It’s Not Bragging When...

Lots of suppliers claim to have “The Best Products”, but do they have AR? AR has been proving it for over 43 years. We’ve built a reputation for products that are more powerful, faster, smaller, and more efficient. And if that wasn’t enough, every one of our products is backed by our commitment to results. AR has the best products, a

Radiant Arrow® Best Element Antenna
We bent the rules and advanced the science of log periodic antennas. Up to 75% smaller, lighter, and more compact to fit in smaller chambers.

Next Hybrid Power Modules
We’ve complemented our previous line of 4-18 GHz HPM’s to cover the entire 1-6 GHz frequency range in one amplifier module. High gain 50 ohm modules provide 15 watts of Class A or 25 watts of Class AB output power in a convenient, small connectorized housing.

Dual Band Amplifiers
For the first time you can go from 0.7 to 18 GHz with the reliability of solid state in a single housing. Numerous models with various output powers help you reduce the footprint and cost of separate instruments.

1.0 to 2.5 GHz Solid State Amplifiers
The solid state alternative to TWTA’s. Improved harmonics, lower noise, superior linearity and now featuring 1,000 watts CW.

RF Conducted Immunity Test Systems
These self contained systems driven by our proprietary software, simplify calibration, testing, troubleshooting and reporting. They allow accurate, sensitive and repeatable measurement in one unit. And did we mention incredible speed with outputs up to 150 watts and 400 MHz.

A Special Family of Antennas for High Intensity Radiated Field (HIRF) Testing
High-gain, high-power microwave horn antennas. Typically 20 dBi over isotropic. Suitable for DO 160 HIRF testing.

16,000 Watts of Pure Power
The new 16000A225 amp. It covers 10 kHz to 225 MHz and delivers 16,000 watts of power and we’re not stopping there.
WHO SAYS YOU CAN'T HAVE IT ALL?
and with next-day, on-time delivery

You Can Have It All when it comes to EMC/EMI testing. A.H. Systems is proud to bring you exciting new products, and many reliable favorites for your evaluation and compliance applications. Our antennas are unique and distinctive with broadband frequency ranges between 20 Hz up to 40 GHz. This enables us to specialize in various sales, rentals and re-calibrations of test Antennas throughout the world. To view our products and get quick answers to your questions, access our comprehensive online catalog. Search for various information about product descriptions, typical AF plots, VSWR, power handling capabilities and links to product data sheets. Or simply request a catalog be sent to you. Not only have we been developing EMI Antennas for over 30 years, we also have organized worldwide sales representation. You can find your local knowledgeable representative in over 27 countries via our website. For quality products, excellent service and support with next-day, on-time delivery.

Antennas...

And Kits too.

A.H. Systems
IMU 3000
MODULAR ARCHITECTURE
EFT UP TO 6kV
SURGE, RINGWAVE & 10/700μs UP TO 8kV
SIMPLE TOUCHPANEL NAVIGATION
LINK TESTS INTO A SEQUENCE
LARGE RANGE OF ACCESSORIES

Electro Static Discharge (ESD)
IEC 61000-4-2 / ANSI C62.41

Common Mode (CM)
IEC 61000-4-16

10/700μs Telecom Impulse
IEC61000-4-5 + ITU K.20/21/44

DC DIPS
IEC 61000-4-29

Differential Mode
IEC 61000-4-19

Magnetic Field AC
IEC61000-4-8

Magnetic Field Impulse
IEC61000-4-9

Combination Wave (CWG)
IEC 61000-4-5 / ANSI C62.41

AC DIPS / Interrupt
IEC 61000-4-11

EFT/Burst
IEC 61000-4-4
ANSI C62.41

Ringwave
IEC 61000-4-12 / ANSI C62.41

WWW.IMU3000.COM
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Rely on the market leader
We have what you need.

Rohde & Schwarz provides EMC customers with state-of-the-art test solutions for all requirements:

- Widest range of test receivers and analyzers for EMI measurements
- Turnkey EMC test systems
- Most advanced and flexible broadband amplifier system
- Software tools for computer-controlled EMC measurements
- Radiated spurious emissions and over-the-air performance tests of wireless communication devices

Want to learn more?
http://www.rohde-schwarz.com/ad/emc
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Quick, easy, permanent retrofit with EESeal® FilterSeals

Installs in seconds, no soldering, just push in

Durable, conformal elastomeric body

Meets wide barrage of mil-standard tests

Pin-to-pin & pin-to-shell capacitors, MOVs, resistors, shorts, etc.

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Get more information and register for this course at www.hottconsultants.com

EMC Exhibits and reception - Wednesday, April 10, 2013
Exhibitors: for information contact Sharon Smith at sharon.smith@incompliancemag.com or (978) 873-7722

EMC Exhibits and reception - Wednesday, April 10, 2013
Exhibitors: for information contact Sharon Smith at sharon.smith@incompliancemag.com or (978) 873-7722

Presented by Henry Ott Consultants in partnership with INCOMPLIANCE Magazine www.incompliancemag.com

In this three-day intensive course we cover practical aspects of noise and interference control in electronic systems and we provide a working knowledge of EMC principles.

Ideas are illustrated with examples of actual case histories and mathematic complexity is kept to a minimum.

Participants will gain knowledge needed to design electronic equipment that is compatible with the electromagnetic environment and in compliance with national and international EMC regulations.

Who Should Attend
This course is directed toward electrical engineers. However, mechanical engineers, reliability and standards engineers, technical managers, systems engineers, regulatory compliance engineers, technicians and others who need a working knowledge of electromagnetic compatibility engineering principles will also benefit from the course.

HENRY OTT
Henry W. Ott is President and Principal Consultant of Henry Ott Consultants (www.hottconsultants.com), an EMC training and consulting organization. He has literally “written the book” on the subject of EMC and is considered by many to be the nation’s leading EMC educator. He is the author of the popular EMC book Noise Reduction Techniques in Electronic Systems (1976, 1988). The book has sold over 65,000 copies and has been translated into six other languages. In addition to knowing his subject, Mr. Ott has the rare ability to communicate that knowledge to others.

Mr. Ott’s newly published (Aug. 2009) 872-page book, Electromagnetic Compatibility Engineering, is the most comprehensive book available on EMC. While still retaining the core information that made Noise Reduction Techniques an international success, this new book contains over 600 pages of new and revised material.

Mr. Ott is a Life Fellow of the IEEE and has served the EMC Society in various capacities including: membership on the Board of Directors, Education Committee Chairman, Symposium Committee Chairman and Vice President of Conferences. He is also a member of the ESD Association and an iNARTE certified ESD engineer. He is a past Distinguished Lecturer of the EMC Society, and lectures extensively on the subject of EMC.
Welcome to the 2013 Annual Reference Guide

Dear Readers,

In your hands, you hold In Compliance Magazine’s 2013 Annual Reference Guide. We welcome you to our fourth edition of this annual compliance engineering handbook. With each passing issue, In Compliance continues to reinforce our commitment to this community of compliance engineering professionals we are pleased to call our readers.

The 2013 Annual Reference Guide presents a collection of articles which have been selected to provide new (and not-so-new) engineers with current reference materials to navigate challenges you encounter in your daily work. These articles span multiple subject areas: EMC, Product Safety, ESD, Telecom and Wireless and focus on standards, design and emerging technology.

For easy navigation of the 2013 Annual Reference Guide, here’s a quick run-down of what you’ll find inside. Beginning on page 12, our Compliance Solutions section highlights 10 companies who present in-depth profiles highlighting their areas of expertise. Technical articles span by subject area from page 32 to page 194. Note the black subject tabs located on the side of the book for quick access to your favorite subject. As you near the back of the book beginning on page 195, don’t miss the Product Showcases, Consultants Directory and Product Spotlights. Beginning on page 204 you’ll find an extensive Buyer’s Guide of industry suppliers. These resources are presented in print to assist you in locating service and product suppliers in an easy-to-use (alphabetical) and easy-to-access medium.

We understand that today’s engineer needs to be able to access information at the fingertips, be it in print or online. You will find the full content of this print edition on our website at www.incompliancemag.com where you can also sign-up to receive our e-newsletters, read the latest industry news, participate in reader surveys and contests, and renew your subscription.

As always, we welcome commentary on the contents of In Compliance. Send your feedback to editor@incompliancemag.com.

We hope you enjoy this year’s Guide!

Until next time,

Lorie Nichols, Editor
editor@incompliancemag.com
When you find a device out of EMI compliance, now you can also understand why. Because the new Agilent receiver is also an X-Series signal analyzer, loaded with diagnostics to show what’s happening.

That’s thinking ahead. That’s Agilent.

Agilent N9038A MXE EMI Receiver
CISPR 16-1-1 2010 compliant
Built-in X-Series analyzer runs applications
Intuitive interface and graphical displays
Upgradable for long-term flexibility

Download Competitive Comparison and App Note:
Reduce Verification Time with Fast Scanning.
www.agilent.com/find/AgilentEMIreceiver
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.

With the economy in a downward spiral, 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.
All you need in one small package

Antennas | Probes | Accessories | Preamplifiers | Low-Loss Cables | Recalibration Services

Travel Made Easy
with Next-Day,
On-Time
Delivery

Don’t Leave home without it. A.H. Systems provides many models of Portable Antenna Kits, each containing all the necessary Antennas, Probes, and Cables to satisfy numerous customer requirements. Excellent performance, portability (compact size and lightweight), along with ease of setup make all of the Antenna Kits your choice for indoor or field testing. Loss and breakage are virtually eliminated as each component has a specific storage compartment within the case. All Antenna Kits are accompanied with a Tripod and Azimuth & Elevation Head, both contained in a Tripod Carrying Case... and don’t forget your keys!

ANTENNAS... and KITS TOO...

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http://www.AHSSystems.com

A.H. Systems
Compliance Worldwide is an independent regulatory compliance testing laboratory founded in 1996. We provide testing and certification services for domestic and international markets. We are A2LA Accredited under ISO Guide 17025-2005 and provide EMC, EMI/RFI, CE Marking, Product Safety, Wireless and Wireline Telecommunications Testing and FCC/Industry Canada approval Liaison Services for manufacturers of Electronic Equipment.

Our testing expertise and core technologies we serve include ITE, Audio/Video, Consumer, Telecommunications, Laboratory, Medical, Security and Wireless products. We work with organizations around the world and also cater to very specific product categories, such as, Automotive Radar, Ground Penetrating Radar, Ultra Wideband (UWB), DECT (UPCS - Un-licensed PCS), Cellular / PCS / LTE (AWS) 4G Amplifiers, 802.11 b/g/a/n Access Points and Client Devices, 802.15.4 Zigbee, 802.15 Bluetooth, and VoIP.

We continue to grow and expand, with the completed upgrade to our anechoic chamber we can measure 9 kHz to 40 GHz in an ambient and reflection free environment. The addition of a second OATS site with scheduled completion by the end of 2012 will double our daily capacity for wireless/emissions testing. We also added a 3 Meter ground penetrating radar (GPR) Test Site to the rear of our enclosed 10 Meter site. Our continued success over the last 16 years can also be measured by our innovation to better serve our clients. Over the last decade we have developed one of the fastest radiated emission pre-scanning capabilities in the country, providing excellent correlation to final measurements made on our 10 Meter OATS. We offer reliable and repeatable data, meaning you can debug your product quickly, saving time and money for your company. Today, customers want maximum flexibility and seamless solutions. Whether you are a start-up or Fortune 500 company, now more than ever, demand for quicker time-to-market continues to grow. We offer a timely lab schedule with options the same day the inquiry is made, and our veteran engineers work closely with you throughout the entire testing process and are always available for consultation.

At Compliance Worldwide, our success is driven by our people and their commitment to excellence. We fully understand our customer’s challenges with global compliance. We think from the client’s perspective and work as a team to ensure total customer satisfaction and support. This has always been our driving force and will continue to set us apart from our competitors.

Compliance Worldwide, Inc.
357 Main Street
Sandown, NH 03873
Tel: (603) 887-3903
Fax: (603) 887-6445
sales@ComplianceWorldwide.com
www.ComplianceWorldwide.com

Year company was founded: 1996
Number of employees: 10
Number of facilities: 1 - 5000 square feet, includes two open area test sites, 3 meter compact semi anechoic chamber and two ground-planes.
Compliance Worldwide, Inc. continues to expand its emissions and wireless capability with the purchase of the NEW Rohde & Schwarz ESR7 EMI Receiver and FSV40 Spectrum Analyzer with K54 EMI Measurement Application. We have the fastest, most accurate and fully compliant CISPR 16-1-1 measurement capability available, providing the lowest measurement uncertainty.

Our continuing investment into low noise preamplifiers, low loss cables and EMC antennas allow us to test at the recommended distances typically 10 or 3 meters for a given standard, providing you with the best possible results. Our Rohde & Schwarz SMB 100A 40 GHz signal generator allows us to quickly verify operation of high frequency cables and special purpose notch filters for testing wireless devices.

