The Orange Book of Knowledge

9th Edition

The Orange Book of Knowledge**

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General EMC

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Frequently Asked Questions About Chambers

- **What is pan-type/style shielding?**

  This shielding structure is constructed by 2mm pan-type galvanized panels and assembled with special fastener M10 and high-performance gasket to ensure a long-life RF shielding attenuation. It is a bent flange that is welded on the corners to close up the "pan" profile.

- **When planning for a new chamber, retrofitting an existing chamber, or expanding test scope, how important is anechoic material selection?**

  The proper selection of anechoic material is critical to your success. The chamber can, and does fail qualification testing due to poor anechoic material or the wrong type. The key to selecting the right microwave absorber(s) is the material's reflectivity performance. Our recommendation is for a thorough technical discussion with AR applications engineers, in order to identify the proper solution for your requirements.

- **What is the range of filter options offered?**

  Includes AC and DC filters from 5A, 16A up to 200A, SPN and TPN, from 50/60Hz to 400Hz. Custom filter options can be discussed on a case by case basis.

- **What size doors are available?**

  From 3' x 7' to 10' x 10' as standard offerings, both single and double leaf doors. Automatic sliding door and gates are also available.

- **Is there a limit in size for an anechoic chamber?**

  The size of the chamber is limited by the space and budget available for the construction, and any limitations given by testing standards.

- **What standards do your chamber comply with?**

For radiated emission:	For radiated immunity:
EN 61000-6-3	IEC/EN 61000-4-3
EN 61000-6-4	EN 61000-6-1
CISPR 11 / EN55011	EN 61000-6-2
CISPR 12 / EN55012	CISPR 14-2 / EN55014
CISPR 14-1 / EN55014-1	CISPR 20 / EN 55020
CISPR 15 / EN55015	CISPR 24 / EN 55024
CISPR 16-1-4	CISPR35
CISPR 25	ISO 11451
CISPR 32 / EN55032	ISO 11452
ETSI TS 102-321	Mil-Std 461
ETSI TR102-273-2	Mil-Std 464
ETSI TR102-273-3	RTCA DO-160
Mil-Std 461	IEC 60601-1-2
Mil-Std 464	EN 61000-4-21
RTCA DO-160	
ANSI C63.4	
ANSI C63.10	
FCC part 15	

- **What type of ancillary equipment do you offer?**

  Positioning equipment, CCTV, shielded converters, test tables for MIL-STD and CISPR standards, 3rd party performance testing, removable ramp, fire detection and suppression, etc.

- **Can I install the shield on my own?**

  While the pan type shielding system is a very practical design, it is highly recommended that it be installed by experienced and qualified technicians in order to maintain performance and efficiencies.

- **Do you offer chambers for 5G testing?**

  Yes, we offer antenna test range with high-power handling microwave absorbers that perform up to 80 GHz.

- **Can you provide a turnkey solution?**

  Yes, AR is a one stop solution provider that can implement complete EMC systems catered to any customer requirements.

- **What are the minimum building requirements for a chamber installation?**
  - Within 50 ft. from the installation site, a 230 Vac /16 Amp (EU/Asia) or 110 Vac / 16Amp (USA) mains power outlet and sufficient lighting shall be available.
  - The max. fluctuation mains voltage in the parent building is 10% of 230VAC.
  - The floor of the installation area for the chamber or shielded room shall meet a floor flatness level of:
    - Length: 1m +/- 1mm
    - Length: 3m +/- 3mm
    - Length: 5m +/- 5mm
    - Overall length: +/- 7mm
  - A floor flatness measuring report prepared on a grid of 1.0 x 1.0m shall be presented to AR 3 weeks prior to the start of the installation.
  - The floor shall be able to withstand the full weight of the total installation and the point load.
  - When on-site installation has started, no interruption of the work is allowed. In case such an interruption occurs beyond control of AR, the costs involved will be charged to the customer.
  - The working site must be a dry and clean area, covered with a roof and the possibility to lock.
  - A declaration of wind and water tightness shall be presented in writing to AR 3 weeks prior to the start of the installation.
  - Working conditions on site shall meet following conditions:
    - Temperature: 15°C minimum / 25 °C maximum
    - Humidity: 70% maximum
  - Working conditions on site during ferrite and absorber installation shall meet following conditions:
    - Temperature: 18°C
    - Humidity: 70% maximum
  - Temperature during validation tests inside the chamber must be 20°C +/- 10%
  - During the entire installation, third party activities inside the shielded room / anechoic chamber are prohibited unless agreed upon with the AR project supervisor on site.
  - For the connection to the EMC power line filters, it should be considered that it cannot be connected to a mains supply with differential current detectors, due to the large capacitors inside the filters.
  - Prior to the execution of shielding effectiveness testing, the customer should ensure that electrical mains power is available both inside and outside of the shielded room / anechoic chamber.

- **How long will the installation take?**

  This will depend on the scope of the project, refurbishment of small chambers, i.e. absorber replacements can be as little as a few days and construction of large EMC chambers such as a 10M Chamber with a 5M quiet zone can be 12 to 14 weeks.

- **How are the chambers commissioned?**

  Once the shielding installation is completed, the chamber will be tested on RF attenuation before the installation of the anechoic materials. Once the full installation is completed, the chamber will be tested by 3rd party for NSA, VSWR and UFA compliance to verify the anechoic performance of the chamber before the system integration process.

- **Do you offer fire protection?**

  Yes, we can provide both dry pipe systems and inert gas systems that can be easily integrated into the chamber design.

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Changes Introduced with IEC 6100-4-3:2020 Edition 4.0

IEC 61000-4-3 is a standards publication covering electromagnetic compatibility (EMC) testing and measuring techniques for radiated electromagnetic field immunity testing. From time to time, changes are made to test standards to address shortcomings, improve testing methods, react or respond to industry changes, and to establish a more controlled and repeatable test process.

IEC 61000-4-3:2020 Edition 4.0 was released in September 2020, which cancels and replaces Edition 3 published in 2006, including Amendment 1:2007 and Amendment 2:2010. The changes that were made in Edition 4.0 are outlined below.

1.0 Multiple Signal Testing

Testing with simultaneous multiple frequencies is now permitted. Using this multiple signal, or multiple-tone, approach can result in a significant decrease in test time due to the reduction in the number of dwell times required, as several test frequencies will be completed at the same time.
Section 8.3 describes multiple signal testing, and informative Annex I (Testing with Multiple Signals) provides additional detail and guidance.

2.0 Cable Layout

More control of and definition of cable layout has been added, with additional description details and figures added. Controlling positioning and location of cables improves test consistency and leads to more reproducible test results. Section 7 contains EUT positioning and cable layout requirements. Additional guidance is provided in informative Annex G (Cable Layout Details) and informative Annex H (Test Setups for Large EUTs).

3.0 Uniform Field Area and Large EUTs

In IEC 61000-4-3:2020 Edition 4.0 there were multiple updates regarding the Uniform Field Area (UFA). To begin with, the lower edge of the UFA previously being fixed at 0.8 meters. It was determined that under this condition, the lower region of floor-standing equipment might not experience controlled illumination. This fixed height requirement has now been removed, and the lower edge of the UFA can be at any height, provided several criteria are met. (See section 6.3.1 and section 7.3.) The intent is to fully illuminate a floor standing EUT, however achieving a UFA close to a metallic floor is difficult, and might preclude full EUT illumination. Additional guidance is provided in informative Annex H (Test Setups for Large EUTs).

Previously, floor-standing equipment required recording of field measurements at 0.4m height. In the current edition, this requirement is eliminated if the EUT can be raised to a height such that less than 0.5m of the EUT is below the UFA. Additional details are provided in Section 7.3.

A note was added in Section 6.3.3 that when performing the UFA calibration, the probe is oriented in the same manner as it was when the probe was calibrated, to lower the uncertainty of the field measurement.

When using the minimum 0.5m x 0.5m 4-point Uniform Field Area (UFA), an additional center 5th point has been added. This provides further characterization of the field within the smaller UFA, ensuring that a small EUT sitting within the 0.5m x 0.5m UFA will see a consistent field. See section 6.3.1.

Also, although the UFA is typically square, this is not required, as long as it can be constructed from 0.5m × 0.5m squares. This is described in section 6.3.1. For example, for an EUT shaped like the letter 'L', an 'L'-shaped UFA could be created using 0.5m x 0.5m squares.

4.0 Maximum Frequency

In the new edition, the upper frequency limit of 6.0 GHz has been removed, allowing the product standard committees to define an appropriate frequency limit. This will allow flexibility for testing at higher frequencies as spectrum use continues to expand to ever higher frequencies.

5.0 Testing Level vs. Calibration Level

Historically, testing at field levels lower than a calibrated field level has been allowed. Testing at field levels higher than the calibration field level is now permitted, provided that the linearity of the system can be demonstrated. This provides flexibility in being able to test multiple requirements without having to run a full 16-point field calibration for each required field level. This is described in Section 6.3.1.

6.0 Harmonics

The -6 dBc harmonic limit measured in field, previously in Section 6, has been removed since a suitable test measurement method is not described. This requirement is under consideration by the committee and may be re-introduced at a future time.

Other notable Annex changes/additions:

- Informative Annex B 'Field Generating Antennas' added a description for 'combination antenna'.
- Informative Annex D 'Amplifier Compression and non-Linearity' includes extensive updates.
- Informative Annex F 'Selection of Test Methods' updated with additional detail.
- Informative Annex G is now 'Cable Layout Details'.
- Informative Annex H is now 'Examples of Test Setups for Large and Heavy EUTs'.
- Informative Annex I is now 'Testing with Multiple Signals'.

Summary

AR RF/Microwave Instrumentation can provide you with guidance and advice on all of your IEC and multiple signal testing needs. If you have any questions, or would like to learn more about how AR can help you achieve your testing requirements, feel free to contact one of our applications engineers at 800-933-8181, or visit our website at www.arworld.us.

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Conducted Immunity Test Method

The foundation for consistent and meaningful conducted immunity testing comes from defining the appropriate combination of amplification, injection device, and test set-up. RF conducted immunity (CI) is the test method and standard that substitutes for radiated immunity (RI) testing at lower frequencies. Due to antenna size, near field and grounding interactions, RI testing at lower frequencies is inherently problematic. Susceptibility to radiated energy at lower frequencies is more likely to find ingress on the equipment input/output lines; consequently, CI methods and standards were developed that replicate these radiated fields that would couple onto equipment cabling. Defining the system components is critical, considering and applying the correct method accordingly will result in dependable CI testing.

1.0 How does radiated energy get induced on to a cable?

Any conductor can act as an antenna and allow energy to be induced upon it. To do so, it must be resonant at that given frequency. The free space impedance of a plane wave is approximately 370 Ω. An effective antenna, or a test cable acting as an antenna must transform this impedance to induce a current on to its conductor. Antenna impedance varies from approximately 73 Ω for 1/4 wave stub to 280 Ω for a folded dipole. (See Figure 1). Therefore, test methods have been established with levels based on lower impedance values, namely 50 and 150 Ω. Currents induced on multiple conductors may not be balanced. That is to say, the level and phase are not equal. All CI injection methods, however, are common-mode or equal level/phase on all conductors.

2.0 What techniques are used to interject current/voltage into the test cable?

There are four different methods that can be used to inject currents onto test cables. These methods include: Coupling/Decoupling Network (CDN), Bulk Current Injection (BCI), Electromagnetic Clamp (EM), and Tubular Wave Clamp (TWC), and Direct Interjection.

2.1 Coupling/Decoupling Network (CDN)

The CDN device shown in Figure 2 uses passive components to inject the test signal onto the test cable conductor(s).
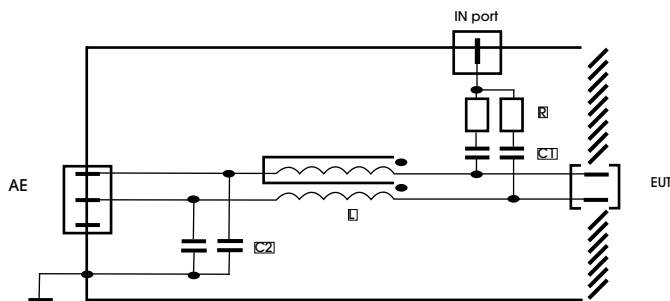
Figure 2. CDN Schematic, two conductors

Far Field (planar wave front)
Radiated electromagnetic wave
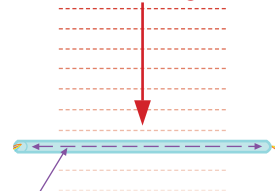
Impedance of Antenna Types

½ wave dipole	70 OHMS
¼ wave stub	50 OHMS
Full wave Loop	100 OHMS
Folded dipole	280 OHMS
Inefficient antenna	Z unknown

Figure 1. Coupling modes.

Isolation to auxiliary equipment (AE), fixed impedance (150 ohms), and low required injection level are the main advantages of the CDN method. Terminating to a fixed impedance permits a stable test level across the test frequency band regardless of the cable's natural resonance. Some disadvantages of this method include the need for many different types of CDNs to match the test cable connector as well as the number of conductors, and current requirements. Serial communication through the AE low pass filter may also be degraded.

2.2 Bulk Current Injection (BCI)

The BCI device shown in Figure 3 uses inductive coupling to inject the test signal on to the test cable conductor(s).

*Figure 3. Bulk Current Injection Probe*

2.2 Bulk Current Injection (BCI)

This method requires only one device to apply test levels to any cable assuming the cable fits the inside diameter. Probe frequency range, loss, and power rating must also be considered. This method, unlike the CDN, does not terminate to a fixed impedance. A cable will have a natural resonate impedance that will vary from near zero to many MΩ resulting in a widely varied induced current over the test frequency. Care must be exercised so as not to over test. However, as noted above, unless the cable acts as an antenna, radiated energy will not be efficiently induced. Therefore, the fact that a fixed test level across a frequency band is applied should not be a significant concern. Test levels are more accurately applied when the resonance approximates antenna impedances.

2.3 Electromagnetic Clamp (EM) and Tubular Wave Clamp (TWC)

Like the BCI, these devices use inductive coupling to apply the test signal onto the test cable conductor(s). The same characteristics of a BCI apply, however, they also provide capacitive coupling (See Figures 4 & 5). Because of this, the frequency range is extended to higher frequencies.

Figure 4. Electromagnetic Clamp

Figure 5. Tubular Wave Clamp
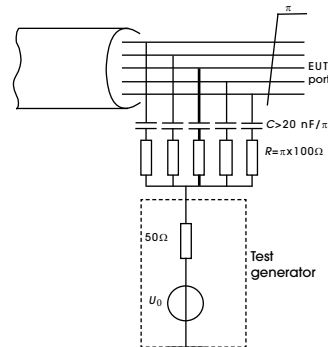
Figure 6. Direct Injection. IEC 6100-4-6

2.4 Direct Injection

Direct Injection is the simplest method of current/voltage injection onto test cables. Resistor(s) and capacitor(s) are tied directly to the conductor(s). Although this is the simplest method, it can also be the most tedious to apply, as it requires cutting any insulation and making good electrical contact with all conductors (See Figure 6).

3.0 Calibration Methods

Due to the potentially high variability in test cable impedance, a calibration must be performed to determine the proper test level according to the test standard being used. Calibration is performed at a fixed impedance, either 50 or 150 ohms, depending on the standard. BCI, EM, and TWC clamps require a calibration fixture. As shown in Figure 7, the calibration clamp is fitted onto the jig over the single conductor. One side of the jig is terminated, and the other goes to the measurement device. In Figure 8, the forward power is recorded across the frequency band as power is adjusted to meet the required test levels. CDN calibration and IEC61000-4-6 are similar except that the termination impedance is always 150 ohms (See Figure 9).
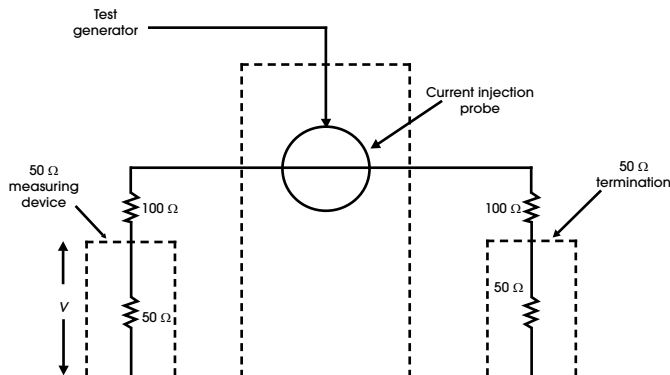
Figure 8. Clamp Calibration set-up. IEC 61000-4-6
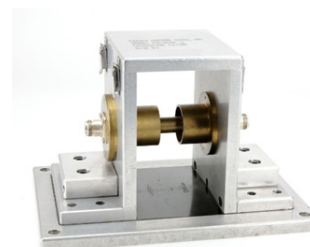
Figure 7. BCI Calibration Fixture
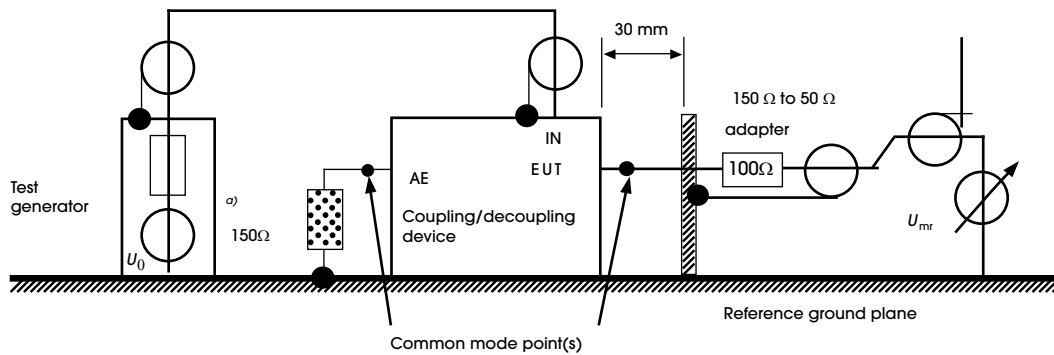
IEC 2604/13

Figure 9. CDN Calibration set-up. IEC 61000-4-6

4.0 Test Methods

Like RI testing, CI testing is performed using substitution or closed loop methods. The substitution method uses the recorded drive level from calibration to 'playback' the test level. Monitoring should be done to ensure an over-test condition will not occur (See Figure 10). Closed loop method actively monitors the current or voltage on the test cable.

The table on which the cable and or equipment under test are placed is a critical consideration as well (See Figure 11). The test standard used gives specific guidance on the recommended configuration.
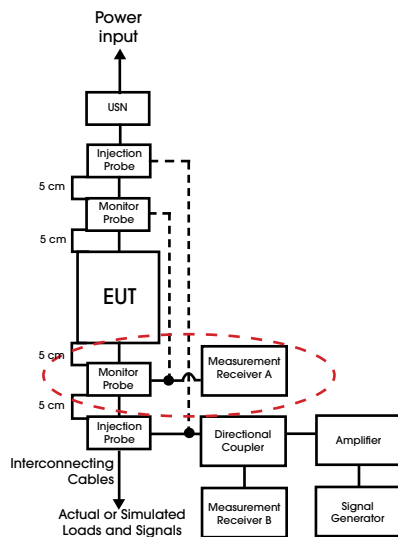
Figure 10. Test set-up MIL-STD 461G CS114
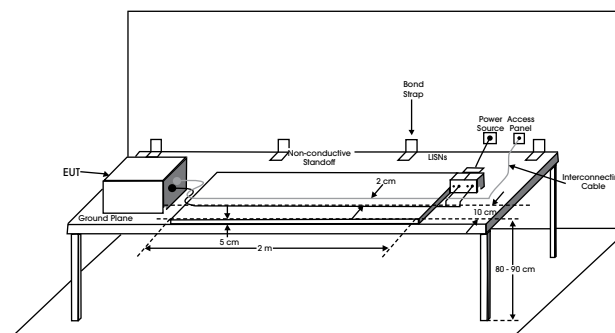
Figure 11. Test Table Configuration MIL-STD 461G

Conclusion

Defining the system components is critical as the appropriate combination of amplification, injection device, and test set-up varies widely. Understanding the foundations is important for consistent and meaningful CI testing. Conducted immunity testing is intended to replicate radiated immunity testing at low frequencies. Be sure to review the requirements defined by the standard you are testing to and make sure an appropriate calibration is performed. Always consider the objective of your test and apply the correct method accordingly.

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Frequency Asked Questions for Designing an EMC Test System

- **What's the most important factor when designing an EMC Test System?**

  Unfortunately, there is no one size fits all method when designing an EMC Test System. The most important factor will vary based on the laboratory's goals, the space available to house the equipment, and the requirements of the testing performed. Considerations should be made if the laboratory needs to test to standards (IEC 61000-4-3, MIL-STD-461, or DO-160), or the goals of the laboratory are to meet requirements for field strength, field uniformity, or frequency ranges.

- **What are environmental considerations that should be looked at when designing an EMC Test System?**

  The chamber's size where the tests will be performed plays a factor, as the test location can vary from a small reverberation chamber to a large semi-anechoic chamber. These matters can affect parameters such as cable loss, test distance, and required amplifier power. In addition, the installation space should always contain adequate power, cooling, and footprint for the equipment being installed.

- **How can we set ourselves up to be able to grow our testing capabilities over the years?**

  When making any large investment, it is always important to consider how that investment will continue to work for you as your needs change. Although standards within the industry are always evolving, it is important to educate yourself on the industry's future requirements with IEEE meetings and working groups and team up with partners that are doing the same. Working with the right partners to enhance your knowledge and education to understand the future testing requirements and how to angle yourself to be prepared is the best way to align your future goals with your investment.

- **Can a GTM cell be cost-effective for testing radiated immunity/emissions pre-compliance? If so, why?**

  Yes. GTEMs are significantly less expensive than a chamber, so if pre-compliance capabilities are all that is required, this cost reduction can be a compelling driver. This component is, of course, if the EUT is small enough to fit into a GTEM. Also, EUTs with cabling can pose problems inside a GTEM as repeatability with cable positioning becomes a concern.

- **What is the rationale behind determining the required amplifier power to perform the test? I have often heard that I will need more power than I think.**

  When determining your required amplifier power, it is recommended to accommodate for the unexpected as, in this industry, there is a lot of room for unexpected effects. Therefore, taking a conservative approach in determining your power requirements is suggested

  Check out our webinar Test Equipment Selection: Knowing the Limits of Power, Frequency and Everything In Between, for more information.

- **In a radiated immunity test setup, is there a way to minimize "amp drift", where the amp's power output changes over time with the same input signal?**

  To begin with, consider the type of amplifier you are using in your setup. Amplitude drift is rarer with solid state power amplifiers (SSPA) than with Traveling Wave Tube Amplifiers (TWTA). Next, warm up your amp. Sometimes amps (even SSPAs) need some time to warm up to stable operation. The effect is much less pronounced in SSPAs than in TWTAs. If, after warming up, the amp is still not performing to the level expected, the signal generator drive could be adjusted to accommodate for a decrease in gain. Using a directional coupler, one can calibrate the forward power required to produce various fields and adjust drive levels to achieve the required forward power. If amplitude drift becomes a concern, the power measured from the directional coupler can also be used to detect these anomalies.

- **What software options are out there that can help us?**

  There are several software options available on the market today. At AR, we offer two great products as part of our commitment to offering a total solution: emcware® 5.0 and Nexio BAT-EMC®. With emcware 5.0, you get over 500 test profiles, a streamlined user workflow that reduces set-up and training time and reporting templates to get you up and running faster than ever. In addition, emcware now includes reverb immunity test methodologies.

  If customization is what you're looking for, AR also offers Nexio BAT-EMC. In-depth equipment management options, custom reporting, and testing profiles gives you complete flexibility.

  To learn more or schedule a demo call us at 215-723-8181.

- **How does AR design test systems to meet specific requirements?**

  The first steps always include a review of the required statement of work with the customer, whether it is a customer written spec or an industry-accepted standard. From there, we can develop a test system with those specifications in mind to meet the standard's requirements. There are other factors that will need to be discussed such as the space available, field strength requirements, and frequency ranges, but meeting the requirements of the statement of work always needs to be considered first and foremost when designing a test system.

  To design the best test system for your needs, contact your local Sales Rep.

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EMC 101

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

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

Definitions:

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

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

EUT – Equipment Under Test

CE – Conducted Emissions – A measurement of the interference emitted from a product, typically measured on power input lines or telecommunications ports, with measurements and limits typically expressed in terms of voltage (dBµV) or current (dBµA).
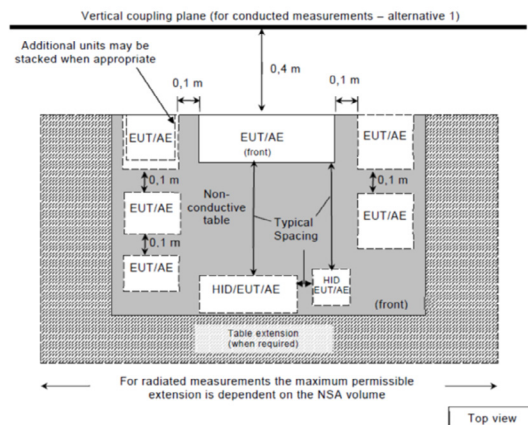
Figure 1: CISPR 32 Conducted Emissions Test Setup

RE – Radiated Emissions – A measurement of the over-the-air interference emitted from a product, from both the enclosure (often called the enclosure-port) or the cabling. Limits typically expressed in terms of Volts per meter (dBµV/m) for electric field, or Amperes per meter (dBµA/m).
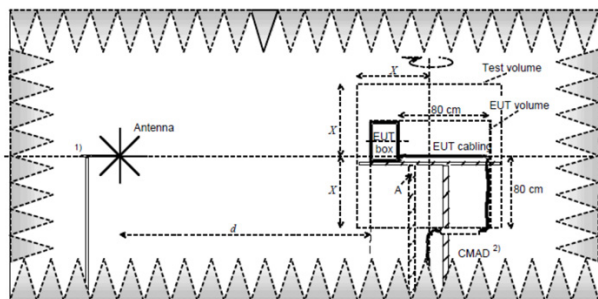
Figure 2: CISPR Radiated Emissions Test Setup

CS or CI – Conducted Susceptibility or Conducted Immunity – The application of a test signal, often imparted onto interfacing cables to EUTs via BCI, CND, EM Clamp, or other means, to observe that the EUT operates acceptably throughout the application of the test.
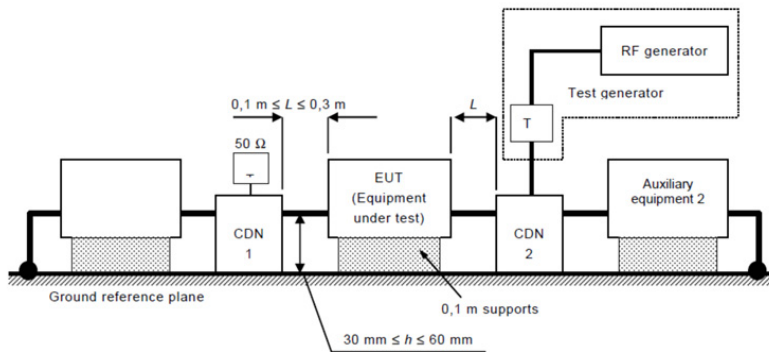
Figure 3: Conducted Immunity or Susceptibility Test Setup

RS or RI – Radiated Susceptibility or Radiated Immunity – The application of a test signal, applied with a test antenna over-the-air, to observe that the EUT operates acceptably throughout the application of the test.
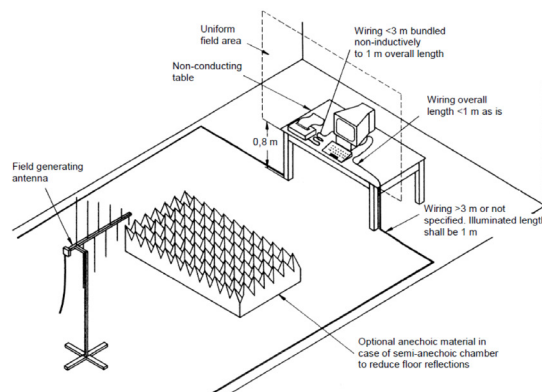
Figure 4: Radiated Immunity or Susceptibility Test Setup

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

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

2.0 What's the difference between Continuous and Transient in the world of EMC Testing?

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

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

During transient testing, an EUT upset or malfunction may be permitted, provided it can return to the previous state or operating mode without user intervention. The compliance criteria for this is dependent on the test standard being tested.
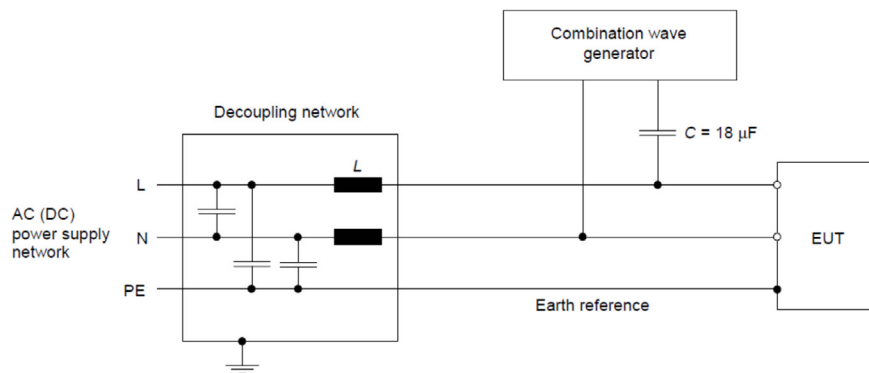
Figure 5: Transient Testing per IEC 61000-4-5, Surge Immunity, Test Setup

3.0 What's the purpose of EMC Testing and Compliance?

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

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

4.0 What's the most important aspect of EMC Testing and Compliance?

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

5.0 Impedance

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

6.0 Okay, so now I think I have understanding of what EMC is, but now what do i do?

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

7.0 I have a product that I want to sell in both the US and in Europe. What's my next step?

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

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

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

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

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

Conclusion

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

References

Title 47 of the Federal Register, Part 15, https://www.ecfr.gov/cgi-bin/text-idx?SID=bd8d7b3d5ac31a5bedaf9455f950fd12&mc=true&node=pt47.1.15&rgn=div5

2014/30/EU, The EMC Directive, https://ec.europa.eu/growth/sectors/electrical-engineering/emc-directive_en

AR RF/Microwave Instrumentation • 160 Schoolhouse Rd, Souderton, PA 18964 • info@arworld.us
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EMC Formulas

1.0 Term Conversion in 50 Ω Environment

Log

dBµV to dBm	$dBm = dB\mu V - 107$
dBµA to dBm	$dBm = dB\mu A - 73$
dBm to dBµV	$dB\mu V = dBm + 107$
dBµA to dBµV	$dB\mu V = dB\mu A + 34$
dBm to dBµA	$dB\mu A = dBm + 73$
dBµV to dBµA	$dB\mu A = dB\mu V - 34$

Log ⇦ Linear

Volts to dBm	$dBm = 20 \bullet Log(Volts) + 13$
Amps to dBm	$dBm = 20 \bullet Log(Amps) + 47$
Watts to dBµV	$dB\mu V = 10 \bullet Log(watts) + 137$
Amps to dBµV	$dB\mu V = 20 \bullet Log(Amps) + 154$
Watts to dBµA	$dB\mu A = 10 \bullet Log(Watts) + 103$
Volts to dBµA	$dB\mu A = 20 \bullet Log(Volts) + 86$

Log ⇨ Linear

dBµV to Watts	$Watts = 10^{\left(\frac{dB\mu V - 137}{10}\right)}$
dBµA to Watts	$Watts = 10^{\left(\frac{dB\mu A - 103}{10}\right)}$
dBm to Volts	$Volts = 10^{\left(\frac{dBm - 13}{20}\right)}$
dBµA to Volts	$Volts = 10^{\left(\frac{dB\mu A - 86}{20}\right)}$
dBm to Amps	$Amps = 10^{\left(\frac{dBm - 47}{20}\right)}$
dBµV to Amps	$Amps = 10^{\left(\frac{dB\mu V - 154}{20}\right)}$

Linear

Volts to Watts	$Watts = \dfrac{Volts^2}{50}$
Amps to Watts	$Watts = Amps^2 \bullet 50$
Watts to Volts	$Volts = \sqrt{Watts \bullet 50}$
Amps to Volts	$Volts = Amps \bullet 50$
Watts to Amps	$Amps = \sqrt{\dfrac{Watts}{50}}$
Volts to Amps	$Amps = \dfrac{Volts}{50}$

Unit Conversion

Log ⇦ Linear

Watts to dBm	$dBm = 10 \bullet Log(Watts) + 30$
Volts to dBµV	$dB\mu V = 20 \bullet log(Volts) + 120$
Amps to dBµA	$dB\mu A = 20 \bullet log(Amps) + 120$
Ω to dBΩ	$dB\Omega = 20 \bullet log(\Omega)$

Used for the conversion of Voltage & Current

Log ⇨ Linear

dBm to Watts	$Watts = 10^{\left(\frac{dBm - 30}{10}\right)}$
dBµV to Volts	$Volts = 10^{\left(\frac{dB\mu V - 120}{20}\right)}$
dBµA to Amps	$Amps = 10^{\left(\frac{dB\mu A - 120}{20}\right)}$
dBΩ to Ω	$\Omega = 10^{\left(\frac{dB\Omega}{20}\right)}$

2.0 Term Conversion/Ohms Law

Log

dBµV to dBm	$dBm = dB\mu V - 10 \bullet Log(\Omega) - 90$
dBµA to dBm	$dBm = dB\mu A + 10 \bullet Log(\Omega) - 90$
dBm to dBµV	$dB\mu V = dBm + 10 \bullet Log(\Omega) + 90$
dBµA to dBµV	$dB\mu V = dB\mu A + 20 \bullet Log(\Omega)$
dBm to dBµA	$dB\mu A = dBm - 10 \bullet Log(\Omega) + 90$
dBµV to dBµA	$dB\mu A = dB\mu V - 20 \bullet Log(\Omega)$

Linear

Find Watts	$Watts = Amps^2 \bullet \Omega, \; Watts = \dfrac{Volts^2}{\Omega}$
Find Volts	$Volts = Amps \bullet \Omega, \; Volts = \sqrt{Watts \bullet \Omega}$
Find Amps	$Amps = \sqrt{\dfrac{Watts}{\Omega}}, \; Amps = \dfrac{Volts}{\Omega}$

dB Calculations

dB Δ Watts	$dB = 10 Log\left(\dfrac{Watts_1}{Watts_2}\right)$
dB Δ Volts	$dB = 20 Log\left(\dfrac{Volts_1}{Volts_2}\right)$
dB Δ Amps	$dB = 20 Log\left(\dfrac{Amps_1}{Amps_2}\right)$
New Watts w/dB Δ	$Watts_{New} = 10^{\left(\frac{dB\Delta + 10 \bullet Log(Watts_{start})}{10}\right)}$
New Volts w/dB Δ	$Volts_{New} = 10^{\left(\frac{dB\Delta + 20 \bullet Log(Volts_{start})}{20}\right)}$
New Amps w/dB Δ	$Amps_{New} = 10^{\left(\frac{dB\Delta + 20 \bullet Log(Amps_{start})}{20}\right)}$

dB Correction for distance change (antenna far field)

$$dB = 20 \bullet Log\left(\frac{distance_2}{distance_1}\right)$$
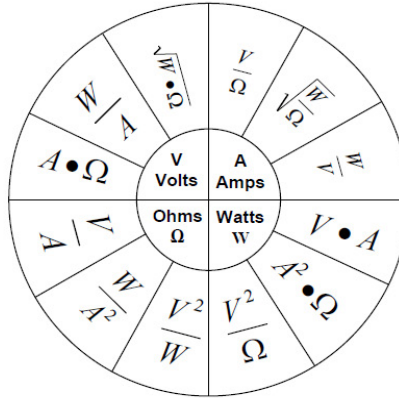
Sine Wave

Voltage levels for a sine wave

$$Volts_{peak} = \sqrt{2} \bullet Volts_{rms} = \frac{\pi}{2} \bullet Volts_{Avg}$$

$$Volts_{rms} = \frac{Volts_{peak}}{\sqrt{2}} = \frac{\pi}{2 \bullet \sqrt{2}} \bullet Volts_{Avg}$$

$$Volts_{avg} = \frac{2}{\pi} \bullet Volts_{peak} = \frac{2 \bullet \sqrt{2}}{\pi} \bullet Volts_{Avg}$$

$$Volts_{peak-peak} = 2 \bullet Volts_{peak}$$
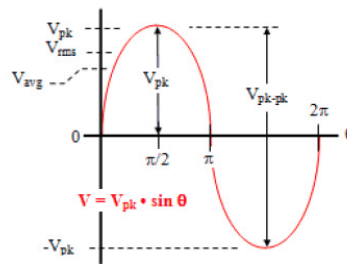
w/ Impedance of air $= 377\ \Omega$

dBμV/m to dBm/m² $dBm/m^2 = dB\mu V/m - 115.8$

dBm/m² to dBμV/m $dB\mu V/m = dBm/m^2 + 115.8$

dBμA/m to dBμV/m $dB\mu V/m = dB\mu A/m + 51.5$

dBμV/m to dBμA/m $dB\mu A/m = dB\mu V/m - 51.5$

dBμA/m to dBpT $dBpT = dB\mu A/m + 2$

dBpT to dBμA/m $dB\mu A/m = dBpT - 2$

Watts/m² to V/m $V/m = \sqrt{Watts/m^2 \bullet 377}$

V/m to Watts/m² $Watts/m^2 = \dfrac{V/m^2}{377}$

Radiated Field

dBμV/m to V/m $V/m = 10^{\left(\frac{dB\mu V/m - 120}{20}\right)}$

V/m to dBμV/m $dB\mu V/m = 20 \bullet Log(V/m) + 120$

New V/m with dBΔ

$$V/m_{new} = 10^{\left(\frac{dB\Delta + 20 \bullet Log(V/m_{start})}{20}\right)}$$

Interpolation values on a graph w/ Log of frequency
This equation works for finding all points on a test
curve where test limit is sloping (i.e. DO 160F BCI
testing)

$$value_{new} = \frac{Log\left(\frac{freq_{new}}{freq_{lower}}\right)}{Log\left(\frac{freq_{upper}}{freq_{lower}}\right)} \bullet (value_{upper} - value_{lower}) + Value_{lower}$$

Current Injection

Power needed for BCI probe (50Ω) for given Insertion loss (IL(dB))

$$Watts = 10^{\left(\frac{IL + 10 \bullet LOG\left(Volts^2/50\right)}{10}\right)}$$

$$Watts = 10^{\left(\frac{IL + 10 \bullet LOG\left(Amps^2 \bullet 50\right)}{10}\right)}$$

$$Watts = 10^{\left(\frac{IL + dB\mu A - 73}{10}\right)}$$

Power needed for BCI probe or EM Clamp (150Ω) for given Insertion loss (IL(dB))

$$Watts = 10^{\left(\frac{IL + 10 \bullet LOG\left(Volts^2/150\right)}{10}\right)}$$

$$Watts = 10^{\left(\frac{IL + 10 \bullet LOG\left(Amps^2 \bullet 150\right)}{10}\right)}$$

Conducted current measurement using a current probe. Where reading is in dBμV and probe factor is dBΩ or Ω

$$dB\mu A = dB\mu V - dB\Omega$$

$$dB\mu A = dB\mu V - 20 \bullet Log(\Omega)$$

Power needed for TEM Cell

$$Watts = \frac{(V/m \bullet Height \bullet 0.5)^2}{Z_{(50\Omega)}}$$

Power needed for GTEM Cell

$$Watts = \frac{(V/m \bullet SpectrualHeight)^2}{Z_{(50\Omega)}} \bullet 1.08$$

Wave length (λ)

$$\lambda[meters] = \frac{300}{MHz} \qquad \tfrac{1}{4}\,\lambda[meters] = \frac{75}{MHz}$$

Period

$$Time(s) = \frac{1}{Hz} \qquad Hz = \frac{1}{Time(s)}$$

VSWR

VSWR given Fwd/Rev power

$$VSWR = \frac{1 + \sqrt{\dfrac{Watts_{rev}}{Watts_{fwd}}}}{1 - \sqrt{\dfrac{Watts_{rev}}{Watts_{fwd}}}}$$

VSWR given Return Loss (RL)

$$VSWR = \frac{1 + 10^{\left(\frac{-RL(dB)}{20}\right)}}{1 - 10^{\left(\frac{-RL(dB)}{20}\right)}}$$

VSWR Given Impedance (Z)

$$\mathbf{Z_O > Z_L} \qquad VSWR = \frac{Z_O}{Z_L}$$

$$\mathbf{Z_L > Z_O} \qquad VSWR = \frac{Z_L}{Z_O}$$

VSWR given reflection coefficient (Γ)

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma}$$

Reflection Coefficient (Γ)

$$\Gamma = \sqrt{\frac{Watts_{Rev}}{Watts_{Fwd}}}$$

$$\Gamma = \left| \frac{Z_{load} - Z_{Amp}}{Z_{load} + Z_{Amp}} \right|$$

$$\Gamma = \frac{VSWR - 1}{VSWR + 1}$$

$$\Gamma = 10^{\left(\frac{-RL(dB)}{20}\right)}$$

Return Loss (RL) in dB

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

$$RL(dB) = 10 \bullet Log\left(\frac{Watts_{fwd}}{Watts_{rev}}\right)$$

$$RL(dB) = -20 \bullet Log(\Gamma)$$

Transmission Loss (TL) in dB

$$TL(dB) = 10 \bullet Log\left(\frac{Watts_{fwd}}{Watts_{fwd} - Watts_{rev}}\right)$$

$$TL(dB) = -10 \bullet Log\left(1 - \Gamma^2\right)$$

$$TL(dB) = -10 \bullet Log\left(1 - \left(10^{\left(\frac{-RL(dB)}{20}\right)}\right)^2\right)$$

$$TL(dB) = -10 \bullet Log\left(1 - \left(\frac{VSWR - 1}{VSWR + 1}\right)^2\right)$$

Antenna Equations

Far Field Distance

Dipole & Log-periodic antenna

$$FarField = \frac{\lambda}{2 \bullet \pi}$$

Horn antenna $\quad FarField = \frac{2 \bullet apeture^2}{\lambda}$

Far Field Equations

Gain over isotropic $\quad Gain_{Numeric} = 10^{\left(\frac{Gain_{dBi}}{10}\right)}$

$$Gain_{dBi} = 10 \bullet Log(Gain_{numeric})$$

$$Gain_{Numeric} = \frac{\left(Meters \bullet {V}/{m}\right)^2}{30 \bullet Watts}$$

$$Gain_{dBi} = 10 \bullet Log\left(\frac{\left(Meters \bullet {V}/{m}\right)^2}{30 \bullet Watts}\right)$$

$$Gain_{dBi} = 20 \bullet Log(MHz) - AF - 29.79$$

Antenna Factor (AF)

$$AF = 20 \bullet Log(MHz) - Gain_{dBi} - 29.79$$

$$AF = 20 \bullet Log(MHz) - 10 \bullet Log(Gain_{numeric}) - 29.79$$

Find Antenna Spot size, Beam Width and Distance

$$Spot_{meters} = 2 \bullet Distance_{meters} \tan\left[\frac{Angle_{3dB}}{2}\right]$$

$$Distance_{meters} = \frac{Spot_{meters}}{2 \bullet \tan\left(\frac{Angle_{3dB}}{2}\right)}$$

$$Angle_{3dB} = 2 \bullet \tan^{-1}\left[\frac{Spot_{meters}}{2 \bullet Distance}\right]$$

Field Strength

$$V/m = \frac{\sqrt{30 \bullet Watts \bullet Gain_{numeric}}}{Meters}$$

$$V/m = \frac{\sqrt{30 \bullet Watts \bullet 10^{\left(\frac{Gain_{dBi}}{10}\right)}}}{Meters}$$

$$Watts = \frac{\left({V}/{m} \bullet meters\right)^2}{30 \bullet Gain_{numeric}}$$

$$Watts = \frac{\left({V}/{m} \bullet meters\right)^2}{30 \bullet 10^{\left(\frac{Gain_{dBi}}{10}\right)}}$$

Power needed if gain remains constant (in Far Field) using same antenna and changing field level or test distance.

For Field Change $\quad Watts_{New} = Watts_{Old} \dfrac{\left({V}/{m\,New}\right)^2}{\left({V}/{m\,Old}\right)^2}$

For Distance Change

$$Watts_{New} = Watts_{Old} \frac{\left(Meters_{New}\right)^2}{\left(Meters_{Old}\right)^2}$$

Power for given Amplitude Modulation %

$$Watts_{peak} = Watts_{CW} \bullet \left(1 + (\% \bullet 0.01)\right)^2$$

$$Watts_{avg} = \frac{Watts_{CW} \bullet \left(2 + (\% \bullet 0.01)^2\right)}{2}$$

$$Watts_{avg} = \frac{Watts_{peak} \bullet \left(2 + (\% \bullet 0.01)^2\right)}{2 \bullet \left(1 + (\% \bullet 0.01)\right)^2}$$

Power for given Pulse Modulation Duty Cycle %

$$Watts_{peak} = \frac{Watts_{avg}}{\% \bullet 0.01}$$

Useful conversions

1 in = 0.0254 m
1 ft = 0.3048 m
1 yd = 0.9144 m
1 in^2 = 0.00064516 m^2
1 ft^2 = 0.092903 m^2
1 yd^2 = 0.83612736 m^2
1 in^3 = 0.000016387064 m^3
1 ft^3 = 0.028316846 m^3
1 yd^3 = 0.764554858 m^3
1 lb = 0.45359237 kg
1 psi.   = 6,894.7573 Pa (Pascal)
1 hp = 550 ft•lb/sec = 745.6999 Watts
°C   = (°F-32)/1.8

1,000,000,000,000,000,000,000,000 = 10^{24}	yotta	Y
1,000,000,000,000,000,000,000 = 10^{21}	zetta	Z
1,000,000,000,000,000,000 10^{18}	exa	E
1,000,000,000,000,000 = 10^{15}	peta	P
1,000,000,000,000 = 10^{12}	tera	T
1,000,000,000 = 10^9	giga	G
1,000,000 = 10^6	mega	M
1,000 = 10^3	kilo	k
100 = 10^2	hecto	h
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000001 = 10^{-6}	micro	μ
0.000000001 = 10^{-9}	nano	n
0. 000000000001 = 10^{-12}	pico	p
0. 000000000000001 = 10^{-15}	femto	f
0. 000000000000000001 = 10^{-18}	atto	a
0. 000000000000000000001 = 10^{-21}	zepto	z
0. 000000000000000000000001 = 10^{-24}	yocto	y

Resistor Color Codes

1st (A)	2nd (B)	Multiplier (C)	Tolerance (D)	Color
0	0	1	1%	Black
1	1	10	2%	Brown
2	2	100	3%	Red
3	3	10^3	4%	Orange
4	4	10^4		Yellow
5	5	10^5		Green
6	6	10^6		Blue
7	7	10^7		Violet
8	8	10^8		Gray
9	9	10^9		White
Gold		0.1	5%	
Silver		0.01	10%	
No color			20%	

Capacitor Color Codes

Ceramic Cap

Disc Cap

White=EIA Code
Black=Military Code
Color=Old EIA

Classification   Mica Cap

Color Codes for Ceramic Caps

Mult iplier (C)	Tolerance (D)		Temp Coef ppm/°C (E)	Color
	Abo ve 10pf	Below 10pf		
1	20	2.0	0	Black
10	1		-30	Brown
100	2		-80	Red
1000	3		-150	Orange
	4		-220	Yellow
	5	0.5	-330	Green
	6		-470	Blue
	7		-750	Violet
0.01	8	0.25	30	Gray
0.1	10	1.0	500	White

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EMC Immunity Testing Standards Overview

EMC (Electro Magnetic Compatibility) Radiated and Conducted Immunity testing is used in many product industries. Different test standards are used by various industries, and the variety of test configurations and requirements can feel bewildering to the beginner.

To help become familiar with some of these tests, several of the more common EMC Radiated and Conducted Immunity (also called Susceptibility) standards are listed below. These tables allow comparing some similarities and differences between various test standards. Note that these tables illustrate basic parameters, however, they do not reflect the full scope and details of the standard. Consult the applicable test standard for full details of the test requirements.

Radiated Immunity

Standard	Industry	Frequency	Test Level	Modulation	Leveling	Distance
IEC61000-4-3 ed 4.0	Commercial Products	> 80 MHz (Upper frequency limit determined by appropriate product family committee)	1 V/m - 30 V/m. Calibrate CW at 1.8x target field level	1 kHz AM, 80% Depth Typical	Substitution	1 m minimum; 3 m recommend-ed
MIL-STD_ 461E/F/G RS103	Military Components and Subsystems	30 MHz - 18 GHz required 10 kHk - 40 GHz optional	5 - 200 V/m, application dependent	1 kHz PM, 50% Duty Cycle	Closed loop	1 m minimum
MIL-STD- 464C External RF EME	Military Systems	10 kHk - 50 GHz	1 V/m - 27k V/m; application and frequency dependent	CW, PM	User - defined	User - defined
RTCA/DO - 160D/E/F/G Section 20.5 (Anechoic Chamber Method)	Commercial Aviation Equipment	100 MHz - 18 GHz	1 V/m - 490 V/m CW, 150 - 7200 V/m PM; Category and frequency dependent	CW, PM	Substitution	1 m minimum
ISO 11451- 2: 2015 Fourth Edition	Automotive Full Vehicle	10 kHk - 18 GHz	User defined; 25 - 100 V/m suggested test levels	CW, AM 1 kHz 80% Depth, PM Frequency dependent Peak Conservation/ Constant Peak	Substitution. 4 field probe method used from 20/30 MHz - 2 GHz, single probe elsewhere	2 m or greater horizontally from the reference point; no part of antenna closer than 0.5 m to the vehicle surface
ISO 11452-2: 2019 Third Edition	Automotive Components	80 MHz - 18 GHz	User defined; 25 - 100 V/m suggested test levels	CW, AM 1 kHz 80% Depth, PMFrequency Dependent Peak Conservation /Constant Peak	Substitution	1 m

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Conducted Immunity

Standard	Industry	Frequency	Test Level	Modulation	Leveling
IEC61000-4-6:2013	Commercial Products	150 kHz - 230 MHz	1 - 10 V, or Special	1 kHz 80% Depth AM Typical	Substitution (with secondary limiting)
MIL-STD-461D CS114	Military Components and Subsystems	10 kHz - 200 MHz primary; 200 MHz - 400 MHz optional	Multiple test curve levels	1 kHz 50% Duty Cycle PM	Substitution (with secondary limiting)
MIL-STD-461E/ F/G CS114	Military Components and Subsystems	10 kHz - 200 MHz primary 4 kHz - 1 MHz for some usages	Multiple test curve levels	1 kHz 50% Duty Cycle PM	Substitution (with secondary limiting)
DO-160D/ E/F/G section 20.4	Commercial Aviation Equipment	10 kHz - 400 MHz	Multiple test curve levels; up to 300 mA	CW, 1 kHz 50% Duty Cycle PM	Substitution
ISO11452-4:2011 4th edition	Automotive Components	1 MHz - 400 MHz BCI 400 MHz - 3 GHz TWC	User defined; 60 - 200 mA typical, frequency and Test Level Category dependent	CW, AM 1 kHz 80%, Depth PM Calibration CW Peak Conservation/ Constant Peak	BCI method allows substitution or closed - loop. TWC method uses substitution. Secondary limiting optional.

rf/microwave instrumentation

EMC Standards Overview

Electromagnetic Compatibility (EMC) can be defined as the ability of systems, equipment, and devices that utilize the electromagnetic spectrum to operate in their intended operational environments without suffering unacceptable degradation or causing unintentional degradation. Threats to a system can be both naturally-occurring and man-made and can be categorized into 4 types of tests: Radiated Immunity, Radiated Emissions, Conducted Immunity and Conducted Emissions. The limits and levels used for these tests are defined in various standards and adopted by various organizations. It is imperative that products meet the requirements set forth in these standards because public safety, among other things, relies on the products to perform as intended.
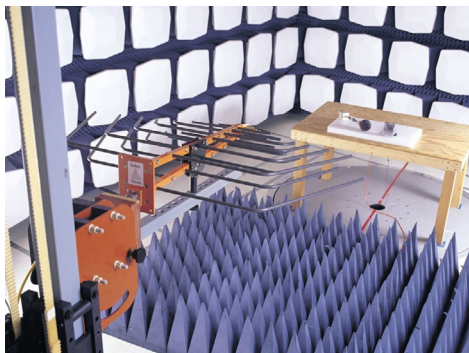
With so many different categories of components and systems with their own specific needs in terms of EMC, it is no surprise that there are a significant number of EMC test standards. Unfortunately, keeping track of and knowing which standard to use can be a difficult task. This document serves as a guide to familiarizing yourself with some of the more common standards used across the industry.

1.0 Major International Standards Organizations

To maintain the many standards relating to EMC testing, a number of organizations, both domestic and foreign, serve as the governing body for different categories of standards.

2.0 International Electrotechnical Commission (IEC)

The IEC is an international organization which prepares and publishes International Standards for all electrical, electronic and related technologies (1). Included in this broad description are standards specific to EMC. They are broken into three categories:

- Basic Standards
  - Basic EMC Standards give general rules achieving EMC. These standards serve as reference, including descriptions of the electromagnetic disturbance under question as well as suggested limits that must be adhered to. Therefore, they cannot be applied to a specific product or system.
- Generic Standards
  - These standards pertain to a specific environment. They include EMC requirements and test procedures and are applicable to any and all products that would need to operate in the described environment.
- Product Standards
  - Product Standards apply to specific products or product families and define test procedures and EMC limits relating to these products.

The IEC has formed and oversees a number of committees which are responsible for defining EMC standards. These standards are either adopted in whole or harmonized with national standards by various governing bodies throughout the world. The two major committees are the International Special Committee on Radio Interference (French title acronym is CISPR) and Technical Committee 77 (TC 77).

CISPR's principal task is at the higher end of the frequency range, from 9 kHz upwards, preparing standards that offer protection of radio reception from interference sources such as electrical appliances of all types, the electricity supply system, industrial, scientific and medical (ISM) RF, broadcasting receivers (sound and TV) and, increasingly, IT equipment (ITE) (2). CISPR typically develops Product Standards for both immunity and emissions.

The other major committee, TC 77, primarily develops Basic and Generic EMC publications with a focus on immunity EMC requirements and environments, though TC 77 does also produce product-family standards covering low-frequency emissions and product immunity standards. TC 77 is broken into three subcommittees:

- SC 77A focuses on low-frequency (up to and including 9 kHz) phenomena
- SC 77B focuses on high-frequency continuous and transient phenomena, including electrostatic discharge (ESD)
- SC 77C focuses on high-power transients such as those resulting from high-altitude electromagnetic pulses (HEMP)

Examples of common IEC and CISPR standards are given in Tables 1 and 2, respectively.

Table 1: Common IEC Standards

Document Number	Subject
IEC 61000-1-X	General Requirements
IEC 61000-2-X	Environments (Description, Classification and Compatibility Levels)
IEC 61000-3-X	Limits (Emissions and Immunity)
IEC 61000-4-X	Testing and Measurement Techniques
IEC 61000-5-X	Installation and Mitigation Guidelines
IEC 61000-6-X	Generic Standards
IEC 60601-X-X	Medical Electrical Equipment
IEC 61326-X-X	Electrical Equipment for Measurement, Control and Laboratory Use

Table 2: Common CISPR Standards

Document Number	Subject
CISPR 11	Industrial, scientific and medical (ISM) equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement
CISPR 12	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers
CISPR 13	Sound and television broadcast receivers and associated equipment - Radio disturbance characteristics - Limits and methods of measurement
CISPR 14-1	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
CISPR 14-2	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 2: Immunity
CISPR 20	Sound and television broadcast receivers and associated equipment - Immunity characteristics - Limits and methods of measurement
CISPR 22	Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement
CISPR 24	Information technology equipment - Immunity characteristics - Limits and methods of measurement
CISPR 32[1]	Electromagnetic compatibility of multimedia equipment - Emission requirements
CISPR 35[2]	Electromagnetic compatibility of multimedia equipment - Immunity requirements

[1]At the time of release of this app note, CISPR 32 replacing CISPR 13 and CISPR 22

[2]At the time of release of this app note, CISPR 35 replacing CISPR 20 and CISPR 24

3.0 International Organization for Standardization (ISO)

A sister organization to the IEC, ISO also is an international organization which develops and publishes international standards. Like IEC, ISO develops standards for a multitude of applications, which include EMC. Where the IEC focuses solely on electrotechnical standardization, ISO goes further by not limiting themselves to one field. ISO standards can be found in nearly any discipline throughout the world, including (but not limited to) sustainable development, food, water, cars, climate change, etc.

Though EMC is only a small part of ISO's reach, they still interact closely with the IEC in terms of EMC and are still recognized as an industry leader in EMC standards development. For example, ISO 11451-X and ISO 11452-X are widely used and relied-upon in the international automotive industry.

4.0 International Telecommunication Union (ITU)

Another sister organization to the IEC (as well as ISO), ITU develops technical standards which focus on telecommunication networks and technology, thus allowing these products to interact without interfering with each other. This effort goes hand-in-hand with EMC as limiting emissions from electronic products will prevent interference of the aforementioned networks and technology. Again, the ITU maintains close connection with IEC and ISO to ensure commonality.

5.0 Major European Standards Organizations

European Committee for Electrotechnical Standardization (CENELEC)

Within the European Union, CENELEC is responsible for electrotechnical standardization. CENELEC develops voluntary standards, but primarily adopts (in part or entirely) international standards, often times IEC and CISPR standards, as European norm (EN). This is done by publishing the standard in the Official Journal of the European Union and Directive 2004/108/EC. The main objective of Directive 2004/108/EC is to regulate the compatibility of equipment regarding EMC (4). Once these standards are published, applicable products are required, by law, to comply. The standards are also given an 'EN' number once published. For example, many of the published CISPR documents are renamed 'EN 550XX' where 'XX' is the CISPR document number (CISPR 11 becomes EN 55011, CISPR 12 becomes EN 55012, etc.). Finally, by showing compliance to all of the applicable standards per Directive 2004/108/EC, a product can apply for and receive a CE mark, thus allowing its sale in European countries.

It should be noted that, although Directive 2004/108/EC is effective as of the release date of this Application Note, Directive 2014/30/EU was published on April 18th 2014 and will go into force on April 20th 2016, thus repealing Directive 2004/108/EC.

European Telecommunications Standards Institute (ETSI)

As its name implies, ETSI produces globally-applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, broadcast and internet technologies (5). As with the ITU, ETSI's goal is to allow the interaction of ICT equipment without any unwanted interference. Typically, ETSI EMC standards can be recognized by having a document number with this format: EN 300 XXX.

6.0 Major North American Standards Organizations

United States of America Department of Defense (DoD)

Within the DoD lies the Defense Standardization Program (DSP). The DSP is responsible for developing a large variety of standards, specifications, handbooks and other documents for a wide range of applications. In terms of EMC, the two most common military standards are MIL-STD-461 and MIL-STD-464. Both documents describe a comprehensive array of immunity and emissions test methods and requirements (see Table 3 for the current list of MIL-STD-461 tests). The main difference between the two is that MIL-STD-461 is intended for controlling and demonstrating EMC on assemblies and subsystems and MIL-STD-464 focuses on total systems.

Despite the intended application being for military use, both of these documents are free and available to the public. In fact, many countries around the world have adopted MIL-STD-461 and MIL-STD-464 for use in testing their military products for EMC.

Table 3: Required MIL-STD-461 Tests

Requirement	Description
CE101	Conducted Emissions, Power Leads. 30 Hz to 10 kHk
CE102	Conducted Emissions, Power Leads. 10 kHk to 10 MHz
CE106	Conducted Emissions, Antenna Terminal, 10 kHk to 40 GHz
CS101	Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz
CS103	Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz
CS104	Conducted Susceptibility, Antenna Port, Rejection or Undesired Signals, 30 Hz to 20 GHz
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz
CS109	Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz
CS114	Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cable and Power Leads, 10 kHz to 100 MHz
RE101	Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz
RE102	Radiated Emissions, Electric Field, 10 kHz to 18 GHz
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz
RS101	Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz
RS103	Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz
RS105	Radiated Susceptibility, Transient Electromagnetic Field

7.0 Federal Communications Commission (FCC)

The FCC regulates interstate and international communications by radio, television, wire, satellite and cable in all 50 states, the District of Columbia and U.S. territories. An independent U.S. government agency overseen by Congress, the commission is the United States' primary authority for communications law, regulation and technological innovation (6). For purposes of EMC, the FCC can be considered analogous to the ITU and ETSI in that these organizations (FCC included) concern themselves with communication interference from ICT products and thus require these products to undergo emissions testing.

The methods and limits of this testing are given in Code of Federal Regulations (CFR) Title 47 Part 15 which is free and available to the public. Depending on the type of device being tested, there are four methods of equipment authorization. These include:

- Verification
- Declaration of Conformity (DoC)
- Certification through the FCC
- Certification through Telecommunications Certification Body (TCB)

Details on what type of authorization is required for a certain device type and the necessary steps to achieve authorization can be found online through the Office of Engineering and Technology (OET).

8.0 American National Standards Institute (ANSI)

ANSI is an American organization that publishes standards for a wide range of applications over a wide range of product types. For EMC, ANSI has developed its own independent standards, as well as adopted international standards for recognition in the United States. ANSI is also deeply involved in accrediting programs that assess conformance to standards, including various ISO systems. ANSI is the US input to IEC and oversees the US National Committee and Technical Advisory Groups. An example of the breadth of ANSI's involvement in accreditation is in Normalized Site Attenuation (NSA), found in ANSI C63.4. T his is a measure of the attenuation of signals propagated over a site and compared with the theoretical attenuation of these signals over an ideal site. Many of the world's EMC standards reference ANSI's NSA method for determining the quality of the chamber intended to be used for EMC testing.

9.0 Lifecycle of EMC Standards

Technology, products, test methods and requirements are constantly evolving, so to keep up, EMC standards must adapt and adhere to these changes. As can be expected, with so many different standards and standards organizations in the world, there are varying lifecycle procedures and durations associated with these different standards. However, most follow the same general process. For the sake of brevity, we will provide an overview of the lifecycle of an IEC publication (7).

