/test-certification/cleanroom-testing

Teledyne LeCroy
Chestnut Ridge, NY USA — http://teledynelecroy.com

TESEO SpA
Druento, Turin Italy — http://www.teseo.net

Test Site Services Inc
Milford, MA USA — http://www.testsiteservices.com

Testing Partners
Youngstown, OH USA — https://testingpartners.com

TestWorld Inc
Rocklin, CA USA — http://www.testworldinc.com

Thermo Fisher Scientific
Tewksbury, MA USA — http://www.thermoscientific.com/esd

Thermotron
Holland, MI USA — http://www.thermotron.com

Thermtest
Fredericton, NB Canada — https://thermtest.com

Timco Engineering, Inc.
Newberry, FL USA — http://www.timcoengr.com

Times Microwave Systems
Wallingford, CT USA — https://www.timesmicrowave.com

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Airdrie, AB Canada — http://tjstechnical.com

TOYO Corporation
Fremont, CA USA — https://toyotechus.com

Transient Specialists, Inc.
Burr Ridge, IL USA — http://transientspecialists.com

Transtector
Hayden, ID USA — https://www.transtector.com

Trescal
Howell, MI USA — http://www.trescal.com

TTE Filters
Arcade, NY USA — http://www.tte.com

TÜV Rheinland of North America
Littleton, MA USA — https://www.tuv.com/usa/en

TÜV SÜD America Inc.
Wakefield, MA USA — https://www.tuv-sud-america.com/us-en

UEMC, Inc.
Hockley, TX USA https://uemcinc.com

United Static Control Products Inc.
Bradenton, FL USA http://ultrastatinc.com

Universal Shielding Corp.
20 West Jefryn Boulevard
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University of Oxford Continuing Professional Development - Technology Programme
Oxford, Oxfordshire UK http://www.conted.ox.ac.uk/about/continuing-professional-development

US Microwave Laboratories
Summerfield, NC USA http://www.usmicrolabs.com

V Technical Textiles, Inc.
Palmyra, NY USA https://www.vtechtextiles.com

Vanguard Electronics
Huntington Beach, CA USA http://www.ve1.com

VDE Americas
Burlington, MA USA http://vdeamericas.com

Vectawave Technology Limited
Newport, Wales UK http://vectawave.co.uk

Verdelite Consulting
Laurel, MD USA http://www.verdeliteconsulting.com

VEROCH - Testing Equipment USA
Sunrise, FL USA http://www.veroch.com

Versus Technology (Versus Global LLC)
Wilmington, DE USA http://www.versusglobal.com

VIAVI Solutions
Wichita, KS USA https://www.viavisolutions.com/en-us

Vitrek Corporation
Poway, CA USA http://www.vitrek.com

VPI Laboratories, Inc.
Draper, UT USA http://www.vpilaboratories.com

VTI Vacuum Technologies, Inc.
Reedsburg, WI USA http://www.vactecinc.com

W. L. Gore & Associates, Inc.
Landenberg, PA USA http://www.gore.com

Washington Laboratories
Frederick, MD USA http://www.wll.com

Wave Computation Technologies, Inc.
Durham, NC USA http://www.wavenology.com

Wavecontrol Inc.
Roseland, NJ USA https://www.wavecontrol.com/rfsafety/en

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Kirkland, QC Canada http://www.wecoconnectors.com

WEMS Electronics
Hawthorne, CA USA http://www.wems.com

Wewontech
Dongcheng - Dongguan, Guangdong China http://www.wewontech.com

Willrich Precision Instrument Company, Inc
Cresskill, NJ USA http://willrich.com

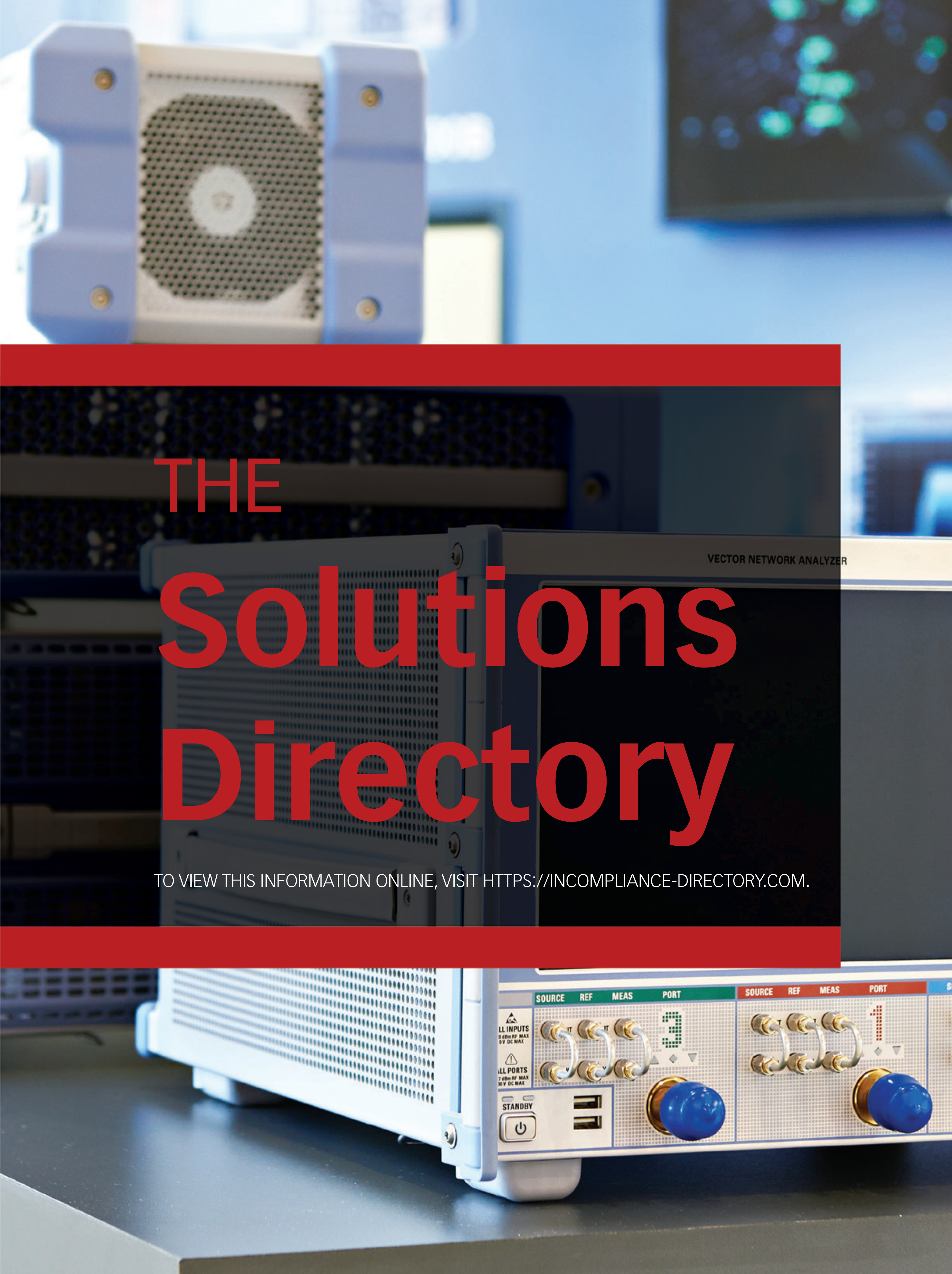
WorkHub
Calgary, AB Canada https://www.workhub.com

Würth Elektronik
Waldenburg, Germany https://www.we-online.com

Wyatt Technical Services LLC
Woodland Park, CO USA http://www.emc-seminars.com

XGR Technologies
Newark, DE USA http://www.xgrtec.com

Yazaki Testing Laboratory
Canton, MI USA http://www.yazakiemc.com



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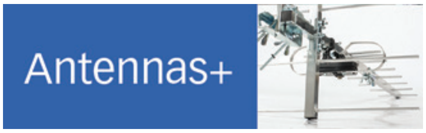

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ETS-Lindgren
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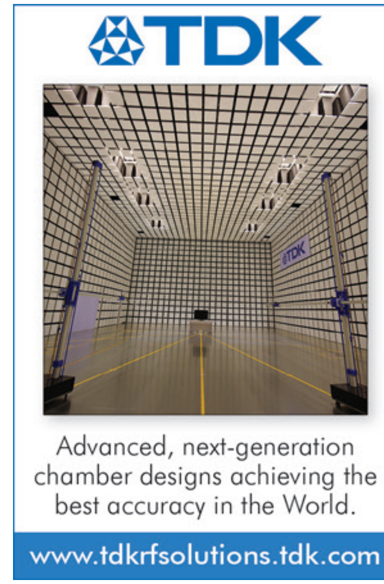

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Electromechanical

Electronic Cooling Fans

Americor Electronics Ltd.
Gemini Electronic Components, Inc.
Jaro Thermal
Seal Science, Inc.