The upgrade to our 3 meter semi anechoic chamber with Panashield HYB-NF Hybrid Absorber, allows us to measure from 9 kHz to 40 GHz in an ambient free environment with minimal reflections, and our state of the art, impressive weather enclosed 10 Meter Open Area Test Site (OATS) ensures you receive the most accurate numbers available. Of course if you need to go higher, we have all the necessary mixers and horns to get you to 110 GHz and in the future 200 GHz.

Our veteran team of RF engineers and experienced technicians provide complete customer service before, during and after your testing is completed. We stay up to date with the new editions of the standards, upgrading our facility as the ever changing requirements occur. Over the last decade we have developed one of the fastest radiated emission pre-scanning capabilities in the country, providing excellent correlation to final measurements made on our 10 Meter OATS, meaning you can debug your product quickly saving time and money for your company.

An additional purchase of the Rohde & Schwarz SMBV100A Vector signal generator allows us to simulate the latest technologies such as 802.11n, WiMax, LTE and other complex modulations to 6 GHz and generate Dynamic Frequency Selection (DFS) Radar pulses for the US (FCC), Canada (IC), Europe (ETSI), Australia / New Zealand (AS/NZS), Japan (TELEC) and South Korea (KCC). The flexibility and support from R&S to create new waveforms and future technology requirements, allows us to always be up to date with the latest standards and current wireless technology.

Photographs Reproduced with Permission, Courtesy of Rohde & Schwarz, Inc.
ETS-Lindgren is one of the world’s largest vertically integrated manufacturers of EMC systems and components. We are engaged in every aspect of the EMC industry; engineering, manufacturing, sales and support, calibration and repair. We are also committed to wireless, microwave, acoustic and medical technologies.

Company Roots
We trace our earliest roots to the 1930’s when the Ray Proof Company began producing x-ray shielding for the medical market. In 1995, EMCO, Rantec and Ray Proof joined together to form EMC Test Systems, known then as ETS. Later, other companies were acquired; Euroshield Oy, Lindgren RF Enclosures, Holaday Industries, and Acoustic Systems. Today our company is known as ETS-Lindgren.

Global Scope
Headquartered in Cedar Park, Texas, ETS-Lindgren conducts business around the globe.

Our diverse and highly skilled global workforce consists of approximately 750 employees in North America, South America, Europe, and Asia. We have four manufacturing facilities in the US, and one each in Great Britain, Finland, and China.

Our sales network of more than 60 independent representative and distributor organizations provides knowledgeable sales, service and support around the world.

Commitment, Growth and Investment
ETS-Lindgren is committed to our industry and encourages our employees to participate in standards committees, as speakers and session chairs at symposiums, and as authors and lecturers. It would be difficult to attend a symposium and not see an ETS-Lindgren team member in front of a podium, or read a journal or trade magazine without reading something authored by one of our engineers.

Our growth is propelled by meeting our customer’s need for systems and components that provide reliable service, repeatable results, and value at a fair price. Our history of success and proven track record virtually eliminates risky outcomes for our customers.

ETS-Lindgren believes in making investments that enable us to serve our customers better. Our manufacturing facilities use efficient, cost reducing systems. Our engineers work with modern equipment. We continue to expand our locations to better service our customers, such as our newest office in Bengaluru, India.

Environment and Safety
As a company and as individuals, ETS-Lindgren take great pride in contributing to the communities where we live and work. Our efforts include the support of local charities, one of which benefits children with hearing disabilities. We also care about the environment and are proud of the many ways in which our employees work to safeguard it.

Our persistent efforts to improve on our safe work environment continue to pay off. We provide ongoing safety training and awareness, and a safe place to work.

Our Work Ethic
ETS-Lindgren recognizes the importance EMC has in a world increasingly dependent on electronic devices operating safely and compliance with regulatory standards. That’s why our employees work daily to design, manufacture and support the systems and components our customers can depend on.
There’s a Reason Why Engineers Choose ETS-Lindgren:

More Experts, Experience and Expertise than anyone else!

ETS-Lindgren has a long history of providing EMC engineers with the tools they need to make accurate, repeatable measurements. Little wonder we are now the largest integrated manufacturer of EMC test equipment in the world; we serve our customers with engineering, manufacturing and support facilities in North America, South America, Europe and Asia. Visit our website at www.ets-lindgren.com or call us to see how our experts can help you.
The staff of HV TECHNOLOGIES, Inc. (HVT), in partnership with EMC Partner AG, Montena Technology, Prana, and TESEO, is focused on providing our clients with top quality, full compliance transient test instruments at the most competitive prices. Our staff has been supporting the EMC testing community by designing, producing, and distributing the best EMC test instruments for over two decades. When using our products, customers experience the most reliable test instruments with the cleanest waveforms, most accurate phase angle synchronization, and repeatable wave shapes available. This has been possible through innovative product design and the deployment of unique leading-edge technologies.

We have the products, delivery, and support you expect today and for years to come.

EMC/EMI transient test and measurement equipment
Our associate, EMC Partner AG was founded by well-known EMC experts and complement our group with the most extensive lines of transient equipment available.
ESD, EFT/Burst, Surge up to 48kV!, Ring Wave, Oscillatory Wave, ANSI, IEC, IEEE, Harmonics/Flicker, Telecom, ITU, MIL-STD, DO160 (Sec 17, 19, 22), Component (relay, surge protection, capacitors)

High Power Class A solid-state amplifiers with absolute mismatch protection
This partnership brings both HV TECHNOLOGIES and Prana together for customer focus: customer service, sales and support. Prana was founded in 1975 and is a very highly respected manufacturer from Europe who has been meeting the needs for RF test equipment for many applications including EMC testing. Offering a 3 year warranty on all products is just the beginning and we will be happy to prove to you why our products and systems will not only meet your needs but exceed them.
10 kHz up to 6 GHz with powers up to 12,000 Watts

EMP, HEMP, 300kV ESD
Our partner Montena has its competencies in the high voltage and high frequencies area and can offer a large set of EMC products and solutions such as pulsed or CW high voltage generators, antennas and field sensors, pulsed systems for decontamination of food and their packaging.
Products meeting many MIL-STD requirements

Fiber Optic Links for use in extreme EMI environments
HV TECHNOLOGIES and TESEO offer the most extensive line of fiber optic extenders on the market. Primarily for use during EMC testing for both Immunity and Emissions, but other applications include use in large buildings and on ships where wireless is not possible.
Camera systems, Intercom/sound systems, BUS extenders, voltage, power, frequency, current
...and Expert Service, too!

Having the best EMC equipment in North America is just not enough. Having the knowledge and service behind the products is what gives us real value.

**Equipment Knowledge**

- Experienced engineers available with actual test experience
- Presence on international EMC and lightning committees: IEC, DO160, and SAE
- Decades of experience

**Testing Knowledge**

- Factory trained and experienced
- On-site service, equipment commissioning, and training

**Standards Knowledge**

HVT, Your Partner for EMC Solutions

Exclusive North American Partners:

EMC - PARTNER

PRÂNA

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TESEO

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NTS PROVIDES SECURITY TO YOUR BRAND’S INTEGRITY, QUALITY, AND LONG-TERM REPUTATION

NTS is your product’s comprehensive lifecycle solution.

With the largest commercial network of product testing laboratories and engineering service centers in North America - NTS has evolved over the past 50 years to meet the ever-changing needs of our highly diverse client base.

Our experience includes everything from participation in some of the largest Aerospace and Defense industry programs of the last half century, to the testing and certification of thousands of consumer and industrial products.

NTS is well known as a highly reputable company in the Telecom industry providing hardware testing and approvals services and our reputation extends further out to other markets including consumer electronics, transportation, medical devices and more.

INTEGRATED ENGINEERING SERVICES
• Ensures product performance, durability, interoperability and more.

TESTING AND CERTIFICATION SERVICES
• Ensures that products are ready for market.

SUPPLY CHAIN MANAGEMENT SOLUTIONS
• Tailored specifically to fit our clients’ needs - helping to bring their products to market both quickly and efficiently.

“NTS’s unique portfolio of services provides a complete end-to-end solution to support our clients through every major phase of their product management lifecycle.”

– Dwight Moore, Chief Marketing and Sales Officer

Contact NTS and put us to the test today and find out how we can help you!

800.270.2516 | sales@nts.com | www.nts.com
Engineering the most comprehensive network of commercial test laboratories in North America.

That’s just one way that NTS works for your success.

At NTS, our heritage lies in the testing and certifications business. Over the last 50 years, through a combination of acquisitions, innovations and organic growth we have become the largest commercial test laboratory network in North America. Our testing capabilities span a very wide spectrum, covering Environmental, Dynamics, EMC, Wireless, Product Safety, Reliability, Quality Assurance, Ballistics and more. Our nationwide network of test laboratories is tied together through our LabInsight customer portal, which enables real-time witnessing and participation in testing programs taking place simultaneously at multiple NTS locations. Simply put, no other commercial test lab in North America can match our capacity and capabilities, which means we get you from test lab to market in the shortest possible time and with the least amount of effort, because helping you achieve your goals is how we achieve ours.
EMC engineers have a daunting task to stay knowledgeable of current international EMC testing standards in order to get their company’s products globally compliant and ready for market in record time. In addition to being knowledgeable, the engineer’s most essential asset to meet this task is an EMC facility designed to meet the needs of global compliance testing standards, with capability for upgrading various key components as the standards change. Whether the engineer’s product is hard-wired or wireless, commercial, military, aerospace, medical or security, products can be designed for differing market applications, and may need to be tested for compliance over a wide range of standards. The EMC facility design should be current to meet the latest requirements, and also allow for upgrades in size, absorber treatment, and cross-market test usage. Another important part of the design should be the ability for relocation when corporate real estate demands change. Contact the designers at Panashield to guarantee the continued success of the most essential asset – the EMC test facility.

To interact with this facility design, visit www.panashield.com
Facility Solutions
For Global EMC

Let Panashield help you with your EMC facility project.
Our experienced personnel will provide technical support to guide you through design, supply and certification.

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RF Shielded Enclosures
Military Test Chambers
Avionics Test Chambers
Free Space Chambers

Reverberation Chambers
P3 RF Sliding Doors
Turnkey Services
Facility
Relocations/Upgrades

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TÜV SÜD’s Medical services division is the leading Notified Body for a number of EU Directives including Medical Devices Directive, Active Implantable Medical Devices Directive and the In Vitro Diagnostic Directive. In addition, TÜV SÜD provides FDA 510(k) reviews and third-party inspections, EMC testing services (60601-1 3rd edition), NRTL services, Japanese approvals, and is an SCC-accredited ISO 13485 Registrar for the Canadian Medical Devices Regulations.

We also provide a number of EM (Electromagnetic Compatibility) and IEC testing services in the military and Aerospace/Defense fields. Services include Wireless testing, testing to MIL-STD-461, RTCA/DO-160, EUROCAE/ED-14, Def-Stan 59-41, Multiple-Burst and Multiple-Stroke Lightning, and HIRF testing up to 9500 Volts/meter.

Our environmental testing services include dynamics (vibration & shock), acoustic, climatic and fluid dynamics testing from our accredited labs, simulating the most hostile environments.

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TÜV SÜD America provides a variety of global conformity assessment services for industrial markets, which include consulting, third-party inspection, material testing, inspection & certification, design reviews, pressure equipment testing services, type approvals and Notified Body services for pressure equipment manufacturers and materials producers seeking to export product to the European Community.

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Contact us today. It all adds up. Discover how our EMC services can create a test plan to keep your international product rollouts on schedule and under budget.
Today’s electrical and electronic devices are subject to mandatory EMC requirements throughout the world. Many devices operate at high frequencies and are very small. They are placed in nonconductive plastic cases providing no shielding. Essentially, all these devices cannot meet these mandatory requirements or they may cause interference to other devices or receive interference causing susceptibility problems without a proper program of EMI control. This program consists of identifying the “suspect” components and circuits that may cause or be susceptible to EMI. This is completed early on in the program to allow for an efficient design in keeping the cost of dealing with EMI as low as possible. A complete EMC program consists of proper filtering, grounding and shielding. This article will discuss the latter, but the other factors cannot and will not be ignored or given insufficient priority.

The article will look into what EMI is and how to design to control it using shielding in conjunction with proper design. Various shielding materials and their uses will be discussed.

WHAT IS EMI?

EMI (Electromagnetic Interference) is a process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths, or both. In electronic components, devices and systems, EMI can adversely affect their performance. The goal of all electronic designers is to achieve EMC (Electromagnetic Compatibility) in their designs. Not only to assure proper operation, but to meet the various mandatory EMC requirements imposed by legislation around the world.

EMI can simply be a nuisance such as static on a radio, or it can manifest itself as dangerous problems such as interference with aircraft control systems, automotive safety systems, or medical devices.

Remember, it is always more efficient and less expensive to deal with EMI at its source. The farther away you get from the source or the farther down the design chain you are, the more difficult and expensive it is to mitigate the problems.

THE PROBLEMS

The trend in today’s electronic devices is faster, smaller, and digital rather than analog. Most equipment of today contains digital circuits. Today’s digital designer must create a circuit board that has the lowest possible EMI, combined with the highest possible operating and processing speeds; generally keeping it as small as possible. Design of the printed circuit board (PCB) is the most critical EMC influencing factor for any system, since virtually all active devices are located on the board. It is the changing current (accelerating electron movement) produced by the active devices that result in EMI.