- The first stage in developing a new IEC publication is known as the Preliminary Stage. This stage is used when all of the details needed to fully realize a new publication have not yet been collected. This stage also applies to work items that have no target date. Depending on the subject of the work item, this stage can have a long duration.

- Once all of the preliminary development for a standard is complete, the next step in producing a new IEC publication is to create a New Work Item Proposal (NP). This is known as the Proposal Stage. By submitting an NP to the IEC, the requester is alerting the IEC that there is a need for a new standard, an update to an existing standard or a technical specification. If the NP is approved, the document moves to the Preparatory Stage.

- In the Preparatory Stage, a Working Draft (WD) of the new or updated publication is prepared. Once the WD is complete, it moves to the Committee Stage.

- In the Committee Stage, the document is submitted as a Committee Draft (CD) to the National Committees for comment and will be available for 12 months. Here, comments from the various committees are returned to the document originator and compiled.

- Next, the document moves to the Enquiry Stage where a Committee Draft for Vote (CDV) is submitted to the National Committees. This is the final opportunity for technical comment. If the document receives a majority vote, a revised version of the document, with incorporated comments, will be submitted for Final Draft International Standard (FDIS) processing. Note that if a CDV is approved unanimously, the document moves straight to publication.

- In the Approval stage, the FDIS (with incorporated comments) is circulated for vote. If it receives a majority positive vote, the FDIS is published.

While there is not necessarily a defined lifecycle duration from standard to standard, once a standard is approved, a stability date is assigned. Typically, this stability date is at least 5 years.

10. What Version of the Standard Should I Use?

With so many standards constantly evolving and changing, it is imperative to know which version of the required standards you should be testing to. Two general rules of thumb can be stated. If military testing is required, ensure that you test to the exact revision stated in the contract. Often times, military contracts will require products to be tested to outdated versions of military standards, so, unless there is a clause within the contract or there is customer permission in place to test to a standard other than what is listed in the contract, test to exactly what the contract dictates.

On the other hand, if a product is required to be tested to commercial standards (IEC, EN, FCC, etc.), two things need to be taken into account. If the product is being tested to a product family standard, then the product must be tested to the individual test standard versions listed in the product family standard. Otherwise, always test to the latest version of the standard(s) in question. This is required by Directive 2004/108/EC, as well as other organizations such as the FCC. Because of this, it is important to be cognizant of the latest standards immediately prior to any test that is to be performed. Additionally, when new versions of standards are released, an evaluation must be done to determine whether a product tested to the previous standards meets the updated requirements. If the product does not meet the new requirements, a redesign is required, and then a retest will need to be performed in a timely fashion to show compliance of the new design. Some organizations, such as the FCC, will sanction fines for products that are non-compliant to the current standard.

11. Major Product Segments and Their Standards

- Automotive
    - ISO, Society of Automotive Engineers (SAE) and CISPR
    - Many auto manufacturers have developed their own standards

- Aviation
    - RTCS DO-160, EUROCAE/ED-14G

- Military
    - MIL-STD-461, MIL-STD-464, DEF STAN

- Medical
    - IEC 60601
    - US FDA and EU Directive

- Instrumentation, Scientific, Medical (ISM)
    - IEC, CISPR and FCC Standards

- Multimedia
    - Information Technology - FCC, CISP 22 (emissions) & 24 (immunity)
    - Audio Video - FCC, CISPR 13 (emissions) & 20 (immunity)
    - Combined - FCC, CISPR 32 (emissions) & 35 (immunity

Conclusion

For over 40 years, AR RF/Microwave Instrumentation has been providing numerous RF amplifiers, antennas, systems, and other equipment for use in testing a myriad of components and systems for EMC. As such, AR has vast experience in designing test solutions for many of the standards governing EMC compliance. Furthermore, AR is at the forefront of standards development as it has representatives on several national and international standards committees. While this application note has provided a cursory glance at the breadth of EMC standards in today's industry, there are many details that have been left untouched. If you would like to learn more, feel free to contact one of our applications engineers at 800-933-8181.

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Shielding Effectiveness and Shielded Enclosure Leakage Detector System (SELDS)

Today both commercial and military industries are more reliant than ever on electronics. In addition, the need to protect those electronics from potential threats has become even more vital. Threats like electromagnetic interference (EMI) and High-Altitude Electromagnetic Pulse (HEMP) have the ability to interrupt or even destroy the functionality of unprotected electronics. The military has long been aware of the effects of electromagnetic interference and has taken proper precautions to shield electronics, but in some cases, additional measures are required to ensure proper operation. Therefore, the military has, for a long time, often used shielded rooms to house their network and other equipment.

Furthermore, as the entire world is moving towards innovations backed by emerging technologies such as IoT (Internet of Things), Blockchain, Automation, AI (Artificial Intelligence), etc., the need for storing and protecting the proprietary information has become extremely critical. With the increased amount of electromagnetic pulse (EMP) and EMI threats, the shielding requirements have become more stringent and time-critical in testing facilities' shielding effectiveness. The AR Model CL-105A/CL-106A, Shielded Enclosure Leak Detection System (SELDS), is an instrument for verifying shielded enclosures' integrity. The SELDS method can be used at almost any stage of enclosure construction, but it is most accurate and efficient when used after the facility electromagnetic barrier is fully complete. SELDS can also be used to evaluate the shielding effectiveness of non-military and commercial applications— banks and financial institutes, data centers, research and medical hospitals, nuclear power plants, subways, submarine pipelines, telecom base stations, etc.

Any closed box could be considered "shielded" to some extent—even a lunch box—but to achieve the level of shielding needed to meet the stringent requirements of standards such as MIL-STD-188/125-1 and MIL-STD-461G, an enclosure must be sealed to the extent that signal leakage is minimal. The primary purpose of the MIL-STD-188-125 Shielding Effectiveness (SE) test is to demonstrate the SE integrity of a shielded room/facility, conduit, and apertures Point-of-Entry (POE) as noted in Appendix C and SELDS survey IAW MIL-HDBK-423. The shielding effectiveness of the shielded barrier required for high-risk HEMP application is necessary to protect ground-based electronics with time-critical missions.

Part 1 of MIL-STD 188-125 "High-Altitude Electromagnetic Pulse Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions Part 1 Fixed Facilities" references the military handbook (MIL-HDBK-423) for Shielding Effectiveness (SE) integrity test methods. SELDS test method is an electromagnetic method for locating leaks in welded and brazed joints, including seams, patches, etc. During construction, the final SELDS test is accomplished when the barrier is complete, prior to the final acceptance test. Furthermore, the SELDS technique is frequently the basis of the built-in shield monitoring capability required by MIL-STD-188-125. So, the ideal EMI shielded room would be a metal box with no seams, openings, or ingress from cables. Still, unfortunately, that's not possible due to the need for access to the equipment and military personnel inside. SE testing often identifies weaknesses in the shield, which are not visually detectable.

There are two characteristics that determine the electromagnetic shielding effectiveness of an enclosure:

- the ability of the enclosure wall material to reflect or dissipate the EM wave energy, and
- the integrity of the wall; i.e., the tightness of the contact between panels, doors, and POE.

This application note will focus on the SELDS approach defined in the military handbook (MILHDBK- 423), to determine SE, using the AR rf/microwave instrumentation (AR) CL-105A/CL-106A, shown in Figure 1.

Figure 1: AR Model CL-105A/CL-160A Shielding Effectiveness Leakage Detector System

AR RF/Microwave Instrumentation has unveiled a Shielded Enclosure Leak Detection System (SELDS) for testing the electromagnetic shielding effectiveness of EMI enclosures. The new CL-105A/CL-106A detection system allows detection at the most likely points of degradation – the seams, doors and filters connections, in a convenient and hassle-free method. Discontinuities permitting RF leakage at welds, seams, corners, etc., can be detected and remedied to ensure that the finished enclosure is properly assembled.

The system consists of a Model CL-105A Transmitter, Model CL-106A Receiver, headphones and a rugged carrying case. The incredible sensitivity of the model CL-106A Receiver allows it to meet the most rigid MIL standards (e.g. MIL-STD-188/125) for shielded room acceptance. The system is designed to make relative shielding effectiveness measurements by passing a current along the surface of an EMI enclosure in order to sense the small magnetic fields formed where breaks in the EMI enclosure may occur.

The Model CL-105A Transmitter is used to generate an output signal (96kHz) which is connected to the EMI enclosure under test. This device has an auto-adjusting output that works with small, medium, and large EMI enclosures. The 96 kHz signal is low enough in amplitude to ensure that a relatively uniform RF current flow occurs on all sides of the enclosure. An LED indicator illuminates green when the Transmitter has adjusted the output to the optimum level for the connected EMI enclosure.

The Model CL-106A Receiver has high sensitivity (dynamic range:120dB) to detect the smallest of magnetic fields produced at breaks/discontinuities in the EMI enclosure under test. This unit autozeros and features an auditory output with a varying amplitude related to the shielding effectiveness. The auditory output is available through the built-in speaker or included headphones. A 4-digit, seven-segment display is provided to indicate relative shielding effectiveness measurement values in dB. In addition, a built-in LED light source provides illumination when used in dark environments.

1.0 Principle operation of the SELD System

The Model CL-105A/CL-106A system is comprised of two main parts; a Transmitter and a Receiver. The Transmitter is designed to drive a current through the skin of a shielded enclosure. The CW output signal has a frequency of 96kHz. The system is designed to drive very low impedances; thus, the Transmitter is operating as a current source. The output current is nominally 800mA RMS.

For normal tests, the Transmitter will be connected via feed wires to opposite corners of the enclosure exterior and will transmit an AC current across the metallic surface of the enclosure. The Receiver cannot detect the signal except at the points where the enclosure has openings or metallic discontinuities, which cause a small magnetic field to form. The unit is designed to detect small leakages within a larger contiguous surface, not for detecting intended openings (e.g., open chamber door, waveguide feed through). There will be a small magnetic field formed at any place in the enclosure with a small leak (e.g., a crack or seam gap). The Receiver is designed to detect these small magnetic fields. As the Receiver is moved along a seam and encounters this magnetic field, the display will indicate a relative decibel value when detecting a sufficient field level, dependent upon the Receiver sensitivity settings. An audible tone will increase in volume at higher value indications. The audible tone is not calibrated but is an indicator that simplifies chamber probing without requiring continuous observation of the display. If a poor seam or opening exists in the enclosure walls, a signal will be detected when scanning with the Receiver. Detected signals will cause the Receiver display to indicate larger values, indicating less shielding effectiveness. The unit of measure is Shielding Units (SU), a relative measurement from the calibration level set at AR's factory. The system's measured values allow identifying areas of potential RF leakage and decreased shielding effectiveness but cannot be directly converted to Shielding Effectiveness measurements obtained using other methods.

The indication of shielding effectiveness is directly related to each seam's quality of workmanship, door seal, and filter connection. When the system is used to probe around these places, the maximum displayed value indication pinpoints the fault's location, which may be, among other things, a loose bolt, bent panel, or corroded door facing. The data acquired by this system may be used as a guide for: (1) immediate corrective actions, (2) correlation for proof of performance test as a basis for future acceptance tests, or (3) enclosure profiling. Due to the high energy electromagnetic fields which surround each feed wire, a strong local effect is created, which may be detected by the Receiver along the path of the feed wire, and if this effect is not taken into account, the resulting readings near the feed wires could be misconstrued as indicating a faulty seam. Due to this effect, a second feed wire configuration is used in which the feed wires are placed in such a way as to be an approximate mirror image of the first configuration. Chamber probing is then repeated along the path of the original feed wire to confirm leakage points. The user familiar with attenuation scales on conventional RF measuring equipment should notice that the system is calibrated to indicate direct shielding effectiveness rather than field strength. Since an increase in received signal occurs when the shielding decreases, an increased signal causes the displayed value to decrease.

2.0 Integration:

Careful attention must be given to the connection and dress of the Transmitter feed wires.
For all Transmitter feed wire configurations used, the Transmitter is connected at diagonally opposite corners of the tested structure. Connecting across diagonal corners will provide the most evenly distributed signal coverage across the structure. By convention, the Transmitter is physically located at and connected to the front wall, which is defined as the most accessible and is typically where the door is located. The second Transmitter feed wire should be dressed along the enclosure's vertical and horizontal edges to a connection point at the opposite diagonal corner (see Figure 3 for an actual setup). Use approximately 12 inches of No. 12AWG insulated, stranded wire for the short cable and as much as necessary for the long cable. If a bolt or screw head is not available for attaching the feed wires' ends, drill and tap the nearest frame member. Do not tap through the panel. These feed wires can be installed permanently if desired to facilitate future testing. The polarity of the connections is inconsequential.
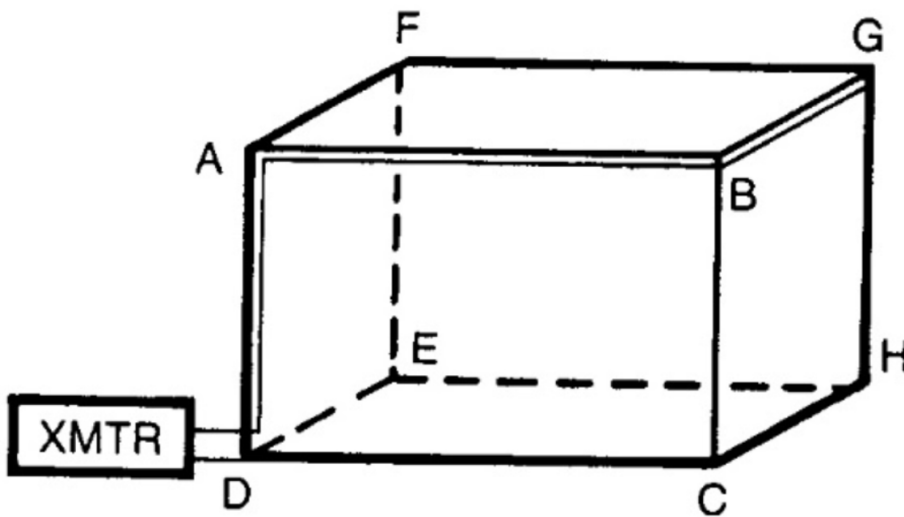

Figure 2: Enclosure Feed-Wire Connection Diagram View

Figure 3: Actual SELDS test setup

3.0 Enclosure probing:

To perform enclosure probing, first examine all six surfaces inside the enclosure with the door closed. Initially adjust the Receiver audio volume knob and gain setting to its maximum (highest sensitivity), then adjust both down as necessary to accommodate the environment. Holding the Receiver so that the probe tip is as close as possible to and perpendicular to the wall (floor, ceiling, or one of the four sides), move the unit slowly (about six inches a second) down each seam. Stop when a sharp increase in the audible signal level is heard, or when the displayed value fluctuates noticeably, record the seam position, the distance of the apparent leak from the nearest active feed wire, and the Receiver reading. For optimum sensitivity, the probe should be perpendicular to the surface being tested. The Receiver units are on a logarithmic scale. When taking measurements, the value indicated on the Receiver display is in relative SUs.

Summary

No matter which standards must be met, selecting the right Shielding Effectiveness Leakage Detector is the key to ensuring commercial electronics and military EMI rooms are adequately shielded and are in compliance with standards.

So, AR has all the technical expertise and Shielding Effectiveness Leakage Detector System that you need to meet the MIL-STD-188/125 requirements. To learn more about AR SELDS system, feel free to contact one of our applications engineers at 800-933-8181 or visit our website at www.arworld.us.

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The Basics of Military EMC Testing

Military EMC testing requirements are defined by industry leaders, procurement specialists, and project leaders. The requirements have been clearly defined so that experienced EMC test engineers and test laboratories know exactly what is needed for compliance testing of systems and components, or a combination of the two. Although the onus is not on the EMC test engineers and test laboratories to make the decisions on test levels, limits, and requirements, they are still required to identify test specifications, define test procedures, as well as perform the tests. Therefore, it is important to have a basic understanding of the requirements that have been put in place for military testing standards.

1.0 MIL-STD-461 vs MIL-STD-464

When testing equipment for use in military applications, a decision needs to be made as to what military standard will be used to confirm your equipment is EMC compliant. Your options are typically between testing to MIL-STD-461 or MIL-STD-464.

There are two major differences between MIL-STD-461 and MIL-STD-464. The first thing to consider when choosing a standard is the equipment that will be tested. MIL-STD-461 is written to perform testing on components and subsystems which are installed on platforms. An example of this would be a display that is installed within the cockpit of an aircraft. MIL-STD-464 however is written to perform testing on entire platforms. So, while the display would be tested to MIL-STD-461, the aircraft itself, such as a F35 Joint Strike Fighter, would be tested to MIL-STD-464.

The other difference between the two standards is the amount of guidance that is provided to complete a test. MIL-STD-461 gives limits and test severity levels which shall be performed within a laboratory, along with clear guidance on how the testing should be performed. In the alternative, MIL-STD-464 only describes the environment where the platform under device may operate, and, therefore, the test levels that may go with it. Although it does not give instructions for testing, it does make clarifications as to how the environmental requirements relate to MIL-STD-461.

2.0 Defining The Test Approach

The test approach will be defined by the contracting/approving body. The first step in determining your requirements and test approaches is to define the test sample. Will you be testing a full vehicle or are you testing a component going inside that vehicle? As previously stated, if you are testing the full vehicle, be it a fighter jet, tank, or drone, MIL-STD-464 requirements would most likely be implemented. If you are testing a component, such as a display going on the bridge of an aircraft carrier, you would implement the requirements of MIL-STD-461. More specifically, you would test to the MIL-STD-461 version for Navy, Above Deck Equipment.

The version of the standard will be called out within the requirements of the equipment to be tested by those writing the contracts and documents. Typically, when writing the contractual requirements, those involved will select the most recent version of the standard. If the procurement of the equipment to be tested takes longer than expected and a new version of the standard is released in the meantime, the version noted within the contractual requirements shall be tested.

However, there is the occasional instance where a version of the standard may be tailored for certain requirements. For example, the United States Navy CVN-78 aircraft carrier was contracted to test to MIL-STD-461E requirements. After the contract was written and approved, but before the testing had been completed, MIL-STD-461F was released. As stated above, the initial test programs were still tested to MIL-STD-461E. However, a tailoring letter from the US Navy's procuring activity was released stating that while the requirements of MIL-STD-461E shall be tested, laboratories were instructed to use some MIL-STD-461F updated requirements for both emissions and susceptibility testing. This led to both time and budgetary savings and was perceived to not affect test results in any way.

3.0 Full Vehicles Installed on Vehicles

There are times when a complete vehicle can be transported and even operated on another complete vehicle or system. For example, fighter jets are often installed/transported within the hull of an aircraft carrier. Does this now make the fighter jet a component or a platform? In this case, the fighter jet is a stand-alone vehicle and treated as a platform. Since the aircraft is inserted into different environments during flight and operation than when taking off, landing, or in storage on an aircraft carrier, it operates both within the confines of the carrier and on its own. Therefore, the aircraft would need to be tested to MIL-STD-464 standards.

A good rule of thumb for this type of questions is if a device can be utilized on its own without being installed within another device, vehicle or system, it should be tested to MIL-STD-464 requirements. Anything that needs support equipment to simulate loads, obtain power from another source, or is not a stand-alone piece of equipment should be tested to MIL-STD-461 requirements. There may be times where this is not always the case, but the contractual requirements, manufacturer, or approving body (if available) should help steer you in the right direction.

Summary

Understanding who defines the military EMC testing requirements can give insight to test programs, the best way to proceed with testing when a requirement is tailored, or to be more knowledgeable regarding performing testing on products. The differences within MIL-STD-461 and MIL-STD-464 should be understood by those performing testing or developing products which may undergo testing for military installations.

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Frequently Asked Questions on Using an EMC Test System

- **What do you recommend when performing a radiated immunity system's calibration in terms of frequency step size? Is it dependent on the EUT or the standard?**

  Due to variables in the flatness of equipment and anechoic chamber inconsistencies, it's best to calibrate the specific frequencies that will be tested. Refer to the test standard to ensure that this is the approach specified.

- **What is the definition of spot size?**

  Spot size, coverage area, beamwidth, or coverage width all mean the same thing. An antenna will cover the area or width when placed a specific distance away from the test object and related to its 3 dB beam width.

- **Spot size, when given as a length ("1.5 meter spot size"). Is that length a radius or a side of a square?**

  1.5 meters by 1.5 meters.

- **Have you ever heard of any reputable EMC labs wrapping cables in aluminum foil to prevent auxiliary equipment from emitting EMI into the EUT or the measurement equipment?**

  When running a test, this may be done if the EUT is not susceptible, but the auxiliary equipment is. To mitigate this, a technician or customer may wrap cables in foil, apply ferrite beads, or rearrange the auxiliary equipment setup to prevent the susceptibility from continuing. This precaution is sometimes done as a mitigation step to determine if cables are culprits for excess radiated emissions. It is important to note that if foil is required as a solution to mitigate immunity or emissions, equivalent shielding will be necessary for the EUTs actual installation.

- **In a radiated immunity test setup, do you recommend having the field probe in the test field for measuring the field strength during the test? Or is the effect of the EUT going to make the field probe measurement useless?**

  This measurement will be defined in the test standard applied. For MIL-STD-461 testing, the standard defines the placement of the field probe during actual testing. For IEC 61000-4-3 and DO-160 testing, the field probe is utilized during a pre-test field calibration where the forward power to achieve the field is recorded and then played back during testing.

- **I was testing radiated immunity and meeting field requirements. The following day, after nothing had changed, I was no longer meeting field requirements. What happened?**

  Several factors could cause you to have issues. Some possibilities are the RF switches could be routed incorrectly, amplifiers were not switched into operate mode, or some other issues could result in a loss of field. Our recommendation is to contact the applications engineers where you purchased your system. AR application engineers are always available to assist in troubleshooting efforts for systems developed by AR at applications@arworld.us

- **When is software automation necessary vs. not?**

  Some test standards require software automation, but not always. If the standard requires graphical data for reporting purposes, then software automation is recommended. If tabular data is specified, then software automation is not necessary. If it is not specified, then you can decide on which will make the test run faster.

- **If I buy an EMC Test System from AR, how will I know how to use it?**

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rf/microwave instrumentation

What is EMC Testing?

EMC is an acronym for Electromagnetic Compatibility (or Compliance). All electronic devices have the potential to emit and be susceptible to electromagnetic fields. With the continuous increase of electronic device into everyday life, there is a huge potential for devices to interfere with each other. No electrical product or installation design can be considered complete unless all EMC aspects are considered. This is not only important for commonly used consumer products such as television sets, computers, washing machines, etc.; it is especially important for larger commercial products such as vehicles, aircraft, ships, and large industrial installations. Without standardized EMC testing, the consequences of equipment malfunction due to EMC interference could be disastrous in cases such as aviation or automotive applications, where life and safety are at stake. For example, the signal from your cell phone interfering with air traffic control tower signals, or traffic radar affecting the operation of a vehicle's engine control or braking system electronics.
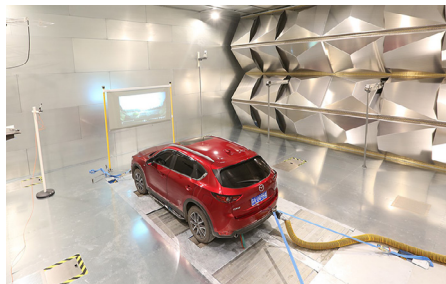
EMC test standards have been developed to provide defined test processes for testing electronic devices. These standards originating from governmental bodies, manufactures, industry groups, or military requirements are important so that EMC testing is performed consistently between test labs, variables are reduced or eliminated, and test results are reproducible.

Different EMC test standards apply to different product categories or usages. For example, vehicle manufacturers, the aviation industry, governmental requirements, military, medical, commercial, large companies, etc., all follow different EMC standards based on their product's category. EMC testing ensures a product meets the appropriate standards to sell into a market. When determining the EMC test standard that applies to a product, the first step is to determine the category the product falls into. Secondly, it is important to consider the country where the product will be sold, as test requirements/ certifications can vary in different countries.

EMC testing can be broken down into two broad classifications; Immunity tests (also called Susceptibility) and Emissions tests. Immunity testing tests the ability of a product to function normally when being subjected to external signals. This test confirms the product will still work correctly, even if other signals are nearby. Emissions testing measures the magnitude of signals the product is producing and unintentionally emitting; these are unwanted signals being emitted from the product that have the potential to affect other electronic equipment in the vicinity.

Immunity and Emissions testing categories can additionally be subdivided into Radiated and Conducted testing methods. Radiated Immunity testing consists of subjecting a product to external signals radiated from an antenna. Conducted Immunity testing is performed by injecting signals into cables which conduct these signals into the product. In a similar manner, Radiated Emissions measures the emissions that emit from a product, while Conducted Emissions measures the emissions from a product that are directed through cables.

EMC Testing is a necessary step in a product's development cycle since it provides evidence that your product complies with relevant EMC regulations and directive(s). After a successful test program, you can be confident that your product's reliability will be increased, thus reducing warranty issues, servicing costs, and encouraging brand loyalty. Testing also highlights potential issues or problems with the product that can be fixed before production. Having the right EMC test equipment and design provided by a reliable strategic partner plays a key role in your product's long-term success.

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EMC testing "Tools of the Trade": Commonly used EMC equations, unit conversions, frequency bands, and more.
Radiated and Conducted Immunity Test Requirements & Solutions: Test levels and setups for various Immunity Test standards.
RF & EMC Formulas and Charts: An extensive compilation of EMC equations, conversions, and information.

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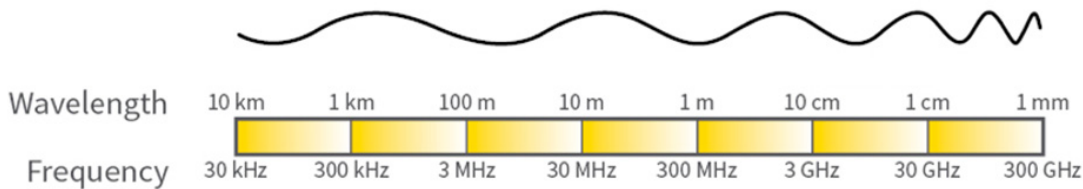**rf/microwave instrumentation**

What is RF Testing?

RF is short for radio frequency. RF is any frequency within the electromagnetic spectrum associated with radio wave propagation. When an RF current is supplied to an antenna, an electromagnetic field is created that is then able to travel, or propagate, through space. Many wireless technologies are based on RF field propagation. These frequencies make up part of the electromagnetic radiation spectrum.

Radio Frequency Spectrum

Wavelength	10 km	1 km	100 m	10 m	1 m	10 cm	1 cm	1 mm
Frequency	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz	300 GHz

Electromagnetic radiation consists of waves of electric and magnetic energy moving together (that is, radiating) through space at the speed of light. Taken together, all forms of electromagnetic energy are referred to as the electromagnetic spectrum. Radio waves and microwaves emitted by transmitting antennas are one form of electromagnetic energy. The terms electromagnetic field or Radio Frequency (RF) field are commonly used to refer to the presence of electromagnetic or RF energy.

An RF field has both an electric and a magnetic component (electric field and magnetic field). It is often convenient to express the intensity of the RF environment at a given location in terms of units specific for each component. For example, the unit "volts per meter" (V/m) is used to measure the strength of the electric field, and the unit "amperes per meter" (A/m) is used to express the strength of the magnetic field.

A wavelength and a frequency can characterize RF waves. The wavelength is the distance covered by one complete cycle of the electromagnetic wave. Simultaneously, the frequency is the number of electromagnetic waves passing a given point per unit of time. An RF signal frequency is usually expressed in terms of a unit called the hertz (Hz). One Hz equals one cycle per second. One megahertz (MHz) equals one million cycles per second, and one gigahertz (GHz) equals one billion cycles per second, or one thousand MHz.

1.0 RF Testing Applications

RF energy is incorporated in a multitude of applications, from telecommunication to non-communication applications and medical purposes. Telecommunication is probably the most common and widely used form of this energy. It can be found in radio and television broadcasting, radio communication for police and fire departments, amateur radio, microwave point-to-point links, cellular devices, and satellite communications, to name a few. RF energy in more specific applications, like in the medical field, have equally specified purposes. MRI (Magnetic Resonance Imaging) uses RF waves to generate images of the human body. RF is also used to destroy cancer cells and perform cosmetic treatments that tighten skin, reduce fat, or promote skin cell healing.

Other non-communication applications that use RF energy are such things as microwave ovens, where the RF energy is used to heat food items. Additionally, RF energy can be used for industrial heating and sealing. Industrial heaters and sealers generate RF radiation that rapidly heats the material being processed in the same way that a microwave oven cooks food. RF energy is also employed in industries for uses such as molding plastic materials, gluing wood products, sealing items such as shoes and purses, and processing food products. Other industrial applications include the testing of RF components and measuring material density. Radar is another valuable tool that uses RF energy and is used in numerous applications such as traffic enforcement, air traffic control, weather monitoring, and military applications.

Because of the multitude of RF applications globally, it is imperative that products and systems operate in their electromagnetic environment and not introduce intolerable electromagnetic disturbances back into the environment. Therefore, before a product or system hits the marketplace, it must be tested for RF immunity and emissions. For RF immunity testing, the equipment is exposed to RF disturbances and fields with field strengths and frequency ranges represented in their operational environment. When a piece of equipment is tested for RF emissions, under normal operation, the equipment is monitored for RF disturbances and fields. For more information on EMC testing, read What Is EMC Testing?

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Signal Generation & Routing

rf/microwave instrumentation

Guide to RF Coaxial Connectors and Cables

Given that typical RF systems are comprised of any number of items, e.g. RF generators, amplifiers, attenuators, power meters, couplers, antennas, etc., it is not uncommon that a great deal of thought is given to these "high end" devices while mundane items such as connectors and cables are often treated as an afterthought. With a wide variety of coaxial connectors and cables available for use in the RF and Microwave spectrum not giving these essential components too much thought is a misstep and can result in undesirable system degradation.

RF coaxial connectors provide vital RF links in communications, broadcast, EMC testing, commercial and military, as well as test and measurement fields. In this guide, you will learn about the different types of RF Coaxial Connectors and Cables and the various uses for each. Guidance and insight will be provided to assist in choosing connectors best suited to accommodate your specific applications.

1.0 RF Coaxial Connectors

The vast array of RF connectors available can be overwhelming, but they are all characterized by just a few key parameters. The most obvious characteristic of a connector is its physical size.
Other considerations include power handling and frequency range capabilities. To ensure maximum power transfer, the characteristic impedance of the connector should match the source and load. All of these characteristics, along with connector durability and cost, must be considered for each application.

The most commonly found connector types in RF applications are available in both male and female configurations, standard and precision grades, high frequency and in some cases high power versions.

1.1 BNC

The BNC connector is perhaps one of the most widely used connectors in the test and measurement field. It was developed by Bell Labs in the early 1950s and is typically used for low power interconnections on RF test equipment such as audio and signal generators, oscilloscopes and amplifiers. The inexpensive BNC utilizes a bayonet retention collar to provide quick mate/de-mate action and also serves to prevent accidental disconnection. The BNC connector is typically designed to provide a characteristic impedance of 50 or 75 ohms, depending on the application. BNC connectors are generally rated for use in the DC – 4 GHz frequency range; however, they are rarely used above 500 MHz. While they are capable of handling 80 – 100 Watts average power up to 1 GHz, they typically do not have a maximum power rating. They do however carry a maximum voltage rating of about 500 V.

1.2 TNC

The TNC connector is merely a threaded-version of a BNC connector. It provides a more secure connection and thus reduces vibration issues that can be found with the BNC. The TNC will operate at higher frequencies than the BNC and there are also high power TNC versions available.

1.3 SMA

The Sub-miniature Type A connector was developed in the 1960s and has proven to be a very popular choice in low power, high frequency applications. It was originally intended for use on 141 type semi-rigid coaxial cable, where the center conductor served as the center pin. Its use was later expanded to flexible cables with soldered on center pins. It consists of an inner contact ring and a hexagonal clamping nut attached via a snap ring. Special wrenches are used to achieve the correct torque; typically 5 lb-inches. There are different versions available such as high frequency, self-locking and precision. Commonly used as interconnects on RF boards, microwave filters, and attenuators, the SMA will operate up to 18 GHz. Precision versions extend the upper frequency limit to 26.5 GHz. Although the SMA will mate to the 2.92mm/'K', 3.5mm, and APC-3.5 connectors, it is not recommended as slight dimensional differences may result in connector damage.

1.4 3.5 mm

The 3.5mm connector is a precision connector primarily developed at Hewlett Packard (now Keysight Technologies). It is similar in design to the SMA but employs an air dielectric for higher performance.
These connectors perform well to 34 GHz, but typically are used to 26.5 GHz. Since the 3.5mm is a precision connector, it is more expensive than similar designs and is thus often found in calibration kits and metrology applications as opposed to common test and production applications.
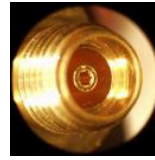
1.5 2.4 mm

Developed in the mid 1980s by Hewlett Packard (now Keysight Technologies), this 50 GHz connector employs a 4.7mm outer conductor arranged around a 2.4mm center conductor. The 2.4mm is available in three grades; general purpose, instrument and metrology. Since these connectors are not directly compatible with the SMA family, precision adapters are required to mate a 2.4mm connector to an SMA.

1.6 2.92 mm/K Type

This connector was designed and developed by Wiltron (now Anritsu Corporation). Performance with this connector is comparable to the 2.4mm, although the maximum frequency is limited to 40 GHz.
The "K type" designator is derived from its ability to cover all the K-band frequencies.

1.7 N Type

This is one of the most common RF connectors in use around the world today. This high-performance connector was designed by Bell Labs in the 1940s with a threaded coupling interface and internal gasket to keep out the elements. The N connector is rugged, relatively inexpensive and the standard version is capable of mode-free operation to 11 GHz. Precision versions push the upper frequency limit to 18 GHz. Commonly found on instruments such as amplifiers, directional couplers, power meters, and coaxial attenuators, this threaded, durable connector provides a very secure connection. There are both 50 and 75 ohm versions available; the latter commonly used in the CATV industry.

1.8 C Type

The C connector was designed by Amphenol to handle high power applications as well as provide quick mate/de-mate action. It uses a dual-stud bayonet retention collar similar in design to the BNC.
The popularity of the C connector has diminished over the years but is still available. The 7-16 DIN has been used as a replacement in many cases due to its similar frequency and power capabilities. There are 75 ohm versions available as well as an "SC" version which incorporates a threaded collar for a more secure connection.

1.9 7-16 DIN

This is a more recent connector in the United States, compared to the other connectors previously mentioned. The 7-16 DIN was developed by the Deutsches Institut fur Normung, (translation: the German National Standards Organization); hence the "DIN" designation. The numerical part of its name refers to the size of the inner and outer conductors; "7" for the inner conductor OD in mm, and "16" for the outer conductor ID in millimeters. The 7-16 uses an M29 x 1.5 threaded coupling nut.
The 7-16 DIN connector was designed with low inter-modulation in mind for communications applications. Other common applications include antennas, base station connections, RF cables, SATCOM and lightning protection systems.

1.10 EIA Series

The EIA series of coaxial connectors are available in EIA 7/8", EIA 1 5/8", EIA 3 1/8", EIA 4 1/2" and EIA 6 1/8" versions, all of which are suitable for RF applications. Designed to support cables with foam or air-dielectric, they consist of a main body, mounting flange with various bolt circles, and typically have interchangeable/removable center conductor "bullets". Due to the flexibility of their design, EIA connectors are often not identified as male or female, as the connector can typically be configured as either. EIA connectors can be found in high power applications on directional couplers, coaxial cables, power amplifier outputs, and interconnects on communication towers and antennas. The most common sizes found in general test and measurement applications are the 1 5/8 and 7/8 EIA. There are a variety of adapters available to adapt the EIA series to some of the larger RF connectors such as the 7-16 and N type.

1.11 Making the Right Selection

Now that you have a better understanding of the most popular RF coaxial connector types, let's consider the thought process that should be applied to make intelligent connector choices.

It is important to remember that the specific application will determine the frequency range and power handling requirements of the connector. The chart below is a reference to use when selecting the proper connector type. The chart provides general guidance on power handling of coaxial connector types under the conditions of matched source/load impedance, in a controlled laboratory environment, with connectors of common construction and materials.

Connector Power Handling
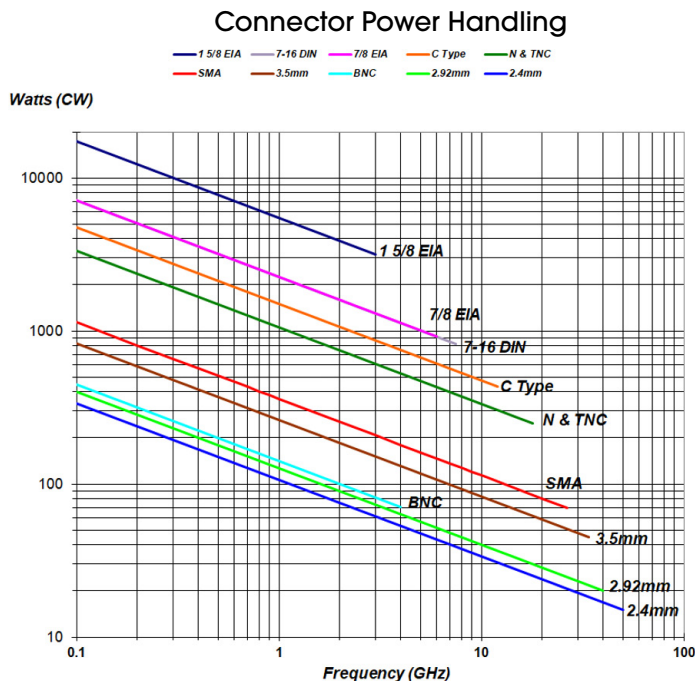
This chart should only be used as a reference. Individual connector manufacture's power ratings may differ from these general ratings. Be sure to consult specific manufacturer specifications prior to use.

Connector power handling can vary greatly depending on connector construction, ambient and equipment temperature, and reflected power. The continuous CW power rating of a connector is primarily based on temperature rise due to dissipated power, which results from a combination of I^2R losses and dielectric losses. Consequently, heat management becomes the primary factor in power rating. These aspects are discussed in more detail below.

1.12 Connector Construction and Materials

Materials used in the connector affect power handling capability, with the dielectric material having the greatest effect. Most connectors today use one of several fluoropolymers to capture and support the center conductor of the connector, with polytetrafluoroethylene (PTFE) being the most widely used. Air dielectric connectors such as precision 2.4, 2.9, or 3.5mm connectors may avoid PTFE altogether, and use a higher-temperature material (e.g. Ultem 1000). In other cases, high power connectors may use thermally conductive dielectrics to provide better cooling of the center conductor than PTFE can offer.

The other material of interest is the plating on the center conductor. High temperatures can cause rapid oxidation of the contact materials, increasing resistance and I2R losses. This increased power dissipation drives the temperature even higher, into an eventual run-away condition. Unfortunately, this behavior is not nearly as easily characterized as the dielectric heating, as it is very dependent on the environmental conditions (eg. lab vs. marine) and often proprietary plating materials and thicknesses. However, the more easily characterized dielectric material limitations are the more typical short-term failure mode and power limit.

1.13 Temperature

The temperature of a connector will be influenced by both the ambient air temperature, as well as the temperature of the connected device. Heat exchange through conduction with the mating connector/device will typically have a greater effect than ambient temperature. The objective is to ensure that the internal connector temperature does not exceed the temperature ratings of the internal components, which is primarily limited by the dielectric material temperature rating. Power handling will de-rate from full rated power at the rating temperature, decreasing to zero power at the maximum allowable temperature of the connector materials. Be sure to consult the connector manufacturer for their temperature derating curve.

1.14 Reflected Power

When operating into a mismatched load, some of the incident power will be reflected back to the source. The combination of incident and reflected power traveling on the same cable causes standing waves to form. The measurement of these standing waves is the Voltage Standing Wave Ratio (VSWR). These standing waves result in current peaks and nulls along the cable at quarter wavelength intervals. Higher current translates to higher power, and thus greater heat. The locations along the cable where the peaks of the standing wave occur will be subjected to increased localized heating, resulting in alternating higher and lower temperature regions occurring along the cable. To account for the localized heating due to peak standing wave power, use the following derating calculation:

This is shown graphically here:

$$\frac{1}{\left(1 + \left(\frac{VSWR - 1}{VSWR + 1}\right)\right)^2}$$
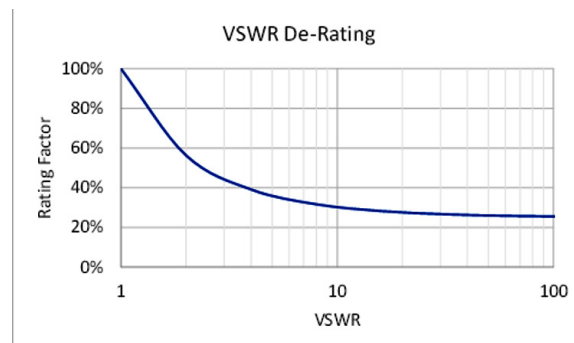
1.14 Reflected Power

At lower frequencies, where wavelengths are long and current peaks are broad and well-separated from the adjacent current nulls, using peak standing wave power is good practice.
However, applying the same rule to smaller connectors used at high frequencies may result in impractically conservative power ratings. Due to the short wavelengths at high frequencies, the localized hot and cold areas are small and in close proximity, thus encouraging heat transfer between these regions, reducing the peak temperatures. This thermal averaging reduces the peak temperatures, and as frequencies increase, the VSWR derating begins to approach the average standing wave power, defined as:

These two derating curves are shown here:

$$\frac{1}{1 + \dfrac{VSWR - 1}{VSWR + 1}}$$

This thermal averaging effect may sometimes allow a more aggressive power rating at higher frequencies, somewhere between the peak standing wave power derating, and the average standing wave power derating. If choosing to do this, consult with the connector manufactures for guidance.

1.15 Pulsed Operation

When operating with pulsed signals, in addition to the aspects previously mentioned, there are several additional factors to consider.

Connectors can handle pulse power levels that are greater than their continuous CW power rating. This is due to the pulse off time, when no heating occurs. This allows the connector to cool during this time, and thus experience thermal averaging over a full waveform cycle. However, the average power over a full cycle of the waveform must not exceed the CW power rating of the connector. The average power is calculated as follows:

$$AveragePower = PulsePower \ast \frac{DutyCycle}{100}$$

In pulsed applications where the average power approaches the continuous CW power rating of the connector, consult the connector manufacture for additional guidance.

Voltage breakdown must also be considered when operating at very high-power levels. Operating with very high pulse power levels with very short duty cycles may result in an acceptable average power level. However, the high voltage during the pulse may exceed the breakdown voltage of the dielectric material. This could result in arcing between the center conductor and shield/ground, with subsequent damaged and burned components. Note that voltage breakdown will occur at a lower level in a coaxial configuration than the breakdown level would be in a simple non-coaxial gap configuration of the same distance. Breakdown voltage levels in a coaxial configuration can be calculated to determine connector suitability for an application.

Dielectric material will have a higher breakdown voltage than air. However, when modeling peak voltage limits, good practice dictates using the air breakdown value rather than the higher dielectric material breakdown voltage, as it is likely an air gap will exist somewhere along the RF chain.

2.0 Connector Mating and Care

Connectors are crucial components in the RF chain and are instrumental in achieving proper performance in the system. As these components incorporate mechanical action, as well as carrying RF, care needs to be taken in use. A damaged connector, if mated, may propagate damage to the mated connector. As connectors can be costly, taking precautions and using care is well-advised.

2.1 Connector Mating

Ensure connectors to be mated are physically compatible and are of the same impedance rating. Be sure to inspect connectors before mating, which may require the aid of a microscope or magnifying glass for sufficient detail. Look for metal particles, fibers, dust, and other contaminants. Check for centered, straight, and undamaged center pin on male connectors, and verify that female jacks are centered, open, and undistorted. Look for body distortion or dents. Depending on jack construction, verify any contacts or spring fingers are in place and undamaged.

Prior to mating, clean both connectors. This is especially important on precision connectors used at higher frequencies, where measurements can be easily affected by contaminants. Clean, dry air, such as canned air, can be used to blow out connectors. Blow across the face of the connector to pull debris out, as blowing directly into the connector may lodge debris more firmly. A small amount of isopropyl alcohol on a lint-free swab can also be used to clean connectors, however, avoid excessive solvent to minimize wicking of solvent into the connector. Air-dielectric connectors are fragile, and if mechanical cleaning of the internal contacts is needed, it must be done with great care. Clean internal and external threads, and check for any burrs or roughness that would interfere with smooth thread engagement.

When mating connectors, carefully align the center axis of both connectors and push straight together as far as possible. While keeping the connector bodies stationary, turn the connector nut by hand to thread onto the mated connector. Never allow the connector bodies to rotate, as this will cause unwanted and unnecessary wear, which may cause permanent damage to one or both connectors' center conductor. The nut should thread freely and fully engage the mating threads by hand. If encountering excessive resistance, remove the connectors to investigate the problem.

After hand tightening the nut, tighten the connector to the specified torque using a torque wrench, while using a wrench to prevent the mating connector from rotating if necessary. Ensure the proper torque spec is used, as excessive torque can deform the connector, while insufficient torque can result in incomplete mating and poor performance. This step is especially important with higher frequency connectors, as slight mechanical changes will have more of an effect with the shorter wavelengths of higher frequencies.

In situations when mating compatible connector types, such as a 3.5mm and 2.92mm connectors, the lower of the two torque specs should be used.

2.2 Connector Care

Connectors are an integral part of a system, and degradation or damage of a connector will affect the overall system performance. Proper connector care is crucial to ensure proper system operation.

Some steps that can be taken to protect connectors are:

- Inspect and clean connectors on a regular basis.
- When not in use, dust caps should be installed on connectors and adapters to protect from damage, debris, and contamination.
- Avoid touching mating surfaces.
- Store connectors in a clean and dry environment, and in a protected manner, not loosely together in a container.
- Do not drop connectors, as this can cause physical damage, especially with precision air-direlectirc high-frequency connectors.

In addition, implementing use of a connector saver can also be a good practice. In usages where cables and connections are frequently changed, commonly in a production or manufacturing environment, a connector saver will take the wear of normal use. The connector saver acts as a sacrificial wear item, thereby protecting the connector on the test equipment. This allows replacing only the damaged/worn connector saver when needed, rather than having the expense and downtime of connector replacement on the test equipment, or replacement of a cable.

It is important to note that the addition of a connector saver, while mechanically beneficial, is an additional pair of connections in the RF path and may have an adverse effect on the system performance, and could increase measurement uncertainty. Measurements should be taken to characterize the effect of the addition of a connector saver.

Ultimately, due to the mechanical processes involved in connector use, with mating and de-mating cycles, connectors will wear, and performance will degrade. Following proper care, maintenance, storage, and mating technique will maximize the usage cycles.

2.2 Adapters

Using an adapter to convert between connector types needs to be done with care, and with the understanding of the limitations involved. Simply the fact that an adapter is available does not imply that it is appropriate for use in your application. Each connector type has maximum frequency and power limits, and the application needs to operate within both of these limits, for both of the connector types.

Maintaining the same connector type in the RF chain as is used on the amplifier output is a good approach. Using an adapter to convert to a different connector type needs to be done with care, considering the maximum possible frequency and power both of the connector types could be subjected to.

2.3 Connector Grades

For a given connector type, not all connectors are made to the same standards of precision. Some connector types, primarily the higher-frequency types, are available in various quality grades. There are three common categories of connector quality that are used in the industry, with variations in design and terminology between manufacturers.

Metrology grade is the highest precision and quality grade connector, and most expensive. These would commonly be reserved for high accuracy applications such as for calibration purposes and use on calibration standards.

Mid-range grade connectors, sometimes called 'instrument grade', have good performance and provide accurate measurements, and are often used on test equipment and in lab use.

The lowest grade of connector, referred to as 'commercial', or 'production', or 'field' grade connector, has looser tolerance and lower performance, and is the least expensive connector grade. These are most commonly used in production and manufacturing.

Note that the maximum frequency rating of a connector type may vary depending on the grade of the connector, thus use care when operating at the higher end of the connector frequency rating to ensure the connectors being used are of a grade to support the frequency in use. For details of the design and performance differences between grades, reference the manufactures product information.

2.4 Inter-Series Compatibility

Although not intuitive, some connector series families are compatible with other connector series, and can be physically connected. However, each series carries its own power and frequency limits.

The 2.4mm and 1.85mm connectors are mechanically compatible and can be inter-mated.

The 3.5mm, 2.92mm/'K', and SMA connectors have the same basic dimensions, and can inter-mate. However, the looser SMA tolerances can lead to damage to the high-precision 3.5mm and 2.92mm connectors. This primarily applies when using a male SMA connector, where variations in the male center pin diameter or height could damage the female jack of the mating connector.

In addition, when connecting an SMA to a 3.5mm or 2.92mm connector, it is very important to carefully align the connectors before mating to avoid damaging the center contacts. Some SMA connectors are categorized as 'precision SMA', which are manufactured to tighter tolerances, allowing safe mating to 3.5mm and 2.92mm connectors. Regardless, the mating process needs to be performed carefully.

2.5 Connector Gender

Connector gender is often assumed to be determined by the gender of the connector center contact, however this is not the case. Although these do agree in many cases, better practice is to understand the different connector configurations possible, and how connector gender is determined. The connector gender designation is not defined by the center pin, but rather follows the connector body configuration. The center pin will then determine if the connector is Standard Polarity (SP) or Reverse Polarity (RP).

The connector with a coupling nut/shell with internal threads is designated as a male connector (or plug). The connector with a body that has external threads is designated as a female connector (or jack).

Once the connector gender is identified, look to the center conductor configuration to determine if the connector is SP or RP. A male connector with a male center pin, or a female connector with a female center socket, is an SP connectors, since the body and center conductor genders match. SP connectors are the common conventional configuration encountered.

A male connector with a female center socket, or a female connector with a male center pin, is an RP connector, as the body and center conductor genders are different. RP connectors are less commonly encountered and were originally developed for use in specialty applications to discourage alteration of the equipment.

Below are images of standard polarity SMA and Reverse Polarity SMA connectors to visualize the configurations.

	SPSMA	RPSMA
Male		
Female		
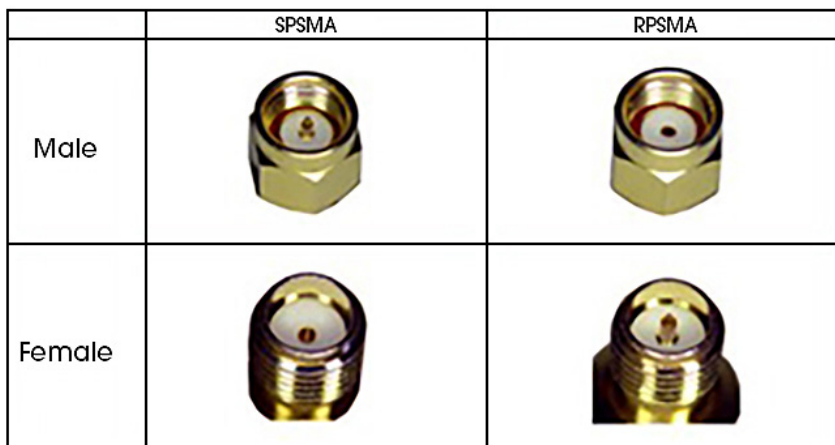
Caution needs to be used in situations where RP connectors are available, as although SP and RP connectors can be physically mated, this would result in either damage to the center pins due to being forced together, or no continuity through the connection if two female center sockets are mated.v

2.6 Connector Gauging

The function of coaxial connectors depends upon the physical interface between the mating connectors. To achieve optimum performance, the center conductor height is very important. If the center conductor is recessed into the connector body beyond the allowable tolerance, the connection will suffer from degraded performance. However, if the conductor protrudes beyond the tolerance, performance may suffer in addition to possible physical damage. A damaged or out-of-tolerance connector may cause damage to each connector it is mated to, spreading damage to other connectors and affecting measurement accuracy as well as causing repair expenses.
For these reasons, gauging connectors is a recommended practice to confirm connector dimensions are within acceptable tolerance. Gauge kits are available for most connector types.

Establishing a regular gauging program for cables and equipment is recommended to detect out-of-tolerance conditions and connector damage or wear. Cleaning and inspection should be performed before gauging. Additionally, it is good practice to gauge any connector before first use in the facility, such as cables, adapters, and connectors on equipment.

2.7 Connector Specifications

The table below further defines maximum frequency, power, and coupling torque parameters for the RF connectors covered in this reference guide.

Maximum frequency, power and coupling torque

Connector Type	Maximum Frequency (GHz)	Maximum CW Power @ Max, Frequency (Watts)	Coupling Torque	
			(N-cm)	(in-lb)
2.4 mm	50	15	90	8
2.92 mm/K	40	20	90	8
3.5mm	34	45	90	8
SMA precision	26.5	70	57	5
BNC	4	70	N/A	N/A
TNC	18	250	N/A	N/A
Type N	11	150	135	12
Type N precision	18	250	135	12
Type C	12	440	N/A	N/A
7-16 DIN	7.5	820	226	20
7/8 EIA	6	920	N/A	N/A
1 5/8 EIA	3	3200	N/A	N/A

2.8 RF Cables

Having selected RF connectors using the guidelines provided above, the next logical step is the selection of appropriate RF cables. There are a myriad of coaxial cable types to choose from. As with the RF coaxial connectors, coaxial cables are classified by physical characteristics as well as electrical parameters. Both flexible, semi-flexible or rigid armored cables are available. Electrical parameters such as characteristic impedance (50 and 75 ohms are common values), insertion loss, maximum voltage and maximum power capabilities must be considered. The application will determine the proper cable choice. Some applications require low loss cable to maximize power transmission. Other applications require flexible cables, perhaps without restrictive armor, for user friendliness. Coaxial cables contribute to the overall performance of the RF assembly and can become a limiting factor for maximum frequency and power handling capability. It is important to keep in mind that any cable assembly will be limited both in frequency and power handling capability by the lowest power rated and frequency capable RF connector.

To facilitate cable selection, AR/ RF Microwave Instrumentation has developed a line of high quality, built-to-order coaxial cables. These low loss cables are characterized by very low VSWR and are tailored to the end users specific needs. There are four basic series; CC1, CC2, CC4 and CC5. Custom lengths are available in 0.1 meter increments with a variety of matched connectors.

CC1 Series – These are armored, low loss cables for applications to 18 GHz. They are available with SMA, TNC, N or 7-16 connectors.

CC2 Series – These are armored, low loss cables for applications to 40 GHz. They are available with 2.4mm, 2.92mm, 3.5mm, SMA, TNC or N connectors.

CC4 Series – These are high power, flexible cables for applications to 6 GHz. They are available with N, 7-16, DIN 7/8 EIA, or 1-5/8" EIA connectors.

CC5 Series – These are low loss cables compatible with higher power applications to 11 GHz. They are available with N, 7-16 DIN, C, or SC connectors.

Summary

RF coaxial connectors and cables are often forgotten components of RF systems. It is important to review all of the specifications discussed when selecting the right RF coaxial connector for your specific application. As mentioned, thinking about the connectors does not end after the selection process. Continued proper care and maintenance will help to ensure accurate system operation. While they may not command the interest and attention of the more costly system components, improper selection of RF coaxial connectors and/or cables can render a sophisticated system ineffective, so it is important to carefully select connectors and cables that are best suited to accommodate your specific applications.

AR RF/Microwave Instrumentation • 160 Schoolhouse Rd, Souderton, PA 18964 • info@arworld.us
To order AR Products, call: 215.723.8181. For an applications engineer, call: 800.933.8181
Direct to Service, call: 215.723.0275 or email: service@arworld.us

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rf/microwave instrumentation

Multi-Tone: Testing, Theory, and Practice

Multi-tone testing has many benefits. While the multi-tone methodology was initially implemented to increase the speed of immunity testing, it has been found that this method also improves equipment efficiency, offers greater flexibility to truly test the equipment (EUT) under real world threat conditions, and can be fully compliant to standards. Benefits can also include more efficient use of finite financial and human resources, as well as faster time-to-market for new and enhanced products.

1.0 What is multi-tone?

Multi-tone signals are composed of multiply single sine waves or tones with a unique amplitude, phase, and frequency. In the spectrum domain, the multi-tone or RF energy will be present at a unique frequency. In the time domain, the multiply signals or tones will be a composite signal in which each of the tones will add or cancel to make a composite signal.

1.2 Where are multi-tones used, and who is using them?

One area in which multi-tones are used is modern audio measurements to test consumers & professional audio devices, broadband devices, and internet audio. Multi-tones can be used in an open-loop audio test where the analyzer does not have to sync up with the generator. This allows an audio signal to be tested over long distances, such as the internet or mobile phone.
Standard multi-tone signals have evenly-spaced tones with equal amplitude; this, however, does not represent real-world test conditions. Therefore custom multi-toned sets need to be created.

Multi-tone tests are part of many test specifications used to test the frequency response of a device and measure intermodulation distortion. Two-Tone and multi-tone signals are used in the communications industry to test for nonlinear distortion for amplifiers, receivers, etc. A vector signal generator, VSG, is the primary hardware in a multi-tone generator system; it can be used in almost every RF and communication application, including the following below:

- Antenna resonant frequency measurement and testing
- Amplifier linearity
- Amplifier frequency response
- Selectivity measurement
- On-site effective sensitivity test
- Cable fault detection
- Filter tuning
- Antenna response to FM
- Frequency hopping
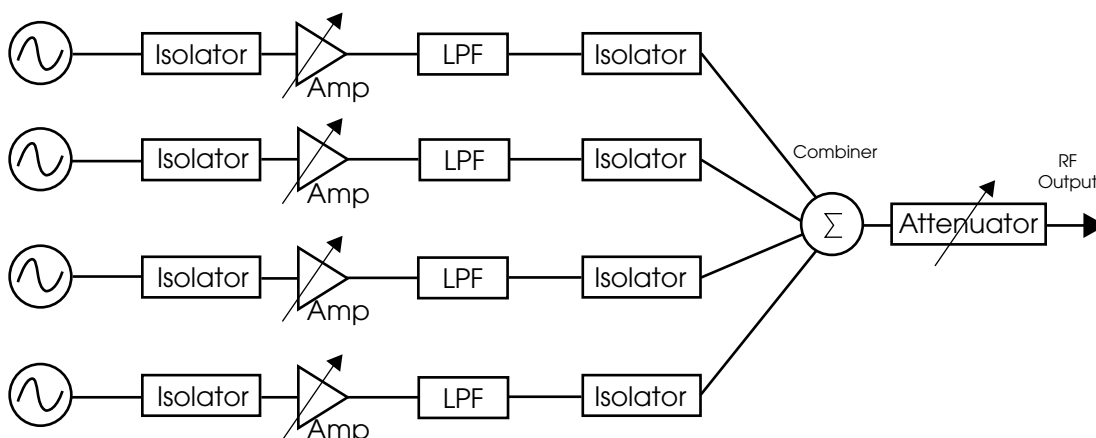
An alternate way to generate multiple signals is to replace each independent signal generators with one vector signal generator (VSG). The VSG does not require multiple signal generators to create multi-tone signals. It can generate fixed or random initial phase sets, deliver accurate repeatable multi-tone signals and is easily configurable by setting each tone independently.
VSGs are useful for simulating a wide variety of digitally modulated signals, including cellular, wireless LAN, Bluetooth, GNSS, and military communications formats.
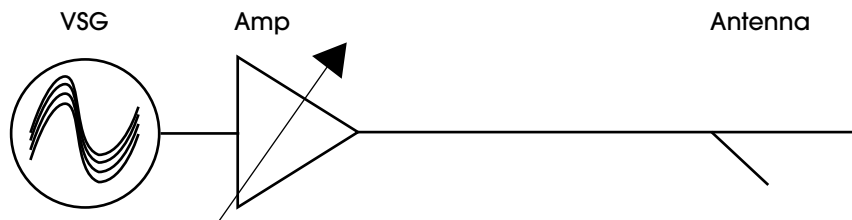
VSG   Amp   Antenna

And a third, more cumbersome, way to generate multiple signals is to have multiple signal generators, multiply amplifiers, and multiple antennas. The signals would be combined in free space. Since there are separate amplifiers, the amplitude of the tone would vary and could be hard to control the phase with respect to each tone.

Sig Gen #1   Amp #1   Antenna #1

Sig Gen #2   Amp #2   Antenna #2

Sig Gen 31   Amp #3   Antenna #3
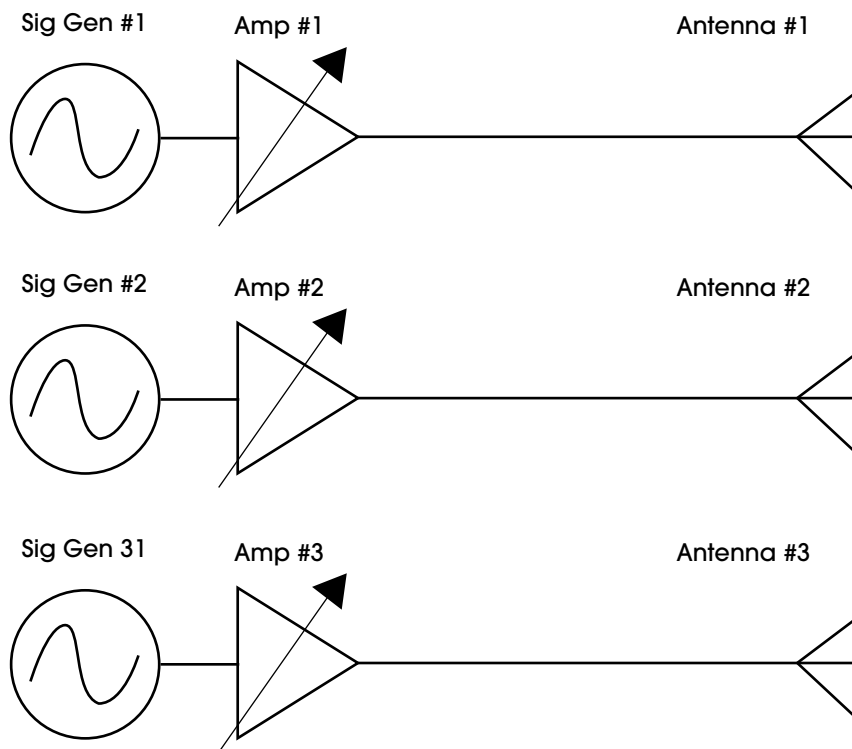
2.0 Comparison of VSG to analog signal generator

2.1 Analog Signal Generator Overview

- Analog signals are generated as CW tones with some amplitude, center frequency and starting phase.
- The introduction of voltage controlled oscillators (VCOs), allow the user to dynamically vary the carrier frequency (FM) and phase (PM) over time.
- Issues that affect the quality of the generated waveform are stability and VCO phase noise as well as distortion and bandwidth limits on the modulation.

