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Electromagnetic compatibility (EMC) compliance testing is mandatory for most electronic products slated for sale throughout the world. Therefore, EMC should be one of the main objectives of designing any electronic product, at the same level as electrical, mechanical, or even software design. However, the training that students receive in relation to EMC is usually scarce, mainly because the specific equipment that this subject requires is rarely present in educational laboratories. This paper presents an affordable EMC pre-compliance test lab for educational purposes, together with lab activities related to four of the most important EMC topics. The aim is to raise the awareness of electronic engineering students, who are the future designers of electronics products, of the importance of considering EMC techniques from the beginning of the design process.

The International Electrotechnical Commission defines EMC as “the ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment” [1]. Excellent books that deal in depth with all aspects of EMC are available [2–5]. Interesting current educational works address EMC instruction regarding power electronics applications [6], printed circuit board layouts [7], and other uses. Many university electronics engineering programs include EMC courses [8–10]; however, such courses focus on coupling methods and do not include EMC testing activities because testing requires expensive and complex installations such as open-area test sites (OATSs) or expensive semi-anechoic chambers. These facilities and the specific instrumentation for the tests are usually not available for use by electronics engineering students who, at most, might make a guided visit to them.

To allow students to perform EMC testing activities, this work presents a design for an affordable EMC lab and four of the most important EMC pre-compliance tests. Although the results are not comparable to those obtained in a full-compliance EMC lab, they can help students understand the importance of EMC testing. The proposed measurement methods can provide a first indication of the product's effectiveness in compliance with the EMC regulations in the prototype phase, allowing for design modifications and for quickly checking their effect in EMC.

EMC Pre-Compliance Tests and Required Equipment

This work is part of the testing and verification of electronic equipment course for the engineering in information technology and telecommunications degree at the Gijón Polytechnic School of Engineering in Spain. It is an optional course for fourth-year students specializing in the area of electronic systems and is worth six credits under the European Credit Transfer System. The course consists of two parts: the first part focuses on EMC regulations and tests, and the second part focuses on design techniques that fulfill EMC regulations. This article summarizes the student activities related to the first part of the course.

EMC tests can be divided into two broad categories: emissions and immunity, as Fig. 1 shows. Emissions tests are run to determine how much radio frequency (RF) energy the product emits. Emissions testing typically comprises two tests: one for conducted emissions on power and telecommunications ports and one for radiated emissions. The breakpoint between the two (conducted and radiated) in commercial standards is 30 MHz. Immunity tests are run to determine that the product will operate as intended when subjected to various sources of electromagnetic energy in its intended operating environment.

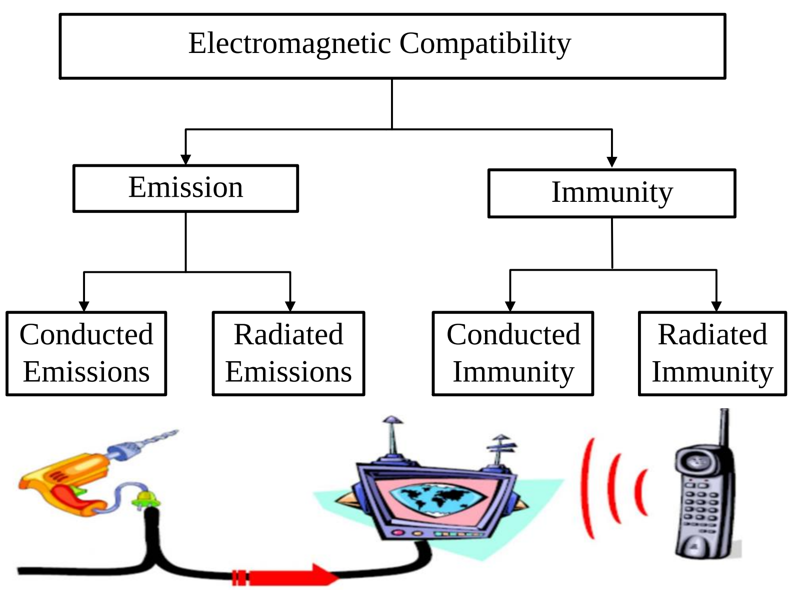


Fig. 1. EMC classification.