The faster the digital speed, the greater the required circuit bandwidth, and the more difficult it is to control both radiated emissions and susceptibility. In this regard, it is useful to first consider the relationship between operating frequencies and radiated emissions. The fundamental frequency for...
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each active device and its associated circuitry must be considered. But the harmonics of these devices can be 10 to 100 times greater in frequency than their fundamentals. The odd harmonics, 3, 5, 7, 9, etc. times the fundamental, are especially troublesome. As a result, increases in EMI with the evolution from analog to high speed digital circuits have been dramatic. RF energy levels at the higher frequency harmonics of analog devices are negligible. The harmonics of an ideal Gaussian wave shape, albeit more a mathematical concept than a practical reality, fall off very quickly at the higher frequencies.

A cosine-squared wave shape, approximately equivalent to that produced by a linear power supply or other analog continuous wave (CW) source having some harmonic distortion, exhibits high frequency harmonic amplitude falloff of 60 dB per decade of frequency. Moving from analog circuits to low speed digital circuits has no significant effect at the fundamentals level, but RF amplitudes increase at the higher harmonic frequencies because falloff occurs at 40 dB per decade rather than 60 dB. In moving from low speed to high speed digital operation, high frequency radio frequency (RF) levels increase even more as harmonics fall off at just 20 dB rather than 40 dB per decade. Given today’s extremely fast rise times, one can see that the high frequency harmonics are much greater than in the past.

**SOME SIMPLIFIED MATH**

Radiation emitted by electronic devices results from both differential and common mode currents. In semiconductor devices, differential mode currents flowing synchronously through both signal and power distribution loops produce time variant electromagnetic fields which may be propagated along a conducting medium or by radiation through space. On simple one- or two-layer PCBs, loops are formed by the digital signals being transferred from one device to another that return by means of the power distribution traces. Loops are also created by PCB traces that supply power to these devices. Common mode radiation results from voltage drops in the system that create common mode potential with respect to ground. In addition, parasitic capacitive coupling, a hard-to-control phenomenon that occurs between all conductive materials, makes external cables act like antennas.

The radiated EMI levels created by the active circuit loops on the board are proportional to the square of the highest created frequencies. These frequencies are determined by the data pulse rise time, and contain significant RF energy at typically 10 to 15 times the operating speed. The rise time also determines the circuit bandwidth. For small circuits whose dimensions are less than the dimensions at resonance, the plane wave emission levels generated by these loops may be calculated by the following equation:

\[ E = \frac{1.3 \times A \times I \times F^2}{D \times S} \]

Where:
- \( E \) = microvolts/meter
- \( A \) = radiating loop area in \( \text{cm}^2 \)
- \( I \) = current in amps
- \( F \) = frequency in MHz
- \( D \) = measurement distance in meters
- \( S \) = shielding effectiveness ratio

Radiated susceptibility, on the other hand, increases linearly with the offending frequency. For small circuits whose dimensions are less than the dimensions at resonance, the maximum voltage induced into the circuit by a narrowband incident plane wave within its passband is given by:

\[ V_i = \frac{2 \pi s A B}{\lambda S} \]

Where:
- \( V_i \) = volts induced into the loop
- \( s \) = field strength of incident wave in V/m
A = circuit capture area in square meters
B_{pb} = passband bandwidth response
\lambda = wavelength in meters of incident wave
S = shielding effectiveness ratio

Outside of the circuit passband, narrowband signal effects will be determined by the circuit attenuation response. Broadband signal effects will be determined by both the attenuation response and the circuit bandwidth. Of course, circuit attenuation can be increased with the installation of shielding.

By examining the two formulae, we can draw some conclusions. For emissions, the field strength is controlled by the specification that must be met or by the highest allowable emissions for the environment in which the device must operate. The distance is set either by the specification, such as three meters for the FCC part 15 requirements, or by the distance from the source to the receptor of the radiated energy. Generally, these factors are beyond the control of the device designer. Of course, 1.3 is a constant and cannot be changed. We now come to factors that the designer can control. We see that frequency is squared; therefore, emissions increase exponentially as frequency increases. This explains why high frequency devices and circuits are the most troublesome. Emissions also increase linearly with current. Therefore, one must place high frequency and high current circuits at the top of the EMI suspect list. However, emissions also increase with loop area. By far, large uncontrolled and even unknown loop areas have proven to be the biggest reason for emission failures.

We see that the designer must control the loop area once the frequency and current have been established. Especially for high frequency and high current circuits, the loop area must be kept to a minimum. This must be done at the beginning of the design. It is far too difficult and expensive to do this once the PCBs are designed, and even manufactured.

Once the frequency, current, and loop area have been set, and the circuit does not meet its emissions requirements, we now see that there is only one factor left in the equation that can bring the circuit into compliance: shielding!

For susceptibility, we see that the same good design practices as for emissions apply. In this case, the voltage induced into the circuit is a function of field strength which is controlled either by the specification or the circuit’s environment. The bandpass bandwidth response is controlled by the choice of...
components and other circuit design components such as the choice of the active components, and inactive components such as ferrite chip beads or filters. Again, we see that loop area is a factor. The larger the loop area, the more efficient the pickup of the circuit and generally, the more susceptible it will be. Finally, we see again that once the circuit design is finalized, if it is still susceptible, the only factor left in the formula is shielding!

**SHIELDING**

Shielding is a conductive barrier enveloping an electrical circuit to provide isolation. The “ideal” shield would be a continuous conductive box of sufficient thickness, with no openings. Shielding deals almost exclusively with radiated energies. Shielding Effectiveness (SE) is the ratio of the RF energy on one side of the shield to the RF energy on the other side of the shield expressed in decibels (dB).

For sources outside of the shield, the absorption and reflection of the shielding material, in dB, are added to obtain the overall SE of the shield. For sources within the shield, roughly only the absorption of the shield can be considered.

The absorption of the shielding material at frequencies of concern is controlled by:

- Conductivity
- Permeability
- Thickness

The reflectivity of the material at the frequencies of concern is controlled by:

- Conductivity
- Permeability

However, this is only true for our “ideal” shield. Two other major factors are:

- “Apertures” - holes or slots in the enclosure.

- The mechanical characteristics and effectiveness of the gaskets used on the enclosure.

“Mechanical characters” is pointed out because the biggest reason that RF gaskets do not perform as specified is because of improper installation, such as “putting a gasket where a gasket was never meant to go.” This is because many times, an RF gasket is used as a “fix” after the design has been set. As we saw in the formulas, shielding is necessary after all other factors in the circuit have been established. Sadly, it is also viewed that way. Rather than design in shielding and gasketing, it is used as a last desperate effort to get the device into compliance; adding the reason for so many failures in shielding and gasketing efforts.

Shielding, which is noninvasive and does not affect high-speed operation, works for both emissions and susceptibility. It can be a stand-alone solution, but is more cost-effective when combined with other suppression techniques such as filtering, grounding, and proper design to minimize the loop area. It is also important to note that shielding usually can be installed after the design is complete. However, it is much more cost-effective and generally more efficient to design shielding into the device from the beginning as part of the design process. It is important to keep in mind that the other suppression techniques generally cannot be added easily once the device has gone beyond the prototype stage.

The use of shielding can take many forms ranging from RF gaskets to board-level shields (BLS). An RF gasket provides a good EMI/EMP seal across the gasket-flange interface. The ideal gasketing surface is conductive, rigid, galvanically-compatible and recessed to completely house the gasket.

A device housed in a metal case is generally a good candidate for RF gasketing materials. When electrical and electronic circuits are in nonconductive enclosures, or when it is difficult or impossible to use RF gasketing, BLS provides the best option for EMI suppression. A properly designed and installed BLS can actually eliminate the entire loop area because the offending or affected circuit will be contained within the shield.

**APERTURES**

Apertures, or holes, have SE. The SE of an aperture and ultimately the entire electronic enclosure is determined by the size, shape and number of the apertures. The formula is:

$$SE_{ap} = k \log\left(\frac{\lambda}{2L}\right)$$

Where:

- $\lambda$ = Wavelength
- $k$ = 20 for a slit or 40 for a round hole
- $L$ = Longest dimension of the aperture

---

Figure 3: Graphical representation of shielding
If there is more than one hole, we subtract from the original formula: the total number of holes within half a wavelength.

Apertures are placed in electronic enclosures for many reasons. Apertures are required for viewing, controls, meters, wire entry, etc. One reason is simply the seam around the perimeter of the cover(s). To maintain the conductivity across the seam, we generally need to use RF gasketing. RF gasketing is also used around display panels, shielded connectors, and other apertures in the enclosure.

**RF GASKETS**

Although there are hundreds of gasket varieties based upon geometry and materials, there are four principle categories of shielding gaskets: beryllium copper and other metal spring fingers, knitted wire mesh, conductive particle filled elastomers and conductive fabric-over-foam. Each of these materials has distinct advantages and disadvantages, depending upon the application. Regardless of the gasket type, the important factors to be considered when choosing a gasket are RF impedance ($R + jX$, where $R =$ resistance, $jX =$ inductive reactance), shielding effectiveness, material compatibility corrosion control, compression forces, compressibility, compression range, compression set, and environmental sealing. However, many other factors may come into the selection decision.

Below is a comprehensive list of selection factors.

- Operating frequency
- Materials compatibility
- Corrosive considerations
- Mandatory compliance
- Operating environment
- Load/forces
- Cost
- Attenuation performance
- Fastening/mounting methods
- Storage environment
- Nuclear, biological, chemical (NBC)
- Cycle life
- Shielding/grounding/other
- Electrical requirements
- Materials thickness/alloy
- Space/weight considerations
- Product safety
- Recyclability

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Metal RF Gaskets (Fingerstock) and Spring Contacts

Metal RF gaskets are made from various materials. They generally have the largest physical compression range and high shielding effectiveness holding steady of a wide frequency range. CuBe is the most conductive and has the best spring properties. They can be easily plated for galvanic corrosion considerations.

Fingerstock and spring contact products are ideal for high cycling applications requiring frequent access, with hundreds of standard shapes available as well as cut-to-length and modified standards.

Wire Mesh and Knitted Gaskets

Wire mesh gaskets can be made from a variety of metal wires, including monel, tin plated-copper clad-steel or aluminum. They are cost-effective for low cycling applications and offer high shielding effectiveness over a broad frequency range. They are available in a wide variety of sizes and shapes with the knit construction providing long lasting resiliency with versatile mounting options.

Conductive cloth knit offers close-knit stitch of the metalized nylon, providing a highly effective EMI shield, as well as a smooth, soft surface. Copper Beryllium (CuBe) Mesh offers superb resiliency for consistent, point-to-point contact requiring the lowest compression forces.

Elastomer Core Mesh combines excellent shielding performance with a high degree of elasticity.

Oriented Wire

Oriented wire is a conductive elastomer in which individual conductive wires of either Monel or aluminum are impregnated into solid or sponge silicone. Oriented wire provides EMI protection and seals against moisture or rain on cast or machined surfaces.

Fabric-over-Foam (FoF)

FoF EMI gaskets offer high conductivity and shielding attenuation and are ideal for applications requiring low compression force. Typical FoF EMI gasket applications include shielding or grounding of automotive electronic equipment seams and apertures. There are a wide range of shapes and thickness to meet any design need.

Electrically Conductive Elastomers

Conductive elastomers are ideal for applications requiring both environmental sealing and EMI shielding. They provide shielding effectiveness up to 120dB at 10GHz with a wide choice of profiles to fit a large range of applications. Conductive fillers include, but are not limited to:

- Carbon (C)
- Passivated aluminum (IA)
- Silver-plated aluminum (Ag/Al)
- Silver-plated copper (Ag/Cu)
- Silver-plated glass (Ag/G)
- Silver-plated nickel (Ag/Ni)
- Nickel-coated carbon (Ni/C)
- Silver (Ag)
- Elastomer options include:
  - Silicone rubber
  - Fluorosilicone rubber
  - Ethylene propylene diene monomer (EPDM)
  - Fluorocarbon rubber, Viton, or Fluorel

Form-in-Place (FiP)

Form-in-Place (FiP) EMI gaskets can be dispensed onto any conductive painted, plated, or metallic surface of an electronics enclosure that requires environmental sealing, has complex or rounded surfaces, or has miniature devices requiring a precision gasket; thus, protecting the enclosure against internally and externally radiated interference and environmental elements.

Board-Level Shielding (BLS)

If done well, PCB level shielding can be the most cost-efficient means of resolving EMI issues. As a low cost, and most common shielding method, a variety of board-level metal can-type shields have been used to eliminate EMI radiation from entering or exiting sections of a PCB. This method has primarily employed solder-attached perforated metal cans being attach and soldered to the ground trace on a PCB directly over the electrical components that need to be shielded.

The can-type-shields are often installed in a fully automated fashion via a surface mount technology process at the same time the components themselves are installed onto the PCB using wave soldering, or solder paste and a reflow process. Such cans offer very high levels of shielding effectiveness, are typically very reliable, and are widely used in the industry.

Board-level shielding metal cans can consist of tin or zinc plated steel, stainless steel, tin-plated aluminum, brass, copper beryllium, nickel silver or other copper alloys.

