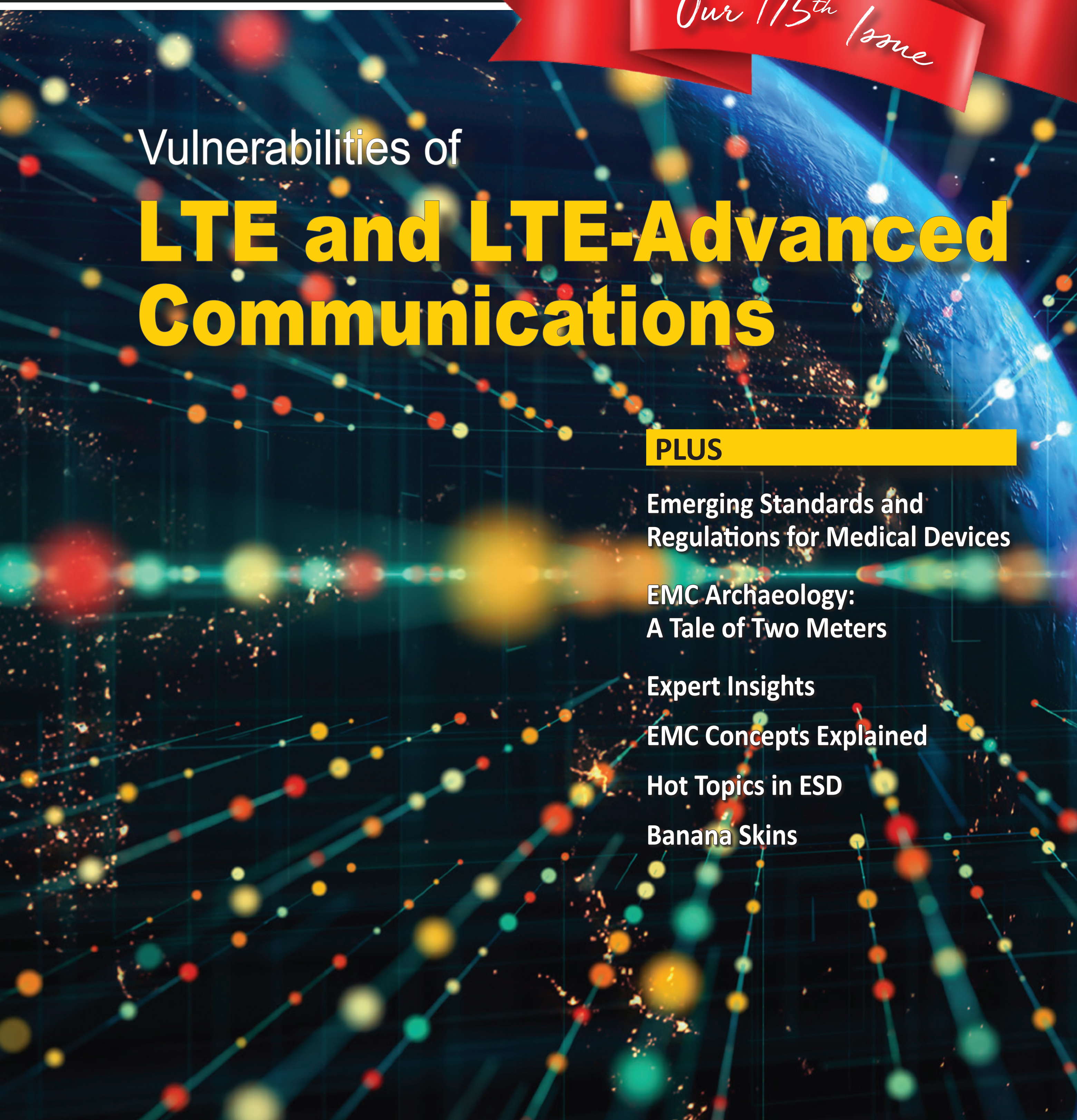
JUNE 2024

IN COMPLIANCE™

THE COMPLIANCE INFORMATION RESOURCE FOR ELECTRICAL ENGINEERS

Our 175th Issue



Vulnerabilities of

LTE and LTE-Advanced Communications

PLUS

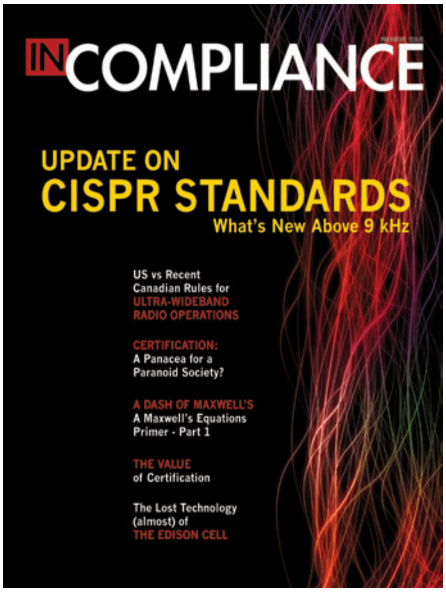
- Emerging Standards and Regulations for Medical Devices
- EMC Archaeology: A Tale of Two Meters
- Expert Insights
- EMC Concepts Explained
- Hot Topics in ESD
- Banana Skins

175 ISSUES, ONE UNWAVERING MISSION

Dear Friends and Valued Members of the Electronics Compliance Community,

It is with immense pride and gratitude that we celebrate a significant milestone in the history of *In Compliance Magazine* - the publication of our 175th issue. This achievement is a testament to the dedication, hard work, and unwavering support of our entire community, including our talented writers, industry experts, loyal advertisers, and most importantly, you, our readers.

Since our inception, *In Compliance Magazine* has been committed to providing the electronics compliance community with the most comprehensive, reliable, and engaging content possible. We have strived to be your trusted source for industry news, technical insights, best practices, and thought-provoking perspectives on the ever-evolving world of electronics compliance.



Premiere Issue 2009

Over the years, we had the privilege of covering important technological advancements, navigating complex regulatory landscapes, and exploring the latest trends and challenges facing electronics compliance professionals. Through it all, our mission has remained the same: to inform, educate, and empower our readers to excel in their roles and drive the industry forward.

As we reflect on the past 175 issues, we are filled with a deep sense of gratitude for the incredible community that has grown around *In Compliance Magazine*. Your passion, expertise, and willingness to share your knowledge and experiences have been the driving force behind our success. We are inspired by your commitment to excellence, your innovative spirit, and your tireless efforts to create a safer, more compliant world.

Looking ahead, we are excited to continue serving as your partner and resource in the electronics compliance field. We remain dedicated to delivering the high-quality content and valuable insights you have come to expect from *In Compliance Magazine*, while also exploring new ways to engage, inform, and support our community.

Thank you for being a part of our journey and for trusting us to be your guide in the dynamic world of electronics compliance. We look forward to continuing to grow and learn together, and to celebrating many more milestones in the years to come.

With heartfelt appreciation,

The *In Compliance Magazine* Team

IN COMPLIANCE

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FEATURE ARTICLES

SPECIAL COVERAGE

COLUMNS

DEPARTMENTS

FCC Fines Major Wireless Carriers for Sharing Customer Information

Wireless Carriers Learn Costly Lesson in Customer Data Protection Compliance

The U.S. Federal Communications Commission (FCC) has issued fines of nearly $200 million against four major wireless carriers for illegally sharing access to customers' location information without consent.

According to a press release issued by the FCC, forfeiture penalties have been issued against Sprint, T-Mobile, AT&T, and Verizon for violations of section 222 of the Communications Act, which requires carriers to protect customer information and to maintain the confidentiality of customer information unless a customer expressly consents to the access or use of their information.

T-Mobile has been assessed $80 million in penalties, followed by AT&T (assessed $57 million), Verizon ($47 million), and Sprint (more than $12 million).

In its press release, the FCC notes that the fines follow investigations of the release of customer information to a Missouri Sherrif by a "location-finding service" that provides communication services to correctional facilities to track the location of individuals. The FCC says that, even after being notified of the violation, the carriers involved continued to operate their programs without putting reasonable safeguards in place to limit access to their customers' data.

FDA Releases Reports on Medical Device Safety Initiatives

The Center for Devices and Radiological Health (CDRH) at the U.S. Food and Drug Administration (FDA) has released its latest reports on the agency's activities in support of the safety and innovation of medical devices.

The "2024 CDRH Safety Report" is a 10-page slide deck highlighting the agency's recent and current efforts to support its regulatory vision for medical devices, that is, ensuring that "Patients in the U.S. have access to high-quality, safe, and effective medical devices of public health importance first in the world."

Specific CDRH activities addressed in the Safety Report include: 1) enhancing manufacturing quality; 2) strengthening post-market surveillance; 3) increasing data transparency; 4) strengthening medical device recall programs; and 5) executing the agency's medical device safety action plan.

The release of the 2024 Safety Report is concurrent with the release of the "2024 CDRH Innovation Report," which addresses: 1) encouraging innovation; 2) increasing regulatory flexibility; 3) partnering with patients and stakeholders; and 4) collaborating with innovators.

Consumer Broadband Label Requirement Now in Effect

The U.S. Federal Communications Commission's (FCC's) rules requiring broadband service providers to display consumer-friendly labels are now in effect.

The new rules, which came into force on April 10, 2024, for wired and wireless broadband service providers with more than 100,000 subscriber lines, are intended to provide consumers with important, up-front information about broadband prices, introductory rates, data allowances, and broadband speeds. According to the FCC, the goal of the new labeling requirements is to help consumers make informed decisions when it comes to subscribing for broadband services. Service providers with 100,000 or fewer subscribers have until October 10, 2024, to comply with the new requirements.

The FCC's consumer broadband label is similar in format to nutrition labels mandated by the U.S. Food and Drug Administration (FDA). The FCC has issued a "Consumer Fact Sheet" that details the required and recommended content for broadband labels.

Amateur Radio Saves Family in Death Valley National Park

Our lives today are filled with new and exciting communications technologies that help us to stay in touch no matter where we are. But, sometimes, it's legacy technologies that come to our aid in times of distress.

A recent posting to the website of the ARRL tells the story of a family trapped in the remote desert that is the Death Valley National Park. It seems that their vehicle became stuck in the mud and they were unable to free the vehicle. Unfortunately, it was an area of the park that had no access to cellular service.

Fortunately, one member of the trapped family is an amateur radio operator, who was able to transmit calls for help on the 10-meter band. The signal was picked up by a fellow amateur operator based in Ohio, who was able to identify the call sign and the general location of the family before he lost the signal. He then posted the information on the "Parks in the Air" Facebook page, asking other operators to scan for the distress signals.

The distress signals were quickly picked up by other amateur radio operators, who were able to contact emergency officials in the area of the Park, leading to the rescue of the family within just a few hours.

Credit: Oleg Kovtun

People

Mark Steffka Honored with Faculty of the Year Award

The University of Detroit Mercy's College of Engineering and Science recently held its 91st annual Slide Rule event, a long-standing tradition that honors the achievements of students and faculty.

This year, Mark Steffka, who began as an adjunct professor in 2006 while working at General Motors and later transitioned to full-time teaching in 2019, was awarded the prestigious Faculty of the Year award for the Engineering department.

This recognition comes as Steffka approaches his retirement at the end of the 2024 school year, celebrating his outstanding teaching and dedication to student success throughout his time at Detroit Mercy.

AI Watch

How AI is Changing Regulation of Medical Devices

A recent paper published in the *Journal of Law and the Biosciences* maps out how the introduction of artificial intelligence (AI)-based medical devices may challenge current regulatory requirements, including the European Union's Medical Device Regulation (MDR). The authors, who are affiliated with the Oxford Internet Institute in the United Kingdom, question the extent to which MDR requirements close the gap between AI's expected benefits and current efforts to assess clinical utility beyond the scope of current performance algorithms. The paper recommends that the EU Commission provide further guidance on the assessment of AI-based medical devices.

Associations

Element Joins the 5G Automotive Association

Element has announced its membership in the 5G Automotive Association (5GAA), a global, cross-industry association of automotive, technology, and telecommunications companies. The company says that its subject matter experts will participate in at least five of the SGAA's seven working groups, enabling Element to contribute its technical knowledge and expertise in the future development of end-to-end solutions for connected mobility systems, devices, and applications.

Awards

University of Sydney Awarded $18 Million for National Quantum Center

The government of Australia has awarded a grant of $18.4 million to the University of Sydney to establish a national quantum research center in that country. The new center, to be named Quantum Australia, is intended to support the growth of the quantum industry and ecosystem in Australia. Australia consistently ranks among the top five nations for quantum research and quantum computing patents, and has one of the largest quantum workforces in the world.

TDK RF Solutions Wins Silver IGUS Vector Award for 2024

TDK RF Solutions has received the 2024 Silver IGUS Vector Award for developing a roller test rig to facilitate vehicle-in-the-loop (VIL) testing for electromagnetic compatibility (EMC). The innovative rig design uses energy chains made of high-performance plastics and slip-ring-free cable drums to guide the high-performance frequency cables, significantly increasing system reliability and reducing maintenance downtime.

Facilities

UL Solutions to Open Advanced Battery Laboratory

UL Solutions is on track to open its new advanced battery laboratory and testing facility in Auburn Hill, MI. According to the company, the new laboratory will use state-of-the-art testing equipment and methodologies to conduct comprehensive battery safety testing and performance evaluations for the EV and industrial battery industries. The advanced battery laboratory is slated to open on August 7th.

Keyystone Compliance Plans Significant Expansion of Facility

Keystone Compliance is moving ahead with plans to dramatically increase its existing laboratory and testing facility in New Castle, PA. The planned expansion includes the construction of three additions to its current facility, totaling more than 14,000 square feet, and is expected to accommodate additional laboratory space at the facility.

Wurth Electronics Midcom Establishing a New Headquarters

Wurth Electronics Midcom, a division of Würth Elektronik, has announced the planned construction of a new 70,000 square foot facility in Watertown, SD. The new state-of-the-art facility will serve as the headquarters of the company's U.S. operations for R&D, engineering, marketing, and sales, as well as providing warehouse facilities for both North and South America. Construction of the new facility is expected to be completed by Spring 2026.

Mergers & Acquistions

Bureau Veritas Closes Mexico Acquisition

Bureau Veritas has announced the acquisition of ANCE S.A. de C.V., a leading Mexican-based organization offering conformity assessment services for electrical and electronic products and devices in that country. ANCE currently employs approximately 400 people in multiple laboratory locations throughout Mexico. Bureau Veritas says that the ANCE acquisition will help to support Mexico's continued importance as an importer, manufacturer, and exporter of technology products, while also expanding Bureau Veritas' presence in the Americas.

