EMC
DESIGN
first time right

GUIDELINE

This guideline has been prepared as a result of the partners' activities and close cooperation through 3.5 years in the Innovation Consortium EMC first time right, co-sponsored by The Danish Agency for Science, Technology and Innovation and The Danish Council for Technology and Innovation. The guideline serves as a broad dissemination of knowledge to Danish companies and educational institutions.

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BANG & OLUFSEN
kk-electronic
DELTA
DEIF
-power in control

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The consortium wants to thank the participants for their contributions in labor, knowledge, examples, hardware, contributions to the project as a whole and finally their dedication to the project scope: To provide guidance on how to do the EMC design ‘first time right’.

Introduction

The present report contains the guidelines derived from the EMC FIRST TIME RIGHT project that was executed by a consortium consisting of participants from Danish industry, Aalborg University and the technological service provider DELTA. The project period was 2009-2013. The project is funded by the Danish Ministry of Science, Innovation and Higher Education with an equal contribution of resources from the industry members.

The participants from Industry:

- Bang & Olufsen
- DEIF
- kk-electronic
- Molex Interconnect

Participant from University:

- Aalborg University, AAU

Participant as Technological Service Provider (and Project Manager):

- DELTA

Electrical engineers have for years been interested in predicting- and performing pre-compliance regarding estimations for radiated emission from product and tests regarding radiated emission at IC or printed circuit board (PCB) level. This document highlights the topics that were found most important by the industry partners in relation to their current EMC challenges. Each section of this guide-line is intended as a separate document that can contain guidelines for pre-testing, simulations, expert tools, construction, or trouble-shooting respectively. All this effort can be done in order to improve the probability that the full product will pass the regulatory testing the first time.

Each section starts with a front page that allows the reader to quickly provide an overview of the section. A figure that describes how far in the product development the consortium has intended the method to be used. A diagram that shows the relevant frequency range and a picture that gives an overview of the method.

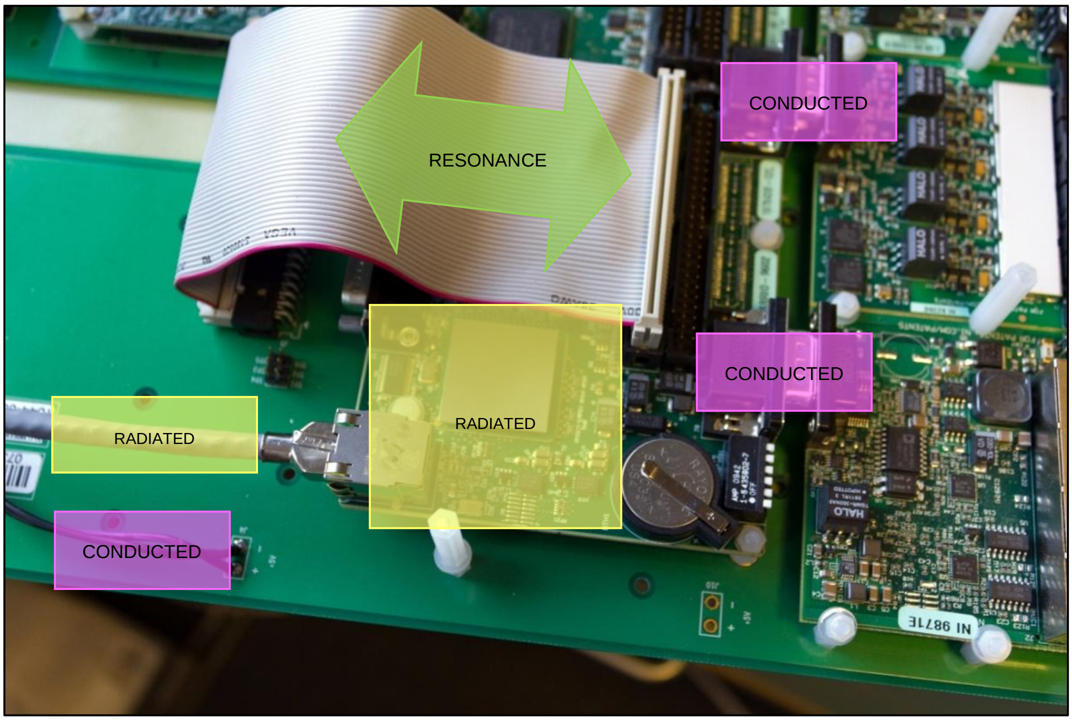


Figure 1. Indication of coupling paths and coupling mechanisms on a system consisting of several PCBs.

The document describes electrical mechanisms and properties related with the conducted and radiated transmission of interference between an electrical circuit and its surroundings. The transmission may occur between modules internally in an apparatus, between circuit parts on a PCB or between an apparatus and its surroundings, as shown in Figure 1 above.

Chapters 1 to 3 highlight electrical emission mechanisms, diagnostic measurement techniques and basic EMC properties of electronics. Chapter 4 will focus on system integration aspects, associated test- and measurement techniques and design rules regarding EMC.

1 Radiated Emission

1.1 Introduction to Radiated Emission

Morten Sørensen, Bang & Olufsen

1.1.1 Introduction

Electrical engineers have for years been interested in predicting- and performing pre-compliance measurements regarding radiated emission from product and tests regarding radiated emission at IC or printed circuit board (PCB) level. In this chapter we will describe different methods for pre-compliance test that covers different radiation mechanisms and frequency spans.

In chapter 2 we will describe some pre-compliance test methods for conducted common mode emission, namely the Workbench Faraday Cage Method, the current probe method and the GTEM method. In chapter 3 we introduce different radiation mechanism in a product and the use of RF simulation tools. In chapter 2.4 a guideline for system integration, including choosing the right cables (transfer impedance) will be introduced, and the importance of the cable terminations will be described. The chapter will handle radiation from the PCB itself and introduce near-field scanning as a hotspot location tool and near-field scan as a more advanced pre-compliance test- and simulation tool. Finally chapter 4 will cover system integration aspects. Considerations for connecting different modules, the type of cables and their placement is described. Expert tools and how they can be utilized are also described. Special ESD considerations and tools for pre-testing and improving the ESD performance of the product is described, and finally conducted emission with respect to near-field coupling is described.

1.1.2 What does radiate in a product?

A contemporary product is configured of many different printed circuit boards, cables, chassis and other metal structures etc. See figure 2. One can ask: What does radiate in a product?

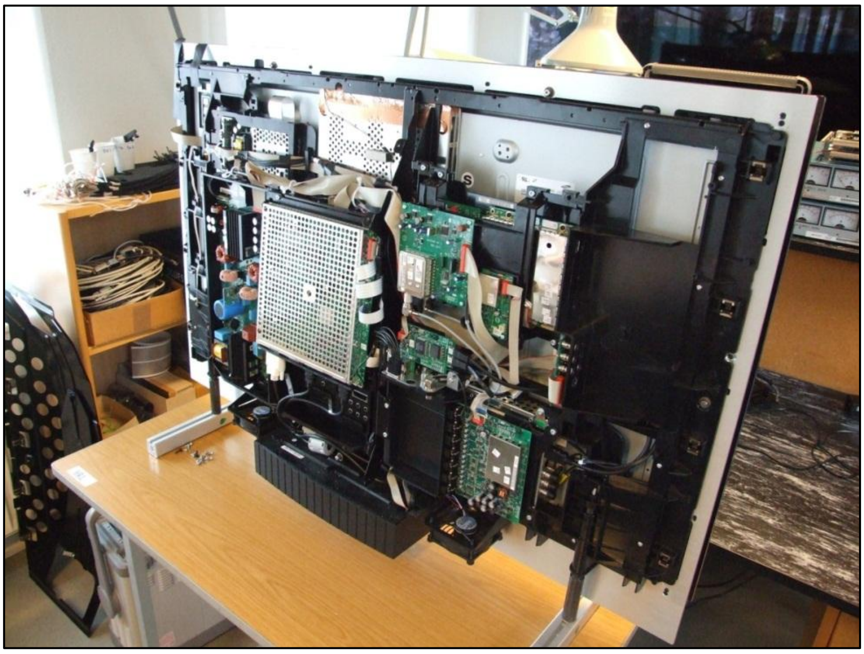


Figure 2. A product with several PCB´s, cables and in addition large metal structures which can resonate at specific frequencies. In this guideline we divide the radiation into the following categories.

- Common mode currents induced on cables attached to PCBs.
- Radiation from the PCBs themselves
- Unintended radiation from the signals on the cables (transfer impedance in cables).
- Resonances in chassis, cavities and the like.

1.1.3 Coupling from PCB to cables

The coupling mechanisms by which the intentional signal induce common mode currents on cables can be divided into two categories: Voltage driven (electric field coupling) and current driven (magnetic field coupling) [1]. This is illustrated in figure. 3.

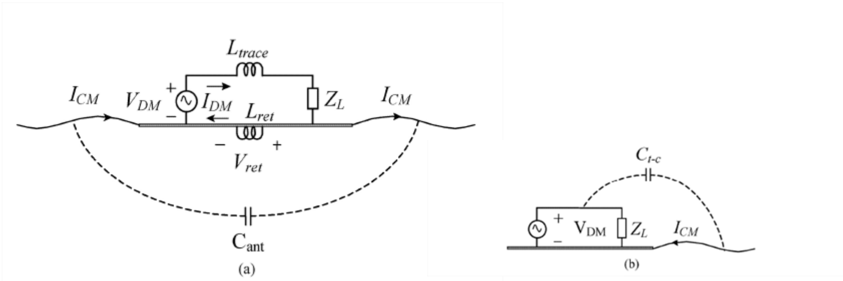


Figure 3. Coupling mechanisms for common mode radiation from attached cables: a) current driven, b) voltage driven.

1.1.4 Conducted emission vs. radiation directly from the PCBs

Let us assume that the right cable is selected, i.e. no radiation caused by transfer impedance in cables (see chapter 4.2); we can set up a rule of thumb for the radiation mechanisms vs. frequency (see figure 4).

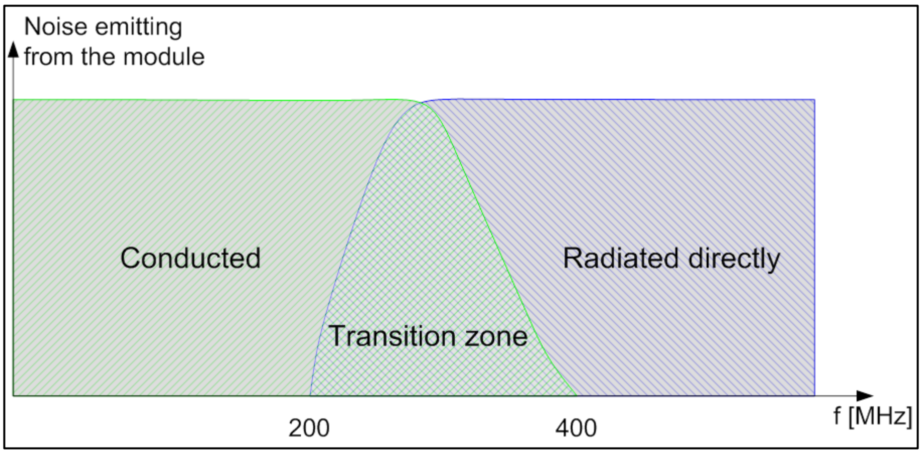


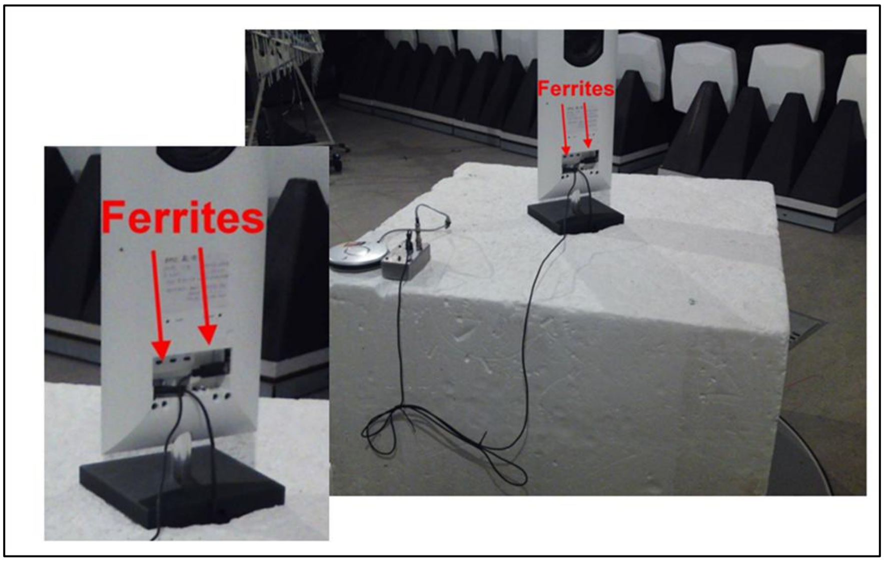
Figure 4. Rule of thumb for conducted emission (common mode radiation from the cables) and radiation directly from the cables.

Below 200 MHz the dominating emission mechanism is conducted, i.e. common mode currents flowing on the cables. When the wave length approaches 1/5 of the largest dimension of the PCB ground plan the transition zone begins, where the dominating radiation can originate from both the attached cables and from PCB´s themselves depending on the cable length and termination impedance. When the wave length approach ½ of the largest dimension of the PCB the transition zone ends and the radiation originates solely from the PCB itself.

In other words, if the PCB is large, PCB radiation becomes dominating in the low end of the transition zone and if the PCB is small, PCB radiation becomes dominating in the high end of the transition zone.