Combination Shielding Products

Combination shields offer two or more technologies combined into one convenient form. These shields are made by molding conductive elastomer walls onto metal shield...
cans to provide any compartment geometry needed. In addition, even more complex applications involve welding spring contact/fingerstock to shield cans to seal compartments in ultra-low profile applications.

CONCLUSION

Basic shielding theory is really not so basic. A comprehensive knowledge of EMI control, circuit design, mandatory specifications, environmental issues and other factors must be considered. Shielding requires a conductive enclosure around a circuit, device, apparatus, or even entire buildings to control EMI. The most cost effective shielding is applied at the source of the problem. However, that is not always possible.

Once the design is established and there are EMI issues, many times, shielding is the only solution. Today there are a myriad of choices for shielding materials from BLS to metal and/or “conductive plastic” enclosures. In most cases, when shielded enclosures are required, RF gasketing is also necessary to provide a conductive interface across the enclosure’s apertures.

Simply trying to pick off-the-shelf shielding materials is not an option. There are many factors involved in the selection of RF shielding materials and RF gaskets. In fact, if one is not intimately familiar with the materials and mechanics of shielding, then it is best left to the experts in the shielding industry.

REFERENCES

- Laird Technologies’ Web Site: 2010

Gary Fenical is an EMC Technical Support Engineer with Laird Technologies, as well as an NARTE Certified EMC Engineer. Mr. Fenical has been with Laird Technologies for 26 years. He is a specialist in RF shielded enclosures and has been responsible for the design and/or measurement and quality control of hundreds of large-scale shielded enclosures as well as a number of shielded equipment cabinets and housings. He was instrumental in the design and construction of Laird Technologies’ state-of-the-art World Compliance Centers. Mr. Fenical has authored many articles on EMC Requirements for Medical Devices, Mutual Recognition Agreements and Guidelines to meet the essential requirements if the EU EMC Directive. He has also authored several seminars on the EU EMC Directive, International Compliance, and Designing for EMC and EMC Requirements for Medical Devices which have been presented worldwide. He holds the patent for the invention of heat-treated beryllium-copper knitted wire mesh gasket.

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It’s been said that nobody grows up wanting to be an EMC engineer. Rather, it usually just happens. Maybe you had incriminating information on your resume, such as being a radio ham. “You’ve created interference, so you must know how to stop it, right?” Maybe you showed a knack for EMC troubleshooting, and suddenly you’re now the company expert - whether you want to be or not.

Or maybe you just zigged when you should have zagged. In any event, you’re now in the EMC trenches. In this article, we’ll discuss what to do next. It won’t happen overnight, but with a plan (and some work), you can move from EMI-novice to EMI-expert.

**FIRST, FIND A MENTOR...**

If you are in a big company with an established EMC group, this may be your boss or a colleague. You need someone who has experience and who is willing and able to share it. Fortunately, most EMC engineers are happy to help - particularly the older guys, so don’t be afraid to approach the more senior members of your engineering staff.

If you are in a smaller company, identifying a mentor may be more difficult, particularly if you are the sole EMC practitioner. In this case, you may need to look outside the company. Good candidates for mentors are your local EMC test lab, or perhaps an EMC consultant. Since both sell their time, fees may or may not be involved, but your company should be willing to invest in your education. After all, they put you in this position, and they want you to do well.

**GET SOME EXPERIENCE - FAST...**

If you are responsible for the front end design work, get to know the design teams. Participate in design reviews even if you don’t feel you know a lot about EMC. Trust us, this is a quick way to accelerate learning, particularly if you are a young engineer.

Be curious, and ask questions. Don’t worry that you don’t know the answers - you are in learning mode. And don’t limit yourself to EMC engineers. Designers in specialized areas like power electronics, RF or analog circuits often have valuable insights applicable to EMC issues.

Witness EMC tests. If you are hired into an EMC lab, you’ll be doing this anyway under the supervision of an experienced EMC test engineer. If you’re doing design work, get in as much test time as you reasonably can. It is amazing how much you can learn by just watching an EMC test. An added advantage - you’ll also get to know the good folks at the test lab.

**START ON YOUR SELF-EDUCATION...**

Unfortunately, undergraduate engineering classes on EMC are few and far between. Graduate programs are even more rare, and those that do exist usually focus on specific research. As a result, you may need to set up your own self-training program. Here are some ideas.
When Everything Falls on Your Shoulders, We Lighten the Load.

As you expand into global markets, you need a partner that understands your approval requirements, and can provide the appropriate global resources to accelerate time to market.

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Books
While we have over a hundred EMC books on our bookshelves, there are four we regularly recommend for newcomers to EMC.

EDN Magazine Designer’s Guide to EMC written by us as a beginner’s guide for non-EMC engineers. Simple explanations and recommendations, with no equations or complex math. A good place to start if you are new to EMC. Published by Kimmel Gerke Associates.

Electromagnetic Compatibility Engineering - written by Henry Ott as a major update to his previous book (Noise Reduction Techniques in Electronics Systems). Well written, with all the equations you need without field theory or complex calculus. Published by Wiley & Sons.

Introduction to Electromagnetic Compatibility, 2nd Edition - written by Clayton Paul, primarily as a college text, so it has lots of technical depth with all the field theory details. At the same time, very readable and practical. Published by Wiley Interscience.

High Speed Digital Design - A Handbook of Black Magic - written by Howard Johnson as the definitive guide on Signal Integrity. Easy to read, with all the great design advice applies to EMC too. Published by Prentice Hall.

Magazines
There are several publications serving the EMC community. The good news is that two are free, and both are filled with practical articles. We’ve also included a third publication, a specialty newsletter that is not free but quite useful for industry events and insights.

In Compliance (you are reading it now) - monthly, with an annual buyers guide. Design, test and regulatory issues. Focus on commercial electronics, blanketing compliance related topics. Free on-line, free hard copy in North America. Same Page Publishing Co.

Interference Technology (formerly ITEM) - annual buyers guide with two additional guides throughout the year. Primarily test and regulatory issues, with an emphasis on EMC. Free. ITEM Publications.


Courses
These are an excellent way to gain focused practical information in a short time. They typically run from 2-5 days in duration and are offered throughout the US. In house classes are another option. Here are three major providers of EMC training.

Kimmel Gerke Associates (us) - EMC Design classes (2-day), plus an optional EMC Troubleshooting class (1-day). Typically, 15-20 public classes are offered per year throughout the US in selected cities. Also provides in-house training classes. Has offered training for 20+ years.

Henry Ott Consultants - EMC Design classes (2-day). Typically, several public classes offered per year. Also provides in-house training classes. Has offered training for 30+ years.

WL Academy - various EMC issues (length varies), with an emphasis on regulatory topics. Classes throughout the year at Washington Labs in Maryland. Offers a unique and very popular class on MIL-STD-461F testing.

REGULATIONS
Last, but not least, you will want to get copies of the EMC regulations applicable to your industry. Most are copyrighted and have a fee, but government regulations such as MIL-STD-461 and MIL-STD-464 are in the public domain and are free. The latter also have detailed appendices that are great tutorials on the “why” along with the “how” of the various tests. (Recommended reading.)

Here are the main EMC requirement by industry (with web sites.) Many of these are tailored by individual companies as internal EMC requirements.

- Avionics - RTCA DO-160F (www.rtca.org)
- Automotive - SAE J551 & SAE J1113 (www.sae.org)
- Telecommunications - Telecordia (formerly Bellcore) GR-1089 (www.telecordia.com)

PARTICIPATE IN THE EMC COMMUNITY...
The community is small, but tight. Don’t worry - fresh recruits are always welcome. Maybe it is a case of “misery likes company”, but you will find most EMC folks are friendly to newcomers.

This is especially true of many EMC old-timers. Most of us have enjoyed the journey and are happy to share what we
have learned. Since little of this is taught in schools, most of us learned (and continue to learn) directly from colleagues and those before us. So if you are a new EMC engineer, don’t hesitate to ask for help.

The IEEE EMC Society is probably the biggest community resource. Among the smallest of the IEEE professional societies, the EMC Society is very active. It hosts chapters throughout the world, along with annual symposiums. Both provide excellent opportunities for ongoing education and professional networking.

Join an EMC Chapter

Our first recommendation is to join your local IEEE EMC chapter. Go to www.emcs.org for a list of chapters, many with links to their local pages. Most chapters host at least four meetings a year, and usually include a speaker discussing a technical topic. Finally, you don’t need to be an IEEE member to attend - if you are interested in EMC, you are always welcome.

If you don’t have a local chapter, consider forming your own. When Daryl moved to Phoenix fifteen years ago, he missed the camaraderie of the Minnesota chapter. He and two other EMC engineers reactivated the local chapter, which had been defunct for years. It is still active fifteen years later. And, again, you are not alone. The EMC Society will help with its Angel and Distinguished Lecturer programs.

Attend EMC Symposiaus

Our next recommendation is to attend an IEEE EMC Symposium. These are held annually around the US, with additional international symposiums around the world. A word of caution - you may need to convince your management of the value of attending. Trade shows are often seen as a boondoggle, but this can be an excellent educational opportunity. Even after 40+ years in this business, we both learn something new from every show.

Here are some suggestions for attending the symposium:

• Attend all five days. While the main technical sessions are Tuesday through Thursday, tutorial sessions are held on Monday and Friday. These tutorials sessions are often aimed at the new EMC engineer, but we find them useful too.

• The Tuesday through Thursday technical sessions are usually heavy on analysis and modeling, so make these a lower priority. Now this may irk the academics, but you can always read the papers later. If a particular paper interests you, by all means attend. Sometimes there are special sessions, and we’ve found those to be very useful. The point is - don’t spend all your time in the meeting rooms.

• Spend time on the show floor. Talk with the vendors to find out about new products, and attend the special tutorial demos. Both can be particularly beneficial to the new EMC engineer.

• Attend the social events. Remember, “All work and no play...” Besides, this is a chance to rub shoulders with those in the business. Although many engineers are introverts, try to mingle, meet and ask questions. Most of those you meet will be fellow engineers.

Use LinkedIn

Finally, use your on-line resources. At this time, LinkedIn is the preferred venue for professional activities. There are several EMC special interest groups which you can join. Your participation can be as much or as little as you prefer. These are also great places to post those perplexing EMC questions.

MAKE A PLAN, AND THEN WORK IT...

First, be patient. It may take a couple of years until you feel like you have really mastered the craft. If you are new, there is a lot to learn. Often this learning is piecemeal, like working a puzzle. But if you study, learn and participate, one day in the not too distant future the overall picture will make sense. At that point, you’ll realize you are finally there - you’re no longer an EMC-novice, but have become an EMC-expert.

A final piece of advice. When you reach that point, don’t stop learning. Even after 40+ years each, we are still learning about EMC. Actually, this keeps us in the game. What weird problem will we see next? Welcome to the wild and wacky world of EMC!

Daryl Gerke, PE and Bill Kimmel, PE are the founding partners of Kimmel Gerke Associates, Ltd. The firm specializes in EMC consulting and training, and has offices in Minnesota and Arizona. The firm was founded in 1978 and has been in full time EMC practice since 1987.

Daryl and Bill have solved or prevented hundreds of EMC problems in a wide range of industries - computers, medical, military, avionics, industrial controls, vehicular electronics and more. They have also trained over 10,000 designers through their public and in-house EMC seminars.

Daryl and Bill are both degreed Electrical Engineers, registered Professional Engineers, and NARTE Certified EMC Engineers. Between them, they share over 80 years of industry experience. For more information and resources, visit their web site at www.emiguru.com.
Sellers and importers of Information Technology Equipment (ITE) must comply with a vast array of hardware regulations when marketing their products in today’s world. The scope of hardware regulations includes the following basic disciplines:

- Product Safety
- Electromagnetic Compatibility (EMC)
- Homologation of wired and wireless telecommunication devices
- Energy Efficiency
- Environmental
- Chemical

Such regulations are established at many levels, including national, regional, state, province and even individual cities or towns. In many case, hardware regulations carry the force of law. Hence, a complete and in-depth understanding of the regulations applicable to any particular product is needed to avoid running afoul of the law. Being aware of all the regulations that apply to a product can be challenging enough, even before understanding all the details.

REGULATORY FUNDAMENTALS

Regardless the discipline, all hardware regulations encompass a common set of basic elements.

- Technical evaluation, which may include testing or engineering analysis
- Documentation of results, often in the form of a test report
- Conformity assessment procedures, including Declaration of Conformity (DOC), verification and certification
- Product and packaging marking
- Information to the user
- Market surveillance and on-going compliance

It should be noted that some regulations may not require explicit action on some of these elements. For example, certain regulations do not require a statement of compliance to be included in the documentation provided to the end user of the product. Other elements may be included as well, such as an audit of procedures and capabilities of manufacturing factories.

The technical evaluation typically includes either testing a sample of the product against some defined standard or set of standards or an engineering analysis or assessment. Restrictions or rules on who can perform the testing or evaluation vary. In some cases, the test or assessment may be performed by the product’s manufacturer, while other regulations for the same basic discipline may require the use of an independent third party. If testing to standards is required, the lab performing the testing may need to be accredited by the regulatory agency or through a designated lab accrediting agency. With the wide possibility of requirements on who can perform the evaluation and what specifically is required or allowed, it is easy to see why
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in-depth knowledge of the applicable regulations is essential for successful compliance.