During the 2015–16 and 2016–17 academic years, students visited the EMC laboratory at the University of Oviedo, Spain, which provides a semi-anechoic chamber and all the equipment to carry out EMC compliance testing. However, this lab is not for educational purposes. In the 2017–18 academic year, to allow students to perform certain EMC measurements, the lab acquired affordable EMC equipment (around $6,915 or €6,000). Table 1 shows the EMC pre-compliance tests and measurements carried out by students. Fig. 2 depicts the equipment.

Table 1. EMC pre-compliance tests and measurements.

EMC Test	Required Equipment
Conduced emission testing	Spectrum analyzer + LISN
Radiation emission testing	Spectrum analyzer + TEM cell
RF immunity testing	RF signal generator + RF power amplifier + TEM cell Alternatively: Spectrum analyzer tracking generator + RF power amplifier + EMC near-field probes
Near field measurements	EMC near-field probes + Spectrum analyzer
Common-mode current measurements	RF current monitoring probe

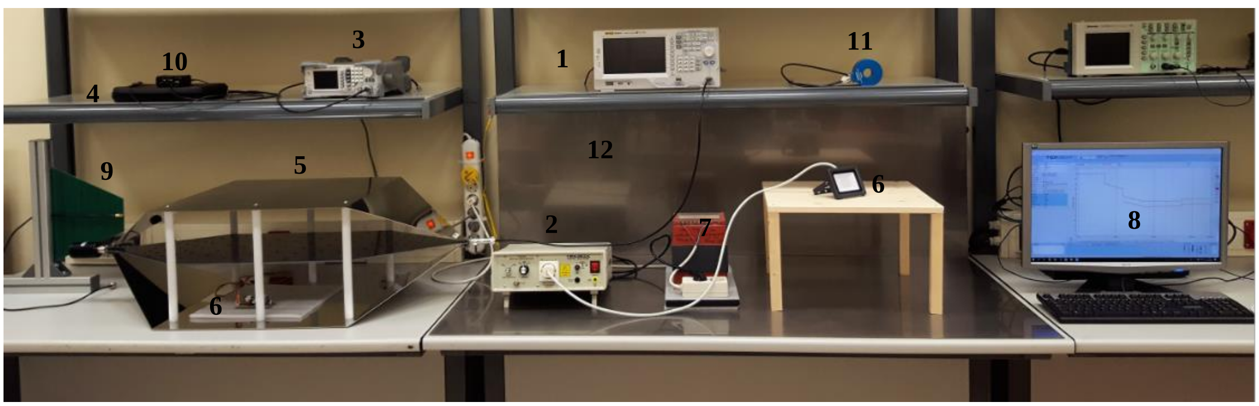


Fig. 2. Equipment for EMC pre-compliance tests and measurements.

1. Spectrum analyzer (Rigol DSA815-TG, with EMI option); 2. LISN (Tekbox TBLC08); 3. RF generator (Rigol TBMDA2); 4. Near-field probes (Rigol NFP-3); 5. Open TEM cell (Tekbox TBTC3); 6. Equipment under test (EUT); 7. Isolation transformer; 8. EMC compliance software (Tekbox EMCview); 9. Log periodic PCB antenna (Kent Electronics); 10. RF power amplifier (Tekbox TBMDA2); 11. HF current monitoring probe (TBCP1-150); 12. Metallic ground reference plane (stainless steel).

Conducted Emissions Testing

A conducted emission is any emission transmitted from equipment to the environment along cables. The main emphasis in measuring line-conducted emissions is on the EUT's main AC input, although other interface ports are becoming increasingly important, such as telecom and network ports on information technology equipment.

For compliance testing, a CISPR 16 EMI receiver and the proper setup are necessary. This generally requires using a certified testing lab and special equipment that can be cost-prohibitive for educational purpose. Pre-compliance testing is not required to conform to international standards; the goal is to uncover potential problems and reduce risk of failure at the compliance test stage, which is expensive. Conducted emissions pre-compliance testing requires a spectrum analyzer with peak detector (quasi-peak optional), a line impedance stabilization network (LISN), and an isolation transformer. Fig. 3 shows the setup for conducted emissions testing. CISPR is the international special committee on radio interference.