Averna Acquires Automated Test Solutions Provider ELCOM

Averna has acquired ELCOM, a.s., a testing and quality solutions provider focused on the automotive, EV, energy, and industrial automation markets. According to Averna, the acquisition, which includes ELCOM subsidiaries RH-Tech s.r.o. and ELTIA s.r.o., significantly expands the company's current capacity in power electronics, machine vision, power grid measurement and analysis, and industrial automation and will support Averna's efforts to meet the automated testing needs of customers around the world.

Send news and updates about your company to: editorial@incompliancemag.com

Upcoming Events

June 13

mmWave Communications Technologies Webinar

June 16-21

★ International Microwave Symposium (IMS)

June 17-20

Military Standards 810 (MIL-STD-810) Test Training

June 18-20

The Battery Show Europe

June 24-26

Sensors Converge Expo

July 11

MIL-STD 461/810 Webinar

July 14-19

2024 IEEE International Symposium on Antennas and Propagation

July 15-18

Military Standards 810 (MIL-STD-810) Test Training

August 5-9

★ 2024 IEEE International Symposium on Electromagnetic Compatibility, Signal Power Integrity (EMC+SIPI)

August 15

Integrating Modules

★ Visit In Compliance's booth at these events!

JUST STARTING OUT IN EMC?

By Kenneth Wyatt

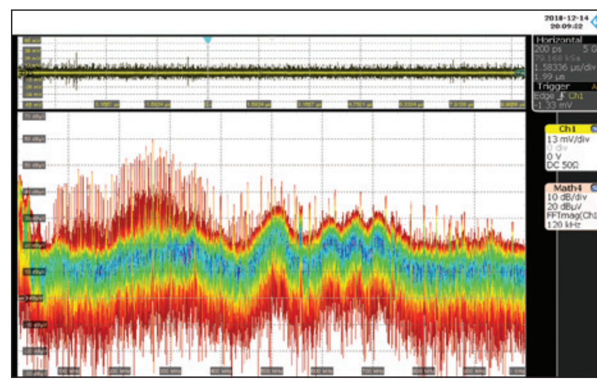
With all the many pressures you have as a product designer, does electromagnetic compliance (EMC) always seems like a stumbling block to delaying product sales? Is your product exhibiting one of the top three failures; radiated emissions, electrostatic discharge or radiated immunity? Are you continually cycling between design/fixing - running to the compliance test lab - failing again - and back to shot-gunning more fixes? Wondering how to attack these issues earlier in the design cycle? Would you like to learn how to characterize and troubleshoot simple design issues right on your workbench? Then this is monthly column is for you!

Unfortunately, most colleges and universities fail to include courses on electromagnetic compatibility, so most product designers are forced to "learn the hard way" through multiple compliance failures. In today's world of multiple digital products and wireless wearables, product-to-product compatibility becomes important. Products must be designed so they don't interfere with other products or communications system (limits on emissions) and must continue to work in an environment with radiated fields (ex., two-way radios) and power line transients (immunity). Compliance testing must be performed for the U.S and worldwide markets before sales can start. Compliance failures are often a roadblock to sales.

This series of articles will help you with some resources, go through some basic EMC design concepts and help you create your own EMC troubleshooting kit to use for in-house characterization and troubleshooting. We'll also discuss simple ways of using these new tools to perform your own in-house emissions and immunity pre-compliance testing.

To start off, I'd like to provide you a list of my most recommended books, web sites with educational content and publications, along with short descriptions.

Do your product emissions look like this? Uh oh, not good!



RECOMMENDED BOOKS

Yes, I'm biased, so have included my three recent books, The "EMC Trilogy", in the listing. In my opinion, those listed in red should be the first to consider adding to your library if you're just starting out in the field.

- ANDRÉ AND WYATT - **EMI Troubleshooting Cookbook for Product Designers,** SciTech Publishing, 2014. Includes chapters on product design and EMC theory & measurement. A major part of the content includes how to troubleshoot and mitigate all common EMC test failures.
- ARMSTRONG – **The Physical Basis of EMC**, Nutwood UK Publications, 2010. An excellent treatment of EMC basics and theory and includes emissions, immunity and coupling/crosstalk.
- ARMSTRONG **– EMC Design Techniques for Electrical Engineers**, Nutwood UK Publications, 2010. This 460-page handbook covers all aspects of product design for EMC compliance.
- ARMSTRONG – **EMC for Printed Circuit Boards**, Nutwood UK Publications, 2010 (2nd edition). Practical aspects of PC board design for EMC.
- BOGATIN - **Signal & Power Integrity - Simplified**, Prentice-Hall, 2018 (3rd Edition). Great coverage of signal and power integrity from an electromagnetic fields viewpoint.
- BOGATIN – **Bogatin's Practical Guide to Prototype Breadboard and PCB Design**, Artech House, 2021. This is a practical textbook used for his students at University of Colorado – Boulder on taking designs from breadboard to final PC boards incorporates all aspects of power integrity, signal integrity and EMC.
- MONTROSE – **EMC and the Printed Circuit Board**, IEEE Press, 1999. Describes basic EMC theory and design for PC boards.

- MORRISON - **Grounding and Shielding - Circuits and Interference**, Wiley, 2016 (6th Edition). The classic text on grounding and shielding with up to date content on how RF energy flows through circuit boards.
- MORRISON - **Fast Circuit Boards - Energy Management**, Wiley, 2018. A brand-new book explaining how digital signals, in the form of electromagnetic energy, moves through circuit boards. Destined to be a classic.
- OTT - **Electromagnetic Compatibility Engineering**, Wiley, 2009. The "bible" on EMC measurement, theory, troubleshooting and product design. The content is somewhat dated (examples are through-hole technology, for example) and the suggested PC board stack-ups are no longer recommended (unless all six of his rules are followed), otherwise his theory is sound.
- PAUL - **Introduction to Electromagnetic Compatibility**, Wiley, 2006 (2nd Edition). The one source to go to for an upper-level course on EMC theory. Again, the content is dated, but the theory is sound.
- SANDLER - **Power Integrity - Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems**, McGraw-Hill, 2014. The latest information on measurement and design of power distribution networks (PDNs) and how the network affects stability and EMC.
- SMITH AND BOGATIN - **Principles of Power Integrity for PDN Design - Simplified**, Prentice-Hall, 2017. Getting the power distribution network (PDN) design right is one key to reducing EMI.
- WYATT – **Create Your Own EMC Troubleshooting Kit (Volume 1)**, WTS Publishing, 2022 (2nd Edition). Lists of test equipment, probes and accessories for performing your own EMC troubleshooting in-house.
- WYATT – **Workbench Troubleshooting EMC Emissions (Volume 2)**, WTS Publishing, 2021. How to use the tools in Volume 1 to troubleshooting radiated and conducted emissions.
- WYATT – **Workbench Troubleshooting EMI Immunity (Volume 3)**, WTS Publishing, 2021. How to use the tools in Volume 1 to troubleshoot the most common immunity issues; radiated immunity, ESD and EFT.

RECOMMENDED WEB SITES

These are some of the leading EMC-related web sites with educational content:

- **Academy of EMC**, https://www.academyofemc.com. A compilation of EMC information.
- **Andy Eadie (EMC Fast Pass)**, https://emcfastpass.com. Consultant with tutorials and videos. Also sells used EMC chambers and rents/sells some new and used equipment.
- **Clemson University Vehicular Electronics Laboratory**, http://www.cvel.clemson.edu/emc/index.html. A compilation of EMC information and on-line tools.
- **Doug Smith (Doug Smith Associates)**, http://emcesd.com. Consultant with tutorials and videos.
- **Grand Valley State University, EMC Center**, https://www.gvsu.edu/emccenter. A compilation of EMC information and blogs.
- **In Compliance Magazine**, http://incompliancemag.com. A monthly publication and online collection of EMC articles.
- **IEEE EMC Society**, http://www.emcs.org. The primary organization of EMC engineers worldwide.
- **Interference Technology**, https://interferencetechnology.com. A collection of EMC articles.
- **Keith Armstrong**, https://www.emcstandards.co.uk. Consultant with tutorials, training and videos.
- **Kenneth Wyatt (Wyatt Technical Services LLC)**, http://www.emc-seminars.com. Consultant with tutorial, trainings and videos.
- **Missouri University of Science & Technology EMC Lab**, https://emclab.mst.edu. A compilation of information, tutorials, and academic papers, largely mirrored at Dr. Todd Hubing's web site.
- **Patrick André (Patrick André Consulting)**, http://andreconsulting.com. Consultant with tutorials.
- **Todd Hubing (LearnEMC)**, http://learnemc.com. Consultant with tutorials, training and videos.
- **University of Oklahoma EMC**, https://www.ou.edu/coe/tcom/laboratories/wecad. A compilation of articles.

RECOMMENDED EMC CONSULTANTS

I know many companies often need a little help towards the end of their design in achieving EMC compliance. Here is a listing of recommended consultants from In Compliance's Consultant Directory: https://www.incompliance-directory.com/onlinedirectory/listing-category/consulting. Some listed here are EMC Test labs (some of which have technical competence in consulting), some are providers of EMC components, and some are independent consultants.

SUMMARY

This is probably more information than possible to digest in the next month, but was much more than I had when just starting out as an EMC engineer for Hewlett-Packard back in 1986! Next month, let's start gathering the minimal tools to start evaluating products earlier in the design cycle.

AMPLIFIER OPERATIONAL CLASSES AND OTHER IMPORTANT RF AMPLIFIER SPECIFICATIONS

By Don MacArthur

Because the typical RF amplifier costs a considerable amount of money, it is important to gain at least a rudimentary understanding of amplifier operational classes and other important specifications before selecting one for a specific application. Not performing some type of "due diligence" could cost dearly. As such, the following provides rudimentary knowledge and additional references should one decide to dig deeper into this very important subject.

Pro Tip: No matter what – always carefully read the datasheet/specifications before deciding to purchase any amplifier!

AMPLIFIER OPERATIONAL CLASS TYPES

Some of us with education or backgrounds in electrical/electronics may recall studying transistor bias modes or the percentage of the time during which the amplifier is "amplifying" or conducting power and different operational classes of amplifiers. The idea is the same here:

- Class A: Conducts over the entire (360°) of the input power cycle.
- Class B: Conducts (with large nonlinearities) over half (180°) of the input power cycle. Not suitable for RF applications.
- Class C: Conducts over less than half (< 180°) of the input power cycle. Primarily used for pulse applications and not addressed in this article.
- Class A/B: Compromise between Class A and Class B where the conduction angle is intermediate; each of the two active elements conducts more than half the time.

From the above list of amplifier operational class types, the two most widely used in RF applications are Class A and Class A/B.

CLASS A AND CLASS A/B AMPLIFIER TYPES, PROS AND CONS

Class A amplifiers provide the most accurate reproduction of the input signal, have lower harmonics, have no cross-over distortion, and are robust to any impedance mismatches between their outputs and the load (VSWR). However, Class A amplifiers are less efficient, requiring greater power requirements and producing more heat than their Class A/B counterparts.

On the other hand, Class A/B amplifiers are more efficient, produce lower junction temperatures, and are physically smaller than their Class A counterparts. However, Class A/B amplifiers do have some drawbacks. These drawbacks include less-than-ideal linear performance, susceptibility to damage from mismatches between their outputs and the load (VSWR), and can suffer from cross-over distortion.

OTHER IMPORTANT AMPLIFIER SPECIFICATIONS

Other important specifications to consider include gain (dB), gain flatness (+/- dB), harmonics (dBc), saturated power (dBm), linear power (dBm), and load Voltage Standing Wave Ratio (VSWR).

LINEAR POWER (P1DB)

Although it is very important to pay attention to all of these specifications in relation to your application, one of the most important to understand is linear power, also known as P1dB. This specification is described as the output power at which the gain has varied by +/- 1dB from its small signal level. If the gain varies by more than +/- 1dB, then the amplifier is not able to reproduce the input signal faithfully, and the signal integrity of the output waveform is suspect and cannot be relied upon. In some instances, this may be okay, but it is not in other areas, such as fully compliant EMC testing to RF immunity standards like IEC 61000-4-3.

VOLTAGE STANDING WAVE RATIO (VSWR)

Another important specification when researching RF amplifiers is Voltage Standing Wave Ratio or VSWR.

When connecting an amplifier's output to a load, the ideal condition is when the impedance of the output matches the input. When both impedances match, the load absorbs all the power generated by the amplifier, and none is reflected into the amplifier. The problem is that this ideal condition does not exist in real life. The load to the amplifier is typically an antenna, and the input impedance changes depending on frequency. If the VSWR is severe enough (load is completely open or short), then the amount of power reflected into the amplifier is extreme and damages it, rendering it inoperable until repaired. Even when used with extreme care, preventing connection to high VSWR loads is nearly impossible. It is, therefore, important that amplifier manufacturers design their amplifiers to handle (continue to operate without damage) situations where VSWR is severe.

SUMMARY

In summary, this article has covered why amplifier class is important depending on the application and reviewed the pros and cons of Class A versus Class A/B amplifiers. It further described the meaning and usefulness of P1dB and Voltage Standing Wave Ratio capabilities when choosing an RF amplifier.

REFERENCES

1. Jones, N., Amplifier selection | What you need to know (video), retrieved from: https://ametek-3.wistia.com/medias/fqxmmg92ck
2. Jones, N., Amplifier selection | What you need to know (PDF), retrieved from https://www.ametek-cts.com/-/media/ametekcts/documents/applicationnotes/tn0111_amplifier-selection_what-you-need-to-know.pdf
3. Amplifier Research, Orange Book of Knowledge, 9th Edition. https://arworld.us/orange-book-request

Specification	Class A	Class A/B
Linearity	Excellent	Poor
Harmonics	Low	High
Cross-over distortion	None	Present
VSWR Capabilities (High reflected power conditions can damage the amplifier)	Excellent (Implemented with hardware)	Poor (Software controlled VSWR foldback protection required)
AC Power Requirements	High	Low
Efficiency	Low	High
Junction temperatures	High	Low
Size	Medium to Large	Small

Class A and Class A/B Amplifier Types, Pros and Cons

WHAT IS THE RTCA?