Once the technical evaluation is completed, the results must be documented. The old adage of the work not being done until the paperwork is completed definitely applies in hardware compliance. Without adequate documentation of the evaluation, one cannot truly demonstrate compliance with the requirements. What product was evaluated? How was the evaluation performed? Who did the work, and were they properly qualified to do it? The list of content that must be included in a test report can be quite extensive. Consider the following example.

1. Test Report Cover Page stating the regulation the report encompasses
2. Test standard and test method that were applied and any deviations from the specified procedures
3. Classification of the product with respect to the regulation (for example, Class A or Class B for EMC emissions test results)
4. Description of the device being tested for approval, including marketing designation or model number
5. Product specification sheet describing its functions and capabilities
6. Functional block diagram
7. Specific identification of the device that was tested, including serial number and detailed list of all hardware content
8. Description of software used to exercise the unit being tested
9. Measuring equipment used in performing the test, including make, model, serial number and calibration details
10. Test results
11. Description of any changes made to the device during testing to meet the test limits
12. Photographs of the test setup
13. Photographs of the device being tested
14. Diagram of the physical arrangement and configuration of the unit tested
15. Drawing or photograph of the product label showing required marking(s) and location of label on the device

The conformity assessment procedures define the specific process steps that must be followed to satisfy the regulation and include things such as filing a report with an agency versus keeping it on file to be made available if requested. These procedures can be placed into three basic categories:

- Certification
- Suppliers Declaration of Conformity
- Verification

Certification generally requires filing specific documentation (such as the test report) with the agency and receiving a certificate in return.

In a Suppliers Declaration of Conformity procedure, the supplier (typically the product’s manufacturer) completes a form attesting, or declaring, that the device complies with the required regulation. The method used for demonstrating compliance is often listed on the declaration. In some cases, the declaration is distributed with the product to the end user, while in other cases, it is kept on file to be made available upon request.

Verification is the simplest form of conformity assessment in which the supplier creates documentation to verify that the product meets the requirements. Typically, this documentation would be a test report that is kept on file and made available upon request.

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Base Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducted and Radiated Emissions</td>
<td>CISPR 22</td>
</tr>
<tr>
<td></td>
<td>FCC Part 15 Rules</td>
</tr>
<tr>
<td>Power Line Harmonic Emissions</td>
<td>IEC 61000-3-2</td>
</tr>
<tr>
<td></td>
<td>IEC 61000-3-12</td>
</tr>
<tr>
<td>Voltage Fluctuations and Flicker</td>
<td>IEC 61000-3-3</td>
</tr>
<tr>
<td></td>
<td>IEC 61000-3-11</td>
</tr>
<tr>
<td>Immunity</td>
<td>CISPR 24</td>
</tr>
</tbody>
</table>

Table 1: Common standards serve as the basis for global EMC regulations
Product marking involves placing a mark or statement on the product. Most often the marking is added to the product’s information label. Some regulations allow alternatives of placing the product marking on the packaging (such as the cardboard box) or in the user manual, but most require the marking on the product.

Information to the user is generally a statement that the product complies with the regulation. It may also include caution or warning statements describing types of locations where the device is, or is not, allowed to be used.

Market surveillance includes any activities undertaken by the authorities to verify that products being sold do, in fact, comply with all applicable regulations. Market surveillance activities take many forms and may include checking products at retail outlets to ensure proper labeling; requesting copies of test reports, DoCs or certificates from the manufacturer or importer; or performing the tests defined by the standards or regulations on samples acquired from manufacturers, importers or retail outlets.

Compliance verification by Customs officials at the time of importation is another form of market surveillance. Verification by Customs typically involves document inspection to see if all the paperwork accompanying a shipment is in order. Noncompliances discovered during Customs verification typically result in delayed product deliveries to customers, as the noncompliant product (or suspected noncompliant product) will likely be held by Customs until compliance can be demonstrated or obtained. Even simple errors in documentation, such as the model number shown on the commercial invoice not matching the information on the certificate issued for the product, can create problems at the time of importation. Therefore, attention to detail is very important.

**EMC**

Let us now explore EMC regulations around the globe.

A device’s ability to exist in its intended operating environment without causing electromagnetic interference with other electronic equipment (emissions) or without suffering undue interference from other equipment (immunity) is regulated in some 50 countries.

Fortunately for manufacturers, importer and other responsible parties, these regulations reference a much smaller set of common standards, as shown in Table 1.
This referencing of common standards substantially reduces the testing burden, although changes and revisions to the reference standards are not always adopted on uniform schedules by the various regulations. A recent example of the variations that can happen in adoption is the roll out of the CISPR 22 limits on radiated emissions between 1 and 6 GHz. Compliance with these limits became mandatory in October 2010 for the Republic of China (Taiwan), in March 2011 for the Peoples Republic of China, and October 2011 in Australia, the European Union and Japan. Depending on the changes introduced in subsequent editions of a standard, the effect of nonuniform implementation schedules can range from simply referencing the correct edition in test reports to testing a single product multiple times to accommodate the technical differences between versions.

<table>
<thead>
<tr>
<th>Geography</th>
<th>Test Type</th>
<th>Conformity Assessment Procedure</th>
<th>Submit Test Report</th>
<th>Product Label</th>
<th>User Manual Statement</th>
<th>Lab Accreditation or Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Emissions</td>
<td>DoC</td>
<td>No</td>
<td>Yes</td>
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<td>Recommended</td>
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</tr>
<tr>
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<td>Emissions</td>
<td>Verification Certification DoC</td>
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<td>No</td>
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<td>DoC</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2: Sampling of compliance details for EMC regulations
Now that the new CISPR 32 standard for emissions from multimedia equipment has been published, it will be interesting to see how the various jurisdictions incorporate the standard into their requirements.

Even with the use of these common standards to establish the test conditions and limits that must be met, the industry must understand and correctly apply differences in the conformity assessment details between various global EMC regulations. A sampling of these details is summarized in Table 2. Note that some regulations include multiple conformity assessment procedures, usually based on the type of product or product classification.

CONCLUSION

Many countries around the world have hardware regulations that must be met before ITE is marketed, sold or imported into those countries. These regulations exist for valid reasons and generally are intended to protect something: people, other equipment or the environment. Meeting the technical details of hardware regulations is only one step in satisfying the regulations. Satisfying the administrative elements of the conformity assessment process that need to be completed after the technical analysis or testing is finished can be more challenging and time consuming than the test or analysis itself.

Effective regulatory compliance engineers must have a solid technical background to understand the intricate details of product design and the related test standards. They must also stay current on the ever-evolving test and analysis standards, related test equipment, laboratory performance and approval criteria, accreditation requirements, import rules and the rules for the declaration and certification regimes of many regulatory agencies throughout the world.

John Maas is Corporate Program Manager for EMC for IBM Corporation and has responsibility for IBM’s worldwide EMC regulatory compliance program. He has over 25 Years of EMC experience including hardware design and test. He has been involved in international standardization for much of his career and currently is active in IEC SC77B/WG10 and the US advisory groups for IEC TC77, SC77A and SC77B and CISPR/L.

Mr. Maas can be reached at johnmaas@us.ibm.com.
This article outlines the administrative obligations contained in the European EMC Directive, 2004/108/EC, with particular reference to the Declaration of Conformity (DoC). It considers the mounting evidence, including that resulting from European market surveillance campaigns, that insufficient attention is paid to ensuring that the supporting documentation is not only in place, but also up to date.

The requirements of the EMC Directive, like all New Approach directives, can be broadly split into two:
• the technical requirements and
• the administrative requirements

Compliance with the technical requirements is demonstrated (in most cases) by assessing a product against the relevant harmonised European standards and compliance with the administrative requirements is demonstrated by ensuring that the requisite documents and paperwork are available and up to date. In the case of the EMC Directive, the requisite paperwork is normally Technical Documentation and a valid DoC.

Only by meeting both the technical and the administrative obligations should the CE Marking be affixed to a product and the product placed on the market.

ADMINISTRATIVE REQUIREMENTS

Whilst concerns regarding the number (or suspected number) of non-compliant products on the market is nothing new, historically many of these concerns have tended to relate to the technical aspects of compliance.

Deficiencies in administrative compliance have, with the exception of market surveillance activities, only tended to come to light when a DoC has been requested by a potential customer and the manufacturer has been unable to supply one in a reasonable time frame.

Under both 89/336/EEC and 2004/108/EC, there is a stated requirement to produce a valid DoC and the minimum requirements of what it should contain are clearly stated as follows:
• reference to the Directive
• identification of the apparatus to which it refers
• name and address of the manufacturer and, where applicable, the name and address of his authorized representative in the Community
• dated reference to the specifications under which conformity is declared to ensure the conformity of the apparatus with the provisions of this Directive
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MARKET SURVEILLANCE ACTIVITIES

The EMC Administrative Co-operation Working Group (ADCO) carried out the 4th EMC Market Surveillance Campaign during 2011.

The primary purpose of the campaign was to assess the compliance of a range of LED lighting products with the administrative and technical requirements of the EMC Directive. Administrative compliance included checking of the DoC.

The results of the surveillance activities were published towards the end of 2011 [1]. The overall administrative compliance was found to be only 28.8% with the main deficiencies relating to the CE marking and the DoC.

Declarations of Conformity were available for only 74.4% of the assessed LED lighting equipment, meaning that 1 in 4 assessed products did not have a DoC available. It is possible that some of those products may have been technically compliant, however as they were not administratively compliant, they did not meet the requirements of the EMC Directive.

Almost half of DoCs presented had major deficiencies including:

- missing reference to the Directive
- incorrect Directive referenced
- inadequate identification of the product
- incorrect standards
- not issued by the manufacturer and/or authorised representative

Overall, only 39.9% of the assessed products were presented with an acceptable Declaration of Conformity. In other words 61.1% of the assessed products were not presented with an acceptable Declaration of Conformity, either because one did not exist or because it had major deficiencies.

Previous EMC Market Surveillance Campaigns raised similar concerns about compliance levels generally and administrative compliance specifically.

FURTHER EVIDENCE

The ADCO market surveillance results of 2011 reflect the compliance position of the LED market; a fast growing and fast changing industry.

Are the deficiencies identified in DoCs for LED lighting products representative of those commonly found elsewhere?

At York EMC Services (YES) we see a significant number of DoCs each year, either via our DoC Checking Service or as part of our wider consultancy work and therefore an answer to the question above is readily available. And that answer is an emphatic “yes”; all the issues identified in the market surveillance activities for LED lighting are commonly observed by YES across a wide range of different industry sectors.

Probably less than 10% of DoCs that arrive at YES for assessment could be classed as being anywhere approaching correct with the other 90% containing a range of deficiencies, many of which would be considered as major.
Given the copious number of sources of information for what should be included on a DoC; specialist training providers, consultants, industry websites and even the EMC Directive itself this is a disappointing state of affairs.

As regards deficiencies, there are a number of recurring themes, of which the top 3 are:

1. The standards are incorrectly applied, out of date or undated
2. The reference to the Directive is incorrect
3. Identification of the apparatus covered by the DoC is inadequate

Each of these will now be considered in turn including typical examples of where and how the requirements have not been met.

**STANDARDS**

The most common issues, by some distance, relate to the presentation of standards on a DoC. These issues break down into a number of subcategories which will be considered in more detail.

Perhaps to start off on a positive note, it is worth stating that it unusual to see a DoC where the manufacturer has selected completely incorrect product specific or generic standards. No doubt these do exist but, it seems, not in significant numbers.

**Listing Basic Standards**

It is relatively common to see a DoC which lists basic standards as opposed to product specific or generic standards. Figure 1 shows a typical example.

CE Marking is based on the correct application of harmonised European standards which includes product specific and generic standards. In lay terms, basic standards, which contain details of the test methods, are the support acts to product specific and generic standards. They are not “CE Marking” standards and are not listed in the OJ. A DoC should be made against product specific and/or generic standards as appropriate.

In relation to Figure 1, there are several questions that the DoC does not answer:

- Against which standards is the product being declared for EMC? The answer to this question is that we simply don’t know. EN61000-4-X immunity standards are referenced by virtually every product specific and generic standard published in recent years. Conspicuous by its absence is reference to EN61000-4-3 for radiated immunity.
- What about emissions? There are no emission standards listed at all.
- Against which standards is the product being declared for electrical safety? The Low Voltage Directive is listed on the DoC but it contains no safety standards, so again the answer is that we simply don’t know.

**Correct Versions of Standards**

By far the most common issue relating to standards occurs when the product has been correctly assessed against a particular version of a standard, but that standard has subsequently been updated and either an amendment and/or a new version has been published. The transition period has then passed and as a result the DoC has become invalid.

Two examples of recently reviewed DoCs are shown in Figure 2 and Figure 3 (page 54). There is plenty of other...
potential discussion relating to the information contained in both Figures 2 and 3.