Motors

Equipnet
Globe Composite Solutions
Omni Controls
Ross Engineering Corp.

Solid State Relays

Applied Physical Electronics, L.C. (APELC)

Switches

Betatronix
Bourns, Inc.
C&K Components, now a part of Littelfuse, Inc.
EaglePicher Technologies
ES Components
Gemini Electronic Components, Inc.
Pickering Interfaces
Ross Engineering Corp.
SCHURTER, Inc.
Würth Elektronik

Filters

Absorptive Filters

KITAGAWA INDUSTRIES America, Inc.
MH&W International Corportion

Air Filters

HEMCO Corporation
Metal Textiles Corporation

Antenna Filters

Würth Elektronik

EMC & RFI Filters

Americor Electronics Ltd.
Astrodyne TDI
BLOCK USA, Inc.
Captor Corporation
Coilcraft Critical Products & Services
Coilcraft, Inc.
CONEC Corporation
Curtis Industries/Tri-Mag, LLC
Diamond Microwave Chambers Ltd
EMC Instrument & Solution
EMI Filter Company
EMI Solutions, Inc.
EMZER
Enerdoor
Gemini Electronic Components, Inc.
High & Low Corporation
KITAGAWA INDUSTRIES America, Inc.
Knowles (UK) Ltd
Leader Tech Inc.
Metal Textiles Corporation
MH&W International Corportion
MPE Ltd
NexTek, Inc.
Nolato Jabar LLC
Okaya Electric America, Inc.
OnFILTER
Premier Filters
Quell Corporation
Roxburgh EMC
Schaffner EMC Inc.
SCHURTER, Inc.
Solar Electronics Co.
Spectrum Control
Spira Manufacturing Corporation
TDK Electronics
TDK RF Solutions
TDK-Lambda Americas
Tech-Etch
TTE Filters
UEMC, Inc.
WEMS Electronics
Würth Elektronik

Filter Coils

Coilcraft Critical Products & Services
Curtis Industries/Tri-Mag, LLC
TTE Filters

Filter Pins

EMI Solutions, Inc.

Frequency Converters

TTE Filters
VEROCH - Testing Equipment USA

Oscillators

Gemini Electronic Components, Inc.

Passive & Discrete

Capacitors

Ceramic Capacitors

Dexter Magnetic Technologies, Inc.
ES Components
Knowles (UK) Ltd
KOA Speer Electronics
KYOCERA AVX Components Corporation
MPE Ltd
RCD Components
TDK Electronics
Würth Elektronik

Decoupling Capacitors

Oak-Mitsui Technologies

EMC Feedthrough Capacitors

Captor Corporation
MPE Ltd
NexTek, Inc.
RCD Components
Schaffner EMC Inc.
WEMS Electronics

EMC Suppression Capacitors

Americor Electronics Ltd.
Captor Corporation
Oak-Mitsui Technologies
RCD Components
Würth Elektronik

Filter Capacitors

Captor Corporation
CONEC Corporation
EMI Solutions, Inc.
NexTek, Inc.
Oak-Mitsui Technologies
Okaya Electric America, Inc.
RCD Components
Würth Elektronik

Planar Array Capacitors

CONEC Corporation

EMI Solutions, Inc.

Oak-Mitsui Technologies

Tantalum Capacitors

KYOCERA AVX Components Corporation

RCD Components

Ferrite Beads, Rods & Forms

Fair-Rite Products Corp.

Faraday Defense Corp.

Gowanda Electronics

iNRCORE, LLC

KOA Speer Electronics

Leader Tech Inc.

MAJR Products

MH&W International Corportion

TDK Electronics

Vanguard Electronics

Inductors/Chokes

Data & Signal Line Chokes

iNRCORE, LLC

NRD LLC

SCHURTER, Inc.

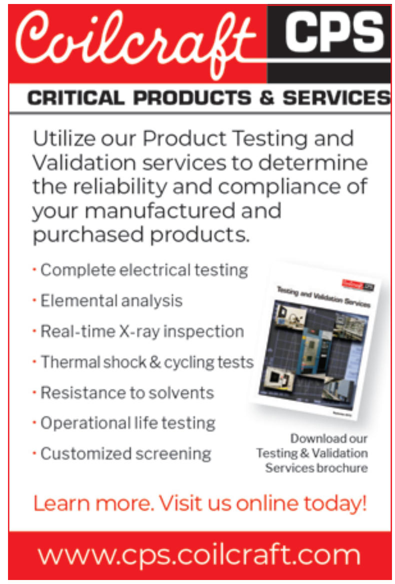
TDK Electronics

WEMS Electronics

EMI/RFI Inductors

Captor Corporation

Coilcraft Critical Products & Services



Coilcraft, Inc.

iNRCORE, LLC

KYOCERA AVX Components Corporation

MH&W International Corportion

NRD LLC

WEMS Electronics

Power Line Chokes

Coilcraft Critical Products & Services

Gowanda Electronics

iNRCORE, LLC

MH&W International Corportion

SCHURTER, Inc.

Vanguard Electronics

WEMS Electronics

Reactors for Frequency Converters

Coilcraft Critical Products & Services

NRD LLC

OnFILTER

RF Chokes

Coilcraft Critical Products & Services

Gowanda Electronics

iNRCORE, LLC

NRD LLC

Schaffner EMC Inc.

Vanguard Electronics

Surface Mount Inductors

Coilcraft Critical Products & Services

Gowanda Electronics

iNRCORE, LLC

KYOCERA AVX Components Corporation

Vanguard Electronics

Switchmode Inductors

Coilcraft Critical Products & Services

Gowanda Electronics

iNRCORE, LLC

Vanguard Electronics

VHF Chokes

Coilcraft Critical Products & Services

NRD LLC

Mains (X & Y)

Okaya Electric America, Inc.

Resistors & Potentiometers

Electronic Loads

ES Components

Gemini Electronic Components, Inc.

Potentiometers

Betatronix

Bourns, Inc.

Power Line Isolation

iNRCORE, LLC

RCD Components

Signal Line Isolation

iNRCORE, LLC

RCD Components

Transformers

Americor Electronics Ltd.

Bourns, Inc.

Coilcraft, Inc.

ELSCO Transformers

Gowanda Electronics

iNRCORE, LLC

Pearson Electronics, Inc

RCD Components

Vanguard Electronics

Varistors

KOA Speer Electronics

KYOCERA AVX Components Corporation

Power Supply & Conditioning

Adapters

Americor Electronics Ltd.
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Oak-Mitsui Technologies
Siglent Technologies North America

Converters

Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
Equipnet
Oak-Mitsui Technologies

Interruptions, AC Power

Astrodyne TDI
DANA Power Supplies
Hilo-Test

Isolators, Power/Signal Line

OnFILTER

Line Conditioning Equipment

DANA Power Supplies
Merus Power
Okaya Electric America, Inc.

Power Amplifiers

Astrodyne TDI

Power Cords

Americor Electronics Ltd.
DANA Power Supplies
SCHURTER, Inc.

Power Generators

DANA Power Supplies
Preen AC Power Corp.

Power Rectifier

Astrodyne TDI
DANA Power Supplies

Power Strips

DANA Power Supplies
SCHURTER, Inc.

Power Supplies

Americor Electronics Ltd.
AMETEK Programmable Power Supplies
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
EaglePicher Technologies
Equipnet
Foster Transformer Company
Hilo-Test
Kikusui America Inc
Langer EMV-Technik GmbH
Preen AC Power Corp.
Siglent Technologies North America
TDK-Lambda Americas

Switching Power Supplies

Astrodyne TDI
Bourns, Inc.
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Kikusui America Inc
Würth Elektronik

Voltage Regulators

Astrodyne TDI
DANA Power Supplies
Preen AC Power Corp.

Printed Circuit Boards

Americor Electronics Ltd.
Candor Industries Inc
Captor Corporation
Curtis Industries/Tri-Mag, LLC
Elma Electronic Inc.
Oak-Mitsui Technologies
KYOCERA AVX Components Corporation
MegaPhase, LLC
Polyonics
SCHURTER, Inc.

Resonators

ES Components

Semiconductors

ES Components
Gemini Electronic Components, Inc.
MH&W International Corportion
Nexperia Semiconductor

Surge Suppressors

Captor Corporation
CITEL, Inc.
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
ES Components
Faraday Defense Corp.
Fischer Custom Communications, Inc.
Gemini Electronic Components, Inc.
NexTek, Inc.
Okaya Electric America, Inc.
OnFILTER
TDK Electronics
Transtector

Absorbing Materials

3Gmetalworx Inc.
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Dutch Microwave Absorber Solutions
Frankonia GmbH
Globe Composite Solutions
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
Marktek Inc.
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Reliant EMC LLC
Seal Science, Inc.
TDK RF Solutions
V Technical Textiles, Inc.

Additives

Marktek Inc.

Adhesives

Alpha Assembly Solutions
ARC Technologies, a Hexcel Company
DELO Adhesives
Master Bond
Metal Textiles Corporation
Polyonics
Seal Science, Inc.