2.2 Digital Vector Signal Generators

- Output is a series of discrete voltage levels instead of a sine wave.
- The series of discrete voltages makes it possible to create a wide range of signals and gives the flexibility to modify signals.
- Any arbitrary signal within the bandwidth of the digital signal can be described mathematically, stored in digital memory and then played out.
- The range of the carrier and modulation frequencies of the arbitrary waveform generator is determined by the sample rate.
- The voltage resolution or effective bits determines the accuracy of each output voltage which the output waveform then translates into noise and distortion.

2.3 Disadvantages of using a Traditional Analog Signal Generator

- Test setup - This can be complicated and time consuming due to the amount of test equipment involved.

- Modification of signal parameters - Since multiple signal generators are used to produce each tone, adding or removing tones requires hardware modifications to the test setup in addition to software modifications to change the amplitude or frequency for each signal generator.

- Random phase sets - It is difficult to generate random phase sets because most CW generators do not have the capability to set the phase of individual tones.

- Cost of test - Capital equipment cost is high because the more tones required directly impacts the number of signal generators required.

2.4 Advantages of using the Vector Signal Generator

- Simple test set up and procedure - VSG requires only one generator and one user interface.

- Signal parameter control - easy to modify signal parameters such as amplitude, tone spacing and phase with digitally accurate fixed or random initial phase setting.

- Test setup repeatable- test waveforms can be easily stored and quickly recalled for playback, ensuring the same test stimulus.

- Accurate and meaningful test results - multi-tone signals with random phase sets that simulate real world operating conditions can be generated easily.

- Save time - spend less time setting up and more time making test measurements.

- Reduce cost - use only one signal generator to produce multiply tones that traditional setup requires multiply analog signal generators and a combiner.

2.5 Vector Signal Generator Concerns/Issues

- **Available Power** - a linear amplifier is required

- **Carrier feed-through** - a high level of carrier feed-through is not desirable because it results in intermodulation produced at one-half the tone spacing instead of the designated tone spacing intervals. The VSG uses the (in-phase/quadrature) I/Q modulator. Small amounts of carrier feed-through are present when an even number of tones are generated. With odd number of tones, there is always a tone at the carrier frequency. This carrier feed-through can be reduced by optimizing the I/Q gain offsets.

- **Images** - occur as a result of the I and Q signals being slightly out of quadrature at the input of the I/Q modulator. When non-symmetric tone patterns are generated, images can be reduced with slight adjustments to the quadrature skew setting in the I/Q Adjustment Menu.

- **Relative tone spacing** - is limited to the bandwidth of the internal baseband generator. The tone spacing, phase and amplitude would be set on a tone-to-tone basis.

3.0 Multi-Tone Theory

The Multi-Tone Test System contains one vector signal generator that generates the multiply signals or tones. A larger RF power amplifier may also be required so the multi-tone signals are not distorted. In addition, either a vector signal analyzer or spectrum analyzer should be used to measure the energy in the spectrum domain because traditional power meters measure the entire spectrum wideband, including the harmonics and intermodulation products.

3.1 Generating Multi-Tone Signals

Many signal generators also offer various types of modulation, including analog and composite (digital) modulation. Classic analog-modulation types include amplitude modulation (AM), frequency-modulation (FM), phase-modulation (ΦM), and pulse modulation signals. Modulation is important because it's the information-carrying part of the signal.

The following below are a list of common test signals:

1. Sine Wave – most common signal for testing

2. Square Wave – superposition of many sine waves at odd harmonics of the fundamental frequency. The amplitude of each harmonic is inversely proportional to its frequency.

3. Triangle and saw tooth – have harmonic components that are multiples of the fundamental frequency

4. Impulse – contains all frequencies that can be represented for a given sampling rate and number of samples.

Chirp signals are sine waves swept from a start frequency to a stop frequency. They generate discrete frequencies within the start and stop frequency band

3.2 Modulation Parameters to Control

To better understand analog modulation, consider the basic equation of a sine wave:

$$V(t) = A(t) \times cos[2\pi f_c t + \Phi(t)]$$

In this equation, three parameters can be varied: amplitude, frequency and phase. Varying the sine wave's amplitude achieves amplitude and pulse modulations. Varying the sine wave's frequency or phase generates FM and ΦM, respectively.

Composite modulation, also known as vector or digital modulation, occurs when two or more modulation types are used to create a composite modulated signal. For example, AM and ΦM can be combined to create various magnitude and phase values. Varying the signal's phase in conjunction with the AM control in the automatic-loop-control, ALC, circuit can produce a digitally modulated signal.

I/Q diagrams are particularly useful because they mirror the way an I/Q modulator creates most digital communications signals. Independent dc voltages (I and Q components) provided to the input of an I/Q modulator correlate to a composite signal with a specific amplitude and phase at the modulator output. All types of modulation can be represented on a polar plane using vector (phaser) notation, although magnitude and phase values aren't typically used when describing the vectors in digital modulation, see examples below. Instead, the polar plane is mapped to a rectangular format (with a horizontal and vertical axis) called the I-Q plane, where I stands for in- phase and Q denotes quadrature.

Vector Signal Changes or Modifications
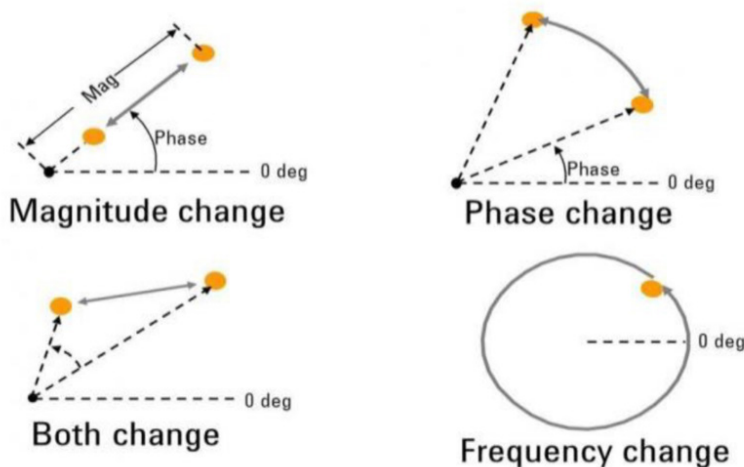
A magnitude change with no rotation represents amplitude modulation (AM), and a vector that rotates along an arc (the length of which indicates the maximum phase deviation) represents phase modulation (ΦM). Simultaneous AM and ΦM are indicated by a vector whose length and phase change with time. FM results in a vector that rotates clockwise or counterclockwise.

Quickly transmitting large amounts of binary bits at high rates in composite signals requires large information bandwidths. The faster the data rate, the wider the bandwidth. Available bandwidth can be used more efficiently by grouping blocks of digital data (1s, 0s) into symbols, although this increases signal complexity. The number of bits per symbol will vary depending on the specific format. Transmitting digital data via multi-bit symbols requires less bandwidth. For example, for two bits/symbol, the symbol rate is one-half the bit rate, and for four bits/symbol, the symbol rate is one-quarter the bit rate.

IQ or vector modulation, which is commonly used in modern digital communications and radar systems due to the large modulation bandwidths and the ease in creating composite modulated signals, has a number of important characteristics. These include symbol rate (the number of symbols/second), modulation bandwidth (the maximum effective bandwidth of the IQ modulator), frequency response/flatness, IQ quadrature skew (a measure of how orthogonal the I. and Q. planes are to each other), and IQ gain balance (a measure of how closely the I. channel and Q. channel are in gain). >When the IQ characteristics aren't ideal, magnitude and phase errors will occur that may cause transmission of incorrect digital information. Digital errors are referred to as bit errors, often expressed as a bit-error rate.

3.3 Amplitude of Mulit-Tone

The composite amplitude of the multi-tone signal can be measured by the crest factor, which is defined as the ratio of the peak magnitude to the signal's RMS value. Relative phases of each tone with respect to each other determine the multi-tone signal's crest factor. A multi-tone signal with a large crest factor contains less energy than one with a smaller crest factor. If you have a higher crest factor, then individual signal sine tones have lower signal-to-noise ratios. Proper selection of phase is critical to generate a useful multi-tone signal. The maximum number of tones needs to be considered to avoid amplitude clipping of the signal. You can use different combinations of phase relationship and amplitude to get a lower crest factor.

3.4 Phase Generation of Multi-Tone

The phase of the multi-tone signal is another parameter that can be controlled and can affect the composite signal crest factor. To create multi-toned signal with low crest factor you can vary the phase difference linearity from 0 to 360 degrees between adjacent single tones like chirp signals. It is recommended that you vary the tone phases randomly to reduce the crest factor. Varying the phases generates multi-tone signals with very low crest factors. Multi-tones are very sensitive to phase distortion. In addition, the signal path may induce non-linear phase distortion. Multi-Tone might display some repetitive time domain characteristics in the multi-tone signal.
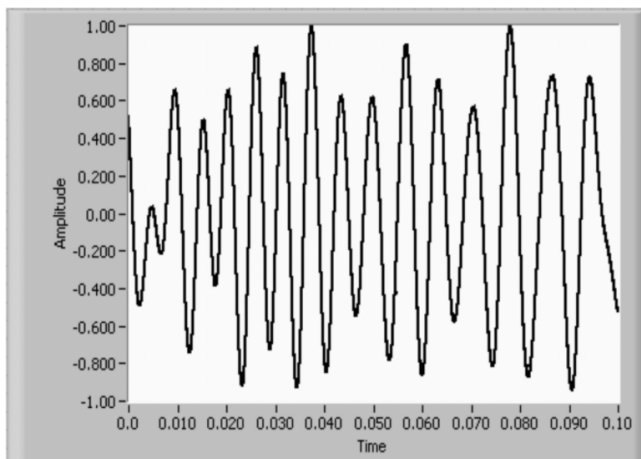

The signal in the previous illustration resembles a chirp signal in that its frequency appears to decrease from left to right. This apparent decrease in frequency from left to right is characteristic of multi-tone signals generated by linearly varying the phase difference between adjacent frequency tones. You might want a signal that is more noise-like than the signal in the previous illustration.

Varying the tone phases randomly results in a multi-tone signal whose amplitudes are nearly Gaussian in distribution as the number of tones increases. In addition to being more noise-like, the signal is much less sensitive to phase distortion. The following illustration shows a signal created by varying the tone phases randomly.
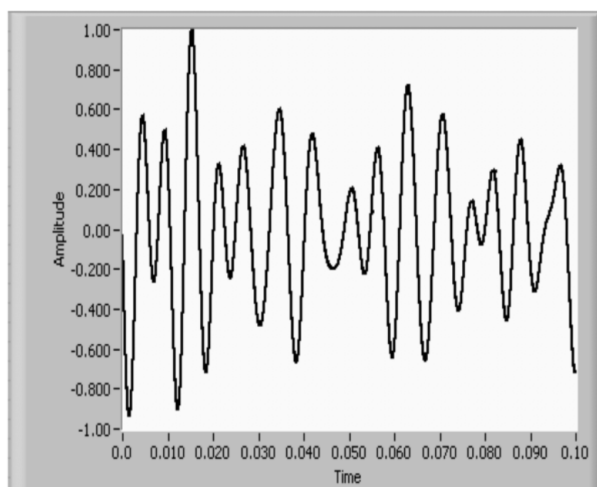
3.5 Generating Multi-Tone Signals with I/Q Modulator

To create a single discrete tone, the modulating waveforms are fed both to the (I) and (Q) inputs. There is full control of the individual discrete tones parameters including amplitude, phase and frequency. Depending on the sign, the modulated waveform on the (Q) input the tone will appear above or below the carrier frequency. To generate multi-tones, additional frequency components are added to the modulating waveform on both the (I) and (Q) input, centered about the carrier frequency.
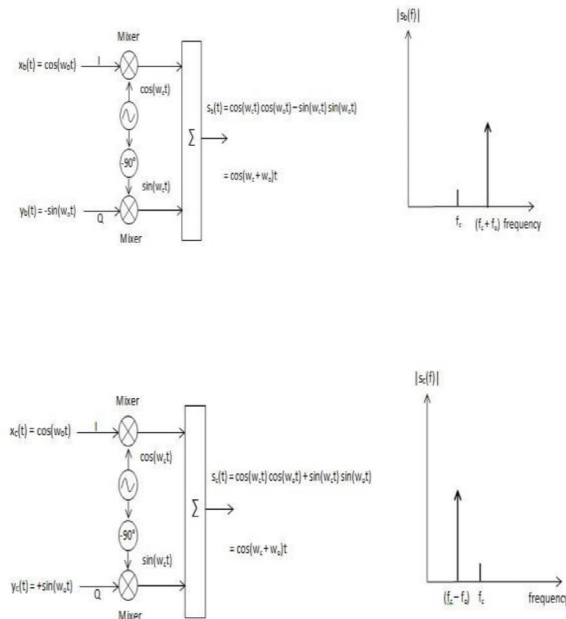
To generate double sideband suppressed carrier amplitude modulation (DSBSC-AM) signals, the modulating waveform is fed to the in-phase (I) and zero is fed to the quadrature (Q). The figure below demonstrates how the output creates two tones symmetrically around the carrier.
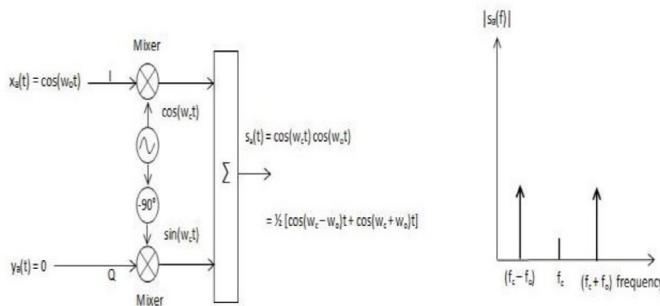
3.6 Intermodulation and Harmonics Distortion

Intermodulation (IMD) and harmonic distortion are types of nonlinear distortion. Intermodulation distortion is the result of unwanted intermodulation between multiple frequency tones that comprise a multi-tone signal. Harmonics are integer tones of the fundamental input signals generated when a signal passes through a nonlinear device.

The output signal tones of a device can be calculated from the input signal tone using a transfer function which provides a mathematical relationship between the output and input tones. Every transfer function can be described by a polynomial called the Taylorseries. Since the Taylor series is infinite, the number of harmonics in the output, in theory, is infinite. Within the signal amplitude, higher order harmonics amplitude decreases exponentially and thus can practically be ignored for multi-tone applications. When decreasing the input signal, the amplitude of the harmonic signal decreases exponentially by a factor of An.

Figure 1 shows what happens when two tones are inputted into a non-linear device. The intermodulation between each frequency tone will form additional signals at frequencies that are not just at harmonic frequencies, but also at the sum and difference frequencies of the original frequencies, as well as at multiples of those sum and difference frequencies. Figure 2 shows the mathematical equations of a two-tone intermod product.
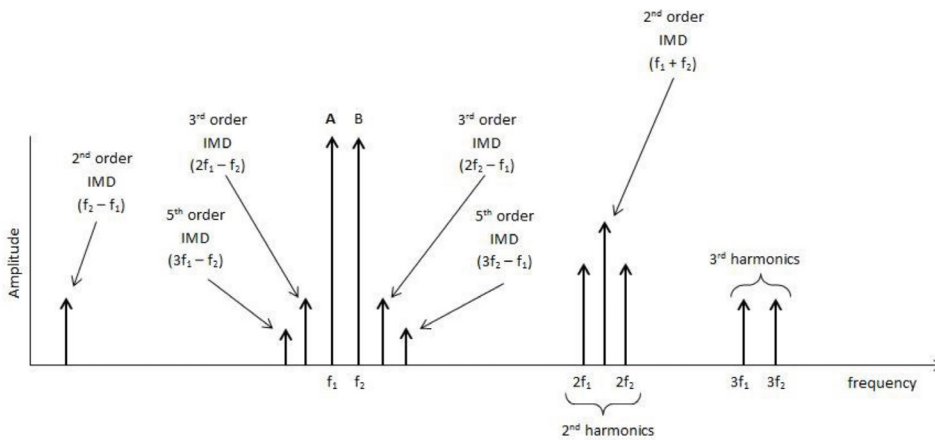
Figure 1: Graphical Representation of Intermodulation

Vo is the transfer function to determine the output signal based on the input signals

$$V_0 = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots$$

The following equation is used to calculate two tone input.

$$V_i = A\cos(\theta_1) + B\cos(\theta_2)$$

$$\text{where } \Theta_1 = \omega_1 t + \Phi_1 \text{ and } \Theta_2 = \omega_2 t + \Phi_2$$

The next equation is used to calculate the 2nd harmonic of two-tone input based on the addition theorem for the cosine function.

$$V_i^2 = (A2/2)(1 + \cos(2\Theta_1)) + AB(\cos(\Theta_1 - \Theta_2) + \cos(\Theta1 + \Theta2)) + (B_2/2)(1 + \cos(2\Theta_2))$$

And the following equation is used to calculate the 3rd harmonic of two tone input.

$$
\begin{aligned}
V_i^3 = & \left(((3\,A^3)/4) + ((3AB^2)/2)\right) \cos\Theta_1 \\
& + \left(((3\,B^3)/4) + ((3\,A^2\,B/2))\right) \cos\Theta_2 \\
& + ((3\,A^2\,B)/4)(\cos(2\Theta_1 - \Theta_2) \\
& + \cos(2\Theta_1 + \Theta_2)) + ((3AB^2)/4)(\cos(2\Theta_2 - \\
& + \cos(2\Theta_2 + \Theta_1)) + ((A^3/4)\cos(3\Theta_1)) \\
& + ((B^3/4)\cos(3\Theta_2))
\end{aligned}
$$

Figure 2: Mathematical representation of Intermodulation products

Care must be taken to ensure that these unwanted signals do not significantly affect the quality of the immunity test. These inter-modulations can be minimized through the use of digital signal generation techniques (VSG) and properly sized amplifiers.

3.7 Power Requirement of Multi-Tone Testing

The level of input power of each tone of a multi-tone signal should be set by taking into account the number of tones and desired level of distortion that can be tolerated. The power required to generate multi-tone signals can be defined in both peak and average terms. The average power is defined as a sum of the power of each tone. The peak power is the maximum instantaneous power of the combination of all the tones. Maximum peak power happens in the moment of time when all the voltage vectors from each of the tones are aligned. The power for average or peak is defined below. Note that this assumes that all the tones are equal in power.

$$P_{MSAVG} = (PSSx + PSSx + PSSx) * N \text{(watts)}$$

or

$$= (P_{SSx} + P_{SSx} + P_{SSx}) * Log(N) \text{ (dBm)}$$

$$P_{MSPK} = (P_{SSx} + P_{SSx} + P_{SSx}) * N^2 \text{ (watts)}$$

or

$$= (P_{SSx} + P_{SSx} + P_{SSx}) * 20Log(N) \text{ (dBm)}$$

Where:
PMSAVG = Average power of multi- tone signals
PMSPK = Peak power of multi-tone signals
PSSx = Power of single tone signals
N = Number of tone signals

To reduce all distortion, the peak power can be used to calculate the number of signals generated by a given amplifier. However, since the individual signals differ in frequency, their relative phase is always changing. The peak power level is only reached when all of the tone signal vectors are aligned; the more tones generated, the shorter the occurrence of the instantaneous peak power.

When the peak power can't be reached, intermodulation distortion occurs. This distortion can be minimized by only using amplifiers within their linear operating limits (P1dB). Ways to remedy this situation are either increasing the amplifier's size or reducing the power of the tones.

The linearity and harmonic checks of immunity standards can be used to determine the number of signals generated by a given amplifier with acceptable distortion. For immunity testing, the required power to generate a disturbance tone signal varies as a frequency function. See Figure 4. Note that due to antenna gain, the required power falls off rapidly with frequency. Here multi-tone testing can take advantage of the full power of the amplifier and reduce overall test time.

In this specific case, a 250 watt amplifier provides a 2x speedup at the lower frequencies with a much greater reduction in test time at the higher frequencies. In many cases, test labs have the power to produce high RF fields but historically have not fully utilized that power because they are running single tone tests that require lower power levels. With multi-tone testing, test labs can better use their unused amplifier power while reducing test times. The justification for adding higher power amplifiers to the test lab has become a little easier because the high power amp will allow for testing at higher field levels and result in a reduction in test time and more efficient use of resources when utilizing multi-tone technology.

IEC 61000-4-3 Vertical 10V/m @ 3 meters Resultant From UFA
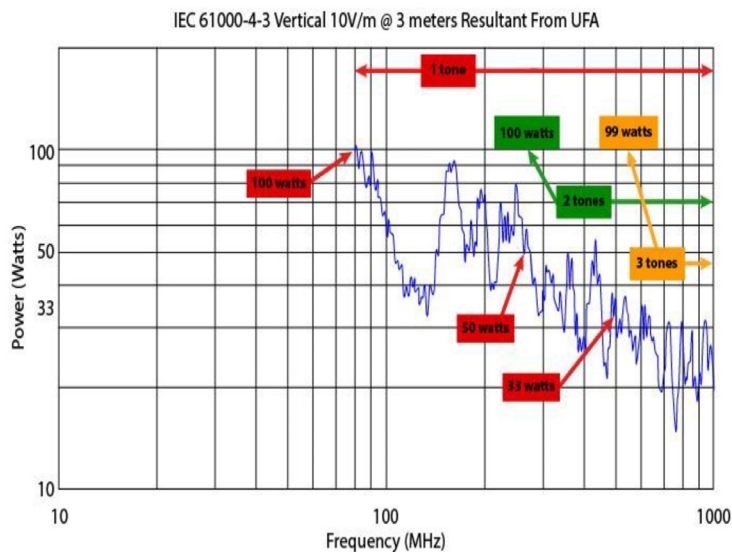
4.0 EMC Testing with Multi-Tone

4.1 Overview

The concept of multi-tone testing is simple. Rather than testing a single frequency during dwell period, multiple frequencies are tested at the same time.

While simple in concept, the actual hardware implementation has always been a hurdle. Simultaneously controlling multiple signal sources and properly combining their output signals in a repeatable fashion has been beyond the scope of traditional, analog test instrumentation. The solution is the combined use of two devices: a Vector Signal Generator (VSG), which can digitally produce multiple tones and complex modulations, and a frequency selective power measurement device, such as a Vector Signal Analyzer or VSA. Using this digital instrumentation under software control, the multiple tones necessary can be generated, measured, and controlled.

4.2 Level Settings

The multi-tone method can be applied to any standard that uses a substitution method of level setting.

For radiated immunity testing, isotropic field probes are used to set the level; these probes are not frequency selective and cannot parse out or measure multiple tones. Therefore, the level setting time cannot be improved using a multi-tone process. The level setting procedure must be done using traditional single tones. In order to use multiple signals, a secondary level setting procedure will need to be performed using frequency selective power measurement equipment such as a vector signal analyzer, VSA. This secondary procedure will use the power required by frequency to assure a test level of a single tone to determine how many signals can be combined into a test set without saturating the amplifier and introducing too much distortion.

Linearity and harmonic content measurements are also required as part of the level setting process. These measurements should be performed on all signals within a test set, adding each new signal until the aggregate of the set fails one or both linearity or harmonic checks. The result is the maximum number of signals that can be used together as a set. The time spent on this additional level setting procedure is offset by time savings achieved by the VSG in leveling to the desired field strength.

4.3 Testing

Once there is a determination of how many tones can be used and in what groups or sets, testing can proceed at record speed. For each dwell time, a set of tones is presented to the equipment under test (EUT). If there is no EUT fault, the test continues. If a fault occurs, the user has the option to immediately investigate with a single tone to verify if the failure also exists when only a single test frequency is used, or continue with the multi-tone test noting where failures occurred. In the second case, after test completion, the failed frequency ranges would be rescanned with a single tone to see if the fault is unique to multi-tone testing or remains even when testing with a single frequency. Additional investigation and thresholding can also be performed at this time. If the EUT demonstrates sensitivity to multi-tones but not with a single tone, the EUT may be considered compliant with the test standard. The only downside is that at these particular frequencies, one cannot reduce the test time. Nevertheless since large sections of frequency ranges can be scanned and tested quickly, the overall test time is still reduced dramatically. The graphical representation in Figure 3 captures this testing concept visually. Note that the test proceeds quickly from the lowest frequency up to when a fault is encountered. At this point, multi-tone testing is suspended, and the test reverts to single tone conventional testing. In this hypothetical scenario, it is seen that the EUT passes the single tone testing, and multi-tone testing is resumed without further failures throughout the remaining frequency range.
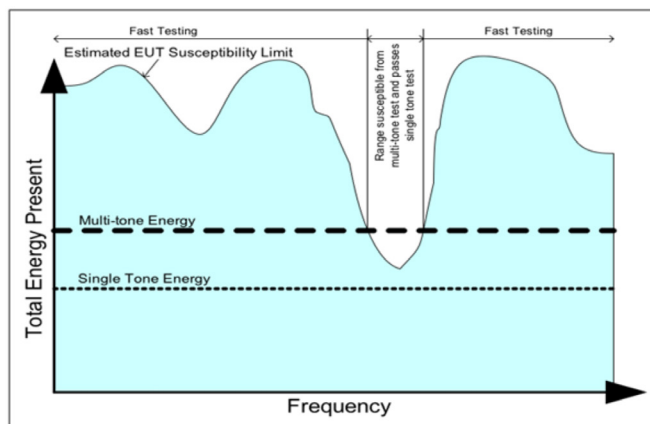

Figure 3: Simulated multi-tone test

4.4 Compliance

The ability to test and demonstrate compliance, while significantly reducing test time, is possible using the multi-tone method. To meet the EMC standard, each and every tone during the test:

- will be at the correct amplitude to produce the needed field
- will be at the required frequency
- will be at the required frequency % step, or in this case % spacing
- will carry the required modulation
- will dwell at the required dwell time for each frequency/tone

5.0 Advantages of Multi-Tone Testing

5.1 Reduced Test Time

Immunity testing can be very time consuming to perform. Often, tests take many hours, which constrains the throughput of a laboratory and limits the testing capacity for many facilities.

Historically, methods used to reduce the test time have focused on reducing the transition times (the time between the measurements of frequency steps) which unfortunately, represent only a fraction of total test time.

Multi-tone testing is a method designed to dramatically reduce test time by better using the required dwell time of the test. It is a process that adds multiple test frequencies (tones) to each test period (dwell time). By testing multiple frequencies simultaneously, the test efficiency is increased by a factor approximately equal to the number of tones used.

For example, if four tones were used, the test would be completed in about one quarter of the normal time or four times faster. See Figure 4.
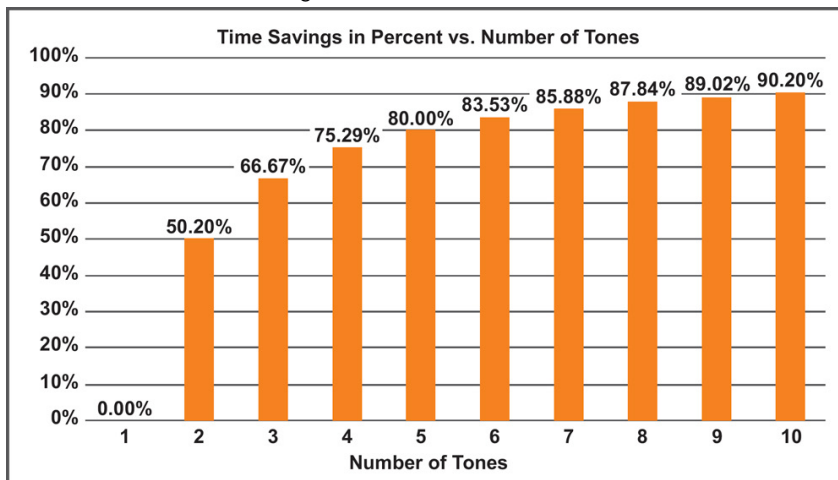

Figure 4: Percent time savings

5.2 Simulation of Real World Threats

Another benefit of using this technology is its ability to simulate real world threats which are multi-tone in nature. Real world applications expose EUTs to more than one tone at a time.
Conventional one tone testing would never uncover susceptibility to these "actual" threats. Some equipment manufacturers have already experienced multi-tone induced EMC failures and have been using multi-tone testing to identify and correct product vulnerabilities. These real world threats may not only be multi-tone in nature; there may be multiple concurrent and interactive threats present. An example would be EUT used in close proximity to a fully populated, multi-use radio tower

The medical standard 60601-1-2 has listed many known threats and requires testing at elevated levels and new modulations in these suspect bands. It also infers that product manufacturers should limit their liability by actively testing for any foreseeable threats. More standards more complex tests will likely follow.

6.0 Future enhancements of Multi-Tone System

EMC testing is standards driven. As more standards are released that require more complex testing, demand for more efficient test methods will follow. This will drive the increased necessity for the use of digital signal generation and measurement techniques. The digital equipment is becoming more readily available and less frequency limited. This will allow this type of testing to see greater use in all application testing from consumer products such as handheld and household devices to more complex assemblies associated with automotive, aerospace and military industries.

7.0 Summary of Multi-Tone System

The digital hardware (VSG, VSA) used to implement the multi-tone method is limited only by its usable frequency range and instantaneous bandwidth. This same hardware could also be used to generate complex modulations schemes as well as noise for broadband testing.

The multi-tone methodology can be adapted to other immunity test standards resulting in similar time-savings and improved efficiencies.

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- High Power Amplifier in Multi-tone Environment, Mini Circuits, Application Note AN-60-037, 4/14/15

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Frequently Asked Questions About Multi-Tone Systems

- **What is multiple signal testing? How does it work?**

  Rather than testing a single frequency during every dwell period, multiple signals, also referred to as multi-tones, are generated to simultaneously test multiple frequencies.

  While simple in concept, the actual software and hardware implementation has always been a hurdle. Simultaneously controlling multiple signal sources and properly combining their output signals in a repeatable fashion has been beyond the scope of traditional, analog test instrumentation.

  One possible solution includes the use of a Vector Signal Transceiver (VST), which incorporates the functionality of both a Vector Signal Generator (VSG) and Vector Signal Analyzer (VSA). Using this digital instrumentation under the proper software control allows multiple tones to be generated, measured, and controlled.

- **Will the IEC 61000-4-3 standard allow multiple signal testing?**

  Allowances for multiple signal testing were added to the 4th edition of IEC 61000-4-3. Annex I of this standard contains useful information regarding multiple signal testing, also known as multi-tone testing, such as: concerns relating to intermodulation, power requirements, level setting requirements, linearity and harmonics check, and EUT performance criteria with multiple signals. For those sectors still in the adoption phase of this test approach, multiple signal testing is still acceptable. In the event of a failure you will need to revert to the traditional single tone testing.

- **Is the multiple signal method over-testing the EUT?**

  The short answer is yes; however, you have the option to reduce to a single signal, or tone, if the EUT fails. Remember that the unit is being exposed to multiple tones and each tone has a field strength equal to the required test level. Each of these tones will have slightly different phases, so there will be additive and subtractive components to the total energy presented at the EUT. The peak of this total power is only reached when all the signals are in phase for a relatively short occurrence.

- **What is the benefit of purchasing the AR Multi-Tone System?**

  The main reason to purchase AR's MT06002 System is to save test time and associated cost. That equates to savings in man-hours as well as a more cost-effective use of your equipment resulting in increased throughput and efficiency of your testing facility.

- **How does the Multi-Tone System save time?**

  The Multi-Tone System saves time by producing multiple signals during a dwell time. Since the minimum dwell time is defined by the harmonized standards and the cycle time of the EUT, and a large part of the total test time is spent during the dwell, multiple tones executed during each dwell will significantly reduce test time. For example; by generating 6 tones during the dwell there is a test time savings of 82% for a typical IEC 61000-4-3 radiated immunity test to 6 GHz when compared to testing a single tone.

- **Can the Multi-Tone System be used for IEC 61000-4-3, 16-point Calibration?**

  Yes, AR's Multi-Tone System can be used for IEC 61000-4-3, 16-point calibration using a single tone. The use of a Vector Signal Transceiver (VST) improves the data throughput through its ability to more efficiently generate, receive and process information, as compared to traditional computer-controlled systems. It should be noted that when performing the 16-point uniform field area (UFA) calibration, using simultaneously generated multiple signals is not an acceptable or approved method due to the inability of field probes to distinguish or produce measured RF field strengths of simultaneously generator RF fields. If you choose to perform the 16-point field calibration, the MT06002 has this capability.

- **What are the limitations of the Multi-Tone System?**

  The most significant limitations of a multiple signal test system is the amplifier power, the MT06002 bandwidth (up to 1 GHz), and field probe bandwidth limitations.

- **How much amplifier power is required?**

  That depends on the number of signals, or tones, being generated at a time. For each tone, the average power is approximately additive, whereas the instantaneous power may be as high as the square of the number of tones generated. The average power is used to calculate the required amplifier power.

- **Will users need to purchase power amplifiers with a lot more power to drive multiple signals?**

  The MT06002 will use your current amplifiers more efficiently, so it is possible to use existing amplifiers and still benefit from multiple signal testing. For instance, when performing an IEC 61000-4-3 test within the frequency range of 80 – 1000 MHz, more power is required from 80 – 200 MHz than from 200 – 1000 MHz due to antenna efficiencies. In the case of an AR W-series amplifier, which operates from 80 – 1000 MHz, the amplifier will need to be sized for the 80 – 200 MHz range. The MT06002 will analyze the amplifier's available power and signal compression to determine the frequency ranges where multiple tones can be applied, as well as the number of tones that can be generated. Therefore, in the 200 – 1000 MHz range, more amplifier power will be available and the MT06002 can thus create more tones.

- **What equipment is included with the Multi-Tone System?**

   The AR MT06002 Multi-Tone system consists of the following:
   - A field probe with a field monitor and fiber optic cable
   - A system controller that switches up to 4 amplifiers and 4 antennas for automated testing
   - A vector signal transceiver (VST) to generate multiple signals or tones, and to simultaneously measure the tones
   - U to 1 GHz instantaneous bandwidth

- **Do I need to purchase a special software to run the Multi-Tone System?**

   No, the AR Multi-Tone system uses the built-in MultiStar software to perform testing. This software is developed by AR software and EMC Engineers.

- **Is the user able to save a test profile once created?**

   Yes, once you create a test set-up you can save the file with all the test settings for future use, saving valuable time. Additionally, calibration information for all equipment is saved, including appropriate correction factors.

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SC2000 System Controller for Automating Radiated Immunity Testing

Systems designed to test for RF susceptibility contain several interconnected RF devices. By necessity, most of these test systems are configured as dynamic turnkey solutions that address more than one of the ever-changing EMC standards. Considering the complexity of the newer EMC standards coupled with the Equipment Under Test (EUT) complexity, the mechanics of simply "running" a standard test can be daunting. While theoretically, one can manually conduct the required immunity tests manually, the amount of time and effort involved is so staggering; manual operation is only feasible when initially configuring a test system, when troubleshooting a system malfunction, or when unique tests are required. The only viable option to this testing dilemma is automating the tests by using a software-driven RF test system controller that provides signal routing through RF switches. While productivity is increased markedly, as a significant decrease in the time required to perform EMC tests, significant benefits also include accuracy and repeatability.

AR RF/Microwave Instrumentation has developed the SC2000 series of RF test system controllers to address the need for flexible automated systems. The SC2000 switch control platform is designed for a multitude of switching applications in RF systems. Each of the main chassis is equipped with five (5), rear-facing, user-configurable slots. Individual slots or groups of slots can be populated with a variety of SCM series RF switch modules.

The Model SC2000 can be fiber-optically combined with up to seven (7) model SCX2000 expansion units. The model SCX2000 is mechanically identical to the model SC2000 but does not contain a control panel. Instead, control is provided by the connected model SC2000.

For backward compatibility with the legacy model SC1000, the model SCP2000 was created. This model provides identical switch configuration and operation to the legacy model SC1000 and its modifications (M1– M5).

These switch controller systems can be controlled manually, using the provided color LCD touch display, or remotely, using any of the four provided remote ports (USB, GPIB, RS-232, and Ethernet).

System interlock capability is provided on the Models SC2000 and SCP2000 by sensing switch closures on three independent inputs. Three separate user-definable configurations are provided for times when interlock switch closures are not sensed.

A user-defined "safe" configuration is also provided for use during signal re-routing to assure cold switching of any attached amplifiers and loads. In addition to the three interlock configurations and single "safe" configuration, eight (8) user configurations can be saved and recalled for ease of use in complex systems. This application note details the various uses and configurations of the SC2000 series.

A positive 24 VDC signal along with four (4) open drain outputs and four (4) digital outputs (TTL) are supplied for applications such as external switch/relay control.

1.0 Benefits of Automation

The SC2000 System controller has many features built into its design that provide a significant increase in overall productivity, as well as improved test quality and repeatability, thereby providing a considerable savings in time and cost.

- One of the biggest cost and time savers is the ability to automatically switch one power meter with two power heads to monitor up to four dual directional couplers. The alternative manual approach requires the use of four dual channel power meters with eight power heads permanently attached to the directional couplers, or just use one power meter and physically move the power heads between the directional couplers each time frequency bands are switched. Since directional couplers are often inconveniently located for manual switching, this latter approach can be quite cumbersome.

- The trend toward higher frequency testing has mandated the use of expensive, high quality, low loss RF cables to reduce signal attenuation. Unlike standard RF cables, precision low loss cables are susceptible to damage resulting from repeated movement and reconnections. Since the physical configuration of an automated system is fixed, the integrity and life expectancy of these expensive precision RF cables is assure.

- Since system reconfiguration between frequency bands is either reduced or totally eliminated, the focus of attention is shifted from the system setup to monitoring the EUT, improving test repeatability.

- Given that signal generators can be switched at will, the system can use generators designed for specific frequency ranges instead of a single expensive broadband generator that covers the entire frequency range. In this situation, a few narrower band signal generators may prove less costly than one that covers all test frequencies.

- The SC2000 not only supports internal coaxial switches, but it can control external RF switches with its series of open collector outputs. In some applications, external switches are necessary when very high-power RF is involved or when it is desirable to physically move the position of a switch to a remote location removed from the system controller.

- By reducing or totally eliminating the need to manually change RF connections and switch antennas, a considerable amount of time is saved, as well as reducing test quality concerns.

- Training of test engineers and technicians is greatly simplified using automated setup routines. Automation provides more consistent test results over time, minimizing the impact that individual test personnel have on the test outcome. Repeatability is thus assured.

- Since the RF cables are not physically handled, they can be permanently configured in the most efficient manner, thus reducing lab clutter. Also, the absence of RF cables running across the floor and dangling from ceilings improves the operational safety of the lab.

- There is always a risk of equipment damage when conducting an EMC test if a damaged RF cable shorts out the system or if an incorrect load or no load is applied. Such setup errors are all but eliminated by automating the test system.

Figure 1 is an example of an EMC test setup in its most basic form. Note that there is only one RF path and thus, no RF switching is required.

In Figure 1 the diagram clearly demonstrates the need for additional RF devices to accommodate the higher frequency requirements of today's EMC standards. The burden of additional test equipment as well as the requirement of multiple RF paths can be mitigated using RF switching. At the very minimum, this system would benefit from the addition of two RF switches.

1. The signal generator output can be routed to different RF amplifiers as required.

2. The output of either of the two lower frequency amplifiers can be applied to the single log periodic antenna.
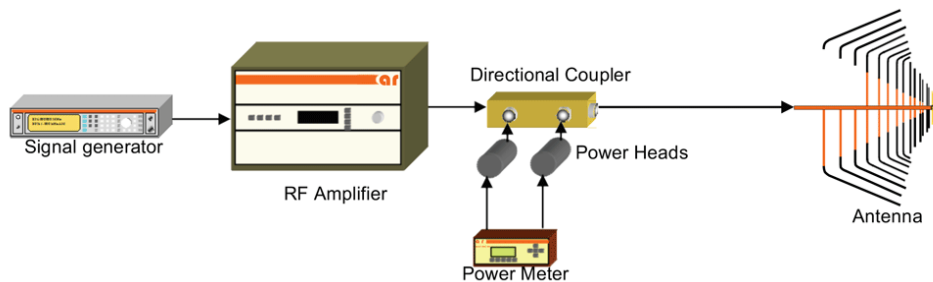

Figure 1: Basic RF immunity setup to test from 80 MHz - 1 GHz

This is just the beginning of the possible productivity improvements an automated switching matrix provides. By adding just two more switches the requirement for three power meters with six power heads is reduced to a single power meter with two power heads.

3. Power head 1 on a single dual power meter can be switched between the forward power ports on all the directional couplers.

4. Power head 2 on the same dual power meter can switch between the reverse power port on all the directional couplers.

While four RF switches seem appropriate for the typical setup shown in Figure 2, additional switches are required for more complex systems. For example, a more complex system would be one where one or more amplifiers need to be switched between two antennas rather than just one, or if the EMC test includes a receiver or spectrum analyzer for emissions testing. As a general rule the more complex the test, the greater the need for RF switching. When configuring an RF system controller, it is best to think ahead and plan for all possible test scenarios to ensure that all conceivable EMC tests can be fully automated.
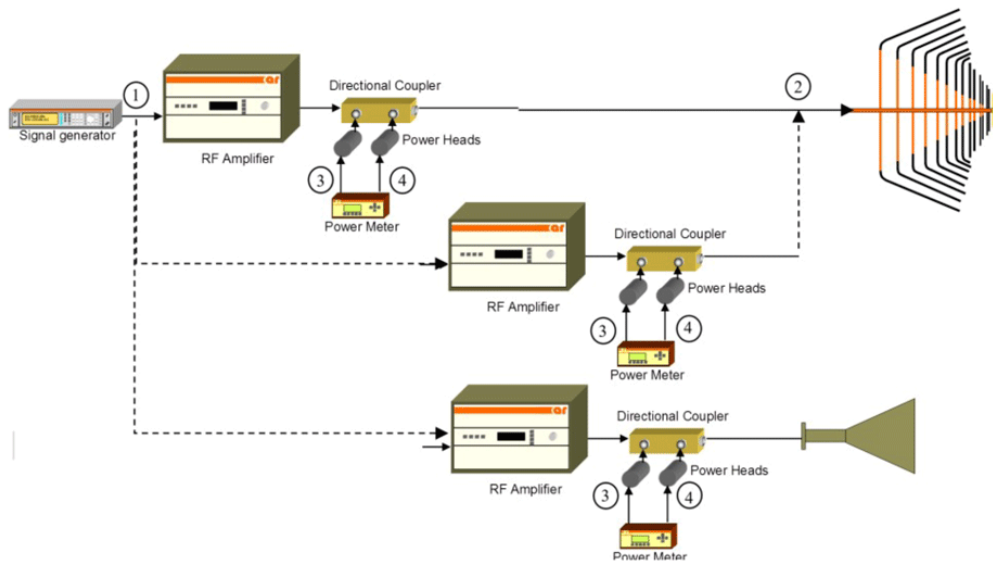
Figure 2: A typical RF immunity setup that accommodates the current mandate to test to higher frequencies (80 MHz - 18 GHz)

2.0 Designing an RF Switch Matrix

The design of an RF switch matrix is directly influenced by the RF equipment that is to be switched and is limited by the specs of the coaxial switches selected. The key parameters are frequency range, Max RF power rating, and insertion loss.

2.1 How RF device's impact RF switch martix:

- Signal generator – Power is not a concern with this RF device since the output of a signal generator is low level RF. The important consideration is the frequency range of the generator.

- RF Amplifier – Since RF amplifiers are used to amplify the low-level RF output of the signal generator, both frequency range and power output must be considered. These specifications will dictate what RF switches can be used or even if a switch is available.

  Antenna – While the frequency range and power handling capability are of importance since the antenna will be sized to accommodate both the frequency range and output power of the power amplifier, these antenna characteristics however do not directly affect the switching matrix.

- Directional couplers – Since the switch matrix interfaces with the low power signal available at the coupling ports, the only specification that affects RF switch matrix design is frequency range.

From the above review of RF device impact on the RF switch matrix, the two specifications that are key in the selection of RF switches are frequency and power rating. RF switches are limited by their coaxial connectors, which are specified for both maximum frequency of operation as well as their power handling capability. Power rating is generally provided at the lower frequency limits with a de-rating curve applied as operating frequency increases. In general, the power handling capability is proportional to connector size and the frequency capability is inversely proportional to size.

For example, a relatively small SMA connector can operate up to 26 GHz with a power rating of 200 watts at 1 GHz while a larger standard Type N connector peaks out at 18 GHz but can tolerate 1000 watts at 1 GHz.

The SC2000 system controller provides switching matrices from DC to 40 GHz at powers ranging from 25 –1200 watts. Higher power and/or higher frequency applications are generally resolved by use of RF devices with waveguide connectors. Since waveguides are very frequency dependent with little overlap between sizes, RF switching is difficult or even unavailable in most cases. For these higher power, higher frequency applications it is best to dedicate antennas to each amplifier. When the frequency does not warrant waveguide connectors, but the power exceeds the capabilities of the SC2000, larger external coaxial switches must be used. As noted above, the SC2000 has a number of open collector outputs and a switchable +24VDC signal that can be used to control these remote high-power switches.

The system diagram in Figure 4 shows the system configured to accommodate the criteria set forth in example 2. Note that two system controllers are combined to automate this large system.

Figure 3
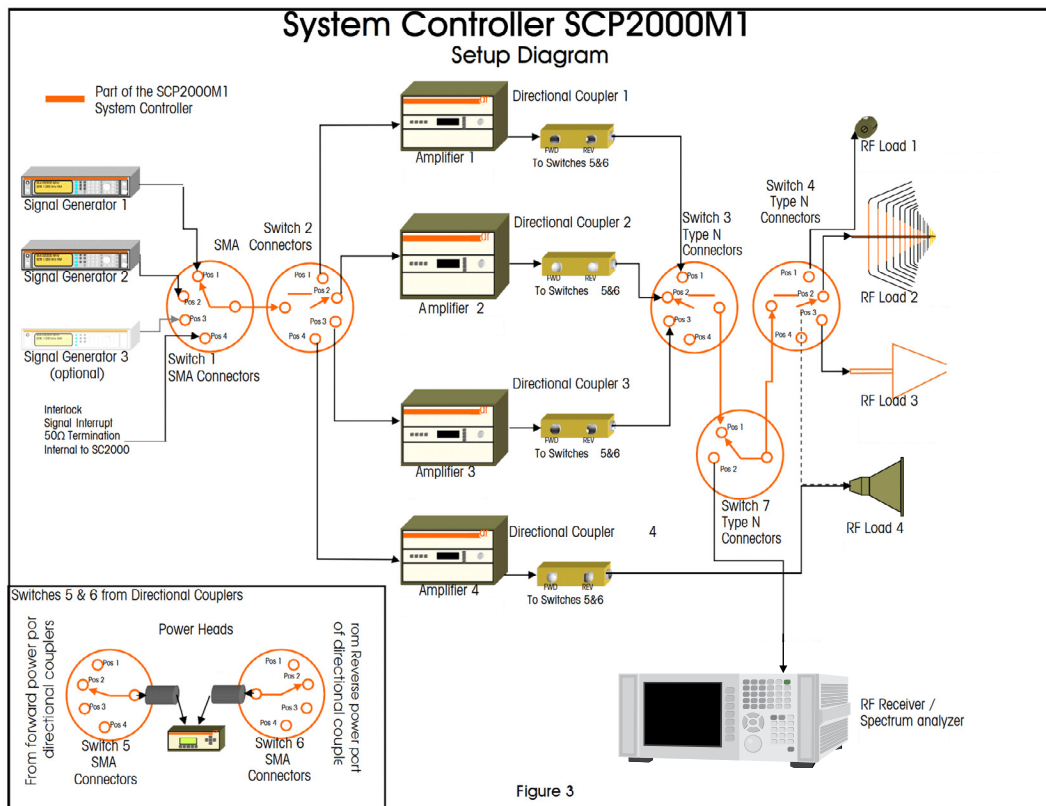
Summary

This application note has identified the benefits of automating EMC test systems. While the focus has been on the AR RF/Microwave Instrumentation family of RF test system controllers, it must be noted that automated systems require system software to function. The versatile SC2000 will operate well with emcware® a comprehensive EMC test software package from AR RF/Microwave Instrumentation, or any customer supplied custom software. If you would like to learn more, feel free to contact one of our applications engineers at 800-933-8181, or visit our website at www.arworld.us.

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Amplification

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AA-Series Field Generating Systems

Traditionally, generating low-level electric fields in the 18 - 40 GHz frequency band has been performed using traveling wave tube amplifiers (TWTA's). These TWTAs often produce much more power than is actually required to generate the required field strengths while also being an extremely costly solution. Why pay for unnecessary power? AR rf/microwave Instrumentation has the answer by introducing its AA-Series field generating systems. These systems can produce field strengths of up to 50 V/m in the 18 - 26.5 GHz and 26.5 - 40 GHz bands. An AA system is composed of a solid-state amplifier and antenna combined in a single housing, which can then be paired with a rack-mountable power and RF routing unit.

1.0 AA-Series Basics

The AA-Series products are designed to be a low-cost and highly reliable solution to a decades-old problem of using costly, unreliable TWTAs to generate low-level, high-frequency electric fields. Typically, in the 18 - 26.5 GHz (K-Band) and 26.5 - 40 GHz (Ka-Band), the smallest-size TWTA available in terms of RF power is about 40 W, which provides a solution for field strengths up to 200 V/m. Until recently, this has been the only solution for generating any electric fields in these frequency bands. Up to this time, solid-state RF amplifiers at these frequencies and power levels were not available. However, this has changed with AR maximizing the potential of the latest technological advances. The AA-Series can produce field strengths of up to 50 V/m at 1 meter from 18 - 26.5 GHz and 26.5 - 40 GHz at almost a third of the price as 'low-power' TWTAs. Remember, too, that TWTA failures can result in months of downtime while they are repaired. This solid-state solution offers a significantly higher mean time between failure (MTBF) and much shorter repair times.

The AA18G26 and AA26G40 each consist of an antenna directly mounted to a solid-state amplifier, along with sufficient heat sink and over-temperature fault detection. By connecting the antenna directly to the amplifier, we have eliminated cable losses and can deliver maximum amplifier power to the antenna. Within each frequency band, there are two available options. The -20 and -50 options indicate the guaranteed minimum field strength (20 V/m or 50 V/m) that each unit delivers. The AA-Series uses antenna gain to minimize cost rather than amplifier gain to achieve higher field strengths. Table 1 lists all the available AA field generating units with their associated frequency ranges, field strengths, and antenna spot sizes.

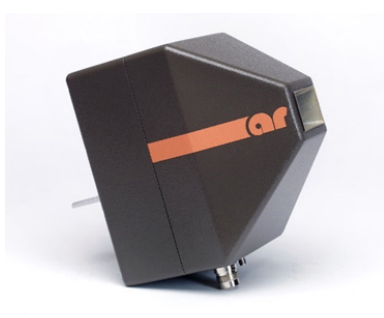| Model Number	Frequency Range (GHz)	Guaranteed Field Strength (V/m)	Spot Size (m)
AA18G26-20	18 - 26	20	0.31 x 0.31
AA18G26-50	18 - 26	50	0.14 x 0.17
AA26G40-20	26 - 40	20	0.29 x 0.32
AA26G40-50	26 - 40	50	0.15 x 0.17

Table 1. AA-Series Options
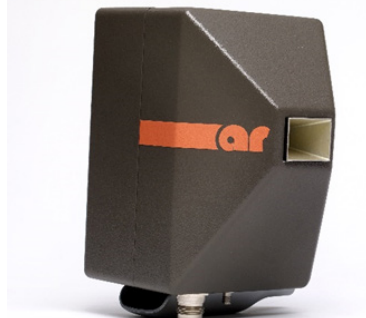

Figure 1: AA18G26-20

Figure 2: AA26G40-20

To interface with the AA18G26 and AA26G40 models, AR has designed the AA1000 (Figure 3). This unit is designed for routing RF and providing DC power to the amplifier and internal cooling fans to all AA-series models. For RF, the AA1000 receives RF from an external signal source and distributes the signal through a switch before leaving the unit and traveling to an AA18G26 or AA26G40 via provided low-loss coaxial cables. This switch acts as an automatic shut-off when faults are detected. Faults are determined by monitoring the DC power delivered to the amplifier and cooling fans. The DC power is generated by internal power supplies and delivered to the unit via provided twinax cables. It is controlled either by the front panel or remote control through GPIB, RS-232, Fiber Optic, USB, and Ethernet. A System Interlock is also provided. Using AR's EMC software suite, emcware, an AA system communicates in the same manner as an AR amp, thus further ensuring the ease of incorporation into a laboratory's test setup.

Figure 3: AA1000 Front Panel

For all of the capabilities described above, the implementation of AA-series equipment is quite simple. Figure 4 provides a basic block diagram of the setup. All of the equipment highlighted in orange is provided by AR.
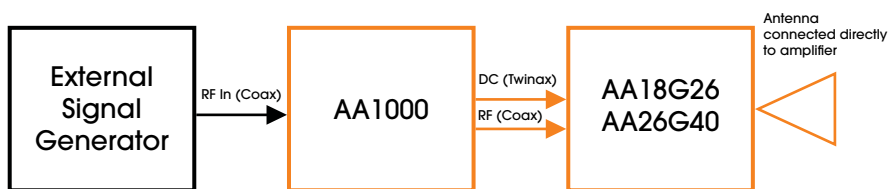

Figure 4: AA-Series Equipment Block Diagram with Provided Equipment Highlighted

2.0 AA-Series Applications

As was already stated, the AA-series was developed as a reliable, low-cost solution for testing low field strengths in the 18 - 26.5 GHz and 26.5 - 40 GHz frequency range. This includes a large variety of applications. First and foremost, the AA-series satisfies several requirements of RS103 of MIL-STD-461. Specifically, the following Platform test levels can be met:

- Ships (Metallic) (Below Decks) - 10 V/m
- Ships (Non-Metallic) (Below Deck) - 10 V/M
- Submarine (Internal) - 10 V/m
- Ground - 50 V/m
- Space - 20 V/m

These requirements are all met with minimal change to the typical test setup for RS103. It should be noted that these changes resulting from using AA-series equipment are acceptable per MIL-STD-461. Figure 5 shows a typical RS103 test setup utilizing AA-series equipment.
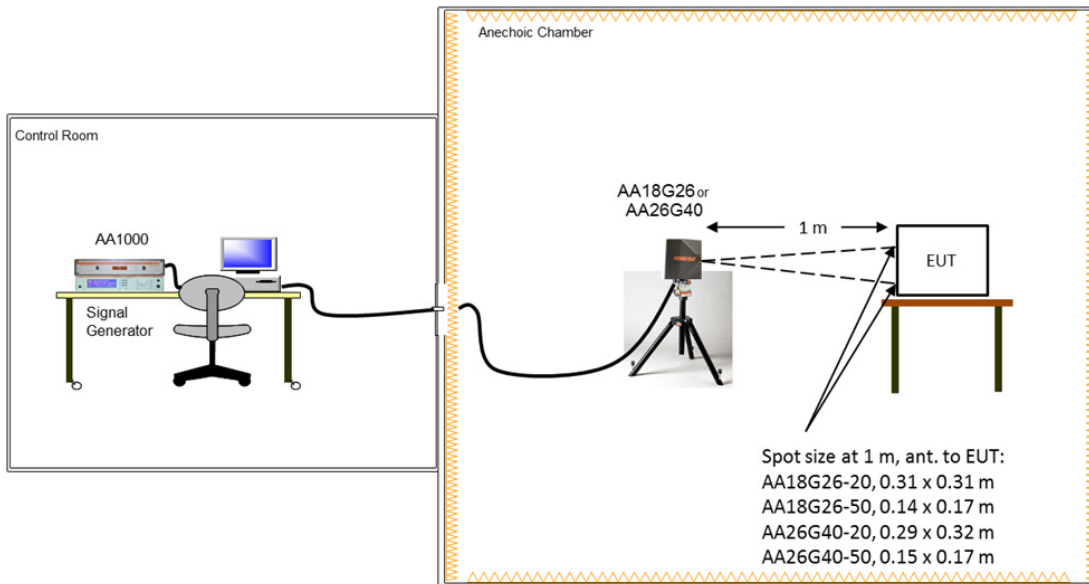
Figure 5: MIL-STD-461 RS103 Test Setup Utilizing AA-Series Equipment

Please be aware that RS103 is not the only application for the AA-series. With today's evolving marketplace, technology is continuing to see contributing threats at higher operating frequencies. One such example is 5G. It's well known that 5G is on its way, and it will be utilizing bandwidth in the Ka-band. Other communication types, such as satellite communications, are already moving into the K and Ka-bands to utilize speed and wider bandwidths. Many current and future radar applications exist in the K and Ka bands as well. Many EMC standards are also beginning to move higher in frequency to accommodate these changes in operational frequencies.

Conclusion

To rectify a decades-old problem of expensive and unreliable TWTAs, AR has developed a new solution for low-field strength radiated immunity testing from 18 - 40 GHz. The AA-series field generating systems can produce field strengths of up to 50 V/m in the 18 - 26.5 GHz and 26.5 - 40 GHz frequency bands. AA-series products utilize solid-state technology for a more reliable, low-cost option over traditional TWTA approaches. Furthermore, by using AR's emcware, the system is controlled and monitored like any other ARI amplifier, making the overall operation easy for the test engineer. If you would like to learn more, feel free to contact one of our applications engineers at 800-933- 8181 or visit our website at www.arworld.us.

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Advantages of Liquid Cooling

Depending on the performance requirements of an amplifier, an amplifier manufacturer may choose to cool the internal electronics with liquid rather than air. Self-contained liquid cooling of an amplifier's solid-state transistors has several advantages:

- **Liquid Cooling allows for precise temperature control of the semiconductors**
  The number one factor determining the reliability of solid-state devices is temperature. By carefully controlling the temperature, engineers can optimize the performance of the amplifier without sacrificing reliability.

- **Liquid Cooling Reduces the Size of the Amplifier**
  Air-cooled amplifiers use large metal heat sinks over which air is forced to carry away heat. In a liquid-cooled amplifier, the transistors are mounted on cooling plates through which water flows. The plates are much smaller than heat sinks, and because you don't have to accommodate airflow, they can be built closer together.

- **Liquid Cooling Reduces the Heat Load On The Amplifier Room**
  Since most of the heat generated is carried away by the cooling liquid, HVAC requirements are reduced, which results in more comfortable surroundings and reduced utility bills.

- **Liquid Cooling Allows for Fewer Fans**
  This makes the amplifier significantly quieter.
  By reducing the noise, operators can work in a safer, more pleasant environment without fatigue. Fans are still typically required for cooling internal electronics other than the RF section, but the number of fans can be greatly reduced.

Prior to implementation, liquid cooling should be carefully considered, tested and researched before being chosen as the preferred method for controlling temperatures in high-power amplifiers.

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Amplifier Selection Tips for EMC Applications

It is important to keep the following in mind when selecting an amplifier for EMC testing:

- **Technology -** In general, EMC amplifiers are based on various technologies and functionality.

  Solid state amplifiers' design involves the biasing of RF transistors (primarily MOSFETs). Alternatively, TWT (Traveling Wave Tube) amplifiers are a specialized vacuum tube that is used in electronics to amplify radio frequency (RF) signals in the microwave range.

  The choice of technology used is dependent on many factors. For high frequency applications (above 1 GHz) utilizing high power (above 100 W or so), a TWT would be the only choice currently available. High power, low frequency applications will utilize solid state technology. Additionally, some amplifiers will use solid state technology above 1 GHz, but power output will be lower than that of a TWT. It is all dependent on what your application requires.

  In addition to choosing the appropriate technology, it is important to consider how the signal will be amplified. A CW amplifier continuously amplifies any signal introduced into its input, as long as it is within the operational range of the amplifier. This includes both continuous wave signals and modulated signals. Pulse amplifiers, however, will only amplify a signal introduced at the input when an additional pulsed signal is applied to a pulse input, resulting in a gating-type function for pulsed applications.

- **Class of Operation -** Amplifiers are classified as Class A or Class AB. Class A solid state amplifiers are generally the best choice for EMC RI and CI testing. They are the most reliable, durable, and rugged compared to other amplifier classes or types. EMC applications and test environments introduce the lack of true 50 Ω loads, so Class A amplifiers are superior due to the ability to withstand the amount of reverse power introduced into the amplifier's output from load mismatch. Class AB amplifiers may be used, but this class's inherent mismatch tolerance will prevent the amplifier from being usable with many common EMC transducers.

- **Good Linearity and Low Harmonic Distortion -** Amps with good linearity and low harmonic distortion result in clean, reproducible, and measurable signals. Class A amplifiers outperform other types in this area.

- **Modulation (AM, FM, PM) Performance -** Modulation of the CW signal is required by most RI and CI test standards. When selecting an amplifier, be sure to ask the amplifier manufacturer to provide data showing how modulation is reproduced and under what conditions. Comparing the reproducibility of the modulated signals should be a key point in the decision-making process.

- **Multiple Signal/Tone Applications -** If planning to use multiple signals/tones or complex waveforms to speed up testing and better represent real-world threats, a single broadband amplifier is the most appropriate choice versus a multiband amplifier or multiple amplifiers. A broadband amplifier can amplify all the signals simultaneously whereas a multiband amplifier may require multiple inputs and outputs.

- **Rated Ouput Power -** Rated Output Power is a manufacturer-defined specification. Beware of typical, average, and maximum power level descriptions, which can be misleading. Instead, try to compare the same data across different amplifiers. If similar power data isn't available from the specification sheet, ask the manufacturer directly for it, with an explanation of how the power measurements were derived. Just because an amplifier specification sheet states that it is rated for 400 W does not mean that the amplifier will produce 400 W across the entire frequency band.