More specifically, and what can’t be seen from the snippet used in Figure 3, is that the DoC was signed in 2003. Therefore all of the standards listed were considerably out of date even at the time the DoC was signed!

Undated Standards
All standards change on a regular basis either by amendment or publication of a new version. The newer standard may contain different tests or test limits/levels or other changes that affect how the product is assessed.

A standard listed on a DoC without an associated date means that it is not possible to identify the precise version of the standard to which the product is being declared and by association the actual test requirements that have been met. Figure 4 (page 56) shows an example of where undated standards have been included on the DoC.

In addition (and leaving aside the fact that most of the standards are undated) Figure 4 shows a DoC for a product meeting an impressively long list of EMC standards. This must certainly be an interesting product; a cross between Information Technology Equipment (ITE) and a household appliance which is also Industrial, Scientific and Medical (ISM) Equipment and used in an industrial environment!

Upon further investigation, it transpired that the product covered by this DoC was in fact a piece of measurement equipment falling within the scope of EN61326-1; which isn’t actually listed!

REFERENCE TO THE DIRECTIVE
When doing presentations on the subject of DoCs I have often found myself anecdotally stating that I am as likely to review a DoC which references 89/336/EEC on as I am one which references 2004/108/EC. Several years since the passing of 89/336/EEC this still seems to be the case.

When researching for this paper, I picked 10 of the most recently assessed DoCs to check the frequency at which 89/336/EEC still appeared. Sure enough the 10 DoCs were split exactly 50/50; 5 referring to 89/336/EEC and 5 referring to 2004/108/EC.

Most of the examples used in this paper to illustrate other issues also make reference to 89/336/EEC.

DESCRIPTION OF THE APPARATUS
One of the key information requirements for a DoC is that the product(s) included should be able to be clearly identified. For manufacturers having a large number of products this can be a challenge but an important one to undertake. It should be possible to uniquely trace each product to a DoC; without ambiguity.

Figure 5 (page 56) illustrates a common issue where the manufacturer is inadequately describing the scope of the DoC.

The phrase “a range of” only defines the scope of the DoC in general terms. What products, types, models and/or variants are included in this range? The answer is that it is impossible to tell without additional information and furthermore it is highly likely that “the range” will change over time further reducing the traceability.

Figure 6 (page 57) shows a good example of how to identify products within the scope of the DoC. In this example the actual product numbers can be identified clearly and unambiguously.

CONCLUSION
There is clear evidence that many products placed on the market are not compliant with the administrative requirements of the EMC Directive and therefore not compliant with the EMC Directive.

Figure 3: References to IEC801-X standards still exist but are fortunately not that commonplace
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A recurring theme, when assessing DoCs, is that many were clearly valid when issued but have become invalid over time through not being maintained. This is demonstrated by the number of out of date standards that are often encountered.

What this reveals is that the issuing of a DoC is perceived by many manufacturers to be a one-off, isolated event rather than part of a compliance process.

In practice, issuing a DoC is simply one event in a whole series of events that when brought together form the compliance process for the product from concept to retirement from sale.

Ensuring on-going compliance (both technical and administrative) after the product is placed on the market is one phase of this process and the one that includes maintenance of the DoC.

A DoC should be a living document that is regularly reviewed to ensure that it accurately reflects the state of compliance of the product to which it refers. There should be a valid DoC for each day that the product is placed on the market.

Often an invalid DoC is just the tip of the iceberg and inevitably raises other questions about the technical compliance of the product.

- Is it simply the case that the DoC hasn’t been updated or is there more to it?
- Is it also the case that the changes to the standards have not been assessed for their technical significance to the product in question?
- If the DoC is invalid, what is the likelihood that the Technical Documentation is also invalid?
- If the DoC hasn’t been updated for several years, is it also the case that the product has changed in the meantime and that an EMC assessment carried out previously is no longer valid?

In other words could an invalid DoC be an indication that the product is actually neither administratively nor technically compliant….?

**REFERENCE**

1. 4th EMC Market Surveillance Campaign, EMC Administrative Co-operation Working Group, 2011
Nick Wainwright has been involved with EMC all his working life, starting as an EMC test engineer in the telecommunications industry before moving into commercial testing.

He joined York Electronics Centre, the predecessor to York EMC Services, in 1990 as an EMC Test Engineer and worked his way up the organization until this year he was given the task of running the 40 strong company as Chief Operating Officer.

Nick takes a very hands-on approach to the roles he undertakes and has specified and designed EMC test facilities and implemented quality systems within laboratories to enable them to achieve accreditation to ISO17025.

Nick is a regular speaker at EMC conferences, courses and workshops on subjects ranging from CE Marking and standards to testing, ISO17025 and measurement uncertainty.

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When people are asked what is the most commonly used component in electrical or electronic circuits, the typical answers are “Well, of course everyone knows it’s resistors”, or “It must be capacitors”, and even sometimes “Nothing operates without transistors.” In fact, none of those answers are correct; the real answer is that conductors are the most common type of component. Obviously, without conductors there would be no such thing as circuits. Even though conductors are the basic component of electrical circuits, there is surprisingly little consideration of the physics involved in conductors (outside of textbooks) and there seems to be even less emphasis on considering the characteristics of conductive structures (such as “chassis grounds”) when those conductors and conductive assemblies are used for the critical current return paths in a circuit. Perhaps this is because wires just don’t seem that exciting! Ironically, successful EMC engineering requires just such an understanding!

This article will refresh (or perhaps initiate) the reader’s knowledge and understanding of key aspects of conductors and conductive paths by looking at a number of topics, including:

- history of conductors.
- fundamentals of electrical energy propagation.
- types of wire conductors.
- models and characteristics of transmission lines.
- use of assemblies as conductive paths.

**HISTORY OF CONDUCTORS**

Although wire made from conductive materials (such as iron or copper) has been in use for perhaps thousands of years, it was used as a mechanical component. It was not until a few hundreds of years ago (during the 1700s) that it was first used as a method to define a path for electrical current flow. Some of those first electrical uses were for protection of wooden structures in colonial America by the attachment of the conductive wire to iron “rods” placed on buildings to (hopefully!) provide a path for lightning strikes to be safely conducted to the earth instead of across the structure (which many times caused fires). The use of wire for this purpose (and the invention of the associated lightning rods) has been attributed to Benjamin Franklin.

During the early 19th century, as interest and worldwide fascination into “electrical flow” grew, Michael Faraday was among the first to perform empirical experiments to understand properties of conductors.

As the 1800s progressed, more uses for electricity were developed, including power distribution and communication (telegraph systems). As these systems became more complex, physically large, and capital intensive, there was an increasing desire to more fully understand these interconnection methods. As a result, Oliver Heaviside developed a number of important concepts and inventions during the 1880s, including transmission line theory and the “coaxial” style cable that we see today.
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WHAT IS THE PURPOSE OF A CONDUCTOR?

From the evolution of wires for lightning protection to power and signal distribution, and even to today, it can be seen that there is only one purpose of a conductor. That purpose is to provide an intended path for propagation of electromagnetic energy.

Therefore, a conductor is used to:

- provide power or signal(s) to where it’s needed.
- divert energy from where it’s NOT desired (such as in lightning grounds or surge suppression).

That intended path of electromagnetic energy is via “conduction”, as described by Professor Maxwell (in addition to his theory of “displacement current”, such as the current that “flows” through a capacitor).

In order to understand how energy is conducted from a source to a load, we start with the concept of the “idealized” energy transfer loop (as shown in Figure 2).

“IDEALIZED” ENERGY TRANSFER LOOP

The figure shows the source of the power (or signal), represented by the “generator”. On the other side of the figure is the load (which can be represented by an impedance). The process of transferring the energy from the source to the load is via the conduction path, defined by the solid lines on the diagram). This transfer is typically explained as being similar to a current in water, in that there is a “current flow” along one conductor, while the other conductor functions as a “current
CONDUCTORS AND “CONDUCTIVE PATHS”: WHAT IS REALLY HAPPENING

RETURN”. While this view is not incorrect, sometimes it is better to visualize the energy as an electromagnetic wave being guided from the source to the load.

CONNECTION PATH IMPEDANCE

Using the idealized energy transfer loop leads (unfortunately) to assumptions in system and circuit design that the conductive path is always characterized by a simple zero impedance connection. The problem is that in actual circuit construction, although conductive materials are used, these materials in reality have “non-zero” physical parameters (such as thickness, width, and material resistivity). Depending upon the physical size of the conductor(s), these actually need to be defined as having relevant volume or surface resistivity as shown in Figure 3. For volume resistivity, it is common to utilize a unit volume, such as a cube of equal dimensions in the X, Y, and Z directions. For surface resistivity (when the thickness of the material is significantly less than the other dimensions) an X and Y dimension is used.

The way we typically establish conductive paths from sources to load is to use wires of various diameters (called “gauges”). Figure 4 shows various wire geometries and the common method for identifying the wire diameter. The resistance of wire is a function of both its material and physical dimension (typically diameter is expressed in “MIL”, which is equal to 0.001 inch).

By using physical dimensions and material characteristics, it becomes a straightforward process to determine the resistance of any wire. This is shown below.

Calculation of the Resistance of Wires

- Resistance (R), is determined by ρ (rho), length (L), and cross sectional area (A).
- Example showing resistance for 1,000 feet of wire of 10,400 circular mils.

\[
R = \frac{\rho L}{A} = \frac{10.37 \times 1000}{10,400} = 1 \text{ ohm (approximately)}
\]

Figure 4: Various geometries of wire and methods for determining gauge
In this example, the 1,000-foot wire has a resistance of 1 ohm. It can be seen that if the length is doubled, the resistance will also double. This makes sense. An interesting observation can be made at this point, however, and that is if the cross-sectional area of the wire decreases (gets smaller), the resistance of the wire increases!

**WIRE SIZE (“GAUGE”)**

In order to provide consistency in wire selection and application, it is typically manufactured in sizes numbered according to the American Wire Gauge (AWG) tables. These tables show wire sizes from 0000 gauge (which is a 460.0 mil diameter for solid wire) to 40 gauge (3.1 mil diameter for solid wire). Of particular note is the fact that, according to these tables, a wire is a single rod or filament of drawn metal. Of course another type of wire is actually a number of solid wires bound together to function as a single wire. This more correctly is known as a stranded conductor or a cable. Table 1 shows DC parameters of typical cables of various AWG sizes. Figure 5 shows the difference between a single conductor wire and a stranded-conductor “wire”.

Why do we have both solid and stranded “wires” (conductors)? It turns out that each has its own advantages that would make the selection of one or the other optimum for a particular application.

In the case of solid wires, they have the following attributes:

- cost-effective.
- high mechanical integrity (keeps form).
- smaller diameter for equivalent “gauge”.

Stranded wires, on the other hand would be used when the following characteristics are desired:

- flexibility.
- reduced “noise” (due to lower inductance compared with a similar length of solid wire).

<table>
<thead>
<tr>
<th>DC Parameters of Some Standard Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (AWG)</td>
</tr>
<tr>
<td>No. 12</td>
</tr>
<tr>
<td>No. 8</td>
</tr>
<tr>
<td>No. 2</td>
</tr>
<tr>
<td>1/0</td>
</tr>
</tbody>
</table>

**Table 1**: Table showing DC resistance of different wires by gauge and diameter

**Table 2**: Table equating solid wire gauge to stranded cable
Conductors and “Conductive Paths”: What Is Really Happening

- redundancy (some broken solid wires will not affect functionality).

In the same way we can define solid wire sizes, we also define physical dimensions for stranded conductors. *An interesting point is that the diameter for “gauge equivalent” solid and stranded conductors are NOT the same!* This is due to the fact that the stranded wires have some amount of open space between them when contained in one bundle (because the wires are circular). This can be seen in the cross-section of the stranded conductor in Figure 5.

Shown is a table for examples of both solid and stranded wires (Table 2). The table is used in the following manner:

- the entry for the wire gauge 12 shows a SOLID wire diameter of 80.0 mils.
- Stranded wire with a 12 gauge can be obtained by combining either 165 solid wires of 34 gauge (165 x 34) or 7 wires of 20 gauge (7 x 20).

**EMC ASPECTS OF WIRES**

While important, DC characteristics of wires are not the primary characteristics of concern in EMC work. The important elements to consider are:

- lines on a schematic (or connections in SPICE) that represent the “ideal” characteristics.
- frequencies of interest in EMC work that require an understanding of “non-ideal” behaviors.

A key consideration when using wires (or any type of conductor) with non-DC current is that there is AC impedance that increases with frequency due to the skin effect phenomenon. The skin effect causes a reduction in the cross-sectional area through which the current flows and, as we saw in a previous equation, the cross-sectional area decreases when the resistance increases. The same condition is a contributor to AC impedance. This is shown in the following figure and equation (Figure 6).

---

**Figure 6: AC impedance of a conductor is composed of two parts: the DC resistance and the AC resistance (once the wire radius exceeds approximately two skin depths)**

---

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In addition, both the AC resistance and reactance of a conductor vary with frequency as a result of the skin effect, and are reflected in the resistance ratio factor (X).