The above rules on distinguishing between the relevant frequency ranges are only rules of thumb, and you can find examples where it is not valid. But a large number of apparatus from DEIF (power control units) and from Bang & Olufsen (audio and video products as well as loudspeakers) has been tested and the results were in agreement with the above conclusion, see example in figure 5.

Please also notice that the above rule of thumb does not tell anything about radiation caused by bad cables or plugs or radiation from chassis, cavities or the like.



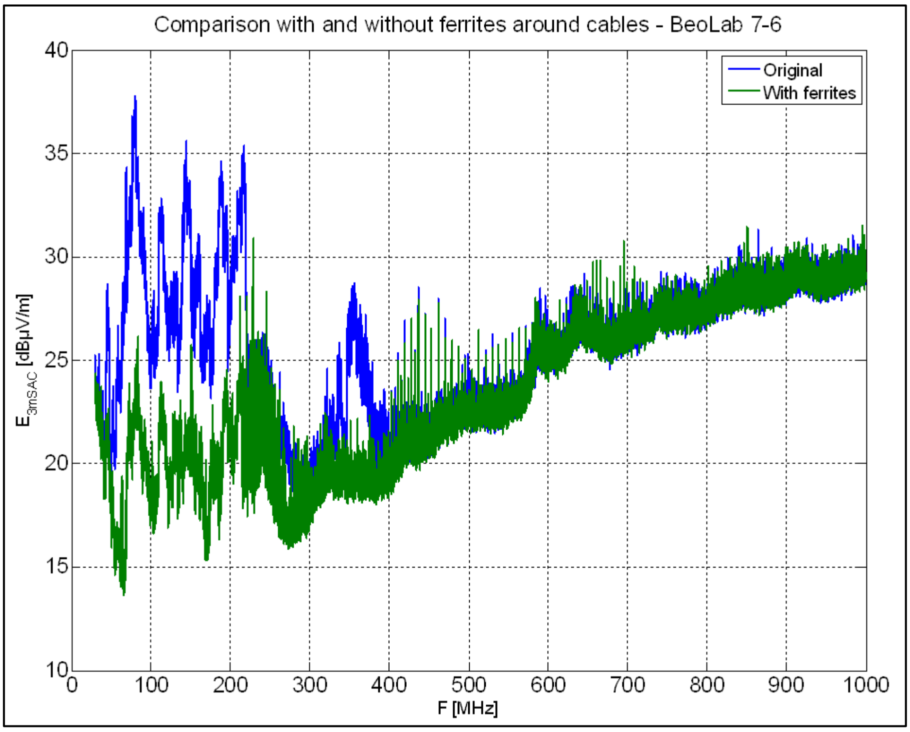


Figure 5. Setup and measurements results. The radiated emission from a loudspeaker was measured with and without ferrites on the mains cable. Below 400 MHz the radiation from mains was dominating and above 400 MHz the ferrites did not reduce the radiation, indicating that the radiation originates from the PCB itself.

1.1.5 References

[1] H-W Shim, T. Hubing, 'Model for estimating radiated emission from a printed circuit board with attached cables due to voltage-driven sources', IEEE Transactions on Electromagnetic Compatibility, Vol 47, No. 4, November 2005.

[2] C. R. Paul, 'A comparison of the contribution of common-mode and differential-mode currents in radiated emissions,' IEEE Trans. Electromagnetic Compatibility, vol. 31, no. 2, pp. 189–193, May 1989.

[3] J. L. Drewniak, T. H. Hubing, and T. P. V. Doren, 'Investigation of fundamental mechanisms of common-mode radiation from printed circuit boards with attached cables,' Proc. 1994 IEEE Int. Symposium Electromagnetic Compatibility, Chicago, IL, pp. 110–115.

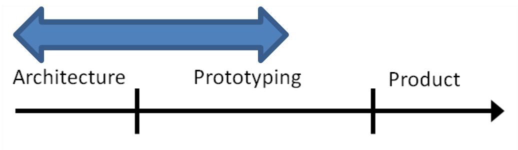
[4] J. L. Drewniak, F. Sha, T. H. Hubing, T. P. V. Doren, and J. Shaw, 'Diagnosing and modeling common-mode radiation from printed circuit boards with attached cables,' Proc. IEEE Int. Symposium Electromagnetic Compatibility, Atlanta, GA, Aug. 1995, pp. 465–470

2 Common Mode Emission

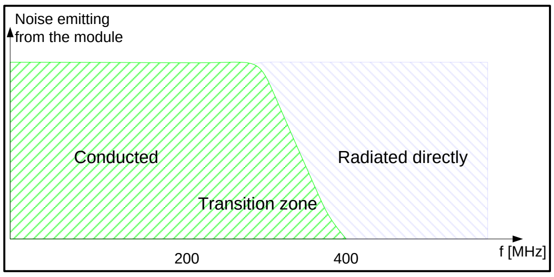
2.1 Common Mode emission – PART I. The workbench Faraday Cage Method

Morten Sørensen, Bang & Olufsen and Claus Vittarp, DEIF

Method applicable during development phase:



Project phase: Is good for early design evaluation



Relevant frequency band: Below 200-400 MHz

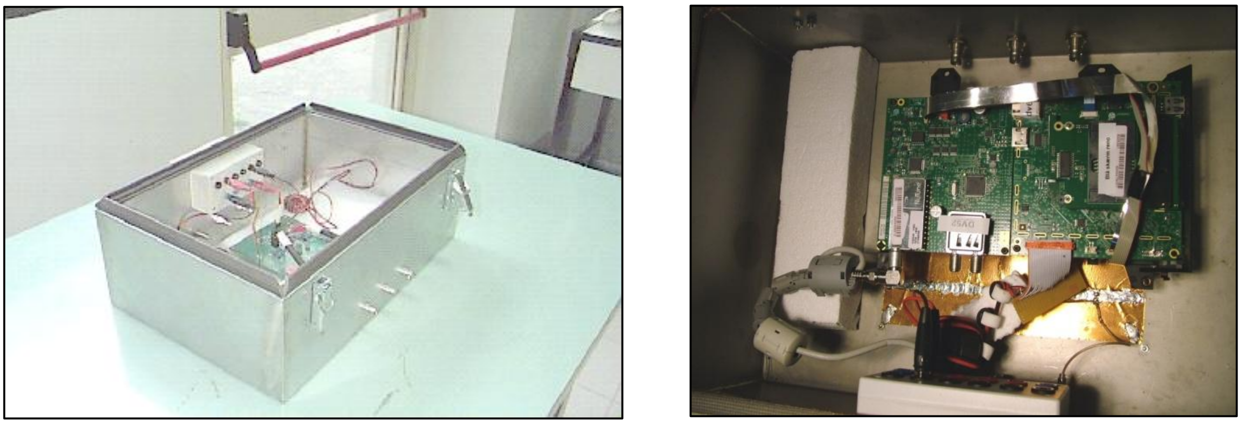


Figure 6. Examples of equipment mounted inside a WBFC (WorkBench Faraday Cage).

2.1.1 Introduction

The WorkBench Faraday Cage Method (WBFC) assumes that supply and signal cable(s) are attached to an electrically small PCB, with dimensions <λ/2, i.e. 0.15 m at 1 GHz. The hypothesis is that connected cables become the dominant antennas, so the emission of electromagnetic signals takes place via these antennas. It is suggested that the maximum conducted emission carried by a cable emerging from DUT can be estimated by loading the common-mode port with 150 Ω resistance and measuring the absorbed power. 150 Ω is widely used in RF emission and immunity standards as average common mode impedance and the justification for this value as a representation for the radiation resistance of long cables arises from empirical data [1].

2.1.2 EMC Challenge

The radiated emission from a PCB at lower frequencies depends on the attached cables and therefore it is difficult to predict the radiated emission from the final product before it is assembled. The WBFC method is designed to predict the maximum conducted emission from the attached cables. The method is not a precise prediction of the entire radiated emission from a specific setup, as some emission may be radiated directly from the PCB.

The WBFC method is a time efficient method which allows the engineer to do trial and error work at his workbench. He can make design changes in e.g. the filtering and immediately see the effect regarding the radiated emission.

2.1.3 Procedure

The method is described in the IEC 61967-5 [2]. Here a short presentation of the WBFC is given. A few practical problems with the method described in the IEC standard are also addressed.

The PCB is placed in a shielded metal box (The WBFC) 3 cm above the box floor. The power supply and the signal cables runs through filters when they enter the metal box, so no external noise will disturb the measurements inside the box. Inside the box the common mode impedance of the power supply and signal cables from the PCB are made high Z >>150 Ω with ferrite beads. All the cables from the PCB are terminated with 150 Ω common mode impedance instead. The current in the terminations has to be measured with at spectrum analyzer one by one. figure 7 shows a wiring diagram of the WBFC setup with a PCB with Power supply, signal input and signal output. The drawing is from the IEC 61967-5.

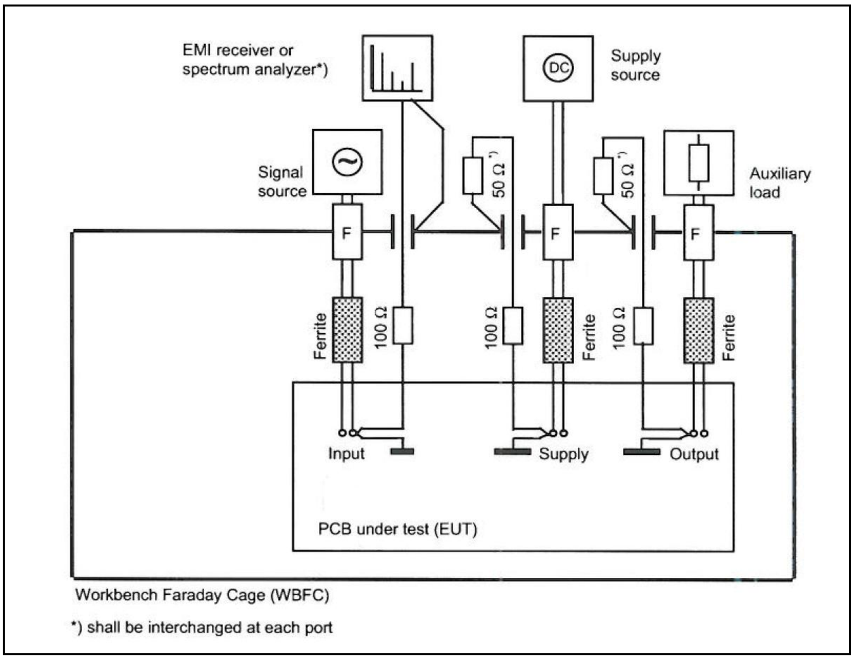


Figure 7. WBFC wiring diagram from IEC 61967-5

In the IEC 61967-5 Annex A the box is described physically. The IEC box is 500*350*150 mm but the consortium investigations show that the box size is not very critical.

2.1.3.1 Practical problems

In the IEC 61967-5 the 150 Ω terminations to the PCB are made with a 13 mm thick gasket placed 30 mm above the bottom of the WBFC that forms a 150 Ω transmission line. In the end there is a crocodile clip that makes the connection to the PCB under test. This is not very practical if 4-5 connections are made. It is nearly impossible to place the gaskets correct so the impedance will be

150 Ω. A practical construction has been made using a piece of 50 Ω coax cable where the shield is connected to the WBFC very close to the point on the PCB that should be measured. The center conductor of the coax cable is connected to a 100 Ω resistor and the other end of the resistor is soldered to the PCB test point. The test setup is easier built this way. The downside of this is that the impedance of the pigtail on the coax cable differs from the 150 Ω impedance. This is however considered being just as close to the desired impedance as the impedance of the crocodile clip and uncontrollable gasket. See the picture in figure 8.

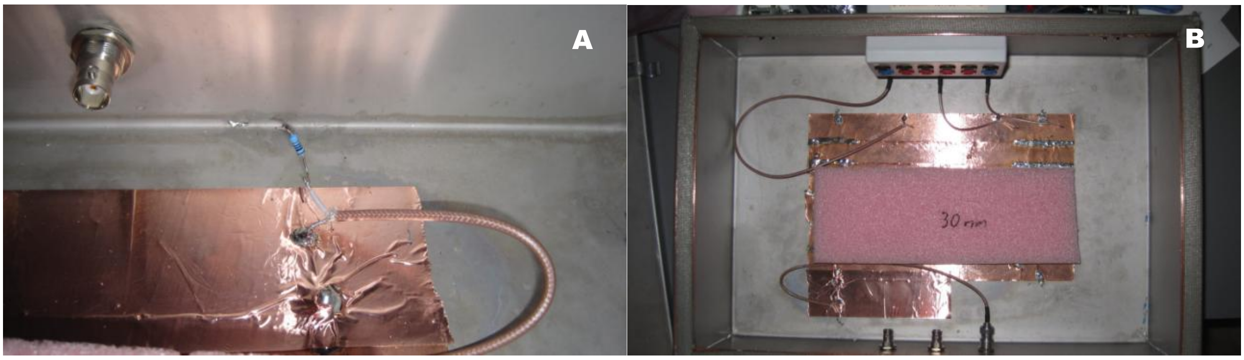


Figure 8. A) 100 Ω resistor and 50 Ω coax cable. The 100 Ω resistor is connected to the test point.
B) Cables for 4 test points mounted in the WBFC.

In figure 8 it is shown that the current is measured on the ground connections of the power supply and on the ground terminals for the signal inputs and -outputs. Common mode currents flowing from the ground connection is investigated this way.

But how should ribbon cables and connectors with many GND- and signal lines be measured?

The noise could easily come from a signal line in a ribbon cable that is not decoupled correct to gnd.