By Patrick André

One question I have heard is, 'What is the RTCA?' In the EMC field, most people know the RTCA as the group that creates the aeronautic environmental standard DO-160. However, beyond establishing tests and test levels for environmental testing of avionics, the RTCA's work reaches far beyond DO-160.

The Radio Technical Commission for Aeronautics, now known as RTCA, was established in 1935 with a focus on the standardization and assurance of safety of radio communication and radar systems. This led to other developments, such as a common system for air traffic controllers across the United States. The work is not specifically performed by the RTCA but rather by groups and committees of industry experts and specialists in a specific field. In doing so, industry has a direct say in how standards are established while recognizing that the quality of these standards must be maintained at a high level.

> The Radio Technical Commission for Aeronautics, now known as RTCA, was established in 1935.

The RTCA is a private, not-for-profit organization and not an agency of the US Government. The organization covers the hardware and software used for flight control and navigation, collision avoidance, audio systems, night vision systems, flight deck displays, weather detection, among other areas. For example, portable electronics used by passengers and flight crew must also be researched and regulated for safe use on commercial aircraft and to ensure that avionics are not affected.

The RTCA has members from over 460 commercial aerospace companies and other interested corporations and groups. The standards, operational situations, architectures, and other documents that are within RTCA's control are in the form of Minimum Aviation System Performance Standards (MASPS), Minimum Operational Performance Standards (MOPS), Safety & Performance Requirements (SPR), Interoperability Requirements (INTEROP) and other publications. There are about 500 documents currently available from the RTCA, with many available in either hard copy or electronic format.

The RTCA works with the FAA in the United States and with EUROCAE - The European Organization for Civil Aviation Equipment. EUROCAE and the RTCA often work in cooperation with each other to create common standards and regulations. For example, DO-160 in the United States has a EUROCAE counterpart, ED-14, which both groups have agreed to in totality.

Committee meetings are typically open to the public. However, voting and suggestions for changes are allowed only by members of the RTCA. However, input from all aspects of the aerospace industry is welcomed.

The website for the RTCA is https://www.rtca.org.

Next time, we will look at DO-160 specifically, its development, and the upcoming revision.

HAM RADIO? IS THAT STILL “A THING”?

By Kimball Williams

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

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

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

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

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

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

> Just how many people are really involved in this activity? Currently available numbers indicate that there are more than 700,000 Ham in the USA and over 3,000,000 worldwide!

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

So, if Ham radio is still “a thing,” just how many people are really involved in this activity? Currently available numbers indicate that there are more than 700,000 Ham in the USA and over 3,000,000 worldwide!

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

kw N8FNC

Ask the Expert

Every company has a story. Get to know some of the most influential compliance partners in the wireless EMC industry.

a special sponsored section

TÜV Rheinland North America

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Our Story

TÜV Rheinland's journey began in 1872 with a dedication to leveraging technology for humanity's benefit. Initially focused on steam boiler safety, we've evolved into a global testing, inspection and certification leader. Our recent expansion includes a state-of-the-art lab in Greater Boston and broader accreditations in Pleasanton, CA, reaffirming our commitment to safety, quality, and environmental responsibility.

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Norm and Mike Violette

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Our founder and my father, Dr. JL Norman Violette, brought this to bear growing up in of all places: China, Maine, a dirt-poor part of these United States and not far from Mud Pond, where the catfish scrabbed for worms and such, and Dad would catch a few and bring them home for dinner. From those modest beginnings on a simple farm with chickens, cows, and a few apple trees, Dad exhibited remarkable courage to start a business and an unparalleled talent for teaching that inspired many to achieve more.

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VULNERABILITIES OF LTE AND LTE-ADVANCED COMMUNICATIONS

Ensuring Proper Communication in Environments with High Interference

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By Naseef Mahmud

Demand for high-volume data streams in the current market for modern wireless communication systems is growing at a fast pace. In order to keep up with the trend to higher throughput requirements within unchanged bandwidth limitations, long-term evolution (LTE) technology has become a popular solution for replacing the transfer of data over 2G/3G communication networks. Although 5G is gaining ground in big cities and throughout the developed world, LTE is still the primary cellular standard in most countries around the globe. The popularity of LTE is driven in large part by the low cost and high performance it delivers. LTE can potentially reach a raw bit rate of 300 Mbps in the downlink channel using advanced MIMO configurations. Further, voice over LTE (VoLTE) enables voice transmissions.

Another major advantage of LTE is that 2G and 3G services are being switched off in many parts of the developed world. As a result, the default fallback system for emergency scenarios is the 4G LTE network.

Other than providing the standard of choice for commercial networks, LTE is also often used to broadcast emergency information in times of natural disasters and national crisis situations.

However, LTE has some vulnerabilities that are a matter of concern since it is possible to completely take down an LTE network or at least partially block communication networks intentionally or unintentionally. Some defined LTE bands are prone to coexistence issues with the S-band radar frequencies, such as those used by air traffic control (ATC) and air traffic surveillance (ATS) radars that scan the horizon up to 500 km range. In addition, at the lower end of the frequency spectrum, LTE has coexistence issues at the ultra high frequency (UHF) bands.

A clear understanding of LTE technology and its vulnerabilities is especially important for commercial, civil-governmental, and defense applications. This article highlights areas of greatest susceptibility to interference and jamming of the LTE network and possible counter-measures and also explores coexistence issues. Our goal is to provide a solid foundation for the use of LTE technology for devices used in commercial, civil-governmental, and military applications.

JAMMING TECHNIQUES

Wireless communication systems are not deployed in an ideal environment. The channels are subject to unwanted interference from other services operating in the adjacent frequency bands. There are also cases of jamming attempts on the network. This causes the performance of the network to degrade. In this section, we'll discuss conventional jamming techniques as well as certain new, smarter, and more power-efficient jamming techniques.

Barrage Jamming

Barrage jamming (BJ) is the most basic jamming technique. This is highly effective when there is no prior knowledge of the network. The entire spectrum of the target signal is jammed by transmitting band-limited noise to the system. This means the signal-to-noise ratio (SNR) decreases over the entire bandwidth. BJ is the most inefficient method of jamming. It requires a lot of power but is taken as a baseline for comparing the efficiency of other forms of jamming and their corresponding effectiveness. More information on BJ analysis can be found in [2]. Figure 1 on page 20 presents the spectrum for a BJ attack.

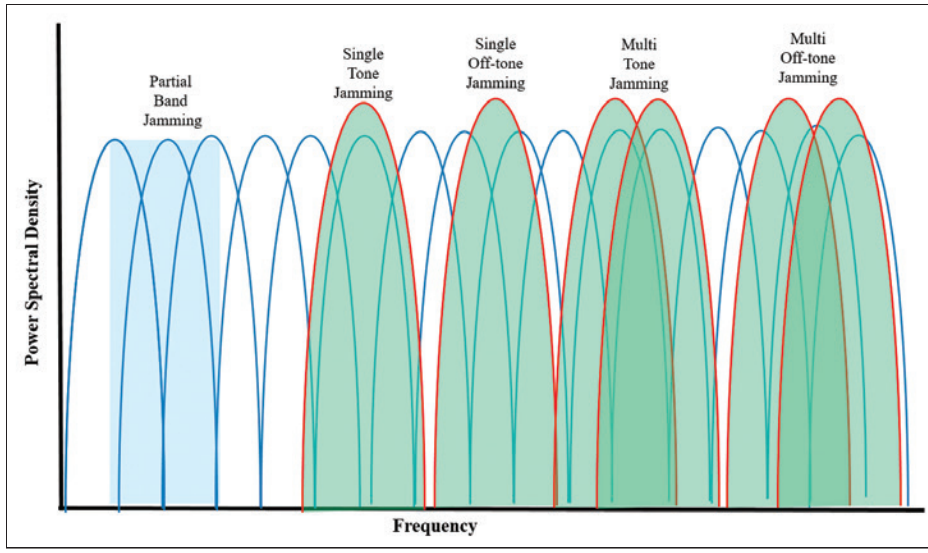

Figure 1: Different jamming attacks on LTE downlink [1]

Partial Band Jamming

Partial band jamming (PBJ) is a technique in which a certain portion of the entire system bandwidth is targeted and jammed by transmitting additive white Gaussian noise (AWGN) over this specific bandwidth. When the power of the jamming signal is constant, the effectiveness of the jamming depends directly on the fraction of the jamming bandwidth and the signal bandwidth. More information on PBJ can be found in [1,2]. In Figure 1, the part of the spectrum affected by PBJ can be seen.

Single-Tone Jamming

In single-tone jamming (STJ), a single high-powered impulse of AWGN noise is transmitted to jam only a certain band of interest. In the LTE downlink, only single subcarriers can be jammed using the STJ technique.

Figure 1 shows the effect of STJ on the spectrum. STJ can also be considered as a special case of PBJ. A more analytical investigation of the STJ can be found in [2]. In STJ, the knowledge of the target system's carrier frequency is required in order to jam the target signal.

Multi-Tone Jamming

Multi-tone jamming (MTJ) is another form of PBJ. Unlike STJ, multiple, equally powered noises are transmitted in order to take down multiple frequency subcarriers within the LTE bands. An MTJ attack is highly effective when there is a power limitation on the transmit side. This means that if there is a strict limitation on the transmit power, an increase in the number of transmitted tones will decrease the power associated with the individual transmitted jamming tones. A detailed analysis of the effect of MTJ on orthogonal frequency-division multiplexing (OFDM) can be found in [3].

Figure 1 shows an illustration of an MTJ attack on the spectrum. In MTJ, knowledge of the target system's carrier frequency is required.

Asynchronous Off-Tone Jamming

There are two types of asynchronous off-tone jamming (AOTJ). The first type is called single off-tone jamming, and the second is a multiple off-tone jamming attack. The operational concept of this technique is to transmit asynchronous off-tones that are not perfectly periodic or that have an offset at the sampling frequencies. As a result, the energy gets smeared from the true frequency into the adjacent frequency bins, thus creating inter-channel interference (ICI) of the OFDM signal at the receiver [1].

Also, the side lobes of the signal (sync function) are not aligned with the OFDM subcarriers because frequency offset can have non-zero components at the sampling period that can be a source of ICI. One advantage of AOTJ is that the jamming signal does not need frequency matching with the target signal or any channel state information (CSI). AOTJ demonstrates superior performance compared to BJ, STJ, and MTJ. An example of the two types of AOTJ can be seen in Figure 1.

Pilot Tone Jamming and Pilot Tone Nulling

In pilot tone jamming, the jammer must be perfectly synchronized with the target signal. This is done through the observation of communications between all the parties involved in the network. For example, a vector jammer signal Zi is equal to 0 (Zi = 0) for non-pilot sub-carriers and qi (Zi = qi) for the pilot tones, which is an independent and identically distributed AWGN [4]. If this AWGN sequence is coherently transmitted on all pilots simultaneously, then the noise is not averaged out for linear combinations.

In case of pilot tone nulling, it is also important to know the channel. The transmitter transmits a signal which is channel-corrected and π-radian phase shifted of the pilot tone. This causes the original pilot tone to cancel out and thus degrades the performance of the network.

COEXISTENCE WITH OTHER SERVICES

Coexistence of LTE and S-Band Radar

Air traffic control (ATC) radar, military air traffic surveillance (ATS) radar, and meteorological radar operate in the S-band frequency range. In fact, 4G communication systems (such as LTE) also operate in the same frequencies. The testing and measurement of their coexistence is absolutely essential as performance degradation of mobile devices and networks has been proven.

Table 1 on page 22 lists the LTE frequency bands for frequency division duplex (FDD) and time division duplex (TDD) modes of operation. Bands 1, 4, 7, 10, 22, 23, and 30 are fairly close to any operational S-Band radar system.

LTE base stations (eNodeB) may be disturbed through radar systems. Depending on the ATC or ATS radar system, a power of up to 7000 MW EIRP is transmitted. The blocking requirements of the LTE base stations (BS) and user equipment (UE) must also comply with these figures by considering the distance of the BS or UE. TS36.141 defines the blocking performance requirement for wide area BS as described in Table 1.

The UE may even be closer to a radar system. According to [5], out-of-band blocking parameters are defined as shown in Table 2.

In 3GPP TS36.521-1 [5], the test purpose of "TC 7.6.2 Out-of-band blocking" is described as "unwanted CW [continuous wave] interfering signal falling more than 15 MHz below or above the UE receive band, at which a given average throughput shall meet or exceed the requirement…". Under minimum conformance requirements, the throughput is mentioned to be "≥95% of the maximum throughput of the reference measurement channel."

As shown in several measurements, disturbance of LTE networks occurs through S-band radar, such as degradation of performance due to lower throughput indicated by an increasing block error rate (BLER). Throughput reduction is unlikely but not a major drawback. However, spectral efficiency, power reduction, and costs are of significant importance for any mobile network operator. Therefore, disturbance through other signals is of great interest.

Unlike mobile communications, radar is not defined by a global specification. Thus, many different systems applying different waveforms, frequencies, and bandwidths are deployed and operate nearly autonomously to detect the desired kind of target. For a radar engineer, bandwidth is also one of the key parameters when defining the radar system, as bandwidth defines range resolution. Depending on the radar, bandwidth can range from nearly zero (just a carrier frequency, CW radar) to measure radial velocity up to several GHz for high-resolution range measurements (e.g., ultra-wideband radar [UWB]).

The 2.7 GHz to 2.9 GHz frequency band is primarily allocated to aeronautical radio navigation, i.e., ground-based fixed and transportable radar platforms for meteorological purposes and aeronautical radio navigation services. The operating frequencies of these radars are assumed to be uniformly distributed throughout the S-band [6]. The two frequency bands for mobile communication and aeronautical radio navigation are very closely located, so the coexistence problem also needs special attention.

Operating Band	Centre Frequency of Interfering Signal [MHz]	Interfering Signal mean power [dBm]	Wanted Signal mean power [dBm]	Interfering signal centre frequency minimum frequency offset from the channel edge of the wanted signal [MHz]	Type of Interfering Signal
1-7, 9-11, 13-14, 18,19,21, 24, 33-43	$(F_{UL\_low}$ -20) to $(F_{UL\_high}$ +20)	-35	$P_{REFSENS}$ +6dB*	See table 7.6-2	See table 7.6-2
	1 to $(F_{UL\_low}$ -20) $(F_{UL\_high}$ +20) to 12750	-15	$P_{REFSENS}$ +6dB*	—	CW carrier

Table 1: Blocking performance requirement for wide area BS [5]

E-UTRA band	Parameter	Units	Frequency			
			range 1	range 2	range 3	range 4
	$P_{Interferer}$	dBm	-44	-30	-15	-15
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43	$F_{Interferer}$ (CW)	MHz	F_{DL_low} -15 to F_{DL_low} -60	F_{DL_low} -60 to F_{DL_low} -85	F_{DL_low} -85 to 1 MHz	-
			F_{DL_high} +15 to F_{DL_high} + 60	F_{DL_high} +60 to F_{DL_high} +85	F_{DL_high} +85 to +12750 MHz	-
2, 5, 12, 17	$F_{Interferer}$	MHz	-	-	-	F_{UL_low} - F_{UL_high}
Note: For the UE which supports both Band 11 and Band 21 the out of blocking is FFS.						