**DC RESISTANCE, AC RESISTANCE, AND INDUCTIVE REACTANCE**

If the fact that AC resistance can dominate DC resistance isn’t bad enough, since the wires are part of a current loop, they also have self-inductance and result in even higher impedance.

Table 3 summarizes these effects. It may even be startling that at only 1 MHz, the AC resistance is an order of magnitude greater than the DC resistance and the inductive reactance (XL) due to the wire partial inductance described in Inductance: The Misconceptions, Myths, and Truth (page 72) is hundreds of times the AC resistance!

Table 3: Comparison of AC resistance, DC resistance and inductive reactance (due to partial inductance) for different wire gauges

<table>
<thead>
<tr>
<th>Size</th>
<th>Length (ft)</th>
<th>R&lt;sub&gt;DC&lt;/sub&gt; (Ω)</th>
<th>R&lt;sub&gt;AC&lt;/sub&gt; (Ω)</th>
<th>L (μH)</th>
<th>XL (Ω)</th>
<th>Z (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 12</td>
<td>100</td>
<td>0.1588</td>
<td>1.23</td>
<td>60.9</td>
<td>382.65</td>
<td>382.65</td>
</tr>
<tr>
<td>No. 2</td>
<td>100</td>
<td>0.0156</td>
<td>0.387</td>
<td>53.8</td>
<td>338.03</td>
<td>338.03</td>
</tr>
<tr>
<td>1.0</td>
<td>100</td>
<td>0.0098</td>
<td>0.307</td>
<td>52.44</td>
<td>329.49</td>
<td>329.49</td>
</tr>
</tbody>
</table>

Now that we have investigated the properties of single-strand wires, let’s look at the characteristics of stranded wires.

It turns out that an approximation can be made in that the resistance (and to a certain degree, self inductance -- ignoring the effects of mutual inductance) of the stranded wire can be modeled as the resistance (inductance) of each strand divided by the number of strands (as each strand is effectively in parallel with the others). Interestingly, this was first empirically observed by Michael Faraday making the simple observation of “sparks” created in a circuit. When the same parallel wires were spread out, the “sparks” were less – without any change to the length of the wire bundle. Of course, we now know that fewer “sparks” mean less series inductance. Faraday’s observation is recorded as follows:

Now “small” values of inductance (a few micro-Henries) have high impedance at EMC frequencies (due to X = jωL).
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As the 1800s continued, the “state-of-the-art” communications systems became the telegraph, and later the telephone, systems. As the infrastructure was developed and built for these, there became a need to understand, in detail, the physics of conductors (which were now called transmission lines). It was discovered that long distance communication paths had unique characteristics that hadn’t been seen before (Figure 8). This was because these installations were the first widespread development of large systems utilizing interconnecting conductors (wiring). This led to the development of the “Telegrapher’s Equations” (discussed later) that became the basis for transmission line theory.

#### AND THEN IT HAPPENED – THE FIRST (AND STILL THE ONLY TRUE) GROUND CONNECTION!

As the telecommunications boom of the 1800’s continued, more and more wire was needed to construct the systems. From this need, one fundamental of all electrical engineering procedures was born, the discovery that by using the earth as a current return path, only half the amount of wire was needed! Thus, the term “ground” was coined for electrical connections (Figure 9)!

#### ANALYSIS OF THE GROUND RETURN

This practice for long distance telephone and telegraph connection was possible due to a unique physical relationship of the geometry and conductivity of the earth. It turns out that, rather than being a return path with a significant variation in impedance, the resistance reached an asymptotic limit just over 4 ohms (Figure 10).

This was due to the large area through which current could flow (similar to parallel wires) and, ironically, the resistance...
of the ground connection was much lower than the long signal wires. This further established the belief that a ground connection was a low impedance path (compared to the rest of the circuits).

HEAVISIDE’S DISCOVERIES: THE TELEGRAPHER’S EQUATIONS

An interesting phenomenon then occurred as the (telegraph) message signal speeds increased. It was discovered that some of the transmission lines caused signals to be affected and changed at the receiving end from their original characteristics at the sending end.

Heaviside then investigated Faraday’s observations of inductance, referenced Maxwell’s work, and from that work he developed the “Telegrapher’s Equations” which revealed how line characteristics affected signal propagation. This became the basis for all transmission line engineering.

This was amazing an insight. Heaviside realized that the use of two conductors in the telegraph transmission line resulted in the capacitive and inductive properties of the line. (This had not been recognized before.) He correctly understood that the capacitance and inductance are continuous along the length of the pair of conductors and therefore could be represented as either lumped or distributed components along the transmission line (Figure 11).

Figure 11: Heaviside realized that capacitance and inductance are continuous along the length of a pair of conductors, and can be represented as “lumped” or “distributed”

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Conductors and “Conductive Paths”: What Is Really Happening

Figure 12: Diagram and equation for the Transmission Line Model

\[ Z_0 \approx \sqrt{\frac{L}{C}} \]

Figure 13: Illustration of how energy propagates along a line (courtesy of Henry Ott, page 218 of *Electromagnetic Compatibility Engineering*)

Figure 14: A coaxial line is shown on the top and a twisted wire pair is shown on the bottom.

Figure 15
We now refer to Heaviside’s work as the discovery of the Transmission Line Model (Figure 12). Most importantly, this discovery allowed for the describing of a transmission in term of its characteristic impedance (Zo), which is a function of the distributed inductance and capacitance along the line and which makes it independent of line length!

**THE TRANSMISSION LINE MODEL**

- Model that utilizes a line of distributed inductance and capacitance.
- Model that shows a line can be represented by a surge (or characteristic) impedance, ignoring small dielectric losses.

**TRANSMISSION LINE SIGNAL PROPAGATION**

Key to transmission line theory is the ability to understand how energy, whether it’s “power” or “signal”, propagates along the line. A very good visualization of this is shown in Figure 13.

As can be seen, the propagation essential takes place by the current flow through the line series inductance and the “charging” of the effective parallel capacitors. Since there is a time constant associated with the charging of the capacitors, this causes the propagation speed to be reduced compared to the traditional “speed of light” electromagnetic wave propagation through air/vacuum. The effect of this reduction in propagation speed is known as “velocity factor” and varies based upon the values of the inductance and capacitance (which is determined both by transmission line geometry and material used in the transmission line construction).

**EXAMPLES OF COMMON TRANSMISSION LINES**

Today’s transmission lines are typically either coaxial or “twisted wire pair” (TWP) (Figure 14). Coaxial cable is used for shielding electrical fields and TWP is used for magnetic field shielding from emissions from either the transmission lines or from external interference.

**OTHER TYPES OF CONDUCTIVE PATHS**

A common practice is to utilize the metal chassis or enclosure as a conductive path (typically called “case grounding”) for either signal or power return. There are a number of reasons that this is done including:

- minimization of wiring costs (similar to telegraph “grounding”).
- resolve of component/system EMC problems.

Unfortunately, due to the fact that the impedance of the “ground” path is unknown, this results in the actual energy transfer loop being quite different from the “idealized” (previously discussed). The actual loop is shown in the Figure 15.

**Implications of Practice**

From that figure, it is easily seen that using the chassis or enclosure as an electrical return path would result in “ground” impedance being undefined and something other than the assumed zero (0) ohms. This impedance is comprised of two terms, the resistance (due to material and frequency) and inductance (due to geometry). Unfortunately, this would not be evident from looking at the schematic for the system and result equivalent circuit from this practice is shown in Figure 16 (page 70).

**Actual “Grounding”!**

Since the chassis conductive path is very small (compared to earth) – there may be significant path impedance (Figure 16), resulting in unexplained “ground shift” conditions.

**Signal “Grounding”**

Connecting the signal return to the conductive chassis can cause undesired results due to impedance in the signal current path and/or the presence of other return currents (Figure 17, page 70).

---

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Signal Return – Best Practice
The best solution is to isolate the signal return from conductive paths that are not well controlled or may have interfering currents on them (Figure 18).

SUMMARY
There are undeniable realities of conductors that we need to be conscious of when working with circuits:
- Real conductors have properties of resistance and inductance that need to be considered.
- Conductors are the defined paths for the propagation of electrical energy.
- Wires can be either solid or stranded, with each having advantages and disadvantages.
- Transmission lines have inductance and capacitance that determine their characteristics.

And the moral is that any conductive path needs to be evaluated – not just assumed!

REFERENCES
Conductors and “Conductive Paths”: What Is Really Happening


This article is based on a presentation made during the “Fundamentals” workshop at the 2011 IEEE EMC Symposium and is an example of the type of material discussed at Fundamentals sessions.

**Mark Steffka**, B.S.E., M.S., is a Lecturer (at the University of Michigan – Dearborn), an Adjunct Professor (at the University of Detroit – Mercy) and an automotive company Electromagnetic Compatibility (EMC) Technical Specialist. His university experience includes teaching undergraduate, graduate, and professional development courses on EMC, antennas, and electronic communications. His extensive industry background consists of over 30 years’ experience with military and aerospace communications, industrial electronics, and automotive systems.

Mr. Steffka is the author and/or co-author of numerous technical papers and publications on EMC presented at various Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) conferences. He has also written about and has been an invited conference speaker on topics related to effective methods in university engineering education. He is an IEEE member, has served as a technical session chair for SAE and IEEE conferences and has served as an IEEE EMC Society Distinguished Lecturer. He holds a radio communications license issued by the United States’ Federal Communication Commission (FCC) and holds the call sign WW8MS.

![Figure 18: Isolation of signal return from the conductive path](image1)

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Inductance: The Misconceptions, Myths, and Truth
(Size Matters)

BY BRUCE ARCHAMBEAULT, SAM CONNOR AND MARK STEFFKA

Inductance is one of the most misunderstood and misused concepts in electrical engineering. While in school, we learn about *inductors*, small components we can hold in our hands and lumped elements we can put in a SPICE circuit, but we seldom learn about *inductance*.

We also learned that “inductors” have a property that causes their impedance to increase as frequency increases (Equation 1) and that, when combined with capacitors, they produce resonant circuits. While inductors certainly have inductance (when used in a circuit), we do not need a physical inductor to have inductance!

\[ X_L = 2\pi fL \]  

(1)

Where:
- \( X_L \) is the inductive impedance
- \( f \) is the frequency
- \( L \) is the inductance

**WHY IS THIS IMPORTANT?**

We are constantly exposed to products and components which claim to have low inductance. *This is one of the main causes of the misunderstandings surrounding inductance.*

The fundamental fact is that the only time we have inductance is when there is a loop of current. Without the current loop, we cannot have inductance. Of course, as soon as there is current, the current must return to its source, so there will always be a current loop whenever there is current. This is a fundamental fact of physics. The goal of this article is to try to dispel some of the misconceptions surrounding inductance and to encourage engineers to think more clearly about these physics.

**DEFINITION OF INDUCTANCE**

The definition of inductance comes from Faraday’s Law (Equation 2). If we dissect this equation, and relate it to Figure 1, we see that both sides of the equation require a loop. The left hand side is the integral (or simply the summation) around a closed loop of the electric field multiplied by the length (which is simply the voltage). The voltage around the loop is the same as the voltage across a small gap, as shown in Figure 1. The point being that a loop is required creating the loop inductance.

\[ \oint E \cdot dl = -\oint \frac{\partial B}{\partial t} \cdot dS \]  

(2)
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When we look carefully at the right-hand side of Faraday’s Law, we see that there is a double integral (area of a surface) where the amount of time-varying magnetic flux density within the surface area is summed. Since there is a surface, there must be a defined perimeter, again forming a loop.

The standard unit of inductance is the henry. It is a derived unit that relates the amount of negative voltage created by a time varying current. If the rate of change of the current is 1 ampere/second, then one henry will induce a voltage across the gap (with a magnitude of negative one volt) to resist the change in current.

If the time-varying magnetic field within the surface area is not changing with position (an electrically small loop, for example), then Faraday’s Law reduces to Equation 3.

If we now induce a time-varying current in this loop, there will be a time-varying magnetic flux within the loop. Equation 3 shows us that there will be a negative voltage induced in the loop, effectively impeding the initial flow of current. Clearly, as the size of the loop area becomes larger, the amount of negative voltage (inductive impedance) will increase. The loop area is the primary physical effect that controls the amount of inductance a current will experience.

It is common for someone to expect the inductance of a circuit will be reduced by increasing the conductor size. This will be examined a little later, but it is worth the time to look at a simple formula for finding the inductance of a

$$V = -A \frac{dB}{dt}$$

(3)

Figure 2: Relative impact on loop inductance from Equation 3

Figure 3: Typical surface-mounted decoupling capacitor loop inductance
the function. The radius of the wire, \( r_0 \), the radius of the loop.

\[
L = \mu_0 a \ln \left( \frac{8a}{r_0} \right)
\]  

Where:

- \( L \) = loop inductance
- \( a \) = loop radius
- \( r_0 \) = wire radius

The size of the loop is determined by \( a \), the radius of the loop. This radius is both outside the natural log function and inside the function. The radius of the wire, \( r_0 \), is only within the log function, and so the inductance varies much more slowly with the radius of the wire. Figure 2 shows the relative change in total loop inductance as either the loop radius or the wire radius changes. It is clear that the loop area has a much more significant impact on loop inductance.