Coatings and Sealants

Eeonyx Corporation
Enviro Tech International
Oak-Mitsui Technologies
Seal Science, Inc.

Conductive Materials

Faraday Defense Corp.
Marktek Inc.
MFG Tray (Molded Fiber Glass) Company
Quell Corporation
Thermtest

Silicone Conductive Sponges

Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MH&W International Corportion
Parker Chomerics
Polyonics
Seal Science, Inc.
Tech-Etch

Thermally Conductive Silicone Materials

Globe Composite Solutions
Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MH&W International Corportion
Nolato Jabar LLC
Parker Chomerics
Polyonics
Seal Science, Inc.
Tech-Etch

Foams & Insulation

Enertech UPS Pvt Ltd

Metals and Alloys

3Gmetalworx Inc.
Alpha Assembly Solutions
Bolting Specialist, a division of Resistant Metal Alloys LLP
Eastern Steel Manufacturing Co.,Ltd
Ferrotec-Nord
Globe Composite Solutions
Johnson Bros Metal Forming Co
Leader Tech Inc.
Magnetic Shield Corporation
The MuShield Company, Inc.
PPG Engineered Materials
Syntakt Packaging Integration
Testing Partners

Plastics

Resins & Compounds

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
DELO Adhesives
Globe Composite Solutions
Jordi Labs
Lubrizol Engineered Polymers
Seal Science, Inc.

Thermoplastics & Thermoplastic Materials

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
Conductive Containers Inc
Crystal Rubber Ltd
Globe Composite Solutions
Lubrizol Engineered Polymers
MFG Tray (Molded Fiber Glass) Company
Parker Chomerics

Resources

Associations

A2LA
EOS/ESD Association Services, LLC
Saf-T-Gard International, Inc.

Education

Seminars

André Consulting, Inc.
Archambeault EMI/EMC Enterprises
BestESD Technical Services
Cherry Clough Consultants Ltd
D. C. Smith Consultants
Eisner Safety Consultants
Equipment Reliability Institute (ERI)
ESD Association
Go Global Compliance Inc.
Hoolihan EMC Consulting
Keysight Technologies Inc.
LearnEMC
Lewis Bass International Engineering Services
Mach One Design
Montrose Compliance Services, Inc.
Purdue Engineering Professional Education
RMV Technology Group LLC
Safe Engineering Services & Technologies
SILENT Solutions LLC
WorkHub
Wyatt Technical Services LLC

Training Courses

A2LA
André Consulting, Inc.
Cherry Clough Consultants Ltd
D. C. Smith Consultants
DEKRA
DG Technologies
Eisner Safety Consultants
Electronic Instrument Associates
EMC FastPass
EOS/ESD Association Services, LLC

Education

Training Courses *continued*

Equipment Reliability Institute (ERI)
Eurofins York
Grand Valley Statue University EMC Center
Hoolihan EMC Consulting
iNARTE
LearnEMC
Lewis Bass International Engineering Services
Lion Technology, Inc.
Mach One Design
Montrose Compliance Services, Inc.
Purdue Engineering Professional Education
RMV Technology Group LLC
Safe Engineering Services & Technologies
SILENT Solutions LLC
University of Oxford Continuing Professional Development - Technology Programme
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

University

Grand Valley Statue University EMC Center
Purdue Engineering Professional Education
WorkHub

Videos

ESD Association
Keysight Technologies Inc.
Purdue Engineering Professional Education
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

Webinars

Cherry Clough Consultants Ltd
Eisner Safety Consultants
Element Materials Technology - Atlanta-Gainesville, GA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
EOS/ESD Association Services, LLC
ESD Association
LearnEMC
Mach One Design
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
WorkHub
Wyatt Technical Services LLC

Publications

Books

EMI/EMC Books

André Consulting, Inc.
Cherry Clough Consultants Ltd
D.L.S. - Military/Avionics
Grand Valley Statue University EMC Center
Montrose Compliance Services, Inc.
Wyatt Technical Services LLC

Product Safety Books

Lewis Bass International Engineering Services

Magazines

In Compliance Magazine

Standards Resellers

ESD Association

Eyes, Face, and Head

HEMCO Corporation
Saf-T-Gard International, Inc.
WorkHub

Hand and Foot Protection

Saf-T-Gard International, Inc.
SW Safety Solutions
WorkHub

Safety & Warning Labels

Abstraction Engineering Inc
Clarion Safety Systems
Coast Label
Enerdoor
HM Cragg
InfoSight Corporation
Lewis Bass International Engineering Services
PAVONE Technologies
Polyonics
Saf-T-Gard International, Inc.
WorkHub

Safety Clothing

Saf-T-Gard International, Inc.
SW Safety Solutions
TECH WEAR, INC.
WorkHub

Services

Calibration & Repair

A.com Electronic Measurement Technology
A.H. Systems, Inc.
Advanced Test Equipment Corporation
Alltest Instruments
Avalon Test Equipment
Barth Electronics, Inc.
Electronic Instrument Associates
Enertech UPS Pvt Ltd
ETS-Lindgren
Excalibur Engineering Inc., a Transcat Company
Fischer Custom Communications, Inc.
Haefely AG
Keysight Technologies Inc.
LUMILOOP GmbH
M Precision Laboratories, INC.
MPB Measuring Instruments
NRD LLC
NSI-MI Technologies
Omni Controls
Pearson Electronics, Inc
Reliant EMC LLC
Ross Engineering Corp.
Sanwood Environmental Chambers Co., Ltd
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
TDK RF Solutions
Techmaster Electronics
Technical Safety Services
TESEO SpA
Trescal
VEROCH - Testing Equipment USA
Willrich Precision Instrument Company, Inc

Codes, Standards & Regulations

A2LA
American Certification Body
American National Standards Institute
Approve-IT, Inc.
Clarion Safety Systems
CSA Group
DEKRA
DG Technologies
Eisner Safety Consultants
EMC United, Inc.
Enerdoor
Enertech UPS Pvt Ltd
Go Global Compliance Inc.
GreenSoft Technology
Grund Technical Solutions, Inc.
H.B. Compliance Solutions
iNARTE
InfoSight Corporation
Micom Laboratories Inc
MiCOM Labs
Omni Controls
The Photonics Group
TJS Technical Services Inc.

Consulting

Cleanroom/Static Control

BestESD Technical Services
Bystat International Inc.
Estion Technologies GmbH
OnFILTER
Protective Industrial Polymers
RMV Technology Group LLC

EMC Consulting

André Consulting, Inc.
Approve-IT, Inc.
Atlas Compliance & Engineering
BestESD Technical Services
Cherry Clough Consultants Ltd
CKC Laboratories, Inc.
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DG Technologies
DNB Engineering, Inc.
E3 Compliance
Electro Magnetic Applications, Inc (EMA)
EMC Instrument & Solution
EMC United, Inc.
EMI Devices
Enerdoor
ESDEMC Technology LLC
ETS-Lindgren
Eurofins York
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
Grund Technical Solutions, Inc.
Hoolihan EMC Consulting
International Certification Services, Inc.
JBRC Consulting LLC
JDM LABS LLC
LearnEMC
Mach One Design
Machinery Safety & Compliance Services
Montrose Compliance Services, Inc.
OnFILTER
R&B Laboratory
Reliant EMC LLC
Remcom
SILENT Solutions LLC
Southwest Research Institute
Spectrum EMC, LLC
Test Site Services Inc.
TJS Technical Services Inc.
Verdelite Consulting
WEMS Electronics
Wyatt Technical Services LLC

ESD Consulting

BestESD Technical Services
Conductive Containers Inc
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Military/Avionics
E3 Compliance
Electro-Tech Systems

Consulting

ESD Consulting *continued*

EOS/ESD Association Services, LLC
ESDEMC Technology LLC
Estion Technologies GmbH
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
JBRC Consulting LLC
Montrose Compliance Services, Inc.
OnFILTER
RMV Technology Group LLC
SILENT Solutions LLC
Verdelite Consulting
Wyatt Technical Services LLC

Government Regulations

BSMI Regulatory Consulting

Approve-IT, Inc.
Atlas Compliance & Engineering
D.L.S. - EMC
D.L.S. - Wireless
Go Global Compliance Inc.
TJS Technical Services Inc.

EU (Europe) Regulatory Consulting

ACEMA
André Consulting, Inc.
Approve-IT, Inc.
Atlas Compliance & Engineering
CKC Laboratories, Inc.
The Compliance Map
Compliance Specialty International Associates
Compliance Worldwide, Inc.
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Product Safety
D.L.S. - Wireless
Eisner Safety Consultants
Elite Electronic Engineering Inc.
F2 Labs - Damascus, MD
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
GreenSoft Technology
International Certification Services, Inc.
JBRC Consulting LLC
Montrose Compliance Services, Inc.
TJS Technical Services Inc.
Verdelite Consulting
VPI Laboratories, Inc.