Table 2: Out-of-band blocking parameters [5]

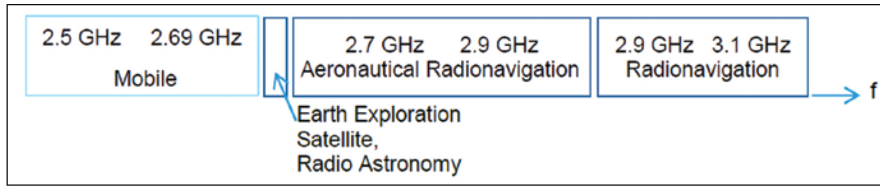

Figure 2: International Telecommunication Union Radio (ITUR) regulations in the band of 2.5 GHz to 3.1 GHz [7]

The application note 1MA211 [6] describes a more detailed investigation of the coexistence problem. The application note also discusses the potential issues concerning S-band radar systems and LTE signals from base stations/mobile devices operating in close range to the signal. It addresses frequency allocation of these systems, explains the performance degradation or malfunction that can be expected, and describes test and measurement solutions for interference testing of radar and LTE networks in detail.

Coexistence with LTE in Critical Environments

In critical environments such as hospitals, it is also important to ensure the coexistence of LTE with other wireless transmissions. The radio frequency (RF) environment of hospitals is very crowded, with many potential sources of interference, including wireless patient monitoring devices, wireless biosensors, smart TVs, etc. In addition, medical staff, patients, and guests in this environment typically introduce additional transmitters into the mix, such as smartwatches, smartphones, and wireless headphones. As a result, WLAN, Bluetooth®, and other mobile standards such as LTE or 5G are simultaneously in operation in a single environment. Therefore, network operators and manufacturers from both the mobile radio and the medical sector have a vital interest in preventing potential interference by performing in-depth testing of their products.

WLAN and Bluetooth® radio communication services operate in the license-free ISM4 band and have a high density of devices in most urban and sub-urban operating environments. LTE band 40 lies very close to the lower end of the ISM band, and LTE band 7 follows, albeit with somewhat more separation at its upper end (see Figure 3). In addition, 5G new radio

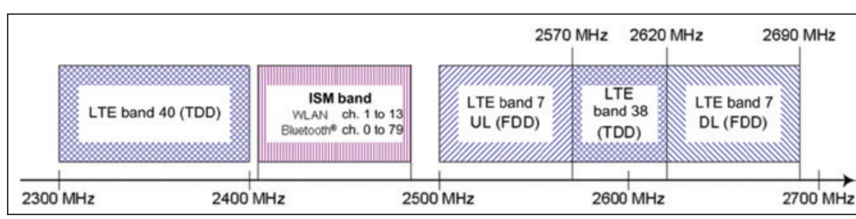

Figure 3: The 2.4 GHz ISM band and adjacent LTE bands

There are various jamming techniques, as well as unwanted interference, that play a role in the degradation of the performance of an LTE communication system.

(NR) technology's use of its Frequency Range 1 (also widely known in the industry as FR1, 410 MHz to 7125 MHz) overlaps with the LTE frequency spectrum and may even share some of the same band numbers. 5G uses these frequencies for ultra-reliable low latency communications required for telemedicine applications.

LTE also operates in the frequency bands that are already available for existing 3G networks. Moreover, additional ranges are available for use, such as the 2.5 GHz to 2.7 GHz band (Europe/Asia) and the 700 MHz band (USA). LTE bands 5, 12, 13, 14, 17, 19, and 20 overlap with digital TV bands and should be checked for vulnerabilities where digital TV services are still in service. In this coexistence scenario, the digital TV transmitter may act as an interferer on the cellular system LTE. Depending on the spectrum situation, the LTE base station receiver or the LTE terminal receiver could be impacted. If the LTE system and the digital TV system are operated in different frequency bands, this coexistence scenario will never be a co-channel scenario. A more detailed discussion on the issue can be found in [8].

In-Device Interference and Coexistence

With the ever-growing usage of various wireless technologies and services, user equipment is typically designed with multiple radio transceivers designed to operate in accordance with standards such as LTE, Wi-Fi, Bluetooth, and global navigation satellite systems (GNSS) simultaneously. This means that in-device coexistence interference becomes a matter of concern due to the extreme proximity of multiple transceivers or different antennas coupling with each other within the same device and that can potentially act as interferers.

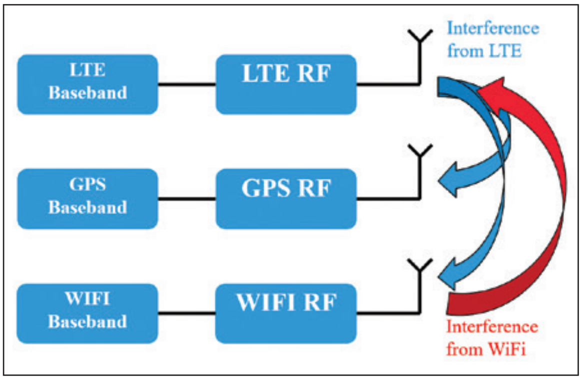

Figure 4: Coexistence interference in a user device supporting LTE, GPS, and Wi-Fi

The extreme proximity of co-located radios due to the small form factor of user equipment and the scarcity of spectrum are the main points that account for this problem. When these radio technologies within the same equipment are working on adjacent frequencies or sub-harmonic frequencies, interference power due to out-of-band emissions from a transmitter of one radio may be much higher than the signal strength of the desired signal for a receiver of a collocated radio. This situation is known as in-device coexistence interference.

Figure 4 shows one situation where user equipment supports multiple standards. The LTE signals undergo interference between different co-located radio transceivers. The Wi-Fi does not interfere with GPS but interferes with Bands 7 and 41 of LTE.

MITIGATION TECHNIQUES

As discussed in the previous section, there are various jamming techniques, as well as unwanted interference that play a role in the degradation of the performance of the LTE communication system. This is important to know when looking at civil-governmental systems as well as military communication systems, which must be robust in both circumstantial and hostile jamming scenarios. Therefore, keeping all the discussed techniques in mind, a few schemes already exist or offer themselves for jamming mitigation.

Jamming Mitigation

One of the most basic ways of mitigating unwanted interference is to rely on RF techniques, such as sufficient filtering or isolation. Unfortunately, the current state-of-the-art filter technology cannot provide sufficient interference rejection, making finding better mitigation schemes necessary.

Certain interference and jamming mitigation schemes such as frequency division multiplexing (FDM) based solutions, time division multiplexing (TDM) based solutions, transmit power control solutions, and frequency hopping solutions are extremely popular.

FDM-Based Solution

The basic idea is to shift LTE or ISM signals away from an interfering band via the frequency domain. This can be done by performing inter-frequency handover within E-UTRAN or removing secondary cells (SCells) from the set of serving cells as shown in Figure 5.

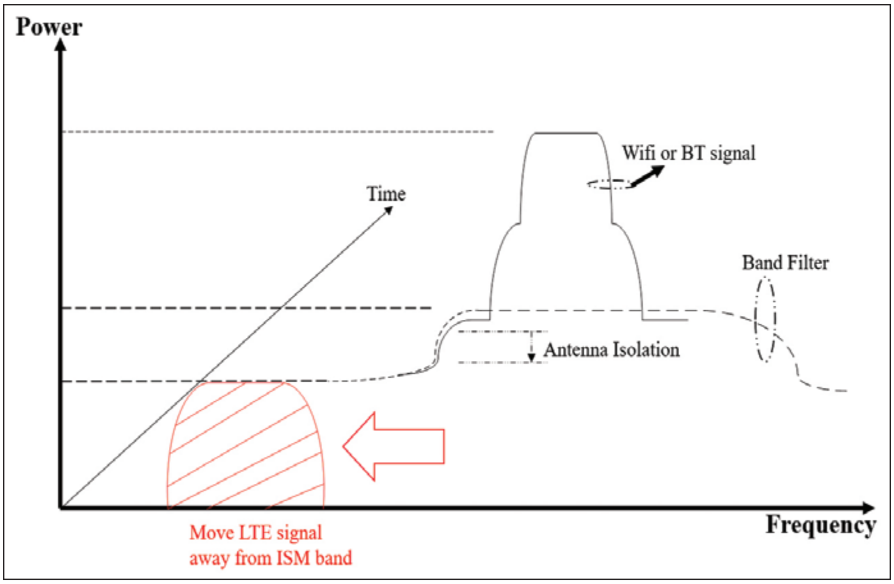

Figure 5: Moving LTE signal away from ISM ban

TDM-Based Solution

The basic idea behind TMD-based solutions is shown in Figure 6. This solution relies on avoiding the overlapping of signal transmission in the time domain. In LTE, a discontinuous reception (DRX) mechanism can provide TDM patterns for the scheduling of LTE transmissions.

Transmit Power Control Solution

This solution relies on reducing the power of the transmitting signal (LTE or ISM) to mitigate interference on the other receivers. Figure 7 shows a graphical depiction of the solution. Reducing the transmit power also means a reduction in the size of the coverage area.

Furthermore, in some cases, the UE can autonomously deny ISM transmission in order to protect important LTE signaling (e.g., radio resource control [RRC] connection configuration).

Frequency Hopping (FH) Solution

Frequency hopping (FH) solutions are widely used to mitigate the effects of hostile jamming. FH is mainly limited by the collision effect, and the spectral efficiency of the FH system is extremely low. In order to develop the spectral efficiency of the FH systems, a space-time coded collision-free frequency hopping scheme based on the OFDM framework and a secure subcarrier assignment algorithm can be used in which each user hops to a different set of subcarriers in a pseudo-random manner at the beginning of each new symbol period and at each symbol period. Different users always transmit on non-overlapping sets of subcarriers, thus making the FH scheme collision-free.

Frequency hopping has also been considered in cases where there is significant additional available bandwidth for use. However, it is difficult to overcome the impact of active jamming, especially

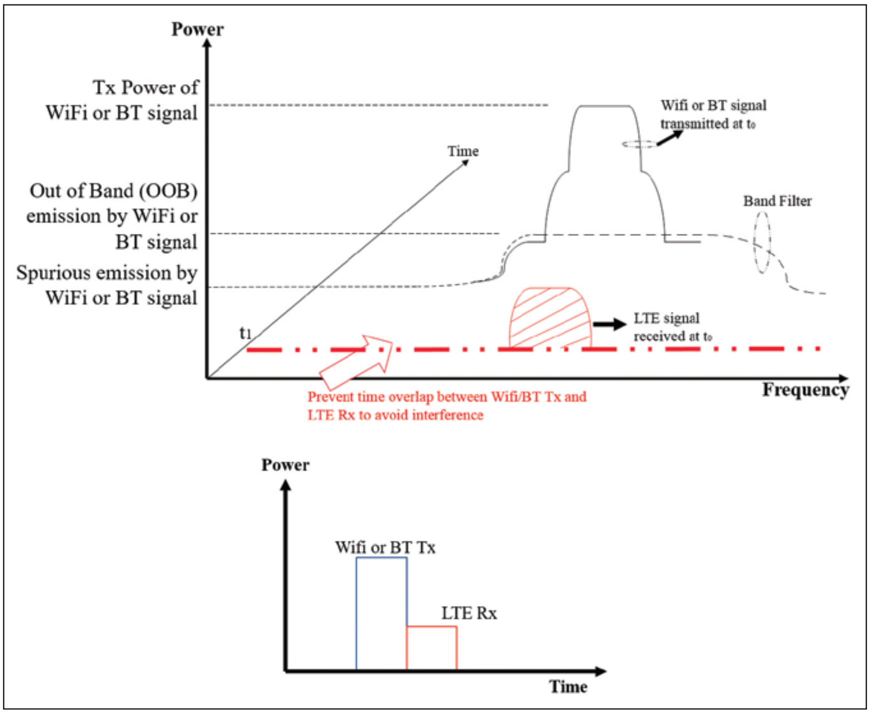

Figure 6: Time division multiplexing for co-existence interference avoidance

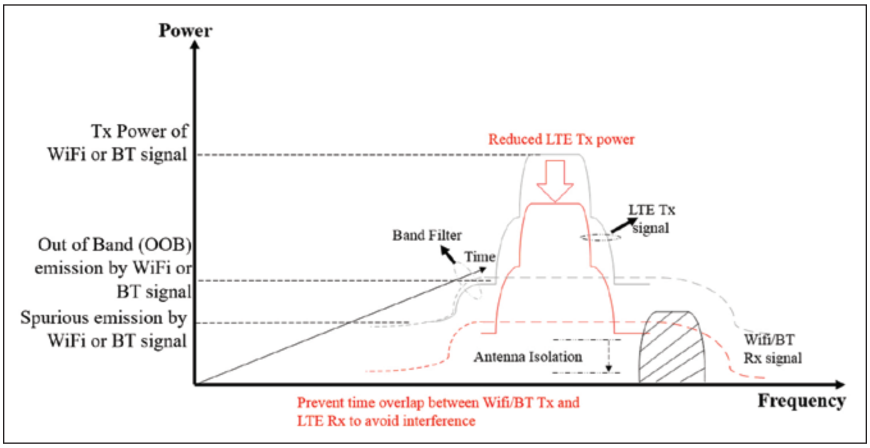

Figure 7: LTE power control for co-existence interference mitigation

when jammers acquire the inherent properties of media access control (MAC) layer protocols. There is a mitigation scheme known as the subcarrier-level radio agility. This is based on the concept that jamming signals will likely experience varying levels of fading on different OFDM subcarriers. As a result, some subcarriers may not be significantly affected by the malicious power emission. As long as a transceiver pair is made aware of which subcarriers these are, they can be temporarily used for legitimate packet transmissions.