A LISN is a low-pass filter placed between an AC or DC power source and the EUT to create a known impedance and to provide an RF noise measurement port. It also isolates the unwanted RF signals from the power source. The LISN used in this setup includes a 150-kHz high-pass filter to reduce lower-order power line harmonics and a 10dB attenuator to avoid large transients that can destroy the front-end circuitry of spectrum analyzers when the LISN is powered on or off or switching from phase (P) to neutral (N). Using an isolation transformer is essential because the LISN's internal capacitors draw significant blind current and, without an isolation transformer, would trip the ground protection switch.

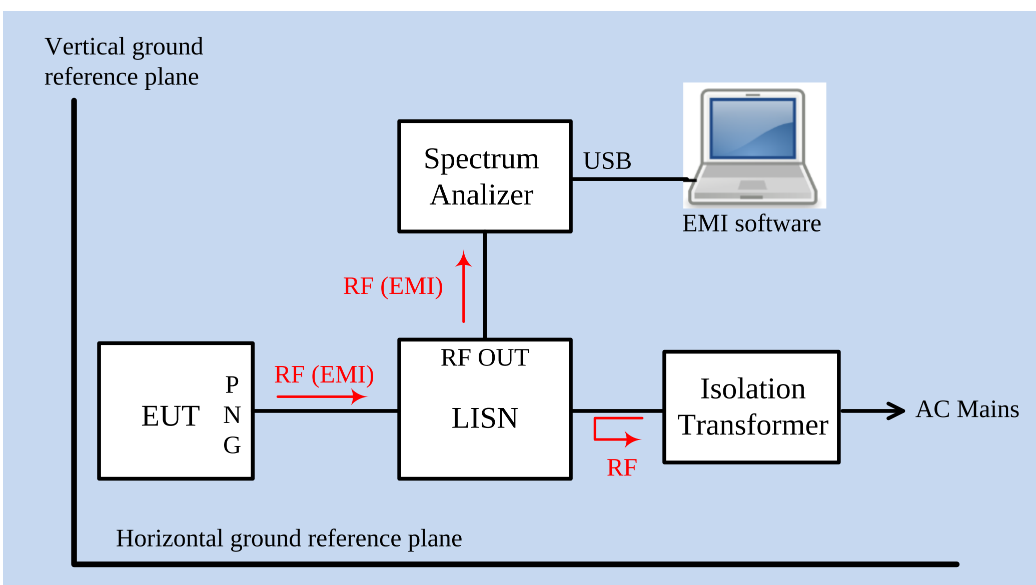


Fig. 3. Setup for conducted EMC testing.

A key EMC pre-compliance test setup component is a spectrum analyzer. Spectrum analyzers have significantly dropped in price in recent years. Entry-level models already start at approximately $1,500. Basic spectrum analyzers are not an alternative to an EMI measurement receiver in a full compliance setup because of their limited sensitivity and dynamic range and susceptibility to overload. However, they are extremely valuable for confirming the frequencies and nature of offending emissions.

Spectrum analyzers used for EMI measurement have a defined receiver bandwidth, method for signal detection, and method for averaging results to achieve signal levels. Detection methods can calculate the positive or negative peak, the RMS or average (AV) value of voltage, or the quasi-peak (QP) value. The compliance labs use QP detectors for the full compliance test, but the pre-compliance measurements can be made with simple peak detectors for a more conservative test margin. A QP detector considers both the amplitude of the interference and its repetition rate. It has a fixed integration time that is significantly greater than that of the other detectors, which considerably increases the sweep time. Generally, a first sweep is performed using a peak detector (pre-scan). The final scan is performed with the peak values of the pre-scan using the QP detector.

The EMI software is an important component of the equipment needed for EMC tests. It allows measurement automation and provides information on compliance with applicable regulations. In this work, the EMI software has been used for automated conducted and radiated noise measurements. It also supports tracking generator control for immunity testing. Any EMC standard is represented by one or more projects. A project summarizes all configurations necessary to carry out measurements and consists of limit files, segment files, a cable file, a LISN file, an antenna file, an amplifier file, and various settings such as graph boundaries, trace colors, and settings for peak measurements.