FCC (U.S) Regulatory Consulting

André Consulting, Inc.
Approve-IT, Inc.
Atlas Compliance & Engineering
CKC Laboratories, Inc.
Compliance Specialty International Associates
Compliance Worldwide, Inc.
D.L.S. - EMC
D.L.S. - Product Safety
D.L.S. - Wireless
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
International Certification Services, Inc.
JBRC Consulting LLC
Montrose Compliance Services, Inc.
TJS Technical Services Inc.
TÜV Rheinland of North America
Verdelite Consulting
VPI Laboratories, Inc.

GOST (Russia) Regulatory Consulting

Go Global Compliance Inc.
TJS Technical Services Inc.

VCCI Consulting

Approve-IT, Inc.
Atlas Compliance & Engineering
CKC Laboratories, Inc.
D.L.S. - EMC
TJS Technical Services Inc.

Lightning Protection

André Consulting, Inc.
D. C. Smith Consultants
D.L.S. - Military/Avionics
Electro Magnetic Applications, Inc (EMA)
NexTek, Inc.

Medical Device

André Consulting, Inc.
Approve-IT, Inc.
CertifiGroup Inc
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Product Safety
D.L.S. - Wireless
Eisner Safety Consultants
EMC United, Inc.
Enviropass Expertise Inc.
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
GreenSoft Technology
MedicalRegs.com
Orbis Compliance LLC
The Photonics Group
Product Safety Consulting
RMV Technology Group LLC
Test Site Services Inc.
TJS Technical Services Inc.

Product Safety Consulting

360 Compliance Partners
Approve-IT, Inc.
CertifiGroup Inc
Clarion Safety Systems
Compliance inSight Consulting Inc.
D.L.S. - Environmental
D.L.S. - Product Safety
Eisner Safety Consultants
Enviropass Expertise Inc.
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
InfoSight Corporation
Intertek
JBRC Consulting LLC
Lewis Bass International Engineering Services
M.C. Global Access LLC
Machinery Safety & Compliance Services
Orbis Compliance LLC

PC Squared Consultants
The Photonics Group
Product EHS Consulting LLC
Product Safety Consulting
RMV Technology Group LLC
Test Site Services Inc.
VDE Americas
VEROCH - Testing Equipment USA

Quality

DEKRA
Eisner Safety Consultants
Estion Technologies GmbH
Globe Composite Solutions
InfoSight Corporation
Spectrum EMC, LLC

Telecom

Compliance Specialty International Associates
CV. DIMULTI
D. C. Smith Consultants
D.L.S. - Wireless
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
Orbis Compliance LLC
PAVONE Technologies

Tempest

Dayton T. Brown, Inc.

Transient

André Consulting, Inc.
BestESD Technical Services
D. C. Smith Consultants
D.L.S. - EMC
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
Grund Technical Solutions, Inc.
JBRC Consulting LLC
NexTek, Inc.
SILENT Solutions LLC

Wireless

Approve-IT, Inc.
PAVONE Technologies

Design

André Consulting, Inc.
BestESD Technical Services
Captor Corporation
Clarion Safety Systems
Conductive Containers Inc
DG Technologies
E3 Compliance
EMC United, Inc.
Empower RF Systems, Inc.
Enertech UPS Pvt Ltd
Globe Composite Solutions
JBRC Consulting LLC
Machinery Safety & Compliance Services
Orbel Corporation
The Photonics Group
SILENT Solutions LLC
V Technical Textiles, Inc.
Verdelite Consulting
VEROCH - Testing Equipment USA
WEMS Electronics

Other

Conductive Painting Services

VTI Vacuum Technologies, Inc.

Shielded Enclosure Design

3Gmetalworx Inc.
Conductive Containers Inc
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Leader Tech Inc.
Slayson
VTI Vacuum Technologies, Inc.

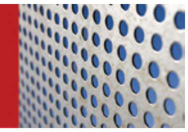
Site Survey Services

Analysis and Measurement Services Corporation
BestESD Technical Services
Clarion Safety Systems
Dayton T. Brown, Inc.
Electronic Instrument Associates
EOS/ESD Association Services, LLC
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
NRD LLC
SGS
Spectrum EMC, LLC
WorkHub

Other Services

E-Fab, LLC
Jay Hoehl Inc.
Machinery Safety & Compliance Services
Premium Packaging
Technical Safety Services

Shielding



Architectural Shielding Products

ETS-Lindgren
Faraday Defense Corp.
Leader Tech Inc.
MAJR Products
Marktek Inc.
Metal Textiles Corporation

Fingerstock

3Gmetalworx Inc.
Leader Tech Inc.
Metal Textiles Corporation
Orbel Corporation
Parker Chomerics
Raymond EMC Enclosures Ltd.
Schlegel Electronic Materials
Tech-Etch

Shielded Air Filters

Leader Tech Inc.
MAJR Products
Nolato Jabar LLC
Nolato PPT
Parker Chomerics
Premier Filters
Spira Manufacturing Corporation
Tech-Etch
Universal Shielding Corp.

Shielded Cable Assemblies & Harnesses

CONEC Corporation
Leader Tech Inc.
MAJR Products

Shielded Coatings

A&A Coatings
ARC Technologies, a Hexcel Company
Leader Tech Inc.
Marktek Inc.
Parker Chomerics
VTI Vacuum Technologies, Inc.

Shielded Compounds

Kemtron Ltd., now part of TE Connectivity
Leader Tech Inc.
Marktek Inc.
Parker Chomerics

Shielded Conduit

Electri-Flex Company
Leader Tech Inc.
Magnetic Shield Corporation

Shielded Connectors

American Swiss
Cinch Connectivity Solutions
CONEC Corporation
Gemini Electronic Components, Inc.
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
Quell Corporation
Spira Manufacturing Corporation
Tech-Etch
Würth Elektronik

Shielded Enclosures

3Gmetalworx Inc.
Comtest Engineering
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Emcor Enclosures
ETS-Lindgren
Faraday Defense Corp.
Frankonia GmbH
Leader Tech Inc.
Lionheart Northwest
Magnetic Shield Corporation
Marktek Inc.
The MuShield Company, Inc.
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Reliant EMC LLC
Select Fabricators, Inc.
Slayson
Universal Shielding Corp.
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.

Shielded Tubing

Electri-Flex Company
Kemtron Ltd., now part of TE Connectivity
Leader Tech Inc.
Magnetic Shield Corporation
Marktek Inc.

Shielded Wire & Cable

Cinch Connectivity Solutions
CONEC Corporation
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
SF Cable

Shielding Gaskets

3Gmetalworx Inc.
Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
Nolato Jabar LLC
Nolato PPT
Orbel Corporation
Parker Chomerics
Quell Corporation
SAS Industries, Inc.
Schlegel Electronic Materials
Spira Manufacturing Corporation
Tech-Etch
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
XGR Technologies

Shielding Materials

EMI/RFI Shielding Materials

A&A Coatings
Aaronia USA
AR/RF Microwave Instrumentation
Bal Seal Engineering
Diamond Microwave Chambers Ltd
Fair-Rite Products Corp.
Isodyne Inc.
Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
Nolato Jabar LLC
Nolato PPT
Orbel Corporation
Polyonics
PPG Aerospace Cuming-Lehman Chambers
Schlegel Electronic Materials
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Universal Shielding Corp.
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
Würth Elektronik
XGR Technologies

Magnetic Field Shielding Materials

3Gmetalworx Inc.
Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
Magnetic Shield Corporation
MAJR Products
The MuShield Company, Inc.
PPG Aerospace Cuming-Lehman Chambers
V Technical Textiles, Inc.

Shielding, Board-Level

3Gmetalworx Inc.
Conductive Containers Inc
Elma Electronic Inc.
Faspro Technologies
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Orbel Corporation
XGR Technologies

Software

Compliance Management Software

GreenSoft Technology
WorkHub

EMC Simulation Software

AE Techron, Inc.
Altair Engineering Inc.
ANSYS Inc.
E3 Compliance
Electro Magnetic Applications, Inc (EMA)
Hilo-Test
Reliant EMC LLC
Remcom
TESEO SpA
TOYO Corporation
Wave Computation Technologies, Inc.

ESD/Static Control Software

ACL Staticide Inc.
Antistat Inc
Desco Industries Inc.
Estion Technologies GmbH
Langer EMV-Technik GmbH

Lab Control Software

AR/RF Microwave Instrumentation
ETS-Lindgren
TESEO SpA
TOYO Corporation

Product Safety Software

OnRule
The Photonics Group

Signal Integrity & EMC Analysis Software

AFJ INSTRUMENTS Srl
Altair Engineering Inc.
E3 Compliance
Remcom
TDK RF Solutions
TOYO Corporation

Wireless Propagation Software

Altair Engineering Inc.
Remcom

Static Control

Air Ionizers

Bystat International Inc.
Desco Industries Inc.
Elimstat.com
Estatec
NRD LLC
Simco-Ion

Clothing & Accessories

ESD Garments

Bystat International Inc.
Correct Products, Inc.
Desco Industries Inc.
Elimstat.com
Estatec
TECH WEAR, INC.
United Static Control Products Inc.