A method that has been used to measure the noise from a connector with e.g. 10 GND/signal lines is to split the 100 Ω resistors shown in figure 9 to 10 x 1 kΩ resistors in parallel and connect each of them to one pin in the connector. See figure 4. The common mode impedance for the whole connector is still 150 Ω. This method could provide a false result, if one pin in the connector has a high noise voltage on it. The 1kΩ resistor in series with the noisy pin would give a low reading on the spectrum analyzer, and the noise would probably be underestimated.

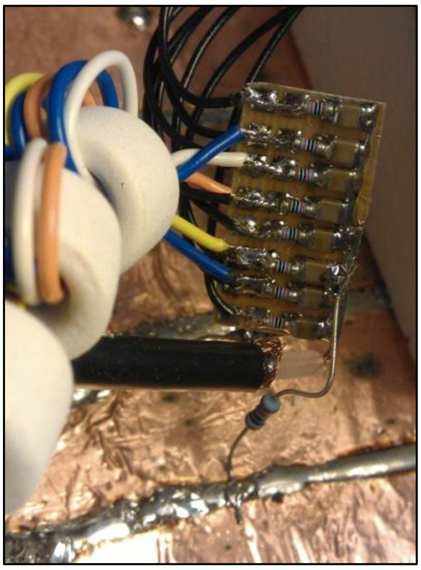


Figure 9. A typical 150 Ω termination of a signal cable with several signal lines.

2.1.3.2 Limit lines

The assumption is that the worst case arises when the measured absorbed power in the load impedance (150 Ω) of the WBFC, in the final apparatus is radiated from a tuned dipole. This assumption gives the following conversion between the limit for radiated emission in 3 m distance according to CISPR 22 and the voltage limit across 50 Ω in

$$V_{WBFC,\,limit}\,[dB\mu V] = E_{3m,\,limit}\,[dB\mu V/m] + 4.8\ dB \quad (1)$$

2.1.4 Investment

The method requires a custom-made Workbench Faraday Cage with the proper feed-through connectors (~ $2.000) and a spectrum analyzer (~ $5.000).

2.1.5 Summary

The usability of the WBFC method and its mode of operation have been investigated in the consortium. The conclusion was that for switch mode power supplies (SMPS) the methods is a very useful pre-compliance test up to 400 MHz regarding radiated emission. The conducted setup has a tendency to overestimate the radiated emission at 3 m distance at low frequencies. Above 400 MHz radiating from the PCB itself is dominating and the WBFC method is essentially useless. The conclusion is stated in table 1. An example of WBFC measurements vs. 3 m semi-anechoic chamber measurements for a SMPS is given in figure 10. The method will in general only predict worst case and not the precise radiated emission.

For other PCB´s like processor modules, the usability was limited compared to the SMPS. The reason for that is still under investigation.

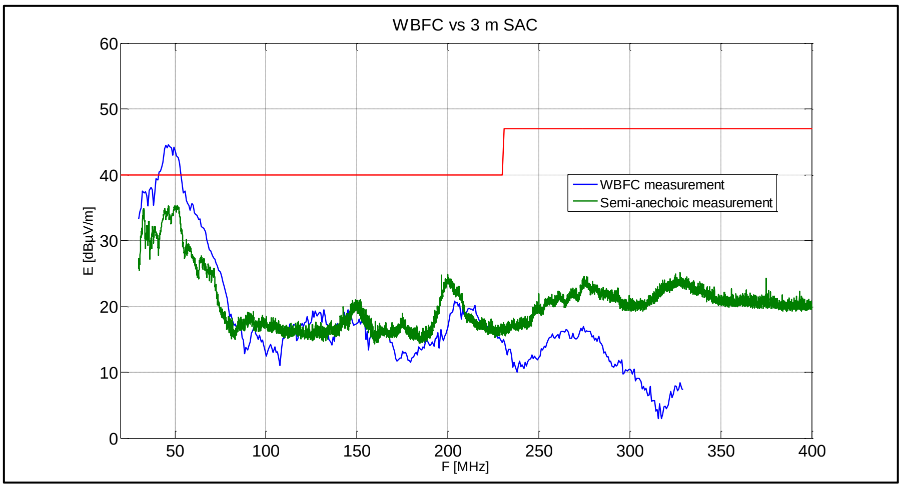


Figure 10. A typical comparison between semi-anechoic chamber and WBFC measurements. At low frequencies the box overestimates the radiation and at 250 MHz the cables do not dominate the radiation any longer.

Frequency [MHz]	Switch mode power supplies
Up to 200 – 400 MHz depending on PCB size	Efficient pre-compliance test for emission caused by common mode currents on cables.
Above 200-400 MHz depending on PCB size	Not useable.
<< 100 MHz	Tendency to overestimate radiated emission (e.g. short cables, large PCB). If you exceed the limit, make a risk assessment before using too many resources in complying with the standard.

Table 1: Summary of the usability of the WBFC method.

2.1.6 References

[1] M.J. Coenen, "Common Mode Impedance Measurements on Cables in the Frequency Range 30 MHz–1 GHz," EIE 92004, Philips Semiconductors 1992.

[2] IEC/EN 61967-5:2003, Integrated circuits - Measurement of electromagnetic emissions, Part 5: Measurement of conducted emissions – Workbench Faraday Cage method

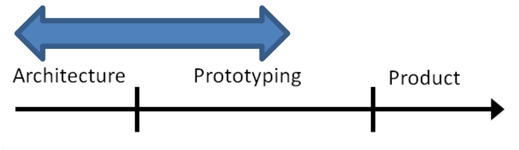
[3] M.J. Coenen, "EMC Workbench: Testing methodology, module level testing and standardization", Philips Journal of Research vol.48 1994.

[4] M. Sørensen, O. Franek, S.K. Christensen, G.F. Pedersen, H. Ebert, " Assessment of the usability of the Workbench Faraday Cage Method", Proceedings 2011 IEEE International Symposium on Electromagnetic Compatibility, Long Beach, USA.

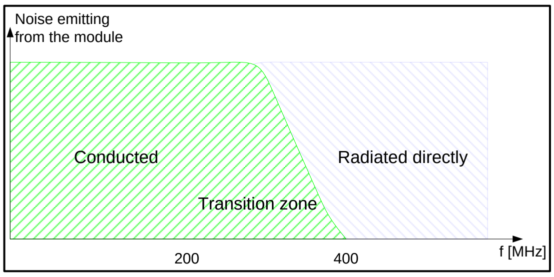
2.2 Common Mode Emission – PART II. RF current probe

Claus Vittarp, DEIF, Morten Sørensen, Bang & Olufsen

Method applicable during development phase:



Project phase: Is good for early design evaluation



Relevant frequency band: Below 200-400 MHz

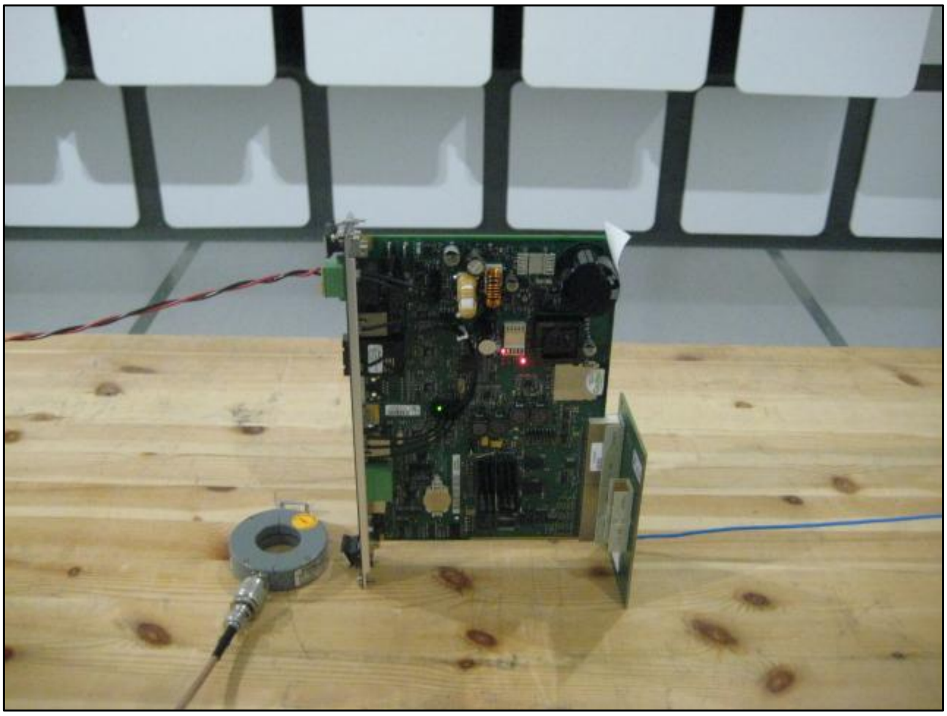


Figure11. PCB and RF probe on wooden table.

2.2.1 Introduction

The wires attached to a PCB or whole apparatus act as antennas, and often there is a good correlation between the radiated emission level and the noise current on the wires. Especially in the low frequency range the radiation from the wires are important. At higher frequencies structures on the PCB itself becomes the most important antennas. Typically it makes sense to use the current probe in the frequency range where the PCB dimensions are < λ/2.

The RF current probe is used for measuring the noise currents on the wires in the frequency range 30-1000 MHz. If the common mode noise current in the wires are above a certain level the PCB or apparatus will probably fail the radiated emission test. In section 3.1 a simple method to convert the current on the wires to radiated emission level is given. A test on a PCB in Semi Anechoic Camber SAC is investigated, and two examples on the use of current probe in EMC work are given.

2.2.2 EMC Challenge

The current probe can be used both as a troubleshooting tool when a product has failed the test in SAC, and as a quick and dirty pre compliance test on a new PCB module. The pre compliance test is uncertain because the current in the wires changes a lot with the positioning of the wires. It is necessary to place the wires in the exact same geometrical configuration expected in the SAC, in order to get a good prediction of the radiated emission level.

2.2.3 Procedure

2.2.3.1 Conversion of current on the wires to Field strength in SAC

How can the measured current amplitudes on the wires be used for calculation of field strength as measured in the SAC? Here a method based on simple antenna theory is given.

Assumptions:

-The wires radiate isotropic.
-Common mode impedance of a long wire is R_{rad} = 150 Ω.
-Ground reflection from the floor in SAC can add up to 5 dB to the field strength.

From antenna theory we have:

$$E_{iso} = \frac{1}{r} \cdot \sqrt{30 \cdot P_{iso}} \ [\frac{Volt}{m}] \quad (2)$$

Where: E_{iso} is the field strength, r meter from an isotropic antenna, radiating P_{iso} Watt.

To get E_{iso}= 40 dBμV/m = 100μV/m in 3 meter distance, the needed power is P_{iso} = 3nW.

The current in the wire is calculated using the following equation:

$$P_{iso} = R_{rad} \cdot I^2 \quad (3)$$

With $R_{rad} = 150\Omega$ and $P_{iso} = 3\ nW$ the current is calculated to be 4.5 μA.

The ground reflection from the floor in SAC can increase the radiation level with up to 5 dB (1.77 times) worst case. The allowed current in the wire with worst case ground reflection is then 2.5μA.

Conclusion:
In many EMC handbooks and papers 3μA = 9.5 dBμA is set to give a radiation level of 40dBμV/m at a distance of 3 meter in the SAC. We will use this value in this document.

Conversion from current to field strength:

$$E\ \frac{dBuV}{m} = I\ dBuA\ + 30.5 \quad (4)$$

Questions to the conversion:

- Should the radiation pattern include directivity?
- Is it correct to assume that the common mode impedance of a wire is 150 Ω?
- At frequencies below 100 MHz the cables are short antennas and another conversion factor could perhaps give a better result.

2.2.3.2 Comparison of current measurements and radiated emission in the SAC

A PCB with a switch mode power supply and a 333 MHz microprocessor is tested in the SAC. Afterwards the current in the wires are measured in 3 different setups. The measured currents are converted to radiation with the conversion factor given in section 3.1 and compared with the result from the SAC. The first current measurement is done in the SAC on the setup used to measure the radiated emission. This gives the best correlation to the measurements in the SAC. If the setup is moved to another location and the wires are placed differently the correlation becomes worse. The position of the wires is very important to get a result close to the SAC measurement.

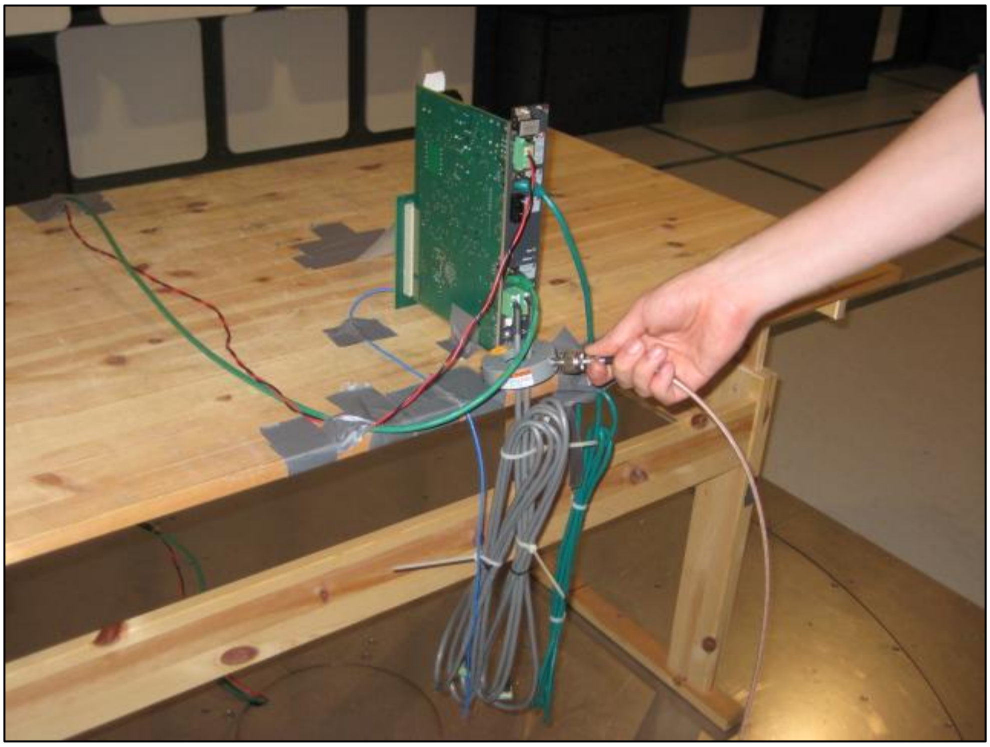


Figure 12. The PCB in SAC with all the wires connected. The current is measured on each group of wires.