The EUT selected for conducted emissions testing was a 10W LED tube without a label. The applicable EMC standard was CISPR 15 (EN 55015). Measurements were made on each conductor of the incoming line separately. QP detector measurements should start at 9 kHz, while AV detector measurements should start at 150 Hz.

First, an empty measurement was carried out to see the ambient noise picked up by the measurement setup. The LISN main switch is turned off and the line selection is switched to “0” (N) or “1” (P) to carry out the conducted noise measurements. Fig. 4 shows the conducted emissions of the 10W LED tube. The green graph represents the results of the measurement with the average detector. The corresponding limit line is in red color. The pink graph represents the results of the measurement with the QP detector. The corresponding limit line is blue. Carrying out an average detector measurement is sufficient to obtain an overview.

The jump at 150 kHz was caused by the change of the resolution bandwidth (RBW) from 200 Hz to 9 kHz as specified in CISPR 16. The result reveals that the tube did not contain a switched mode regulator. Consequently, it was equipped with an aluminum heat sink and therefore was less efficient. The visible peaks are all ambient noise picked up by the measurement setup.

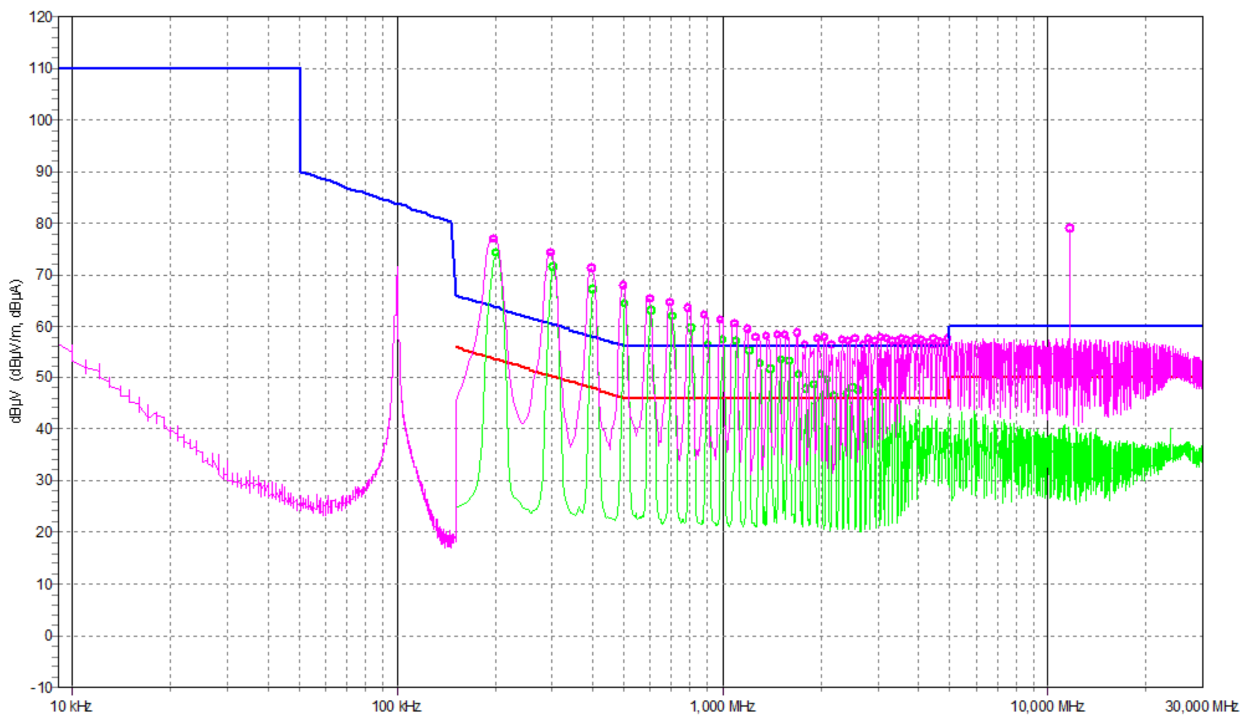


Fig. 4. Conducted noise result of 10W LED tube with the CISPR 15 project loaded.