Thus, a framework is created that allows a transceiver pair to exchange information about these unaffected subcarriers in the available spectrum, where the jamming signal experiences significant fading. Once such subcarriers are identified, the maximum allowable transmit power is assigned to these channels. These channels are then used for packet transmissions to increase the probability of successful packet delivery, thereby increasing the long-term throughput (while being actively jammed).

Coexistence Problem Mitigation Techniques

Different approaches can mitigate disturbances on radar and 4G base stations. One approach is to reduce transmit power at the base station and radar. Also, increasing frequency separation or distance between the two services is a potential solution. However, these two approaches reduce the maximum range of the radar and coverage of the base station, and frequency selection may be impossible due to technical restrictions. One approach to mitigate the problem is to avoid letting mobile service base station antennas point toward the S-Band radar. Also, the improvement of receiver selectivity, filtering of transmitter signals, and reduction of unwanted spurious emissions on both sides allows coexistence.

The latter choice is the most straightforward mitigation measure, both at the radar and base station side. Receiver saturation can be avoided through inter-modulation, and a blocking filter can be placed on the radar's receiver before the low noise amplifier (LNA). At the base station side, a filter can be placed on the transmitter close to the antenna to suppress the out-of-band LTE emissions in the spurious domain. Furthermore, a revision of the ETSI 3GPP technical specifications TS 136.101 (for user equipment) and TS 136.104 (for base stations) is recommended.

Currently, these standards impose flexible power levels for spurious emissions in non-protected bands, while these levels are much more stringent in the protected bands. Because the S-band (and the L-band) are used for security and safety services, a more stringent maximum power level for spurious emissions should be defined.

In any case, the test and measurement of radar, LTE base stations, and user equipment is necessary to confirm spectral emission masks and prove robustness against other co-existing signals [6]. Off-the-shelf test & measurement equipment and dedicated test systems to characterize susceptibility to interference and jamming exist and can aid in the development of more robust communication equipment or in designing more efficient targeted jamming scenarios.

INTEGRATION OF 4G LTE WITH TACTICAL NETWORK

Advanced communication technology is a key component of military success. The integration of the 4G LTE network allows the dissemination of secured mission command data, imagery, streaming video, and voice transmission between dismounted soldiers and command centers. The availability of real-time, complete situational awareness of the surrounding area gives combat soldiers a clear advantage. Military mobile communications must keep up with the innovations in the commercial space. LTE offers lower latency, faster speeds, and a more efficient architecture than the latest wireless military network technology when it comes to two-way communication.

Mobilization of a military 4G LTE network can be done by installing the base stations on a moving vehicle or an unmanned aerial vehicle (UAV, commonly referred to as drones) overhead or even on satellites operating at UHF (300 MHz – 3 GHz). Streaming video feeds from various individual endpoints and UAV cameras can be safely transmitted on this 4G network. Depending on the frequency band, LTE service is supported for terminals moving at up to 350 km/h (220 mph) or 500 km/h (310 mph).

4G LTE makes it possible for the military to set up beyond-line-of-sight radio communication at a low cost. The low frequency bands (i.e., 700 MHz) make it possible for deployment in rural areas as the signal travels further and provides better in-building coverage. This means fewer base stations are required to serve the same area. On the other hand, with 700 MHz in urban areas, there is a higher possibility of running into capacity issues, as there are more users per cell. Typically, higher frequencies (such as 2.6 GHz) are used for small cells (micro, pico, femto, etc.) to increase system capacity in hotspot areas. Users are handed over to these cells to free up resources on the macro cell. It's basically an overlay to the macro layer, which typically uses lower frequencies to provide wide-area coverage.

With 3GPP Release 12, two essential features were added to the LTE standard. First, there is device-to-device (D2D) communication. Here, two or more devices can directly communicate with each other, using uplink spectrum (FDD mode) at certain periodically occurring moments in time or uplink subframes (TDD mode). This feature is defined for in-coverage scenarios, where a base station still serves these devices, and out-of-coverage scenarios, where no network is available. Second, there is group communication on top of D2D, which, for instance, enables these devices to establish voice communication throughout the group using the D2D functionality.

With Release 13, the standard has been enhanced even further to support, for instance, mission-critical push-to-talk (MCPTT) services utilized by all types of terminals, ranging from popular smartphones to ruggedized devices. These and other features and applications are of interest in the case of public safety. When an emergency, disaster, or any unexpected event occurs, communication infrastructure is particularly important and plays a vital role. In many instances, the terrestrial communication infrastructure, especially core network functionality, can be seriously compromised and fail to ensure reliable communication for rescue teams. In times like these, the isolated EUTRAN operations, also part of Release 13, might be an interesting and effective solution to the problem. This feature enables the local routing of the communication (i.e., via base station only) when the interface to the core network is harmed or unavailable.

All-in-all, the features incorporated with Release 12 and 13 make LTE an interesting candidate for tactical communications as the underlying technology for next generation battlefield communications.

Testing and measurement are key components in all steps of the development and maintenance process of LTE and LTE-Advanced systems and devices.

CONCLUSION

This article is intended to point out vulnerabilities of LTE and LTE-Advanced. We've discussed a number of commonly used jamming techniques as well as more recently developed "smart" approaches, such as barrage jamming, partial band jamming, single-tone jamming, multi-tone jamming, asynchronous off-tone jamming, and pilot tone jamming and nulling. Even though every jamming scheme has its own advantages and disadvantages, asynchronous off-tone jamming has shown to be more efficient in terms of figure of merit than the other schemes.

This article has also reviewed unwanted interference and jamming mitigation schemes. We've offered a few solutions, including frequency division multiplexing-based solutions, time division multiplexing-based solutions, transmit power control-based solutions, and the popular frequency hopping-based solution.

We've also addressed the coexistence issue of LTE with S-band frequencies and in critical environments such as hospitals. The coexistence issue of LTE and S-band frequency is extremely critical and requires constant attention because air traffic control radars and air traffic surveillance radars operate in the S-band. A coupling of the LTE transmitted power in the receiver of a radar may cause a rise in the noise floor and result in a failure to detect an object in the sky.

We have identified the vulnerabilities of the technology and shared strategies and techniques to address them. It goes without mentioning that user equipment and the eNodeB need to be more robust in design. Both are used in security-relevant applications and should be designed to be "self-aware" of interference and jamming cases and programmed to take action to maintain un-degraded communication.

Testing and measurement are key components in all steps of the development and maintenance process of LTE and LTE-Advanced systems and devices, ensuring proper communication even in environments with high interference.

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EMERGING STANDARDS AND REGULATIONS FOR MEDICAL DEVICES

Understanding Requirements Within the IEC 60601-1 Series of Standards

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By Vik Chandna

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

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

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

KEEPING UP WITH INNOVATION

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

Several key trends are contributing to this evolution:

- *Integration of advanced technologies:* Medical device manufacturers are increasingly incorporating cutting-edge technologies such as artificial intelligence (AI), machine learning, home healthcare, robotics, and wearable technologies into their products. These technologies enhance the capabilities and functionalities of medical devices, leading to more accurate diagnoses, personalized treatments, and improved efficiency in patient diagnostics and treatments.
- *Rise of startup companies:* The once high barriers to entry in the MedTech industry have been significantly reduced in recent years, fostering the formation of an increasing number of startup companies focused on developing innovative medical devices. These startups often have strong cross-functional teams involved in the development processes, allowing them to bring products to market more quickly and more efficiently than larger, established companies. In addition, innovation hubs, incubators, and accelerators are further supporting the formation and growth of startup companies by providing funding, resources, and mentorship.
- *Focus on user-centered design:* Previous usability studies show a growing emphasis on designing and developing medical devices that improve the user experience for both healthcare providers and patients. This involves understanding the needs and preferences of these users and designing devices that align with these factors and are easy to use.

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

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

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

COMMON STANDARDS

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

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

  Key aspects covered in IEC 60601-1 include:

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

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

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

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

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

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

The standards are further broken down into the following types:

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

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

STANDARDS ADDRESSING EMERGING ISSUES

Home Healthcare

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

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

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

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

Medical Equipment Used by a Lay Operator

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

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

Device Classification

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

Figure 1: Protective earth (grounded) equipment not permitted

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

Internally Powered Devices

Battery-operated ME equipment and devices offer an additional level of safety by eliminating the need

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AMP2080C	10kHz-250MHz	300	55
AMP2080D	10kHz-250MHz	600	58
80-1000MHz, VHF, UHF Range Amplifiers			
AMP2032	80-1000MHz	300	55
AMP2071-2	80-1000MHz	500	57
AMP2071A-LC	80-1000MHz	750	60
AMP2115-LC	80-1000MHz	1300	61
AMP2121-LC	80-1000MHz	2000	63
700MHz-6.0GHz, Broadband Amplifiers			
AMP2070C	0.7-6.0GHz	100	50
AMP2070A	1.0-6.0GHz	150	52
AMP2030-LC	1.0-6.0GHz	300	55
AMP2030-600-LC	1.0-6.0GHz	600	58
AMP2030D-LC	1.0-6.0GHz	750	59
AMP2030LC-1KW	1.0-6.0GHz	1000	60
2.0-8.0GHz, SC Band Amplifiers			
AMP2085-1	2.0-8.0GHz	120	51
AMP2085C	2.0-8.0GHz	200	53
AMP2085E-1LC	2.0-8.0GHz	250	54
AMP2085E	2.0-8.0GHz	400	56
6.0-18.0GHz, High Frequency Amplifiers			
AMP2118	6.0-18.0GHz	40	46
AMP2111	6.0-18.0GHz	50	47
AMP2033-LC	6.0-18.0GHz	100	50
AMP2065A-LC	6.0-18.0GHz	200	53
AMP2065B-LC	6.0-18.0GHz	300	55
AMP2065E-LC	6.0-18.0GHz	500	57
18-26.5GHz, K-Band, Millimeter Amplifiers			
AMP4032	18.0-26.5GHz	10	40
AMP4065LC-1	18.0-26.5GHz	20	43
AMP4065-LC	18.0-26.5GHz	40	46
AMP4065A-LC	18.0-26.5GHz	100	50
AMP4065B-LC	18.0-26.5GHz	200	53
26.5-40.0GHz, Ka-Band, Millimeter Amplifiers			
AMP4072	26.5-40.0GHz	10	40
AMP4066LC-1	26.5-40.0GHz	20	43
AMP4066-LC	26.5-40.0GHz	40	46
AMP4066A-LC	26.5-40.0GHz	100	50
AMP4066B-LC	26.5-40.0GHz	200	53
18.0-40.0GHz, Millimeter Amplifiers			
AMP2145A-LC	18.0-40.0GHz	10	40
AMP2145B-LC	18.0-40.0GHz	25	44
AMP2145C-LC	18.0-40.0GHz	50	47
40.0-50.0GHz, Q-Band, Millimeter Amplifiers			
AMP4076-1	40.0-50.0GHz	5	37
AMP4076A	40.0-50.0GHz	20	43
AMP4076B	40.0-50.0GHz	40	46
AMP4076C	40.0-50.0GHz	80	49

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

Patient Connections

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

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

- *Type B applied parts:* These are applied parts that offer the lowest level of protection against electrical shock and patient leakage current. They are typically found in medical devices intended for use in professional healthcare settings, where electrical grounding is reliable and stringent safety measures can be enforced. However, in the home healthcare environment, where electrical grounding may be less reliable, the use of Type B applied parts is restricted due to the higher risk they pose under fault conditions.
- *Type BF and CF applied parts:* These applied parts provide a higher level of isolation compared to Type B applied parts. Type BF (body floating) applied parts are designed for use in direct contact with the patient's body, offering a higher degree of protection against patient leakage current. Type CF (cardiac floating) applied parts provide an even greater level of isolation, specifically for devices used in close proximity to the heart or other critical areas.

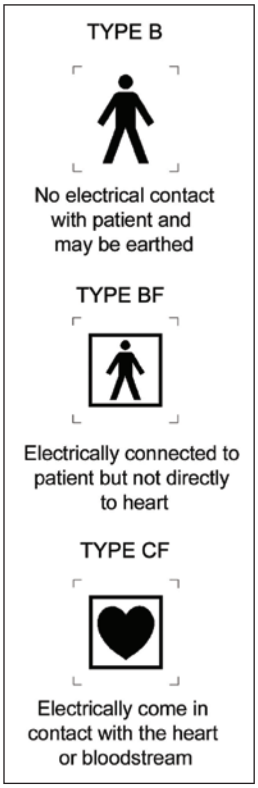

Figure 2: The three types of applied parts within the 60601-1 series of standards [1]

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

Environmental Conditions

- *Operating temperature range:* The operating environment within the home is not as controlled as what is typically found in a professional environment such as a hospital. Therefore, IEC 60601-1-11 stipulates that ME equipment intended for use in the home healthcare environment shall be operable within an expanded temperature range of +5 to +40 degrees Celsius.
  - *Water ingress protection:* Coinciding with the previously discussed requirements for the home environment, IEC 60601-1-11 also requires that ME equipment used in the home healthcare environment conform with the requirements of an IPX1 or IPX2 (transit-operable, hand-held, and body-worn) rating:
    - *IPX1 rating:* An IPX1 rating for a device is classified as the lowest level of protection against liquid penetration. This test involves dripping water vertically onto the ME surface. The ME equipment is placed onto a turntable rotating at one round per minute and under a drip box proving a flow of water of one millimeter per minute for a duration of 10 minutes. Upon completion of the test, the testing lab identifies any water penetration within the device that could cause a failure of basic safety and/or essential performance requirements.
    - *IPX2 rating:* Similar to IPX1, the IPX2 test involves dripping water vertically onto the ME surface. The ME equipment is placed onto a turntable rotating at one round per minute and under a drip box providing a flow of water of three millimeters per minute. The test duration is also 10 minutes, but the unit is tested in four 2.5-minute test sections each with

a 15-degree tilt. Similar to the IPX1 test, the ME equipment is then evaluated for any water penetration that could compromise basic safety and/or essential performance.

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

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

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

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

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

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

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

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

Artificial Intelligence

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

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

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

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

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

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

Cybersecurity

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

With manufacturers now including network capability in ME equipment, there comes a need to ensure that devices are protected against cybersecurity threats.

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

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

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

THE FUTURE OF IEC 60601-1

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

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EMC ARCHAEOLOGY: A TALE OF TWO METERS

Of Decibels and Centibels, and EMC Engineers in a Row

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By Ken Javor

The ubiquitous 41” rod antenna has been used to measure electric fields below 30 MHz for over seven decades. Most EMC engineers know that the effective height of an electrically short whip is precisely half its physical length. But the effective height or length of the 41” rod element is taken to be a half-meter. Given that a meter is not 41 but 39.37 inches, there appears to be a small discrepancy.