- **1 and 3 db Compression Points (P1dB and P3dB) -** The X dB compression point (PXdB) is the output power level at which the gain decreases X dB from its constant value. Once an amplifier reaches this point, it goes into compression and becomes a non-linear device, producing distortion, harmonics and intermodulation products. The typical compression points are P1dB and P3dB. This is an important rating for applications with strict linearity requirements, such as IEC 61000-4-3 and R&D.

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Frequently Asked Questions For EMC Testing

- **What should be my top considerations when looking for an amplifier?**

  When determining which amplifier to purchase, the top considerations should be output power, linearity, frequency range, and VSWR tolerance.

  Not only does the amplifier need to generate enough power for your test setup to generate the required fields or injection levels, but linearity requirements are also often present within test standards. The amplifier should be used within its stated operating frequency range and be VSWR tolerant.

- **What class of amplifier works for EMC? Class A or AB?**

  For an EMC application, and due to the lack of true 50 Ω loads present in EMC test environments, Class A amplifiers are superior due to the ability to withstand the amount of reverse power coming back into the amplifier's output. AB amplifiers may be used, but this class's inherent mismatch tolerance will prevent the amplifier from being usable with many common EMC transducers.

- **I have a test that I want to run from 80 MHz - 6 HZ, and I need to reach a field level of 60 V/m/ What amplifier do I need?**

  Since you want to test at such a wide frequency range, you will typically need two amplifiers and two antennas. Depending on the antennas selected, the power required for an amplifier to generate a given field should be somewhere in the antenna's datasheet. If this data is not given, then you will need to base your power requirement on the antenna's gain. Cable losses may be significant and need to be taken into consideration at higher frequencies. Chamber effects (reflections) can be unpredictable and therefore should also be considered by adding margin onto your power requirements.

- **My laboratory tests military equipment, commercial equipment, trains, cars, etc. Can I use the same amplifier to test all these devices?**

  If the amplifier's output power is sufficient and you are using it within the stated operating frequency range, you can use the same amplifier. Be sure to read the test standard to ensure that the amplifier selected meets any requirements stated within the standard, such as linearity. Different antennas, loads, etc., may be required.

- **How do I know the output connector onto the back of my amplifier is appropriate?**

  Typically, amplifiers are supplied with appropriate connectors based on the power output. We recommend reading our Guide to RF Coaxial Connectors and Cables, to learn about connectors and how they may affect amplifier performance. Care should be taken to use the same power rated connectors on cables, bulkheads, antennas/loads, etc.

- **Do I need to control my amplifier via software?**

  In most EMC tests, software control of an amplifier is not required. However, it is a great feature when utilizing equipment that is installed in another room or location further away. It is also helpful to know what the amplifier is doing in the event of issues during the EMC test.

- **What can I do to minimize system loss and increase my delivered power?**

  Quality, low-loss cables can only go so far in reducing loss at high frequencies as there will always be some inherent loss. The best approach is to minimize cable length. To do this, AR routinely moves higher-frequency field generating equipment into the chamber. In these instances, AR will often mount antennas and antenna masts directly to an equipment rack or rolling system platforms. This equipment must be housed in shielded racks as the fields generated in these systems can often exceed the amplifiers' (and other equipment's) verified compliance levels. Another alternative is AR's AA-series field generating systems in the 18 – 40 GHz range.

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High-Power Solid-State Pulsed Amplifiers

For years, when discussing high field-strength electromagnetic compatibility (EMC) radiated susceptibility testing, Traveling Wave Tube Amplifier (TWTA) technology has been the only available option for pulsed field generation. Now, there is a very attractive alternative to this technology. AR RF/Microwave Instrumentation is now offering high-power solid-state pulsed amplifiers. These SP-series amplifiers include various frequency ranges and output power levels to meet several standards. Additionally, designs can be tailored to suit your specific application. This application note will discuss some of the key features and benefits of AR's line of solid-state pulsed amplifiers.

Figure 1: 1000SP1G2

1.0 Characteristics

Inherent to TWTA technology's nature, there are a number of undesirable characteristics for EMC applications, one of which is harmonic distortion. TWTAs are rich in harmonic content. While many consider this to benefit the world of audio amplification, the opposite is true of RF amplifiers in EMC testing applications. When producing an electric field for EMC testing, harmonics lead to an inaccurate representation of the intended field. Many EMC specifications go as far as requiring that harmonics be below a certain threshold. Often, TWTAs have difficulty meeting these requirements. This is not the case with solid-state amplifier technology. AR's SP-series are specified with typical harmonic content of -18 dBc or better at P1dB. Additionally, the SP-series has a much higher compression point than their TWTA counterparts, thus allowing for a wide range of linear gain.

Another extremely important feature of RF amplifiers is mismatch tolerance. In EMC applications, there are an abundance of available antennas for use in field generation. While this provides a lot of options for frequency range, gain, power handling and so on, this can lead to significant variances in the antennas' voltage standing wave ratio (VSWR), meaning that the impedance of the antenna can vary greatly from an ideal 50Ω, thus causing reflected RF power. While antennas most often used in the frequency range in question typically have a relatively stable VSWR, this, along with chamber loading and large EUTs (common for high field strength applications), can be a serious issue for TWTAs. Generally, TWTAs have a poor mismatch tolerance and will begin to foldback or even shut off for a relatively small VSWR. Solid-state amps on the other hand, tend to have a much higher mismatch tolerance than TWTAs. For example, AR's SP series amps will not begin to foldback until the reflected power reaches half that of the rated output power. Better still, solid-state technology does not exhibit the parasitic oscillations that occur in TWTAs.

Solid-state amplifiers also have much higher reliability than TWTAs. Tube technology suffers from numerous deficiencies in reliability, including repeatability in production, parts availability, and decreasing tube manufacturers throughout the world. Performance of the TWTAs can even dwindle when left on standby or sitting unpowered on the shelf. If a TWTA does not have any planned use, it is necessary that the user periodically run the amp to prevent the tube's degradation. These solid-state pulsed amplifiers also have a much lower noise figure (NF) than their TWTA counterpart. In addition to the above advantages, the warranty for these AR solid-state amplifiers is 3 years, and repairs are much easier to accomplish and can be completed during a much shorter time frame.

Other characteristics of SP amplifiers include pulse widths up to 100+ μsec, duty cycles up to 10%, a front panel digital display providing forward and reflected power, as well as system and transistor status, IEEE-488 and Ethernet interfaces, and forced air and water cooling options.

2.0 Frequency and Power Levels

AR's line of Solid-state pulsed amplifiers are designed for a variety of frequency bands between 1 and 4 GHz. These bands primarily line up with automotive, aviation and military standards. Particularly, these frequency bands cover L and S band radar pulse testing as required by automotive standards, as well as various high-power offerings for specific octave frequencies from 1 – 2 GHz and 2 – 4 GHz as required by MIL-STD-464 and DO-160, as well as full vehicle automotive testing.

Within these frequency bands, a number of standard output power options from 1 kW to 20 kW are available. Paired with the appropriate antenna, these amps can generate a wide range of field strengths at a wide array of antenna distances. Additionally, AR has the capability to build custom amplifiers up to 150,000 watts depending upon frequency and pulse conditions.

Below is a table showing our standard product lines and their applicable applications.

Frequency Range	Power Level Offerings	General Applications
0.8 - 2.5 GHz	1 kW, 2 kW, 8 kW	EMC testing to MIL-STD-464 and DO-160 Standards, Radar Systems, Communications, TWT Replacement and Particle Accelerators
1 - 2 GHz	1 kW, 2 kW, 4 kW, 8 kW, 10 kW, 12 kW, 18 kW, 20 kW	EMC testing to MIL-STD-464 and DO-160 Standards, Radar Systems, Communications, TWT Replacement and Particle Accelerators
2 - 4 GHz	3 kW, 6 kW, 10 kW, 15 kW	EMC testing to MIL-STD-464 and DO-160 Standards, Radar Systems, Communications, TWT Replacement and Particle Accelerators
1.2 - 1.4 GHz	1 kW, 2 kW, 4 kW, 8 kW	EMC testing to Automotive Standards, Radar Systems, Communications, TWT Replacements and Particle Accelerators
2.7 - 3.1 GHz	1 kW, 2 kW, 4 kW, 8 kW	EMC testing to Automotive Standards, Radar Systems, Communications, TWT Replacements and Particle Accelerators

2.1 Example Applications

As previously described, the SP series amplifiers have been designed for a number of different applications. Pairing AR's solid-state pulsed amps and high-gain antennas can provide you with a wide range of field strengths. AR's PSP series of wideband USB pulse power sensors is a product of choice to precisely measure the pulse shape, characteristics, and peak amplitude produced by the amplifier and delivered to the antenna. The PSP series also allows you to verify other modulations' cleanliness as required by various EMC standards. The following table gives an example of field strength levels and some corresponding applications when using an AR ATH800M6G high-gain horn antenna. This table assumes reasonable losses.

Frequency Range	Power Level Offering	Field Strength	Antenna Distance	EMC Application
1 - 2 GHz	1 kW	650 V/m	1 meter	DO-160G (Cat B, Cat D), MIL-STD-464C (Table 1, 3)
	4 kW	1100 V/m	1 meter	DO-160G (Cat F)
	12 kW	2200 V/m	1 meter	DO-160G (Cat G), MIL-STD-464C (Table 2)
	18 kW	2500 V/m	1 meter	MIL-STD-464C (Table 4)
2 - 4 GHz	3 kW	1500 V/m	1 meter	DO-160G (Cat B, Cat D, Cat F), MIL-STD-464C (Table 3)
	6 kW	2000 V/m	1 meter	DO-160G (Cat F)
	15 kW	>3000 V/m	1 meter	DO-160G (Cat G), MIL-STD-464C (Table 1)
1.2 - 1.4 GHz	1 kW	600 V/m	1 meter	Automotive L-Band Radar Pulse Testing at 1 m
	4 kW	600 V/m	2 meter	Automotive L-Band Radar Pulse Testing at 2 m
2.7 - 3.1 GHz	1 kW	1000 V/m	1 meter	Automotive S-Band Radar Pulse Testing at 1 m
	2 kW	700 V/m	2 meter	Automotive S-Band Radar Pulse Testing at 2 m

3.0 SP-Series Amplifier Performance Verification and Monitoring Using PSP-Series Pulse Power Sensors

In some cases, SP-series amplifiers can be used in mission critical applications where disruption or degradation of performance can have significant consequences. As a result, users may want to perform incoming inspection or performance verification and/or on-going performance monitoring. This section provides an overview of how to use the PSP-series Pulse Power Sensors for this purpose.

To illustrate the process for performing incoming inspection or performance verification and/or on-going performance monitoring, the AR 1000SP1G2 amplifier will be used as an example device-under-test. The Model 1000SP1G2 is a self-contained, forced air cooled, broadband solid-state microwave amplifier designed for pulse applications at low to moderate duty factors where instantaneous bandwidth and high gain are required. With an input power of 1 mW applied from 1 to 2 GHz, the 1000SP1G2 provides a conservative 1000 watts minimum peak RF pulse power at the amplifier output connector. Additional specifications include:

FLATNESS: ±1.5 dB typical, ±2.5 dB maximum
GAIN (at maximum setting): 60 dB minimum
GAIN ADJUSTMENT (continuous range): 20 dB minimum
INPUT VSWR: 2.0:1 maximum
MISMATCH TOLERANCE: Output pulse width foldback protection at peak reflected power exceeding 500 watts. Will operate without damage or oscillation with any magnitude and phase of source and load impedance.

PULSE CAPABILITY:

Pulse Width	0.07 - 50 microseconds
Pulse Rate (PRF)	50 kHz maximum
Duty Cycle	5% maximum
RF Rise and Fall	50 ns max (10% to 90%)
Delay	600 ns maximum from pulse input to RF 90%
Pulse Width Distortion	±100 ns maximum (50% points of output pulse width compared to 50% points of input pulse width)
Pulse Off Isolation	60 dB minimum
Pulse Input	TTL level, 50 ohm nominal termination

Figure 2 shows the test configuration for incoming inspection or performance verification. For on-going performance monitoring the termination on the right would be replaced with whatever the amplifier will feed in its intended application.
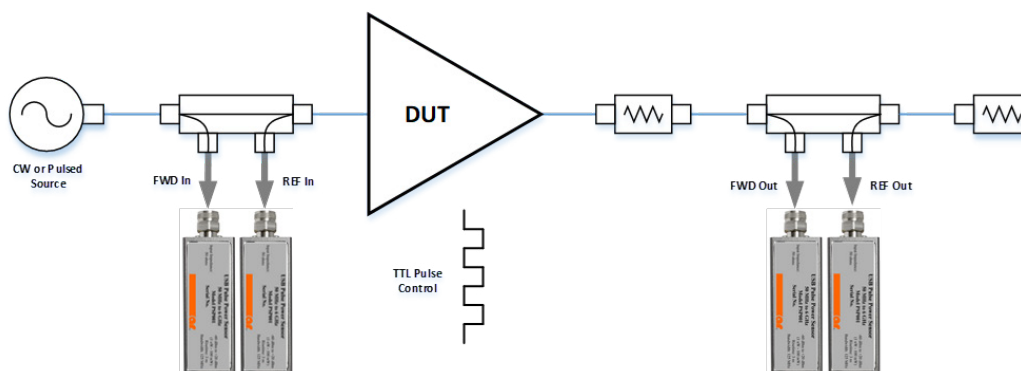

Figure 2: Solid-State Pulse Amplifier Incoming Inspection Setup

The coupling and attenuation values should be such that the input power to the PSP sensors is less than +10 dBm or 10 milliwatts.

The PSP sensors are then connected to a PC via USB cable and are controlled from the AR pulsewARe software, Figure 3. This software allows you to make a myriad of automatic measurements including peak amplitude, pulse width, pulse period, rise and fall time and much more.
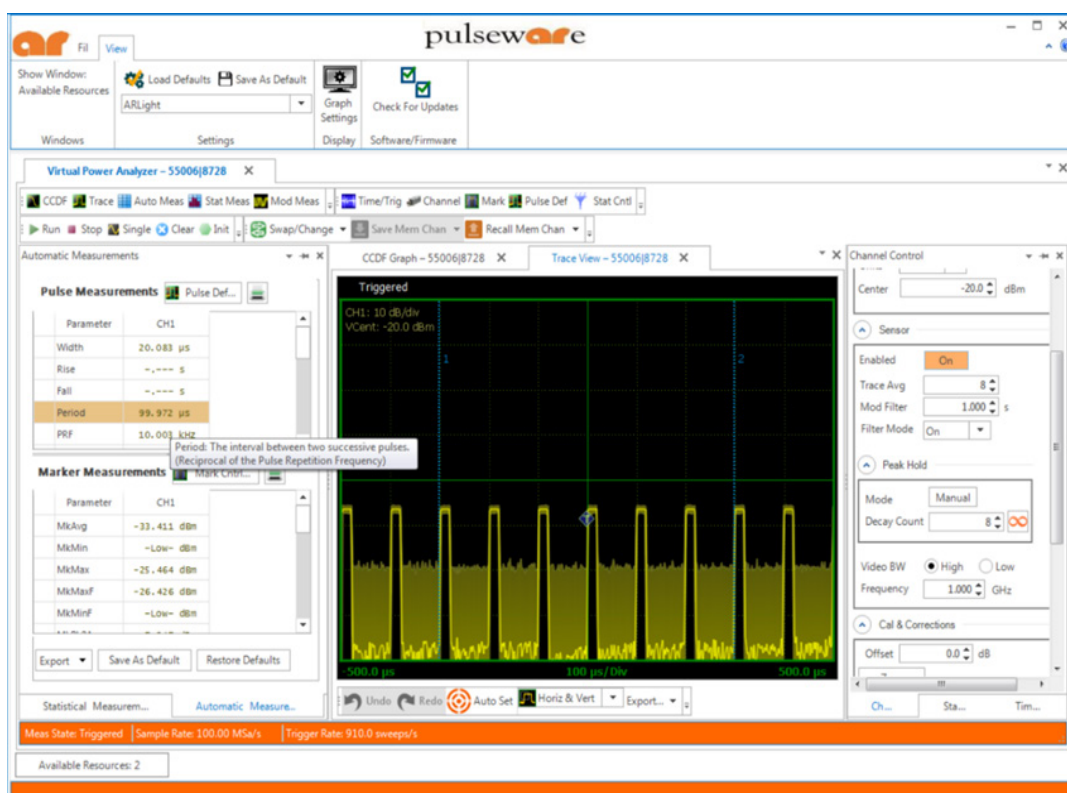

Figure 3: AR pulsewARe User Interface

Conclusion

To date, pulsed high-power RF amplifier performance from 0.8 – 4 GHz has been dominated by low Mean Time Between Failure (MTBF) and low warranty TWTAs, but AR's solid-state pulse amplifier designs offer better performance and reliability, and backed by the AR brand with a 3-year warranty. These amplifiers provide an attractive alternative to TWTA solutions. If you would like to learn more, feel free to contact one of our applications engineers at 800-933-8181 or visit our website at www.arworld.us.

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Application and Use of the 350AH1A Low Frequency Amplifier

Most RF amplifiers have what has come to be known as "standard" 50Ω output impedance. The AR RF/ Microwave Instrumentation model 350AH1A RF amplifier is unique in that its output impedance is typically less than 1Ω. With such low output impedance and a broad frequency range of 10Hz to 1MHz, one might mistakenly assume that the 350AH1A is merely a high-end audio amplifier. This amplifier, however, was not designed to be used in any stereo system. It was specifically designed as a very versatile and rugged bench-top instrument for lab use in R&D applications, product quality testing, magnetic research, and Electromagnetic compatibility (EMC) testing per MIL-STD-461F: CS101, CS109, CS114, RS109, DO160F sections 18 & 19, as well as many automotive EMC standards. The extremely rugged design ensures that the 350AH1A will deliver the required voltage and/or current to any load without fear of amplifier shut-down or failure. This Application Note will explore this unique amplifier's characteristics, cover methods of interconnecting amplifiers for enhanced performance, and discuss some of the applications addressed by this robust, versatile amplifier.

350AH1A Basic Specifications

Frequency Response:	10 Hz - 1 MHz
Output:	14 Amps & 25 Volts, 10 Hz - 300 kHk De-rated at higher frequencies with a gradual sloping down to 5.5 Amps & 10 Volts at 1 MHz.
Input Impedance:	600 Ω typical
Output Impedance:	< Ω typical
Mismatch Tolerance:	100% rated voltage or current available into any load without amplifier shutdown or failure.
Display:	Color with both voltage & current or VA display
Interface:	GPIB, serial RS232, Ethernet, and USB

1.0 Voltage and Current Limiting

The 350AH1A amplifier differs from all other AR amplifiers in that it guarantees a minimum value of voltage and/ or current delivered to the load rather than output power. The load impedance determines whether the output will be voltage or current limited in a manner similar to that of a conventional DC power supply.
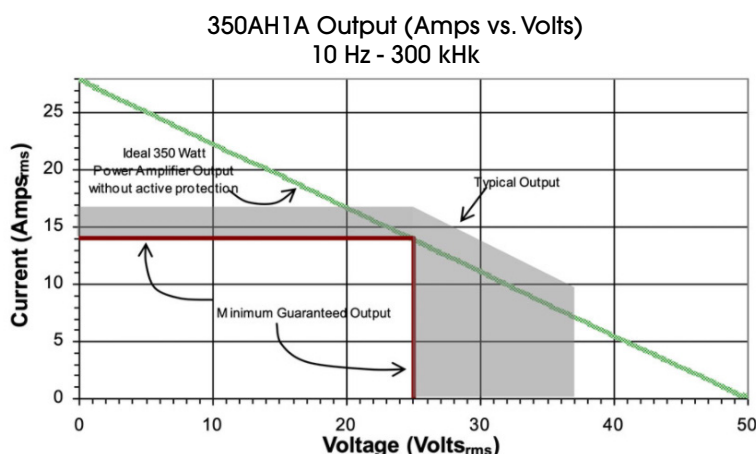

350AH1A Output (Amps vs. Volts)
10 Hz - 300 kHk

Figure 1: Current vs. Voltage

In particular, for a load impedance exceeding 1.8 Ω, the output voltage is limited. Typically one could expect a minimum of 25 volts, but no more than 37 volts. Conversely, an output impedance of less than 1.8Ω results in output current limiting. In this situation, one can expect an output current of at least 14A but no more than 16.5A. Figure 1 clearly shows the minimum guaranteed voltage and current values as well as the typical levels. Note that the "gray" area containing typical voltage and current voltage values assumes minimal transmission loss in the output lead wires.

Output power is generally considered the major criteria when specifying a power amplifier. However, some applications call for either a fixed voltage or current, and in this situation, the power delivered to the load can be determined by applying Ohm's law. The Ohm's law pie chart shown in Fig. 2 shows the various combinations of the four variables, I, V, Ω and W. As shown in Fig. 3, an ideal output impedance of 1.8Ω will deliver a minimum output power of 350 W. Above this impedance, the amplifier will voltage limit, and below this impedance, the amplifier will current limit. More information is available in RF Amplifier Output Voltage, Current, Power, and Impedance Relationship.
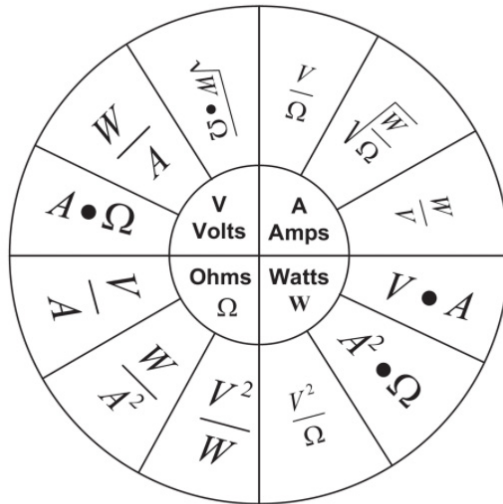

Figure 2: Current vs. Voltage

2.0 Wire Inductance

When operating at frequencies up to about 100 kHz the amplifier's output is very predictable. Unfortunately, as frequency increases, the inductive reluctance of the output cables begin to adversely affect delivered power. While insertion loss from 100 kHz to 300 kHz is noticeable, it is not excessive. However, beyond 300 kHz losses can be significant and one must pay particular attention to output cabling to ensure adequate power is delivered to the load.
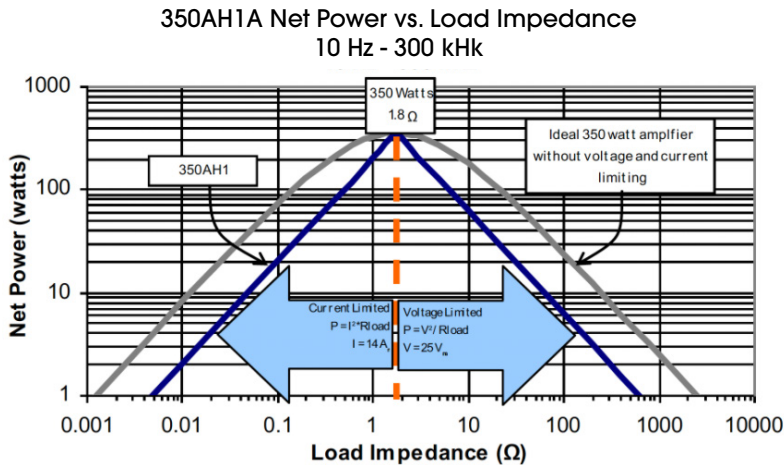

Figure 3: Power vs. Load Impedance

To minimize reactive losses when the load is close to the amplifier, ensure that the wired output is as short as possible and physically large. Bus bars are particularly well suited for this application. By keeping the inductance low, the losses are tolerable. Often the application involves some degree of separation between the amplifier and the load. In this case, matched coaxial cables are recommended to minimize VSWR and maximize delivered power. Since the amplifier's output impedance is approximately 1.8Ω, the matched cable will need to be <2 Ω. Unfortunately, 2 Ω cable is not readily available. However, with a little ingenuity, one can fashion a serviceable low impedance cable from standard cables. For example, a 2 Ω coaxial cable can be formed by combining ten 20 Ω coaxial cables in parallel.

A less attractive method is to use a wide copper strap or thick wire braid. The more surface area the strap has the better. This approach works well at lower frequencies but may be limited at 1MHz.

Standard wire is only viable at the lower frequencies or for short distances. Much of the power will be lost as a result of the inductive reluctance at the higher frequencies.

3.0 Subampability

For applications that require voltage or current levels beyond the capabilities of a single 350AH1A, the outputs from two or more 350AH1A amplifiers can be combined. Depending on the physical configuration, one can double either the voltage or current, quadruple the current, or double both the voltage and the current.

3.1 Examples of the "Subampability" of the 350AH1A:

To double the output current, tie both outputs together in a parallel configuration.
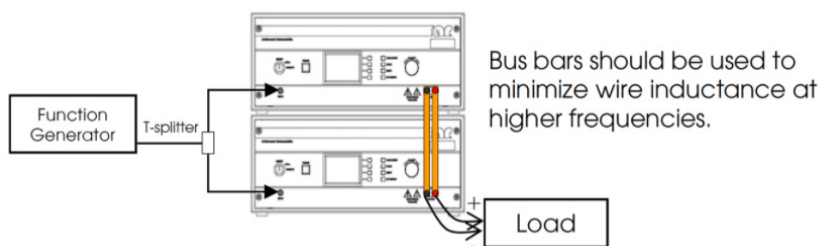

Figure 4: 2x 350AH1A in a Parallel Configuration

If the application requires more voltage than a single 350AH1A can provide, two amplifiers can be combined in a bridged configuration. The second amplifier is set to invert the output signal and the load is placed between the two outputs. The effect is a doubling of the output voltage. This technique is analogous to a residential 220VAC line (commonly used in the United States) where two 110VAC lines 180° out of phase are combined to provide 220VAC.
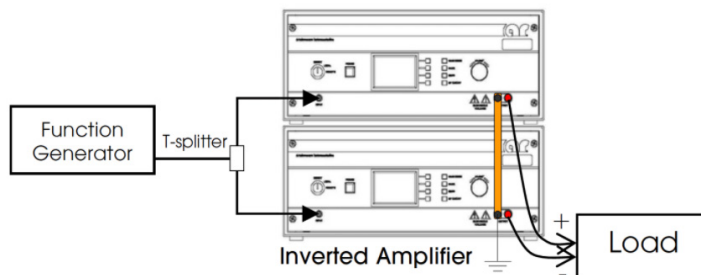
Figure 5: 2x 350AH1A in a Bridged Configuration

By combining four amplifiers, one can quadruple the output current via a parallel configuration or double both the voltage and current via a bridged & parallel configuration.

Note: In parallel configuration 2, 3, 4, 5 ... amplifiers can be combined; it is not limited to just 2 and 4.
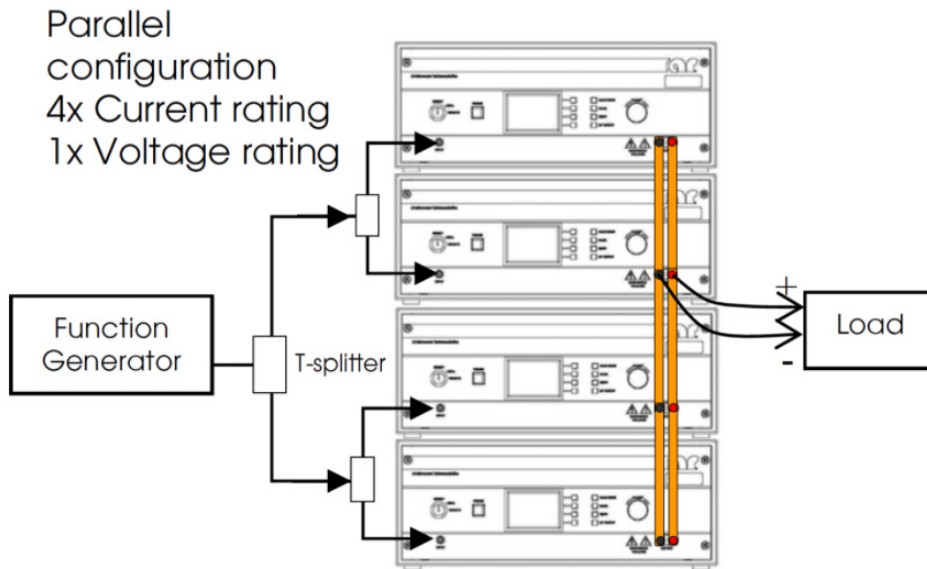

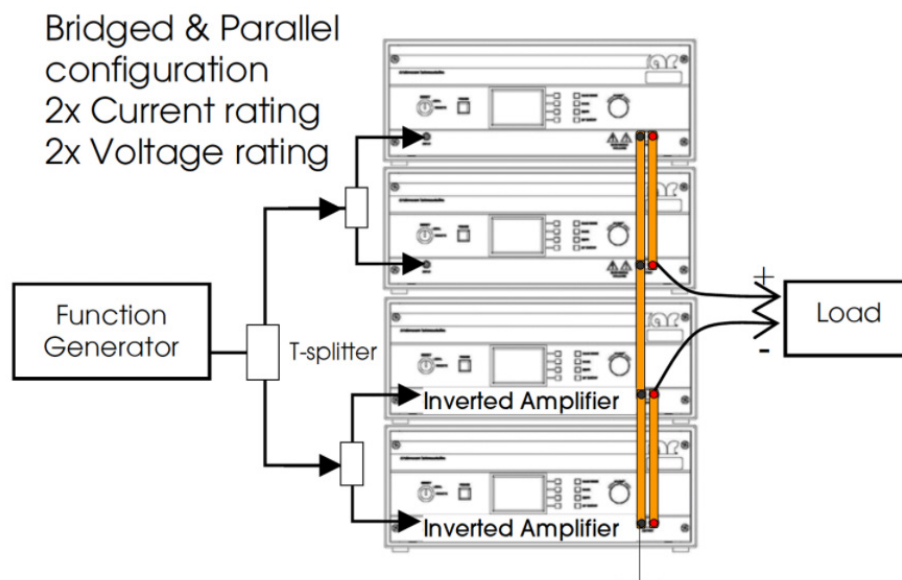Figure 6: 4x 350AH1A in Parallel Configuration

Figure 7: 4x 350AH1A in Bridged & Parallel Configuration

4.0 Expected Output Summary

The parameters listed in the table below are useful when operating at frequencies <300 kHz. At higher frequencies, inductive losses become significant, and as noted in the spec sheet, current and voltage are gradually de-rated from 300 kHz to 1 MHz.

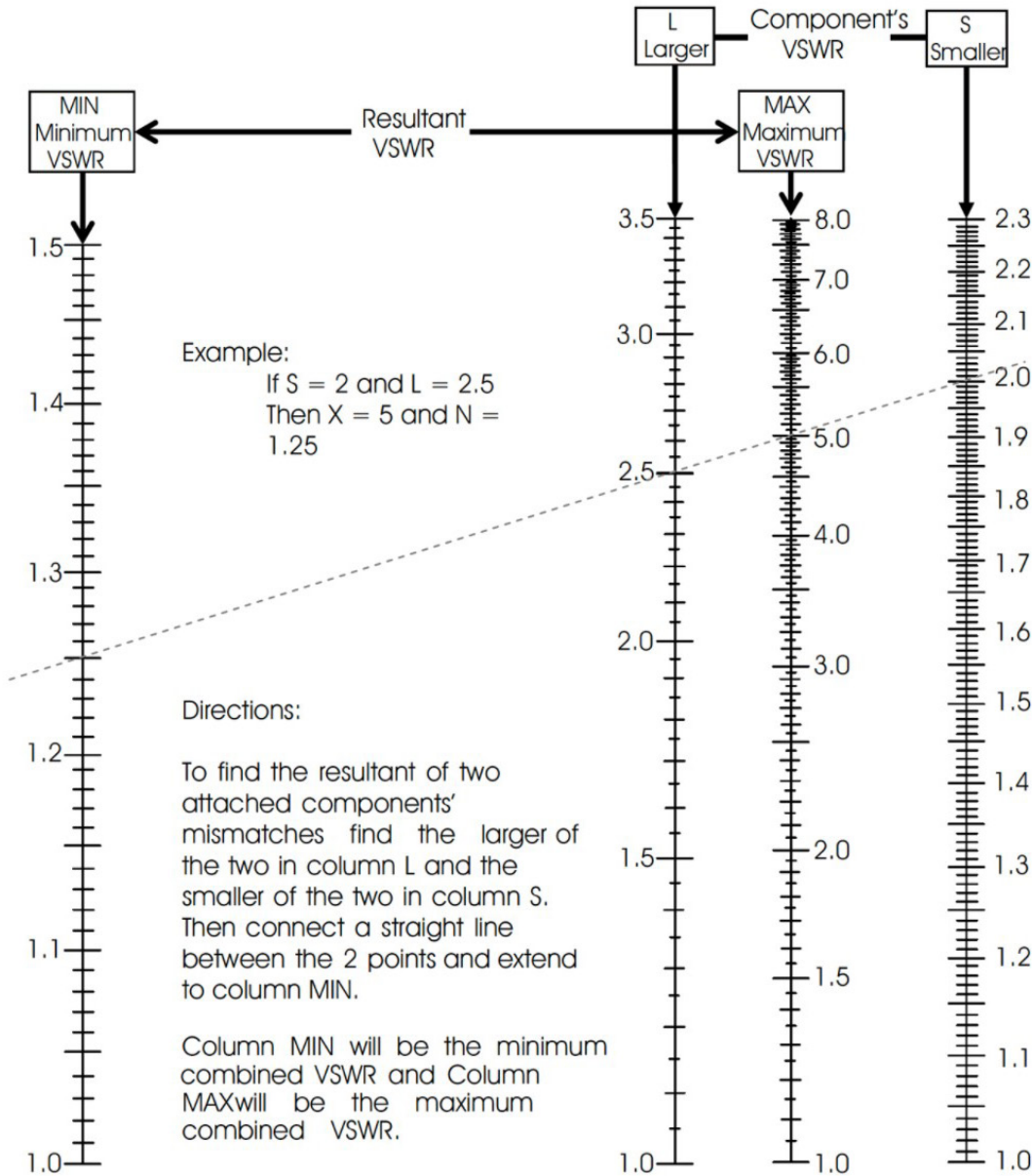|	Voltage	Current	Effective Output Impedance (EOI)	Power at (EOI)*
	Volts	Amps	Ohms V / A = Ω	V * A = VA
A single 350AH1A	25	14	1.8	350
2X 350AH1A in Parallel	25	28	0.89	700
2X 350AH1A Bridged	50	14	3.57	700
4X 350AH1A in Parallel	25	56	0.45	1400
4X 350AH1A Bridged & in Parallel	50	28	1.8	1400

5.0 Applications

Due to the versatility of the 350AH1A's rugged design, it lends itself for use in a myriad of applications. One of the most promising applications is EMC testing. Prior to the introduction of the 350AH1A, there were no instrument amplifiers available for these demanding tests. Test engineers were forced to compromise with audio amplifiers and sacrifice some of the following desirable features: broad frequency response, durable design, full mismatch tolerance into opens and shorts, and voltage and current output display.

- EMC Testing
  - MIL-STD-461D/E/F
  - CS101 - Audio frequency conducted RF (30 Hz - 150 kHk)
  - CS109 - Audio frequency conducted RF on Housing (60 Hz - 100 kHk)
  - CS114 - New requirement in MIL-STD-461F extended testing to 4kHk from 10 kHk. There is a whole new setup just for this new frequency range (see Guide to RF Coaxial Connectors and Cables).
  - RS101 - Magnetic field testing (30 Hz - 100 kHk)
  - DO160D/E/F
  - Section 18 audio frequency conducted RF (10 Hz - 150 kHk)
  - Section 19 magnetic field susceptibility (350 Hz - 32 kHk)
  - Automotive
  - SAE J1113-2 audio frequency conducted RF
  - SAE J1113-22 magnetic field testing
  - ISO 11452-8 audio frequency conducted RF
  - Chrysler
  - PF-9326, PF-10540 section 3.8.2: audio frequency conducted RF (15 Hz - 250 kHk)
  - PF-9326, PF-10540 section 3.8.3: Audio frequency conducted RF (125 Hz – 20 kHz)
  - PF-9326, PF-10540 section 3.8.7: Magnetic field testing (15 Hz – 30 kHz)
  - DC-10614 (RS101) Magnetic field testing (15 Hz – 100 kHz)
  - GM
  - GMW3097 Section 3.4.4 MS (16 2/3 Hz – 180 Hz)
  - GMW3100 Section 3.2.1.2.5 MS (16 2/3 Hz – 180 Hz)
  - Ford
  - RI140 (RS101) Magnetic field testing (50 Hz – 10 kHz)
  - RI150 Radiated Susceptibility (0.6 kHz – 10 kHz)
  - CI210 Audio frequency conducted RF (50 Hz – 10 kHz)
  - CI250 Voltage offset (50 Hz – 1 kHz)
- Magnetic Field Research
- Magnetic Field Disinfecting
- Low Frequency Transient Testing
- AC Voltage or Current Supply

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Component VSWR Resultant Chart

L
Larger

Component's
VSWR

S
Smaller

MIN
Minimum
VSWR

Resultant
VSWR

MAX
Maximum
VSWR

Example:
If S = 2 and L = 2.5
Then X = 5 and N = 1.25

Directions:

To find the resultant of two attached components' mismatches find the larger of the two in column L and the smaller of the two in column S. Then connect a straight line between the 2 points and extend to column MIN.

Column MIN will be the minimum combined VSWR and Column MAX will be the maximum combined VSWR.

$$VSWR_{MAX} = VSWR_L * VSWR_S$$

$$VSWR_{MIN} = \frac{VSWR_L}{VSWR_S}$$

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Importance of Mismatch Tolerance for Amplifiers Used in Susceptibility Testing

RF amplifiers have a nominal output impedance of 50 Ω, and ideally would only be used in applications where the load impedance is also 50 Ω. This ideal situation results in maximum power transfer from the amplifier to the load, where all power is absorbed in the load with no power reflected back to the amplifier. Unfortunately, broadband RF amplifiers are used in "real life" applications that are characterized by load impedances other than 50 Ω. In fact, encountering a pure 50 Ω load is indeed rare. Not only is load mismatch common in most applications, but since load impedance, and to a lesser extent amplifier output impedance, vary with frequency, the extent of mismatch will also vary widely over the test frequency range. Susceptibility testing is just one such application where load mismatch can be extreme. This application note will focus on the oft overlooked issue of mismatch in RF systems, the harmful effects of even a modest amount of mismatch, and finally, how proper selection of the system amplifier can mitigate the ill effects of mismatch. Functioning as a key element in an EMC susceptibility system, the RF amplifier must be capable of dealing with extreme mismatches without compromising performance or reliability.

1.0 Mismatch

The condition whereby the output impedance of the RF source differs from that of the load is said to be a "mismatch." The extent of mismatch can be characterized in terms of Voltage Standing Wave Ratio (VSWR). (See Annex A for VSWR formulas). In its simplest form, VSWR is seen as the ratio of the source output impedance (amplifier output) to the load impedance at a given frequency. For our purposes we will assume a nominal amplifier output impedance of 50 Ω. If the amplifier is driving an ideal load impedance of 50 Ω, the VSWR is 1:1 and there is no mismatch. This ideal condition results in maximum power transfer and zero power reflection. Real life applications are rarely characterized by 50 Ω loads and the resultant VSWR is greater than 1:1. In this typical situation, power is reflected from the load back into the source, or amplifier. The amplifier must be designed to routinely dissipate this reflected power without adversely affecting performance or reliability.

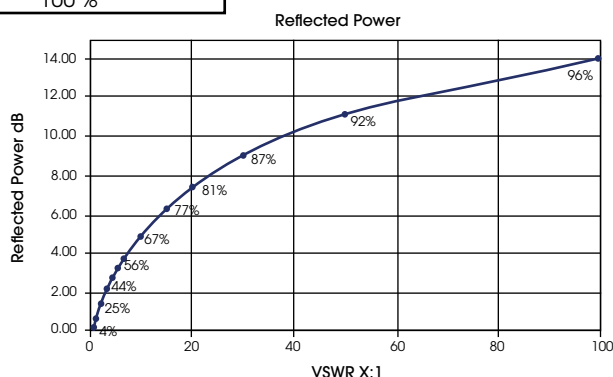| Load VSWR	dB mismatch loss at load	% Power reflected back to source
1:1	0	0%
1.5:1	0.18	4%
2:1	0.51	11%
3:1	1.25	25%
4:1	1.94	36%
5:1	2.55	44%
6:1	3.10	51%
10:1	4.81	67%
∞:1	∞	100 %

Figure 1. Power delivered to the load and reflected back to the source as a function of VSWR

The obvious solution to avoid mismatch issues would be to utilize broad band matching networks to ensure the output impedance of the amplifier is identical to the load. This might be theoretically possible, but in reality the output of the amplifier as well as the load impedance varies as a function of frequency. Furthermore, while we will restrict ourselves to discussing resistive loads in this application note for simplicity, actual loads are complex impedances consisting of resistive and reactive elements. While impedance transformers can be designed for specific impedances and narrow frequency ranges, a universal matching network covering the broad frequency ranges offered by modern amplifiers is virtually impossible to design. Even if it were available, it would most likely introduce an unacceptable level of insertion loss.

2.0 Mismatch in EMC Test Systems

Susceptibility testing covers extreme frequency ranges and uses broadband loads such as Bulk Current Injection (BCI) probes, transmission lines, biconical, log periodic, and horn antennas. While designers strive to hold the impedance of all these RF devices to 50 Ω, it is all but impossible. A perusal of the salient data sheets indicates a typical VSWR range of 1.5:1 for some log periodic antennas to a maximum of 100:1 for a biconical antenna operated at 20 MHz.

Let's look at a typical situation where an amplifier with a 50 Ω output is driving a well-matched antenna with a VSWR of 2:1. It can be seen from the formulas in Annex A that for this VSWR, the load could either be 100 Ω or 25 Ω. From the VSWR equations, 11% of the forward power will be reflected while only 89% will be available for radiation.

To complicate matters, simple devices like cables and connectors contribute to the overall system mismatch since they are not a perfect 50 Ω across the broad frequency range required for susceptibility testing. A short or open, however brief, constitutes an infinite VSWR and 100% of the power is reflected back to the amplifier. It is essential that the RF amplifier be capable of absorbing reflected power from extreme mismatches encountered in normal EMC test applications. The amplifier must not only be capable of providing the necessary power, but it must be rugged and reliable.

3.0 High VSWR Protection

Figure 1 demonstrates the exponential rise in reflected power as a function of VSWR. Even a relatively small system VSWR of 2:1 may be cause for concern. Certainly, more typical values ranging from 2:1 to 10:1 result in sufficient reflected power to cause damage to an amplifier that has not been designed to tolerate this amount of reflected power. Amplifiers that are unable to sink large amounts of reflected power require protection. One approach is to simply attach an attenuator at the output of the amplifier. This technique is described in IEC 61000-4-6 where an optional 6 dB pad is inserted between the amplifier and the load. By doing so, the poor load VSWR is improved and the resulting reflected power is reduced. Not only is there less reflected power, but any reflected power is reduced by 6 dB by the attenuator, further protecting the amplifier. While initially this approach sounds plausible, the downside is that the forward power into the load is also attenuated by 6 dB. (Figure 2) This reduces power delivered by 4X thereby requiring an amplifier with 4X the power to compensate.
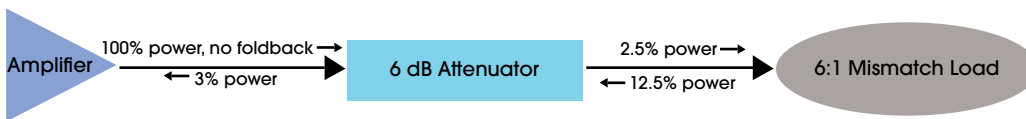

Figure 2. IEC61000-4-6 Solution.

As mentioned previously, many applications will present poorly matched loads resulting in high reflected power. AR has designed rugged amplifiers that can withstand full reflected power without the need for the IEC protection approach. Hence, no power is lost due to the addition of attenuators.

4.0 Class AB Amplifiers

Class AB amplifiers are typically unable to absorb reflected power. One of the following protection techniques must be used to protect the output stages from reflected power:

1. Continuously monitor the internal temperature of the amplifier. When the temperature exceeds a predetermined safe level, immediately shut down the amplifier.

2. Directly monitor the reflected power and when a dangerous threshold is hit, shut down the amplifier.

3. Monitor the reflected power and adjust the gain of the amplifier or reduce the drive level as the reflected power increases. This approach is often called "foldback" and is used to ensure that the reflected power never exceeds the maximum allowable level.
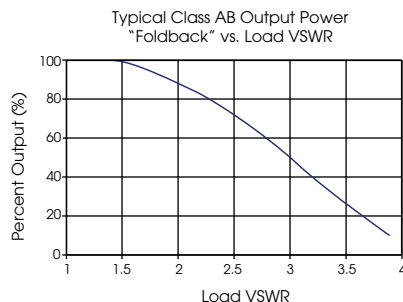

Figure 3. Manufacturer's data for Class AB "foldback"

The first and second approaches are not desirable since they will shut down the test. Each time an inevitable mismatch occurs not only is the test terminated, there is no apparent means to proceed. Since a "real life" load can not be swapped out with one approaching an ideal 50 Ω, and broadband impedance matching is out of the question, the only practical recourse would be to add a 6-dB attenuator as described above. Unfortunately, as noted previously, this "fix" requires that the amplifier be resized to 4X the original power, which is a hefty penalty to pay.

Of the three approaches, the "foldback" scheme is most common. Figure 3 shows a Class AB output power vs. load VSWR curve taken from the manufacturer's published literature. This curve shows an alarming inability of the RF devices to dissipate even a minimal amount of reflected power. The amplifier must implement a "foldback" of the available RF output power, in an effort to protect its output stages. Specifically, the curve clearly shows that a 100 watt amplifier could not sustain even 100 watts into a modest typical antenna VSWR of 2.0:1. It reduces its output power to 89 watts. Thus, with as little as 11% of the output power reflected, the forward power has dropped to 89 watts. Considering a minimal increase in VSWR to a value of 3:1 and with only 25% of the output power reflected back, the Class AB amplifier has cut back its forward power to a meager 50 watts. This is clearly not the kind of performance needed in a susceptibility test system which must maintain prescribed field levels, in spite of VSWR variations.

There are situations where the above protection is unable to react quickly enough, or the reflection is of such a magnitude that complete protection is impossible. In these situations, the amplifier is weakened or damaged. An extreme case occurs when a defective cable or load shorts or opens resulting in an infinite VSWR. As a result, 100% of the forward power is reflected back into the output stages of the amplifier. This occurrence is not as rare as one may think. The simple mistake of not thoroughly checking the integrity of all RF cables and connectors before running a test can cause such a catastrophic result.

For EMC susceptibility testing where transducers can typically present high VSWRs, it can be seen that the size, weight, and efficiency advantages of Class AB amplifiers are inconsequential if they are unable to handle reflected power. Just as important to EMC testing is the ability to maintain power over frequency and load. As a result, AB amplifiers are typically not recommended for EMC and high mismatch applications.

4.1 Class A Amplifiers

In Class A operation, the active devices are biased to ensure that output current flows for 360 degrees of input signal. A properly designed Class A amplifier dissipates maximum power in its quiescent state and must be built to handle a great deal of power dissipation. Contrasted to a Class AB amplifier, the Class A design necessarily requires the use of larger active devices, and quite often, a larger number of devices to share the heat dissipation. Furthermore, additional attention is paid to heat sinking, cooling considerations, and rugged component selection. When rated input signal is applied to an AR designed class A amplifier, the RF devices actually run cooler. Since they are thus operating below their normal operating temperature, power reflections resulting from operating into high levels of VSWR are not a problem, as the devices will still not exceed maximum temperature.

Not all Class A amplifiers are made alike. Some Class A amplifiers are not designed to handle extreme mismatches and may fail instantly or may weaken over time with everyday use. In some cases, Class A amplifiers must institute the same protection features found on a Class AB amplifier. While all Class A amplifiers generally tolerate reflected power better than Class AB amplifiers, some can be damaged by the severe reflected power that occurs when the occasional short or open is encountered while conducting an EMC test. Unfortunately, this is not all that uncommon in busy EMC test facilities, especially when tests are running behind schedule and the pressure is on.

4.2 Summary of Class A/AB Amplifiers

A summary of mismatch performance for typical Class A and AB amplifiers is shown in Figure 4. The 100 watt curve is representative of most amplifiers below 500 watts. An analysis of our 100W1000B shows that the amplifier delivers a Minimum Available Power (MAP) of 100 watts irrespective of the load VSWR, including opens and shorts. As the rated output power of an amplifier increases it becomes increasingly difficult to absorb all of the reflected power uniformly. Hot spots at these elevated power levels can cause damage or at least affect reliability. Consequently, for rated powers >500W, AR has developed techniques that continue to offer mismatch tolerance up to a load VSWR of 6:1. Once this level is reached, the output power is limited to 50% of rated power. For example, a 1000 watt amplifier will provide a MAP of 1000 watts up to a load VSWR of 6:1. At this point approximately 500 watts is reflected. From this point on, as load VSWR increases the output power is gradually reduced until it reaches 500 watts for an infinite load VSWR. Figure 4 clearly shows the advantage of this implementation when compared to the conventional "foldback" scheme used by typical Class AB amplifiers. In practice, the conservative AR VSWR compromise of 6:1 works well, in that load VSWR is often held to this value or better. If it strays beyond, rest assured your AR amplifier has sensed the increase and has implemented sufficient limiting to protect the amplifier from any damage. See Annex B for a detailed case study of how Class A and Class AB amplifiers deal with mismatch.
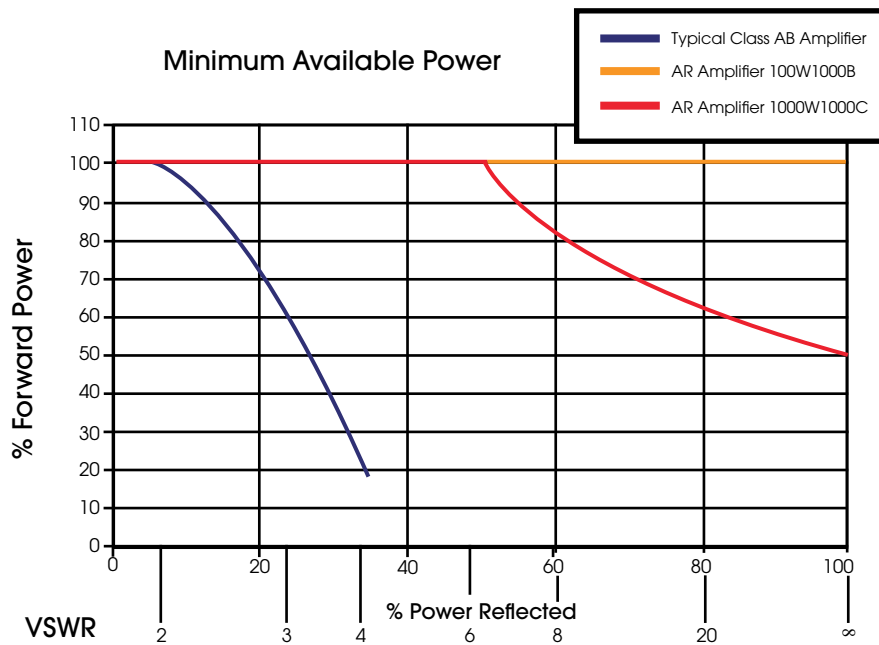

Figure 4. Foldback schemes of AR amplifiers compared to typical Class AB amplifiers

Conclusion

AR has taken a ruggedized approach to the design and implementation of our amplifiers. From the very first amplifier developed, to the extensive line of amplifiers offered today, we have understood the extent of mismatch encountered by our customers and are devoted to delivering the maximum output power into any load, regardless of mismatch, without compromising the integrity of the amplifier. A statement of this commitment is found on our data sheets for amplifiers up to 500W, …" Will operate without damage or oscillation when connected to any load impedance without the aid of foldback circuitry." For amplifiers > 500W, the data sheet statement is… "Will operate without damage or oscillation when connected to any load impedance without the aid of foldback circuitry. However, mismatch above 6.0:1 may limit output".

If you would like to learn more about mismatch tolerance and AR's approach, feel free to contact one of our applications engineers at 800-933-8181 or visit our website at www.arworld.us.

Annex A: VSWR Calculations

vswr = Voltage Standing Wave Ratio, P = Power (watts), Z = Impedance (ohms)

$$vswr = \frac{1+\sqrt{\frac{P_{Rev}}{P_{Fwd}}}}{1-\sqrt{\frac{P_{Rev}}{P_{Fwd}}}}, \quad vswr = \frac{1+p}{1-p}, \quad vswr = \frac{Z_L(for Z_L > Z_O)}{Z_O}, \quad vswr = \frac{Z_O(for Z_O > Z_L)}{Z_L},$$

ρ = Reflection Coefficient

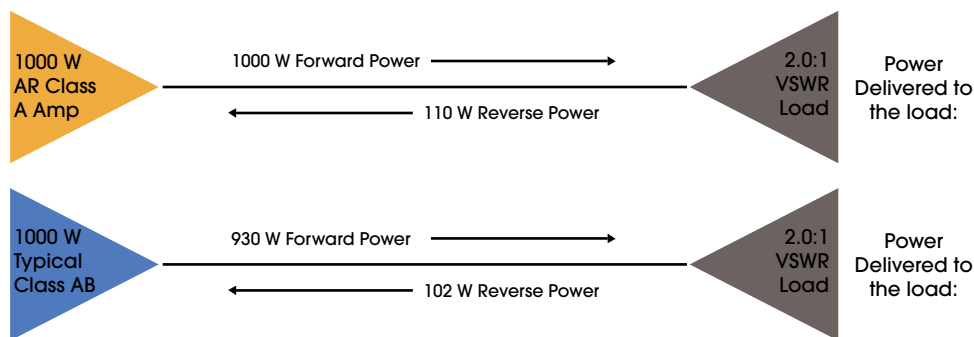$$\rho = \left|\frac{Z_1 - Z_2}{Z_1 + Z_2}\right|, \quad \rho = \sqrt{\frac{P_{Rev}}{P_{Fwd}}}$$

RL (dB) = Return Loss

$$RL\ (dB) = 20\log(\rho), \quad RL\ (dB) = 10\log\left(\frac{P_{Fwr}}{P_{Rev}}\right), \quad RL(dB) = -20\log\left(\frac{vswr - 1}{vswr + 1}\right)$$

ML (dB) = Mismatched Loss

$$ML\ (dB) = 10\log\left(\frac{P_{Fwr}}{P_{Fwr} - P_{Rev}}\right), \quad ML\ (dB) = -10\log(1 - \rho^2), \quad ML(dB) = -10\log\left(1 - \left(\frac{vswr - 1}{vswr + 1}\right)^2\right)$$

Annex B: AR Class 'A' Amplifier vs. Typical Class AB Amplifier Power Absorbed by the Load

In the above example, the Class A amplifier is able to provide full rated output to the load. Since 110 watts is reflected back into the output port, 890 watts is actually dissipated in the load. The Class AB amplifier has already employed foldback protection, therefore limiting its output power to approximately 930 watts. Since 11% of the forward power is reflected back to the amplifier, only 828 watts is dissipated in the load.
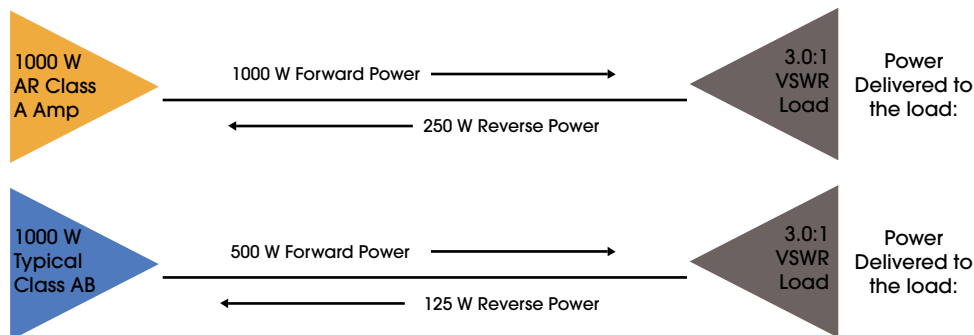
In the above example, the Class A amplifier is able to provide full rated output to the load. Since 250 watts is reflected back into the output port, 750 watts is actually dissipated in the load.
The Class AB amplifier has already employed foldback protection, therefore limiting its output power to approximately 500 watts. Since 25% of the forward power is reflected back to the amplifier, only 375 watts is dissipated in the load.

Annex B: AR Class 'A' Amplifier vs. Typical Class AB Amplifier Power Absorbed by the Load

| 1000 W AR Class A Amp | 1000 W Forward Power → | 6.0:1 VSWR Load | Power Delivered to the load: |
| | ← 500 W Reverse Power | | |

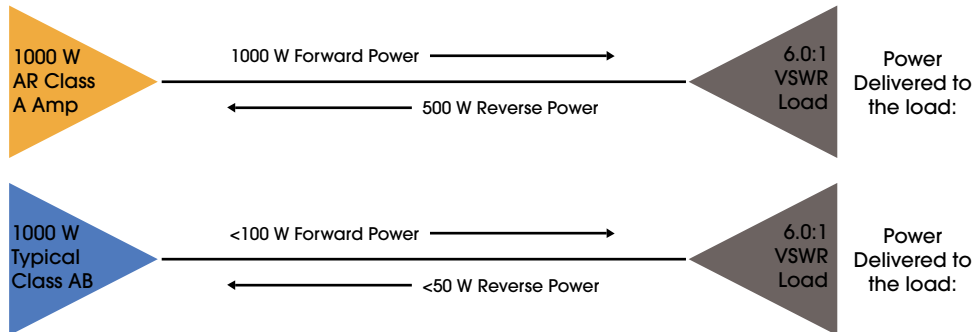| 1000 W Typical Class AB | <100 W Forward Power → | 6.0:1 VSWR Load | Power Delivered to the load: |
| | ← <50 W Reverse Power | | |

In the example on the following page, the Class A amplifier is able to provide full rated output to the load. Since 500 watts is reflected back into the output port, 500 watts is actually dissipated in the load. The Class AB amplifier must employ even more foldback protection thus limiting its output power to less than 100 watts. Since 50% of the forward power is reflected back to the amplifier, less than 50 watts is dissipated in the load.

*Also representative of less capable Class A amplifiers.

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rf/microwave instrumentation

Pulse Traveling Wave Tube Amplifiers

AR RF/Microwave Instrumentation's pulse traveling wave tube amplifiers (TWTAs) offer a cost-effective high RF power source for applications. Only a low to moderate RF duty cycle is required, i.e., where the RF power is on for only a small percentage of the time. A typical application is electromagnetic compatibility (EMC) RF pulse susceptibility testing. This Application Note discusses the unique specifications and characteristics applicable to pulse TWTAs.

Pulse-rated TWTAs use a traveling wave tube (TWT) incorporating a control grid that can turn on and off the TWT's beam current. The TWT acts as an RF amplifier only when the beam is turned on. Turning the beam off when no RF output is needed results in a significant reduction in power consumption and reduces the amount of heat to be dissipated.

When compared to a continuous wave (CW)-rated amplifier with similar power specifications, a low to moderate duty cycle PULSE TWTA typically: uses less AC input power, produces less heat, is smaller and lighter, costs less, has lower noise power output during the pulse off time, and allows the use of peripheral components (connectors, cables or waveguide, directional couplers, loads, and so forth) with lower CW power ratings. AR's pulse TWTAs are explicitly designed for pulsed applications. They cannot be used to produce CW output. AR's TP series of pulse TWTAs incorporates many of the excellent features of AR's T series of CW TWTAs such as foldback protection, bright 4 line by 20 character alphanumeric display, and extensive remote status and control via a GPIB (IEEE- 488) interface. For CW applications, contact AR RF/Microwave Instrumentation for information on its extensive CW-rated amplifiers line.

1.0 Unique Specification for Pulse TWTAs

PULSE CAPABILITY	
Pulse Width	0.07-30 microseconds
Pulse Rate (PRF)	100 kHk maximum
Duty Cycle	4% maximum
RF Rise and Fall	30nx minimum (10% to 90%)
Delay	300ns maximum from pulse input to RF 90%
Pulse Width Distortion	± 30ns max (50% point of output pulse width compared to 50% points of input pulse width)
Pulse Off Isolation	80 dB minimum, 90 dB typical
NOISE POWER DENSITY	(Pulse on) xxxx
	(Pulse off) Minus 140dBm/Hz (typical)
CONNECTORS	
Pulse Input	Type BNC female on rear panel

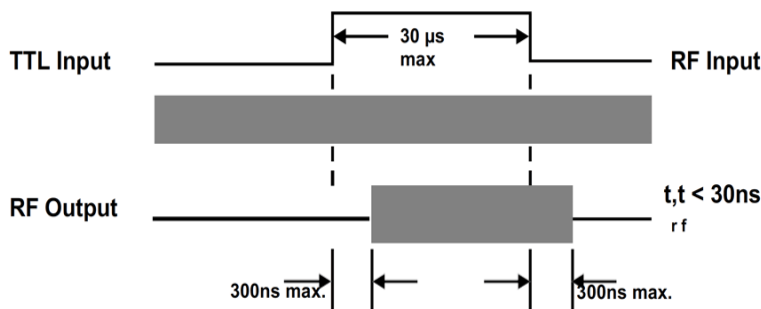## 2.0 Delay, RF Rise and Fall time and the Pulse Input

Figure 1: CW RF Input

After this initial delay in enabling the RF output, the RF output level will respond to the level of the RF input. As with a CW amplifier, the subsequent RF rise and fall times are inversely related to the RF bandwidth of the specific TWTA, with typical rise and fall times in the low- or sub-nanosecond range.

If the RF input remains and the TTL level goes low (logical 0), then the RF output would reach 10% of its prior "on" value within 300ns (Delay). The observed RF Fall time would be less than 30ns (10 to 90%). (See Figure 1.) Using the TTL input to modulate the RF output may result in some small distortion of the output pulse width (usually shrinkage), as compared to the TTL-level input pulse width, and therefore is not recommended for producing pulses lasting less than 0.2 microseconds, or for applications where the pulse width must be accurately preserved. Alternately, the RF input can be turned off prior to the end of the TTL pulse to obtain a fast and well-defined RF fall time.