Radiated Emissions Testing

Radiated emissions testing looks for signals broadcasted for the EUT through space. This type of measure is the main challenge because the teaching lab is surrounded by electromagnetic noise from the devices present in the lab as well as from mobile networks. The frequency range for these measurements is between 30 MHz and 1 GHz and, based on regulation, can go up to 6 GHz and higher.

Radiated emissions may be measured in either an OATS or an RF semi-anechoic chamber. Emissions from the EUT are measured using an antenna for the appropriate frequency range, a pre-amplifier (if necessary), and a measuring receiver. Measurements are taken with the antenna in both the vertical and horizontal polarization.

An alternative method uses transverse electromagnetic (TEM) waveguides. This method is supported by the EN 61000-4-20:2010 standard. TEM waveguides include open structures (e.g., stripline) and closed structures (e.g., TEM cells). The frequency range depends on the specific testing requirements and the specific TEM waveguide type.

Fig. 5 shows the setup for radiated emissions using a stripline device, also called an “open” TEM cell. It consists of two parallel plates between which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes. A flat inner conductor or septum of a coaxial transmission-line system is positioned symmetrically with respect to the outer conductor. The TEM cell is supplied with a 50 Ω/25W RF termination and a DC block to protect the spectrum analyzer from high levels of DC voltage. It presents a 50 Ω stripline and has a length of 1,038 mm and a septum height of 150 mm. The frequency range is up to 2 GHz. The EUT is placed between the bottom wall and the septum.

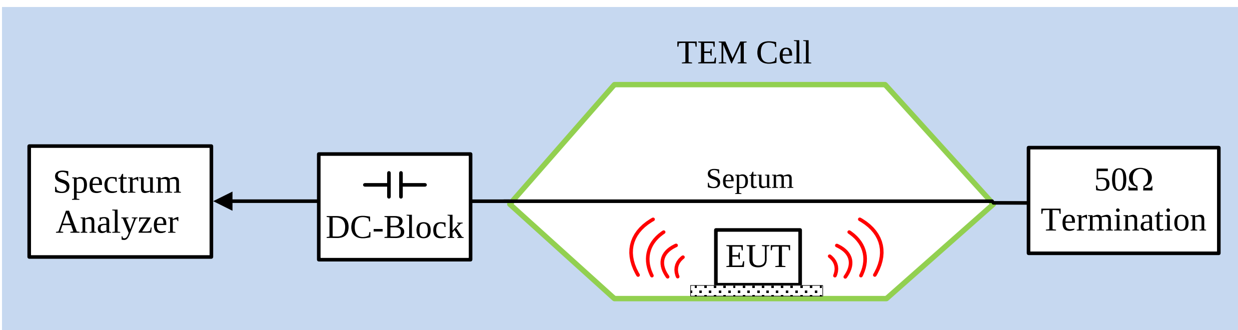


Fig. 5. Setup for radiated emission testing.

The standard applicable to information technology equipment is CISPR 22 (EN 55022). This standard provides the QP limits of radiated disturbances in the far field, and the result is in μV/m; however, an open TEM cell simulates a plane wave propagating in free-space, with a result in dBμV (or V, dBm). EN 61000-4-20 describes a procedure for correlating TEM waveguide voltages to E-field data, which is intended to establish an alternative to OATS emissions test methods. This method assumes that the radiated power, as derived from a TEM waveguide measurement, will be radiated by a dipole positioned above a perfectly conducting ground plane. However, its application requires considerable effort. Therefore, the open TEM cell is used to obtain only relative measurements, such as a fail in the test house.

The EUT selected for radiated emissions testing was a 15W DC–DC single-output switching power supply. Fig. 6 shows the results of the radiated emissions measurements, in which the emissions display a relatively broad spectrum of peaks that are above the limit line.