The bottom line is that a loop must be defined before the term 'inductance' has any meaning. A simple, straight wire, a braided ground strap, and a surface-mounted capacitor do NOT have inductance by themselves! We could discuss the partial inductance of those items, but until the loop is defined, the inductance is not defined.

When a vendor discusses the inductance of a braided ground strap, how the inductance is determined should be understood so that the user can determine if the braided strap will or will not perform in a similar fashion in his or her application. Similarly, a surface-mounted capacitor often has a specification for an equivalent series inductance (ESL). How is this possible without defining the loop where the current will flow? Again, we need to understand the measurement process. The vendor simply places the capacitor over a very thin insulator with a ground plane beneath it. A voltage is applied between the capacitor's port #1 and ground-reference, the current flows through the capacitor and returns directly below in the ground plane, forming as small a loop as possible. Of course, when the capacitor is used in a real-world printed circuit board and connects to internal PCB layers, the amount of actual inductance is much greater than in the ideal ESL.

**DECOUPLING CAPACITOR CONNECTION INDUCTANCE**

As mentioned in the above section, the actual inductance of a decoupling capacitor mounted on a PCB is much higher than the vendor’s reported ESL. The connection inductance depends on the distance between the vias and the distance from the top (or bottom) mounting location to the planes that are to be decoupled. Figure 3 shows a side view of a typical decoupling capacitor mounting on a PCB.

It is obvious that if the vias are placed close together and the planes to be decoupled are near the top of the PCB (when the capacitor is mounted on the top of the PCB), the connection inductance, represented by the loop, will be minimized. However, there are limits to how close the vias can be placed due to manufacturing issues. There are also limits to how close to the top surface the power/ground-reference planes can be located. So it is important to understand how the mounting will affect the performance of the capacitor and the connection inductance.

Connection inductance alone does not tell the complete story. The inductance associated with the spacing between the power/ground-plane pair, as well as any inductance associated with the distance between the IC and the decoupling capacitor, is not included in the connection inductance calculations.

---

1. The relative impact of the wire size was so small compared to the loop area that a log scale was required to see the effect of wire radius change!

2. Partial inductance will be briefly explained in a later section.
Figures 4 and 5 show common mounting configurations for capacitors of size 0603 and 0402, respectively, for typical manufacturing limits. Table 1 shows some calculated connection inductances (without ESL) for 0805, 0603, and 0402 size SMT capacitors for different depths to the power/ground-reference plane pairs [3-4].

These values are calculated with the example of 7-8 mils from capacitor-to-mounting-pad-edge, 20 mils from capacitor-mounting-pad-edge-to-via-pad, via pad diameter of 20 mils, via barrel size of 10 mils, and trace width equal to 20 mils. The absolute minimum distance from via pad to capacitor mounting pad edge is reported to be 10 mils, but typically 20 mils is used to be safe.

The distance between the via pad and the capacitor mounting pad was kept to a small value in the above calculations. If this distance is increased slightly to 50 mils, the connection inductance increases to the values in Table 2.

The connection inductance plays a much greater role in the performance of decoupling capacitors than the typical ESL of these components. Connection inductance values of 1 to 3

---

<table>
<thead>
<tr>
<th>Distance from board to planes (mils)</th>
<th>0805 typical/minimum (148 mils between via barrels)</th>
<th>0603 typical/minimum (128 mils between via barrels)</th>
<th>0402 typical/minimum (106 mils between via barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.2 nH</td>
<td>1.1 nH</td>
<td>0.9 nH</td>
</tr>
<tr>
<td>20</td>
<td>1.8 nH</td>
<td>1.6 nH</td>
<td>1.3 nH</td>
</tr>
<tr>
<td>30</td>
<td>2.2 nH</td>
<td>1.9 nH</td>
<td>1.6 nH</td>
</tr>
<tr>
<td>40</td>
<td>2.5 nH</td>
<td>2.2 nH</td>
<td>1.9 nH</td>
</tr>
<tr>
<td>50</td>
<td>2.8 nH</td>
<td>2.5 nH</td>
<td>2.1 nH</td>
</tr>
<tr>
<td>60</td>
<td>3.1 nH</td>
<td>2.7 nH</td>
<td>2.3 nH</td>
</tr>
<tr>
<td>70</td>
<td>3.4 nH</td>
<td>3.0 nH</td>
<td>2.6 nH</td>
</tr>
<tr>
<td>80</td>
<td>3.6 nH</td>
<td>3.2 nH</td>
<td>2.8 nH</td>
</tr>
<tr>
<td>90</td>
<td>3.9 nH</td>
<td>3.5 nH</td>
<td>3.0 nH</td>
</tr>
<tr>
<td>100</td>
<td>4.2 nH</td>
<td>3.7 nH</td>
<td>3.2 nH</td>
</tr>
</tbody>
</table>

Table 1: Connection inductance for typical capacitor configurations

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4. See references for details on the formula used for this calculation.
Inductance: The Misconceptions, Myths, and Truth (Size Matters)

MUTUAL INDUCTANCE

Mutual inductance is a measure of the current induced in a second loop, due to the flux from the first loop (Figure 6). As described above, a time-varying current in the first loop will create time-varying magnetic flux. If a second loop is close to the first loop, a significant portion of this magnetic field flux will penetrate the second loop, inducing a time-varying current in the second loop.

Figure 6 shows the two loops in a co-planar orientation. If they are oriented perpendicularly to each other, then the lines of flux from Loop 1 will not penetrate Loop 2, and there will be no mutual inductance. If one of the loops is made much smaller, then the amount of flux is reduced, again reducing the mutual inductance. And finally, as the loops are moved further apart, the magnetic flux penetrating the second loop decreases rapidly, which also reduces mutual inductance.

5. This is approximate. There would be a small amount of flux lines within the conductors, creating a small amount of mutual inductance.

Table 2: Connection inductance for typical capacitor configurations with 50 mils from capacitor pad to via pad

<table>
<thead>
<tr>
<th>Distance from board to planes (mils)</th>
<th>0805 (208 mils between via barrels)</th>
<th>0603 (188 mils between via barrels)</th>
<th>0402 (166 mils between via barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.7 nH</td>
<td>1.6 nH</td>
<td>1.4 nH</td>
</tr>
<tr>
<td>20</td>
<td>2.5 nH</td>
<td>2.3 nH</td>
<td>2.0 nH</td>
</tr>
<tr>
<td>30</td>
<td>3.0 nH</td>
<td>2.8 nH</td>
<td>2.5 nH</td>
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<td>40</td>
<td>3.5 nH</td>
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<td>2.8 nH</td>
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<td>50</td>
<td>3.9 nH</td>
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<td>4.5 nH</td>
<td>4.2 nH</td>
<td>3.7 nH</td>
</tr>
<tr>
<td>80</td>
<td>4.9 nH</td>
<td>4.5 nH</td>
<td>4.0 nH</td>
</tr>
<tr>
<td>90</td>
<td>5.2 nH</td>
<td>4.7 nH</td>
<td>4.3 nH</td>
</tr>
<tr>
<td>100</td>
<td>5.5 nH</td>
<td>5.0 nH</td>
<td>4.6 nH</td>
</tr>
</tbody>
</table>

nanohenries are typical with the most common surface-mount capacitor sizes and manufacturing technologies. Using the tables, engineers can decide if a decoupling capacitor is better placed on the top or bottom surface of the PCB in order to provide charge to the power/ground-reference plane pairs.

Figure 6: Mutual inductance from current in one loop creating flux in second loop

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The definition of inductance requires a current flowing in a loop. Without a complete loop, there cannot be inductance. Practical considerations, however, lead us to discuss the inductance of a part of the overall current loop, such as the inductance of a capacitor. This idea of discussing the inductance of only a portion of the overall loop is called partial inductance [4]. Partial inductances can be combined to find the overall inductance. For the simple case of a rectangular loop of wire where sides 1 and 3 are parallel to each other and so are sides 2 and 4 (see Figure 7), Equation 5 can be used to calculate the total inductance from the partial inductances.

\[ L_{\text{total}} = L_{p1} + L_{p2} + L_{p3} + L_{p4} - M_{p13} - M_{p24} \]  

(5)

Figure 7 shows this distributed inductance concept and relates back to Equation 5. In each portion of the loop we assign a partial inductance value as well as partial mutual inductance between all parts of the loop. Though the conductors may have different sizes, it is not a problem to calculate the partial inductance values. Naturally, if the current follows a more complex path, additional partial inductances and partial mutual inductances will be needed.

The concept of partial inductance is especially useful when the physical geometry is complex and it is difficult to assign the loop inductance to any one location around the loop. For example, Figure 8 shows current flow from the power plane in a PCB through the output driver of an IC, through a trace to the IC load, and finally through the ground-reference plane back to the power supply source. Since there is a closed loop of current, there is an inductance associated with that current path … but where could we place the loop inductance in this circuit? First of all, since the various conductors have different sizes, it would be impossible to find a formula to find the loop inductance. However, since we know this inductance exists (even if we cannot calculate it easily),

6. In this case, we only show the partial mutual inductance of the parallel sections, since perfectly perpendicular conductors will not have any mutual inductance.
where would we place the inductance? If we choose location ‘A’, then we ignore any voltage drop in the other conductors due to inductive impedance. The same is true for the other locations (B, C, and D). The inductance is actually a distributed quantity and must be considered to be throughout the loop. The concept of partial inductance allows us to do this.

The partial inductance for a length of wire is given by (6), and the partial mutual inductance between a pair of parallel wires is given in (7).

\[
L_p = \frac{\mu_0}{2\pi} \left[ \log \left( \frac{l}{r} \right) + 1 \right] \left[ \frac{r}{l} - \frac{r}{l} \right] + 1
\]

(6)

\[
M_{12} = \frac{\mu_0}{2\pi} \left[ \log \left( \frac{l}{d} \right) + 1 \right] \left[ \frac{d}{l} - \frac{d}{l} \right] + 1
\]

(7)

Where:
- \( l \) = length of wire
- \( r \) = radius of wire
- \( d \) = distance between parallel wires

Figure 9 shows the partial mutual inductance for two parallel 10 cm long wires. Note that when the wires are close together, the partial mutual inductance is very high. Referring back to (5), we see that when the partial mutual inductance is high, the total inductance is low (because it is subtracted). When the wires are close, the loop area would be smaller, resulting in a lower inductance, as expected. Calculations for more complex geometries can be found in [5].

**SUMMARY**

The basic principle that inductance requires current to flow in a loop is an important concept to understand. This is not unreasonable since current *must* flow in a loop. The size of the current loop determines the amount of inductance.
Inductance is a basic building block in electronic circuits. That is, as soon as metal conductors are used and current flows through them, inductance exists. This inductance becomes the limiting factor in all high-frequency circuits. When capacitors are used as filter elements, the natural inductance associated with the current flowing though the capacitor limits the frequency range where the capacitor is an effective filter component.

Partial inductance is a useful concept, since with partial inductances one can discuss the contribution of a single part of the loop to the total inductance. An example is the via connecting between different layers on the PC board, the metal stand-off post between the PC board and the chassis, and traces on the PC board connecting filter components. Each of these metal structures can be analyzed to find their partial inductances, and the results can then be combined to find the total inductance.

This has been a very brief introduction to inductance. A much more complete study of this subject is available in the references.

REFERENCES

Dr. Bruce Archambeault is an IBM Distinguished Engineer at IBM in Research Triangle Park, NC and an IEEE Fellow. He received his B.S.E.E degree from the University of New Hampshire in 1977 and his M.S.E.E degree from Northeastern University in 1981. He received his Ph. D. from the University of New Hampshire in 1997. His doctoral research was in the area of computational electromagnetics applied to real-world EMC problems. He is the author of the book “PCB Design for Real-World EMI Control” and the lead author of the book titled “EMI/EMC Computational Modeling Handbook”.

Sam Connor is a Senior Technical Staff Member at IBM and is responsible for the development of EMC and SI analysis tools/applications. Mr. Connor’s current work activities and research interests also include electromagnetic modeling and simulation in support of power distribution and link path design for printed circuit boards. He has co-authored more than 20 papers in computational electromagnetics, mostly applied to decoupling and high-speed signaling issues in PCB designs. He is a Senior Member of the IEEE and is currently the Chair for the TC-9 subcommittee of the IEEE EMC Society.

Mark Steffka, B.S.E., M.S., is a Lecturer (at the University of Michigan - Dearborn), an Adjunct Professor (at the University of Detroit – Mercy) and an automotive company Electromagnetic Compatibility (EMC) Technical Specialist. His university experience includes teaching undergraduate, graduate, and professional development courses on EMC, antennas, and electronic communications. His extensive industry background consists of over 30 years’ experience with military and aerospace communications, industrial electronics, and automotive systems. Mr. Steffka is the author and/or co-author of numerous technical papers and publications on EMC presented at various Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) conferences. He has also written about and has been an invited conference speaker on topics related to effective methods in university engineering education. He is an IEEE member; has served as a technical session chair for SAE and IEEE conferences and has served as an IEEE EMC Society Distinguished Lecturer. He holds a radio communications license issued by the United States’ Federal Communication Commission (FCC) and holds the call sign WW8MS.
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