To obtain well-defined RF timing while minimizing power consumption, the RF and TTL-level inputs should be timed as shown in Figure 2:
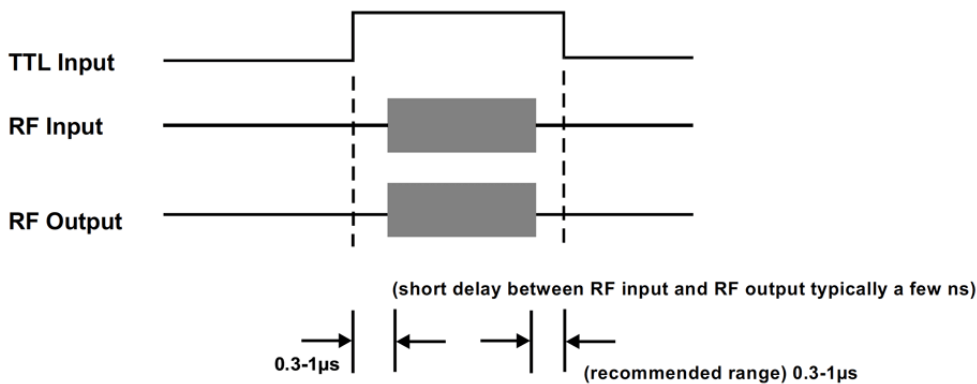

Figure 2: RF Input

3.0 Pulse Width

The Pulse Width specification (0.07-30 microseconds) defines the range of acceptable pulse widths that must be presented at the TTL input to operate the TWTA. The maximum value (30 microseconds) describes the greatest RF pulse width available from the TWTA. RF output pulse widths less than 0.2 microseconds can best be produced by providing a correspondingly short RF pulse at the RF input, with timing as shown in Figure 2.

The Pulse Width Distortion specification further defines the maximum pulse width distortion at the 50% points of the output pulse width compared to 50% points of the input pulse width when using the pulse input. Lower distortion can be obtained with timing as shown in Figure 2.

4.0 Pulse Rate

The Pulse Rate (PRF) specification (100 kHz max.) defines the rate of the maximum continuous pulse stream that may be fed to the TTL-level input. In other words, each succeeding TTL-level input pulse (of a continuous stream of pulses) must begin no sooner than 100 microseconds (1/10,000 sec.) following the beginning of the previous pulse. There is no minimum rate specification. Users should contact AR RF/Microwave Instrumentation regarding any specific requirements they may have for non-continuous pulse-stream applications with higher burst rates.

5.0 Duty Cycle

The Duty Cycle specification (4% max.) is an additional limitation on the TTL-level input that must be observed by the user. This specification defines the maximum percentage of the time that the TTL-level input can be allowed to remain positive (logical 1). For example, if the chosen PRF is 5 kHz, then the maximum allowable TTL input pulse width is reduced to 8 microseconds (1/5,000 x .04 sec.).

6.0 Pulse Off Isolation

Pulse off isolation specifies the reduction of signal level, input to output, when the Pulse Input is not high (i.e. in the pulse-off condition), causing the beam to be off.

7.0 Noise Power Density

Noise Power Density describes the noise level at the TWTA's output. TWTs typically produce considerable broadband RF noise when they are operating (TTL high). When the TTL-level input is not high, (i.e. in the pulse-off condition) the TWT noise is significantly reduced. A typical Noise Power Density level is thus indicated.

8.0 Foward and Reflected Peak Power

AR RF/Microwave Instrumentation Pulse TWTAs feature a display for peak RF power output to supplement the usual display for average RF power output. This display is developed from a measurement of the peak RF and is especially convenient for setting the peak power level when using a varying duty cycle.
This feature operates when the pulse width is greater than 1 microsecond and the RF input is present before the start of the TTL pulse.

Peak power measurements using laboratory power meters are typically accomplished by measuring the average power and then calculating the peak power using the known duty cycle:

Peak Power = Average Power ÷ Duty Cycle.

For accurate indirect measurements of peak power, it may be desirable to measure the actual RF output pulse width to determine the duty cycle.

Summary

This Application Note has discussed some features of AR RF/Microwave Instrumentation's Pulse high power TWTAs and their unique specifications, those not commonly specified for CW rated amplifiers. A number of conditions have been defined which must be observed to obtain proper operation of these Pulse TWTAs (though TWTA design prevents damage when these conditions are exceeded). Be sure to refer to the appropriate AR Data Sheet for detailed amplifier specifications.

Users should contact AR RF/Microwave Instrumentation at 215-723-8181 to discuss any specific application requirements for high burst rates, low off-level noise and special off-level timing (such as in NMR spectroscopy applications), Peak Power measurement of narrow pulses or other characteristics.

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RF Amplifier Output Voltage, Current, Power, and Impedance Relationship

How much output voltage, current and power can RF amplifiers provide? This question is often asked by novice test engineers as well as seasoned RF professionals. Depending on the application, there is often an underlying desire to maximize one of the three parameters; power, voltage or current.

While one would think that a simple application of Ohm's law is called for, this would only apply given ideal conditions, such as when an RF amplifier with a typical 50 Ω output resistance is driving a 50 Ω load. In this rare case where the load impedance perfectly matches the amplifier output impedance, the power delivered to the load is simply the rated power of the amplifier. There is absolutely no reflected power and thus, there is no need to limit or control the gain of the amplifier to protect it from excessive reflected power.

Unfortunately, such ideal conditions rarely apply in actual "real world" applications. Real amplifiers are required to drive varying load impedances. The mismatch between these "real" loads and the amplifier's output impedance result in a percentage of the forward power being reflected back to the amplifier. In some cases, excessive reflected power can damage an amplifier and precautions that may affect forward power are required. Given these realities, how does one go about determining output voltage, current and power? Again Ohm's law comes to the rescue, but with the caveat that the actual power delivered to the load (net forward power after the application of any VSWR protection less reflected power) must be determined before applying Ohm's law.

This Application note will highlight some of the major RF amplifier characteristics that impact forward power, as well as net power allowing the use of Ohm's law, even when conditions are far from ideal.

1.0 Back to Basics: Ohm's Law

Ohm's law states that the amount of current flowing between two points in an electrical circuit is directly proportional to the voltage impressed across the two points and inversely proportion to the resistance between the points. Thus, the equation I=E/R is the basic form of Ohm's law where the current I is in units of amperes (A), the Electro-motive Force (EMF) or difference of electrical potential E is in volts (V), and R is the circuit resistance given in ohms (Ω). Applying the standard equation relating electrical power to voltage and current (P=V•A), cross multiplying and rearranging each of the variables results in the equations shown in the Ohm's law pie chart (see Fig 1) showing the various combinations of the four variables, I, V, Ω and W. Let's use Ohm's pie chart to determine the output voltage, current, and power of a 50 Ω amplifier operating under ideal conditions.
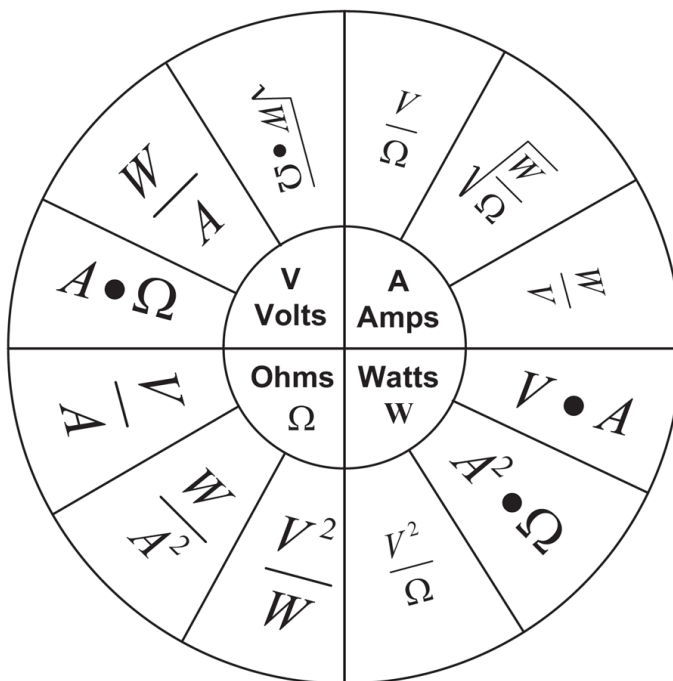

Figure 1: Ohm's Law pie chart

Assume we have a 100 watt amplifier with 50 Ω output impedance driving a 50 Ω load. This is an ideal situation in that 100% of the forward power will be absorbed in the load and therefore there is no reflected power in this example.

- The full 100 Watts will be delivered to the 50 Ω load

- Selecting appropriate formulas from the Ohm's pie chart, one can easily characterize this ideal amplifier.

$$Volts = \sqrt{Watts * \Omega}$$

Substituting known values:

$$Volts = \sqrt{100\,W * 50\Omega} = 70.7\,V_{rms}$$

Thus, the output voltage across the 50 Ω load is 70.7 Vrms

$$Amps = \sqrt{\frac{Watts}{\Omega}}$$

Substituting known values:

$$Amps = \sqrt{\frac{100\,W}{50\,Omega}} = 1.41\,A_{rms}$$

The output load current is 1.41 Arms

As can be seen from the above example, when impedances match, power, voltage, and current are easily determined by the application of Ohm's law. Now let's consider "real life" amplifiers and the effects they have on the determination of output voltage, current and power.

2.0 Impedance Mismatch: The danger of impedance mismatch and methods used to protect amplifiers

Maximum power is transferred to the load only when the load impedance matches the amplifier's output impedance. Unfortunately, this is rarely the case. In these "typical" situations, reflections occur at the load and the difference between the forward power and that delivered to the load is reflected back to the amplifier. A voltage standing wave is created by the phase addition and subtraction of the incident and reflected voltage waveforms. Power amplifiers must either be capable of absorbing this reflected power or they must employ some form of protection to prevent damage to the amplifier.

For example, an open or short circuit placed on the 100 watt power amplifier discussed above would result in an infinite voltage standing wave ratio (VSWR).

Since $VSWR = \dfrac{Z_0}{Z_L}$ for $Z_L > Z_O$ and $= \dfrac{Z_L}{Z_0}$ for $Z_L > Z_0$ it can be seen that $VSWR$ is always ≥ 1.

With no active VSWR protection, an open circuit at the load would result in a doubling of the output voltage to 141.4Vrms, while a short circuit would increase the output current to 2.82Arms. In either of these worst case scenarios, the 100 watt power amplifier must tolerate a maximum power of 200 watts (100 watts forward + 100 watts reverse).

Clearly this is cause for concern and amplifier designers must deal with the very real possibility that the amplifier's output might either be accidentally shorted or the load could be removed. Consequently, all amplifiers should employ some form of protection when VSWR approaches dangerous levels. The following is a partial list (most desirable to least desirable) of some methods used:

- Overdesign:
  - All Solid-state devices and power combiners are conservatively designed to provide sufficient ruggedness and heat dissipation to accommodate infinite VSWR.
  - No additional active VSWR protection circuitry is required with this approach.
  - This conservative approach is found on AR's low to mid power amplifiers.

- Active monitoring of VSWR resulting in a reduction in amplifier gain when VSWR approaches dangerous levels:
  - When VSWR exceeds a safe level the forward power is reduced. This technique is sometimes referred to as "gain fold-back" or just "foldback".
  - AR's high power solid-state amplifiers will fold-back when reflected power reaches 50% of the rated power corresponding to a VSWR of 6:1and will withstand any amount of mismatch.

- Active monitoring of VSWR leading to a shut down when VSWR exceeds a safe level
  - This is considered a brute-force technique that can lead to undesirable test disruptions.
  - AR does not use this technique in any of its amplifiers.

- Active thermal monitoring
  - High VSWR will cause a buildup of heat. When a predetermined temperature threshold is exceeded, the amplifier is shut down.
  - Due to the nature of thermal time constants, this approach is relatively slow. Extreme variations in VSWR may not immediately result in shut down.
  - AR amplifiers employ some degree of thermal monitoring for circuit protection but do not rely on this relatively slow method to protect against extreme VSWR.

- Active monitoring of both output voltage and/or current
  - Limits are set for both voltage and/or current similar to restrictions placed on DC power supplies.
  - If either of the two parameters is exceeded, the amplifier is shut down.

Many amplifiers are designed with little or no concern regarding load mismatch. It is assumed that the application involves a load that matches that of the amplifier. In applications like electromagnetic compatibility (EMC) immunity testing where impedance mismatch is the norm, care must be taken in selecting an amplifier that can tolerate any mismatch while still delivering the required power.

AR solid-state amplifiers have been designed to tolerate extreme load mismatch. They are exceptionally rugged and provide superior protection while delivering maximum output power to any load. Impedance mismatch is discussed in further detail in "Importance of Mismatch Tolerance for Amplifiers Used in Susceptibility Testing".

3.0 What will be the effect of VSWR protection on forward power, or power available to the load?

Let's first look at the various methods used to protect AR amplifiers from the ill effects of extreme VSWR.

- Class A amplifiers designed to tolerate infinite VSWR: This type of amplifier will not fold-back or shut off when operating into a high VSWR. (Most AR low to medium power amplifiers fit in this category.)
  - With these amplifiers, the forward power is always the rated power, and is independent of load
  - Example: A 100 watt amplifier will provide 100 watts forward power irrespective of load variations

- Fold-back based on reflected power: This technique is used for high power AR amplifiers where the reflected power is not allowed to exceed 50% of the rated power.
  - These larger amplifiers provide full rated power to the load for any VSWR up to 6:1. As VSWR increases beyond this level, fold-back is used to limit the reflected power to no more than 50% of the rated power, regardless of load variations.
  - In this case, available forward power is equal to the rated power until a VSWR of 6:1 is reached. At this point, 50% of the forward power is reflected. For any VSWR greater than 6:1, the forward power is reduced sufficiently to insure that the reverse power never exceeds 50% of the rated power.
  - Example: A 1000 watt amplifier will limit forward power to 50% of the rated power for any load mismatch greater than 6:1. Thus, since 500 watts is the maximum amount of reflected power, the forward power is 1000 watts for VSWR ≤ 6:1 and somewhere between 1000 and 500 watts for VSWR ≥ 6:1.

- Voltage and current limited
  - For a Voltage/Current limited amplifier, calculations are much simpler. Ohm's law can be directly applied to find net power, voltage, and load current.

    The amplifier output impedance is:

    $$Zo = \frac{Volts_{\text{min rating}}}{Amps_{\text{min rating}}}$$

  - For load impedance higher than the amplifier output impedance the amplifier is protected by the voltage limit. Regardless of the load impedance the output voltage is clamped near the specified minimum voltage rating.

    Applying ohm's law:

    $$Watts_{net} = \frac{Volts_{\text{min rating}}^2}{\Omega_{load}}$$

    and

    $$Amps = \frac{Volts_{\text{min rating}}}{\Omega_{load}}$$

  - For load impedances lower than the amplifier output impedance the amplifier is protected by the current limit. Regardless of how small the load is, the output current will not exceed a value near the specified minimum current rating.

    Again applying ohm's law:

    $$Watts_{net} = Amps_{\text{min rating}}^2 \bullet \Omega_{load}$$

    and

    $$Volts = Amps_{\text{min rating}} \bullet \Omega_{load}$$

The following comments apply to amplifiers that don't use one of the AR style VSWR protection methods listed above:

- Amplifiers that protect by shutting down or turning off the RF output:
  - Forward power will be 0 if VSWR is excessive. This may occur at a VSWR as low as 2:1, but more often occurs for a VSWR somewhere between 2:1 and 3:1.

Clearly, amplifiers that either don't employ VSWR protection or use this brute force VSWR scheme cannot be used in applications where load mismatches are expected. Amplifiers that employ fold-back schemes at even lower VSWR levels than noted above are also in this category and are unsuitable for applications characterized by high load VSWR such as EMC immunity testing and research applications where load impedance is unknown.

4.0 Output power loss due to load mismatch

We have concentrated on the topic of forward power up to this point. This is the power actually available at the load. Jacobi's Law, also known as the "maximum power theorem" states that "Maximum power is transferred when the internal resistance of the source equals the resistance of the load, when the external resistance can be varied, and the internal resistance is constant." This effect is clearly observed when load impedance differs (greater or less) from the amplifier's output impedance. As VSWR increases, an ever greater portion of the forward power is reflected back to the amplifier. Since net power is calculated by subtracting the reflected power from the forward power, it is apparent that any VSWR other than 1:1 will reduce the actual power absorbed by the load.

The amount of power delivered to the load can be calculated using the following standard RF formulas:

Reflection Coefficient:

$$r = \left| \frac{Z_2 - Z_1}{Z_2 + Z_1} \right|$$

where the two impedances are the load impedance and the output impedance of the amplifier.

Once the forward power has been determined and the reflection coefficient calculated, the net power delivered to the load is found by merely substituting values into the following equation:

$$Watts_{Net} = 10^{\left(\frac{10 \bullet Log(1-r^2) = 10 \bullet Log(Watts_{FWD})}{10} \right)}$$

Furthermore, given the net power and load impedance one can then calculate the output current and voltage using Ohms law.

5.0 Real Examples

Now that we have investigated the nuances involved in determining output power, voltage and current of RF power amplifiers in general, let's look at four existing AR amplifiers and how they deal with load mismatch.

Example 1: Most low and medium power amplifiers are of the Class A design and have nominal 50 Ω output impedance. A typical amplifier of this type is the 75A400 power amplifier:

- 10 kHz – 400 MHz bandwidth
- 75 Watts minimum RF output
- No active protection is required given its very robust, conservative design
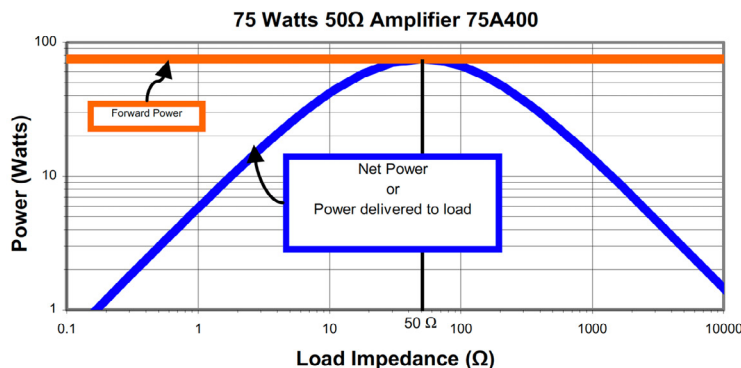- Full forward power is provided into any load impedance

Figure 2: Power vs. Load Impedance 754A400

Figure 2 clearly demonstrates the best possible scenario provided by the 75A400. The forward power is constant at 75 watts irrespective of load impedance. The center point of the graph demonstrates maximum power transfer per Jacobi's Law where the 50 Ω amplifier is driving a 50 Ω load and the blue output power curve clearly demonstrates the reduction in net power per the maximum power theorem as the load varies from the ideal of 50 Ω. Note that even though 75 watts is available independent of the load impedance (orange curve), there is only one point where the power delivered to the load is equal to the forward power; the point where the load impedance matches the amplifiers output impedance. The fall-off of the power delivered to the load on either side of the 50 Ω load impedance is the result of load VSWR causing an ever increasing portion of the forward power to be reflected back to the amplifier. Recall that
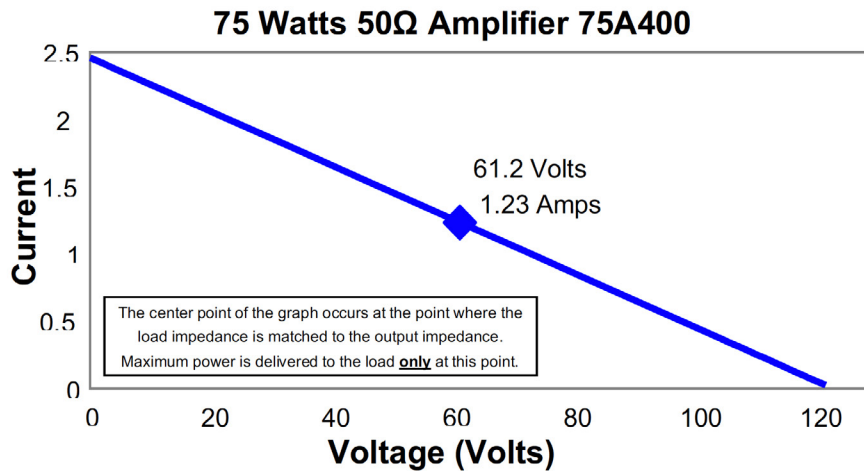
$$P_{net} = P_{fwd} - P_{ref}$$

Figure 3: Current vs. Voltage 75A400

Figure 3 plots the voltage and current over the entire range of load impedance. The center point represents the voltage and current produced when the load impedance matches the amplifiers 50 Ω output impedance. Loads greater than 50 Ω are plotted to the right of the center point and loads less than 50 Ω appear to the left. The end points demonstrate the two possibilities of a worst case mismatch; an open where the output voltage is at a maximum with zero current, and a short where the current is maximum with zero voltage.

The above graphs are based on the minimum rated output of the amplifier across its entire operating frequency range. There most likely will be spots within the frequency range where the output power will exceed the specified minimum rated output power. To avoid unexpected results, always request a copy of specific production test data before placing an amplifier in service.

Example 2: High Power Solid-State amplifiers by necessity employ active VSWR protection. Take, for example the 1000W1000D.

- 80MHz – 1000MHz bandwidth

- 1000 watts minimum RF output delivered into a 50 Ω output impedance

- Active protection kicks in to reduce the gain when reverse power is measured at 500 watts; this is a VSWR of 6:1 when using the amplifier at rated power.

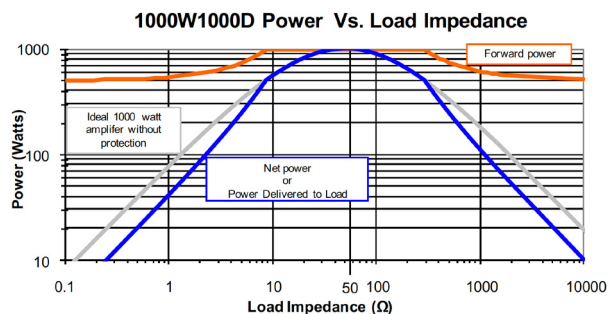- This fold-back protection limits the reflected power to 500 watts maximum

Figure 4: Power vs. Load Impedance 1000W1000D

The 1000W1000D is an example of one of AR's high power amplifiers that folds-back when reverse power reaches 50% of rated power. Even though the amplifier does foldback, a considerable amount of power is still being delivered to the load. In many cases, other manufacturers of high power amplifiers would not be able to handle such conditions and forward power would either be shut-down completely or reduced drastically.

In power critical applications, an impedance matching transformer similar to the one used in the AR 800A3A could be used to match the amplifier to the load. However, since matching transformers tend to be narrow band, this approach may prove impractical if the 1000W1000D were to be operated over its entire frequency band. In this case, a series of narrow-band transformers could be switched into the application as the frequency dictated or simpler yet, the user could opt for a higher power amplifier.
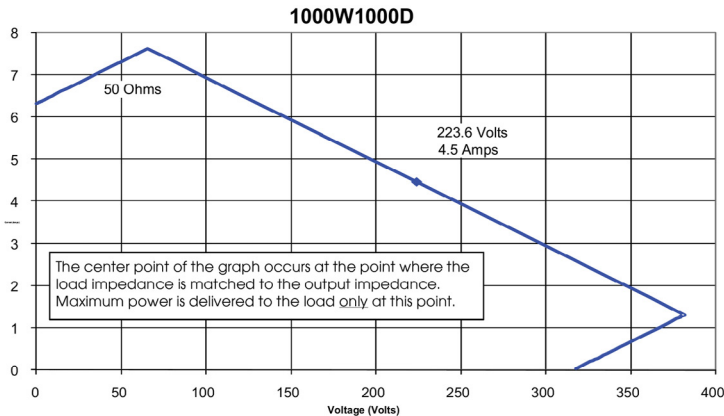

Figure 5: Current vs. Voltage 1000W1000D

The above graph demonstrates that even though fold-back occurs at a VSWR of approximately 6:1, significant output voltage and current are still delivered to the load.

Example 3: Much has been said so far regarding the importance of impedance matching. The 800A3A is an example of a unique amplifier that provides the user with selectable output impedance to match a wide variety of applications.

- 10 kHz – 3MHz bandwidth

- 800 Watts minimum output power rating

- An internal user selectable impedance transformer provides 12.5, 25, 50, 100, 150, 200, or 400 Ω to facilitate a closer match to the load impedance

- Active protection kicks in when VSWR exceeds 6:1 to reduce the gain

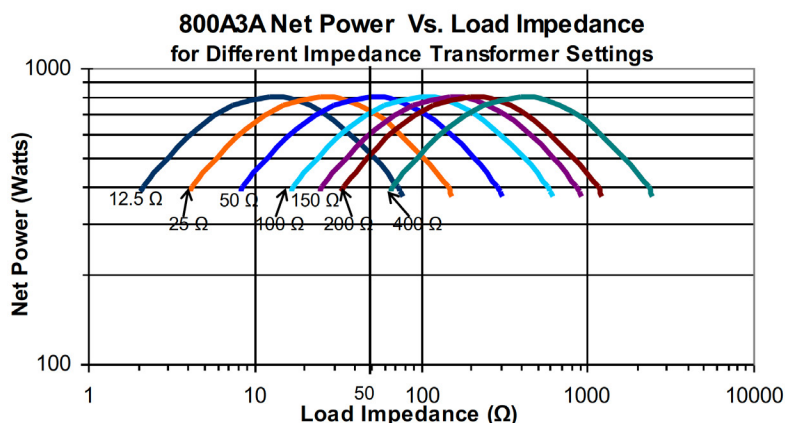- This fold-back protection limits the reflected power to 400 watts maximum

Figure 6: Power vs. Load Impedance 800A3A

The internal impedance transformer of the 800A3A allows this amplifier to have output impedance that matches that characterized by a variety of applications. External transformers are available to extend the usefulness of the 800A3A to include even more applications.
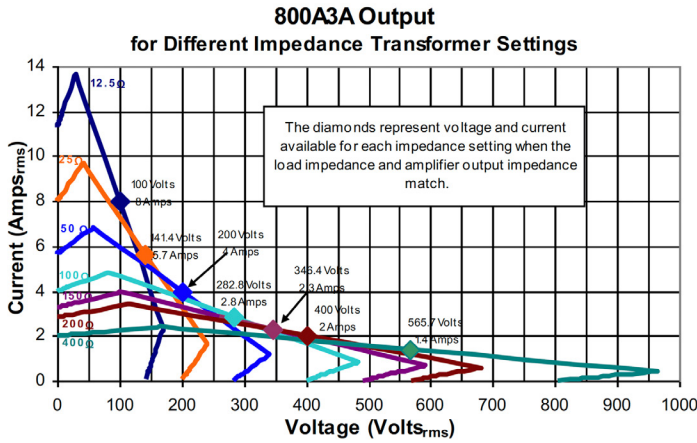
800A3A Output
for Different Impedance Transformer Settings

The diamonds represent voltage and current available for each impedance setting when the load impedance and amplifier output impedance match.

Figure 7: Current vs. Voltage 800A3A

Figure 7 clearly highlights the benefits of an amplifier with an internal impedance matching transformer that facilitates a better match with varying loads. The range of output voltage and current is considerably greater than what is provided by a standard 50 Ω amplifier.

Example 4: The salient characteristics of high power, broadband, and very low output impedance (typically <1 Ω) of the 350AH1 uniquely appeal to low frequency applications. The 350AH1 differs from other amplifiers in this class in that it is a full sized bench-top instrument with "real-time" graphical color displays of output voltage and current. It's extremely robust design ensures that it can stand up to the most demanding applications.

- 10 Hz – 1 MHz bandwidth

- The minimum rated output power is 350 watts into a 1.8 Ω load. This equates to a minimum of 25 volts and 14 amps into 1.8 Ω. (Power de-rated above 300 kHz)

- Source impedance is rated at <1 Ω (Since the output voltage and current are specified, output impedance is not used in the forward power calculations.)

- Effective source impedance is 1.8 Ω (Zo=Vo/Io= 25V/14A)

- Output protection limits both the voltage and current at rated values into any load. For loads less than 1.8 Ω, the output current is limited. For loads exceeding 1.8 Ω the output voltage is limited.

350AH1 Net Power Vs. Load Impedance
10 Hz - 300 kHz

Ideal 350 watt amplfier without voltage and current limiting

350 Watts
1.8 Ω

350AH1

Current Limited
$P = I^2 \cdot R_{load}$
$I = 14 A$
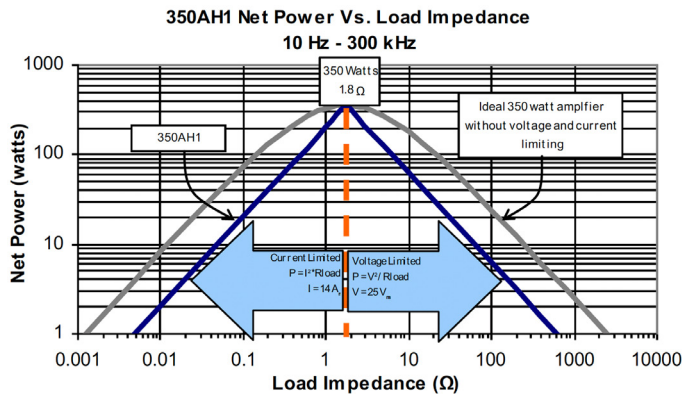
Voltage Limited
$P = V^2 / R_{load}$
$V = 25 V$

Figure 8: Power vs. Load Impedance 350AH1

This is an example of an amplifier with a 1.8 Ω effective output impedance. Due to the voltage and current limiting protection of the amplifier, VSWR does not play a role in lost power delivered to the load.
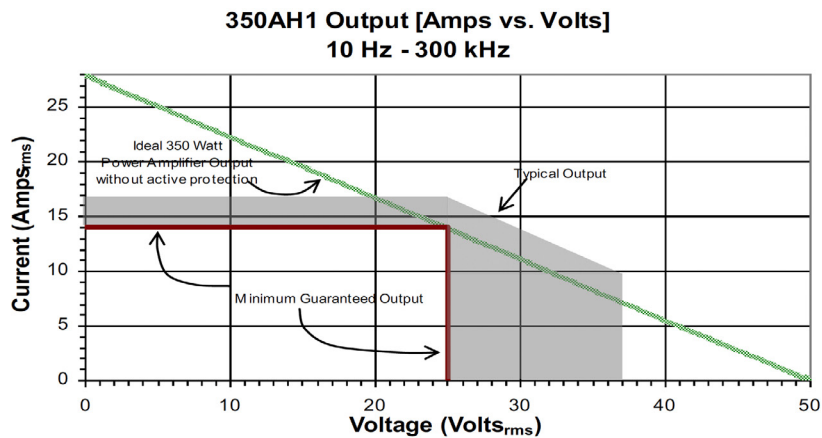
350AH1 Output [Amps vs. Volts]
10 Hz - 300 kHz

Figure 9: Current vs. Voltage 350AH1

Figure 9 plots the available output voltage and current from the 350AH1. The gray area is provided to indicate a more "typical" output profile. Individual amplifier characteristics will vary and are somewhat influenced by operating frequency and system losses.

Summary

The age old question of "How much output voltage, current, and power can I expect from my amplifier?" can in rare cases be answered by merely applying Ohm's law assuming the net power or power delivered to the load is simply the rated power output of the amplifier. In most cases, practical issues such as VSWR and forward power concerns must be considered before applying Ohm's law. While this application note has provided guidance in this matter, AR firmly believes that the best approach is to apply actual test data when calculating output parameters. If you are the least bit uncomfortable with this exercise, feel free to contact one of our Application Engineers. We would be more than happy to guide you through the process.

AR RF/Microwave Instrumentation • 160 Schoolhouse Rd, Souderton, PA 18964 • info@arworld.us
To order AR Products, call: 215.723.8181. For an applications engineer, call: 800.933.8181
Direct to Service, call: 215.723.0275 or email: service@arworld.us

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rf/microwave instrumentation

Selecting RF/Microwave Power Amplifiers for EMC Testing

Can you imagine the world without electronic devices? Today's electronic gadgets, machines, and appliances have become an integral part of our lives. This is most apparent with recent developments in technology like drones, mobile internet, medical devices, Internet of Things (IoT), and autonomous vehicles. The result is a higher potential for harmful electromagnetic interference. This interference ranges from a small nuisance to complete product or system failures.

Historically, amplifier selection for Electromagnetic Compatibility (EMC) testing was based mainly on tribal knowledge and information scattered across the EMC industry. However, proper EMC amplifier selection is an important step in achieving required RF levels. It should be noted that quality and support are of equal importance as features when selecting an amplifier. Down-time from equipment failures often means test lab's throughput slows, thus impacting the lab's profitability and customer schedules.
Additional considerations are numerous. It is important to properly understand the following in order to make a proper decision:

- Common EMC test standards
- Amplifier specification definitions
- Types of amplifiers
- Other considerations

1.0 EMC Test Standards

EMC can be defined as a system's or equipment's ability to operate in their intended environments without suffering unacceptable degradation or causing unintentional degradation due to electromagnetic spectrum interference. Threats to a system can be both naturally occurring and man-made and can be categorized into four main types of tests: Radiated Immunity, Radiated Emissions, Conducted Immunity, and Conducted Emissions. The limits and levels used for these tests are defined in various standards and adopted by various organizations. Products must meet the requirements outlined in these standards because public safety, among other things, relies on the products to perform as intended.

In many instances, the standard will drive the selection of the amplifier. In addition, the end-user will often have unique requirements. End-user considerations can be just as important as the industry standards. Standards commonly used in sectors such as military, aviation, automotive, and consumer are shown here:

Radiated Immunity
- IEC 61000-4-3: Commercial
- MIL-STD-461, RS103: Military Components
- MIL-STD-464: Military Systems
- DO-160, Section 20: Aviation
- ISO 11451, ISO 11452-2: Automotive

Radiated Emissions
- FCC Part 15
- CISPR 11, 22, 25, 32: Commercial
- MIL-STD-461, RE102: Military Components
- DO-160, Section 21: Aviation

Conducted Immunity
- IEC 61000-4-6: Commercial
- MIL-STD-461, CS114: Military Components
- DO-160, Section 20: Aviation
- ISO 11452-4: Automotive

Conducted Emissions
- CISPR 11, 22, 25, 32: Commercial
- MIL-STD-461, CE101, CE102: Military Components
- DO-160, Section 21: Aviation

2.0 Amplifier Specification Definitions

In many instances, the standard will drive the selection of the amplifier. In addition, the end-user will often have unique requirements. End-user considerations can be just as important as the industry standards. Standards commonly used in sectors such as military, aviation, automotive, and consumer are shown here:

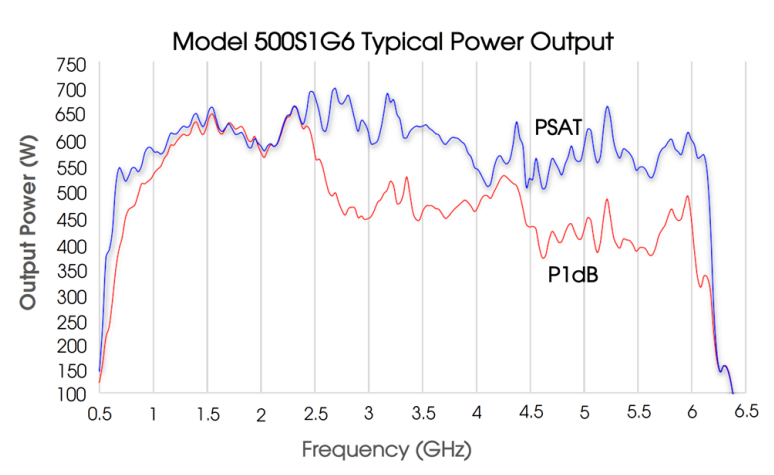| Parameter	Definition	Relevance
Frequency Response	Instantaneous operational frequency band	Amplifiers are only specified to operate within this defined frequency band. Some solid state amps will operate just outside of the band with significant power reduction (Figure 1), whereas TWT amplifiers have a much harder cutoff due to waveguide (Figure 2).

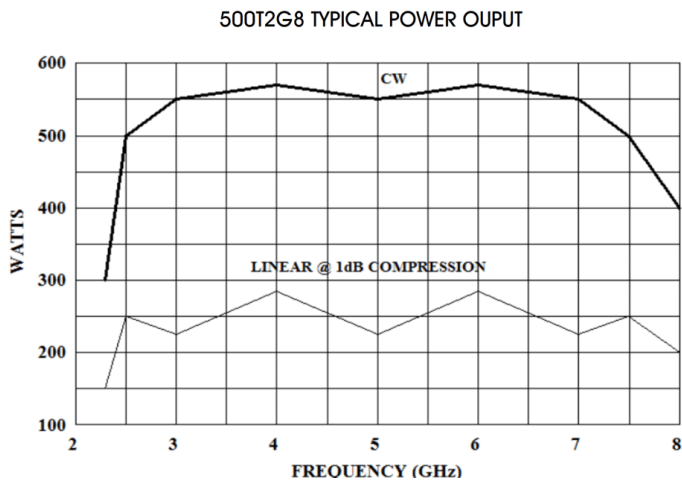Figure 1: Example of Solid State amplifier output power over frequency

Figure 2: Example of TWT amplifier output power over frequency

Parameter	Definition	Relevance
Rated Output Power	The definition of 'Rated Power' varies by manufacturer. Some manufacturers will define it as the output power for a given input power across the operational bands others will define it as the amplifier's saturated output power. There are additional definitions manufacturers will use. The key takeaway is to be cognizant of the definition used by the manufacturer in question.	It is important to remain cognizant of the manufacturer's definition as their definition of rated power may not satisfy your requirements. For example, if you require linear power and the manufacturer rates their amplifiers at something other than P1dB, you will want to size your amplifier according to the P1dB specification, rather than rated power. On the other hand, some manufacturers may specify rated power at P1dB, leaving extra power available for applications where linearity is not critical.
Power Output @ 1 db Compression	Power generated by amp at the 1 dB compression point	Important power rating for applications where there are strict linearity requirements (IEC / EN). Can be considered the top-end of linear power. Amp saturation increases after P1dB.

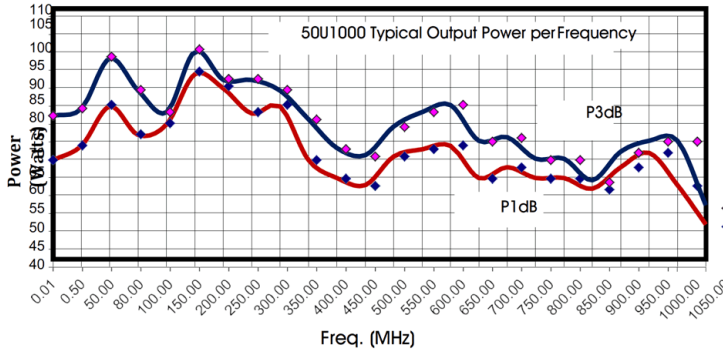*Figure 3: Example of P1dB and PdB levels fro the 50U1000*

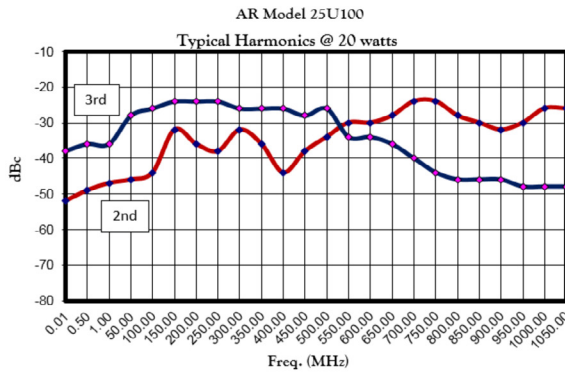| Harmonic Distortion	The ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency	Many test specifications require at least -6 dBc. It is important that the selected amplifier not contribute harmonic distortion more than what is required by the standard.

Figure 4: Example of Amplifier Harmonics

Parameter	Definition	Relevance
Gain	The amplification factor, also called gain, is the extent to which an analog amplifier boosts the strength of a signal. Amplification factors are usually expressed in terms of power.	Many amplifier factors result from an amplifier's gain, such as output power, size, and the power required to operate that amplifier. Gain is called S21 using S-parameter terminology
Flatness	This specifies how much the amplifier's gain can vary over the specified frequency range.	Variations in the flatness of the amplifier's gain can cause distortion of distort signals passing through the amplifier.
Efficiency	The ratio between the power of the output and total power consumption	Although Class A amplifiers are inherently less efficient than other amp classes, design techniques can improve amplifier efficiency. Highly efficient amplifiers are smaller and require less input power than other amplifiers with equivalent rated output power.
Pulse Capabilities	Limitations on Pulse Width, Pulse Rate, and Duty Cycle	Pulsed SSPAs and TWTs produce higher-peak power than-CW power but are limited in how much RF can be passed through the amplifier
Modulation (AM, FM, PM) Performance	A variation to the properties of a periodic signal.	While there are a multitude of types of RF modulations used in today's world, there a few specific modulations used by EMC test standards to approximate real-world threats, such as pulse modulation (PM) and amplitude modulation (AM). It is imperative that the amplifier used in testing be able to faithfully reproduce the required modulation without altering or adding extraneous distortion.
Mismatch Tolerance	Ability of an amplifier to handle un-matched loads and thus varying amounts of reflected power	In EMC applications, especially at lower frequencies, transducers (antennas / clamps / etc.) can be a very poor match to 50 Ohms. Field reflections / standing waves can cause significant reflected power as well. During tests, it is important to continue to deliver forward power and protect the amp from reflected power damage.

3.0 Amplifier Input and Output Requirements

How much input power is required to achieve full-rated output power is a common concern when choosing an amplifier. Some manufacturers have specified input of 1 milliwatt. However, that is not the case for every manufacturer, so it is important to verify. In these cases, while the rated input power is defined as 1 milliwatt, most amplifiers provide rated output power with less than 1 milliwatt input. This output power is because the specified value will often have built-in conservatism. Pay close attention, though, to an amplifier's maximum input. It varies by vendor and possibly by model family.

The input signal strength has a profound effect on the amplified output signal. It determines the operating region and, thus, the degree to which the amplifier output is compressed. Ideally, an amplifier will simply amplify the input signal without adding any additional signals or artifacts. Unless operated in the extreme linear region, amplifiers will distort the input to some degree. The extent to which the amplifier affects the input signal is a function of the output compression. The higher the amplitude of the input signal, the risk of output compression increases. At the 1dB compression point there may be a slight flattening at the top and bottom of a CW sine wave signal. As the amplifier is driven further into saturation, additional distortion will become apparent and eventually the CW input signal will approach a square wave output (See Figure 5). The 1 dB and 3 dB compression points are further shown in Figure 6.
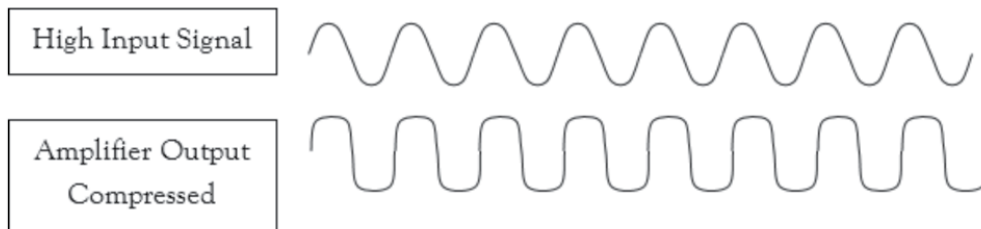

Figure 5: Example of Amplifier Saturation
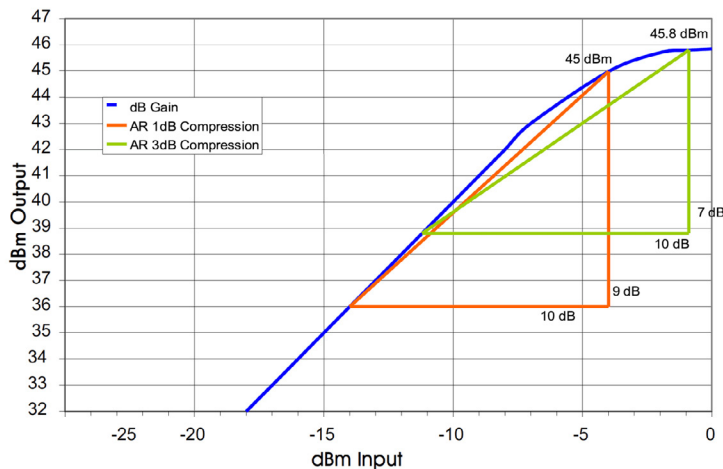
Figure 6: Linearity Characteristics

Distortion creates new unwanted signals at frequencies not present at the amplifier's input, as observed in the frequency domain with a spectrum analyzer. Figure 7 shows the effect of driving a TWT amplifier into saturation. This figure shows the harmonic having only a slightly lower amplitude compared to the fundamental signal. This situation causes unnecessary problems for the test engineer. Under this scenario, if the EUT fails during radiated immunity testing, the test engineer will not know if the failure's cause was due to the fundamental or the harmonic. To further complicate matters, if additional harmonics have high amplitudes, the test engineer must evaluate all harmonics to determine the failure's cause. It is also possible that neither the fundamental nor a single harmonic causes a failure, but rather a combination of the fundamental and harmonic(s). The most commonly used power meters and field probes themselves are wideband measurement devices that will display the total energy across the entire band, fundamental, harmonics, and spurious; this can make measuring the amplifier output power or generated field additionally challenging.

Figure 7: Image of the Fundamental Signal and Harmonic
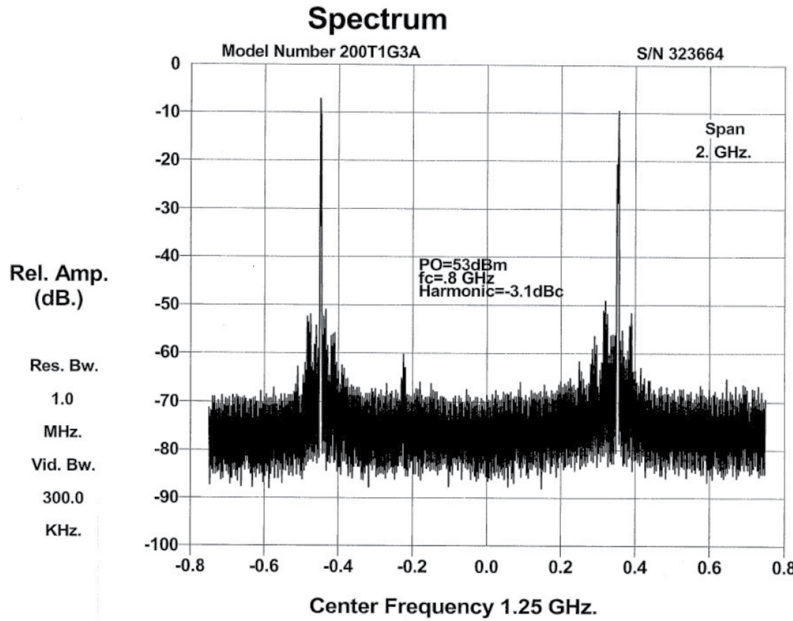
4.0 Types of Amplifiers

EMC amplifiers range in types, such as Solid State, TWT, CW, Pulse, and their class of operation - Class A and Class AB.

4.1 Class A and Class AB Amplifiers

Class A and Class AB amplifiers both have their strengths and weaknesses. Class A amplifiers are the most robust. They provide the highest levels of mismatch tolerance which is needed when significant RF levels reflect into the amplifier, a common effect with many EMC antennas and other transducers. Additionally, linearity and harmonic distortion are much better with Class A amplifiers compared to other amplifier classes.

Class AB amplifiers have their own benefits. Generally, the cost of the amplifier is less than Class A amplifiers. The physical size of these amplifiers is also generally smaller. These amplifiers are much better suited for use with matched loads. Read AR's Importance of Mismatch Tolerance for Amplifiers Used in Susceptibility Testing to learn more.

Shown in the table below is a summary of the differences between Class A and Class AB amplifiers.

Characteristics	Class A Amplifier	Class AB Amplifier
Output Distortion	Low distortion, highest Linearity	Higher distortion, poor Linearity
Cost	More expensive	Less expensive
Ruggedness	Amplifier will safely operate without damage regardless of load mismatch	Output limits are generally used to protect the amplifier when operated beyond a stated level of mismatch
Size/Weight	Larger/Heavier	Smaller/Lighter
Construction	More components required to share the head load	Less component requires to share the heat load
AC power to RF power efficiency	Less efficient	More efficient
Bias Scheme	Output current flows for 360° of the input signal	Output current flows somewhere between 180° and 360° of the input signal

4.2 TWT Amplifiers

For years, when discussing microwave, high field-strength electromagnetic compatibility (EMC) radiated susceptibility testing, Traveling Wave Tube Amplifiers (TWT Amplifiers or TWTAs) were the only choice for wide frequency coverage and power. TWTs are lower-cost solutions, in most cases, but they do have drawbacks. Their unique properties allow them to be used in a pulsed mode, which can lower the total required average power and maximize their peak power, thus, reducing cost further. However, TWTs produce high harmonics, have a greater noise floor, longer purchase lead times, longer repair times, and lower reliability than solid state amplifiers. Some advanced TWTs combine multiple tubes together to reduce harmonic content and increase total power. Another solution to reduce harmonics is to use filters on the amplifier output. It is important to remember that there are always losses associated with filters that must be considered for amplifier power sizing. The VSWR associated with the filters is another consideration, which can cause amplifier foldback.

4.3 Solid State Pulse Amplifiers

For years, when discussing microwave, high field-strength electromagnetic compatibility (EMC) radiated susceptibility testing, Traveling Wave Tube Amplifiers (TWT Amplifiers or TWTAs) were the only choice for wide frequency coverage and power. TWTs are lower-cost solutions, in most cases, but they do have drawbacks. Their unique properties allow them to be used in a pulsed mode, which can lower the total required average power and maximize their peak power, thus, reducing cost further. However, TWTs produce high harmonics, have a greater noise floor, longer purchase lead times, longer repair times, and lower reliability than solid state amplifiers. Some advanced TWTs combine multiple tubes together to reduce harmonic content and increase total power. Another solution to reduce harmonics is to use filters on the amplifier output. It is important to remember that there are always losses associated with filters that must be considered for amplifier power sizing. The VSWR associated with the filters is another consideration, which can cause amplifier foldback.

4.4 Solid State Pulse Amplifier

The difficulties associated with pulse TWT amplifiers can be mitigated with a desirable alternative. Solid state pulse amplifiers offer high-power RF levels that rival those of TWTs. Modern solid state pulse amplifiers include various frequency ranges and output power levels to meet several standards and user requirements. These solid state pulse amplifiers offer higher reliability, better mismatch tolerance, much better harmonic distortion, and better MTBF (Mean Time Between Failure) than TWTs.

4.5 Dual Band Amplifiers

If a single band amplifier is not available over the desired frequency band, a dual band amplifier may be an attractive solution. A dual band amplifier consists of two amplifiers combined into one "box" with a single I/O interface, RF input and output, and two bandwidths equivalent to the two amplifiers it replaced. This approach simplifies the test setup.

While the system seems simplified on the surface, a closer look within the "box" reveals a different story. While the two amplifier modules in a dual-band amplifier may share a common power supply, the overall system is complicated because it now consists of not one but two complex amplifier modules.

Furthermore, additional RF switching, cabling, and connectors are required, which will adversely affect both amplifier's RF output. The additional components add insertion loss that may not present a problem at lower frequencies but can account for significant losses at higher frequencies. In addition, simultaneous signal generation across the entire band is impossible due to the required switching from one frequency band to the other.

Figure 8 and Figure 9 show the schematic differences between a single band and dual band amplifier, respectively.
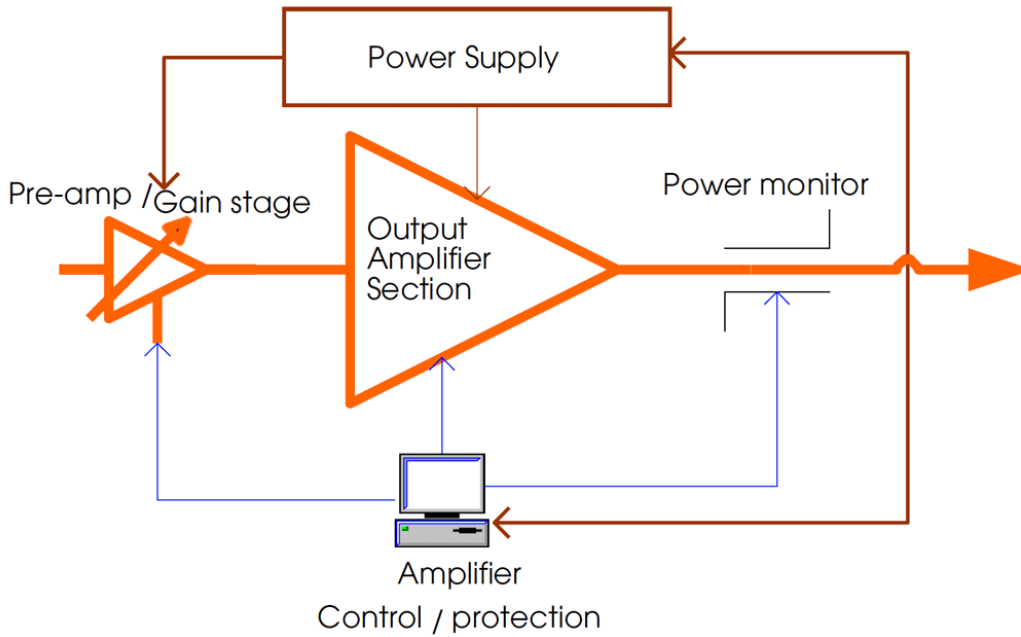
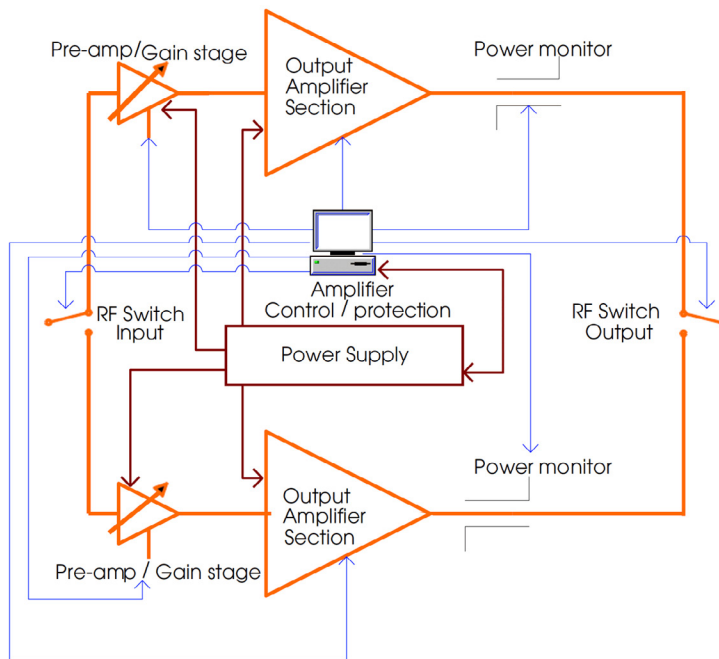*Figure 8: Basic Diagram of a Single-Band Amplifier*

Figure 9: Basic Diagram of a Dual-Band Amplifier

5.0 Amplifier Accessories

An often overlooked important part of an EMC test setup are the accessories. The cost and time associated with EMC testing warrants the use of high quality accessories. AR offers all the accessories needed to round out your system. This includes a family of antennas that operate up to 50 GHz and handle up to 20 kW. AR's in-house antenna designers and experienced EMC design engineers have collaborated over the years to develop antennas that provide very attractive alternatives to traditional antenna designs. Examples include the models Radiant Arrow, ATT Pyramidal Log Period and AA series amplifier antenna products.

AR offers these accessories, with an experienced sales and engineering organization available to offer customers the best solution. Figure 10 and Figure 11 are examples of accessories used in radiated and conducted RF immunity test setups, respectively.

Basic Radiated Immunity Equipment

Power Amplifiers

RF Signal Generators

Horn and Log-periodic Antennas

Directional Coupler

RF Power Meter

Isotropic Field Probe And Monitor

EMI Filters

Anechoic Chamber
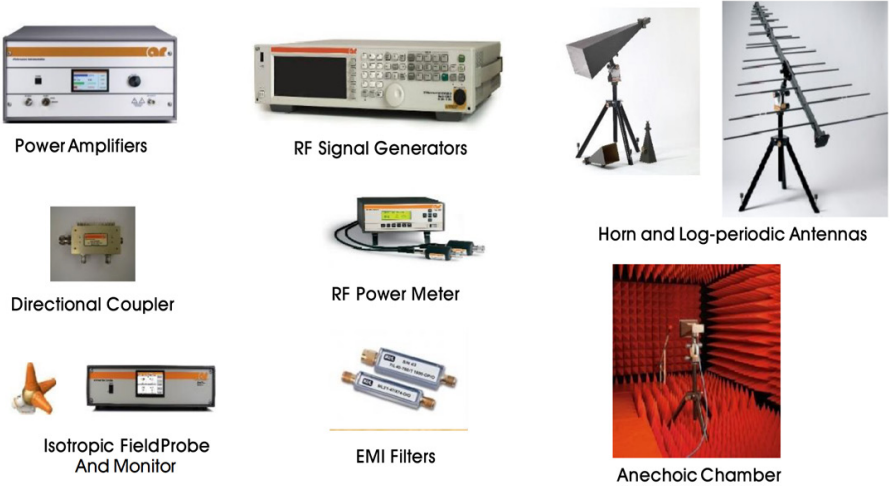
Figure 10: Basic Diagram of a Dual-Band Amplifier

Basic RF Conducted Immunity Equipment

Power Amplifiers

RF Signal Generators

Current Injection and Monitoring Clamps

Directional Coupler

RF Power Meter
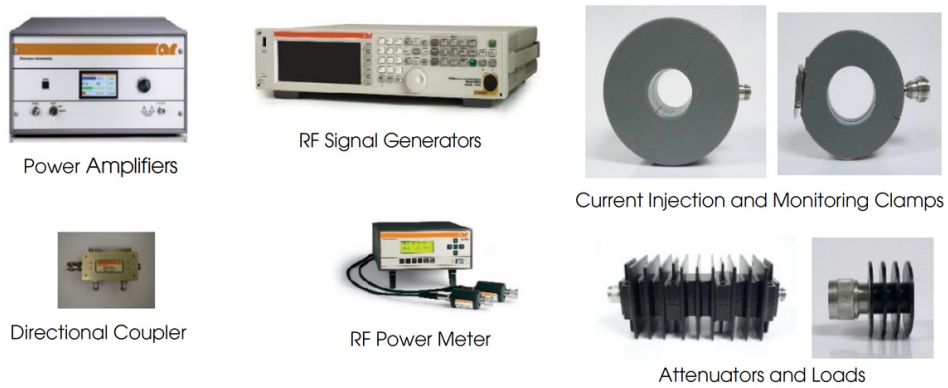
Attenuators and Loads

Figure 11: Components Used in a Typical Conducted Immunity Test Setup

6.0 Other Considerations

6.1 Transistor

The transistors used in the amplifier are a main component of the amplifier. They can provide hints about the design and provide you with another data point in your purchasing decision. Different transistor technologies have been used throughout the years, including LDMOS, GaAs and GaN, among many others. While each technology poses various inherent pros and cons, GaN technology has become more prevalent in today's marketplace. The benefit of GaN is greater power density than other technologies, which translates into higher power amplifiers and smaller overall packages compared to similarly powered amplifiers. Benefits like these are especially important in EMC applications as increased power is paramount for testing.

6.2 Amplifier Regulatory Compliance

Almost always forgotten is the importance of product regulatory compliance. It is crucial for amplifiers to undergo safety, EMC, and hazardous substance evaluations. Not all amplifier manufacturers have made a commitment to global regulatory compliance. Because of this, some manufacturers are not able to distribute their product to certain regions of the world. Even in regions that don't require such compliance, it is important to meet these requirements on all products in order to reduce potential harm to users and the environment. Independent third-party laboratories are often favored to evaluate products to international safety and EMC test standards, so there is no question about the validity of compliance compared to those manufacturers who choose to perform in-house evaluations.

6.3 Multiple Signal/Tone Applications

If planning to use multiple signals/tones or complex waveforms to speed up testing and better represent real-world threats, a single broadband amplifier is the most appropriate choice versus a multiband amplifier or multiple amplifiers. A broadband amplifier can amplify all the signals simultaneously whereas a multiband amplifier may require multiple inputs and outputs. To learn more about Multi-Tone testing, read AR's Multi-Tone: Testing, Theory and Practice.

Summary

There are many factors to consider when selecting an amplifier. Proper EMC amplifier selection is an important step in achieving required RF levels for the multitude of applications that exist today. To keep harmful interferences happening between military, automotive, medical devices, or even just the common household electronic devices; the necessary standards have been put in place. Once the standard at which the device needs to be tested against is determined, it is important to consider these other important factors during the amplifier selection process.

Need help selecting the right amplifier? AR's Applications engineers have years of amplifier experience in areas such as EMC, wireless component R&D testing, and more. We are happy to discuss your requirements and assist you in selecting the right amplifier for your specific purpose. If you need assistance, please feel free to call at 215-723-8181.

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Measurement & Emissions

rf/microwave instrumentation

Ensuring Test Site Compliance for Radiated Emissions With Normalized Site Attenuation

Normalized Site Attenuation (NSA) is utilized to determine the suitability of a test site, whether the test site is an Open Area Test Site (OATS), a semi-anechoic shielded enclosure chamber (SAC), or a fully anechoic room (FAR). The requirements for NSA are defined in CISPR 16-1-4 and ANSI C63.4, which each have very similar requirements. Site VSWR measurements for above 1 GHz site characterization will be discussed in a future resource.

NSA is the measurement of the loss between two antennas, which is then compared to defined values for an ideal test site. The deviation between the test site's NSA and the NSA for an ideal test site is caused by imperfections in the test site, such as in the ground plane configuration on an OATS or in the absorber configuration for a chamber or room.

The typical frequency range of NSA measurements and validation is from 30 MHz to 1 GHz but can be expanded in certain cases, depending on test standard applicability. These measurements are performed for a test volume which defines the largest potential EUT size of the test site.