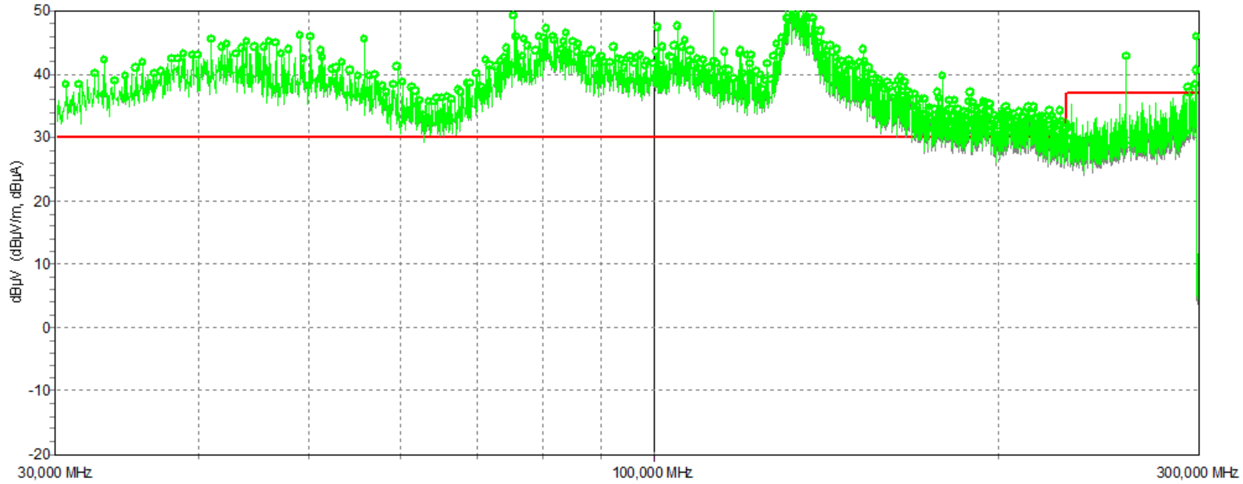


Fig. 6. Radiated emissions of a DC–DC converter.

Radiated Immunity Testing

Radio frequency interference (RFI) can be a serious problem for all kinds of electronic systems. At high frequencies, typically above 80 MHz, electromagnetic energy easily couples directly into equipment and/or its cables.

RFI standards are devoted to controlling or limiting a product's susceptibility to electromagnetic fields. The commercial standard for most products is IEC 61000-4-3. Table 2 gives the test levels related to general-purpose, digital radio telephones, and other RF-emitting devices. Product committees select the appropriate test level for each frequency range requiring testing as well as frequency ranges. The test field strength column gives values for the unmodulated carrier signal. For testing of equipment, this carrier signal is 80% amplitude modulated with a 1-kHz sine wave to simulate actual threats.

Table 2. Test level according to Standard EN 61000-4-3.

Level	Test field strength (V/m)
1	1
2	3
3	10
4	30
x	Special

An affordable solution for testing radiated immunity is to use an RF signal generator, a power amplifier, and the open TEM cell, as Fig. 7a. The RF signal generator must be capable of covering the frequency band of interest and of being amplitude-modulated by a 1-kHz sine wave with a modulation depth of 80%.

Testing radiated immunity requires simply connecting an RF source at one end of the TEM cell and terminating the other end in 50 Ω. The E-field generated is 90 degrees to the plane of the interior septum and reasonably uniform. It does not require a high RF signal level to create large E-field levels within the cell. Connecting to a spectrum analyzer gives a good indication about whether the product suffers excessive radiation.

The E-field for industrial electronics such as EN61000-6-4 is typically 10 V/m before the application of modulation and, according to the TEM cell's manufacturer, the required RF power is 45 mW (16.5 dBm). The larger the TEM, the larger the product that can be tested, but more applied RF power is needed to produce a given field strength.

The selected EUT for radiated immunity testing is an Arduino board running a simple program to turn on an LED. According to IEC 61000-4-3, the test result is classified as a normal performance.

A cheaper setup is to use the tracking generator (TG) output of the spectrum analyzer instead of the RF signal generator (see Fig. 7b). When the spectrum analyzer is set to zero span, the tracking generator outputs RF at a constant frequency. Changing the center frequency of the spectrum analyzer changes the TG output frequency accordingly.