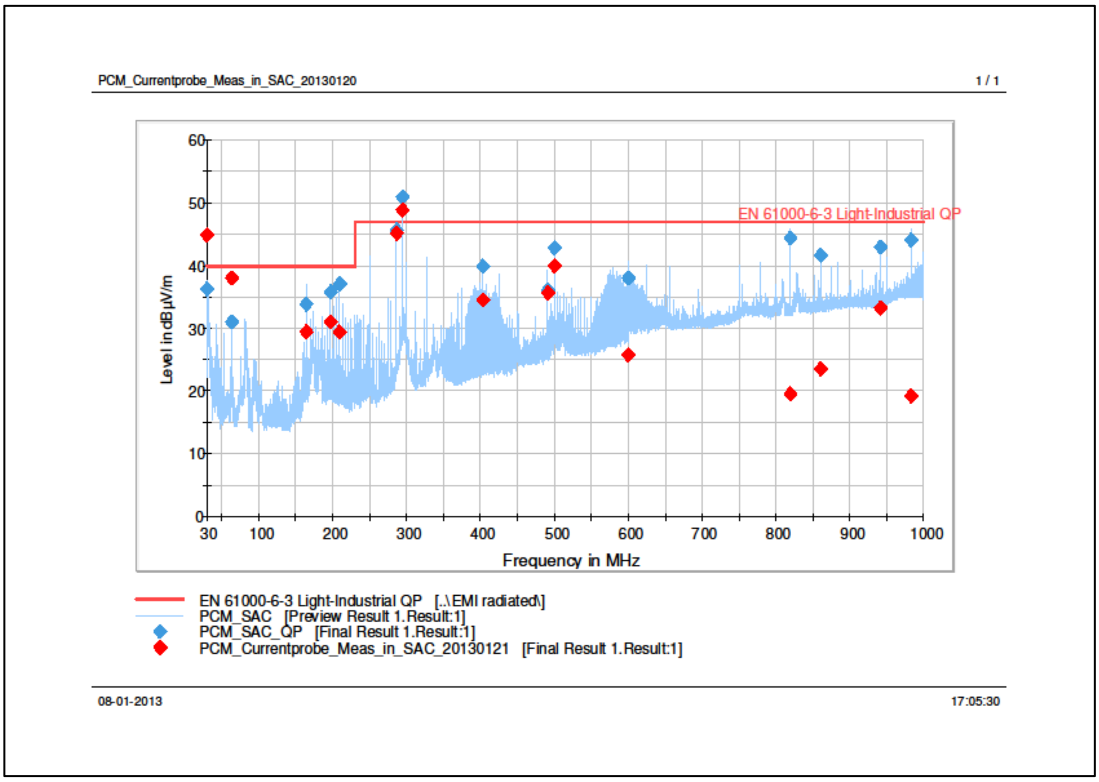


Figure 13. SAC measurement (blue dots) compared with current probe measurement in SAC (red dots).

Results:

- The estimation is quite good up to 500 MHz.
- On frequencies < 100 MHz the radiated emission is lower than expected. The wires are short compared to the wavelength and radiates less than the antenna model used for the conversion predicts.
- On frequencies >500 MHz the current measured on the wires is mall, but the radiated emission level is still high. The radiation comes from structures on the PCB, not from the wires

2.2.3.3 Practical guide

- The common mode current is measured on one cable or group of wires at a time. Example: Power supply, RS485, CAN bus. The highest current on each frequency is used for the calculation of the radiated emission.
- Where on the wire should the current be measured? In most cases the current is higher when measured near the connector. Sometimes it has been seen that the current is 2-3 dB higher further away from the connector. In our test the current is measured 1-2 cm from the connector.
- What current probe can be used? It is important to have sufficient sensitivity and at the same time not alter the currents on the wires too much with the probe. Here the F61 from Fischer Custom Communications are used. It has a transfer impedance of about 24 dBΩ.
- How sensitive is the current probe to your hands? The F61 current probe from FCC is not sensitive to how you hold it, but the wire you measure on is very sensitive. Don't touch it or come close to it with your hands during measurement.
- In what room can the test be done? You don't need a shielded room for the test, but it is certainly a big advantage. There will be induced signals on the wires that are not coming from the DUT, if the test is performed outside a shielded room.

- How should the wires be placed during measurement? For the pre compliance test, the wires must be placed as close to the setup in SAC as possible. The current level changes significantly with the probe position on the wire; especially below 100 MHz. Below 100 MHz it is very important to control the common mode impedance in the wires. A wooden test fixture for the wires could be a solution.

2.2.4 Investment

You need a current probe and a Spectrum Analyzer. The F-61 current probe from Fischer Custom Communications costs about $2000. The spectrum analyzer needs to have a good sensitivity or a built-in pre-amplifier; alternatively an external low noise amplifier can be used. A suitable spectrum analyzer costs about $12.000-20.000. The tests can be made on a wooden worktable, but it is preferred to do it in a shielded room, especially if there are many noise sources and radio transmitters close by.

2.2.5 Summary

The current probe can be used in 2 ways:

2.2.5.1 Method 1: Fault finding

From the tests it can be seen that there is a good correlation between the noise level measured in SAC and the noise current on the wires. This correlation can be used during the process of lowering the radiation from apparatus that has failed the radiated emission test in SAC.

Example of use:

- The radiation level is found to be too high in SAC. Modifications must be made.
- Place the product in a shielded room or in a place where the background noise is low. Use a nonconductive table.
- Place the wires on the table much like they were in the SAC.
- The common mode current on the wires are measured at the frequency where the problem was seen. Note the current level on the wire showing the highest current.
- Do modifications to the product and measure the current again. You can quickly see the relative level of improvement. The wires must not be moved between the tests.
- When the current level has dropped the wanted number of dBs, do the test in SAC again. Often you will see an improvement in the same magnitude as you saw with the current probe.

It is important to place the wires in a fixed position when measurements are compared. On frequencies where the PCB is bigger than $\lambda/2$ you will probably only see very low currents on the wires, and the method will not be useable. The main part of the radiation is instead coming from structures on the PCB itself. Use a loop probe to search for the fields instead.

2.2.5.2 Method 2: Pre compliance test on a PCB or whole product

The tests have shown that doing accurate pre compliance testing with the current probe is difficult. The wire position alters the current in the wires significantly, and the results become more uncertain.

A quick and dirty pre compliance test of a module can be performed if the module is placed on a table with the wires in the same position as expected in the SAC. The common mode currents on all the wires are measured. Using the simple antenna theory, the current should be below 9,5dBµA for the module to pass the 40 dBµV/m@3meter limit and below 16,5dBµA to pass the 47 dBµV/m@3 meter limit.

In practice you will often pass the test at frequencies below 100 MHz with a higher current (6-8 dB), because the wires are too short to form a good antenna. On higher frequencies you will sometimes fail the test with less than 9.5dBμA on the wires. The radiation is not only coming from the wires. Don't expect to see significant currents at frequencies where the module is bigger than λ/2.

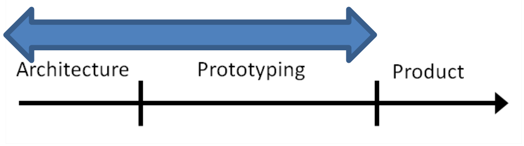
2.2.6 References

[1] Henry Ott, Electromagnetic Compatibility Engineering, 2009 John Wiley & Sons, Inc [p. 690-692].

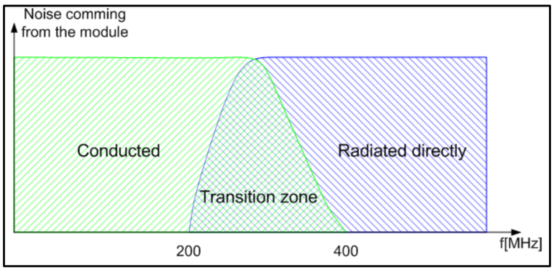
2.3 Common Mode Emission – PART III. GTEM cell measurements

Jan Clausen, DEIF

Method applicable during development phase:



Project phase: Is good for early design evaluation



Relevant frequency band: 30-1000 MHz

Figure 14. GTEM cell (Courtesy of ___??__er der indhentet tilladelse til dette foto???_

2.3.1 Introduction

The GTEM cell method is used to predict the radiated emission generated from an equipment-under-test (EUT), in the frequency range 30MHz-1GHz. The GTEM cell method is described in IEC 61000-4-20 Annex A. The predicted emission levels will be compared with SAC (Semi Anechoic Chamber) measurements in 3 meter distance. The SAC measurements are performed according to CISPR 16-2-3. The concept of emission measurements in a GTEM cell is simple, since only the cell and a receiver are required. In order to correlate the GTEM results to a 3 meter SAC, a set of at least three measurements and some computational post processing of the results are required according to IEC 61000-4-20

2.3.2 EMC Challenge, EUT arrangement

Setup and orientations of EUT can be very complex according to the size of the GTEM cell.

2.3.3 Procedure, size of EUT

The maximum size of a EUT is related to the size of the usable test volume. The EUT shall be verified not to be larger than 0,6 x W times 0,6 x L. The maximum usable EUT height is recommended to be 0,33x H, with H equal to the distance between the inner and outer conductors (conductor spacing) at the center of the EUT in the test volume (for example, between septum and floor in a TEM cell). For all TEM waveguides the EUT shall fit within the usable test volume for all rotation positions.

2.3.3.1 EUT arrangement

The EUT is placed in the center of the usable test volume in the GTEM. For EUTs with cable(s) the following rules for cable routing applies: Long cables should be bundled in a serpentine fashion at the approximate center of the cable with the bundle 30 cm to 40 cm in length. See figure 15. The exit cable(s) should be routed perpendicularly from each EUT case to the boundary of the usable test volume. The cable is then routed along the border of the usable test volume to the corner and the lower edge of the test volume. The exit cable(s) are routed from the lower corner of the usable test volume to the absorbing clamp(s) or clip-on ferrites at the wave-guide ground plane see figure 3. The insertion loss of the clamp (or clip-on ferrite) should be greater than 15 dB for the frequency range of 30 MHz to 1000 MHz The connection cable should not touch the inner or outer conductor of the GTEM waveguide. Up to 1,3 m of cable are to precede the clamp location. If the cable is shorter than 1,3 m, then all of the cable precedes the clamp location.

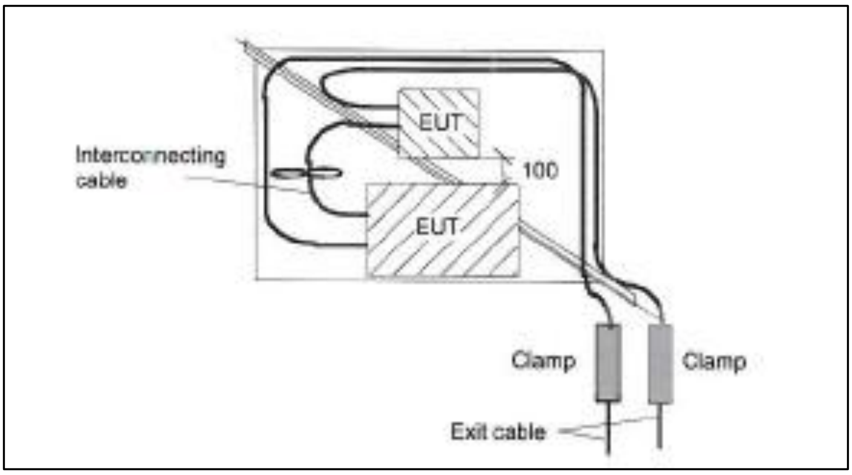


Figure 15. Cable routing.

2.3.3.2 Orientations of the EUT

The three orientations of the EUT have to be orthogonal to each other so that each axis of a co-ordinate system of the EUT is aligned in turn with the vertical axis of the cell.

This can be realized in the following way: The cell is given a co-ordinate system (x,y,z) where the z-axis is the direction of wave propagation (the longitudinal axis), the y-axis is vertical and therefore aligned with the electric field strength, and the x-axis is horizontal and aligned with the magnetic field. The EUT is now given a 'primed' coordinate system (x',y',z') and, for the first orientation, this is aligned with the co-ordinate system of the cell. For the other two orientations, the x'-axis and the z'-axis are in turn aligned with the y-axis of the GTEM, as shown in figure 14. For a real EUT, these orientations would appear as shown in figure 16. A EUT shall be tested using two start positions in the TEM waveguide. The procedure shall be carried out with start position a1 and a3 of figure A.4 in IEC 61000-4-20 (a total of 2 x 3 = 6 positions). The highest correlated field strength from these two data sets shall be reported at each frequency.