For a three (3) meter test site, guidance and requirements are given in the applicable emissions testing standards. For example, EN 55032 / CISPR 32 state that the maximum width of the EUT shall be within the test volume defined during NSA measurements. So, if the maximum volume of the test samples to be tested are defined as 1 meter by 1 meter by 1 meter, the NSA can be performed for that test volume. However, if a test sample exceeds the NSA volume, then NSA must be performed for that specified volume (or larger).

EN 55011 / CISPR 11 define sizes of equipment. For a three-meter measurement, the EUT, either floor standing or tabletop, must fit within a cylindrical test volume of 1.2 meters in diameter by 1.5 meters above the ground plane. Anything larger, including the cables, must be tested at 10 meters, provided the test site meets NSA requirements.

For the FCC (United States) and ISED (Canada), the guidance for different types of test sites and their testable volumes is given in ANSI C63.4:2014.

For a test site, the NSA is performed once per laboratory-defined calibration cycle, which is generally on an annual basis. Additional NSA measurements should be made if there are changes to the test site, such as, but are not limited to:

- Change in ground plane configuration on an OATS
- Change in OATS weather protected enclosure
- Change in anechoic material loading in a shielded enclosure

Discrete frequency measurements are made and compared to tables listed in either CISPR 16-1-4 or ANSI C63.4. Swept frequency measurements can be made and require broadband antennas.

It should be noted that the antennas used during NSA measurements are not required to be the same antennas utilized during testing. The purpose of these measurements is to qualify the physical test site for attenuation and not the antennas. For clarification of the antennas used, the responsible body should refer to the applicable test standard, version specific, for the subject tests and measurement.

1.0 Measurement Method for an OATS and Semi-Anechoic Chamber (SAC)

Initially, two (2) antennas are set up on the test site in the appropriate geometry. The first measurement, VDirect, is measured with the transmit and receive coaxial cables disconnected from their respective antennas and connected directly with an adapter, and the signal source set to a value (V1). This measurement gives a direct source-to received measurement, of which all other measurements are based. Care should be taken to ensure that the cables and adapters used are appropriate for the frequency being measured. The second measurement (VSite) is taken with the cables connected to the antennas and the maximum signal measured by raising and lowering the receiving antenna. Note that the signal source (V1) continuously remains constant.
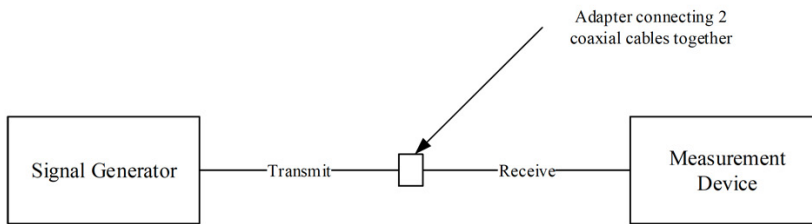
Figure 1: Measurement of V_{Direct}

The measurements are repeated for multiple positions and each polarity (horizontal and vertical) of the antennas. For test sites where larger EUTs are measured, multiple antenna locations are used to ensure that the usable volume of the test site meets NSA requirements.
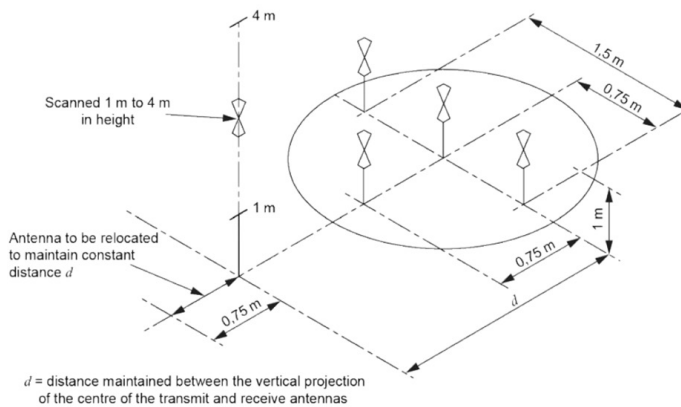
NOTE   EUT does not exceed a volume of 1 m depth, 1,5 m width, 1,5 m height, with the periphery greater than 1 m from the closest material that may cause undesirable reflections.

Figure 2: Typical Antenna Positions for a Weather-Protected OATS or SAC - Vertical Polarization Validation Measurements

Source: CISPR 16-1-4, Edition 4.0
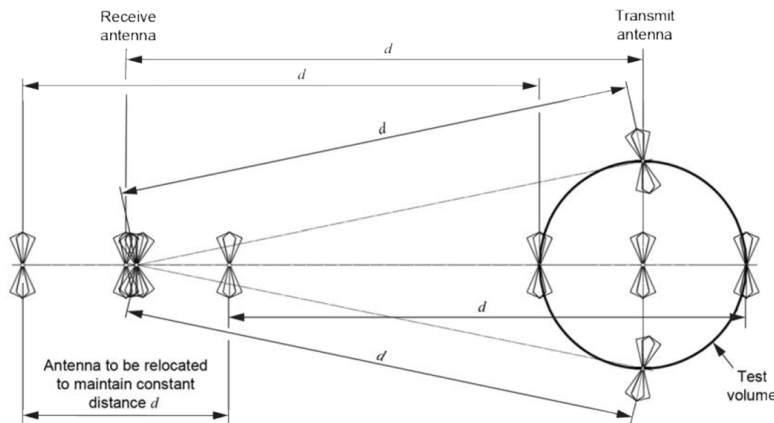
Figure 3: Typical Antenna Positions for a Weather-Protected OATS or SAC - Horizontal Polarization Validation Measurements

Source: CISPR 16-1-4, Edition 4.0

Once the measurement is recorded, the NSA is calculated via the following equations

- AN = VDirect – Vsite – AFT – AFR – ΔAFTOT, for tuned dipole
- AN = VDirect – Vsite – AFT – AFR – GSCF, for biconical
- AN = VDirect – Vsite – AFT – AFR, for all other antennas

Where:

- AFT is the antenna factor of the transmitting antenna (dB/m)
- AFR is the antenna factor of the receiving antenna (dB/m)
- ΔAFTOT is the mutual impedance correction factor (dB)
- GSCF is the geometry-specfic correction factor

Note: the equation above is derived from ANSI C63.4. CISPR 16-1-4 equations are the same with the variables having slightly different abbreviations

Once the calculations are complete for the attenuation, the result is then compared to the theoretical NSA listed in either ANSI C63.4 or CISPR 16-1-4. If the result is within ±4 dB of the theoretical NSA, then the test site is deemed to comply with the Normalized Site Attenuation requirements for that specific position, frequency, and polarization. If not, the source of the error must be investigated, and the process shall be repeated.

For a weather-protected OATS or a shielded anechoic chamber, a single measurement height is insufficient given the possibility of reflections from construction materials and trapped moisture in the walls of the enclosure. For these scenarios, a 'test volume' must be defined, which is the volume of the largest potential EUT tested and rotated about its center. Multiple heights are also required to ensure that the roof of the weather protected OATS or top of the SAC do not affect the NSA.

2.0 Reference Site Method for Fully Anechoic Rooms

Near field effects can be observed when measuring at test distances of less than 5 meters in a Fully Anechoic Room (FAR). A Reference Site Method (RSM) accounts for those effects involving a biconical antenna at three (3) meters.

To account for the near-field effects, an additional factor, AAPR is subtracted from the initial attenuation calculation:

$$A_N = V_{Direct} - V_{Site} - A_{APR}$$

Where AAPR, is the measured results of the Antenna-Pair Reference. AAPR is measured and calculated by increasing the height of the antennas to $h = d * \frac{8}{3}$

Where h is the height of the antennas and d is the distance between them. The reason for this increase is to suppress influence from the ground. The same suppression can be achieved by covering the coverage area with RF absorber material suitable down to 30 MHz.

Once the height is achieved, the measurement can be made by the equation:

$$A_{APR} = V_{DirectRS} - V_{SiteRS}$$

Where the VDirect RS and VSite RS are the same measurements obtained above, just with the height increased as above stated.

For CISPR 25, the RSM method can be utilized for comparison to an Open Area Test Site, provided the OATS meets the requirements of CISPR 16-1-4 or ANSI C63.4. The challenge here is to have a laboratory with each of the two test environments for comparison (reference) measurements.

Summary

The above synopsis of Normalized Site Attenuation and Reference Site Method measurements indicates a challenging but important aspect of radiated emissions measurements on an OATS, SAC, or FAR.
A compliant test site produces repeatable test results and instills confidence in both customers and test personnel. Amplifier Research offers turnkey solutions and systems, which can be accessed at http://www. ARWorld.US, or call our applications engineers at 800-933-8181.

References

ANSI C63.4 (2014), American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz

CISPR 16-1-4, Edition 4.0, International Standard, Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements.

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Application of Field Probe Correction Factors

To better achieve accurate field level measurements, it is helpful to have an understanding of field probe calibrations, the factors generated, and what's presented as data during testing. Previous application notes have dealt with field probe selection, proper use, and configuration. This application note shows the customer how to utilize the factors presented for inclusion into test data, how to generate composite measurements, and why calibrations are performed at selected frequencies.

1.0 Field Probe Measurement and Correction Factors

Upon purchase, Amplifier Research supplies correction factors with each of our field probes. As the manuals state, the field probe factors are given in both dB and linear multiplier values. For each probe, a 3-axis correction factor is given.

For many EMC test standards, only a composite value is required. To calculate the composite field value, a simple root-sum-of-squares calculation of the field values measured in each axis is performed.

$$Measurement_{Composite} = \sqrt{(x^2 + y^2 + z^2)}$$

Where: x, y, and z are the individual axis measurements for the specific field probe

For each calibration frequency, the three (3) separate axis factors are given. It is up to the user to calculate the composite value using a script or spreadsheet.

2.0 Correction Factor Example

The given example shows the outcome of the composite measurement as derived from the three individual axis measurements and factors:

Linear Correction Factors:

Frequency (MHz)	X-ais	Y-axis	Z-axis
80.0	0.99	0.98	0.99

Measurement Results (V/m)

Frequency (MHz)	X-ais	Y-axis	Z-axis
80.0	5.86	47.86	1.03

The equation, from above, would show the following (via a root-sum-of-squares calculation):

$$Measurement_{Composite} = \sqrt{((0.99 * 5.86)^2 + (0.98 * 47.86)^2 + (0.99 * 1.03)^2)}$$

$$Measurement_{Composite} = \sqrt{(2234.56)}\,V/m$$

$$Measurement_{Composite} = 47.27\,V/m$$

When separable-axis field measurements cannot be used, and a composite factor must be used, a simple way to calculate the composite factor is to take an average of the 3-axis factors:

$$Factor_{Composite} = \frac{x + y + z}{3}$$

So, for the example above, the composite factor would be:

$$Factor_{Composite} = \frac{0.99 + 0.98 + 0.99}{3} = 0.9867$$

If the uncorrected measurement above was 48.23 V/m, the corrected composite measurement is:

$$Measure_{Composite} = 48.23 * 0.9867 = 47.58\,V/m$$

3.0 Calibration of AR's Field Probes

All of AR's field probes are calibrated by an accredited calibration laboratory in accordance with ISO 17025:2017. The accreditation falls under the scope of the ILAC (International Laboratory Accreditation Corporation) MRA (Mutual Recognition Agreement), and each calibration laboratory is accredited to an approved ILAC signatory. Each calibration is traceable to NIST, the National Institute of Standards and Technology.

For calibrations performed by Amplifier Research, an approved calibration procedure in the form of a Standard Operating Procedure and Work Instruction is performed. When calibrations are performed by an outside vendor, those calibrations are performed by the vendor's calibration procedure.

The calibration procedures performed are generated with guidance contained within Annex I (informative) of IEC 61000-4-3, Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test, and IEEE 1309, IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes (Excluding Antennas) from 9 kHz to 40 GHz

4.0 Application of Calibration Data

To apply the correction factors, refer to the manual of the specific field probe utilized. If the correction factor of the field probe needs to be determined for a given frequency, a linear interpolation can be utilized between two frequency points via the following:

$$a_x = \frac{a_0(f_1 - f_x) + a_1(f_x - f_0)}{f_1 - f_0}$$

Where:
a_x is unknown correction factor amplitude
a_0 is first known correction factor amplitude
a_1 is second known correction factor amplitude
f_x is wanted frequency value of correction factor
f_0 is first known frequency
f_1 is second known frequency

This equation assumes a linear relationship between the correction factor and the frequencies of interest.

Summary

AR's Field Probes can measure fields and return data via 3-orthogonal axis or composite values, depending on the application and testing performed. The procedure to calculate the composite factors is straightforward for any technical user. If you would like to learn more, feel free to contact one of our applications engineers at 800-933-8181, applications@ARWorld.US, or visit our website at www.arworld.us.

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Proper Use of RF Field Probes Used in EMC Radiated Immunity Testing

RF field probes are perhaps one of the most underrated components of a radiated immunity test system. While we rely heavily on data sheets to select all the other devices required to generate a given field level, only a live test using a trusty field probe will measure the resultant field level and validate the RF test system. While we assume that all measurements meet the accuracy published in the probe's data sheet, it must be noted that these indispensable tools can be a source of considerable error if not used correctly. This application note will review the underlying concepts of field measurement, emphasizing the proper application of field probes.

Broadband Isotropic RF field probes are commonly used in immunity testing applications. Ensuring these exact measuring devices' accuracy over their entire frequency range can be challenging for both the probe designer and the user. The user should understand how these devices operate and what influences could affect their resultant readings to minimize errors.

1.0 Test Methods

There are two generally accepted methods used to determine field strength; the closed-loop method and the substitution method. While each method has its advantages and disadvantages, the test standard will ultimately determine the method used.

Closed Loop Method: In this method, an RF field probe is positioned in front of or on top of the EUT during susceptibility testing. The field is adjusted to each frequency step's intended field strength across the entire test frequency band. Since the commonly used diode-type field probe can not accurately measure a modulated RF signal, one must either apply correction factors to the probe readings or take measurements using only a CW signal and only apply modulation later during the actual test run.
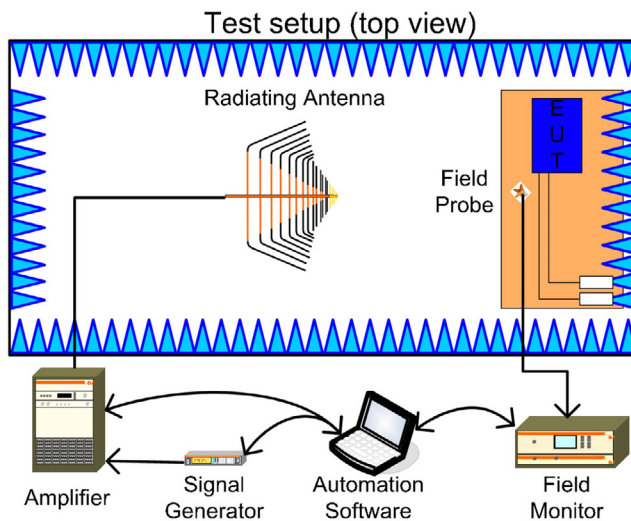

Figure 1: Closed Loop Method

Closed loop testing provides a "real-time" reading of field level and a direct correlation between instantaneous field level and the operation of the test device. This immediate feedback adds confidence in both the system performance and the immunity of the EUT. Closed loop testing also proves to be the fastest method since no additional time is required to calibrate and level the RF field. Some argue that this approach is a better representation of the actual RF levels seen by the EUT. This method is ideal for testing small EUTs where reflections from a relatively small reflective surface area have a minimal effect on the RF field. As the size of the EUT increases, a point is reached where reflections from the larger reflective surface area of the EUT will have a noticeable effect on the field. The resultant standing waves create an unstable situation whereby the probe readings can vary dramatically when moved about the room or as a function of frequency. In short, the results are unpredictable and most likely unrepeatable from one setup to another, not to mention from one test lab to another.

MIL-STD-461 is one example of where the closed-loop method is mandated.

Substitution Method: In this method, the RF field is first calibrated in an empty chamber. For every increment of the frequency, the system is adjusted to achieve the test level, and the RF drive level is recorded. All readings are conducted with a CW signal to ensure proper levels. Armed with the room calibration data, the actual immunity test is run. The EUT is positioned in the test environment, and the drive levels noted during the calibration phase are replayed to produce the CW field. The appropriate RF modulation is then applied. Since this method does not require field monitoring during the test run, probe errors resulting from EUT effects on the field are eliminated. One drawback of the substitution method is that additional time must be allotted to perform the calibration/leveling phase prior to the actual test run. Regardless, this method has become more accepted and is referenced in many EMC test standards.

Figure 2: Substitution Test Method
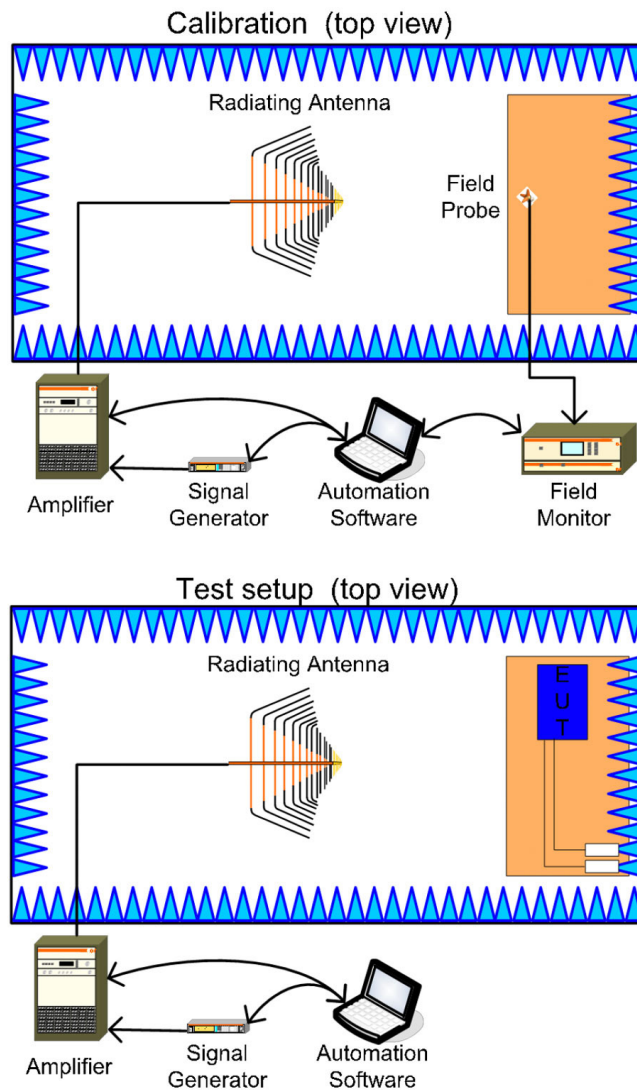
While not required, a probe is often used during the test run to monitor the RF field. This direct feedback assures system performance. For example, a simple test equipment failure, cable failure, or even human error would be picked up by merely monitoring the field during the test run.

Both IEC 61000-4-3 and DO160 use the substitution method but use different calibration procedures.

Harmonics: If the RF amplifier is operating in saturation or exhibits harmonics, the field will consist of more than just the test frequency. For example, the output of a TWT amplifier operating at a fundamental test frequency of 1GHz could contain a 2GHz harmonic only 3dB down from the fundamental level. This output, coupled to a typical antenna that exhibits increasing gain as a frequency function, could yield a field where the harmonic level is greater than the fundamental. Since the RF field probe reads total energy, the displayed field level would be much higher than the actual field at the desired 1GHz test frequency. If this source of error is not understood and controlled, the immunity test results are invalidated. The simplest way of minimizing harmonic related errors is to either select an RF amplifier with low harmonics or at very least operate well below the amplifier's saturation point. In the event that these precautions are not practical, one must apply low pass filters to absorb the harmonic energy.
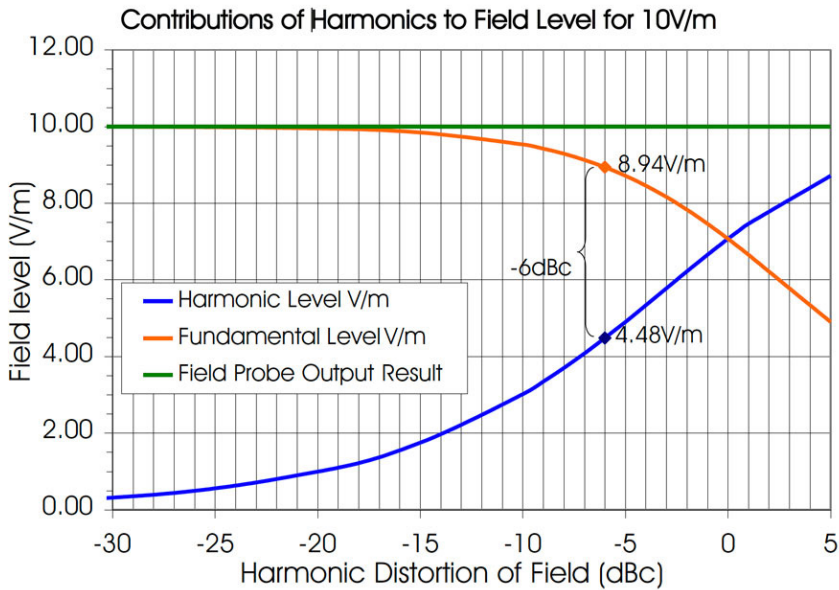

Figure 3: Graph of the Fundamental and Harmonic Relation to Field Strenght Reading

In an effort to control harmonic related errors, some standards mandate a maximum harmonic content within the RF test field of - 6dBc while others focus directly on the RF power amplifier and mandate that its harmonics be held to no greater than -15dBc.

Let's take a look at the -6dBc field requirement. By reducing the harmonics to this extent, the harmonic power is ¼ that of the fundamental power which results in an acceptable amount of field probe error.

Given that a -6dBc harmonic level within the test environment is satisfactory, let's work back to determine the maximum acceptable level of harmonics from the RF power amplifier.

1. Some antennas exhibit as much as 5 dB more gain at the harmonic frequency that at the fundamental test frequency.

2. Typically a 3dB margin is applied to account for variables like probe and test environment inconsistencies.

3. Summarizing the above observations: Spec requirement   6 dBc
   Max antenna gain between harmonic and fundamental   5 dB
   Other effects from setup and room (safety factor)   3 dB
   Total 14 dB

While it can be seen that a minimum of -14dBc harmonic distortion from the RF power amplifier is acceptable, one should strive to reduce amplifier distortion even further to minimize any error caused by harmonics. From the above graph it can be seen that the - 6dBc requirement will result in about an 11% margin of error. The equations in Annex A can be used to more accurately calculate the contribution of harmonics on probe error. **Probe Positioning:** When a probe is used during an immunity test, it is recommended that the probe be positioned in the same orientation as during calibration. There are some common sense rules that can be applied when positioning a probe in the test field.

- Use the probe on axis when the polarization of the field is known; this is accomplished by aligning one of the probe's axis with the horizontally polarized field and one with the vertically polarized field.

- Make sure the probe's metal housing is not causing reflections. This is common when using a "stalk" type probe with a square housing located about 10 inches from the probe. The flat reflective housing should not be located directly behind the probe since this can cause a reflection. The reflection can result in standing waves at the probe head. This is especially possible above 1GHz.

- For closed loop testing it is best to keep the probe in a position where direct reflections from the EUT will not cause a standing wave at the probe head. It is therefore best not to place the probe in front of the EUT. Since this may not be possible, experiment with various locations or use multiple probes to find a way to achieve a stable field.
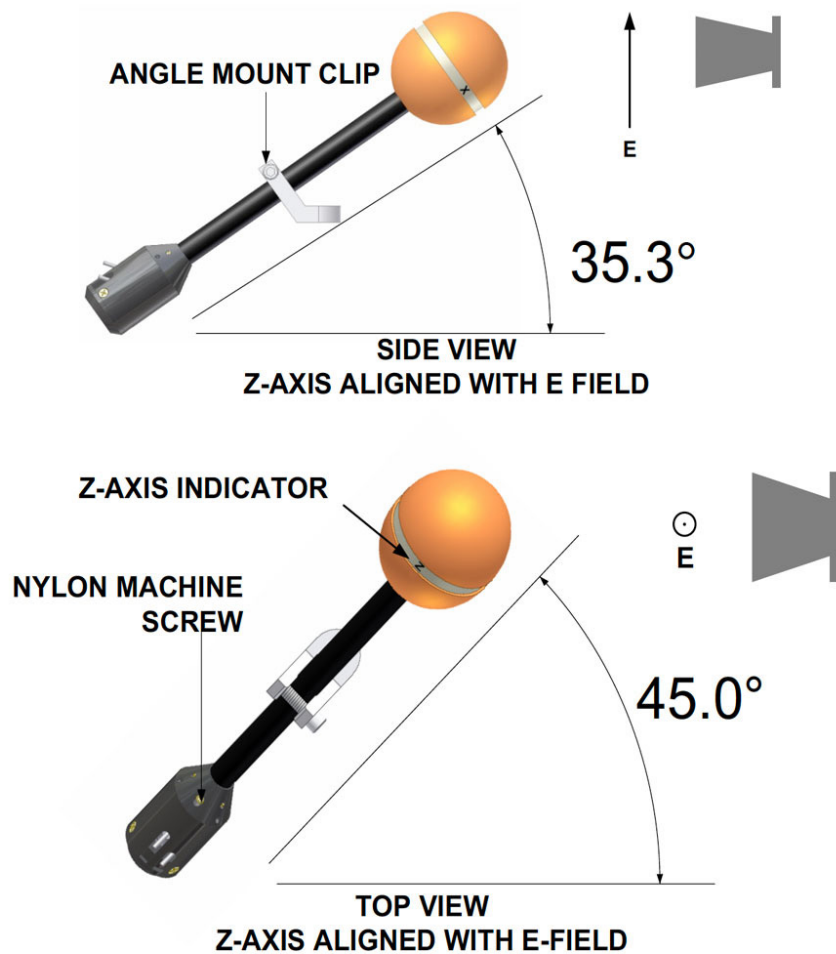

Figure 4: Probe Alignment

Due to an isotropic field probe's orthogonal design, one would expect field readings to be independent of probe position. Regrettably, this is not the case, and a figure of merit has been established. The isotropic field response provides the variation one can expect as a function of probe positioning. To preclude this error component, orient the test probe in the exact position used when running the calibration. **Calibration Factors:** Ideally, a field probe would provide a precise reading of the test field across its entire frequency range. Since this is unpractical, field probes are supplied with correction factors that, when applied, result in a value within the probe's stated accuracy. Correction factors are obtained by a periodic calibration performed by a qualified calibration lab. These correction factors need to be applied to all probes' readings to meet published specifications.

Some newer probes, such as those sold by AR RF/Microwave Instrumentation, offer the ability to automatically apply correction factors if the system is configured to communicate the test frequency to the probe monitor. This must be done since the correction factor is a function of frequency, and the probe does not have the ability to sense the test frequency. This inability is generally not an issue since automated test software can easily parse out correction factors as a function of frequency and supply this data to the probe. While some test facilities do not apply correction factors unless they are greater than 0.5dB, this policy is ill-advised since this is an error component that is easily corrected. Since other error sources are not so easily corrected, it makes no sense to overlook one that can be dealt with so easily.

Modulation Correction Factors: Most standards require the RF test signal be modulated. Since common diode-type probes do not exhibit a linear response to modulated fields throughout their usable range, readings should always be taken with a CW signal. One simple way around this probe shortcoming is to create a custom calibration for the particular modulation in use. This calibration is accomplished by first adjusting the system to produce the required CW field level. At this point apply the modulation mandated by the standard and note the resultant field level. This new reading will represent the required test level with modulation at the test frequency and will be very reproducible for that specific frequency and field level. This reading should not be scaled up or down since the field probe does not respond linearly to modulation across its frequency range.

Note: A Thermocouple probe directly measures a repetitive modulated field's average amplitude, but the modulation envelope would need to be known if a maximum reading was required. Since thermocouple probes are less sensitive and have a narrower dynamic range than diode-type probes, they are not commonly used in EMC immunity applications.

Temperature Compensation: If there is a significant variation of temperature between probe calibration and the actual test run, the probe reading will likely contain an error component directly proportional to the temperature variation. Some probe manufacturers supply a temperature correction equation that must be applied to correct ambient temperatures that differ from the temperature at which the probe was calibrated. Since high field levels and even operating EUTs can generate a great deal of heat, it is difficult to determine the "dynamic" heat fluctuation at any given moment, much less apply the correction factor. Thus, this cumbersome chore is often ignored, leading to a significant source of error. AR RF/Microwave Instrumentation recognizes how difficult this correction process can be and has instituted automatic internal temperature compensation in all of its laser powered probes. As long as the probe is used within its stated parameters, no additional temperature compensation is necessary.

Zeroing: To minimize probe error, some probes incorporate an internal reference and automatically initiate a zeroing function to offset probe error resulting from the internal component drift partially.

Zero Offset: A word of caution regarding the use of a zero offset function, if available. Unfortunately, some probes allowed users to "zero out" static probe readings prior to conducting a test. While it seems like the logical thing to do, adjusting the probe introduces an error component equal to the adjusted signal level. In reality, most probes are not designed to read zero in the absence of a field. The relatively small steady-state reading represents the probe itself's noise floor or, more likely, the noise floor and the test lab's ambient field. Operators have mistakenly believed that they must force this reading to zero to minimize probe error, but the probe is not affected by this small initial offset. The zero offset function should only be used by qualified personnel conducting the periodic probe calibration at a certified calibration lab and never adjusted in the field.

Conclusion

The ultimate goal with all immunity testing is to minimize errors and measurement uncertainty. By insuring the integrity of the test system, one can expect reproducibility between setups in the same lab as well as from outside labs. If field probes are used within the guidelines noted in this application note, accurate, repeatable results are possible. To achieve this goal, not only should field probes be used correctly but the entire test setup along with procedural details needs to be documented in detail. Finally, it is important to keep in mind the capabilities and limitations of any measurement device to insure that erroneous data is not taken.

Annex A

If one harmonic is dominating, then the equations listed below can be used to find the values. The dominating harmonic would most likely be the 2nd or 3rd harmonic.

$$V/m_{\text{Total}} = \sqrt{V/m_{\text{Fundamental}}^2 + V/m_{\text{Harmonic}}^2}$$

$$V/m_{\text{Fundamental}} = \sqrt{\frac{V/m_{\text{Total}}^2}{1 + \left(10^{\frac{dBc_{\text{Harmonic}}}{20}}\right)^2}}$$

$$V/m_{\text{Harmonic}} = \sqrt{\frac{V/m_{\text{Total}}^2}{1 + \left(10^{\frac{dBc_{\text{Harmonic}}}{20}}\right)^{-2}}}$$

$$V/m_{\text{Fundamental}} = \frac{V/m_{\text{Harmonic}}}{10^{\frac{dBc_{\text{Harmonic}}}{20}}}$$

$$V/m_{\text{Harmonic}} = V/m_{\text{Fundamental}} \cdot 10^{\frac{dBc_{\text{Harmonic}}}{20}}$$

Note: Since dBc refers to the level of a harmonic relative to the carrier, in most situations this will be a negative number. This is of course desirable, and the greater this negative number, the better. Unfortunately, there are situations where harmonics can exceed the carrier and in this case, the dBc figure is a positive number.

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RF Field Probe Specifications and Design Charactertistics

RF (Radio Frequency) field probes are an essential piece of equipment used for measuring the intensity of radiated RF fields. Although this instrument is crucial in implementing a radiation immunity test system, system specifiers often gloss over this essential element after spending a considerable amount of time and energy selecting amplifiers, antennas, and other equipment to generate the required RF field. A live test using a field probe will then determine if the RF test system's expected performance has been achieved.

These specialized RF measuring instruments carry a unique set of specifications. Understanding the specification definitions, field probe design characteristics, and other varying features will, in turn, allow a confident and informed decision in choosing a suitable field probe.

1.0 Field Probe Specifications

1.1 Frequency Response or Frequency Range

The frequency response of a probe is one of the first probe specifications to consider and is the frequency range over which the probe's performance is defined. Since no probe can provide a completely flat response across the entire frequency range, this spec is accompanied by a tolerance figure, generally provided as a ±dB allowable variation band. An example of a frequency response curve is shown in Figure 1. If the probe does not cover the entire frequency range of the test application, multiple probes may be required.
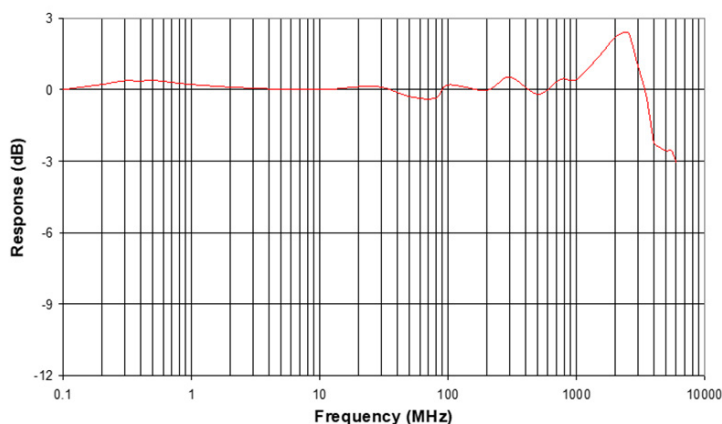

Figure 1: Frequency Response

1.2 Sensitivity

The sensitivity of a probe determines the lowest field level the probe can accurately measure and is important to consider when low field levels need to be measured. Some specs call for a field level of 1 V/m or even less, which may be below the sensitivity of many probes, or very close to its noise floor. The most sensitive probes can accurately measure a few hundred mV/m.

1.3 Field Strength Range

Field strength range is the amplitude range of RF field levels a probe can read. The greater this range, the better a probe is suited for test applications that span a wide range of test levels. An example of Field Strength Range is 0.5 - 800 V/m.

1.4 Dynamic Range

Dynamic range, used in the context of field probes, is closely related to the Field Strength Range. Dynamic Range conveys the magnitude between the lowest and highest specified field strengths (the Field Strength Range), expressed in logarithmic units of decibels (dB). As an example, a Field Strength Range of 0.5 - 800 V/m is expressed as 64 dB Dynamic Range.

1.5 Linearity

The linearity spec is a measurement of deviation from an ideal response over the probe's dynamic range. Linearity data is provided since an RF probe's response may vary somewhat as a function of the applied field level. This characteristic can cause some variation in accuracy when testing at levels other than that used during calibration. For example, one might encounter a variation of ±0.5 dB across a dynamic range of 0.5 – 800 V/m.

1.6 Overload or Damage Level

This rating refers to the field level where damage can occur to the probe. Care should always be taken not to exceed this field strength with the probe present, even if the probe is turned off. Overload can be stated as a max pulsed level or a CW level. Example: 1000 V/m CW.
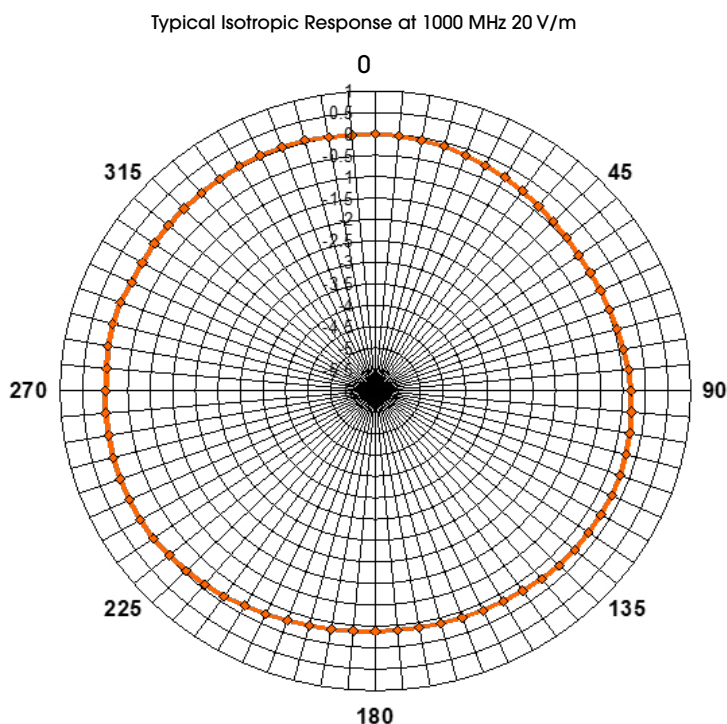
Typical Isotropic Response at 1000 MHz 20 V/m

Figure 2: Typical Isotropic Response at 1000 MHz 20 V/m

1.7 Isotropic Deviation

The variation of the probe's response from ideal as it is rotated in the field is called isotropic deviation. While this deviation in measurement is usually verified at one frequency and in one rotational plane, some advanced probe calibrations can offer a more extensive calibration with isotropic response measurements taken at multiple frequencies. The graphic shown in Figure 2 shows a typical isotropic response of a probe. If calibration factors were applied to each axis, the resultant curve would approach an ideal concentric circle or completely isotropic. The term isotropic gives the impression that measurements are taken as the probe is rotated in every direction, however this is not the case due to the time this would take, and the resultant calibration cost. Example: ±0.5 dB, 0.5 MHz – 2 GHz.

1.8 Temperature Stability

The temperature stability is the deviation of the probes reading over the operating frequency range as temperatures vary. Example: ±0.5 dB over the operating temperature range.

1.9 Control

Control refers to the method used to communicate with the probe. When performing EMC testing, fiber optic control is the only viable choice, as fiber optic cables are nonmetallic and will not interfere with the radiated immunity test setup. Furthermore, they are not susceptible to data corruption from voltage/current induced by the RF field.

2.0 Field Probe Design Characteristics

2.1 'E' vs. 'H' Fields

Probes are designed to either detect 'E' (electric) fields or 'H' (magnetic) fields. E-field probes are more commonly used in many EMC tests and cover a much larger frequency range than H-field probes. H-field probes are more commonly used at low frequencies, typically below 1 MHz.

2.2 CW vs. Modulated

The most common type of field probes are probes designed to measure non-modulated Continuous Wave (CW) electric fields over a broad range of frequencies and amplitudes, and as such, these are commonly referred to as 'CW' probes. This is the field probe type that has been used within the EMC industry for many years.

However, many EMC specifications use modulation in some form, primarily Pulse Modulation (PM) or Amplitude Modulation (AM). A CW-only field probe is not appropriate for measuring these signals, and an alternative type of probe needs to be selected based on the modulation being used.

The product specification sheet should be consulted to understand the probe's capability. Some probes are limited to specific modulation types, while others will measure CW, PM, and AM fields. When deciding on a field probe for measuring modulated fields, ensure that the probe selected is appropriate for the modulation being used. A CW-only field probe will often produce values in a modulated field; however, the readings will likely be erratic and would not be usable for field measurements. Consult the test standard being used for guidance on appropriate probe selection.

Here are some examples of test standards and associated modulation schemes:

EMC Standard	Modulation(s)
RTCA/DO-160	4% Duty 1 kHz Pulse
	90% Depth Square Wave 1 kHk
	4uS Pulse 1 kHk AM
IEC 61000-4-3	80% Depth 1 kHk AM
ISO 11452	3uS Pulse
	80% Depth 1 kHk AM Peak Conservation
MIL STD-461 (revisions E and later	50% Duty 1 kHk Pulse
	50% Duty 400 Hz Pulse

2.3 Isotropic vs Non-Isotropic

Most modern EMC field probes are isotropic, with the probe measuring the field level's total value and unaffected by field polarity. This total value is determined by combining the three different sensors' measurements. The sensors are mounted orthogonally (perpendicularly) to each other, and are commonly referred to as X, Y, and Z. This configuration allows the detection of RF fields regardless of the probe orientation. Many current EMC standards require isotropic probes.

Some older probe designs, classified as non-isotropic, use a single sensor and can only detect a single field polarity. With this type, the probe must be carefully oriented, with respect to the field, to perform field measurements. Most EMC test standards require isotropic probes, precluding the use of non-isotropic models in these cases. Consult the test standard being used for guidance on appropriate probe selection.

2.4 Composite-only vs. Separable-Axis

Three-axis isotropic probes can be further differentiated as 'separable-axis' or 'composite-only.' Separable-axis probes allow detection and reporting of each axis's field intensity individually. In contrast, three-axis isotropic probes that only provide a single composite field value are categorized as composite-only probes. Some test standards require the use of separable-axis probes, while other standards do not have this requirement.

2.5 Stalk vs. Monopole-Over-Ground Plane

Field probes come in various physical configurations, with common configurations being 'stalk'-style and 'monopole-over-ground plane' style.

The stalk-style presents as an antenna ball on a pole, or stalk, remote from the probe's body, as shown in Figure 3.3. This configuration separates the RF sensors from the reflective electronic housing via a stalk, which provides performance benefits. Separating the sensor elements from the housing allows minimizing the size of the sensor elements (antennas) in the probe head, resulting in the ability to operate at higher frequencies while also reducing disturbance to the field being measured. Minimizing the housing/body size will also reduce the disruption of the field. While the stalk probe is an excellent approach, there may be limitations in usage due to the measurement location's physical constraints.

The monopole-over-ground plane style, seen in Figures 3.1 and 3.2, is typically seen as a metal cube or sphere, with three protruding orthogonal antenna elements. The cube or sphere body contains probe circuitry and acts as a ground plane for the antenna elements. The smaller overall physical size relative to the stalk probe may allow for use in applications where the stalk probe is too large.

Cube-style monopole-over-ground plane probes have a cubical-shaped body and come in various sizes. In general, the smaller, the better since a small probe has less effect on the RF field resulting in improved performance.

Sphere-style monopole-over-ground plane probes are typically preferred over cube-style probes by housing the electronics in a sphere that inherently has less effect on the RF field. In addition, the minimal field distortion is not position-dependent since there are no flat probe surfaces to contend with, reducing measurement variation due to probe orientation. The result is that a spherical probe style yields a flatter frequency and isotropic response than a cube probe.
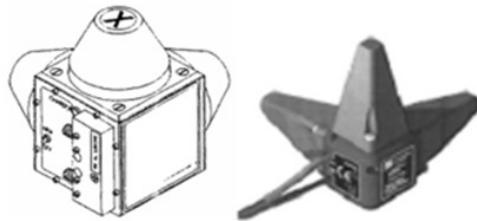

Figure 3.1: Cube-style monopole-over-ground plane probes

Figure 3.2: Sphere-style monopole-over-ground plane probes

Figure 3.3: Stalk-style

Figure 3: Several cube, sphere, and stalk probe sizes and styles (not to scale)

2.6 Diode Sensor vs. Thermocouple Sensor

Diode sensor probe type is currently the most common sensor used for RF field probes. Diodes have excellent sensitivity as well as a larger dynamic range than thermocouple sensors. However, diode sensors can have a non-linear response to modulated fields if steps are not taken in the probe's design to correct this effect.

An alternative sensor type is a thermocouple sensor. Thermocouple sensors can measure the average amplitude of a repetitive modulated field correctly; however, the modulation envelope would need to be known if a maximum reading was required. These sensors do not suffer from the same nonlinear response to modulated fields that diode type sensors do; however, thermocouple type sensors have a much slower response time than diode-based sensors. Since thermocouple probes are less sensitive and have a narrower dynamic range than diode-type probes, they are not commonly used in EMC immunity applications.

2.7 Laser vs. Battey Power

There are two methods of powering a field probe: battery power and laser power. Providing power to the probe using wires is not recommended since the metallic power cord would adversely affect field uniformity. Energy induced by the RF field in the power cord may introduce errors in the field measurements.

Battery-powered probes contain batteries in the probe housing. While battery-powered field probes and monitors are useful for hand-held mobile usage, the trade-off is reliability. Rechargeable batteries have a limited charge life as well as occasional failures. Since some probe vendors require that the probe be returned to the factory for battery replacement and recalibration, a simple battery failure can shut down an immunity test system. Running out of battery power in the middle of a test is also a limitation of battery-powered probes.

For applications that do not require the mobility provided by a battery-powered field probe, laser powered probes have been designed to avoid the reliability issues encountered with rechargeable batteries. This Power over Fiber (PoF) system uses a high energy laser driver to deliver laser energy to the probe via the same fiber optic cable used for communications. A converter within the probe converts the IR back to electricity to power the probe. Unlike a probe that relies on rechargeable batteries for power, a laser-powered probe can operate indefinitely, which translates to a vast improvement in reliability and productivity.

Laser safety must be considered whenever products are used that contain lasers. These products will fall into various categories dependent upon laser characteristics and power. Regardless, products containing lasers need to comply with safety standards that exist to protect the user.
Product manufacturers must ensure their product design incorporates proper safety mechanisms and labeling to conform to the applicable safety standard requirements.

2.8 Temperature Compensation

If there were to be a significant variation of temperature between when the probe was calibrated and when the probe was used during a test, the probe reading would likely contain an error component due to this temperature variation. Some probe manufacturers supply a temperature correction equation that must be applied to correct for ambient temperatures that differ from the temperature at which the probe was calibrated. Since high field levels and even operating EUTs can generate a great deal of heat, it is difficult to actually determine the "dynamic" heat fluctuation at any given moment, much less apply the correction factor. Thus, this cumbersome chore is often ignored, which introduces a source of error. Some manufactures provide probe models with internal temperature compensation that automatically adjusts as probe temperature changes.
For these probes, as long as the probe is used within its stated parameters, no additional temperature compensation is necessary, removing a source of thermal measurement error.

Conclusion

Field probes are specialized measuring devices and are available in various configurations and capabilities. Understanding these multiple configurations and functionality is critical when choosing a field probe. Frequency and dynamic range, E or H field, CW or modulated, composite or separable-axis, and laser or battery-powered are all important aspects to consider when selecting a probe. It is also important to review any test standards being used, as many test standards contain requirements for the field probe and thus should be consulted during the probe selection process.

Selecting the proper field probe with the appropriate characteristics and functionality is the first step toward performing RF field measurements. Once a probe is selected, using proper measuring techniques and best practices in operating the probe is important to achieve accurate measurements. These aspects are described and discussed in separate documents.

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RF Field Probe Calibration and Usage

RF field probes are a required piece of test equipment used for measuring the intensity of radiated RF fields. The use of a field probe may seem straightforward; however, there are numerous aspects of using field probes that can affect the accuracy of RF measurements. Probe mounting positioning and orientation, and sources of additional field contributions should be considered when making field measurements. Understanding these factors is important to allow achieving the best accuracy in field measurements.

Calibrations and Correction Factors are also important concepts to understand to achieve accurate field probe measurements. Improper, or lack of use of Correction Factors, will affect the accuracy of the field measurement. Since the field probe is used to establish the field intensity, poor measurements could lead to over-testing of the test object, where the test object is subjected to higher fields than intended. Conversely, poor measurements could cause the test object to be under-tested, where the test object is tested to field intensities less than required by the test standard. Understanding the factors that affect field probe accuracy is crucial to achieving the best results in making RF field measurements.

1.0 Field Probe Calibration

1.1 Calibration Overview

Ideally, a field probe would have a flat response curve across its rated bandwidth; however, the reality is that there will be frequency-dependent variations that deviate from nominal across the band. Calibration by a qualified calibration lab is necessary to determine the compensation needed to correct for these variations of the probe response. The calibration lab will measure the probe output in an RF field of known intensity. It will then determine the Correction Factor (CF) necessary to correct the probe field measurement at this frequency. This process will be performed at multiple frequency steps across the band, resulting in a table of CFs at multiple frequencies. CFs are an important aspect of probe usage and will be discussed in greater detail in a separate section.

Other probe characteristics may be part of the probe calibration, dependent upon calibration lab and/or customer requirements. These can include isotropy, the measurement of variation when the probe is rotated about an axis, linearity, the measurements at various field levels, or various combinations.

Probe calibration should be performed regularly. This interval is ultimately determined by the customer's metrology or quality policy, based on the probe manufacturer's recommended calibration interval. In the absence of a defined requirement, annual calibrations are commonly employed.

1.2 Calibration Lab Accreditation

When discussing probe calibration, references to ISO/IEC 17025 or NCSL/ANSI Z540 are often encountered. These two terms refer to standards of technical requirements for calibration labs. These standards provide guidelines and requirements for calibration labs to follow to standardize processes and procedures in performing calibrations to ensure consistent results. While very similar, these two standards do have some differences and as a result, some calibration labs may conform to one over the other or both.

Labs can self-declare conformance to these standards. However, many customers will require that their probe calibrations be performed at calibration labs accredited to one of these standards by a third-party accreditation body. Accreditation bodies such as A2LA, ANAB or NVLAP (in the US), among others, provide such accreditation services. Accreditation is a formal third-party auditing of the calibration lab's processes and procedures to ensure that the lab conforms to a standard's requirements. Calibrations at accredited labs are often referred to as an 'accredited calibration' or 'A2LA calibration', however these phrases are not technically correct as the calibration itself is not what is being accredited. These calibrations would more accurately be described as 'a calibration performed by a lab A2LA-accredited to ISO/IEC 17025', as an example.

Accreditation bodies exist worldwide providing calibration lab accreditation to the same standards (such as ISO/IEC 17025); however, customers are unlikely to be familiar with these bodies outside of their home countries. This situation led to the International Laboratory Accreditation Cooperation (ILAC) establishment to develop international cooperation for facilitating trade by promoting the acceptance of accredited test and calibration results. Accreditation bodies signatories to the ILAC establish a Mutual Recognition Arrangement (MRA), which allows an accredited calibration to be accepted as comparable and acceptable between accreditation bodies, thus easily allowing the international flow of calibrated products.

Additionally, a calibration can be classified as 'NIST-traceable' (National Institute of Standards and Technology). In the United States, a NIST-traceable calibration is a calibration that has been carried out with equipment whose calibration can be traced back to a National Institute of Standards and Technology (NIST) calibration. Note that this refers to the lab's equipment's calibration, not the field probe's calibration. Other countries may have their own nationally recognized calibration lab for traceability, for example, PTB in Germany or NPL in England. Traceability to a national or international standards lab is a requirement of ISO/IEC 17025.

1.3 Calibration Lab Measurements Uncertainty

When reviewing calibration results, the user must be aware of and keep in mind the Expanded Measurement Uncertainty (EMU) of the lab, which will be listed on the probe calibration certificate from an accredited lab. EMU is provided in a ±dB or % format and describes the accuracy range of measurements, with the probe calibration data falling within the EMU of the true value. The EMU is determined by considering many possible sources of variations involved in creating a known RF field level and measurement of the field and applying statistical analysis. The EMU may be defined in multiple frequency bands dependent upon equipment used. The calibration lab EMU has a trickle-down effect and impacts the EMC lab's measurement uncertainty using the field probe.

The magnitude of the EMU may be surprising when first encountered to those not familiar with field probe calibrations; however, this band-of-uncertainty reflects the realities of working with field probes and needs to be kept in mind. All measurement equipment has some amount of tolerance or uncertainty in a measurement, although field probe uncertainties are of a larger magnitude than what is typically encountered with other measuring equipment. Field probe uncertainties of ±0.5db to ±1.0dB, or higher, are not uncommon.

Repeatable field-level accuracy is inherently challenging. Reflection, refraction, and antenna near field effects combine to aggravate the uncertainties. Some probe calibrations are performed in a Transverse ElectroMagnetic (TEM) cell. A TEM cell can provide a more predictable and uniform field than free-space or semi/fully anechoic chamber environments. However, even these have a degree of uncertainty and are limited to their rated frequency ranges.

More details of field probe calibrations and EMU calculations can be found in IEEE-1309 Standard for Calibration of Electromagnetic Field Sensors and Probes.

2.0 Field Probe Correction Factor

2.1 Correction Factors Basics

A theoretical ideal field probe would provide an exact reading of the test field intensity across its entire frequency range. In the real world, however, probe response varies at different frequencies. Correction Factors (CFs) need to be applied to the field value reported by the probe to compensate for this. When applied, the effect is to flatten the probe frequency response across the entire frequency range to minimize errors. CFs are generated by a calibration lab and will consist of a table of frequencies and the correction to apply at each frequency. CFs can be expressed as a linear multiplier and/or a dB adjustment value, depending on the calibration lab's format. If plotted, the CFs yield a curve that is the inverse, or mirror image, of the probe's frequency response curve.

For separable-axes probes, CFs are provided for each axis independently (X, Y, Z) for each defined frequency. For composite-only probes, a single CF is provided for each defined frequency.

It is imperative for the user to take steps to ensure CFs are being used. Probe accuracy depends upon the application of the CFs generated by the calibration lab, and neglecting to use this data may cause substantial errors depending on the magnitude of the unused CF.

It is up to the user to determine how and where to apply CFs. This is commonly accomplished by entering the CF data into automated control software, where the software will then apply the proper CF as the test progresses. Alternatively, CFs may be loaded into an external field monitor or probe, depending on equipment functionality. Regardless, it is up to the user to ensure CFs are properly loaded and enabled. It is important to ensure CFs are applied at only a single location, not in the automated control software and an external device, which would cause the CFs to be applied twice.

Field probes are broad-band devices, and as such, are not able to discriminate the operating frequency. However, CFs are frequency-dependent, thus, to apply the proper CF, the test frequency must be known. When using automated control software, the software will control the test frequency at the time of field measurement and, therefore, apply the appropriate CF when configured to do so, interpolating between CF frequencies, as necessary. If using an external field monitor or probe system with CF capability, the equipment will need to know the frequency. The test software can accomplish this by communicating the test frequency to the equipment, or the operator can enter the frequency manually if operating in a stand-alone setup.

A CF as supplied by the calibration lab will be in the form of a linear multiplier and/or a dB adjustment value at each calibration frequency, depending on the lab. Using a multiplier is the more common and simpler method to implement, as the multiplier can be directly applied to the V/m field level reported by the probe.

2.2 Applying Correction Factors

When CFs are loaded into control software or equipment and properly enabled, the correction will occur automatically, and no manual user intervention is required. However, it is helpful to understand how CFs are used, so the process of manually applying CFs as a multiplier and calculating the composite field is described below.

When working with a composite-only probe, apply the CF multiplier for the operating frequency to the probe-reported composite field, resulting in a final corrected composite field value.
Example below:

$$ReportedField * CF = CorrectedField$$

$$14.7\,V/m * 1.09 = 16.02\,V/m$$

When working with separable-axis probes, individually apply the axis-specific CF at the operating frequency to each axis-reported field value (X, Y, Z). Example below:

X-axis   13.9V/m*1.1=15.29V/m

Y-axis   1.6V/m* 0.95=1.52V/m

Z-axis   2.2V/m*1.04=2.29V/m

2.3 Calculating Composite Field

On separable-axis probes, an additional step is needed to calculate the final composite field. After CFs have been individually applied to each axis, the composite field measurement is calculated by combining the corrected field measurements from the three axes using a Root Sum of Squares (RSS) calculation as follows:

$$CorrectedCompositeField = \sqrt{x^2 + y^2 + z^2}$$

Where:
'CorrectedCompositeField' is the final corrected composite field level in V/m
X is the corrected X-axis reported field level in V/m
Y is the corrected Y-axis reported field level in V/m
Z is the corrected Z-axis reported field level in V/m

Example of calculating a composite field using the individual corrected field values from the earlier example:

$$\sqrt{15.29^2 + 1.52^2 + 2.29^2} = 15.54\,V/m$$

2.4 Interpolating Correction Factors

The Correction Factor table supplied by the calibration lab provides CFs for discrete frequencies. When operating at frequencies between those provided in the probe CF calibration table, the recommended solution is to linearly interpolate between the adjacent frequencies to determine the CF as follows:

$$a_x = \frac{a_o(f_1 - f_x) + a_1(f_x - f_0)}{f_1 - f_0}$$

Where:

$$a_x \ is \ the \ desired \ CF$$
$$a_0 \ is \ the \ first \ known \ CF$$
$$a_1 \ is \ the \ second \ known \ CF$$
$$f_x \ is \ the \ frequency \ of \ the \ desired \ CF$$
$$f_0 \ is \ the \ first \ known \ frequency$$
$$f_1 \ is \ the \ second \ known \ frequency$$

2.5 Alternate Applications of Correction Factors

Occasionally situations may arise where the format required to apply CFs does not match the available CF data.

If using a separable-axis probe that will have individual XYZ CFs per frequency but need to enter only a single CF (e.g., test software allows only a single CF per frequency), average the three CF multipliers:

$$CF_{avg} = \frac{X_{cf} + Y_{cf} + Z_{cf}}{3}$$

An example of calculating an average CF multiplier from individual CF multipliers:

$$\frac{1.1 + .95 + 1.04}{3} = 1.03$$

In the opposite scenario, using a composite-only probe that will have only a single CF per frequency but need to enter XYZ corrections (e.g., test software requires entering individual XYZ CF's), use the same CF for all axes.

3.0 Field Probe Positioning, Orientation, and Mouting

3.1 Probe Positioning

RF fields radiating from an antenna may be reflected if encountering a metallic object, such as the Unit Under Test (UUT). These reflected fields can interact with the field radiating directly from the antenna, resulting in spatial areas of high and low field levels. These regular patterns of high and low field levels are called 'standing waves.' Standing waves can occur at any location where RF fields are reflected, although the effect is more likely to occur in front of the UUT, where reflections can more easily interact with the radiating field. When measuring field levels in close proximity to the UUT, experiment with various locations to find a configuration that provides reliable measurements.

In non-anechoic chambers or anechoic chambers with less-than-optimal performance, standing waves may also be present, affecting optimal field probe placement. In such applications, it may be appropriate to dampen the room resonance with strategically placed RF absorbers.

Field probe measurements can be affected by items in the probe's vicinity, such as the UUT, or if multiple probes are being used simultaneously. Measurements taken under these conditions may not provide a true measurement of the intended radiated field being generated. As a rule of thumb, maintain a minimum distance of 9 inches (23 cm) between adjacent probes. The minimum distance between a probe and a UUT will be dependent on the UUT and, therefore, must be determined by experimentation.

3.2 Probe Orientation

When mounting the probe, orient it such that the probe's metal housing is not causing reflections. This is primarily an issue with stalk-type probes with a square housing separate from the probe head. The housing body should not be located directly behind the probe head as this can cause a reflection resulting in a standing wave at the probe head. This reflection becomes more of an issue at higher frequencies in the gigahertz range.

Due to an isotropic field probe's orthogonal design, one would expect field readings to be unaffected by the field probe's orientation. However, RF field measurement's reality is that isotropic probes may exhibit some variation depending on the probe orientation, described as isotropic deviation. This value provides the variation that could occur as a function of probe orientation to the field. As the probe's accuracy depends on the use of the CFs generated at the calibration lab, the effects of Isotropic Deviation can be minimized by aligning the probe in the same manner as was used for calibration, which will include aligning one of the axes to the field.

Subjecting a test object to both horizontally and vertically polarized E-fields is a common requirement of many EMC test standards. To accommodate this, some users will mount the probe such that one of the probe's axes is horizontal; another axis is vertical, with the third axis pointing toward the transmitting antenna. See Figures 3 and 4, showing the mounting angles and orientation.

Figure 1: Side View: Z-Axis Aligned with E Field

With the probe mounted in this manner, if the antenna is rotated between horizontal and vertical polarization, the radiated field will be aligned with one of the probe axes in each polarization orientation.

Note that orienting the probe in this manner, although convenient for the user, may differ from the orientation used when the probe was calibrated. The user should be aware of and understand that aligning the probe to the field in an orientation that differs from the orientation used when the probe was calibrated may increase the uncertainty of measurements. Review the test standards being used for requirements or recommendations on how the probe is to be oriented.
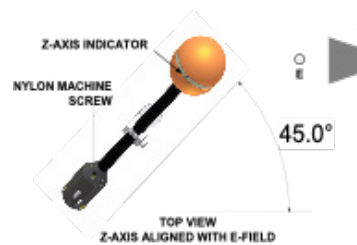

Figure 2: Top View: Z-Axis Aligned with E Field

For best accuracy, the probe should be used in the same orientation to the field as was used when the probe was calibrated.

3.3 Probe Mounting

Always mount a probe on a nonconductive (nonmetallic) stand/support using only nonconductive (nonmetallic) hardware, including screws. It is imperative to keep conductive objects away from a field probe. Any such objects in the proximity of the probe may distort the field and compromise measurement accuracy.

4.0 Field Probe Usage Consideration

Field probes are broadband devices, and as such, will report the total RF field energy detected. The RF field energy includes the expected fundamental frequency during the test, harmonics of this frequency, and other environmental signals. In EMC testing, the expectation is that the carrier frequency is the primary RF energy source. The user should perform testing and/or calculations of the test setup and environment to understand the magnitude of any ambient signals and harmonics to ensure they are at acceptably low levels. Many test standards define specific testing and verification processes for these characteristics, so it is always important to consult the test standard for any requirements.

Emissions from the UUT can contribute to the field measured by the probe. Where active field monitoring is to be used during UUT operation, it is recommended to first operate the UUT and test equipment together with the probe, however without a test field to determine any ambient field. The ambient field level should be low enough such that the error contribution to the field measurement is consistent with the application requirements.

Broadband or wideband noise energy from an amplifier can also contribute to the RF field in situations such as testing at low field levels using a substantially oversized amplifier. TWT amplifiers are especially prone to producing noticeable broadband noise power, as well as harmonic content. Although the noise is at a low noise power density level, the noise from broadband RF sources accumulates over the probe's broad frequency range. This situation would most often be seen if operating an amplifier at a small percentage of its full power. Operating the amplifier with no input signal and measuring the field can help detect amplifier noise power contribution to the measured field. Using space loss or other attenuation can help alleviate this situation.

4.1 Out-of-band Response

Although field probes have a specified operating frequency range, they may respond to frequencies above and below their specified range. Users should be alert to unexplained readings that may be caused by unintended fields, whether in-band or out-of-band. Pay special attention to fields generated by a UUT or by test equipment located very close to a probe, including AC power lines and power supplies.

4.2 RMS vs. Peak

RF field probes are designed to measure the root mean square (RMS) value of the field. This is true regardless of if the probe is a CW or a modulated probe, as the probe is responding to and measuring the RF carrier.