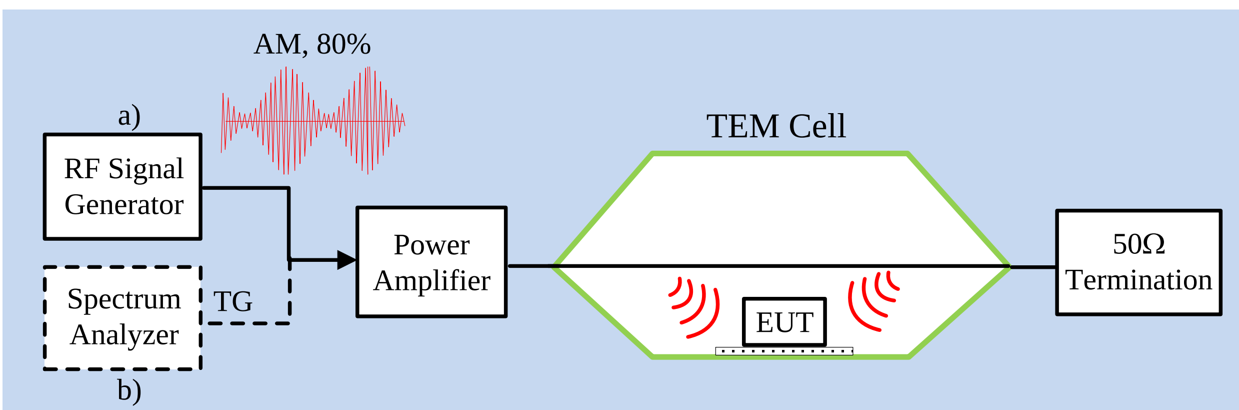


Fig. 7. Setup for RF immunity testing using an RF signal generator and a power amplifier.

Near-Field Testing

Far-field testing has limitations because it cannot identify emission sources. Radiated emissions may come from a USB port, a LAN port, the seam of a shield, a cable, or even a power cord. Near-field radiated measurements cannot be used in "absolute sense" but should be mainly adopted for identifying the most emitting sources, using a signal analyzer and near-field probe. Additional applications are RF immunity tests, which feed an RF signal into the probe and radiate it into potentially susceptible circuit sections.

During near-field testing, the probe's angle and distance from the EUT change, making the absolute field strength result irrelevant. It is the comparison of data results that is significant in identifying which frequency point has the highest emission.

Various probes are used to detect emissions in each field type. If radiation is generated by a high-voltage and low-current circuit or component, the E-field will dominate the EMI near field. If part of the EUT has a high current and low voltage, the H-field will dominate. In near-field testing, the H-field fades faster than the E-field as the distance increases. This is why H-field probes are more commonly used than E-field probes to locate emission objects in close-field testing.

To select an H-field probe for near-field testing, its sensitivity, resolution, and frequency response are important factors to consider. A larger-size H-field probe offers better sensitivity and detects emissions from a larger area; however, its resolution degrades, making it difficult to isolate the precise emission source. It is best to start EMI evaluations using a bigger probe with better sensitivity to determine the rough area of emissions and then use smaller probes with higher resolution to determine the precise location of the emission source. Probe orientation (rotation, distance) is also an important consideration. The probes act as an antenna, picking up radiated emissions. Exposing the loop to the largest perpendicular field possible will maximize the signal strength, as Fig. 8 shows.