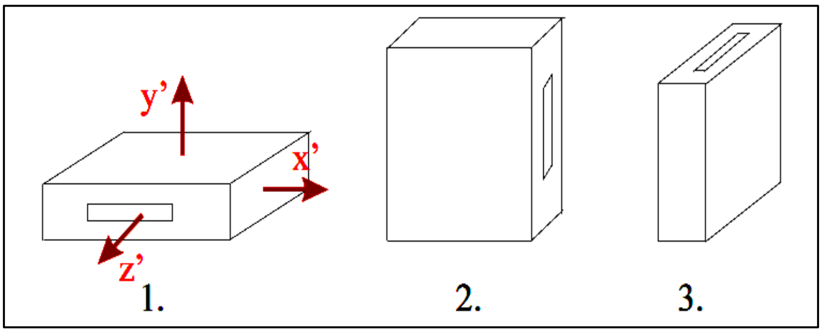


Figure 16. Axis allocations of the test object.

2.3.3.3 The correlation algorithm

The one-port correlation algorithm is based on three voltage measurements made in a GTEM waveguide from which the total radiated power of the EUT may be calculated, it is described in IEC 61000-4-20 part A.3.2.3.2. This algorithm automatically calculates the result using the emission measurements software package EMC32.

2.3.4 Investment

You will need a GTEM cell. The cell used by DEIF is an ETS-Lindgren model 5405. A GTEM cell costs about $40.000 depending on the cell size. A suitable spectrum analyzer costs about $20.000. The EMC32 software package costs about $8000.

2.3.4.1 Boards

- Board 1: The first board is a very simple PCB with one track and a comb type signal generator producing a spectral line every 20 MHz up to approx. 2 GHz. (PCB size: 225x150mm).
- Board 2: The second board is a microprocessor- and communication board. The main components on the board are a switching power supply, a 333 MHz microprocessor, RAM memory DDR 2, Ethernet transceiver phy's and other communication devices.

2.3.5 Summary, board 1

Board 1 without any wires:
The prediction performance is given in the following table:

Frequency range	Prediction performance
30-1000 MHz	Good + / - 6 dB except some few measurements

Table 2 Conclusions for Board 1 without any wires.

Board 1 with one wire:
The prediction performance is given in the following table:

Frequency range	Prediction performance
30-920 MHz	Good (+ / - 6 dB)
920-1000 MHz	Poor prediction are 6-10 dBs to high

Table 3 Conclusions for Board 1 with 1 wire connected.

2.3.5.1 Summary on board 2

Board 2:
The prediction performance is given in the following table:

Frequency range	Prediction performance
30-40 MHz	Very poor prediction. The GTEM cell measurements predict too low emission levels (up to 15 dB too low)
40-320 MHz	Many predictions are more than 6 dBs too high
320-1000 MHz	Good prediction on almost all frequencies. With exception for a few frequencies, the prediction results are accurate to within 4 dB

Table 4 Conclusions for Board 2.

2.3.5.2 Conclusion on the GTEM method

Uncertainty on simple boards: ±6dB

Uncertainty on advanced boards: ±10dB

The GTEM cell method is good for debugging, but not for pre-compliance- and final measurements

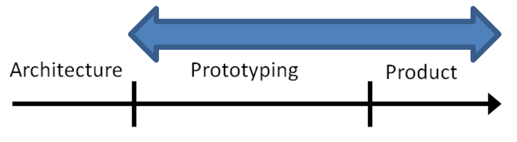
2.3.6 References

[1] IEC 61000-4-20 (2010): Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides.

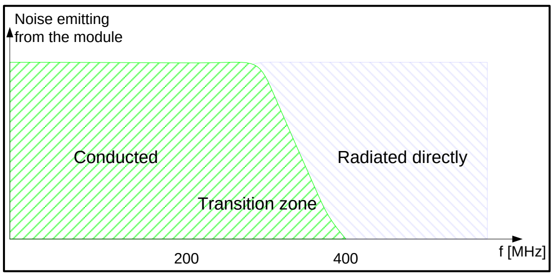
2.4 Common Mode Emission – PART IV. Cable termination impedance

Kim Jensen, Bang & Olufsen

Method applicable during development phase:



Project phase: Is good for early design evaluation



Relevant frequency band: Below 200-400 MHz

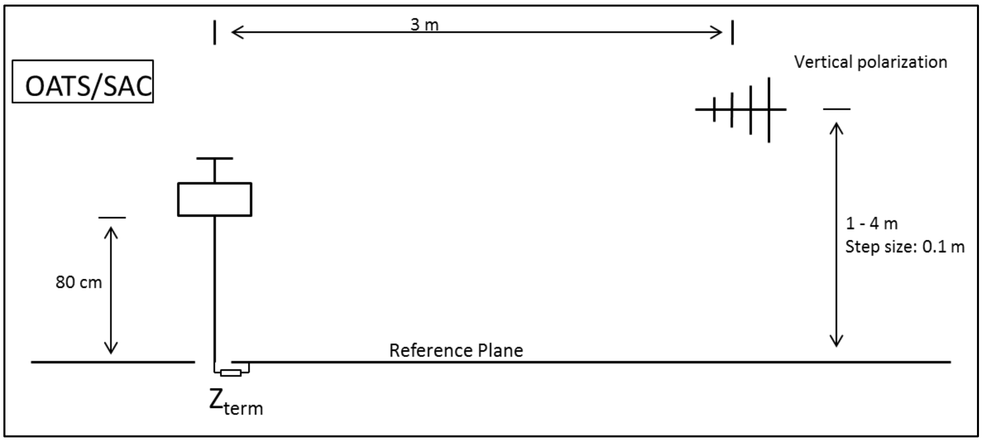


Figure 17. Diagram of test setup in SAC.

2.4.1 Introduction

The study shows how much the common mode termination of cables attached to an EUT and leaving the setup through the reference plane affects the level of radiated emission measured in a 3 m Semi Anechoic Chamber.

2.4.2 EMC challenge

A continuous challenge in EMC is to control the test setup, such that it is the problem the engineers are trying to solve that is being measured, and not another part of the system. When comparing measurements between different laboratories it was found that significant changes in the measured radiated emission was seen on the same equipment with the same setup. Thus the cause for the differences had to be found. The findings are also closely related to the cable terminations when interconnecting different modules.

2.4.3 Procedure

The measurement of radiated emission in a SAC at low frequencies in the range of 30 MHz to approximately 270 MHz will for vertical polarization be very dependent on the Common Mode Impedance terminating the cables attached to the equipment under test. This will in particular be the impedance of the cables leaving the room or passing through the reference plane. The complex Impedance seen at the reference plane, Z_{term}, depends on the cable routing and the length of cable routed below the reference plane, the LISN (and/or ISN, if used) in the setup and filters in the shielded room, if the cable leaves the room.

The study shows the result of simulations and measurements on a wideband field generator (a white noise broadband noise generator manufactured by the company York: 'York Generator') in a 3 m SAC where the EUT is connected to one wire going down to the reference plane and terminated with various passive complex impedances. I.e. $|\Gamma_L| \leq 1$. The orientation of the York generator produces a vertical linear polarized electrical field.

The figure below shows the **MEASURED** radiated emission results using three different loads. The red trace represents the measurement where the wire is connected directly to the reference plane. The blue trace shows a measurement with an arbitrary mains cable routed below the reference plane. The black trace is a measurement with the same mains cable, but with four ferrites attached on the cable just underneath the reference plane just at the penetration point.

Especially at frequencies below 100 MHz there is a huge difference in the radiated emission depending on the cable termination, up to 20 dB! This is just one case of cable termination in a real setup. Other impedances can give even higher differences. Please refer to the simulations on the next page.

Above 270 MHz the cable termination does not affect the radiated emission.

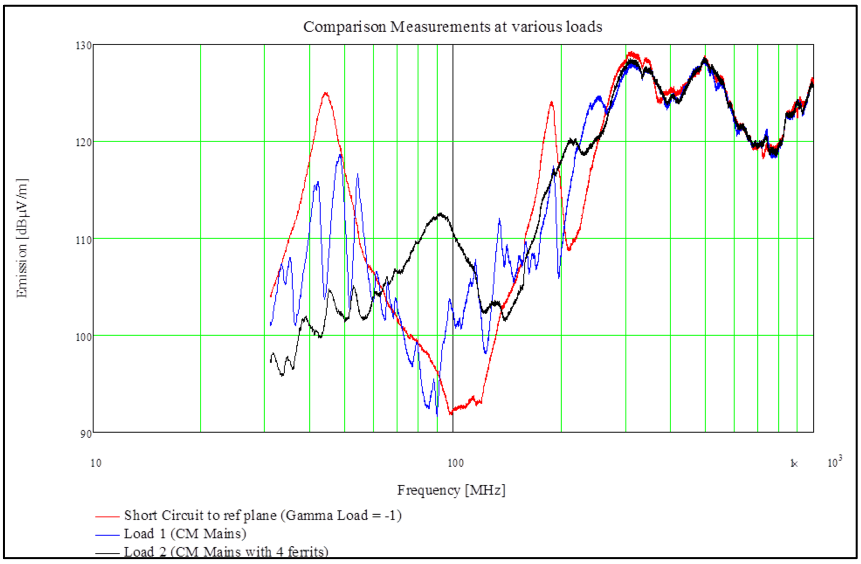
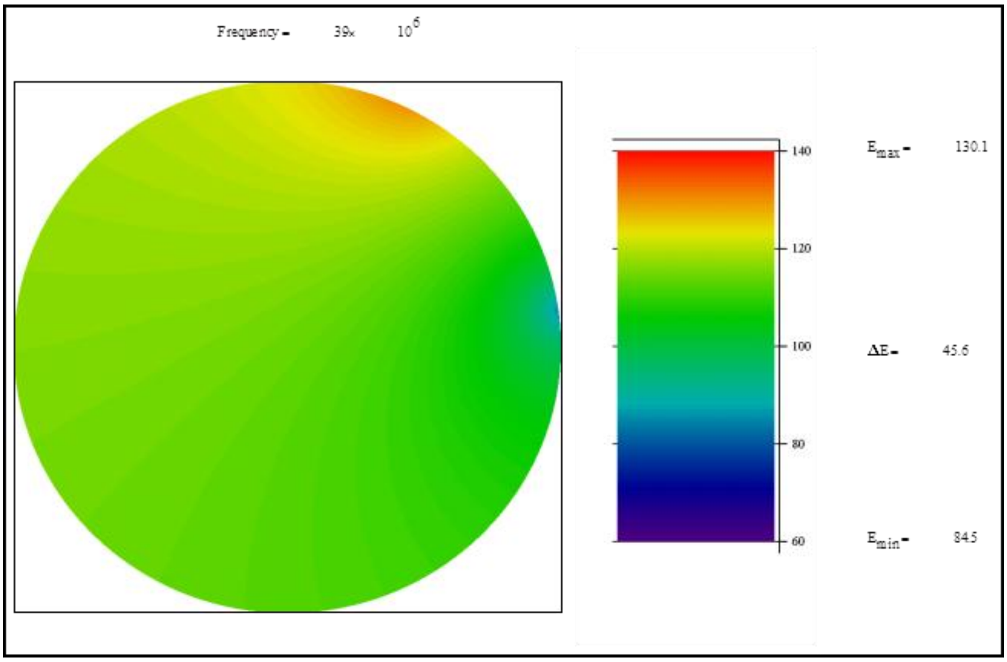


Figure 18. Measured radiated emission in SAC with three cable terminations.

The figures below show **SIMULATED** results, and show for each plot the radiated emission level for one frequency. The position in the colored area (Smith Chart 50 Ω) represents the complex impedance and the color the emission level. The worst case difference in emission level is at 39 MHz, top most figure, and can be found to 45.6 dB! The minimum and maximum positions are at $|\Gamma_L| = 1$ which means no loss in the cable termination.

Looking at the plot for 600 MHz we find that the cable termination only affects the emission level slightly with a difference of 1.8 dB. Again, the positions for minimum and maximum are found at $|\Gamma_L| = 1$.



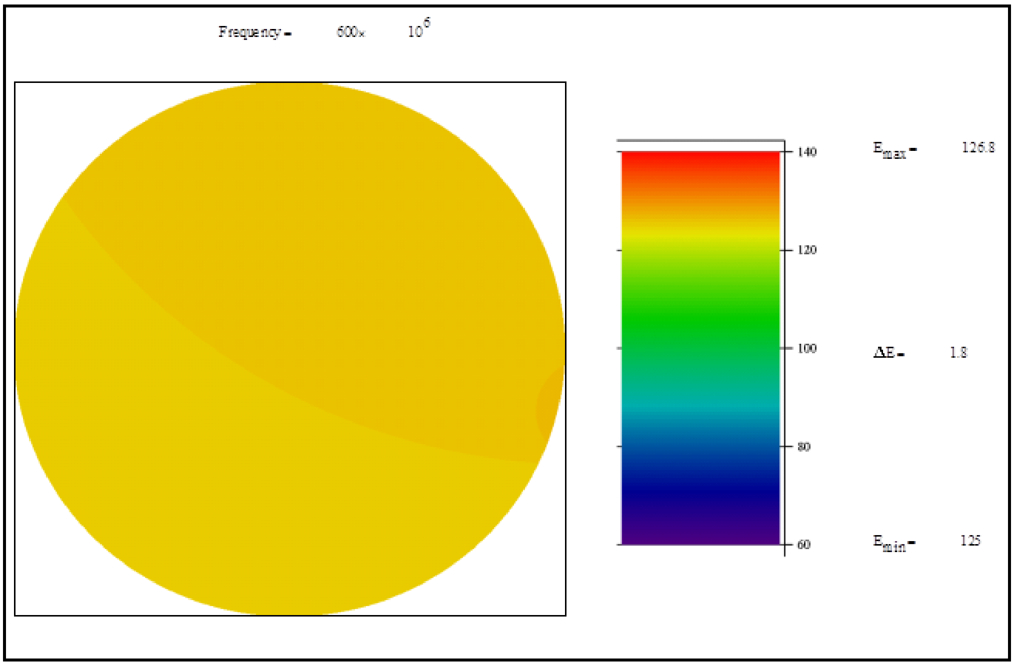


Figure 19. Positions in the Smith chart showing the largest variations in emission amplitude. Frequencies: 39 MHz (above), 600 MHz (below).