When working with pulsed signals, signal levels are often referred to as the 'peak' level; however, this would more accurately be described as the 'RMS level of the pulse.' The instantaneous peak of an RF field can be calculated in the same manner as a peak value can be calculated of any cyclical signal, although this peak value is not used in EMC test standards.
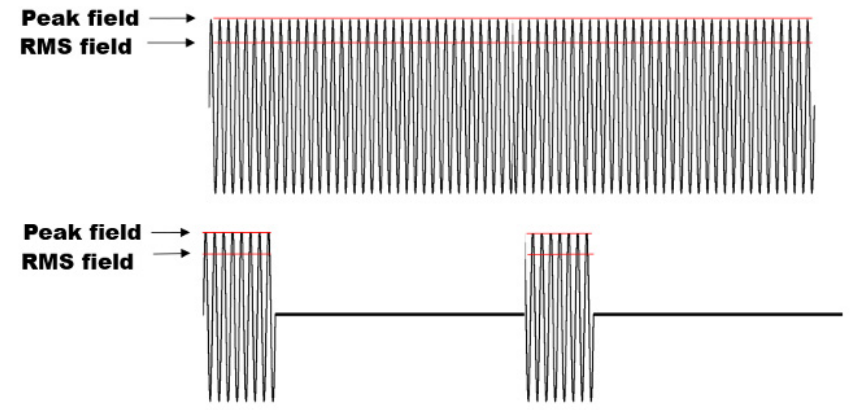
4.3 Operation in TEM Cell

An ideal field probe would measure the RF field without having any effect on the field. Field probes, however, are physical objects, and by necessity, include conductive parts and thus will affect the field to some degree. Probes with smaller bodies and antennas reduce field distortion caused by the probe.

This sizing factor becomes an important consideration when using a probe in a confined space, such as in a small TEM cell. Since probes have metallic content, when a probe is in a TEM cell, the probe's metallic portions can act to partially 'short' the field, thus causing more significant disruption and effect on the field than when measuring a field in a free-space environment. The user should be aware of this effect when operating in a TEM cell. The probe's metal body is recommended to be no more than 1/3 of the septum-to-body measurement when using a probe in a TEM cell.

Summary

Field probes are an important part of a radiated immunity test setup. A field probe will report the field it detects at its location; however, this field can be influenced by outside factors as discussed. Things such as probe calibration, use of Correction Factors, probe mounting and orientation, and other RF energy in the area can all contribute to the accuracy of the field level measurement. Accurate field measurements are important to avoid over or under-testing the UUT. Being aware of the external factors affecting field measurements, and taking the steps necessary to evaluate each, is important to achieving accurate measurements.

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5

Software Automation

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As technology evolves, electronic devices continue to take on a more mobile and virtual nature. While RF and microwave amplifiers themselves may never become truly 'mobile', the way we control them can be. AR's ampwebwARe gives you the capability to monitor and control your amplifier remotely without needing any software of your own. If the user switches to 'remote', the front panel locks and the user can control the amplifier from an embedded webpage. Through this webpage, you can look at the power the amplifier is generating, the hours of operation, and manage all the controls remotely that you would normally do from the front panel of the amplifier.

1.0 ampwebwARw Features
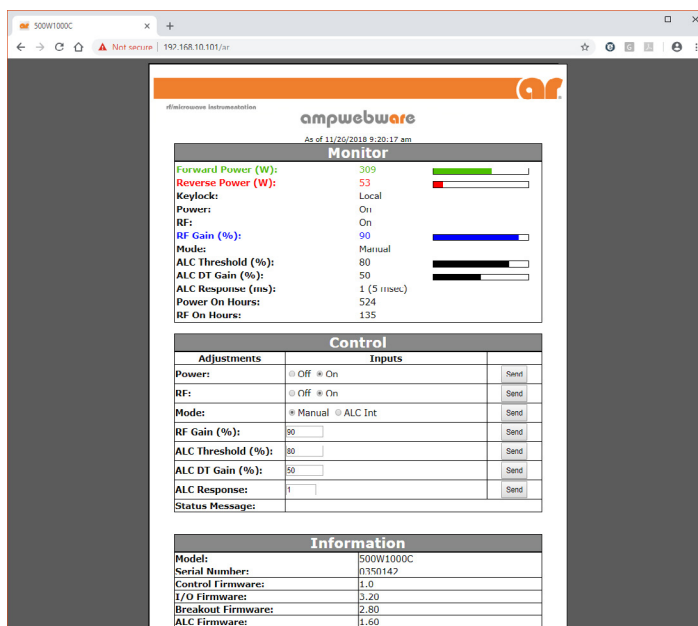
Beginning in 2019, AR will be embedding ampwebwARe in all new amplifiers. Once an amplifier is connected to a network and an IP address is set, any other device connected to that network can access the amplifier's embedded webpage. The features of this embedded webpage include:

- All information shown on one screen
- Simple user interface
- Allows for remote diagnostics
- Monitor Status from anywhere
- Multiple simultaneous browser connections
- Many supported web browers

2.0 ampwebwARe Layout and Tables

The data presented to the user is categorized into various sets. Each set of data is shown as a table with its own header. Different amplifier models will contain different sets of data, depending on its complexity. At a minimum, a webpage will contain a monitor table and control table. The monitor table will always come before the control table. The monitor table shows data which is updated periodically. Above the monitor table there is a time stamp which indicates the last time that the information in the table was updated.

The control table allows data to be entered to control the amplifier. This data is sent to the amplifier via a 'Send' button corresponding to each adjustment. Examples of monitor and control functions include monitoring forward and reverse power, adjusting gain and setting the amp's internal ALC. Depending on the amplifier model, other tables may be available as well. These tables can include status information about an amplifier's firmware revisions, transistor currents, and module temperatures. An example layout is shown in Figure 1.

Summary

In order to modernize our amplifiers, AR is providing ampwebwARe in all of our new amplifiers. This software allows for remote communication to AR amplifiers through any device connected to the same network as the amplifier, via an embedded webpage. From this embedded webpage, the user can both monitor and control the amplifier. If you would like to learn more about ampwebwARe, feel free to contact one of our applications engineers at 800-933-8181 or visit our website at www.arworld.us.

rf/microwave instrumentation

Frequently Asked Questions About emcware ® 5.0

- **What is emcware?**

  emcware is a test Software solution that automates Electromagnetic Compatibility (EMC) testing and report generation.

- **Can I get a free copy of emcware for assessment?**

  As of June 1, 2020 live demos will be available for assessment of emcware. To request a demo contact your local AR sales representative or AR Sales directly at 215-723-8181.

- **How can I purchase emcware 5.0?**

  Please contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us for more information.

- **Can I see a demonstration of emcware?**

  You can contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us. These can be in-person demonstrations or through webinar.

- **How and where can I purchase a support contract for emcware?**

  You can contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us

- **What are the EMC tests I can perform using emcware?**

  emcware supports the following test modes:
  1. Raditated Susceptibility
  2. Conducted Immunity
  3. Radiated Emissions
  4. Conducted Emissions

- **What are the EMC test standards covered in the emcware package?**

  Over 500 pre-defined test setups for IEC, CISPR, MIL-STD-461, DO-160, Automotive, etc.

- **Can I get an automatic notification for emcware revision updates?**

  Yes, emcware will send you an automatic revision update notification when the registered user's computer is connected to the internet.

- **Can I perform Chamber Uniform Field Area (UFA) calibration using emcware?**

  Yes, emcware is a tool of choice to perform chamber/site calibration.

- **Can I build a customized EMC test profile in emcware?**

  Yes, emcware is designed to support customized test profiles.

- **Does emcware support non-AR equipment?**

  Yes, emcware has a library of over 300 equipment drivers. A complete list can be found on emcware's data sheet.

- **What if the driver I need isn't already in emcware's driver list?**

  AR has provided a template .dll file for the user to develop their own equipment driver. AR will also develop custom drivers, for a cost.

- **Does emcware offer any EUT monitoring capabilities?**

  Yes, through NI DAQ or custom EUT monitoring drivers, emcware can communicate with an EUT, detect a failure and automatically pause all testing to prompt the user for an investigation. AR provides a C template for the user to develop custom EUT monitoring drivers.

- **Can I upgrade my version of 4 to 5? How does this work?**

  To learn more about emcware 5.0, contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us

- **What if I have a service contract on my current 4.1 version?**

  Please contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us for more information.

Software Automation
Find it Fast

ampwebwARe

Frequently Asked Questions
About emcware 5.0

- Can I continue to use version 4?

  Yes, emcware v4 (or previous versions) will continue to work on your computer but will no longer be supported after 12/31/2020.

- Can I still download a copy of emcware 4.1?

  As of June 1, 2020 emcware 4.1 is no longer available for download.

- Will AR supply a V2C file to allow registration of version 4?

  As of June 1, 2020 new V2C registrations are no longer available.

- Will AR support emcware 4.1? What if I have questions on how to use, or find a bug? Bug Fixes?

  Support for emcware 4.1 will be available until 12/31/2020.

- I downloaded emcware for free previously, but now it looks like I have to pay. Does AR have a free version of emcware?

  As of June 1, 2020, only emcware 5.0 is available. Contact your local AR sales representative, call AR Sales directly at 215-723-8181 or email us at info@arworld.us to learn more.

- Where can I download the latest emcware and driver versions?

  After purchasing emcware 5.0 please visit emcware.arworld.com

- What do I get with an emcware support contract?

Service	emcware 5.0 Purchase	Service Contract
Access to emcware Support Website	✓	✓
Bug fixes, maintenance updates and driver updates for current version	✓	✓
Free upgrades to new versions		✓
Automatic notification of available downloads	✓	✓
Access to AR Applications and Software Engineers		✓
Setup Support		✓
Problem acknowledgement within 24 hours		✓
Email, phone and remote support		✓
Dedicated support staff focused on providing solutions Software Support		✓
Equipment Driver Support	✓	✓
Driver Creation	Available upon request [1]	
Driver Support	✓	✓
DIY Driver Templates [2]	✓	✓
DIY Driver Templates with Example code [2]		✓

1 Additional charges may apply - call for more information
2 User knowledge of a programming language that can generate Windows Dynamic Link Library files (*.dll) is required.

- Does emcware work with Keysight GPIB controllers?

  emcware by default will work with National Instruments GPIB controllers. If using emcware with a Keysight GPIB controller, additional setup is required. Please reference the below articles for more information:

  From Keysight's website:
  https://www.keysight.com/us/en/assets/7018-02086/application-notes/5990-3731.pdf

  From NI's website:
  https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z0000019L2jSAE
  https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z000000P9t6SAC

AR RF/Microwave Instrumentation • 160 Schoolhouse Rd, Souderton, PA 18964 • info@arworld.us
To order AR Products, call: 215.723.8181. For an applications engineer, call: 800.933.8181
Direct to Service, call: 215.723.0275 or email: service@arworld.us

1 of 2

6

General Wireless Applications

sunar rf motion

Distributed Antenna System (DAS) for IoT, Cellular & Other Wireless Applications

The Internet of Things (IoT) has continued to grow at a rapid rate in recent years. With the connectivity of cellular devices, computers, vehicles, buildings, sensors, and more electronics, it's more important than ever that these devices are able to connect, communicate and meet the needs that users covet. The wireless connectivity for the IoT will use many network access technologies, including Global System for Mobile (GSM), cellular Long Term Evolution (LTE), 4G and the much anticipated revolutionary 5G to name a few. There are plenty of other wireless protocols and air interfaces available for supporting IoT applications (WiFi, Bluetooth, LoRa, ZigBee, and Z-Wave, to name a few), but it's clear the landscape is changing and IoT devices will take advantage of the protocals offering the greatest data throughout. Distributed Antenna Systems (DAS) provide strong and reliable wireless connectivity in location where connectivity is a problem with standard wireless routers or cellular connectivity, such as: inside multistory buildings, outside industrial settings, and subterranean environments So, DAS in conjunction with (LTE/4G/5G) based IoT services will continue to grow in coming years.

1.0 Why DAS?

While some of the IoT applications will be outdoors (connected cars and trucks or street lighting infrastructure, for example), most IoT applications will be within buildings. Industrial control, point of sale, asset tracking, medical, environmental monitoring, security, smart lighting, and other applications will require strong in-building wireless connectivity or signals. Ideally, the wireless network solution should deliver seamless blanket coverage throughout the building so as not to restrict where IoT sensors can be placed. However, in reality, this blanket coverage can be difficult to achieve with simple wireless routers. DAS is particularly helpful in providing the needed wireless coverage. Access to wireless IoT communication not only aids the public, but is also mandatory for law enforcement, emergency medical, and fire services. As realization of the importance of DAS for IoT applications became apparent, so has backing from local and federal governments through proposed rulemaking.

Furthermore, DAS should support multiple frequencies, because mobile operators use 700 MHz, 1900 MHz, and AWS frequencies for LTE, among other frequencies. The solution should also support complex modulations such as time division duplexing (TDD) as well as frequency division duplexing (FDD) because mobile operators will use both technologies in their networks.

DAS also offers single-zone wireless coverage in a building: unlike small cells, it isn't subject to inter-cell interference and handoffs from one coverage area to another as devices move through a building. In addition, DAS infrastructure natively supports multiple wireless frequencies. Finally, some DAS support both TDD and FDD transmission schemes, whereas today's small cells do not.

2.0 What to look for when selecting a DAS

There are many DAS solutions on the market. The main component of any DAS is the selected amplifiers and antennas. These amplifiers and antennas must offer a wide operating frequency range, and good linear RF performance to cover WiFi and all cellular and wireless services. In addition, these amplifiers and antennas must be unobtrusive, easy to install and maintain, durable, and high quality.

DAS systems can be separated into three categories:

Active DAS: When there is a huge demand from users or IoT based systems to access cellular coverage or WiFi, the active DAS system will help increase capacity and reduce the load from the macro network.

When additional capacity is needed, like in a football stadium or airport, an active DAS system is typically used. A state of the art active system can cover virtually any size of building and up to any capacity. Some of the most ambitious, active DAS systems have been designed to cope with the load of over 70,000 Super bowl attendees or the 2.47 million sq. ft. of coverage.

Active DAS systems often use fiber optic cable to distribute the signal between a centralized signal source and "remote nodes" placed around a building. The signal source is typically a "head-end" that combines signals from multiple carriers, which each need to provide their own signal source to the system, typically via their own fiber backhaul.

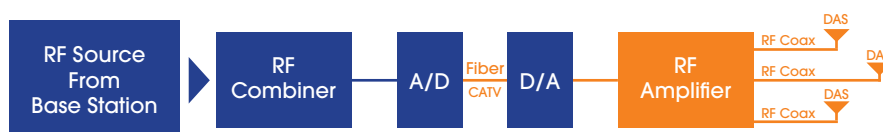The block diagram and elements of an active DAS system are shown below:

Figure 1: Block diagram of an Active DAS System

Passive DAS: Passive DAS systems typically use passive components like coaxial cable, splitters, and duplexers to distribute signal, and unlike active DAS, they use bi-directional amplifiers to rebroadcast the signal from the macro cellular network using a donor signal on the building roof.

There are limitations to the reach of passive DAS solutions. Because they use coax cable to distribute signal, signal loss is higher than with active DAS. The further away the antennas are from the amplifier, the higher the signal loss. The signal loss generally results in lower downlink output power.

These restrictions mean that the maximum coverage area for a passive DAS system is typically around 500,000 sq ft. But the advantages of passive DAS systems are considerable. In particular, they are considerably less costly than active DAS.

The block diagram and elements of a passive DAS system are shown on the next page, Figure 2:

Figure 2: Block diagram of a Passive DAS System

Hybrid DAS: A hybrid system works a lot like an active DAS system. Hybrid DAS uses some fiber for backbone distribution of signal, and relies on passive coaxial cable for much of the remaining signal distribution. Hybrid systems can be a good solution for medium-sized spaces, or unusual signal problems. Multiple passive systems can also be linked by fiber cable to a remote amplifier unit.

The block diagram and elements of a Hybrid DAS system are shown below, Figure 3:
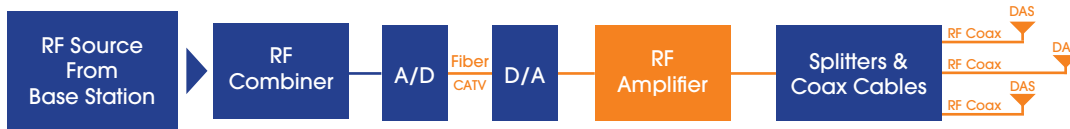

Figure 3: Block diagram of a Passive DAS System

3.0 The Solution

To meet these demands – to boost cellular network coverage and add capacity to reduce load from the macro network, AR rf/microwave instrumentation (ARI) and SunAR RF Motion have developed a series of broadband solid-state amplifiers and antennas to address DAS requirements. More specifically, SunAR DAS antennas are more directional than standard DAS antennas, allowing them to excel in applications requiring directivity, such as airport terminals, subway tunnels, hotel hallways, or directed at crowds at a sports venue.

In addition, ARI amplifiers and antennas are broadband, allowing them to cover a larger number of communication bands, potentially reducing the number of deployed DAS antennas in a system, versus standard narrowband DAS antennas. The SunAR DAS antennas' innovative design and manufacturing techniques result in long-lasting strength, excellent performance, and provide an aesthetic appearance. These antennas can be used in large, small, passive, active, and hybrid systems.

SunAR offers four antenna models for DAS solutions.

Model LP425R is a directional antenna designed for transmitting and receiving wireless communications signals. The broadband characteristics of the log-periodic structure enable it to operate over a very wide frequency range with constant gain. This DAS antenna outperforms many antennas in this class and is designed for more rugged environments. Below, Figure 4, is an image of the LP425R.

Figure 4: LP425R 400 MHz - 3 GHz

Model's LP425PCB, LP6530PCB, and LP6560PCB are low-profile directional antennas designed for transmitting and receiving wireless communications signals. These antennas are etched onto a low-loss microwave substrate material and mounted in a weather resistant housing that is only 1/2" inch thick. Like the LP425R, the broadband characteristics of the enclosed antenna structures enable it to operate over a very wide frequency range with constant gain. There are four mounting holes for installation onto any flat, non-conductive surface, such as an office wall or ceiling. Figure 5 shows the LP425PCB, LP6530PCB, and LP6560PCB.

Figure 5:

LP425PCB 400 MHz – 3 GHz

LP6530PCB 650 MHz – 3 GHz

LP6560PCB 650 MHz – 6 GHz

The MIMO (multiple input, multiple output) antenna, shown in Figure 6, is actually a set of two broadband directional antennas, cross-polarized, in a single package with two RF connectors. This design provides polarization diversity in a MIMO environment. This configuration results in greater throughput than a single antenna.

Figure 6: LP65330PCB-MIMO 650 MHz - 3 GHz

Each antenna is innovative and uses manufacturing techniques that result in long-lasting strength and performance. Specifications for each DAS model is shown in Table 1.

Table 1: SunAR's DAS Antenna List

Model	Freq. Range	Gain (dBi)	BW (deg.)	Ω	VSWR	Conn.*	Input PWR. (W)	Length x Width (inches)	Weight in lbs (kg)
LP425PCB	400 MHz - 3 GHz	5.5	70° V Plane 100° H Plane	50	<2:1	N Female	25	15.5 x 11.5	2 (0.7)
LP425R	400 MHz - 3 GHz	7	70° V Plane 100° H Plane	50	<1.8:1	N Female	200	19 x 16	2 (1)
LP6530PCB	650 MHz - 3 GHz	7	70° V Plane 100° H Plane	50	<1.5:1	N Female	25	15.5 x 11.5	2 (0.7)
LP6560PCB	650 MHz - 6 GHz	6	70° V Plane 100° H Plane	50	<1.5:1	N Female	15	15.5 x 11.5	2 (0.7)

ARI offers Class A solid-state, linear, robust and versatile broadband RF amplifiers, see Table 2. These high performing RF amplifiers allow DAS systems to cover a large number of communication bands, helping increase the coverage throughout areas hindering RF signal strength, or over use of available bandwigth. Figure 7, is just one example of a DAS solution in an office building setting.

Table 2: ARI RF Amplifiers for DAS Applications

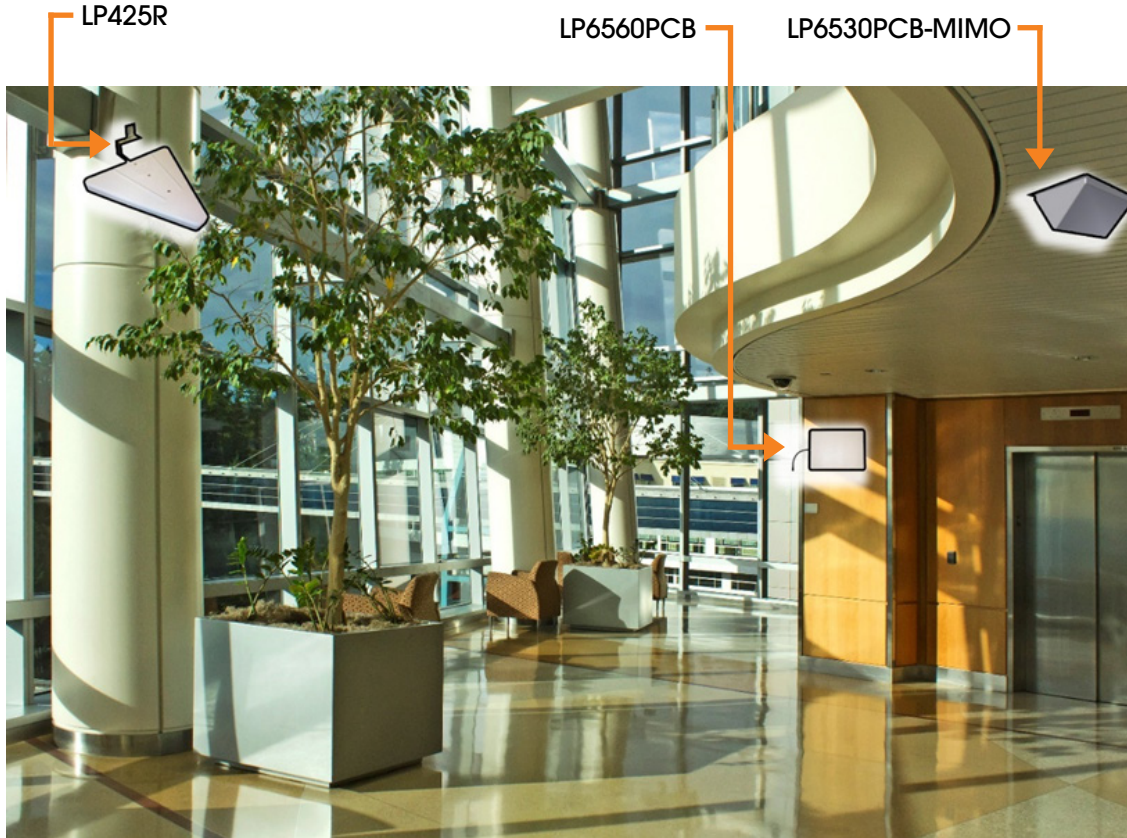| Amplifier Model	Frequency Range	Output Power (W)
10U1000...50U1000	10 kHk - 1 GHz	10 W - 50 W
100U1000...250U1000	100 kHk- 1 GHz	100 W - 250 W
150W1000B...500W1000B	80 MHz - 1 GHz	150 W - 500 W
100S1G2z5A...500S1G2z5	1 - 2.5 GHz	100 W - 500 W
20s1G4...350S1G4	700 MHz - 4.2 GHz	20 W - 350 W
15S1G6...500S1G6	700 MHz - 6 GHz	15 W - 500 W

LP425R

LP6560PCB

LP6530PCB-MIMO

Figure 7: Typical Office Setting for a DAS Application

Conclusion

The rapid growth in connected devices (IoT) promises lucrative business opportunities. In places where traditional distribution services cannot provide the required signal strength, DAS can be used. By deploying a robust and economical DAS system, governments or businesses can ensure robust support for IoT within their facilities and be positioned to deliver critical wireless services now and in the future. The amplifiers and antennas described in this application note meet these demanding requirements, and more.
AR's wide array of amplifiers and antennas help you select the right system for your application. These amplifiers and antennas are designed using quality processes and components that are reliable, consistent performance from unit to unit, and allow for easy installations in a wide variety of situations, both indoor and out.

Using ARI DAS solutions will enable you to achieve your goals. To learn more about ARI DAS solution, feel free to contact one of our applications engineers at 800-933-8181 or visit our website at www.arworld.us.

rf/microwave instrumentation

Telecommunications Testing Using AR Amplifiers

On September 2nd, 1837, Samuel Morse demonstrated a device for transmitting information by electromagnetic energy through conductive wires. 60 years later, Guglielmo Marconi founded the Wireless Telegraph & Signal Company, and since then, the world has never looked back. Progressive advancements have climbed the electromagnetic spectrum and pushed device technology to ever greater heights. This has been especially true since 1980 when cellular communications systems became commercially viable. This application note will explore some of the testing requirements for telecommunication devices and how to benefit from AR RF/Microwave Instrumentation's products.

We will consider two broad categories of device testing: characterization and reliability. Characterization testing focuses on device performance as related to its operation in a defined and specified condition. Reliability testing aims to determine the life expectancy and limits of the device. This application note will focus on mid to high power systems (> 1watt peak). Low power systems (<28dBm peak) such as Bluetooth, Zigbee, and LAN do not typically require test bench amplification.

1.0 Characterization Testing

Telecommunication system devices must be characterized over temperature, voltage, modulation, drive level, and frequency. Common test parameters are power saturation, isolation, and linearity. This generates a vast quantity of data, and thus a test system must be highly reliable and faithfully replicate the desired stimulus over the parametric range. AR amplifiers provide the widest frequency bandwidth (BW) in the industry and cover power levels from 1 watt to well over 10 kW.

2.0 Linearity Tests

Common measurements are intermodulation or multi-tone (IM3/IP3/OP3), spectral emission mask (SEM), error vector magnitude (EVM), and adjacent channel leakage ratio (ACLR). For many decades, multi-tone, typically 2 tones, have been the principal metric in determining a device's linearity. Early telecom methods did not contain much data, and analog modulation was enough. Modern digital modulation schemes continue to push data rates ever higher (see Figure 1), increasing the need for greater linearity over a large bandwidth and power range. AR amplifiers are predominantly Class A, providing the best possible linear amplification.
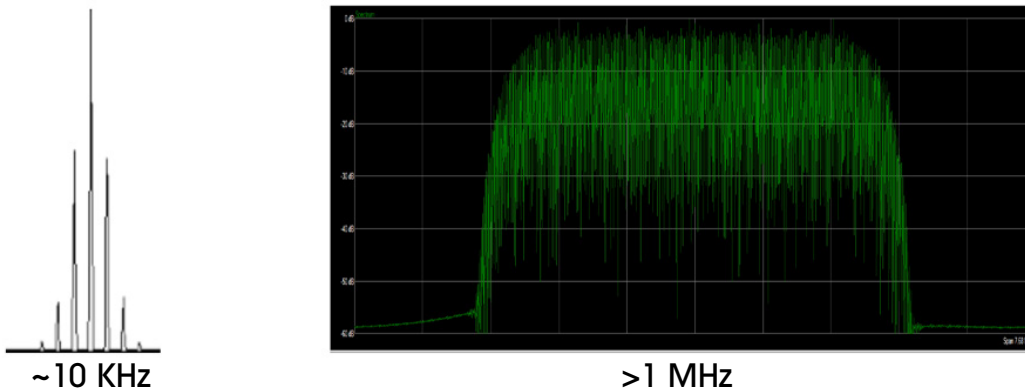

~10 KHz   >1 MHz

Figure 1: BW of Analog vs. Digital Modulation

3rd Generation Partnership Project (3GPP) is the standards development body for mobile communications. Successive generations 3G, 4G to the current 5G chronicle this expansion of spectrum bandwidth. 3GPP defines the test models (TM) or modulation profiles for testing linear performance of user equipment (UE) and base station (BS), and by extension the devices used in those systems. 5G modulation schemes for both uplink and downlink range from channel width of 5 to 100MHz with peak to average ratios (PAR) up to 14dB. See Figure 2 below.
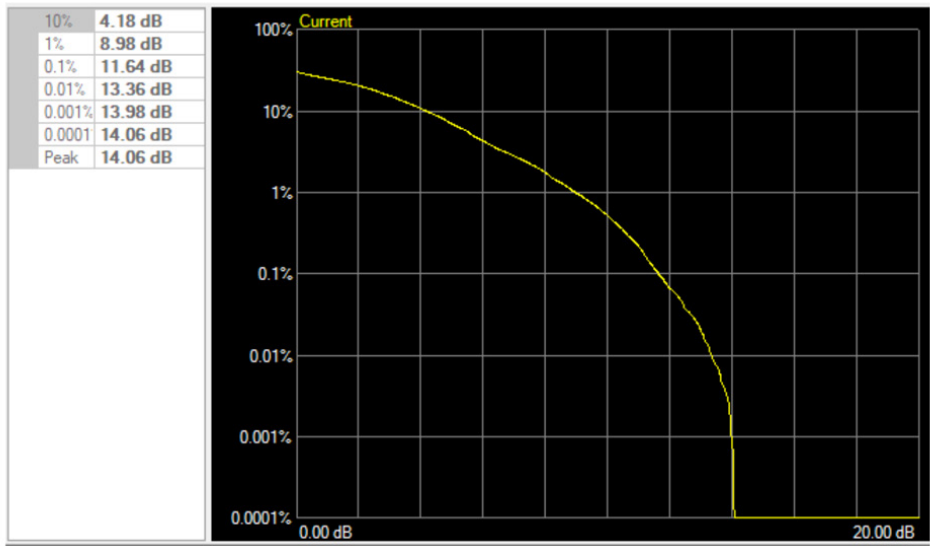
Figure 2: 5G CCDF Plot/PAR Test Model 2a

Channel power is specified by average power. High PAR therefore will require the lab amplifier to maintain good linearity to the peak value (avg power = 23dBm, PAR = 14dB, peak power = 37dBm). Figure 3 is a measurement of AR Model# 30S1G6 using TM 1.1. This plot shows the average power output for a given linear target. By comparison, Class AB power amplifiers are by nature less linear and are prone to gain expansion from small signal to max power. This adds to the distortion on high PAR modulations.
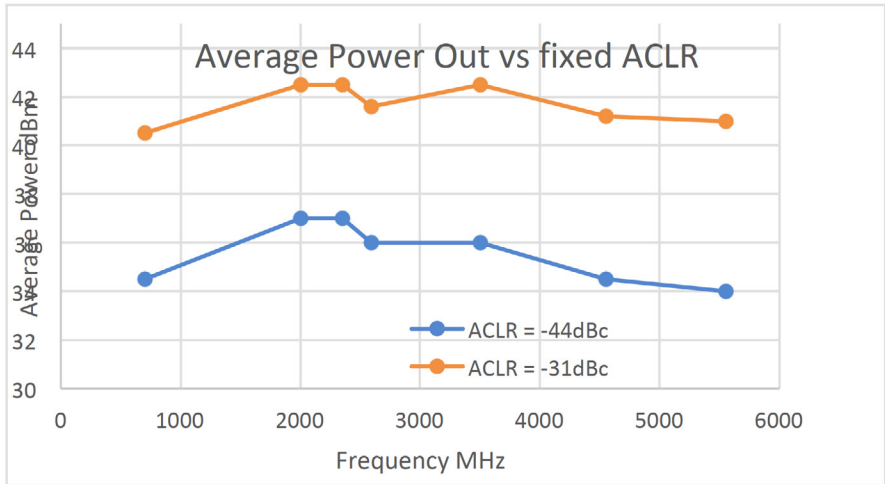

Figure 3: TM 1.1 ACLR measurement of AR Model# 30S1G6

Multi-tone intermodulation measurements can benefit as well from a power amplifier. While this is a 'small signal' parameter, very high IP3 devices, such as a base station T/R switch, require a large dynamic range. For an input IP3 of 50 dBm and a total tone power of 0 dBm, IM products will be ~ -109dBm (dynamic range = 109dB). This can be difficult to measure accurately. By increasing RF drive while keeping level below saturation, IM products are exponentially increased and dynamic range reduced to a comfortable level (IIP3 = 50dBm, total tone power = 30dBm, IM product = -19dBm, dynamic range = 46dB). High power devices will also need drive amplification to measure deep saturation and isolation.

3.0 Reliability Tests

Long-term operating life, burn-in, and drive level failure are critical tests to determine a device's reliability. High temperature operating life (HTOL) is the common method to determine the life cycle of a device. Burn-in is a method to weed out the weak product. Drive level failure determines a device's susceptibility in its operational environment. Any of these tests require drive levels to meet or exceed the DUT maximum rating. Since device failure is an expected condition, the drive amplifier must withstand a possible short or open condition. AR amplifiers have long been known for their immunity to high VSWR. HTOL and burn-in tests are typically applied to many DUT's at the same time. AR can offer RF distribution systems scalable from 8 to 80 channels. See Figure 4.
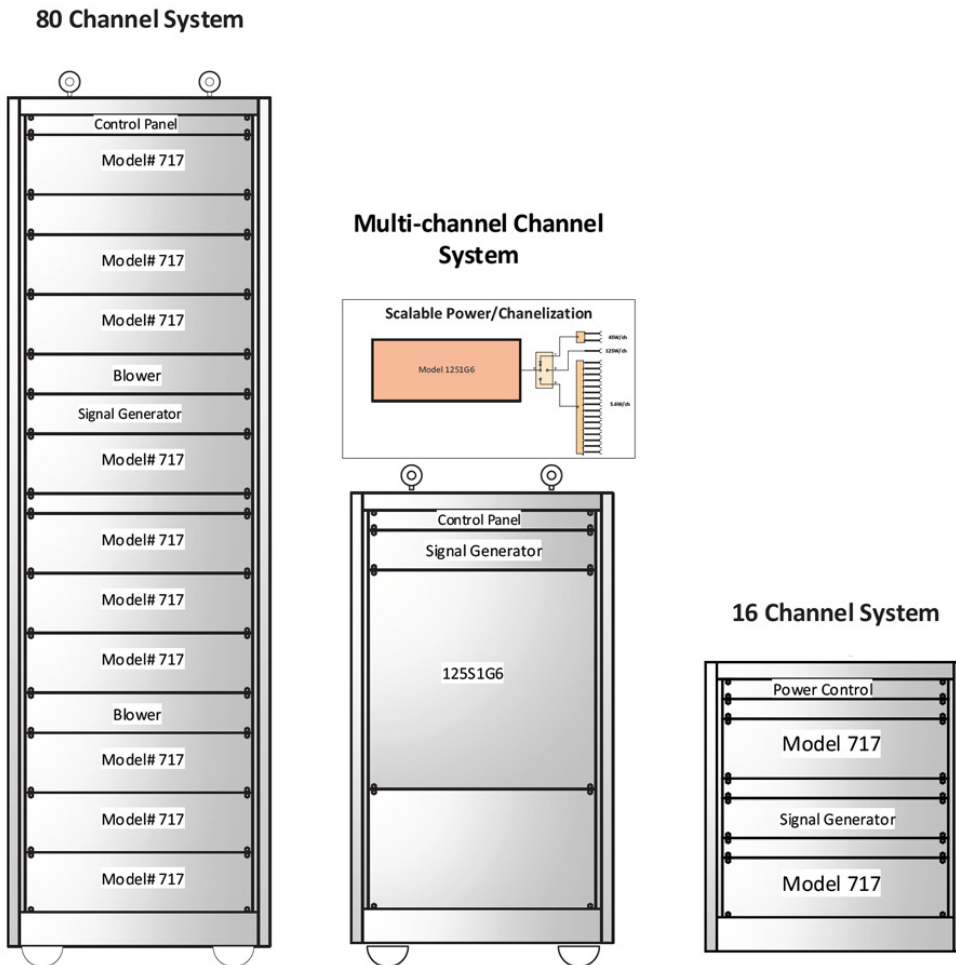
80 Channel System

Multi-channel Channel System

16 Channel System

Figure 4: HOTL RF distribution systems

4.0 Recommended Models for DUT Characterization

AR's S-series line of amplifiers specifically targets existing cellular frequency bands (15 to 500 W). See Table 1 for a recommended model matrix matched to your testing requirement. We also have an extensive line to cover other frequencies as low as 10KHz and as high as 50 GHz. Please contact AR's expert application team to ascertain the right model for your specific requirement.

Model #	Linear Power (W)	Frequency Range (MHz)	Application	Testing Profiles
15S1G6	15	600-6000	User Equipment (UE) Mobile Handset	Pre-amp for Linearity Test IMD/ACLR/SEM/EVM
30S1G6	30	600-6000	Pre-amp for Linearity Test IMD/ACLR/SEM/EVM	Pre-amp for Linearity Test IMD/ACLR/SEM/EVM
60S1G6	60	600-6000	Macro-cell Base Station UE Reliability	Pre-amp for Linearity Test IMD/ACLR/SEM/EVM UE HTOL/Burn-in
125S1G6	125	600-6000	UE and BS Reliability	UE/BS HTOL/Burn-in
250S1G6	250	600-6000	UE and BS Reliability	UE/BS HTOL/Burn-in
500S1G6	500	600-6000	UE and BS Reliability	UE/BS HTOL/Burn-in

Summary

Our products are the industry leader in warranty and reliability. Tolerance to RF loading to short or open condition is guaranteed under absolute maximum rating conditions. This is important in a test lab environment where the amplifier may be subject to high VSWR. Downtime is eliminated or reduced. Whatever your testing need, we have the solution either in our existing line or as a custom system solution.

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To order AR Products, call: 215.723.8181. For an applications engineer, call: 800.933.8181
Direct to Service, call: 215.723.0275 or email: service@arworld.us

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rf/microwave instrumentation

Integrated Circuits (ICs) & Component EMC Testing

Can you imagine the world without Electronic devices? Today's electronic gadgets, machines and appliances have become an integral part of our lives. This is most apparent with recent developments in technology like drones, Mobile internet, medical devices, Internet of Things (IoT) and autonomous vehicles. The "core" of these amazing technologies is built with today's faster and smarter electronic components.

Due to the demand for high performing electronic devices, multi-chip package (MCP) and system on a chip (SoC) technologies have become widely employed. In addition, as operating frequencies of these emerging technologies (IoT and 5G) have increased and circuits used in those technologies have become more complex, it has become impossible to ignore the large amounts of parasitic emissions generated by such complex integrated circuits (IC's). Most IC devices operate within the Radio Frequency (RF) spectrum. When these devices co-exist with many other products, the RF spectrum becomes more congested and creates a complex electromagnetic environment. The heart or core of these electronic devices-"components"-must be hardened to operate safely and reliably in the intended electromagnetic environment. Additionally, the more electronic devices that these technologies interact and co-exist with, the greater the potential for disturbance (RF interference) among them. The largest challenge for emerging applications will be RF compliance of products and their component parts, not only with regard to regulatory requirements, but also a greater emphasis on operational environments to ensure proper performance and public safety.

Almost every Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) problem ultimately starts or ends at an electronic circuit. Due to the focus on energy savings and reduced power consumption, there is an increased demand for low power ICs and circuits designed with reduced supply voltages. This results in the degradation of circuit immunity levels as incident RF disturbances can easily influence a lower-power circuit. Therefore, it is required to evaluate the performance of these components for both EMI and EMC during the design stage.

Suppose you are in the business of producing IC products that are built to operate in demanding electromagnetic environments. In that case, you must also take precautionary measures to test and pass all the regulatory EMI and safety requirements to achieve early time to market and profitability.

So, how can one test these electronic "components" to electromagnetic fields? EMC testing is performed to ensure these components can be used in the intended environment (i.e., 5G, IoT, drones, automobiles, and more) without failing, degrading, or causing other equipment to fail.

The International Electrotechnical Commission (IEC) established a standard for measuring the electromagnetic interference and susceptibility to characterize ICs up to 1 GHz, IEC 62132. IEC 62132-1 provides general information on the measurement of conducted and radiated electromagnetic susceptibility. The following table provides an overview of IEC 62132 standard.

Table 1: IEC 62132 EMC test standard and some of its parts

Part of IEC 62132	Standard Title	Test Coupling to	Frequency Range & Modulation	Test Type
1	General conditions and definitions	Integrated circuits (ICs)	150 kHk - 1 GHz	NA
2	Transverse electro-magnetic (TEM) cell	EUT and/or Wiring harness	150 kHk - 1 GHz 1 kHk, 80% AM or 100% Pulse	RI
3	Bulk current injection (BCI)	EUT Pins and Wiring harness	150 kHk - 1 GHz distur-bance = 10 mA min.	CI
4	Direct RF power injection (DPI)	EUT Pins	150 kHk - 1 GHz 1 kHk, 80% AM	CI
5	Workbench Fara-day cage method	EUT and/or Wiring harness	150 kHk - 1 GHz 1 kHk, 80% AM	CI

In a nutshell, component EMC testing addresses two categories of RF interference:

- EMI: Emissions testing measures RF interference that is radiated or conducted from the component. Emissions from any component can cause malfunctions in nearby components/ equipment.

- EMC: Susceptibility testing measures the component/device's immunity to external RF interference that are conducted or radiated into the component/device. Emissions testing confirms that the device is unlikely to interfere with other devices, while Susceptibility testing confirms that the device will keep operating despite outside interference.

The Transverse Electromagnetic (TEM) cell test method is used for measuring the emissions or immunity of an integrated circuit between 150 kHz to 1 GHz. The frequency range of this method is limited by the characteristics of the TEM cell.

Either a two-port TEM cell or a one-port TEM cell may be used. A two-port TEM cell is referred to as a TEM cell while a one-port TEM cell is referred to as a wideband Gigahertz TEM (GTEM) cell. Emissions from an EUT can be measured off these ports, or RF signals can be injected into these ports to create electric fields inside the TEM cell (Figure 1 shows the basic test set-up for TEM and GTEM cell immunity test setup).

Figure 1: TEM cell immunity test set-up   *GTEM cell immunity test set-up*

To reduce variations from test to test, components are mounted to special boards. The test board controls the geometry and orientation of the EUT relative to the cell and eliminates any connecting leads within the cell. Rotating the test board in the four possible orientations in the wall port of the TEM or GTEM cell is required to determine the sensitivity of the EUT to induced magnetic fields.

The injected CW or Pulse disturbance signal exposes the EUT to a plane wave electromagnetic field where the electric field component is determined by the injected voltage and the distance between the EUT and the septum of the cell. The intent of this test method is to provide a quantitative measure of the RF immunity of ICs (refer to IEC 61000-4-20 for TEM cell characteristics of RI testing). Using this method, the RF immunity of the EUT shall be evaluated at critical frequencies. Critical frequencies are frequencies that are generated by, received by, or operated by the EUT. Critical frequencies include, but are not limited to oscillator frequencies, clock frequencies, data frequencies, etc. (refer to IEC 62132-1 for more test specific requirements).

The BCI test, defined in IEC 62132-3, is a method for measuring the immunity of the IC in the presence of conducted RF disturbances. It differs from the general immunity test setups, as described in IEC 61967-1, requiring monitoring of output signals to determine if the IC is affected by the RF. Figure 2 shows the basic test set-up for BCI testing. Table 2 shows the frequency steps and test severity levels for BCI testing.
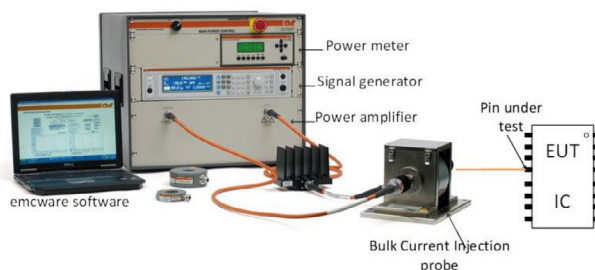

Figure 2: Basic BCI test-up

Table 2: BCI Test Frequency Steps

Frequency Band	Max Freq. Step Size (linear)	Freq. Step (Log)
10 kHk - 100 kHk	2 KHz	10%
100 kHk - 1 MHz	< 20 kHk	
1 MHz - 10 MHz	200 kHk	5%
10 MHz - 100 MHz	2 MHz	
100 MHz - 1 GHz	5 MHz	2%

BCI Test Severity Levels

Test Severity Levels	Current (CW value) No Insertion Loss
I	50 mA
II	100 mA
III	200 mA
IV	300 mA
V	Customer Specific

The bulk current injection (BCI) and direct power injection (DPI) method have become standard test methods. Because the BCI test uses a current injection probe to inject magnetically coupled electromagnetic (EM) fields, there is a significant difference between the power supplied by the radio frequency (RF) generator and that transferred to the integrated circuit (IC). As mentioned above, DPI testing is another method of EMC characterization of IC components. DPI testing measures the immunity of an integrated circuit as a function of the effective power transmitted to the circuit. However, due to impedance mismatch, most of the RF power delivered by the generator is reflected towards the source, and only a small amount enters the PCB and IC under test. To evaluate the immunity of an IC, the forward power needed to cause malfunction is measured. The malfunction may be classified from A to D according to the performance classes defined in IEC 62132-1. Figure 3 shows a typical DPI test setup.
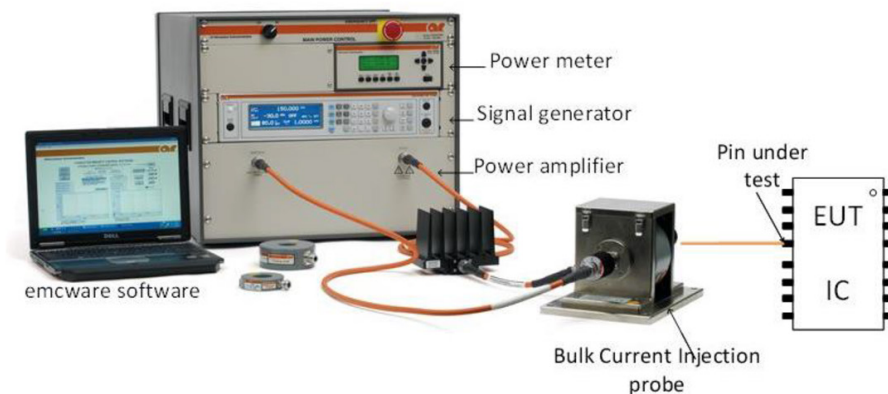

Figure 3: Basic Direct Power Injection (DPI) test-up

Many approaches have been proposed to enhance the immunity of ICs. A commonly used method is to have an IC with on-chip decoupling capacitors (RC circuit) which showed the highest immunity to RF energy. However, the actual power injected using an AR amplifier to the IC depends on the frequency of injected EM noise and the transfer characteristics of the measurement equipment, the PCB, the package, and the IC impedance. IEC 62132-3 recommends a minimum of a 50-watt linear amplifier for BCI testing to overcome these factors and deliver the necessary power to produce the required test level.

The condition whereby the output impedance of an RF amplifier differs from that of the load is said to be a "mismatch". The extent of mismatch can be characterized in terms of Voltage Standing Wave Ratio (VSWR). In its simplest form, VSWR is the ratio of the source output impedance to the load impedance at a given frequency. AR has taken the conservative and reliable approach to design VSWR tolerant amplifiers that will operate without damage or oscillation with any magnitude and phase of the source and load impedance (see ARI app note Importance of Mismatch Tolerance for Amplifiers Used in Susceptibility Testing).

AR's new U-series, 50U1000, class A, VSWR tolerant, the solid-state amplifier is the product of many IC manufacturers' choice for component BCI testing. Using this new VSWR tolerant and power transfer efficient amplifier, the real injected power into the IC is achieved and used as a reference for the new required power level to test the IC susceptibility. The largest geometry found in an integrated circuit is the leadframe. The size of the leadframe is in the range of a few centimeters or smaller. For a frequency range below 1 GHz, this leadframe and the structures on-chip are not regarded as efficient antennas for the reception of unwanted RF energy. The cable harness and/or the traces of a printed circuit board constitute efficient antennas. Thus, an IC receives the unwanted RF energy through the pins connected to the wires of such cables. Because of this, the electromagnetic immunity of an IC can be characterized by conducted RF disturbances (i.e., RF forward power) instead of field parameters, as is usually the case in module and/or system-level testing.

The test levels and required forward power depend on the application of the EUT and the pin tested. The maximum forward power level of a CW (continuous wave) RF signal for testing an externally unprotected IC-pin is up to approx. 5 W (37 dBm). If the IC pin is designed to operate with external protection, then the maximum forward power level can be decreased.

IEC 62132- 4 recommends an amplifier with a higher power capability (10–50 W) than needed for the maximum forward power level (i.e. 5 W). The output impedance of the power source shall be 50 Ω (recommended VSWR <1.2:1) to absorb reflected waves and the harmonics / spurious emission of the RF power source shall be at least 20 dB below the carrier level.

AR's new U-series, class A, VSWR tolerant, solid-state amplifiers exceed the standards and IC manufacturers' requirements for direct power injection testing. Also, AR offers a wide range of highly linear solid-state, VSWR tolerant class A amplifiers (A and U-Series), which are highly recommended for both BCI and DPI component testing (DPI test set up shown in Figure 3). It should be noted the direct injection of RF disturbance to the IC package is very small and often negligible compared to the disturbance injected through the connected cables(s). Hence, the IEC 62132-5 workbench method is derived from the IEC 61000-4-6 (see ARI app note Conducted Immunity Test System for BCI and TWC Methods of Automotive, Military and Commercial Test Standards from 10 kHz to 3 GHz). The method described assumes that supply and signal cable(s) are attached to an electrically small test board, with dimensions ≤ λ /2, i.e., 0.15 m at 1 GHz. These connected cables become the dominant antennas; the induced RF disturbance is injected to the test board via these "antennas." Using this concept, the circuit board layout's RF performance, the IC supply decoupling, and discrete components (capacitors and inductors) can be measured.

AR's emcware® provides automated EMC testing and report generation for all types of user-defined test profiles. It is configured in modules based on different types of EMC testing. Within each module, there are predefined test profiles based on EMC standard test requirements. The emcware® suite is designed to be user-friendly yet extremely flexible. To make testing more flexible, it is designed to allow the user to select between manual and automatic signal routing. Automatic signal routing is implemented using up to two AR RF/Microwave Instrumentation Model SC2000 System Controllers. It is a standalone software application designed to operate on a Microsoft Windows operating system computer.

Summary

In every product sector, new emerging technologies (IoT, 5G, drones, automobiles, and others) rely increasingly on highly robust and efficient electronic components for critical operation. There is a growing concern on their performance and co-existence in the presence of an electromagnetic environment. It is crucial for an integrated circuit to operate without error in the presence of relatively high RF levels, while also limiting EMI levels to avoid damage or disruption to other components within the multi-chip packages. By following the techniques outlined in this application note, and through the selection of AR's appropriate test solutions, manufacturers are able to design robust integrated chips, enabling emerging technologies to operate reliably without EMC or EMI problems. Furthermore, by using AR's emcware® greater efficiency is gained while also achieving increased quality of test results. If you would like to learn more, feel free to contact one of our applications engineers at 800-933-8181, or visit our website at www.arworld.us.

AR RF/Microwave Instrumentation • 160 Schoolhouse Rd, Souderton, PA 18964 • info@arworld.us
To order AR Products, call: 215.723.8181. For an applications engineer, call: 800.933.8181
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AR Modular

modular rf

Communication Amplifiers: Can They Really Take You Farther & Help You Be Heard Better?

As a designer and manufacturer of RF amplifiers we have always been confident in telling our customers that the more power output you have, the "better" your communications link. Just what is "better" needs defining of course; but simplistically you can either "go farther" or "be heard better," sometimes both at once, all other things being equal. The question of just how much "better" is a lot harder to quantify.

1.0 Being Heard Better

Systematically, all system losses (propagation path loss, physical obstructions, coax and connector losses etc.) and antenna gains are all "reciprocal" and as such they affect both communication directions equally. However, additional transmit power affects only one end of the path, specifically the end of the path receiving the amplified signal. In many scenarios the portable location has less power than the base or vehicle mounted system. This is exactly the reason for needing a small portable amplifier system.

By using an accessory amplifier to raise the transmit power, a signal that was previously a poor copy (3/5) with noise or interference can become a full copy (5/5) signal. The amplifier's extra power (20W or more) is sufficient to raise the received signal above the detection threshold of the far end receiver with enough signal to noise margin to make the copy "in the clear". Adding a 20W amp to a system that previously ran at a 5W level means you can add 6dB to the receive signal level. If the signal was originally very broken it was probably very close to the receiver threshold or had some other interference, so the extra 6dB of signal can give you almost a full 6dB of signal to noise. That may not sound like much to audio buffs, but it is huge when you are close to a radio system threshold; enough to make the amplified signal sound relatively loud and clear. If you were to further boost the signal another 6dB (80W) it probably would not have such a dramatic effect, because now you are only improving the signal to noise of a signal that is already a solid copy so it's not perceived to be as big of an improvement. It may result in a little less background noise or if you're in a digital mode, less dropped packets or digital errors, pops etc.

2.0 Going a Farther Distance

We are asked all the time, "So how much farther can we go with your amp?," and our first answer is nearly always the same: "Well, it all depends on a lot of factors, none of which are consistent from place to place or circumstance to circumstance". This is a truthful answer, but not one that is much help in answering the question in any kind of practical way.

A simple answer is to say that doubling the distance of a link in "free space" adds 6dB to the path loss, so at best adding our 20W amplifier to a 5W system (i.e. a 6dB gain) will give you no more than twice the distance. This answer is always followed by another question: "So how far is that," and then we are back to the first answer: "Well, it all depends!!" Aside from the humorous part of this loop conversation it is frustrating not to be able to give a quantifiable answer to a very valid question.

If the path is mostly clear open country (high level site to high level site, with line of sight), then adding the amp could nearly double the path length. So if it was 5 miles with a 5W output then it could be up to 10 miles with a 20W amplifier, assuming that you are still in the clear. But how many clear open paths like that do you encounter? Probably not too many! Unfortunately doubling the distance of the path nearly always means you will encounter some new path obstruction, more trees, more terrain hills, or more buildings, so you are not likely to double the distance in reality for a relatively long path like this. We have had reports of shorter 1km paths with trees that have become usable to 2 to 3km or so when using a 2 watt SINCGARS unit fully driving our man-pack amplifier to its full 20W. Now this power increase is a 10 times or 10dB jump in power and that corresponds mathematically quite nicely to tripling the distance. From the operator's point of view this was a significant improvement and something that he really wanted to have on a daily basis under all conditions. Of course the "under all conditions" statement is the difficult part because the variable conditions are almost limitless.

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The urban warfare environment is even harder. You could still run the rule of thumb, 5 blocks without the amp, 10 blocks with the amp, all things being equal. It probably won't be equal as the new buildings might be taller, might be steel structure based and so on, but it's a reasonable place to start. As the adverts say, "your mileage may vary." Plus a very important factor is whether one or both ends of the link are inside the buildings. Being inside a building is nearly always a negative condition due to the attenuation of the signal due to the structure of the building.

We've had customers tell us that they were surprised when they used a 100W amp "to burn through a long path" and didn't get quite the big boost expected. There's no denying that 100+ Watts is a lot of RF power and compared to a 20 W backpack transceiver it certainly sounds like a lot, but mathematically it's only 7dB more. So how much farther do you think it'll go - yes that's right, just over double because 6dB is double. "But only in a perfect world with free space paths" - which of course was far from the conditions in which they were operating. It's just physics and math, darn it!

3.0 Real World Testing

Having quoted the propagation theory, tests were made in the urban environment surrounding our manufacturing facility to see what happens in the real world. The area around our factory in Bothell WA is a demanding area from an RF propagation point of view, very hilly and heavily wooded with Pine and Poplar trees of up to 100ft tall in many places. Most of the industrial park area is comprised of 2-story 25 ft. tall tilt-up concrete structures surrounded by 30 to 40-foot trees.

4.0 The Paths Under Consideration

Two paths were considered in these tests.

1. The first was a path to the south from our business along the course of a river/slough in a valley area. The path is essentially flat with buildings and a small city center along the first 1 mile of the path; after that it's a mixture of single story buildings, open land and dense intermittent wooded areas, with trees up to 75ft tall.

a. PATH ONE GROUND PROFILE PICTURE
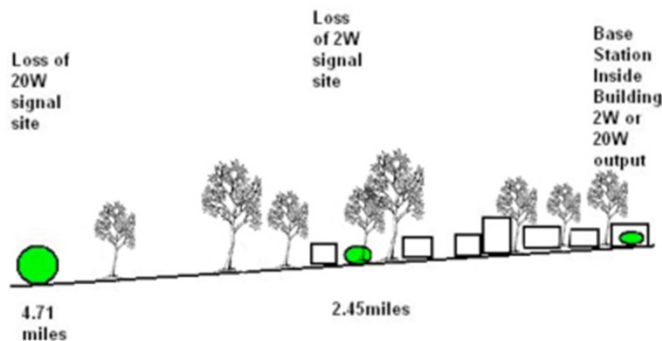
2. The second path was to the north across a densely built business park area on mostly flat but steadily rising ground that becomes residential buildings surrounded by heavy pine trees up to 100 ft. tall. The path rises to a ridge about 4 miles away and then rapidly falls away causing additional ground obstruction losses on the path.

a. PATH TWO GROUND PROFILE PICTURE

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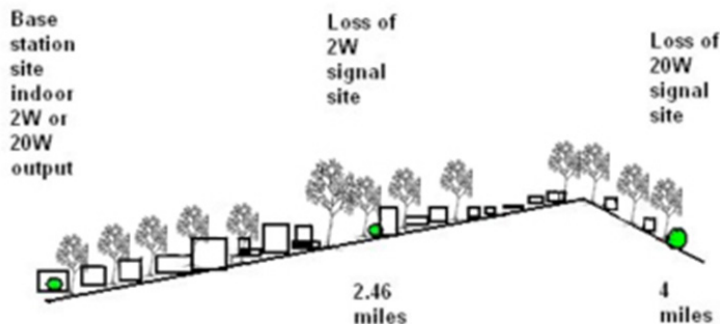
b. TYPICAL ON PATH TREE OBSTRUCTIONS

In order to give a "worst case" urban situation, the base station was set up inside our facility with a 2W transceiver running in the middle of the VHF band driving a KMW1031 20W PA on which we mounted a Trival 30-512 "gooseneck" backpack antenna. The two paths were driven and receive levels monitored until the communications link failed due to squelch action on the mobile receiver. At that point the base station PA was turned on to give a 10dB increase in output power (nominal 20W) and then we continued to drive the path until communications failed again.

At no time was either path a "clear line of sight" condition. There was considerable above ground obstruction from buildings and trees across the whole length of the path. Our 10dB of PA gain essentially gave us nearly double the transmission distance or about 2/3 of the theoretical improvement, which considering the extensive above ground obstruction loss was better than expected. The path to the north was shortened due to the effect of the ridge at about the 4 mile distance. The additional losses due to that ground obstruction as well as the above ground tree losses made the path fail more quickly than the fairly flat ground path to the south.
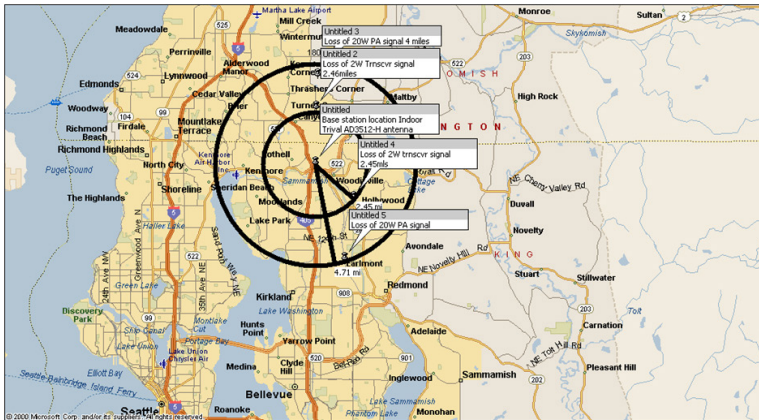
ADDITIONAL LOSSES

Tree losses can be substantial and CCIR (International Radio Recommendations) cite tree losses as follows

- 200MHz at 0.05dB loss per meter
- 500MHz at 0.1dB loss per meter

So it's easy to add 10dB of path loss if you are in a heavily wooded area like urban Seattle, WA!

Building losses vary based on the type of construction and can easily add 6dB or more dependent on the frequency being used. If the building has a steel structure and/or mesh floors it can act like a screened room and essentially prevent radio communications from within the building other than through windows.

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5.0 Managing Losses

Managing losses is an important part of operation of a radio system. Military operation of radios is usually done under less than ideal conditions and usually little can be done to improve performance. However, we reviewed a number of operator antenna set-ups to see what kind of performance variation occurs in real world situations.

The general rule should be, "use the highest gain antenna (in broadband antenna this often really means less loss!!), wear it as high on the body as possible, DO NOT shorten the antenna by folding it up and keep it away from walls and the ground. It should be noted that many systems reduce the output power when operated into a high VSWR (mismatch) as can exist when an antenna is tight against the body, or a wall or the ground. Antenna performance varies from vendor to vendor. We noted a 5dB variation in VHF signals when comparing 3 different 30-512MHz antennas. Using a less broadband antenna or one designed specifically for a sub-band (low band SINCGARS, AIRBand VHF) or high band VHF/UHF can make a dramatic improvement in received signals of 6dB or more.

The AR man-portable booster systems do not have this power management system and will attempt to transmit full power in spite of the high VSWR. When copy is poor, try to orient the body such that the antenna isn't shielded (obstructed) by the body. Here is a quick guide to how user configuration can affect the system performance based on actual measurements on our system.

> 1. REFERENCE CONDITION: Full antenna height, at shoulder level, facing the line of sight to the distant site
>
> 2. Additional losses (vary with frequency and type of antenna so these are "averaged numbers")
>
>> a. Antenna worn within the webbing vest close to the body and below shoulder level, 2 to 3 dB
>>
>> b. Antenna shortened by folding tape, single fold 2dB, double or multiple folds 6dB or more depending on frequency
>>
>> c. Antenna shielded by body due to orientation, 1-2dB

Summary

Adding a booster amplifier to your portable system such as the KMW1031 will give the user a significant improvement in "readability and/or operational distance" as shown by this report.
Defining what that actual range is ahead of time is only possible after significant engineering effort with advance knowledge of the path conditions and isn't really appropriate for the kind of dynamic use environment in which these systems operate.

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PA Linearization for Modern Communication Systems

In third generation (3G) mobile communication systems, ultra linear amplification is required for complex modulation formats. Nonlinear amplification yields inter-modulation distortion (IMD) products and results in unacceptable spectral regrowth in the adjacent channels. To achieve ultra linear amplification, special linearization techniques are usually employed. Various techniques have been developed to reduce IMD products in high power amplifiers and generally, three main linearization methods are used. They are the predistortion method, the feedback method and the feedforward method.