Footwear

Amstat Industries, Inc.
Estatec
Lubrizol Engineered Polymers
Saf-T-Gard International, Inc.

Wrist Straps

Amstat Industries, Inc.
Bystat International Inc.
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
Static Solutions, Inc.
United Static Control Products Inc.

Containers

Bystat International Inc.
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
MFG Tray (Molded Fiber Glass) Company

ESD Tape

Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Elimstat.com
Leader Tech Inc.
Polyonics
United Static Control Products Inc.

Flooring

Carpet

Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
StaticStop
StaticWorx, Inc.

Solutions Directory

Flooring

Floor Coatings

ACL Staticide Inc.
Correct Products, Inc.
Estatec
Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
Static Solutions, Inc.
StaticStop
StaticWorx, Inc.
United Static Control Products Inc.

Mats

Bystat International Inc.
Correct Products, Inc.
Elimstat.com
Estatec
Static Solutions, Inc.
StaticStop
StaticWorx, Inc.

Tiles

Bystat International Inc.
Ground Zero
Julie Industries, Inc.
StaticStop

StaticWorx, Inc.

Furniture

BIMOS
StaticWorx, Inc.

Packaging

Bystat International Inc.
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
EaglePicher Technologies
Elimstat.com
Estatec
Lubrizol Engineered Polymers
MFG Tray (Molded Fiber Glass) Company

Simulators

EMP Simulators

Fischer Custom Communications, Inc.
Grund Technical Solutions, Inc.
montena technology sa

ESD Simulators

Electro-Tech Systems
ESDEMC Technology LLC
Hilo-Test
Kikusui America Inc
montena technology sa

Transient Detectors & Suppressors

CITEL, Inc.
EMI Solutions, Inc.
Fischer Custom Communications, Inc.
NexTek, Inc.

Workstations

ACL Staticide Inc.
BIMOS
Bystat International Inc.
Conductive Containers Inc
Correct Products, Inc.
HEMCO Corporation
Langer EMV-Technik GmbH
Lubrizol Engineered Polymers
MFG Tray (Molded Fiber Glass) Company
NRD LLC
United Static Control Products Inc.

Test and Measure

Accelerometers

Clark Testing
Essco Calibration Laboratory
PCE Instruments
Techmaster Electronics

Amplifiers

Amplifier Modules

AR/RF Microwave Instrumentation
Empower RF Systems, Inc.
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana

Low Power Amplifiers

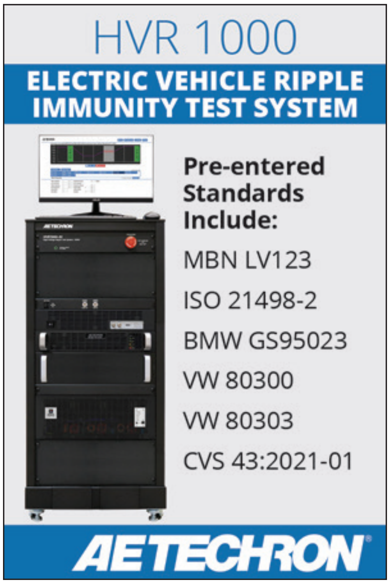
A.H. Systems, Inc.
Advanced Test Equipment Corporation
AR/RF Microwave Instrumentation
ETS-Lindgren
Exodus Advanced Communications
Siglent Technologies North America

Microwave Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
Applied Systems Engineering, Inc.
AR/RF Microwave Instrumentation
Axiom Test Equipment Rentals
CPI TMD Technologies
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Lionheart Northwest
OPHIR RF/Ophir EMC
Prana
Reliant EMC LLC

Power Amplifiers

Advanced Test Equipment Corporation
AE Techron, Inc.



AMETEK CTS
AR/RF Microwave Instrumentation
CPI TMD Technologies
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
OPHIR RF/Ophir EMC
Prana
Reliant EMC LLC
Rohde & Schwarz
TESEO SpA
TOYO Corporation
Vectawave Technology Limited

RF Amplifiers

A.H. Systems, Inc.
Advanced Test Equipment Corporation

AMETEK CTS
AR/RF Microwave Instrumentation
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
OPHIR RF/Ophir EMC
Prana
Rohde & Schwarz
US Microwave Laboratories

Solid State Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
AR/RF Microwave Instrumentation
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana

Traveling Wave Tube Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
AR/RF Microwave Instrumentation
Avalon Test Equipment
CPI TMD Technologies
CPI, Inc.
Empower RF Systems, Inc.
Hilo-Test
OPHIR RF/Ophir EMC

Analyzers

EMI/EMC, Spectrum Analyzers

Aaronia USA
Absolute EMC LLC
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
Agile Calibration
Alltest Instruments
Anritsu Company
Axiom Test Equipment Rentals
Electro Rent Corporation
Electronic Instrument Associates
EMC Instrument & Solution
Excalibur Engineering Inc., a Transcat Company
GAUSS INSTRUMENTS
Keysight Technologies Inc.
Laplace Instruments Ltd
MPB Measuring Instruments
RIGOL Technologies USA, Inc.
Rohde & Schwarz
Siglent Technologies North America
Signal Hound
TOYO Corporation
VIAVI Solutions

Flicker Analyzers

Advanced Test Equipment Corporation
Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc
Lionheart Northwest

Solutions Directory

Analyzers

Harmonics Analyzers

Advanced Test Equipment Corporation
Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc
Laplace Instruments Ltd

Network Analyzers

AFJ INSTRUMENTS Srl
Agile Calibration
ConRes Test Equipment
Copper Mountain Technologies
Electro Rent Corporation
Excalibur Engineering Inc., a Transcat Company
Keysight Technologies Inc.
PCE Instruments
Rohde & Schwarz
Siglent Technologies North America
TOYO Corporation
VIAVI Solutions

Power Quality Analyzers

Axiom Test Equipment Rentals
Electro Rent Corporation
Excalibur Engineering Inc., a Transcat Company

Telecom Analyzers

MPB Measuring Instruments

Audio & Video

Audio Systems

Audivo GmbH

CCTV

Audivo GmbH
TDK RF Solutions
TESEO SpA

Automatic Test Sets

AFJ INSTRUMENTS Srl
Essco Calibration Laboratory
General Test Systems LLC
Omni Controls
Pendulum Instruments
Preen AC Power Corp.
TOYO Corporation
United Static Control Products Inc.

Avionics Test Equipment

Advanced Test Equipment Corporation
AE Techron, Inc.
Alltest Instruments
Cincinnati Sub Zero, LLC
CPI TMD Technologies
The EMC Shop
Essco Calibration Laboratory
HV TECHNOLOGIES, Inc.
Omni Controls
Pickering Interfaces
Preen AC Power Corp.
VIAVI Solutions
Vitrek Corporation

Burn-in Test Equipment

ALI Testing
Essco Calibration Laboratory
General Test Systems LLC
inTEST Thermal Solutions
Mechanical Devices
OPHIR RF/Ophir EMC
Preen AC Power Corp.
Sanwood Environmental Chambers Co., Ltd

Data Acquisition Monitoring Systems

Analysis and Measurement Services Corporation
ConRes Test Equipment
Degree Controls, Inc.
Desco Industries Inc.
DG Technologies
Essco Calibration Laboratory
NSI-MI Technologies
RIGOL Technologies USA, Inc.

Fiber-Optic Systems

Absolute EMC LLC
DG Technologies
Essco Calibration Laboratory
Excalibur Engineering Inc., a Transcat Company
Ferrotec-Nord
HV TECHNOLOGIES, Inc.
Michigan Scientific Corp.
montena technology sa
Reliant EMC LLC
Ross Engineering Corp.
TESEO SpA

Flow Meters

Essco Calibration Laboratory
Omni Controls
PCE Instruments
VEROCH - Testing Equipment USA

Generators

Arbitrary Waveform Generators

Absolute EMC LLC
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Eurofins York
GIGA-TRONICS INCORPORATED
Hilo-Test
Keysight Technologies Inc.
RIGOL Technologies USA, Inc.
Siglent Technologies North America
Suzhou 3ctest Electronic Co., Ltd.

EMP Generator

Advanced Test Equipment Corporation
HV TECHNOLOGIES, Inc.
montena technology sa
Suzhou 3ctest Electronic Co., Ltd.

ESD Generators

Absolute EMC LLC
Advanced Test Equipment Corporation
AMETEK CTS
The EMC Shop
Grund Technical Solutions, Inc.
Haefely AG
HV TECHNOLOGIES, Inc.
M Precision Laboratories, INC.
montena technology sa
Suzhou 3ctest Electronic Co., Ltd.

Fast/Transient Burst Generators

Absolute EMC LLC
Advanced Test Equipment Corporation
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
M Precision Laboratories, INC.
Suzhou 3ctest Electronic Co., Ltd.