2.4.4 Investment

The knowledge of the cable impedance can be found in various books but to investigate the differences between the different cases requires either a 3D EM simulation tool or a semi anechoic chamber. These tools cost in the range of $80.000 to $800.000. However, the analysis on the system level can be made with good approximation by using low cost circuit simulation tools as for instance Spice, and then solve for the maximum current on the wire connected to ground. Such tools are free of cost, but will require a substantial understanding of the subject.

2.4.5 Conclusion

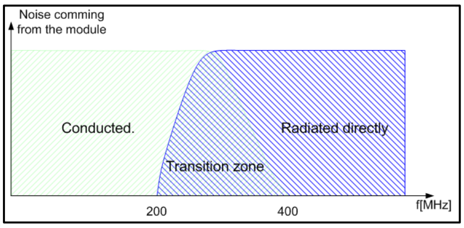
It was found that changes in the load impedance of a wire to the ground plane can change the radiated emission by up to 20 dB. By analyzing the Smith chart, the variations have been seen to be larger in the outer regions of the Smith chart, i.e. when the impedance is very high or very low

3 PCB radiation

3.1 PCB radiation – PART I. Near-field scanning, emission directly from the PCBs

Anders P. Mynster, DELTA og Morten Sørensen, Bang & Olufsen

Method applicable during development phase:



Project phase: Is good for early design evaluation

Relevant frequency band: Above 200-400 MHz

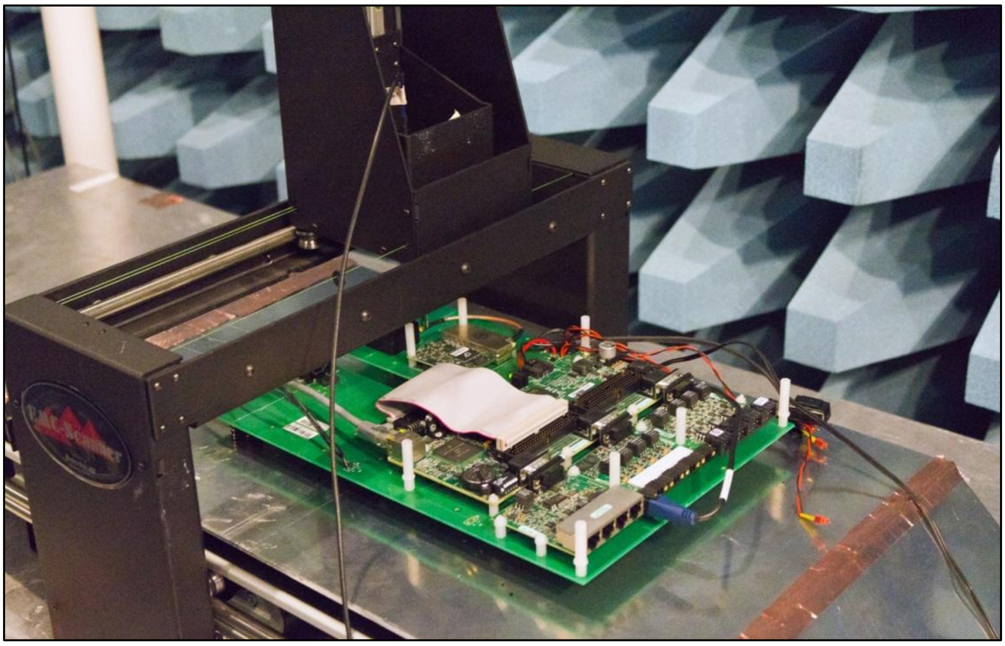


Figure 20. Near-field scanning of a prototype board

3.1.1 Introduction

When working with radiated emissions it has been shown that the PCBs will radiate directly when the larger dimension of the PCB is close to a quarter of a wavelength. For most PCBs this will occur at frequencies in the range of 200 to 400 MHz. Near-field scanning can be used to identify this type of radiation. In this section the near-field scanning method will be described with respect to setting up the EUT, how to set up the measurement, ensuring that the measurement is correct, and how to utilize the results.

3.1.2 EMC Challenge

The EMC aspects of PCB design has been addressed by numerous books, and with good reason. The PCBs are often the origin of the radiated noise since it contains the active components, which provide the drive signal for the radiating structure, the antennas. In the lower frequency range the current can be transferred to cables which will the act as antennas and in the upper frequency range the current will run on PCB traces and radiate. There are two main objectives of the EMC near-field scan.

1. To detect the location of the generators on the PCB and their frequency spectrum
2. To determine if the generated signal is radiated directly from the PCB
3. To determine if there is risk of coupling to other radiating structures

An often overlooked advantage of the near-field scanner is the communication it enables. In many companies it can be difficult for the EMC engineer to discuss the problems with non-EMC electronic- or mechanical engineers or the management. Having visual plots of the problem often makes it much easier to show the EMC problems of a specific design.

3.1.3 Procedure

3.1.3.1 System description

The near-field measurement consist of several parts

1. The mechanical scanner and control software
2. Near-field probes
3. Cables
4. Pre-amplifiers
5. Measuring equipment

The full setup is controlled by software, which typically comes with visualization of the measured fields. Most software will control spectrum analyzers but support for the use of a fast sampling oscilloscope is rarely seen.

3.1.3.2 Setting up the EUT

To make a setup in the near-field scanner is fairly easy. Position the PCB roughly aligned to the coordinate system of the scanner. Attach all cables needed for auxiliary equipment. It is recommended that the cables are fixed with tape such that the EUT does not move due to a pull in the cable. Use a set of spacers under each of the corners such that the PCB I planar. For repeatability and precision in the setup the position of the PCB must be adjusted. Use the near-field probe, or a pointer pen mounted as probe, to locate the corner of the PCB and note the x,y,z coordinates. Then move the probe in the x direction to the next corner of the PCB and note that the y and z values of the corner should not change. If that is not the case realign the PCB and repeat from first corner. As a final step the probe should be moved in the y direction and the z value should be observed to match the two previous corners. When the alignment procedure is completed the PCB position is known accurately and the PCB is aligned with the scanner coordinate system.

As for most other EMC measurements the most important and difficult task is to obtain a repeatable setup. That is to ensure that the surroundings affect the setup as little as possible. In practice this means that great care must be taken in the cable positions. In Figure 21 it can be seen that the measured amplitude can change by 4 dB over the PCB surface, just by changing the cable positions. Since the fixture of the cables have not yet been standardized it is recommended that the position should be as close as possible to the real setup of the EUT, but made such that it is easy to repeat.

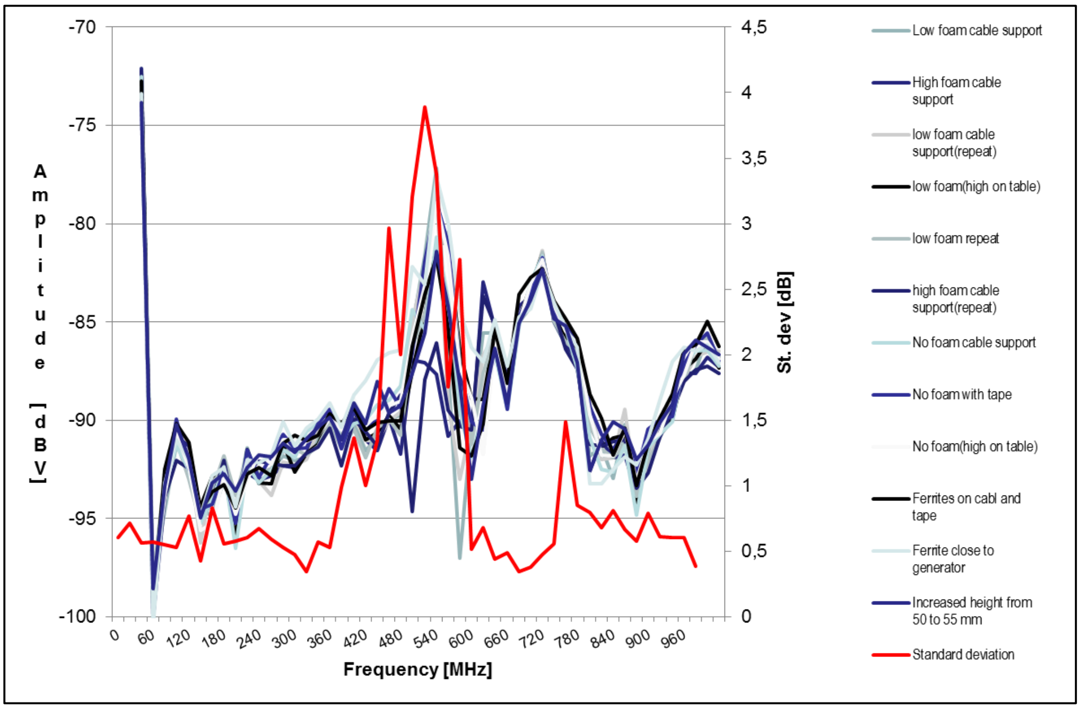


Figure 21 The blue and black traces show the measured amplitude spectrum in a specific point over the PCB with different positions of the cable to the power supply. The red trace shows the standard deviation

3.1.3.3 Measurement height and step size

Typically near-field scans are conducted in a height of 1 to 40 mm. At close distances the resolution, i.e. the possibility to separate two close sources, is higher. The use of the dynamic range for the emission measurement is also better at a short distance. The maximum step-size of the scanner and the scan height over the PCB are related by the formula (5).

$$\Delta s = \frac{\lambda}{2\sqrt{1+\left(\frac{\lambda}{d}\right)^2}} \qquad (5)$$

Where Δs is the maximum step-size, d is the height over the PCB and λ is the wavelength. When $d \ll \lambda$ the formula can be approximated by $\Delta s \approx d/2$, such that the step size is half the distance. The time T to conduct the total scan can be calculated by T=t*Nx*Ny, where t is the time per point and Nx, Ny is the number of points in the x and y direction respectively. The total scan time thus depends on the step size squared and reducing the step size from 10 mm to 5 mm will increase the scan time by a factor of 4, going from 40 mm to 5 mm is a factor of 64. Thus to get an overview of a PCBs performance with respect to emissions radiated directly from the PCB, a scan in 40 mm distance is a good starting distance. From this scan it can be seen if there will be direct radiation from the PCB and in what regions of the PCB the noise is originating. If a better resolution is needed the scan can be repeated.

3.1.3.4 Choosing the right probe

The probe is the interface between the near-field and the measurement system. In practice most of the system is fixed but it can be advantageous to change the probes between different scans. A small probe will have a good resolution but poor sensitivity compared to large probes. In general the guide is to use a probe no larger than the step size. This will ensure that the field from the next measurement point will not ‘leak’ into the current measurement point. If the amplitude of the noise is large a smaller probe can be used.

Since there are both E- and H-field probes many have asked the question whether to use E, H or both. In 95% of the cases the emissions can be detected with H-field probes only. A strong electric field in the near-field is only present if the structure measured is high impedance. It is important not to think of this as high impedance at DC but to consider the RF impedance. Thus in practical cases it is only structures such as heat sinks and unconnected cable connectors that exhibit this behavior. This does not imply that the E-field does not exist in the near-field, but that the H-field will often be significant enough to detect the emission problems.

3.1.3.5 Validating the measurement

Several error sources exists when near-field scanning. The most typical is listed here.

1. Interference from other sources than the PCB
2. Probe influencing the PCB resonance
3. Scanner structure reflection
4. Insufficient measurement time
5. Insufficient distance to system noise floor (dynamic range)
6. Thermal drift of the EUT
7. Scan channel to reference channel crosstalk

All of these can be detected by having two measurement probes simultaneously. A typical scan probe mounted in the scanner positioner and a reference probe located in a fixed position under the EUT. By plotting the reference probe signal instead of the scan probe signal the changes to the EUT can be monitored. If the signal from the reference probe is the same for each measurement position the above error sources can be ruled out [2].

3.1.3.6 Detecting radiation problems

The near-field from a small dipole antenna can be described by the formulas

$$
\begin{aligned}
E_r &= \frac{Il}{j\omega}\frac{e^{-jkr}}{2\pi\varepsilon_0}\ \ \frac{1}{r^3}+\frac{jk}{r^2}\ \ \cos\theta \\
E_\theta &= \frac{Il}{j\omega}\frac{e^{-jkr}}{4\pi\varepsilon_0}\ \ \frac{1}{r^3}+\frac{jk}{r^2}-\frac{k^2}{r}\ \ \sin\theta \\
H_\phi &= \frac{Il}{j\omega}\frac{j\omega e^{-jkr}}{4\pi}\ \ \frac{1}{r^2}+\frac{jk}{r}\ \ \cos\theta
\end{aligned}
\tag{6}
$$

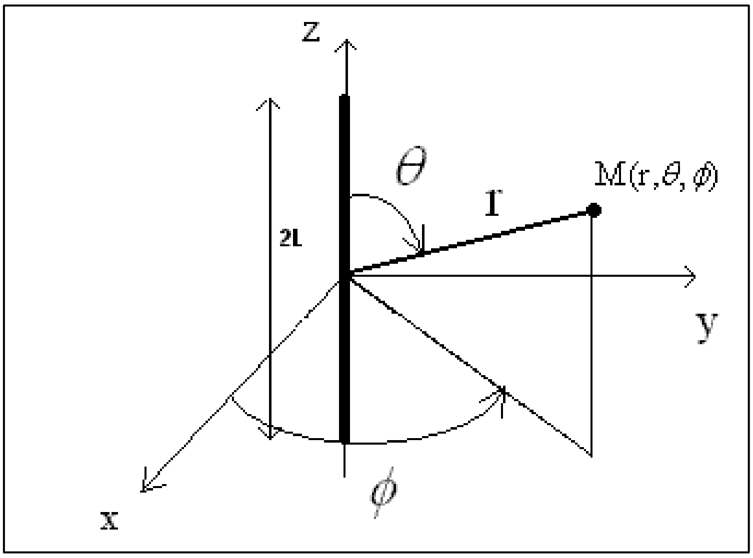


Figure 22. Axis and angles related with formula (6)

Since it is not easy to detect in the near-field if a field component is a non-radiating $1/r^3$ component or a radiating 1/r component the spectrum in the near-field it can be difficult to see if a given frequency will be a problem in 10 meter distance or not. By the untrained eye a near-field spectrum from a PCB will almost always look like the PCB is poorly designed, but may not have a radiation problem in the far-field. There are 3 checks that with training can be used for detecting most radiation problems.