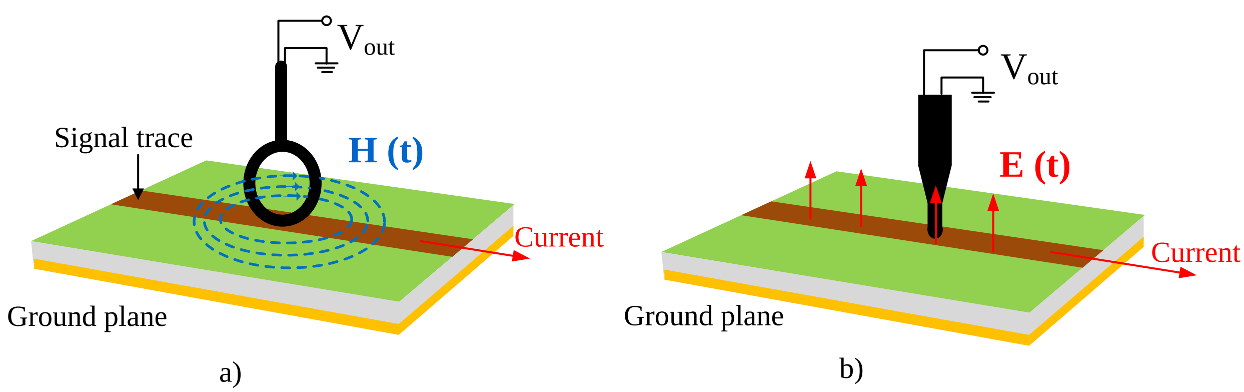
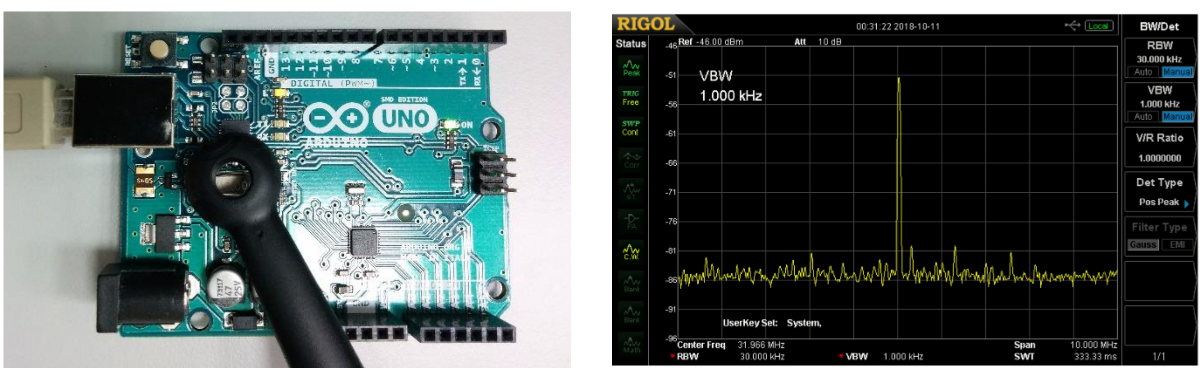


Fig. 8. a) Position an H-field probe in line with current flow so magnetic field passes through the loop. b) Position an E-field probe perpendicular to the conductor to observe electric fields.

For near-field testing, a spectrum analyzer is used to measure electromagnetic radiation from an Arduino board using a near-field probe, as Fig. 9a shows. For low-power circuits, a preamplifier can be used to increase sensitivity. The most important steps are the following:

- Connect the probe to the spectrum analyzer.
- Configure the spectrum analyzer to use the peak detector. This setting ensures that the instrument is capturing the “worst case” peak RF. For highlighting the presence of intermittent signals, it is advisable to use the max-hold function.
- Place the probe close to the PCB board power supply and the oscillator.
- View the interferences frequencies of the spectrum analyzer.
- Change the probe orientation (rotation, distance) and verify its effect on the EMI measurement.
- Take care to test enclosure seams, openings, traces, and other elements that could be emitting RF.

Fig. 9b shows the results obtained in testing the near field in an Arduino board using an H-field probe over the oscillator. A spectrum analyzer narrow resolution bandwidth (RBW) provides higher frequency resolution and a lower noise floor. Video bandwidth (VBW) smooths the trace and makes it easier to see the true signal.



a) b)

Fig. 9. a) Using an H-field probe to detect emissions in an Arduino board; b) 32 MHz clock frequency on a spectrum analyzer with RBW set to 30 kHz and VBW set to 1 kHz.

Conclusion

Education on EMC compliance testing is an important challenge because the equipment required to conduct it is expensive. This paper presents an affordable instrumentation to familiarize students with EMC pre-compliance tests. It also includes descriptions of lab activities focusing on four of the main EMC topics. The results achieved in pre-compliance tests do not assure the compliance of EUT to the applicable standards, but they can help students understand the importance of EMC testing. The positive results obtained through the students' learning assessment are encouraging for planning more activities, such us using a current probe to measure high-frequency currents flowing through power cables or using a low-cost EMI antenna for radiated emissions.

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