Impulse Generators

Absolute EMC LLC

Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Grund Technical Solutions, Inc.
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
M Precision Laboratories, INC.
montena technology sa
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Interference Generators

Absolute EMC LLC
Suzhou 3ctest Electronic Co., Ltd.

Lightning Generators

Absolute EMC LLC
Advanced Test Equipment Corporation
Avalon Test Equipment
The EMC Shop
Haefely AG
HV TECHNOLOGIES, Inc.
M Precision Laboratories, INC.
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Signal Generators

Aaronia USA
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
Alltest Instruments
ConRes Test Equipment
Electro Rent Corporation
EMI Devices
Eurofins York
Excalibur Engineering Inc., a Transcat Company
GIGA-TRONICS INCORPORATED
Keysight Technologies Inc.
Kikusui America Inc
Laplace Instruments Ltd
Reliant EMC LLC
RIGOL Technologies USA, Inc.
Rohde & Schwarz
Signal Hound
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
TOYO Corporation
VIAVI Solutions

Surge Transient Generators

Absolute EMC LLC
Advanced Test Equipment Corporation
AMETEK CTS
Avalon Test Equipment
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
M Precision Laboratories, INC.
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
Thermo Fisher Scientific

Meters

Field Strength Meters

Absolute EMC LLC
AR/RF Microwave Instrumentation
Desco Industries Inc.
LUMILOOP GmbH
Narda STS, USA
United Static Control Products Inc.
Wavecontrol Inc.

Gaussmeters

Omni Controls
PCE Instruments
Wavecontrol Inc.

Magnetic Field Meters

AR/RF Microwave Instrumentation
MPB Measuring Instruments
PCE Instruments
Wavecontrol Inc.

Megohmmeters

ACL Staticide Inc.
Amstat Industries, Inc.
Axiom Test Equipment Rentals
Chroma Systems Solutions, Inc
Megger
PCE Instruments
Ross Engineering Corp.
Static Solutions, Inc.
United Static Control Products Inc.

Radiation Hazard Meters

AR/RF Microwave Instrumentation
EMC Test Design, LLC
Wavecontrol Inc.

RF Power Meters

Absolute EMC LLC
Alltest Instruments
Anritsu Company
AR/RF Microwave Instrumentation
ConRes Test Equipment
Electro Rent Corporation
Keysight Technologies Inc.
LUMILOOP GmbH
OPHIR RF/Ophir EMC
VIAVI Solutions

Solutions Directory

Meters

Static Charge Meters

ACL Staticide Inc.
Electro-Tech Systems
Estion Technologies GmbH

Static Decay Meters

Electro-Tech Systems

Monitors

Current Monitors

Grund Technical Solutions, Inc.
PCE Instruments
Pearson Electronics, Inc

EMI Test Monitors

DG Technologies
OnFILTER

ESD Monitors

Bystat International Inc.
Elimstat.com
Estion Technologies GmbH
Static Solutions, Inc.

Static Voltage Monitors

Desco Industries Inc.
Michigan Scientific Corp.

Oscilloscopes & Transient Recorders

Agile Calibration
Alltest Instruments
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
Electro Rent Corporation
Essco Calibration Laboratory
Keysight Technologies Inc.
PCE Instruments
RIGOL Technologies USA, Inc.
Rohde & Schwarz
Siglent Technologies North America
Techmaster Electronics
Teledyne LeCroy

Pressure Measurement

Gauges

Willrich Precision Instrument Company, Inc

Probes

Current/Magnetic Field Probes

A.H. Systems, Inc.
AEMC Instruments
Alltest Instruments
Fischer Custom Communications, Inc.
General Test Systems LLC
Langer EMV-Technik GmbH
montena technology sa
MPB Measuring Instruments
Pearson Electronics, Inc
Prana
Siglent Technologies North America
Solar Electronics Co.
Techmaster Electronics

Electric Field Probes

Absolute EMC LLC
Advanced Test Equipment Corporation
AR/RF Microwave Instrumentation
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Langer EMV-Technik GmbH
montena technology sa
MPB Measuring Instruments
Narda STS, USA
Siglent Technologies North America
Wavecontrol Inc.

Voltage Probes

ConRes Test Equipment
Fischer Custom Communications, Inc.
Hilo-Test
Langer EMV-Technik GmbH
Laplace Instruments Ltd
OnFILTER
Ross Engineering Corp.
Solar Electronics Co.

Receivers

EMI/EMC Receivers

Absolute EMC LLC
AFJ INSTRUMENTS Srl
AR/RF Microwave Instrumentation
EMZER
Excalibur Engineering Inc., a Transcat Company
GAUSS INSTRUMENTS
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG

RF Receivers

AFJ INSTRUMENTS Srl
ConRes Test Equipment
GIGA-TRONICS INCORPORATED
Narda STS, USA
NSI-MI Technologies
Rohde & Schwarz

TEMPEST Receivers

Rohde & Schwarz

RF Leak Detectors

AR/RF Microwave Instrumentation
MPB Measuring Instruments
NRD LLC

Safety Test Equipment

Absolute EMC LLC
AE Techron, Inc.
AEMC Instruments
Chroma Systems Solutions, Inc
Cincinnati Sub Zero, LLC
E. D. & D., Inc.
EMC Test Design, LLC
Kikusui America Inc
Micom Laboratories Inc
MPB Measuring Instruments
Packaging Compliance Labs
Preen AC Power Corp.
Product Safety Consulting
Saf-T-Gard International, Inc.
Sanwood Environmental Chambers Co., Ltd

United Static Control Products Inc.

VEROCH - Testing Equipment USA

Vitrek Corporation

SAR Testing Equipment

ART-MAN

GIGA-TRONICS INCORPORATED

Lionheart Northwest

Shock & Vibration Testing Shakers

Cincinnati Sub Zero, LLC

Globe Composite Solutions

Micom Laboratories Inc

Sanwood Environmental Chambers Co., Ltd

Thermotron

Wewontech

Susceptibility Test Instruments

Advanced Test Equipment Corporation

DG Technologies

EMC Test Design, LLC

ESDEMC Technology LLC

Grund Technical Solutions, Inc.

Laplace Instruments Ltd

Lionheart Northwest

montena technology sa

Pendulum Instruments

TDK RF Solutions

Telecom Test Equipment

AE Techron, Inc.

Anritsu Company

Avalon Test Equipment

Axiom Test Equipment Rentals

Cincinnati Sub Zero, LLC

Electro Rent Corporation

Fischer Custom Communications, Inc.

Haefely AG

Megger

Pickering Interfaces

RIGOL Technologies USA, Inc.

VIAVI Solutions

Test Equipment Rentals

Advanced Test Equipment Corporation

Alltest Instruments

Avalon Test Equipment

Axiom Test Equipment Rentals

Barth Electronics, Inc.

ConRes Test Equipment

Electro Rent Corporation

Electro-Tech Systems

The EMC Shop

ESDEMC Technology LLC

Excalibur Engineering Inc., a Transcat Company

Grund Technical Solutions, Inc.

Megger

Michigan Scientific Corp.

MPB Measuring Instruments

Techmaster Electronics

TestWorld Inc

Transient Specialists, Inc.

United Static Control Products Inc.

VEROCH - Testing Equipment USA

Testers

Common Mode Transient Immunity (CMTI)

Barth Electronics, Inc.

Current Leakage Testers

Associated Research, Inc

Chroma Systems Solutions, Inc

ESDEMC Technology LLC

Kikusui America Inc

Megger

Ross Engineering Corp.

Dielectric Strength Testers

Associated Research, Inc

Chroma Systems Solutions, Inc

Megger

Ross Engineering Corp.

Electrical Safety Testers

Associated Research, Inc

Chroma Systems Solutions, Inc

Kikusui America Inc

Megger

Saf-T-Gard International, Inc.

EMC Testers

Absolute EMC LLC

AMETEK CTS

DG Technologies

EMC PARTNER AG

EMC Technologies

EMC Test Design, LLC

ESDEMC Technology LLC

Grund Technical Solutions, Inc.

Langer EMV-Technik GmbH

OPHIR RF/Ophir EMC

Pendulum Instruments

Solutions Directory

Testers

ESD Testers

CDM (Charged Device Model)

Barth Electronics, Inc.
Electro-Tech Systems
Thermo Fisher Scientific

HBM (Human Body Model)

Electro-Tech Systems
Thermo Fisher Scientific

TLP (Transmission Line Pulser)

Barth Electronics, Inc.
Thermo Fisher Scientific

Ground Bond Testers

Ground Resistance Testers

AEMC Instruments
Associated Research, Inc
Megger

Hipot Testers

Applied Physical Electronics, L.C. (APELC)
Associated Research, Inc
Chroma Systems Solutions, Inc
Electro Rent Corporation
GW INSTEK
Kikusui America Inc
Ross Engineering Corp.