Similarly, the capacitance of a short whip is a function of both length and diameter. A capacity of 10 pf is almost universally used for the 41” rod element, but in fact, that is the capacity of a one-meter length whip with 1/8” diameter. Since rod elements are 41” and range in diameter from around ¼” to a centimeter or more, depending on manufacturer, the capacity is always higher than 10 pF.

If these conundra have had the reader tossing and turning, lying awake at night, reading this short article will reveal the historical reason behind the disparities, and that, while the history is interesting, the disparities do not significantly affect measurement accuracy. Having read this very short article, the reader will be better informed, his concerns will be allayed, and he can rest easy.

Frontispiece: 1930s vintage Ferris Model 32 radio frequency volt and field intensity meter on the left; 1950s replacement AN/PRM-1 (Stoddart Aircraft Radio Company NM-20) meter on the right. The NM-20 “big leap forward” was the inclusion of a peak detector circuit. (Image and all images in this article courtesy of the Museum of EMC Antiquities.)

A small consulting job recently brought to the author’s attention that the latest revision of SAE ARP-958 lists the effective height of the 41” rod antenna not as the traditional 6 dB below one meter but instead as 5.6 dB below one meter.[1] This is based on using the 41” (1.04 m) length as opposed to precisely one meter, the latter having been the custom for seventy years, even including previous revisions of ARP-958, going back thirty years.

There are two interrelated aspects to this: one trivial and the other more interesting.

The trivial aspect is that if one is computing to the nearest centibel in a field of endeavor where +/- 3 decibels is a holy grail, at least do it right. Compute in millibels and round off to the nearest centibel:

$$41 \text{ inches} \cdot 0.0254 \text{ m / inch} = 1.0414 \text{ meter}$$

$$h_e = 20 \log(\text{physical length}/2) =$$
$$20 \log(1.0414 \text{ m} / 2) = -5.668 \text{ dB meter}$$

That rounds to -5.7 dB above one meter, not -5.6. If we are going to be pedantic, let’s do it right.

The more interesting question, though, is why have we used a 41” rod element all this time and always approximated the effective height as one-half meter. While the 0.3 or 0.4 dB error is truly minor (unless one is enamored of centibels), it would have been just as easy to have a one-meter-long element instead of 41 inches.

To answer this question, we have to step into the EMI testing way-back machine, conveniently located on the premises of the Museum of EMC Antiquities.

We turn the dial back some 90 years to the development of the Ferris Model 32 Radio Noise and Field Strength Meter (see Figure 1) and first offered for sale in 1932.[2] This radio frequency voltmeter had a frequency range of 150 kHz to 20 MHz, less 200 kHz between 350 – 550 kHz, using five different octave tuning bands.

The Ferris Model 32 is *the* EMI receiver of note in all military EMI standards before the early 1950s.[3] It is not only mentioned by name, but sundry specs and standards describe how to build various adapters when using the Model 32 for different EMI measurements. It could be used as a two-terminal rf voltmeter (conducted EMI) or, employing the 41” rod element with which it was supplied, could be used to measure field intensity. The effective height of the supplied 41” rod element was stated to be one-half meter, and it nearly was (5.99 dB below one meter).

Figure 1: Ferris Model 32 rf volt and field intensity meter. The collapsible 41” rod (non-original substitute in place) was specifically designed so that the collapsed elements would fit in the lid.

Figure 2 portrays side-by-side images of the 1930s-era Ferris 32A and the 1950s-era Stoddart NM-20 receiver that eventually replaced it, showing both antenna ports (a) and antenna connections (b).[4] We can see that both are outfitted with a rod element. The difference is this. The (supplied) Ferris element was a 41” long 1/8” diameter collapsible Monel rod with no connector at the base. It simply slid into a hole in the faceplate of the Ferris Model 32.[5] The depth of the hole was 1.5”, leaving 39.5” above the faceplate. Compare that to 39.37” per meter, and the 6 dB (5.99 for millibel fetishists) effective height factor becomes apparent.

It will be noted that in Figure 2, all rod antenna connections are at the meter itself, not as in modern-day practice, with antenna remote, and connected via a low impedance (50 Ω) transmission line. The inputs to these meters were high impedance and designed specifically for the 10 pF capacity of the 41” rod antenna. In fact,

Figure 2a: Close-ups of rod antenna ports for the Ferris Model 32 on the left, and the Stoddart Aircraft Radio Company Model NM-20 on the right. Light-colored material surrounding the 1/8” diameter hole in the Ferris antenna port is a non-conductive standoff limiting shunt capacity to chassis. On the right, the two twinax pins are both connected to the rod element. The connector is not being used as twinax.

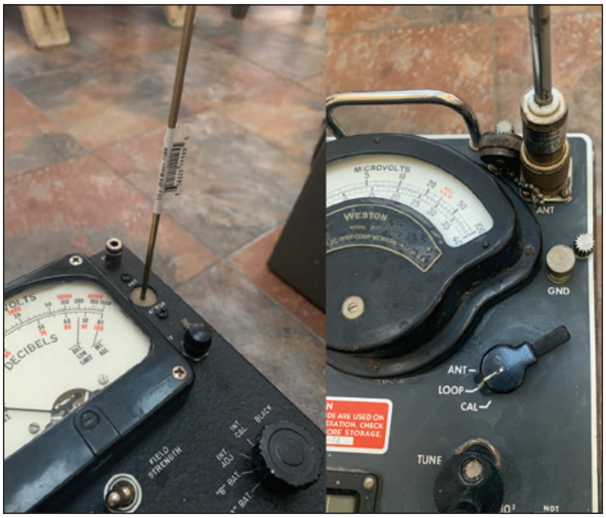

Figure 2b: Close-ups of rod antenna connections for the Ferris Model 32 on the left and the Stoddart Aircraft Radio Company Model NM-20 on the right.

to use these meters to measure anything other than a 10 pF output impedance source, adapters had to be built (Ferris) or were supplied as part of the receiver set (AN/PRM-1).[6] The use of 50 Ω input receivers and remote antennas with impedance transformation built into the antenna base was still a generation beyond the AN/PRM-1.

As soon as the AN/PRM-1 became available commercially, it shows up in the standards as the primary choice to be used below 20 MHz, with the Model 32 reclassified as acceptable under certain circumstances. This was due to the AN/PRM-1 including a peak detector, which the earlier Ferris model lacked. But since the AN/PRM-1 was, in fact, designed to replace the Ferris Model 32, it had to include a 41" rod antenna.

The "mistake" made by Stoddart and all who followed was to copy the 41" but put all of it above a connector that protrudes from the top of the meter or antenna base (Figure 3). Of course, there was nothing stopping anyone from collapsing the rod element to precisely one meter, but with few exceptions, that wasn't mentioned or required in standards and, therefore, wasn't done.[7,8,9]

Reference 8, paragraph 6.1.1.9.1. instructs as follows: "Each meter should be provided with rod antenna adjusted to give an effective height of approximately 1/2 meter."

Some might consider the use of the term "approximately" in a contractual specification as less than ideal. But fortuitously, this "closes the loop," tying the first issue of centibel hair-splitting to the second of whence the 41" long "meter."

The Ferris Model 32 instruction manual on the topic of splitting decibels explains the proper use of significant figures:

> *"It is evident that the accuracy of the entire measurement depends directly on the accuracy of the calibrating source, and can never exceed this; in fact, it can seldom equal it due to the accumulation of errors. Since the errors of voltage in the signal generator as the reference standard can seldom be less than about plus or minus 10%, even in the latest and most accurate instruments, it follows that no measurement of r.f. microvoltage or field can be relied upon to better this value. This is true no matter what type of receiver or field intensity set is used as the transfer indicator. These statements are made to clear up some popular misconceptions as to the degree of accuracy which can be attained in radio frequency measurements. Actually, in recording test data, it is never permissible to set down more than two significant figures, or to carry more than this through subsequent calculation of data."*

Figure 3: Stoddart Aircraft Company Model 90291-2 collapsible rod antenna assembly for use with NM-20 meter above, and 1/8" O.D. brass rod suitable for use with Ferris Model 32 meter below.

Now let's apply these instructions to the 41" rod antenna teapot tempest. 41" is 1.0414 meters. 1.0414 rounded to two significant digits is 1.0 meter, and thus we arrive at the -6 dB meter effective height, which was satisfactory for over seven decades.

Also, compare the cited +/-10% amplitude tolerance value (+0.8 – -0.9 dB) to the MIL-STD-461 +/- 2 dB requirement for a measurement receiver. And +/- 2 dB is still representative of total amplitude measurement accuracy of the latest EMI receivers as of this article's publication.

ROD CAPACITY

Figure 4 on page 44 gives the expression for and graphs the dependence of rod capacity on diameter. The 1/8" diameter one-meter length Ferris element clocks in at 10.2 pF. All other manufacturers' collapsible rod elements within the author's experience have a larger diameter, closer to ¼." Errors arising from calibrating with a 10 pF capacitor vs. the rod having some other value, as per Figure 4, are not large.

Figure 5 on page 44 shows the range of errors over a range of rod diameters and FET gate capacities. For normal collapsible rod diameters up to ¼" and FET gate capacities below 10 pF, Figure 5 indicates errors less than 1 dB. Figure 5 is also indicative of why European manufacturers of rod antennas with up to 15 mm diameter elements asked that MIL-STD-461G change the rod antenna calibration injection capacitor from a fixed value of 10 pF to that value cited by the manufacturer.

CONCLUSION

Everyone has heard and understands the riddle, "When is a door not a door? When it is ajar." If one were to pose, "When is a meter not a meter? When it is 41 inches.", the response will be nothing but a blank look, unless the respondent happened to be an EMI test engineer. And even then, he couldn't have explained why that is.

Until now.

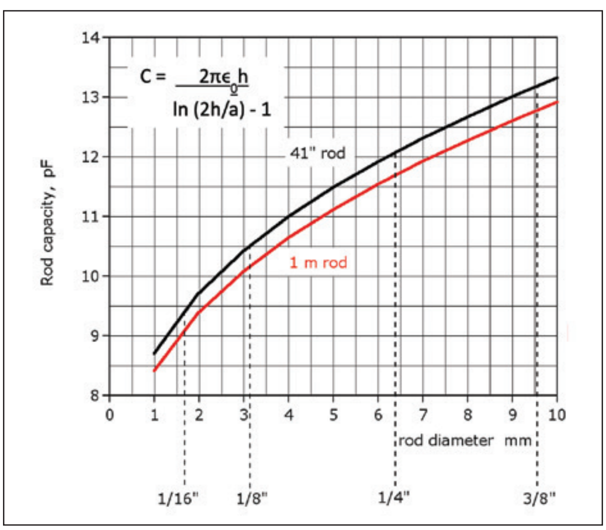

Figure 4: Rod capacity as a function of rod diameter

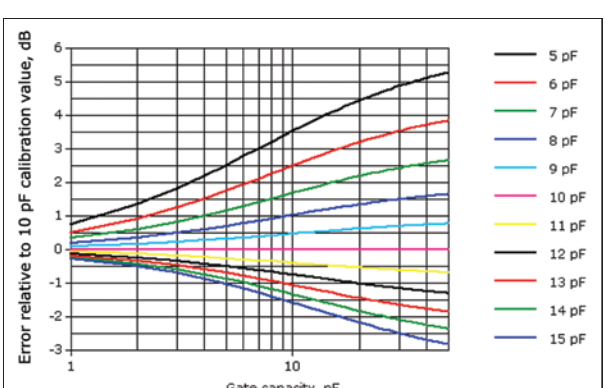

Figure 5: Errors arising from calibration injection through 10 pF when the rod capacity is different.

ENDNOTES

1. SAE ARP-958E, "Electromagnetic Interference Measurement Antennas; Calibration Method" (2021)
2. Parker, A. T. "A Brief History Of EMI Specifications," Presented at the 1992 IEEE EMC Symposium.
3. The Model 32 instruction manual barely mentions the application of measuring interference, and not at all with respect to the use of the 41" rod antenna. The Model 32 was envisioned as being used to map field contours of broadcast radio station antennas, and the manual goes into considerable detail on how to do that.
4. The AN/PRM-1 manual, by contrast mentions interference measurement first, and then mapping broadcast fields, and then as a microvoltmeter.
5. Two items of importance. In the Ferris meter, the cutout around the 1/8" diameter shaft is not metallic, but plastic. It serves the same purpose as the cutout at the top of a modern-day 41" rod antenna: to avoid shunt capacitive loading of the rod's output. Second, the museum's Model 32 is missing the original collapsible rod. Museum personnel followed the manual's instructions that a 1/8" diameter rod or pipe of brass or other metal could be substituted if the collapsible rod wasn't available.
6. See for example, MIL-I-6181B "Military Specification: Interference Limits, Test and Design Requirements, Aircraft Electrical and Electronic Equipment," dated 29 May 1953. Figure 15 is a fully dimensioned, build-to-print level of detail drawing for a Ferris meter connection to provide a 50 Ω termination while interrogating a 5 uH LISN.
7. MIL-I-16910A dated 1954, "Interference Measurement, Radio, Methods and Limits; 14 Kilocycles to 1000 Megacycles"
8. MIL-STD-826, "Electromagnetic Interference Test Requirements and Methods," dated 20 January, 1964 refers only to "1/2 meter rod (electrical length = 1/2 meter), not a 41" rod antenna.
9. MIL-STD-461A, "Electromagnetic Interference Characteristics Requirements for Equipment…" dated 01 August 1968, refers to "a 41-inch rod antenna (electrical length = 0. 5 meter)."

CROSSTALK BETWEEN PCB TRACES – TIME AND FREQUENCY DOMAIN MEASUREMENTS

Part 1: Impact of the PCB Topology

By Bogdan Adamczyk, Mathew Yerian-French, and Ryan Aldridge

This article is the first of a two-article series devoted to the topic of crosstalk between PCB traces. This topic was previously discussed in [1] and [2]. In [1], we used a first-generation PCB and concentrated on signal integrity or the time domain measurements. In [2], we used a redesigned PCB to show the time domain impact of the guard trace on crosstalk. This two-article series presents measurements taken with a third-generation PCB. These measurements were taken both in the time domain using an oscilloscope and in the frequency domain using a near-field *H* probe. In Part 1 of the series, we vary circuit topology, i.e., the distance between traces and the distance to the ground plane. Both the time domain and frequency domain measurements show (for the topologies tested) that bringing the ground plane closer to the signal plane has a larger impact on reducing crosstalk than increasing the distance between traces. In Part 2 (to appear in the next issue), we investigate the impact of guard trace on crosstalk reduction, both in time and frequency domains.