1. Checking the absolute amplitude of the field
2. Checking the amplitude vs. distance from PCB trend-line
3. Analyzing the area where the fields have sufficient amplitude

Checking the absolute amplitude of the near-field can often be misleading. Since the field can be a $1/r^3$ component the field strength can appear to be a problem for excessive radiation, but vanish as the distance increases. Newer the less, it is a good rule of thumb for initial screening. To establish a limit the maximum permissible current must be found. Several calculation rules for small loops and small dipoles exist and have been compared.

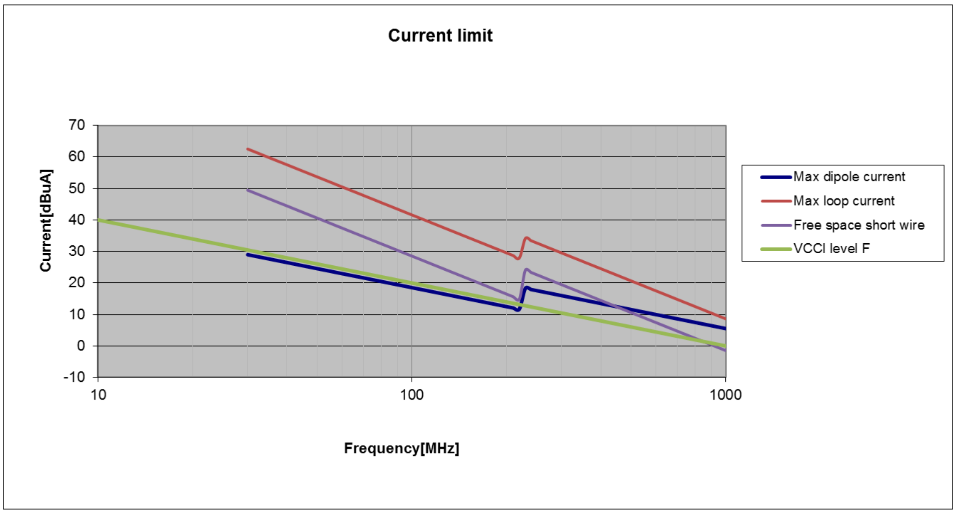


Figure 23. Acceptable current in order to meet various emission requirement limits

From these limits it is clear that the VCCI limit for level F modules is a good lower approximation for the permissible current in a trace. Inserting this current in an expression for the electric or magnetic near-field will yield a maximum field strength for a given scan height, frequency and length of dipole. If this is not calculated a good rule of thumb is that if magnetic field is in the range of 1 mA/m in a height of 1 cm there can be radiation problems.

The second check is to investigate if the field is a 1/r component of the field. This can be done by making a height scan: Position the probe over the area with the highest amplitude field strength. In small steps increase the distance between the probe and the PCB while monitoring the amplitude at the frequency of interest. By plotting the field strength vs. distance, use double logarithmic scales for a linear trend, it is possible to examine if it is a $1/r^3$, $1/r^2$ or 1/r component. Note that the higher order terms are rarely seen alone, there will often be a portion of the field which is radiating. Experience has shown that if an exponent is less than 1,25 there will be a risk that the source is radiating and more than that, it will not pose as a far-field problem in terms of direct radiation.

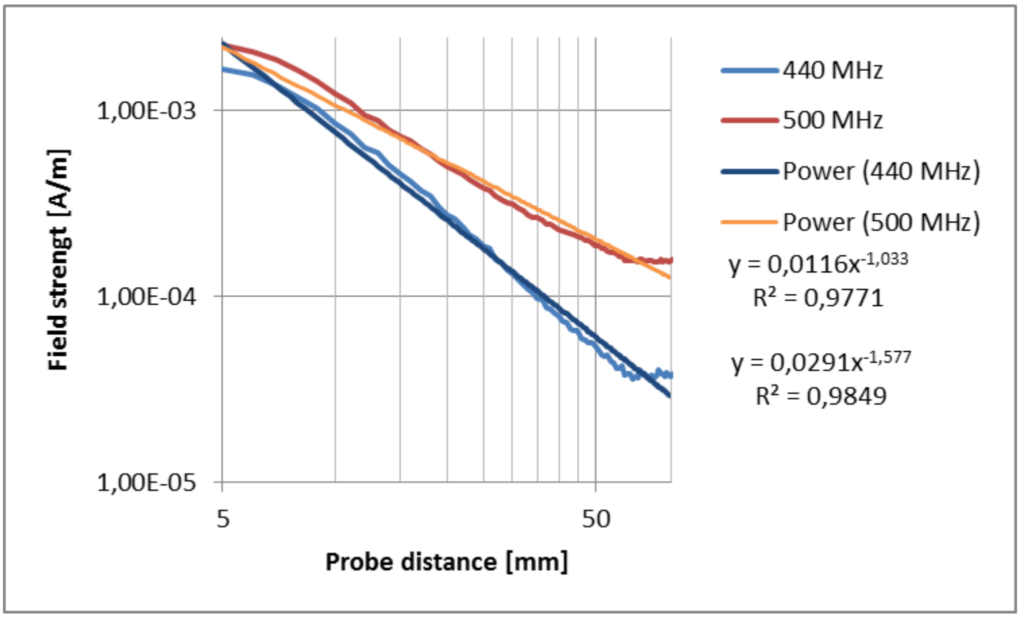


Figure 24 Relationship between magnetic field strength and probe distance for various values of the exponent.

The third check is the area of the amplitude. In some cases the scan distance has been too large to distinguish between sources. This can often be the case for closely spaced differential lines. An example could be the communication between a processor and a ram block. This will be hard to detect as the noise is not only originating from a single source. Here an investigation is to look at the size of the area where the near-field is strong. A specific rule of thumb for this check is not easy to make and usually requires experience, but is possible over time. Experience has shown that if the area in either direction is larger than a quarter wavelength or if the area is larger than a quarter of the PCB area, care should be taken.

3.1.3.7 Example 1 Smart shielding box

To demonstrate the usefulness of near-field scanning, an example is given below.

As mentioned earlier, there is not necessarily a direct connection between a strong near- and a strong far-field. But a near-field scan together with a general electromagnetic understanding and other information can provide valuable information.

Figure 25. Emission plot at 200 MHz.

The color map above shows a problem with radiated emission at 200 MHz and its harmonics. A near-field scan clearly shows that the emission comes from the communication to the RAM memory module. A small shielding box capable of covering the processor IC and the RAM IC could solve the problem.

3.1.3.8 Example 2 Interference problem

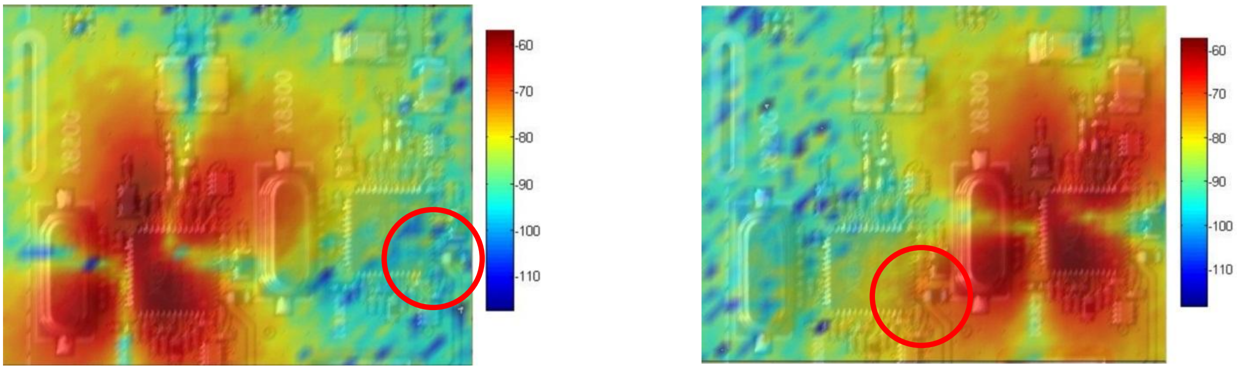


Figure 26. Emission plot at 612.5 MHz (left plot) and 652.4 MHz (right plot).

This IC with a clock frequency of 612.5 MHz (left hand side) did not interfere with the IC on right hand side. But the IC with a clock frequency of 652.4 MHz (right hand side) did interfere with the IC on left hand side. The sensitive area of the IC is marked with a red circle on the color maps. It is clear that the right hand side IC radiates into the left hand side IC but not vice versa.

3.1.3.9 Example 3 WIFI-antenna as unwanted emitter

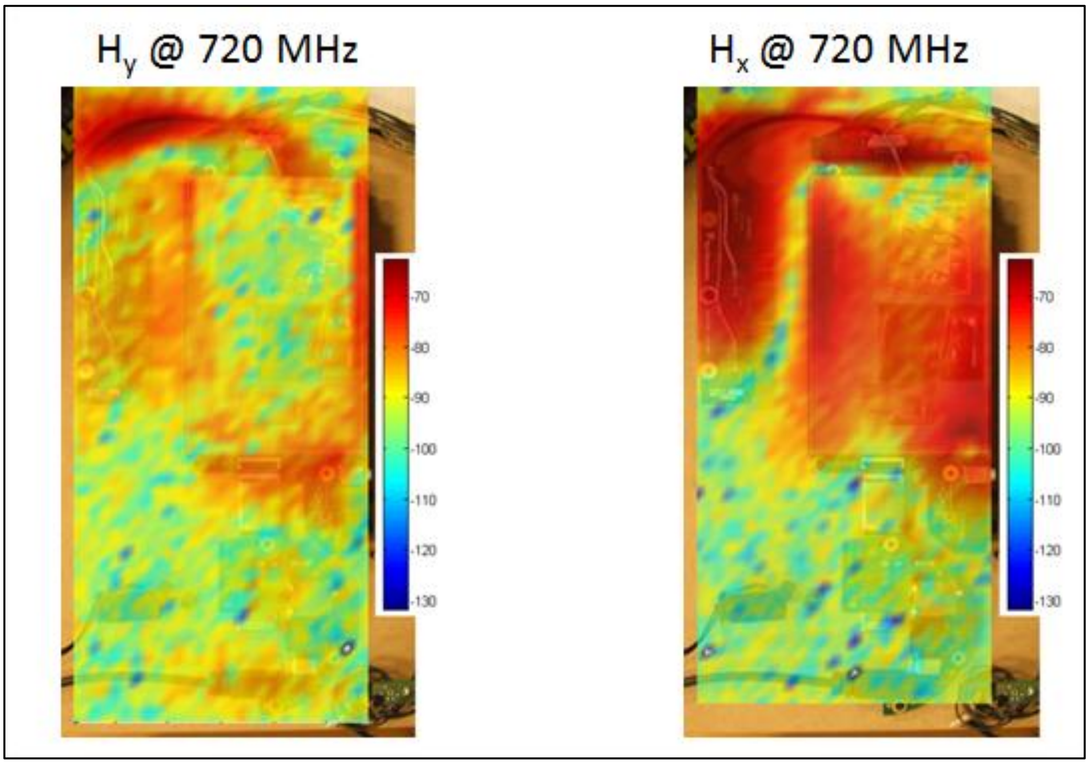


Figure 27. Emission plot at 720 MHz. Y-component (left plot) and X-component (right plot).

A shielded module had problems with radiated emission at 720 MHz. The near-field scan showed that the noise was transferred from the shielding box via the WIFI-antenna.

3.1.3.10 Example 4 Keep cables away from noisy areas

A near-field scan can help the electrical engineer in the architecture phase of a project, when the signal tracks on the PCB or the cables are to be routed. A near-field scan of a switched mode power supply showed that the noisiest area was near the transformer.

An experiment was carried out. A cable was placed first away from the noisy area, and then just above the noisy area. In both configurations the radiated emission was measured. When the cable was placed nearby the transformer, the radiation increased up to 15 dB. In other words, a near-field scan can show you where you cannot place your cables.

3.1.3.11 Example 5 Prediction of radiated emission

In the final example a demonstration of using the Huygen box method described in section 3.2 combined with near-field scanning is described. Here the amplitude and phase of tangential magnetic near-field was measured on a closed surface around a PCB. The measured magnetic near-field was exported to a FDTD simulation to extract the electric field and finally the far field at 3 meters distance was simulated and the maximum value was plotted as function of frequency. Finally the measurement was compared to a SAC measurement. The result can be seen in figure 28. Notice that the deviation is largest at the frequencies that was seen to have a large standard deviation in figure 21 and can thus be known by changing the setup. The same frequencies will be critical during module integration. In the rest of the frequency range the deviation is less than 6 dB.