Thermocouples

Applied Physical Electronics, L.C. (APELC)
Pickering Interfaces
VEROCH - Testing Equipment USA

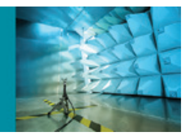
Used & Refurbished Test Equipment

Advanced Test Equipment Corporation
Alltest Instruments
AR/RF Microwave Instrumentation
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
Electro Rent Corporation
Techmaster Electronics

Vibration Controllers

ALI Testing
Cincinnati Sub Zero, LLC
Excalibur Engineering Inc., a Transcat Company
Globe Composite Solutions
Micom Laboratories Inc
Thermotron

Testing



Accredited Registrar

ANAB ANSI-ASQ National Accreditation Board
DEKRA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Excalibur Engineering Inc., a Transcat Company
Green Mountain Electromagnetics, Inc.
MiCOM Labs
QAI Laboratories

Calibration Testing

Agile Calibration
Bharat Test House Group
Essco Calibration Laboratory
Haefely AG
ITC India
M Precision Laboratories, INC.

CE Competent Body

Bureau Veritas Consumer Products Services Inc.
D.L.S. - Environmental
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Enviropass Expertise Inc.
QAI Laboratories
Rogers Labs
SGS

CE Notified Body

American Certification Body
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
DEKRA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
Eurofins York
MiCOM Labs
Nemko
QAI Laboratories
Rogers Labs
SGS
TESEO SpA
Test Site Services Inc.

Environmental Testing & Analysis Services

Bharat Test House Group
Brighton EMC
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc
The Compliance Management Group
D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Wireless
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Element US Space and Defense
Elite Electronic Engineering Inc.
Enviropass Expertise Inc.
ITC India
Micom Laboratories Inc
Quanta Laboratories
Retlif Testing Laboratories
RMV Technology Group LLC
Sanwood Environmental Chambers Co., Ltd
SGS
Test Site Services Inc.
Washington Laboratories

Homologation Services

American Certification Body
Approve-IT, Inc.
Bharat Test House Group
Bureau Veritas Consumer Products Services Inc.
Compliance Specialty International Associates
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Enviropass Expertise Inc.
Go Global Compliance Inc.
Lewis Bass International Engineering Services
MiCOM Labs
Orbis Compliance LLC
SGS
Versus Technology (Versus Global LLC)

Pre-Assessments

A2LA
American Certification Body
Analysis and Measurement Services Corporation
Bharat Test House Group
Brighton EMC
Clark Testing
Compatible Electronics, Inc.
Curtis Industries/Tri-Mag, LLC
CVG Strategy
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Product Safety
D.L.S. - Wireless
DEKRA
E3 Compliance
Eisner Safety Consultants
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
EMC United, Inc.
Enviropass Expertise Inc.
EOS/ESD Association Services, LLC
F2 Labs - Damascus, MD
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
International Certification Services, Inc.
Lewis Bass International Engineering Services
Product Safety Consulting
Quanta Laboratories
Rogers Labs
SGS
SILENT Solutions LLC
Spectrum EMC, LLC
Testing Partners
VPI Laboratories, Inc.
Washington Laboratories

Product & Component Testing Services

Agile Calibration
Analysis and Measurement Services Corporation
ART-MAN
Bharat Test House Group
Brighton EMC
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc
The Compliance Management Group
Compliance Specialty International Associates
Compliance Testing, LLC
CVG Strategy
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DEKRA
DNB Engineering, Inc.
E3 Compliance
Element Materials Technology - Atlanta-Gainesville, GA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
Energy Assurance LLC
Enviropass Expertise Inc.
EOS/ESD Association Services, LLC
F2 Labs - Damascus, MD
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
FEMA Corporation
Ferrotec-Nord
Green Mountain Electromagnetics, Inc.
International Certification Services, Inc.
ITC India
Micom Laboratories Inc
PAVONE Technologies
The Photonics Group
Product Safety Consulting
R&B Laboratory
Retlif Testing Laboratories
RF Solutions, LLC
RMV Technology Group LLC
Rogers Labs
Sanwood Environmental Chambers Co., Ltd
SGS
Southwest Research Institute
Testing Partners
VPI Laboratories, Inc.
Washington Laboratories
Wyatt Technical Services LLC

Testing Laboratories

Accelerated Stress Testing

Core Compliance Testing Services
D.L.S. - Environmental
D.L.S. - Wireless
Dayton T. Brown, Inc.
Element US Space and Defense
Elite Electronic Engineering Inc.
Intertek
Product Safety Consulting
Quanta Laboratories
Radiometrics Midwest Corporation

Testing Laboratories

Acoustical Testing

A2LA
Clark Testing
The Compliance Management Group
Core Compliance Testing Services
D.L.S. - Environmental
D.L.S. - Product Safety
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Electronic Instrument Associates
ETS-Lindgren
Intertek
Nemko
Quanta Laboratories
Retlif Testing Laboratories

Avionics Testing

D.L.S. - Military/Avionics

BSMI Compliant Certification Testing

Atlas Compliance & Engineering
Compliance Worldwide, Inc.
Core Compliance Testing Services
D.L.S. - EMC
D.L.S. - Wireless
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Nemko

CB Test Report

CSA Group
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Energy Assurance LLC
Eurofins MET Labs
F2 Labs - Indianapolis, IN
Intertek
Nemko
TÜV Rheinland of North America

CE Marking

Abstraction Engineering Inc
Atlas Compliance & Engineering
Brighton EMC
CertifiGroup Inc
CKC Laboratories, Inc.
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Product Safety
D.L.S. - Wireless
DNB Engineering, Inc.
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Element US Space and Defense
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
Energy Assurance LLC
Enviropass Expertise Inc.
Eurofins MET Labs
F2 Labs - Damascus, MD
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
International Certification Services, Inc.
Intertek
Lewis Bass International Engineering Services
Nemko
Retlif Testing Laboratories
Rogers Labs
SGS
TESEO SpA
Test Site Services Inc.
TÜV Rheinland of North America
VPI Laboratories, Inc.

China Compulsory Certification

D.L.S. - EMC
D.L.S. - Product Safety
G&M Compliance, Inc.
Nemko

Electrical Safety Testing

Abstraction Engineering Inc
Bharat Test House Group
CertifiGroup Inc
Coilcraft Critical Products & Services
CSA Group
CVG Strategy
D.L.S. - Product Safety
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Element Materials Technology - Atlanta-Gainesville, GA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
EMC Bayswater Pty Ltd
Energy Assurance LLC
F2 Labs - Indianapolis, IN
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
Intertek
ITC India
MiCOM Labs
Nemko
Orbis Compliance LLC
TÜV Rheinland of North America

EMC Testing

A2LA
Abstraction Engineering Inc
AHD
APREL Inc.
ART-MAN
Atlas Compliance & Engineering
Bharat Test House Group
Brighton EMC
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CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
CSA Group
CVG Strategy
D.L.S. - EMC

D.L.S. - Environmental
D.L.S. - Military/Avionics
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DNB Engineering, Inc.
E3 Compliance
Electronics Test Centre
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Element US Space and Defense
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
International Certification Services, Inc.
Intertek
ITC India
MiCOM Labs
Montrose Compliance Services, Inc.
National Institute for Aviation Research
Nemko
Parker Chomerics
QAI Laboratories
R&B Laboratory
Radiometrics Midwest Corporation
Retlif Testing Laboratories
Rogers Labs
SGS
Southwest Research Institute
Spes Development Co
Test Site Services Inc.
Timco Engineering, Inc.
TÜV Rheinland of North America
TÜV SÜD America Inc.
VPI Laboratories, Inc.
Washington Laboratories
WEMS Electronics
Yazaki Testing Laboratory

Energy Efficiency Testing

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Bureau Veritas Consumer Products Services Inc.
CSA Group
Nemko

Testing Laboratories

Environmental Simulation Testing

ALI Testing

Coilcraft Critical Products & Services

The Compliance Management Group

Core Compliance Testing Services

CVG Strategy

D.L.S. - Environmental

D.L.S. - Military/Avionics

DNB Engineering, Inc.

Energy Assurance LLC

FEMA Corporation

H.B. Compliance Solutions

Nemko

Quanta Laboratories

Retlif Testing Laboratories

RMV Technology Group LLC

Sanwood Environmental Chambers Co., Ltd

ESD Testing

Barth Electronics, Inc.

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Compliance Worldwide, Inc.

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DNB Engineering, Inc.

E3 Compliance

Electro-Tech Systems

Element Materials Technology - Brooklyn Park, MN

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Element Materials Technology - Washington, Columbia, Oakland Mills

EOS/ESD Association Services, LLC

ESDEMC Technology LLC

Estion Technologies GmbH

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F2 Labs - Middlefield, OH

H.B. Compliance Solutions

Nemko

RMV Technology Group LLC

Rogers Labs

VPI Laboratories, Inc.

GOST R Certification

G&M Compliance, Inc.

Nemko

Green Energy Compliance

Enviropass Expertise Inc.

GS Mark Certification

TÜV Rheinland of North America

Halogen Testing

Enviropass Expertise Inc.