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Ryan Aldridge is the Operations Manager for Grand Valley State University's Innovation Design Center. He works closely with Prof. Adamczyk, developing EMC educational material, and assists him with GVSU's EMC Center. He attended Grand Valley State University for his bachelor's and master's degrees in electrical and computer engineering.

CROSSTALK CIRCUIT MODEL

When two circuits are in the vicinity of one another, a signal propagating in one circuit can induce a signal in another circuit due to capacitive (electric field) and/or inductive (magnetic field) coupling between the circuits [1,2]. This phenomenon is referred to as crosstalk. An example of such an arrangement and its circuit model is shown in Figure 1.

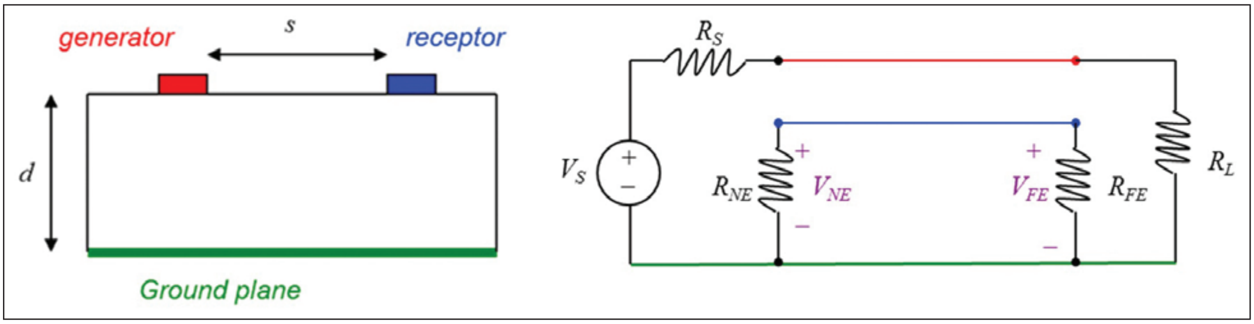

Figure 1: Microstrip line PCB configuration and its circuit model

Two PCB traces in a microstrip configuration are separated from each other by a distance *s* and from the ground plane (which is a return conductor for both) by a distance *d*. The first trace (generator conductor) is driven by a time-varying voltage source V_S with the impedance R_S and terminated by a load resistor R_L. The second trace (receptor conductor) is terminated by the load resistors R_{NE} and R_{FE} on the near end and the far end, respectively.

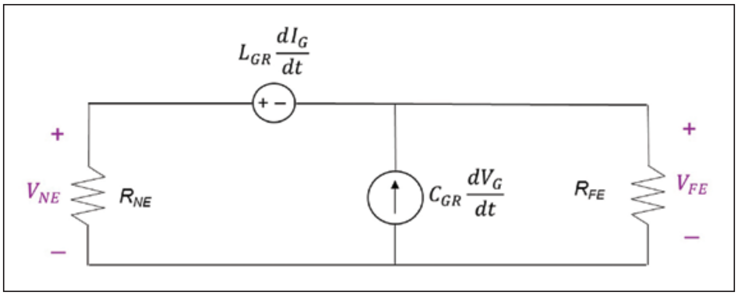

Figure 2: Receptor circuit model in time domain

Superposition of the inductive and capacitive coupling mechanisms results in the receptor circuit shown in Figure 2, where L_{GR} and C_{GR} represent the mutual inductance and mutual capacitance, respectively, between the generator and receptor circuits (this model is valid for electrically short structures).

The near- and far-end voltages in the time domain are given by [1,2]

$$V_{NE}(t)=\left[\underbrace{\frac{R_{NE}}{R_{NE}+R_{FE}}L_{GR}\frac{1}{R_S+R_L}}_{Inductive\ Coupling}+\underbrace{\frac{R_{NE}R_{FE}}{R_{NE}+R_{FE}}C_{GR}\frac{R_L}{R_S+R_L}}_{Capacitive\ Coupling}\right]\frac{dV_S(t)}{dt}$$

Eq. 1a

$$V_{FE}(t)=\left[\underbrace{-\frac{R_{FE}}{R_{NE}+R_{FE}}L_{GR}\frac{1}{R_S+R_L}}_{Inductive\ Coupling}+\underbrace{\frac{R_{NE}R_{FE}}{R_{NE}+R_{FE}}C_{GR}\frac{R_L}{R_S+R_L}}_{Capacitive\ Coupling}\right]\frac{dV_S(t)}{dt}$$

Eq. 1b

Equation 1 reveals several important aspects:

1. If V_S = const, then $V_{NE}(t) = 0$ and $V_{FE}(t) = 0$.
2. A faster rise or fall time, dV_S/dt, results in larger values of $V_{NE}(t)$ and $V_{FE}(t)$.
3. On the rising edge of $V_S(t)$, $dV_S/dt > 0$, and both the inductively and capacitively induced near-end voltages are positive; $V_{NE,ind} > 0$, $V_{NE,cap} > 0$.
4. On the rising edge of $V_S(t)$, the inductively induced far-end voltage is negative, $V_{FE,ind} < 0$, while the capacitively induced far-end voltage is positive, $V_{FE,cap} > 0$.

On a microstrip PCB, the inductive coupling usually dominates the capacitive coupling [3] and, thus, the far-end voltage, on the rising edge of $V_S(t)$ is usually negative.

TIME DOMAIN MEASUREMENT SETUP

The measurement setup for time domain crosstalk measurements is shown in Figure 3.

Three different circuit topologies were investigated and are described in Table 1.

Figures 4 through 6 show the generator signal, V_S, as well as the resulting near-end voltage, V_{NE}, and far-end voltage, V_{FE}, induced in the receptor circuit.

The source signal is an open-circuit voltage of 0-5 V_{pp}, 1-MHz trapezoidal pulse train having 100-ns rise time, 200-ns fall time, and a 50% duty cycle.

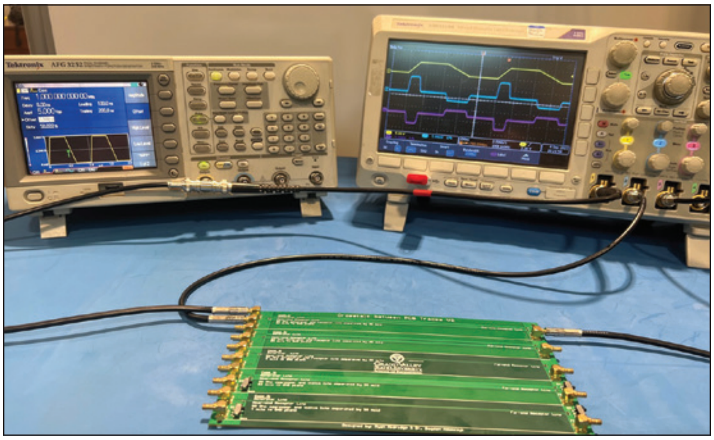

Figure 3: Experimental setup for time domain measurements

Case	Line separation s [mils]	Distance to ground plane d [mils]
1	30	52
2	60	52
3	30	4

Table 1: Circuit topologies

Case 1 Observations

Voltage induced at the near end during the rise time is V_{NE} = 6.4 mV. while the voltage induced during the fall time V_{FE} = -3.2 mV. Since the value of the rise time is twice that of the fall time, according to Equation 1a, the induced voltages should differ in magnitude by a factor of two, which indeed is the case. We also note that the polarities of the two voltages are opposite, which is to be expected from Equation 1a. Similar observations can be made for the voltages induced at the far end. Furthermore, since the coefficients of coupling for the near-end voltage (Equation 1a) are positive, the induced voltage during the rise is also positive. The far-end voltage is negative during the rise time, indicating that the inductive coupling dominates the capacitive one (see Equation 1b).

Case 2 Observations

Increasing the distance between the traces from 30 to 60 mils while keeping the distance to the ground plane unchanged reduces both the NE and FE voltages.

Case 3 Observations

Decreasing the distance to ground reduces both the NE and FE voltages. The impact of bringing the ground closer to the signal layer is larger than the impact of increasing the distance between traces.

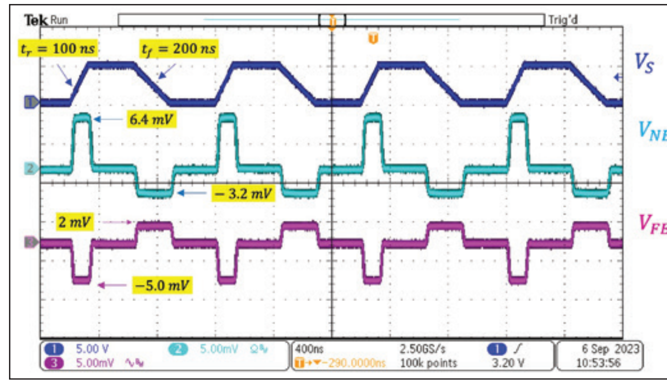

Figure 4: Crosstalk induced voltages – Case 1

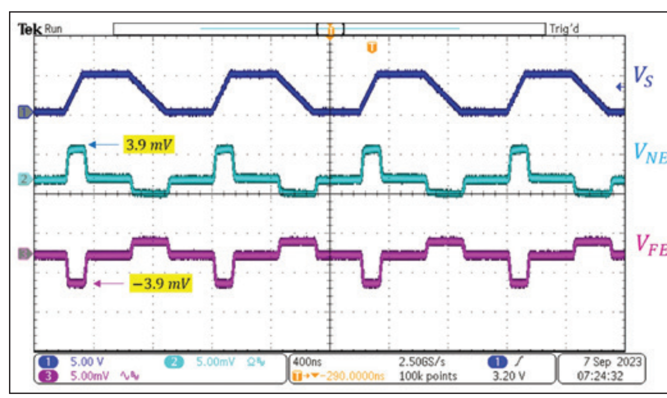

Figure 5: Crosstalk induced voltages – Case 2

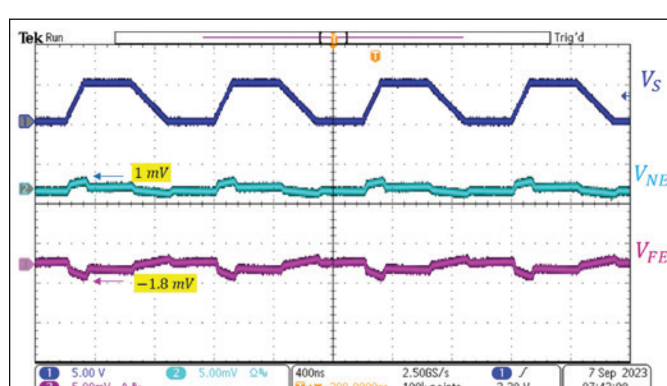

Figure 6: Crosstalk induced voltages – Case 3

FREQUENCY DOMAIN MEASUREMENT SETUP

The setup for the near-field *H*-probe measurements is shown in Figure 7.

The source signal had the same parameters as in the time domain setup, except for the rise and fall times, which were set to 10 ns. The *H*-field probe in the near field scanner took measurements at 9 MHz and 49 MHz.

Figure 8 shows the measurement results at 9 MHz, while Figure 9 shows the results at 49 MHz. These measurements are summarized in Table 2.

Observations

Increasing the distance between the traces from 30 to 60 mils while keeping the distance to the ground plane unchanged reduces the near-field intensities. Decreasing the distance to ground also reduces the field intensities. The impact of bringing the ground closer to the signal layer was larger than the impact of increasing the distance between traces. The frequency domain results are consistent with the results obtained in the time domain.

Figure 7: Experimental setup for frequency domain measurements

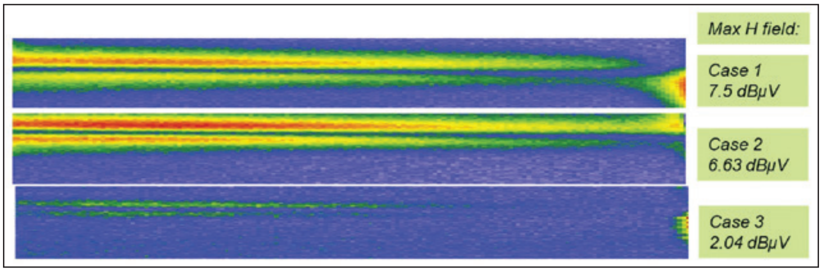

Figure 8: H-field measurement results at 9 MHz

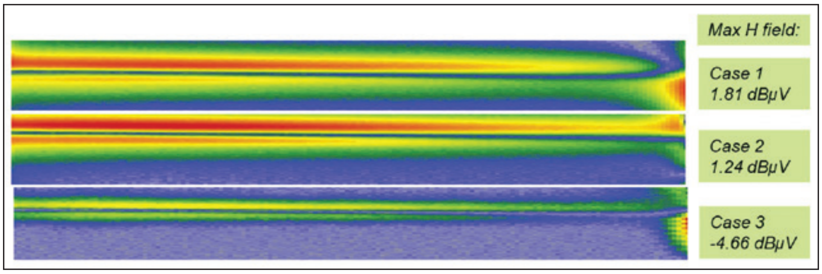

Figure 9: H-field measurement results at 49 MHz

Case	s (mils)	d (mils)	Max @ 9 MHz	Max @ 49 MHz
1	30	52	7.5	1.81
2	60	52	6.63	1.24
3	30	4	2.04	-4.66

Table 2: Near field measurement summary

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2. Bogdan Adamczyk, *Principles of Electromagnetic Compatibility: Laboratory Exercises and Lectures*, Wiley, 2024.
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MODELING THE RF SWITCH FRONT END MODULE ESD PROTECTION

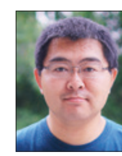
By Nathaniel Peachey and Jian Liu for EOS/ESD Association, Inc.

Due to the proliferation of wireless applications ranging from cellular and automobile communication systems to the Internet of Things, RF switching and tuning solutions continue to provide challenges for both device and system-level ESD protection. Most of the RF switching that is needed is built in the silicon-on-insulator (SOI) process technology, as shown in Figure 1. Thin-film SOI provides the substrate that enables both the high RF performance and the transistor isolation needed for high-power RF signal processing. One of the intrinsic advantages of the SOI RF switch is the self-protection it can provide for device-level ESD threats [1]. Furthermore, when properly co-designed with the system-level ESD protection, the SOI switch can contribute to the protection of the total antenna system.