AR Modular RF located in Bothell, Washington designs and manufactures high power amplifiers using traditional backoff plus the linearization techniques mentioned above for different applications in the communications and wireless industry. Further more, we have developed a combination of "Doherty technique" along with analog predistortion techniques in the traditional feedforward method to further improve our goal of **"HIGH EFFICIENCY AND HIGH LINEARITY"**

Analog Predistortion Technique
It is well known that analog predistortion is a widely used linearization method in power amplifier (PA) designs. AR uses this technique in certain applications in order to improve the linearity to a certain level while increasing the efficiency and yet keeping the build costs low.

A typical analog predistortion PA at AR is shown in figure 1. The backoff of the output stage is typically 6 or 7 dB (2 or 3 dB less than the normal HPA), thus, improving the efficiency and the linearity of the amplifier. Our analog predistortion can improve the IMD3 by 6 to 10dB for an amplifier in the band 450 MHz to 2.2 GHz.
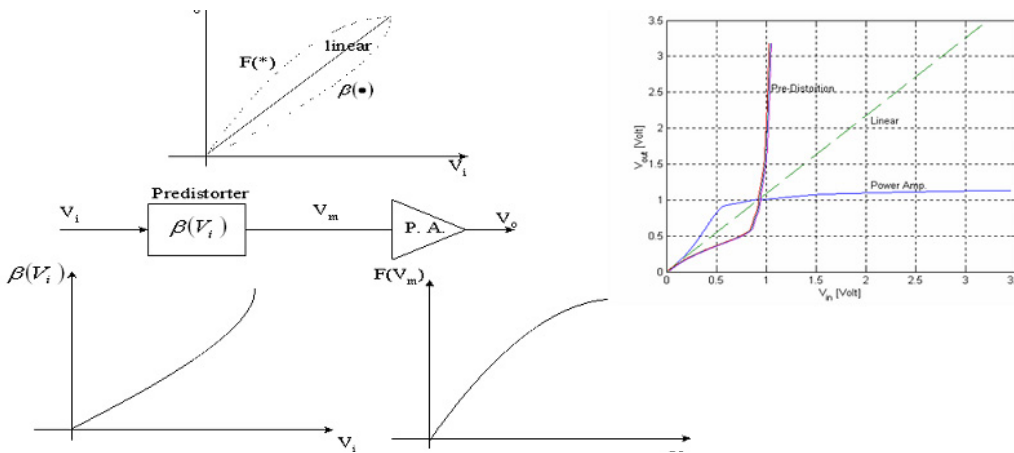

Figure 1: Analog Predistortion

Feedback Technique
The feedback technique is used in some narrow band applications in order to improve the linearity. The improvement is about 3 to 5dB and depends on the bandwidth and frequency of operation. The phase and amplitude flatness are the major items affecting the improvement especially the phase flatness.

The diagram of the feedback PA is shown in figure 2 below. AR engineers have designed this kind of PA structure using the first (canceling) loop in the feedforward structure.
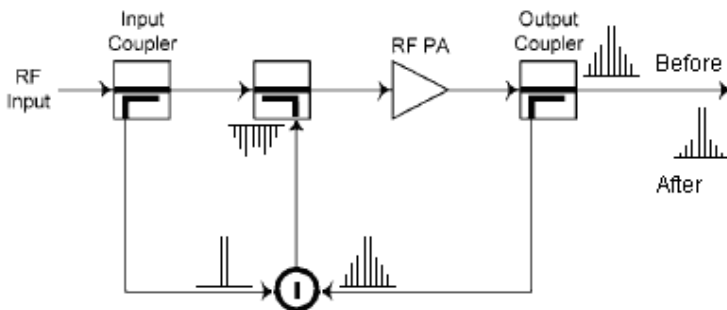

Figure 2: Diagram of Feedback

Feedforward Structure

A feedforward amplifier consists of two loops. The first loop, Loop 1, is the carrier cancellation loop that is used to cancel the carriers and obtain the IMD products of the main amplifier (denoted as error signal). The second loop, Loop 2, is the IMD cancellation loop, which is used to reduce the output IMD products with the error signal. The typical feedforward structure (block diagram) is shown in Fig.3
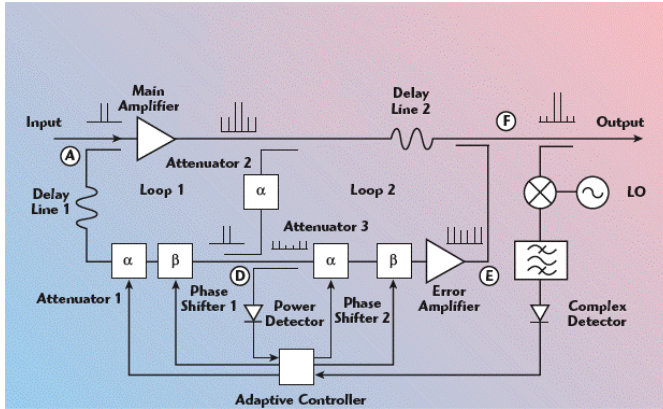

Figure 3: Feedforward Structure

The feedforward structure is very complicated but it is still widely used in the narrow band wireless market because of its dramatic improvement on the linearity of the amplifier. The normal improvement on the IMD of 2-tones and ACPR for the CDMA or WCDMA application is better than 20dB.

However, this structure has a very negative affect on the efficiency since there are essentially two PAs in it and also because of the additional insertion loss of the delay lines especially the 2nd (main) delay. Due to these effects, the efficiency of the normal feedforward structure is only about 6% to 7%.

In order to improve the efficiency of the structure, our engineers have combined the technique of analog predistortion with the Doherty technique in the main PA as shown in figure 4. Our new design of the feedforward LPA has a much improved efficiency of around 10% to 13%.
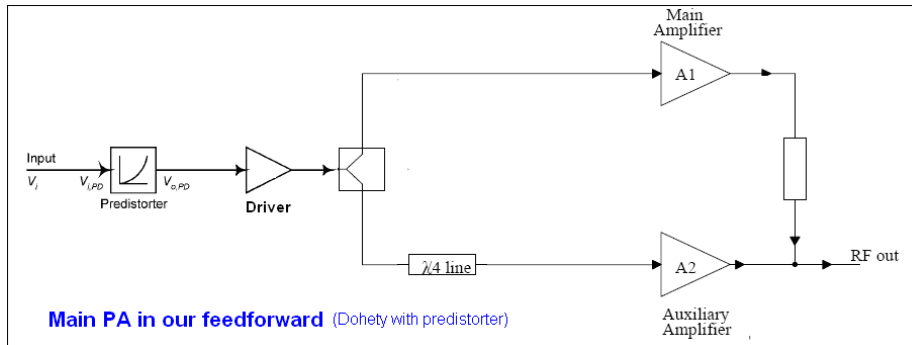

Figure 4: New Main PA in the Feedforward Structure

We have the ability to design the feedforward PA for operation from 450 MHz to 2100 MHz, and with output powers ranging from 10W to 60W for 2-tone CW, CDMA and WCDMA modulations for single or multi-carrier PAs to meet the demanding needs of the wireless communication market. Typical output plots of the feedforward PA showing the improvement effects are shown in figure 5.
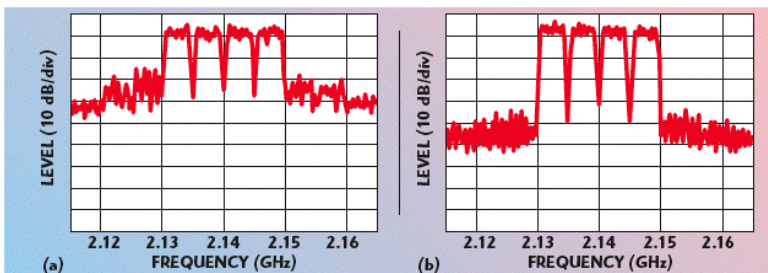

Figure 5: Typical Spectrim Plots of the Ouput from the Feedfprward

modular rf

Special Features - Dual Band RF Power Amplifiers

Described here are the features and operating controls of all AR Modular RF dual band RF power amplifiers.

Over-Temperature Protection: Amplifier module(s) are protected by thermostats. Indication: Red blinking LED. Off = safe, red = temperature >160°F. Amplifier shuts down as indicated by BLANKING LED being lit. Returns to normal operation at temperature <130°F.

Overdrive Protection: Function of ALC circuit. At about 10% over rated power output, ALC limits further increase in output. Indication: Red LED (ALC). Off = safe, red = with ALC control in the OFF, full clockwise position, the system is being overdriven. Reduce input signal to safe level.

VSWR Protection: Amplifier protected against all load mismatch conditions by proportional power sensing/ limiting control circuit. Automatically limits reflected power to a level equivalent to that realized with rated power output when the output VSWR ratio exceeds a preset level, 3:1 for most models. The amplifier may be programmed to shut down when this ratio is exceeded. Indication: Red, blinking LED. Off = safe, red = reflected power exceeds pre-set level or amplifier has shut down. Control: (VSWR)(RESET)AUTO/MAN alternate action push button switch. AUTO position = automatic reflected power/output power limiting. MAN position = amplifier shuts down when reflected power exceeds set limit. Button must be depressed twice to reset system to manual operation.

Automatic Level Control: Amplifier output level may be set to fixed level ±0.5 dB, with input variation of up to 20 dB. Selectable response time, fast or slow. Indication: red LED. Off = no ALC action, red = ALC active. If the indicator is lit with the ALC control in the full clockwise position (ALC OFF) the amplifier is being overdriven, reduce input level. Controls: (ALC)-(MODE)-FAST/SLOW alternate action push button switch. (RF OUTPUT POWER)-LEVEL SET linear potentiometer marked ALC OFF in full clockwise position.

Input Blanking: Input to the amplifier may be blanked by pushbutton operation. Indication: red LED. Off = input active, red = input blanked. Control: (RF CONTROL)BLANKING on/off. Alternate action pushbutton, in = blanked.

RF Power Meter: The amplifier has a front panel-mounte¬d, dual scale, analog power meter with a single marked indication for rated WATTS forward power.

Remote Control: All control functions may be remotely controlled either with connections made through the 25-pin, D-subminiature con¬nector mounted on the rear panel or via the optional integral IEEE-488.2/ RS232 interface controller. Indication: yellow LED. May be lit from remote control panel to indicate that unit is under remote control. Local RF gain and ALC controls as well as VSWR mode selection, ALC mode selection and blanking are disabled under remote control operation.

Door Interlock: The amplifier may be blanked as a function of interrupting a contact loop by means of a SPST switch operated by the door mechanism of the shielded testing area. A contact closure enables the amplifier; open disables the amplifier. Input is via a BNC connector on the rear panel. A BNC shorting cap is chained to the rear panel next to it to override this function if not used. Indication: red LED (BLANKING). Off = input active, red = input blanked.

FRONT PANEL CONTROLS AND INDICATORS

The following front panel controls and indicators are standard (refer to figure on next page):

(1)   **(AC LINE)SYSTEM** – Green LED. Indicates system power.

(2)   **(AC LINE)ON/OFF** – Alternate action push-button switch. Turns equipment on and off.

(3)   **(RF CONTROL)(BLANKING)** – Red LED. Indicator is on when amplifier is being blanked; off amplifier is operating.

(4)   **(RF CONTROL)(BLANKING)ON/OFF** – Alternate action push-button switch. Inhibits the RF input to the amplifier. Switch action is indicated by the red LED above it.

(5)   **(RF BAND)(LOW)** – Green LED. Indicates low band has been selected.

(6)   **(RF BAND)(HIGH)** – Green LED. Indicates high band has been selected.

(7)   **(RF BAND)(SELECT)LOW/HIGH** – Alternate action push¬button switch to select desired frequency band. Selected band is indicated by green LED's.

(8)   **(METER)** – Meter for relative forward power measurements. Accuracy typically 10% when operating into a 50-Ohm load.

(9)   **(ALC)(MODE)** – Red LED. Indicates when ALC action is taking place. When this LED comes on with the ALC control in the OFF position the system is being over driven and the ALC is limiting the output power to about 10% over the rated power of the amplifier. Reduce input drive.

(10)   **(ALC)(MODE)SLOW/FAST** – Alternate action push-button switch to select either the slow or fast response of the ALC action to incoming signal level changes.

(11)   **(VSWR)** – Red, blinking LED. Indicates red when load VSWR exceeds 2:1.

(12)   **(VSWR)(RESET)AUTO/MAN** – Alternate action push-button switch to select automatic or manual mode for the operation of the power control circuitry. When the system operates in the manual mode, this push-button performs the RESET function after a VSWR trip condition. The button must be depressed twice for reset and return to the manual mode.

(13)   **(FAULT)TEMP** – Red, blinking LED. Indicates when the amplifier heatsink temperature reaches 160°F. The amplifier shuts down. Operation will resume when the temperature returns to normal, approximately 130°F, and if no failure has occurred.

(14)   **(REMOTE ACTIVE)** – Yellow LED. May be turned on from a remote location to signal that the amplifier is under remote control and local controls are inactive.

(15)   **(INPUT)** – N-type female connector. Front panel installation is standard, but may have been installed on rear panel upon user request.

(16)   **(INPUT)GAIN** – Linear potentiometer control providing approximately 0   30 dB attenuation on the input signal. The maximum amount of attenuation possible is somewhat frequency dependent, less at higher frequencies.

(17)   **(RF OUTPUT POWER)LEVEL SET** – Linear potentiometer control. Controls the ALC action and allows the output to be adjusted to a desired constant level. Full clockwise position, ALC OFF, removes ALC action.

5.25" 2—BAND FIG005F2
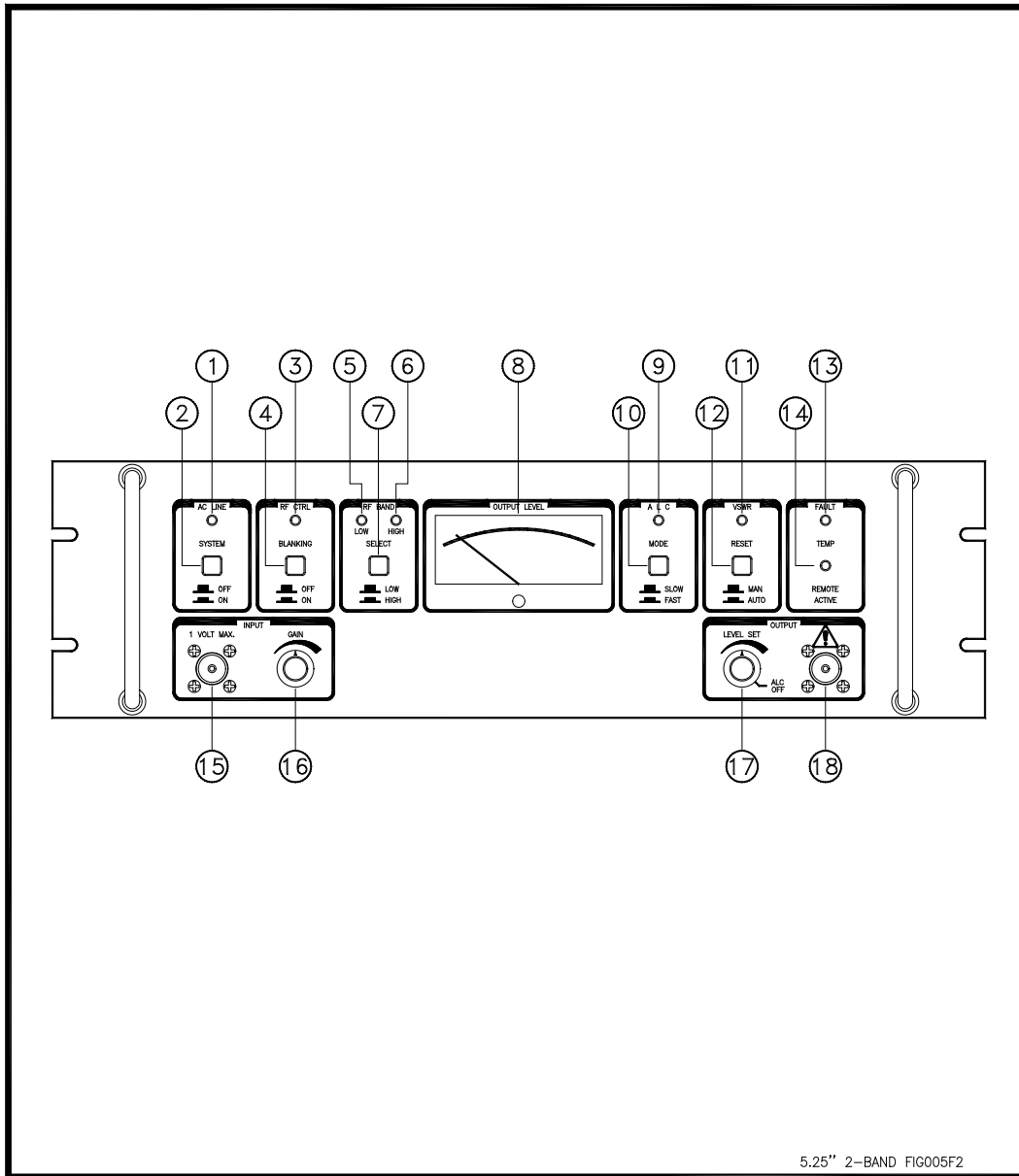
(18)   **(OUTPUT)** – N-type female connector. Front panel installation is standard, but may have been installed on rear panel upon user request.

modular rf

Tactical Booster Amplifiers

Modern communications equipment keeps getting smaller with each new generation. Radio transceivers have become capable of the most complex encryption and digital modulations known to man. As the size decreases, the ability to carry this equipment to places that were previously difficult or impossible to access – and our dependence upon these latest devices – is growing at an ever-increasing pace.

We can now take these communication devices into vehicle of all types – boats, planes, bunkers and fire control centers. We're able to crawl through building cellars, jungles and into forward observation positions with the ability to reach out and connect to others in the group via direct mobile to mobile links, or indirectly mobile to base station via satellite.

1.0 Wider Frequency Ranges

Demand Wider Antenna Systems

Transceivers have grown smaller and now cover wider frequency ranges, which has meant that antenna systems have had to be widened to match the new operating spectrums. Unfortunately, the laws of physics still prevail; so wide-band antennas have fairly poor performance compared to narrow-band systems. It's often joked that they "transmit equally poorly in all directions" or "hardly better than a piece of wet string."

Portability Creates New Problems

VHF and UHF spectrums really work well in "line of sight" applications and fairly low transmit powers can go a great distance. For instance, a hand-held 5-watt transceiver with a moderately efficient antenna used on a hilltop to hilltop path may go many dozens of miles. However, due to the fact that we can now take these systems into locations where we don't have line of sight, transmission capabilities are further hampered by the additional propagation losses due to walls, trees, proximity to ground and other obstructions surrounding the remote user. So now our transceiver is struggling to make a communications link of a mile or less. What can be done to overcome this problem?

Antennas can be improved. "Size is important" is certainly a true statement when it comes to antenna performance. Some operational improvements can be made, but they are fairly limited in scope and still require more space than is available at many remote locations. Furthermore, large, unwieldy antennas and cables are just not compatible with modern urban warfare or remote special ops reconnaissance missions.

More Power.

Adding more transmit power is an option now that broadband technologies allow the use of a single amplifier to cover the full operating spectrum. Increasing the output power by four times (6dB) will essentially double the range, and this can easily be achieved with compact modern transmitter amplifiers. For instance, hand held transceivers with a man-pack 20-watt amplifier will essentially double the communication distance. A bonus of using this kind of amplifier is that the hand-held transceiver could be reduced in power down to 1 watt and yet still achieve an output power of 20 watts. This would extend the life of the battery pack in the "handy talky," keeping that last line of defense available for a longer period.

Higher power man-portable systems are available for use with tactical transceivers that can provide system gains of up to 20dB (i.e. 1 watt input with 100 watts output that make long links in the VHF and UHF bands a reality). A system like this will provide at least a 3-fold increase in the range of the basic transceiver as well as improving the quality or readability of transmissions sent. This can be a vital improvement that prevents comprehension errors or delays in transmission due to having to repeat everything twice.

2.0 AR Worldwide Booster Amplifier

To The Rescue

AR Worldwide Modular RF offers a family of tactical radio "booster amplifiers," namely the KMW1030, KMW2030, and the KMW2050, for use in conjunction with a wide range of military man-pack and man-portable transceivers such as the Thales MBITR, Raytheon PSC5-D and the Harris 117F.

The man-pack KMW1030 and man-portable KMW2030 models cover the 30 to 512MHz band in 20 watt and 125 watt ruggedized packages. The man-portable KMW2050 model covers the SATCOM band from 225 to 400MHz with an output power of 200 watts. Additionally, the KMW2030 and KMW2050 amplifiers have adjustable output power as well as optional pre-amplifiers for SATCOM band use. All amplifiers are built to high standards and incorporate RF sensing circuits to switch from "receive" to "transmit" and have been designed with optimal switchover timing for use with modern complex waveform transceivers.
The KMW1030 man-pack amplifier, which has proven to be a real life saver in the field, is available in 12 watt and 20 watt configurations, and can be supplied to operate from 12Vdc or 24Vdc, while the KMW2030 and KMW2050 models operate from 24Vdc.

This family of booster amplifiers is "Battle Tested" with the US Army, Navy, Marines, Coastguard, and FEMA. They meet applicable MIL standards plus the KMW2030 and KMW2050 units have been certified by JITC for interoperability with the PSC5-D and Harris 117F transceivers. The AR Modular RF family of amplifiers is built to exceptionally high standards. Each amplifier incorporates RF sensing, Transmit-to- receive switching circuitry, Automatic Level Control (ALC), low pass harmonic or band pass filters as appropriate to improve transmit and receive performance; and they incorporate protection against antenna mismatch (VSWR) and over-temperature. Protection against accidental power line polarity reversal is also provided. Remote control is available on selected models.

3.0 Mission: Extend the Range

Tactical Military Radios
AR Modular RF's mission is to provide amplifiers that can be counted on to extend the range of tactical military radios in the field, under the harshest conditions, and for use in extreme environments. AR's units are designed for rugged use and field operation, so the units are built to meet applicable sections of the MIL 810F environmental specifications

The world is constantly becoming more complex, and no one set of products can fit all circumstances. With that in mind, AR has made custom configurations and packaging available for these models. This approach is radically different from that of most military packaged products. AR Modular RF has successfully created customized versions for a variety of military applications. The units are easily adaptable to vehicular, fixed - site, airborne, and man-portable configurations. When lives are on the line AR is ready to meet the demand. We offer expert service worldwide along with the "best in the business" warranty. "Mission accomplished!"

modular rf

The Making of a WiMax Power Amplifier

The power amplifier in telecommunication is one of the oldest pieces of the transmission system and has continuously evolved over the years. Over the past decade, RF power amplifier design has witnessed tremendous improvement with the advent of window-based computer-aided design, allowing engineers to do real-time modeling and load-pull measurements before even lifting a soldering iron. In addition, manual and cumbersome test equipment that could only do basic modulation has given way to sophisticated test equipment that allows us to create complex digital signals and make measurements in seconds.

The days of fickle transistors with limited power handling and low frequency response are no more. Better power devices and gain blocks are available and continue to improve each year with regard to linearity and efficiency. Today's new power devices include:

- GaAsFET devices that have better power linearity and the comfort of operating at elevated temperature.

- LDMOS devices that provide lots of power and efficiency without running into complex circuitry to achieve high output power.

- MMICs that not only provide higher power and gain but also serve as RF power pull down and gain controls.

- GaN (gallium nitride) and SiC (silicon carbide) devices, all promising happy days for power amplifier designers.

Every component that is involved in the making of power amplifiers has seen a dramatic improvement in quality and functionality.

With all these advancements in power device technology one can imagine that designing a "good" power amplifier should be easy. In some ways that is true, but in many others it is not.

The growth in communication technology brings with it a more stringent demand on power amplifier design engineers to come up with amplifiers that can handle analog and digital modulated signals with little or no distortion, higher efficiency and offer many different interface/ communication protocols. Yes, there are engineering tools available to help meet these challenges but the complexity of the new modulation modes, demands for ultra high linearity and differing interface control systems have taken the task to a new level. An engineer with specific experience in wireless power amplifier design is an absolute must, as these designs are no longer "kitchen table projects."

As an example, this article will examine a WiMAX orthogonal frequency division modulation (OFDM) amplifier. This is a standard (IEEE 802.16)-based wireless technology that promises broadband connectivity and can be deployed for various applications. This power amplifier (PA), like in any base station, is usually the most expensive module in the system and the one most likely to diminish the mean time between failure (MTBF) of the base station, so the issue of quality and reliability has to be addressed from the design conception of the PA.

The power amplifier design engineer must understand the system requirements of the amplifier and the IEEE 802.16 requirements effect on the amplifier:

What is the downlink power need?

- What is the peak-to-average power ratio of IEEE 802.16 OFDM signal?

- What parameters effect the error vector magnitude (EVM)/(RCE) relative constellation error characteristics of the power amplifier?

- The environment that the PA will be operating within is very important as it will influence the choice of power devices, taking into consideration the junction resistance, channel temperature, drain efficiency, along with the mechanical structure and heat sinking.

1.0 A New PA Design

In designing the AR Modular RF 20 W model KMS1070 WiMAX amplifier, Eudyna (formally Fijitsu) GaAsFETs and Hittite devices were chosen considering the power supply requirements and the hostile environment the PA must operate in. The block diagram in *Figure 1* illustrates the basic building block of the KMS1070 PA module.
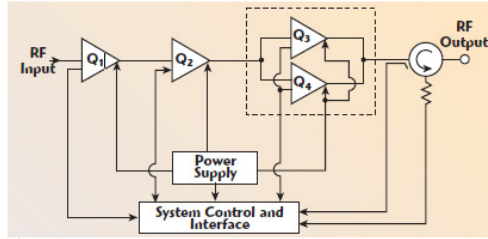

Figure 1: Layout Block Diagram

In addition, quality factors were taken into consideration since this module is likely to be produced in thousands, so no technician tweaking will be needed after the board has gone through an automated assembly line. The circuit topology using a balanced configuration was chosen to enhance repeatability and also to take into account the wide band requirement of the PA. Signal reflections due to mismatches caused by component discrepancies that normally degrade digital signal performance will be canceled out using this arrangement. A small-signal simulation was done to optimize gain and stability of the amplifier. The driver stages are perfectly matched I/O power devices that will further reduce the need for tuning the cascade sections in production.

Sparing the mathematical and simulation details of this WiMAX power amplifier design, which, of course, is not any different from any other digitally modulated signal power amplifier, there are some pertinent issues that are vital to achieve a better EVM number in a WiMAX power amplifier. One of the key issues is the physical location of the DC insertion points to the gate and drain of the power devices. This has a big effect on the RCE number and the quality of the output signal. Phase and amplitud mismatches are also an issue to watch for.
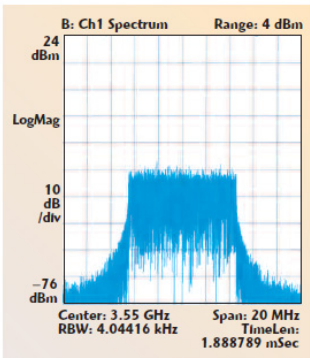

Figure 2: The output spectrum of the KMS1070 PA module wtih a 3 W WiMax signal output.

Separating the RF and DC bias voltage ground at the drain of the FET is a good practice which will diminish the chances of the power amplifier going into oscillation because of the large signal envelope swing and the high peak-to-average power ratio of the WiMAX-OFDM signal with approximately 200 sub-carriers.

The Agilent E4440A PSA spectrum analyzer and the 89600 vector signal analysis software were used to verify the design. The results in *Figure 2* show the spectral quality of the KMS1070 at 3 W output power of a WiMAX (IEEE 802.16) signal. The OFDM subframe information in *Figure 3* shows the details of the modulation format used, while *Figure 4* shows graphic results, indicating how tightly guarded the I/Q and the tabular function is (shown in *Figure 5*).

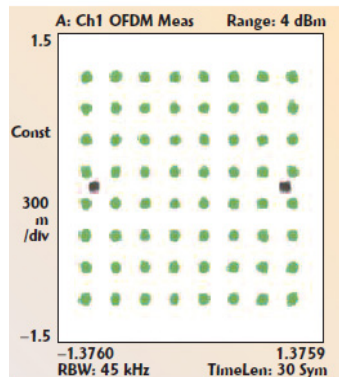*Figure 3: Downlink Subframe Information*

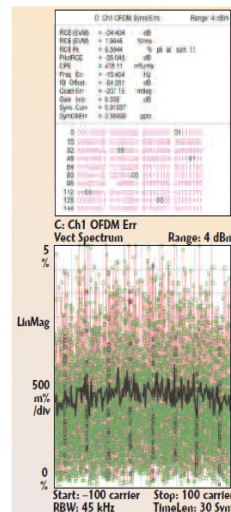*Figure 4: I/Q Constellation Results*

Figure 5: RCE/EVM Results

These data verify that the module has an impressive 1.9 percent EVM across the frequency band of 3.4 to 3.7 GHz. The complementary cumulative distribution function (CCDF) curve (see *Figure 6*) shows the peak-to-average power deviation is below the Gaussian noise reference line with little power waste. It should be noted that there is no change in the quality of the signal when the bandwidth is increased from 10 to 20 MHz.

The gain-frequency response has to be extremely stable across the entire operating frequency band and a temperature range of 0° to 60°C. *Figure 7* shows a ±0.25 dB result. This number was maintained at all temperatures.
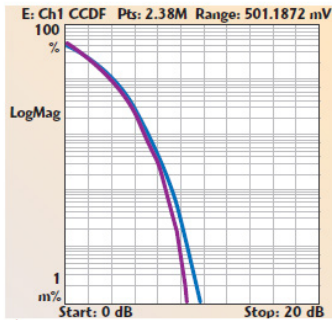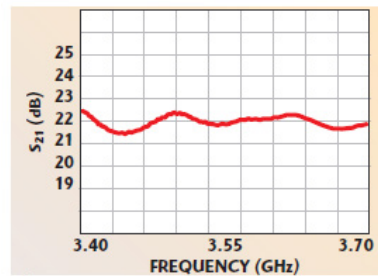

Figure 6: CCDF Plots

Figure 7: Gain vs Frequency Response

2.0 Packaging and Layout

The housing of an amplifier such as this unit is an important part of the design. It is important to try and contain the RF fields and RF ground currents within the RF amplifier portions of the housing. Ideally, if room exists, the RF and control systems should be separated by some physical distance, or contained within a walled structure or box. Secondary components on the ground side of the board should be avoided if possible as that will require the box to be relieved so there is room for the components or wiring. Wherever possible continuity should be maintained across the ground side of the board and narrow ground connections avoided, while utilizing multiple securing screws to keep RF ground currents to a minimum. As much wall thickness as possible should be maintained around the devices or heat sources to help reduce the temperature gradients within the unit. The KMS 1070 is housed in 6″ × 3″ × 1″ chassis, which is particularly small, and a complex box structure is required to keep the outside dimensions to a minimum. The operational environment (high temperature and low air flow) for this unit's initial application meant that the module has been built to withstand high operating temperatures. The unit has been equipped with all necessary interfaces to operate an OFDM transmitting terminal. The unit can be shut down via the power circuitry (usually a relatively slow means of controlling the amplifier), or via the gating provided on the early amplification stage. This gating stage will give 50 dB of isolation at the output of the amplifier and is very fast in its operation, typically allowing a turn on and turn off time of 74 nanoseconds.

Conclusion

A power amplifier meeting the OFDM specification has been designed that features consistent performance and long-term reliability. The new KMS1070 power amplifier module utilizes state-of-the-art device technology and the latest innovative design techniques to meet today's demanding communications requirements.

modular rf

The Most Common Power Meter Mistake

At least 50% of all power meter users make this mistake. It has happened to you. You measured an RF power level and later someone said, "…but I measured the power and got a different number." Who was right? Measuring RF power appears easy. Modern wattmeters and power meters are simple to use, and can provide digital measurement data to several decimal places in dBm or watts. But if they are so accurate, why is it so difficult to make good measurements? If you are making the most common mistake, correcting for it will dramatically improve your measurement accuracy.

For the most common power meter application, measuring the level of power in a signal, many users tend to forget that a power meter is not measuring what you want to know- the power level of the signal. Instead, it is measuring the total power over the entire bandwidth of the sensor, which for measurement purposes is practically infinite.

1.0 Power Meter Versus Wattmeters

Most people recognize that a calibrated power meter is a superior measurement instrument compared to a wattmeter. But what is the difference between a wattmeter and a power meter? Generally, a wattmeter is similar to a power meter in that they both measure broadband power, but unless you are correcting the power meter for frequency, you are using it as wattmeter. The perceived plug-and-go measurement ability of power meters is one of the misconceptions that endear power meters to users. This paper describes how to account for frequency in your power meter measurements, making them as accurate as possible.

2.0 Correction Factors, What Are They?

Power meter sensors that do not employ electronic calibration come with a graph or tabular data showing the calibration factor and correction factors by frequency. Most users will take the reference calibration factor (CF) in percent and use it to cal the power meter at the cal reference frequency, for instance at 50 MHz. But what are all the other numbers for? They are correction factors, similar to the reference CF, and indicate the response of the sensor to power as measured at those frequencies across the entire measurement range of the sensor. The numbers are usually a percent of the full scale response, and can vary from 80% or so to 100%. Let's say your sensor reference CF is 100% (not uncommon) and the CF of the frequency at which your signal of interest occupies is 95%. If you, like many users, carefully perform a cal and then plug the sensor to the signal port and make your measurement, it is still in error by at least 5%, or about 0.2 dB. Since power sensors are available with correction factors as low as 90%, your measured power can be in error by as much as 10% without taking other known uncertainties into consideration. Assuming the power to be measured is within the sensor range, the signal-to-noise ratio is acceptable, and the VSWR of the measurement port is acceptable, the most important correction you can make to improve the error is to account for the frequency of measurement.

First, remember that measurement accuracy at higher power levels makes a much bigger difference than those made at low power. At -20 dBm, a 0.2 dB error is only about 0.5 uW, but at +55 dBm the error is over 15 Watts.

3.0 Correcting for the Test Frequency

When you are using a power sensor with a correction table by frequency you must enter the percent correction as shown on the sensor for the frequency being measured. If you are using a power sensor with electronic calibration data you must still enter a frequency to allow the meter to make the correction. The main advantage of the electronic calibration sensors is you don't have to interpolate the correction percentage by frequency from the data table or graph. When you enter frequency, the meter will apply the correction, but you must input frequency. CF Uncertainty is still a factor when using power sensors, even when correction for frequency is applied. CF Uncertainty increases with frequency from about 1% to 3% depending on the frequency range, but failing to apply the correct CF to the measurement compounds the error.
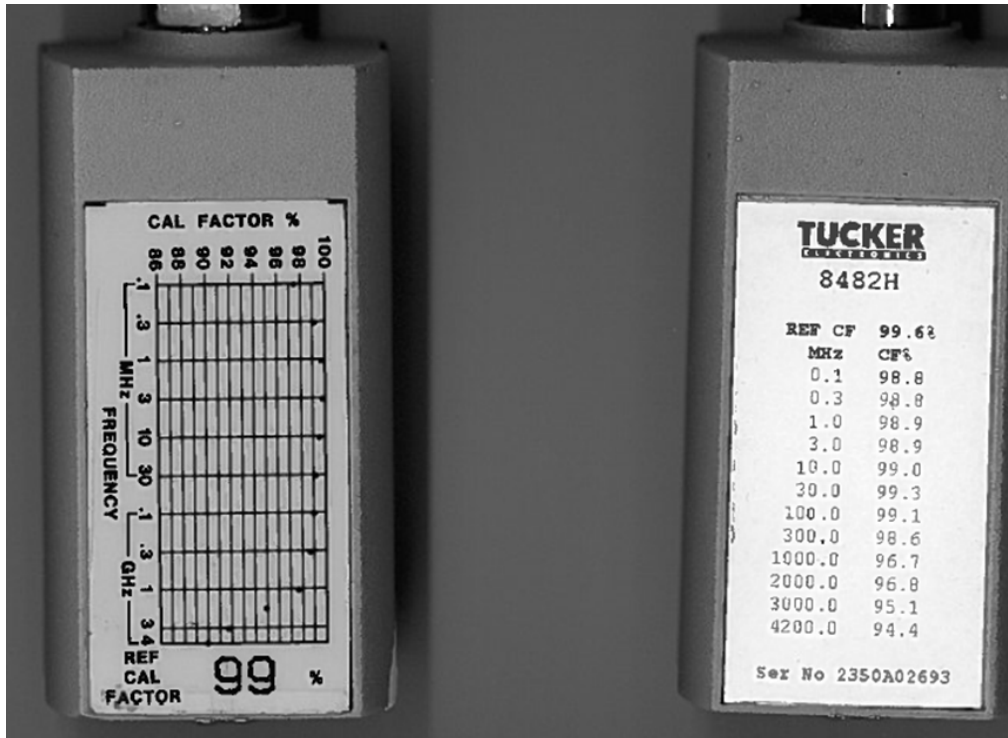
Figure 1: Power Sensors with Cal Factor (CF) Data

Fig. 1 Power sensors with Cal Factor (CF) data. CF as low as 90% is shown. For frequencies not enumerated, use straight-line interpolation of adjacent data. If your measurement frequency is not enumerated or between data provided, you are using the wrong sensor.

4.0 Measurement System Slop and Offsets

Applying corrections by frequency to power measurements goes beyond simply correcting the sensor. If the RF power level to be measured is not connected directly to the power meter head, whether the RF path is just an attenuator or an entire test bench setup, you must account for the "slope" of the RF path to correct your measurement. A common method uses a measurement "Offset" to add the attenuation of the path loss the power measurement displayed. Unfortunately, a single offset is frequently used, as the meter may only retain a single value. The Offset value must be changed for each measurement frequency that has a different loss. Some e-cal power meters allow you to input a table of offsets that will be interpolated by the meter. This is a great feature, but will occur only when you input the measurement frequency. High quality attenuators will come with calibration data, or measure the slope with a network analyzer for reference.

5.0 Bandwidth and Noise

Due to the high bandwidth of a power sensor, when using a power meter to measure power in a signal, the signal-to-noise ratio is important. Remember that Noise Power = KTB, and for a sensor BW of 26 GHz, B > 100 dB! Noise power can dominate the total power measured when signals fall as low -50 dBm or so. Adding a post-amplifier will not help the signal-to-noise, as the noise will be amplified as well as the signal. In this situation a filter is wanted, ideally a band-pass filter at the frequency of interest. Lacking a band-pass filter, a high- or low-pass filter (or both) can help. Check the ON/OFF power level of the system noise without the signal to see if the noise power is a factor in your measurement.

When making measurements of signals at higher power levels it is important to be aware of strong harmonics or other spurious signals that may contribute too much to the total power measured. Check the signal with a spectrum analyzer to make sure. In this case, again, filters need to be used to subtract that power before the sensor can see it.

At lower power levels a good spectrum analyzer (SA) may make a better measurement than a broadband power meter, as the SA will employ detection and filters that exclude the noise power.

6.0 VSWR Can Make a Difference

Another practical power meter measurement correction that you can easily make is to assure yourself that the measurement uncertainty created by VSWR is minimized. When measuring with a sensor on an unknown port, you can make a quick check with a 6 dB pad to see if the measurement improves. Adding 6dB of loss increases the return loss by 12 dB, and will improve poor VSWR by a substantial amount, allowing a better measurement. The easiest way to do that is to use the power meter "Relative" measurement feature to "zero" the displayed power level, then add the pad and see if the level changes by 6 dB. As long as the signal level is still in the sensor range, if it changes more than the pad value the VSWR is adversely affecting the measurement, and you should use the pad. It might need more attenuation than 6 dB. In any case, you must enter the percent correction as shown on the attenuator for the frequency being measured or you must input the measurement frequency.

To reduce the measurement uncertainty of a relative measurement, try to keep the power applied to the sensor at the low end of the power range. The relative uncertainty can be as high as 6% at the high end, and as low as 1% at the low end.

Many factors contribute to making a successful power measurement- using the correct type of detector for your signal of interest, making allowances for gating and various forms of modulation, and more. But if you can avoid the biggest mistake and remember when you use a power meter that you are making a broadband measurement, not just measuring a discrete signal, you are on the way to getting better and more consistent results.

modular rf

Trends in Military Communication Systems

Military communications is no different than the rest of the world's communications; they want it smaller, lighter, covering more bands and carrying more voice and data than the last generation of products. But there are other changes that are potentially much more profound that will eventually change the way that battlefront communications is carried out.

Traditional tactical communications has been via specialized individuals or locations that were the hubs for information exchange using terrestrial links or, more recently, a combination of ground and UHF SatCom uplinks. AR Modular RF has been making man-pack 20 Watt KMW 1030 and man portable/vehicle KMW2030 & KMW2050 125/200 Watt units for a number of years to address the traditional hub and spoke kind of communications. These kinds of systems are still the backbone of military communications, but the wind of change is already blowing and vendors like AR Modular RF are constantly looking into the future for product enhancements and new product developments.

1.0 New and Improved Multiband Tactical Communication Amplifiers

A recent product improvement to reduce operator intervention has been to make these units auto-tuning, such as our recently upgraded man pack, the KMW1031. This unit provides a minimum of 20 Watt output for only 1 Watt input, making it operable with just about any single or multiband "handie-talkie" transceiver. This high gain unit (minimum of 13dB) will therefore give potentially up to 4 times the operational reach of a 1 Watt handheld unit used under the same terrain conditions.
Recent improvements include a new power supply module that allows the unit to operate from both 12 and 24 Vdc supplies. It also has vehicle power spike suppression circuits included so that the unit can be run from vehicle supplies without fear of damage from power surges. The unit is smaller and lighter than the old one and consumes only about half the current, which allows it to be operated from a single tactical battery such as the UBI-2590 or similar item. Battery use management software maximizes operational life when operated on batteries. In line with its predecessors, this unit is fully submersible to 66ft.

There is also a new vehicle mount amplifier, the KMW1040, which provides at least 50 Watt output with an input of between 1 and 5 Watts. The unit is designed to be mounted directly to vehicle structures without the need for shock mounting; it is also waterproof, making it a great choice for waterborne or weather exposed vehicle applications and, like its sibling, the KMW1031, it can be used on both 12 and 24Vdc vehicles without any additional hardware. In addition to making both of these units automatic band switching and capable of filtered operation in the SINCGARS 30 to 88MHz band, they have been designed using the latest generation semiconductor devices, making them significantly more efficient and therefore, they use less vehicle power or need fewer batteries per mission. The latter of which is a vital consideration as more "electronic gadgets" are carried by frontline troops.

2.0 Legacy Systems Still Need Support

Old HF and low band VHF equipment for voice have been augmented or replaced by multi-band voice and data VHF/UHF systems with frequencies up to 512MHz using both old legacy modulation as well as modern complex modulations. However, legacy communication products are not dead yet and AR Modular RF has supported a number of programs to provide modern power amplifier designs to support older legacy government communication systems. Amplifier systems such as our 100 Watt KMW2025 covering 30 to 512MHz, and the 100 Watt KMW2040M14 covering 225 to 450MHz, and the custom designed rack mounted 500 Watt KAW4040M13, offer the high performance necessary for modern modulation formats and give years of new life to older legacy systems for a relatively low investment. Custom configured designs like our 50 Watt KMW2040M13 covering the 200 to 400 MHz band include RF sensing transmit/receive switching and the ability to survive +80C case temperatures.

3.0 Even Higher Frequencies and Secure Modulation Formats

Frequencies are climbing up the spectrum and in the near future designs will have to go up to 3GHz and be able to handle a multitude of secure modulation formats in order to be "multinational" in nature. It's now becoming essential that our military groups communicate with other "friendly forces" as well as our own Homeland Security groups in times of war or national emergency. All of which means more modes of operation, new frequency bands and/or spectrum for our new systems to handle.

4.0 Next Generation IP Systems are Needed

Next generation highly mobile front line communications are tending to move away from the high power single line of contact methods, toward a low power "mesh" system where more operators are linked together by means of a multi-node mesh system. These systems will be less susceptible to single points of failure and will be self healing such that the communications packets find the best route to the destination based on traffic levels and available system bandwidth. Additionally, these new systems will need to be
IP compliant and have a network port into the "IP pipe in the sky", thus being able to carry encrypted voice and data information instantly to and from locations all over the planet. PDA devices, laptops, head-up displays, surveillance radars, scopes and other frontline systems will all connect seamlessly into the communications pathway, allowing individuals to be better informed of the big picture as well as allowing the big picture guys to see/hear the details at the source of the action.

5.0 Satellite Links are a Vital Part of Communications for a High Mobile Force

UHF SatCom "on the move" systems are a vital part of modern highly mobile forces. So, in addition to the multimode systems discussed above, dedicated UHF communication amplifiers like the legacy KMW2050 can provide up to 200 Watt uplink power, thus allowing relatively "minimal gain" antenna systems. Plus, a variety of custom configured "embeddable" SATCOM modules such as the KMW2040M17 can provide up to 100 Watt with VSWR and automatic level control ALC built right into the unit, allowing it to be neatly integrated into a larger and multi-functional communications package. Designed to be rugged, these systems meet applicable sections of the MIL STD 810F environmental specifications.

6.0 Converged Communications and Countermeasures

The need for converged communications and electronic war systems such as jammers exists, too. The use of a combination of software defined radio (SDR) and broadband amplifiers like AR Modular RF's KMS1033 20 to 2500MHz, or one of our KMW1090 series 10 to 1000MHz amplifiers allow multi-carrier communication and jamming to be carried out simultaneously by a single operator in the band 30 to 2500MHz. New high efficiency amplifier designs use the latest generation GaN devices offering high efficiency and tolerance to high temperature without threatening the system reliability. Our future soldiers will be better informed and better protected than at any time in history due to the high tech systems that they carry in their backpacks or on the dashboards of their vehicles and AR Modular RF will be there to support them.

5 Steps to Selecting the Right RF Power Amplifier

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

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

1.0 Step 1 - Know Your Signal

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

1.1 Signal Modulation and Power - CW, SSB, FM, and PM are Easy

To avoid distortion, amplifiers need to be able to faithfully process your signal's peak power. No matter what the modulation type is, you need to know the Peak power. Fortunately, for many modulation types Average power is the same as Peak power: CW, SSB (single tone and voice), FM, and Phase Modulation all have Average equal to Peak power. The power in these RF carriers is relatively easy to measure with an Average power meter, a Spectrum Analyzer, or an RF Wattmeter. Many RF amplifiers are rated for CW power, so that spec will apply for SSB (single tone and voice), FM, and Phase Modulated signals as well.

1.2 Watch Out for AM Modulation

AM Peak power depends on the percentage of modulation, but you should allow for 100% modulation, which creates signal peaks of 4x the un-modulated carrier, or +6dB. That means that you would need a 400W amp to faithfully AM modulate a 100W CW signal. If you have less power available, or "headroom", your amplifier will be operating in compression, which will distort the signal by "clipping" or cutting off the peaks of the waveform.

$$\text{AM Peak Power (dBm)} = \text{CW Power (dBm)} + 6db \text{ (100\% modulation)}$$
$$\text{AM Peak Power (Watts)} = \text{CW Power (Watts)} * 4 \text{ (100\% modulation)}$$

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

Note that AM average power is not the same as CW average power, as it varies with the modulation depth.

1.3 Multi-Tone and Complex Modulation Peak Power

If your signal is composed of multiple discrete CW, SSB, FM or PM carriers, you can essentially add the powers of all the carriers to arrive at a Peak power level. If the number of carriers is dynamic, or the signal is created by complex (phase and amplitude) modulation you will need to resort to other means of measurement. If you have a Peak Power Meter, and you are sure no other significant contributions to the signal power are present, it should provide a valid Peak measurement. Checking with a spectrum analyzer is always prudent to be sure of what a broadband power sensor is "seeing". Lacking a Peak power meter, a spectrum analyzer with a broadband statistical power measurement like CCDF, or a format-specific analyzer that can report Peak power, with an Average power measurement you can estimate a Peak power level based on your signal format Peak-to-Average ratio (PAR) or Crest Factor. For example, 64QAM has a PAR value of about 3.7dB. PAR actually uses the RMS value, not average, so add 1.5dB to the average power to get RMS power. For a 64QAM signal with 0 dBm average power:

$$0\text{dBm average} + 1.5\text{dB} \cong 1.5\text{dBm RMS}$$
$$1.5\text{dBm RMS} + 3.7\text{dB PAR} \cong 5.2\text{dBm Peak}$$

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

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

So What if the Amplifier Runs out of Headroom?
Running an amplifier out of the linear range doesn't just mean you get less power out. It can create big problems:

1. You can damage the amplifier. Power amps typically specify a P1 level to represent a safe power output level (see Step 4 for a brief discussion about P1). It is good practice to make sure your Peak signal levels stay under the P1 level to avoid over-driving the amplifier. Some of the excess power that can not be translated into the output waveform can appear on the output transistors as heat. Typical destructive levels for these expensive devices are about P6 or P7 , only 5-6 dB above P1. Add attenuation to the amplifier input as necessary to keep under P1 levels. Many AR Modular RF amplifier designs offer over-drive protection in the form of an Automatic Limiter Circuit (ALC) to prevent accidental over-drive levels. Amplifiers employing newer Gallium-Nitride (GaN) devices are more damage-resistant than the LDMOS devices that preceded them.

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

3. You can make other problems. The power that is missing from your distorted signal is appearing somewhere else- as interference out of your frequency channel or as harmonics way off-frequency. Complex-modulated signals can create interference in adjacent channels. Harmonics is especially a problem with broadband amplifiers that amplify the 1st or 2nd harmonic of the lower frequencies covered. Since no filters can be employed, a conservative design with lots of headroom is needed.
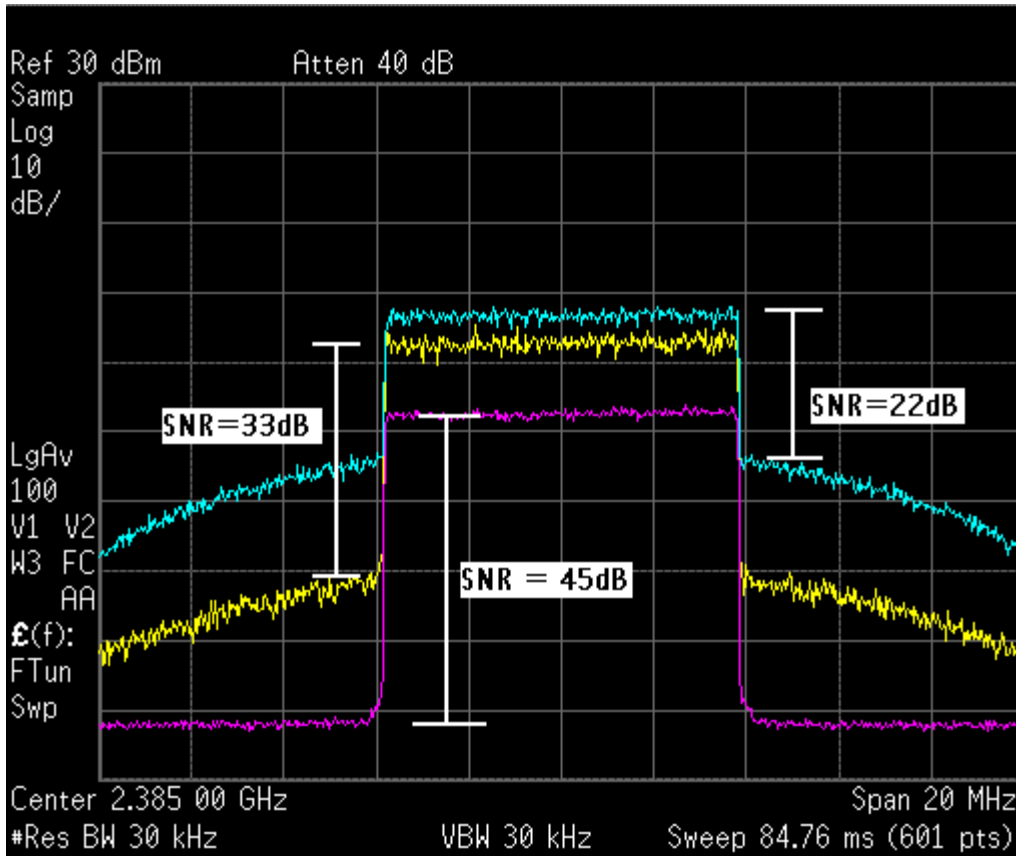
Figure 1: OFDM Signal-to-Noise Ratio (SNR) decreases and IMD increases
as Peak Power ouput is compressed

Figure 1 shows an OFDM signal degrading in an amplifier as the Peak power approaches and crosses over the P1 compression point. The lowest trace is an uncompressed signal with better than a 45dB signal-to-noise ratio (SNR). The middle Trace 2 shows the input signal 10dB higher than for Trace 1, with signal peaks just touching the P1 point. While the gain across the data channel has increased by 10dB, Intermodulation distortion has created "shoulders" of noise, reducing the SNR to 33dB. Increasing the drive by only 5dB in Trace 3 shows that the power in the adjacent channels has increased by 16dB, and SNR has been reduced to about 22dB. Your specific application will determine what level of SNR is required or can be tolerated.

1.4 Complex Modulation Needs More Headroom, But How Much?

As shown, complex-modulation formats exhibit high Peak powers compared to their Average power. With Crest Factor reduction (CFR) schemes, digital and amplifier linearization techniques, and the variables of the signal payload, the effective PAR and range of acceptable non-linearity is wide. Most digital formats can suffer modest to moderate distortion and remain usable. For example, absent other distortion, WLAN modulation can still provide acceptable performance when Peak power is limited to an amplifier's P1 power point (see Step 4 for an explanation of P1).

OFDM modulation with a PAR of 12 may allow a Peak power de-rating of as much as 6 dB from Peak. Even de-rating by 6dB leaves the Peak power still 6dB over average, and that must allowed for by either backing off the CW P1 point by 6dB or by adding 6dB of headroom to the output power rating of the amp. Your specific application must determine the effective PAR value you apply to the average power of your signal when calculating the Peak power, but Peak power will always be significantly more than average power. Using an effective PAR of 6-7dB should provide a useful working number.

1.5 Pulse Modulation

Measuring pulse Peak power can be done easily with a Peak power meter regardless of pulse width. You can also calculate Peak power by dividing Average Power by the duty cycle of the pulse modulation. For example, for a pulsed RF train with an Average power of 0dBm and a duty cycle of 15%:

$$\text{Duty Cycle (dB)} = 10 \log(\text{duty cycle ratio})$$

$$0\text{dBm} + 10 \log(0.15) = 8.24\text{dBm Peak}$$

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

2.0 Step 2 - Do the Math, Do You Need Gain or Power Number?

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

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

For example, you may know the Peak Envelope Power (PEP) required to provide a specific Effective Radiated Power (ERP) at an antenna. In that case, for a signal with a Peak power of +10dBm and a desired PEP of 50 Watts:

dBm = 10 log(milliwatts)

10 log(50,000 mW) = +47 dBm
+47dBm PEP - 10dBm Peak = +37dB Gain @ 50W Peak Output (+10 dBm Input)

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

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

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

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

Power (Watts) = antilog10(dBm/10)

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

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

If your signal level is below 0dBm, you can search for amplifiers with higher gain that will produce the desired power level in Step 3. To determine the maximum Input Power level for an amplifier, subtract Gain from the CW P1 power out:

Peak power out dB – Gain dB = Peak Input level

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

20W = +43dBm
+43dBm – 48dB = -5dBm

3.0 Step 3 - Window Shopping, Select Type, Frequency, and Power

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

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

3.1 Remember, Cheap Specs will Shrink in the Wash, Shop for a Size Larger

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

4.0 Step 4 - Comparing Apples to Apples

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

4.1 Signal Linearity and Usable Watts

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

AR Modular RF can provide Class A RF power amplifiers that exhibit the highest signal linearity for the most demanding applications, like the KAW2180, a 100W minimum dual-band Class A amplifier that operates from 0.01-1000 MHz. All other types of RF amplifier (usually Class AB) will provide some more distortion in exchange for efficiency, and may require some spec-diving to figure out how many linear watts you will really get.

RF power amplifier ratings can be expressed in many kinds of Watts: Average, P1, CW, Peak, ALC Watts, even Peak-to-Peak (P-P). You job here is to "normalize" all the results to a common and meaningful value, like P1 Watts, so a direct comparison can be made.

4.2 P_1 Power vs. Saturated Power

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

Saturated Power P_3 – 2dB = Usable Power P_1

For example, for an amp specified at 100W out P_3 saturated power, the actual "usable" power, or P_1 level, is found:

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

Modulation usually requires some of linearization to be effective when using power levels above P_1. Your job here is to look through all the specs of amplifiers that have "made the cut" so far, and make sure that for any amp specified in Watts, or anything other than P_1 watts, you find the P level specification. If you don't, you may discover that the rated power is the saturation level.
AR Modular RF typically specifies a minimum power level below P as the rated power out. See if any amp specifications provide you with a margin, and when you look$_1$ at P power levels, include that margin in your comparison.

4.3 Gain - Too Much of a Good Thing?

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

4.4 Converting CW to AM Modulation Specs

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

CW P_1 Watts / 4 = AM Peak Watts

For P_1 in dB:

CW P_1 dB – 6dB = AM Peak Watts

4.5 Flatness and ALC Power Levels

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

Automatic Level Control (ALC) is a feature mainly used for CW modulation. RF power amplifiers with ALC will usually specify an ALC Power level in addition to P1 Watts. The main function of ALC is to provide overdrive protection to the device at the output of the amplifier. For CW signals the ALC level defines the maximum RF level available from the amplifier, regardless of drive level. ALC can help protect the amplifier from over-drive, and can also provide improved Flatness, especially
for CW signals.
An adjustable ALC can allow you to vary the ALC level below the P1 point. ALC is a "friendly" limiter, creating much lower distortion than P1. The ALC function will need to be slowed or disabled for non-CW modulated signals, or serious distortion will result. Amplifiers with ALC Fast/ Slow selection can enable some limited ALC functionality for non-CW signals, but it will be less responsive. For amplifiers with variable Gain, reducing the gain below the ALC Limit will also reduce Flatness as the gain lowers.
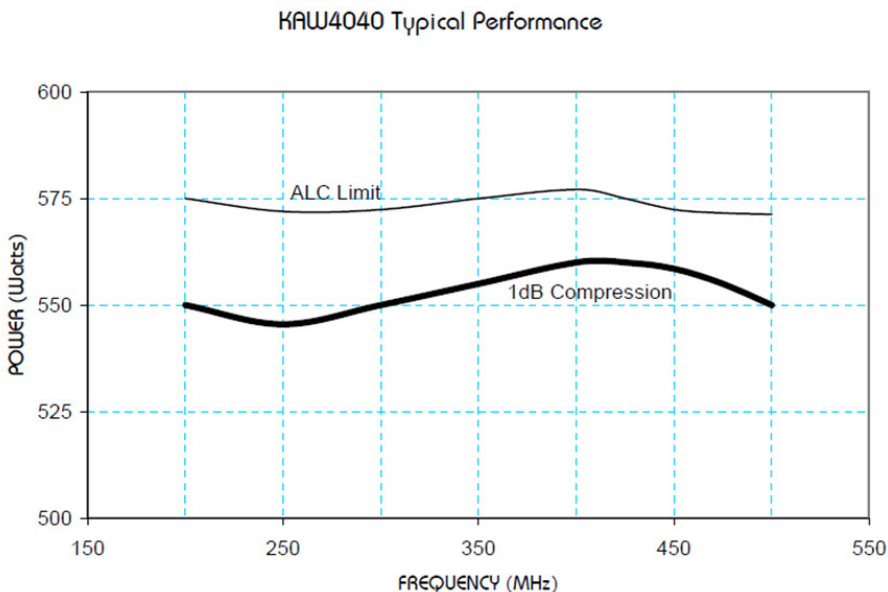

Figure 2: KAW4040 Typical Performance

4.6 RF Pulse Amplifiers - A Different World

Pulse amplifiers are a separate breed of RF amplifier. Pulse amplifiers are rated in Peak Watts. Pulse-specific amp designs come in two types depending on the pulse modulation method. The first, Pulse Gated amplifiers can have a CW signal applied to the input and an external gating signal is applied to the amp to produce the pulsed output. Alternatively, a pulse train is applied to the amp input and the gating is used to quiet the amp between pulses. The non-Gating type has design features specifically for preserving the shape of pulsed signals with fast rise-times. A CW rated amp can also pass pulses, but the highest pulse fidelity is obtained by design features not usually contained in a CW amp. If your main requirement is for pulse performance, select from pulse amps with the correct Peak power rating. If your modulation format is not strictly "pulse", but is a TDMA or "Bursted" signal with very fast rise-times, you may find a CW amplifier will not be able to faithfully reproduce your signal, as the signal for practical purposes is really more like a pulse, and you may be better served by a non-gated pulse-type amplifier

4.7 Harmonic Distortion - Trouble is Just an Octave Away

Having worked your way down to a short list of amps that will meet your P1 , gain and frequency requirements, you need to pick an amplifier with low Harmonic levels, as compared to other like designs. Harmonics are a relative indicator of amplifier design quality and stress. Harmonic distortion is measured in dBc, or the power level as compared to the output carrier power. Harmonic specs vary widely, from relatively high levels in the low teens, like -13 dBc, to much lower levels like -60 dBc or less. The higher power range of numbers is usually associated with broader-band amplifiers that can not employ a filter at the harmonic frequency as it is in the gain passband. Out of the gain passband, filters can knock Harmonics down, but a filter following a high power amplifier can get really hot, depending on the energy absorbed, and that heat can lead to a short filter life. For narrower amps with a bandwidth less than an octave wide, a better scheme is to reduce them with a conservative design and then a cooler-running filter, if needed. Make sure when comparing Harmonics specs you understand any big differences as they can be the result of completely different types of amplifiers. If you require the absolute minimum of Harmonic distortion, use a Class A amplifier.

4.8 Wide-Band or Band-Switched - Automatic or Manual Transmission?

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

5.0 Step 5 - Shop for Features, The "Bells and Whistles"

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

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

5.1 About Impedance Mismatch Tolerance

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

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

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