Lithium-Ion Battery Testing

Bharat Test House Group

CSA Group

Element Materials Technology - Atlanta-Gainesville, GA

Element US Space and Defense

Energy Assurance LLC

F2 Labs - Indianapolis, IN

F2 Labs - Middlefield, OH

ITC India

Quanta Laboratories

Marine Electronics Testing

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D.L.S. - Military/Avionics

D.L.S. - Wireless

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F2 Labs - Indianapolis, IN

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D.L.S. - Military/Avionics

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E3 Compliance

Element Materials Technology - Atlanta-Gainesville, GA

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Washington, Columbia, Oakland Mills

Energy Assurance LLC

F2 Labs - Damascus, MD

F2 Labs - Indianapolis, IN

F2 Labs - Middlefield, OH

G&M Compliance, Inc.

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H.B. Compliance Solutions

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Bicerano & Associates Consulting

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc

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Compatible Electronics, Inc.

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D.L.S. - Product Safety

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F2 Labs - Middlefield, OH

G&M Compliance, Inc.

Global Testing Laboratories

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Product Safety Consulting

SGS

TÜV Rheinland of North America

TÜV SÜD America Inc.

Washington Laboratories

Radio Performance & Functionality Testing

American Certification Body

Applied Physical Electronics, L.C. (APELC)

Brighton EMC

CVG Strategy

D.L.S. - Wireless

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Element Materials Technology - Irvine, CA

Element Materials Technology - Washington, Columbia, Oakland Mills

EMC Bayswater Pty Ltd

Eurofins MET Labs

F2 Labs - Damascus, MD

H.B. Compliance Solutions

Nemko

Testing Laboratories

Radio Performance & Functionality Testing *continued*

Orbis Compliance LLC

Radiometrics Midwest Corporation

Test Site Services Inc.

Washington Laboratories

RoHS Directive Compliance

CertifiGroup Inc

D.L.S. - Product Safety

Enviropass Expertise Inc.

F2 Labs - Indianapolis, IN

F2 Labs - Middlefield, OH

ITC India

Nemko

TÜV Rheinland of North America

Shock & Vibration

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Clark Testing
Coilcraft Critical Products & Services
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Elite Electronic Engineering Inc.
Energy Assurance LLC
Eurofins MET Labs
FEMA Corporation
ITC India
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
WEMS Electronics

Standards Council of Canada Certification Body

CSA Group
F2 Labs - Damascus, MD

Telecommunications Testing

A2LA
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F2 Labs - Damascus, MD
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
Megger
Nemko
NetSPI
Orbis Compliance LLC
Retlif Testing Laboratories
Southwest Research Institute

Wireless

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MiCOM Labs
Nemko
Orbis Compliance LLC
Rogers Labs
Test Site Services Inc.
TÜV Rheinland of North America
TÜV SÜD America Inc.
VPI Laboratories, Inc.

Events

★ Visit In Compliance's booth at these events!

March 25-27
EMV 2025

March 30-April 4
EuCAP 2025 – The 19th European Conference on Antennas and Propagation

April 1-3
TCB Council Spring Workshop

April 6-8
EMCH2025 International Conference on Electromagnetic Compatibility

April 6-9
A2LA Annual Conference 2025

April 7-9
The Battery Show Middle East 2025

April 24
Cyber Security and The Cyber Resiliency Act

April 24-25
Principles of Electromagnetic Compatibility

April 28-May 2
EMA Expo

May 6
★ 2025 Chicago IEEE EMC Mini Symposium

May 8
★ Southeastern Michigan EMC Fest 2025

May 12-16
2025 International ESD Workshop (IEW-Europe)

May 13-15
★ 2025 IEEE International Symposium on Product Compliance Engineering (ISPCE)

May 18-21
2025 International Applied Computational Electromagnetics Society (ACES) Symposium

May 19-21
EMC & Compliance International Exhibition & Workshops

May 19-22
2025 IEEE International Instrumentation and Measurement Technology Conference

May 19-23
2025 Asia-Pacific International Symposium and Exhibition on Electromagnetic Compatibility (APEMC)

June 3-6
WPTCE 2025IEEE Wireless Power Technology Conference and Expo

June 15-20
★ IMS 2025 – IEEE International Microwave Symposium

June 26
Cybersecurity Maturity Model Certification for Federal Government Procurements

July 13-18
2025 IEEE International Symposium on Antennas and Propagation & ITNC-USNC-URSI Radio Science Meeting

July 31
Internet of Things: Testing and Protections for Devices and Systems

August 18-22
★ 2025 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC + SIPI)

August 28
Radio Regulations for Module Integrators

September 1-5
EMC Europe

September 13-18
★ 47th Annual Electrical Overstress/ Electrostatic Discharge Symposium

September 21-26
European Microwave Week 2025

September 25
★ 2025 Minnesota EMC Event

October 2-3
Principles of Electromagnetic Compatibility

October 6-9
★ The Battery Show 2025

October 20-23
TCB Council Fall Workshop

October 30
Meeting MIL-STD 461 and MIL-STD 810 Test Requirements

November 2-7
★ 47th Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA)

November 20
Year 2026 Regulatory Regulations Outlook: FCC TCBC Training

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https://incompliancemag.com/events

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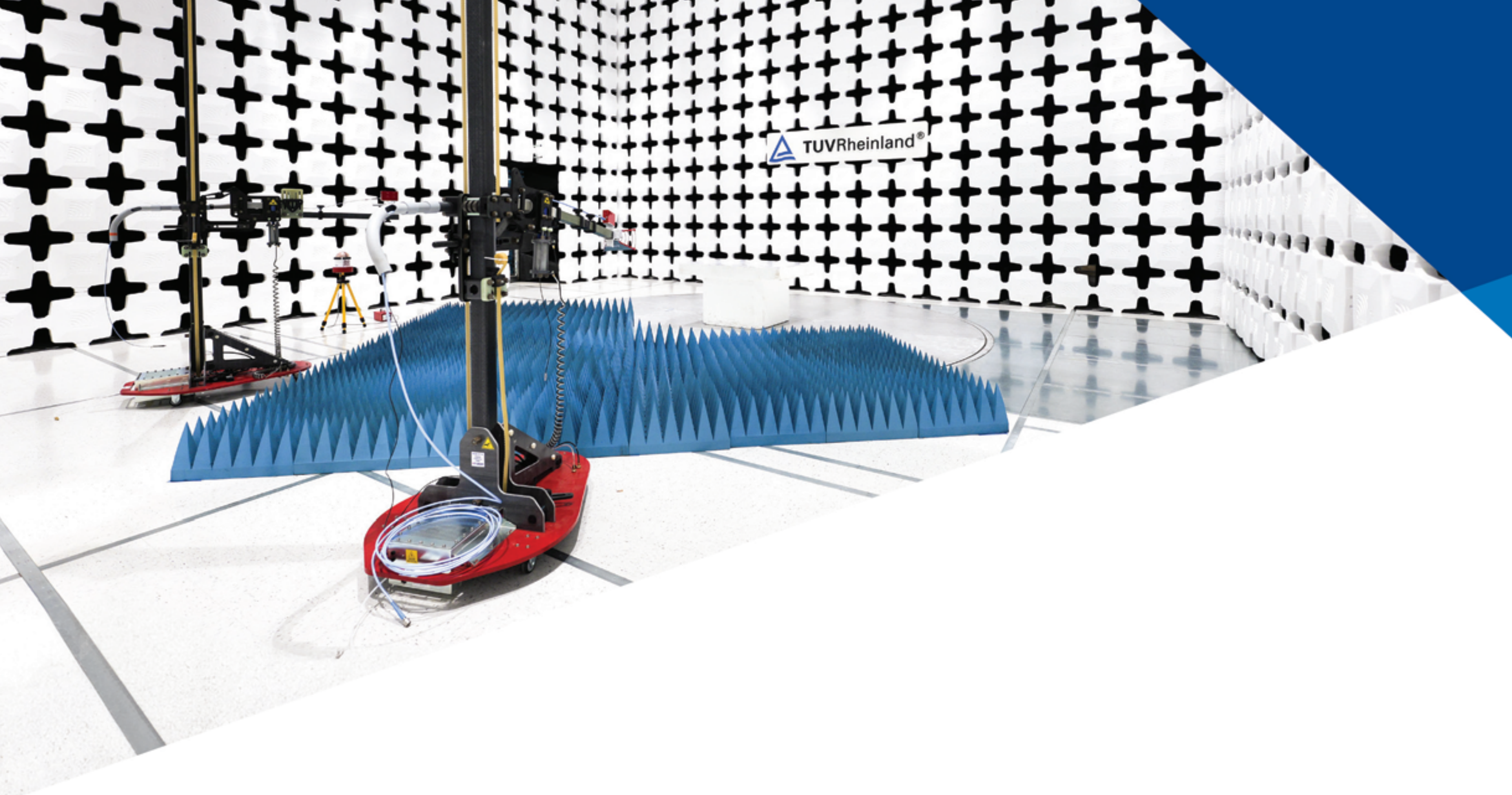
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