Understanding this self-protection mechanism and then successfully modeling it is critical for the SOI switch circuit designer. The turn-on mechanism for the switch in an ESD event is actually the synergy of two mechanisms [2,3]. The large gate resistance (R_G) and the gate capacitance (C_{GD}) result in an RC time constant that is sufficiently large that, when the ESD pulse strikes the switch, the switch transistor gate couples up, turning the transistor array on. Assisted by

Nathaniel (Nate) Peachey received his Ph.D. in Physical Chemistry in 1994 from the University of Nebraska–Lincoln. In 2005, Nate joined RFMD (now Qorvo) as the ESD engineering manager, a capacity in which he continues to serve. Nate has authored and coauthored approximately 40 technical papers and holds 13 patents. Nate is a Senior Member of the IEEE.

In 2011, Dr. Liu joined the ESD group of RF Micro Devices (RFMD, now Qorvo), where he is working as a staff device engineer on the CMOS ESD protection design. Dr. Liu is an IEEE peer reviewer and has published over 40 technical papers for conferences and in journals. He has been a member of ESDA since 2012.



Founded in 1982, EOS/ESD Association, Inc. is a not for profit, professional organization, dedicated to education and furthering the technology Electrostatic Discharge (ESD) control and prevention. EOS/ESD Association, Inc. sponsors educational programs, develops ESD control and measurement standards, holds international technical symposiums, workshops, tutorials, and foster the exchange of technical information among its members and others.

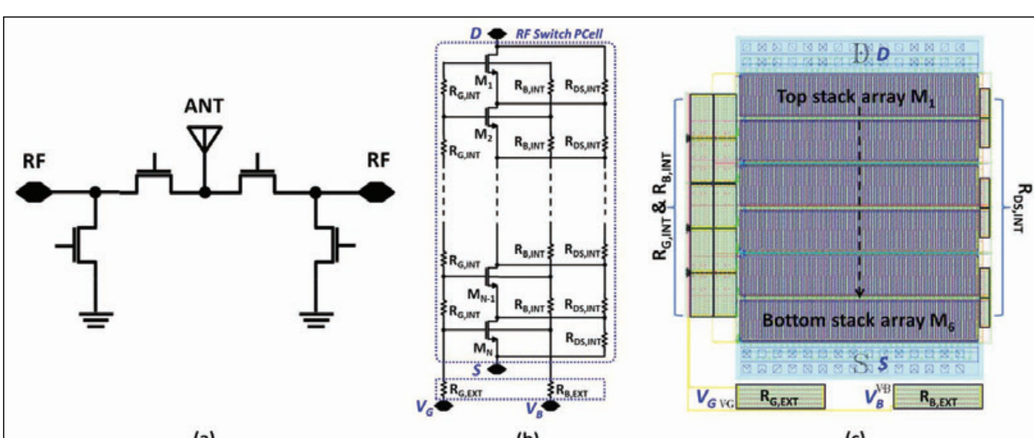


Figure 1: (a) The series-shunt structure of SOI RF switches. (b) the schematic and (c) the layout of multiple stack bottom-bias RF switch with key parameters.

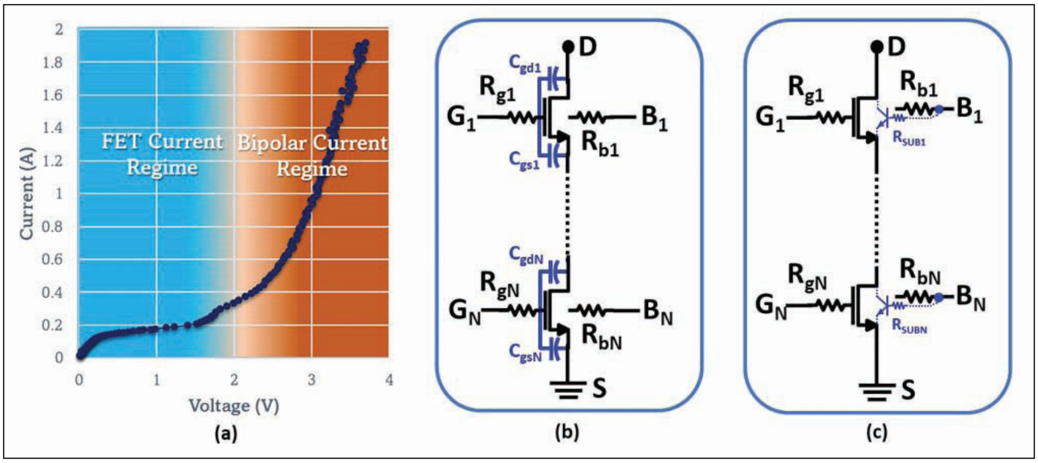


Figure 2: (a) TLP plot of single-stack SOI switch showing the two ESD protection mechanisms. (b) NMOS FET channel conduction triggered by gate coupling and (c) parasitic bipolar turn-on.

this channel current and initiated by the avalanche breakdown at the transistor drain, the parasitic bipolar turns on, providing the secondary ESD protection mechanism. The TLP plot of the response of a single stack switch to the ESD pulse, as well as the dual protection mechanism, is shown in Figure 2. In Figure 2(a), the gate bias during the TLP testing was 1V.

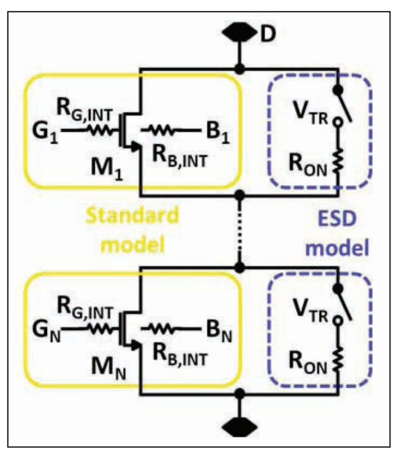


Figure 3: The behavioral model for the multi-stack RF NMOS showing the bimodal characteristic of the ESD self-protection response.

Early attempts to model the ESD self-protection of the SOI switch utilized TLP data and curve-fitting polynomial equations. The curve fit equation in the previous approaches contained parameters for stack width W_T and number N_S and can identify the failure current I_{FAIL} for the switch. However, there were severe limitations with this approach. First, these were not scalable models for transistor gate length. Additionally, it could not predict the effect of R_G on the gate-coupling mechanism. Since the ESD self-protection of the switch is initiated by the gate-couple effect, which is determined by the (R_G*C_{GD}) RC time constant, the inability to properly simulate this coupling severely limits its usefulness.

To address the deficiencies of the curve-fitting model, a behavioral model that comprehends the dual mechanism of the switch turn-on in an ESD event has been proposed [3,4]. Figure 3 graphically shows the behavioral model of the NMOS in a multiple-stack RF switch. This model contains two parts connected in parallel: the standard FET model for NMOS channel conduction and the ESD model for the parasitic bipolar turn-on. While this is an oversimplification of the behavior observed in Figure 2(a), the ESD model is considered an ideal switch in series with a resistor. The switch turns on at the parasitic bipolar trigger voltage (V_{TR}) to shunt the ESD current with a fixed on-resistance (R_{ON}). The values of the two ESD model parameters can be extracted from the TLP measurement data of multiple-stack SOI RF switches.

Figure 4 shows the time-domain voltage and current waveforms of a 16-stack RF switch from the TLP measurement and the corresponding transient simulations for stress voltages of 5V to 50V. As is observed in Figure 4, the simulation and measurement match quite well for TLP voltages below 20 V. However, for stress voltages above 20V, the simulation and measured data begin to diverge. This divergence is due to the oversimplification of the ESD model for bipolar conduction. To model the ESD behavior more accurately in the high current regime, the simple turn-on of an ideal switch with a fixed on-resistance would need to be replaced with the more complicated model of the turn-on of the NMOS parasitic bipolar transistor. This is one of the ongoing efforts in the refinement of the ESD modeling of the SOI switch response to the ESD event.

One of the more important features of a useful ESD model is its ability to predict I_{FAIL}. Indeed, I_{FAIL} is often more important than failure voltage V_{FAIL} since I_{FAIL} can be used to predict the HBM failure current level. The simple ESD behavioral model can predict I_{FAIL} by monitoring the voltage at which the parasitic bipolar is triggered. If the gate coupling is not sufficiently strong, the voltage of the transistor will rise above a failure level prior to the onset of the bipolar conduction. This failure voltage is determined empirically from TLP data. Exceeding this failure voltage indicates failure of the switch due to the $R_G{}^*C_{GD}$ time constant being too short. For a switch with a sufficiently large time constant, I_{FAIL} does not occur until one of the transistor arrays reaches the failure voltage well after the parasitic bipolar turns on.

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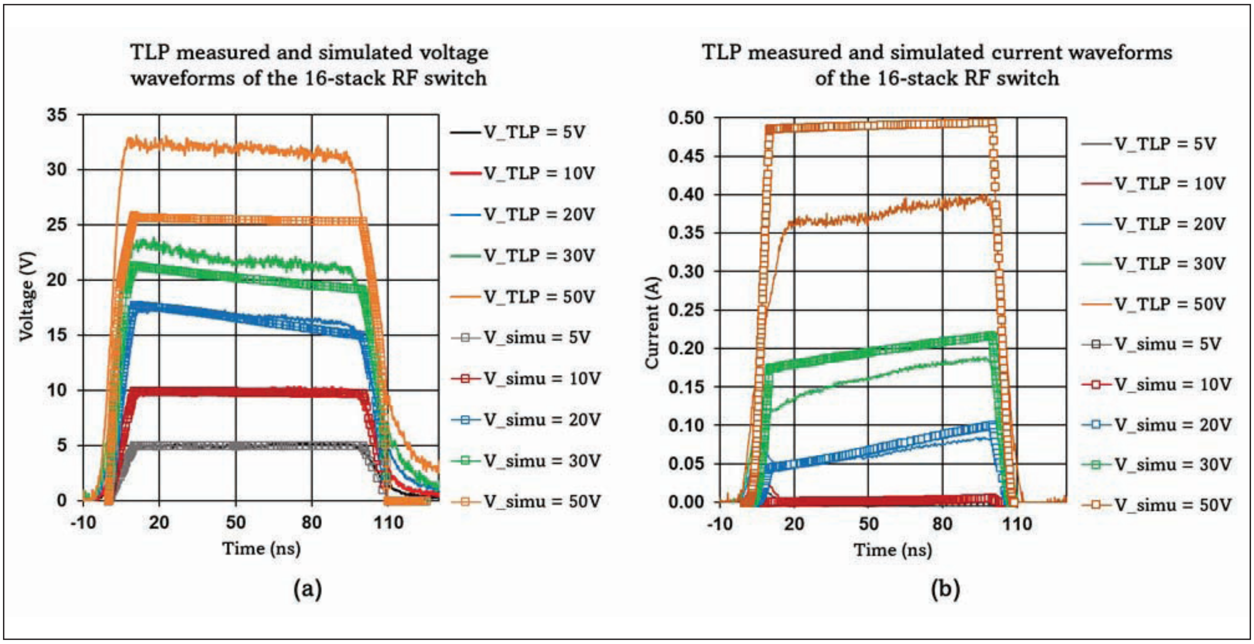

Figure 4: TLP time-domain (a) voltage waveforms and (b) current waveforms of the 16-stack RF switch with various stress voltages from measurement and simulation with the single-stack NMOS ESD behavioral model.

Banana Skins

452 More on mobile phones and medical devices

Since the beginning of the nineties there have been warnings not to sue mobile phones in the vicinity of medical devices. Functional failures of dialysis machines, respirators and defibrillators prompted the banning of their use *(mobile phones – Editor)* in many hospitals in Scandinavia, and then in other countries. Since we believe that a general ban in hospitals is problematic, we decided to investigate the influence of mobile telephone on life-saving and/or life-support systems, with the aim of establishing rules for its use in hospitals.

A total of 224 devices classified into 23 types of devices were examined. Nine different sets of transmission conditions were applied, giving a total of 2016 tests.

We would therefore recommend that all life-saving and life-support systems that can be used outside the hospital should be made mobile phone proof *(this implies testing at the relevant frequencies, with the relevant modulations, at polarisations and levels – probably at 50V/m at least – Editor)*. When apnoea monitors and respirators are protected from such interference, hazardous situations could be avoided by establishing the rule: "No portables, and mobile phones only at a distance of at least 1 metre from medical devices". With regard to emergency telephones, the minimum distance to medical devices should be at least 1.5 metres.

(Taken from a translated abstract of "Effect of mobile phone on life-saving and life-sustaining systems," Irnich W, Tobisch R, Biomed. Techn. (Berl) 43(6):164-173, 1998.)

453 Evidence of the dangers of mobile phone use in hospitals

- Electrocardiogram traces--interference caused baseline noise (generally not severe enough to be clinically relevant) [5]
- Electrocardiogram traces--interference caused baseline noise (generally not severe enough to be clinically relevant) [5]
- Defibrillators--affected by screen judder; with more powerful phones the units switched off, changed input selection, dumped their stored energy, and displayed asystole incorrectly [4]
- Anaesthetics machines--displayed incorrect oxygen values when mobile phones were used 1 m or less away [4]
- External pacemakers--incorrectly sensed pulses and consequently failed to deliver paced output [4]
- Infusion pumps--prone to alarms and error messages and even reversal in pump direction when phones were less than 1 m away [4]
- Medical monitors--61% had changes to readings, severe judder, buzzing, and system crash when phones were further than 1m away [4]
- Dialysis machines--at 0 m, readings were distorted by phones [4]
- The maximum distance at which any phone caused interference was 2 m; phones closer than 88 cm caused the most severe interference [5]

[4] Medical Devices Agency. Electromagnetic compatibility of medical devices with mobile communications. London: Medical Devices Agency, 1997. (MDA DB 9702.)

[5] Ri JL, Hayes DL, Smith TT, Severson RP. Cellular phone interference with external cardiopulmonary monitoring devices. Mayo Clin Proc 2001;76:11-5.

(Extracted from "Using mobile phones in hospitals: what's the worst that could happen?" by Layla McCay and Andy Smith, BMJ 2003;326:030352, https://www.bmj.com/content/326/Suppl_S3/030352.)

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