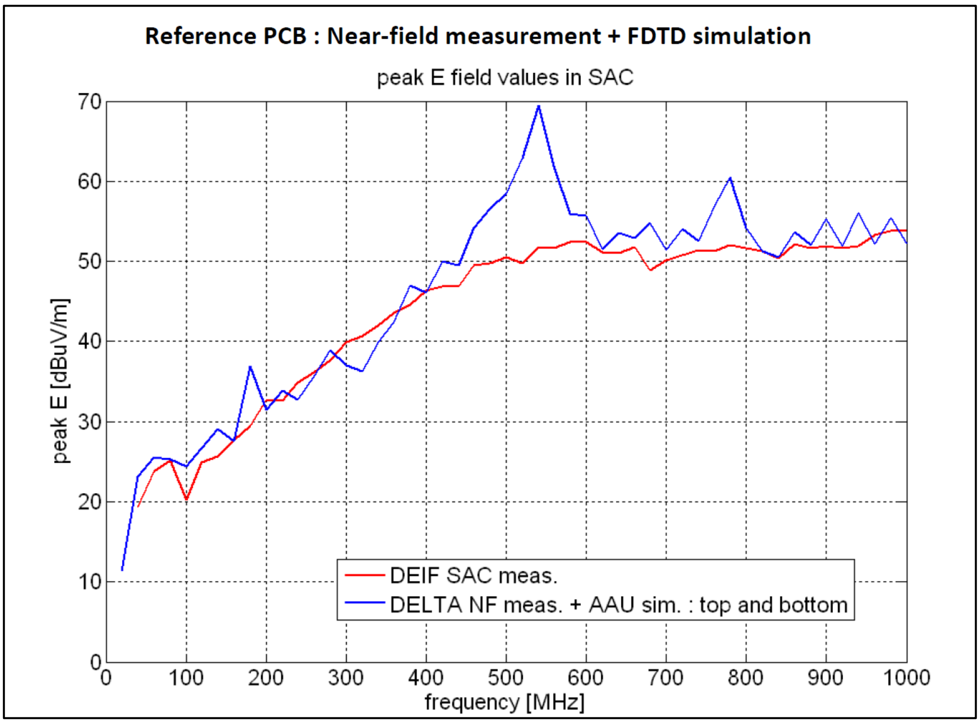


Figure 28 Comparison between the fields simulated from a near-field scan and a SAC measurement.

3.1.4 Investment

The investment for a near-field scanner is dominated by the scanner itself. The mechanical scanner is typically in the price range of $30.000. If the laboratory is equipped with high speed oscilloscopes or spectrum analyzers the second part can be omitted. Otherwise the prices start at approximately $2.000. Probes can be manufactured easily from rigid coaxial cables or can be purchased for $300 for a set and the pre-amplifiers are in the range of $400 each. Thus the total investment will be in the range of $33.000. It should be noted that analyzing near-field measurements is not a trivial task. The test operator must invest some time in getting familiar with analyzing the results.

3.1.5 Summary

In this section the most important aspects of the near-field scanner has been described. First the setup has been described and what equipment is needed for a scanner. Secondly the types of problems that can be troubleshooted by the near-field scanner were highlighted. The far field was predicted to an uncertainty of 6 dB outside the frequencies where it was known that a large deviation was present due to the setup variation.

3.1.6 References

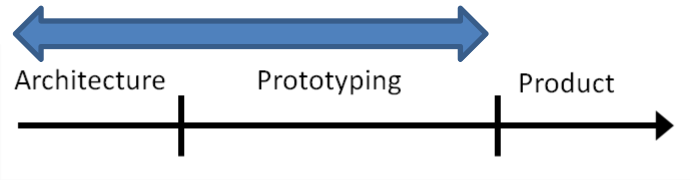
[1] O. Franek, M. Sørensen, H. Ebert and G. Frølund, ”Sampling criterion for EMC near-field measurements”, PIERS proceedings 2012

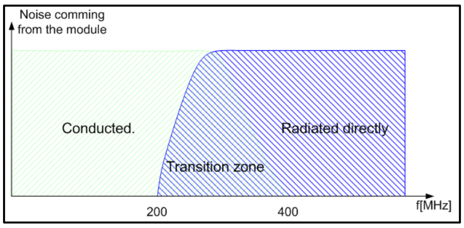
[2] A.P. Mynster and M. Sørensen, ”Validation of EMC Near-field scan amplitude and phase measurement data”, EMC Europe 2012

3.2 PCB radiation - PART II. Huygens Box method

Ondrej Franek, Aalborg University

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: Above 200-400 MHz

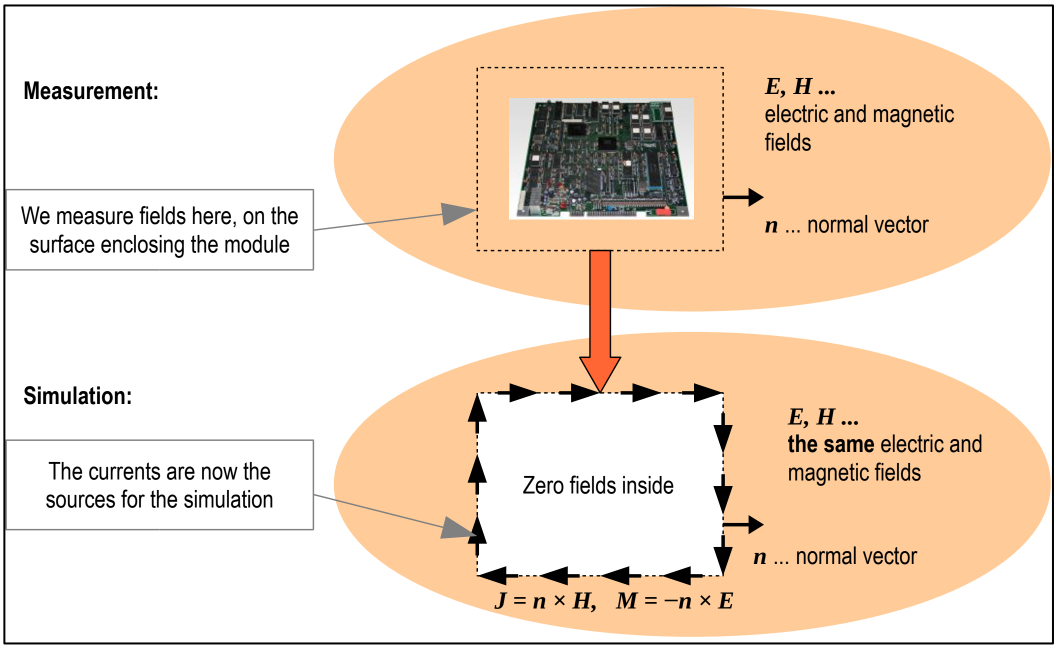


Figure 29. Huygens box method in the basic form; when we can measure both electric and magnetic fields

3.2.1 Introduction

In this chapter we are going to introduce an artificial construct that will serve as a source in simulations – the **Huygens box**. Important aspects of usage of this construct will then be explained.

3.2.2 EMC Challenge

An electronic apparatus consisting of one or several modules in an enclosure may often fail to fulfill requirements on electromagnetic compatibility (EMC) in terms of radiation, in spite of the fact that the particular modules may pass the requirements. There has been a growing interest in the possibility of identifying such situations early in development stage of the modules, since later changes in the design of the apparatus are costly. Electromagnetic simulations of the interaction between the modules and the apparatus have been instrumental to achieve this goal.

However, it is not always possible to simulate a full model of the electronic module, often because the internal structure of some parts of the module (typically integrated circuits) is unknown. Instead, it has been suggested to characterize the module by the near-fields it produces. These are obtained by measurement and serve as sources in the simulation.

3.2.3 Procedure

3.2.3.1 Huygens box

According to the surface equivalence theorem, an arbitrary source of electromagnetic field (the module, for instance) can be replaced by electric (J) and magnetic (M) surface currents running over a surface entirely enclosing the source, whereas the currents are uniquely determined by electric (E) and magnetic (H) fields tangential to the surface (and obtained by measurement)

$$J = n \times H, \quad M = -n \times E \tag{7}$$

The electromagnetic field outside of the surface is identical in both cases, so we can now perform the simulation without knowing anything about the module, substituting it with the J and M sources on the surface. The surface often takes form of a box, hence the name Huygens box (figure 29).

In formulas (7) all quantities are vectors. Symbol n denotes the normal vector that is always oriented outwards the surface. The cross product means that the resulting current will always be tangential to the surface and its value will be equal to the tangential component of the particular field. Thus, we need to measure only tangential fields.

For example, if we measure the fields on a horizontal plane over a PCB, whereas x and y axes lie in the horizontal plane and z axis points upwards, then we have to measure only the x and y components, and the obtained current densities will be

$$J_x = -H_y, J_y = H_x, \quad M_x = E_y, M_y = -E_x \tag{8}$$

For the other sides of the Huygens box, the coordinates will be permuted accordingly.

3.2.3.2 Do we have to measure both E and H fields?

Measuring both E and H fields requires having both types of probes, and the measurement will naturally take twice as long time. The surface equivalence theorem says that we actually need only one set of components, either electric or magnetic, if we fill the box in simulation with so-called perfect electric conductor (PEC) or perfect magnetic conductor (PMC), respectively. In case we want to obtain both fields and use the Huygens box empty, we have the possibility to use following a two-stage procedure (figure 29):

1. Measure only one field, H or E
2. Recreate the original fields using only one set of currents, J or M, running over Huygens box with PMC or PEC inside
3. Take both fields, H and E, on a slightly larger surface, enclosing the original surface
4. Recreate the original fields using both sets of currents, J and M, running over empty Huygens box

Figure 30 depicts this procedure in case we measure only H fields.

It is worth mentioning, however, that with this procedure the dominant field for the particular module should always be measured, and the other, weaker, calculated. Otherwise we risk amplifying any errors (especially noise) up to the point when the calculated fields are unusable.

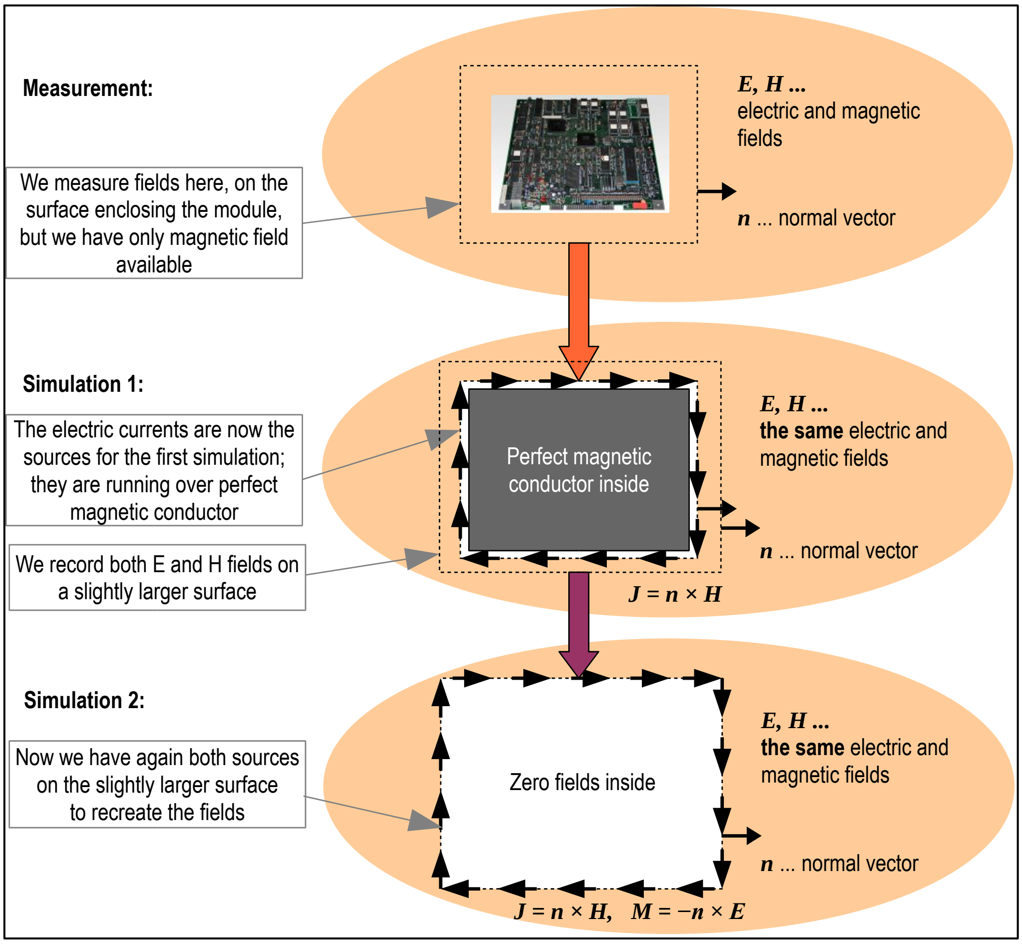


Figure 30. Two-stage recreation of both field components in case we decide to measure only magnetic field.

3.2.3.3 What happens if the Huygens box is placed inside a chassis or enclosure?

According to the surface equivalence theorem, the environment outside the Huygens box should be the same in both the measurement and the simulation scenarios. However, this is seldom the case, because we measure the module in a laboratory environment with no obstacles around, whereas the simulation will incorporate also nearby parts of the designed apparatus – other modules, cables, but most importantly the (usually) metallic chassis or enclosure. What happens if the condition is not fulfilled then?

In real life, when the module is placed inside an enclosure, the fields produced by the module will be reflected from the enclosure and then again reflected from the module, which might result in resonances. Such resonances are particularly dangerous, as they can cause over-the-limit radiated emission from the apparatus. When we try to simulate such a scenario with Huygens box obtained from near-field measurement in laboratory conditions, the fields will get reflected from the enclosure, but not from the module, because the Huygens box is empty (figure 31). The resonances will not occur, radiation will be low, and we might be misled into assuming that the designed apparatus conforms to the emission standards.

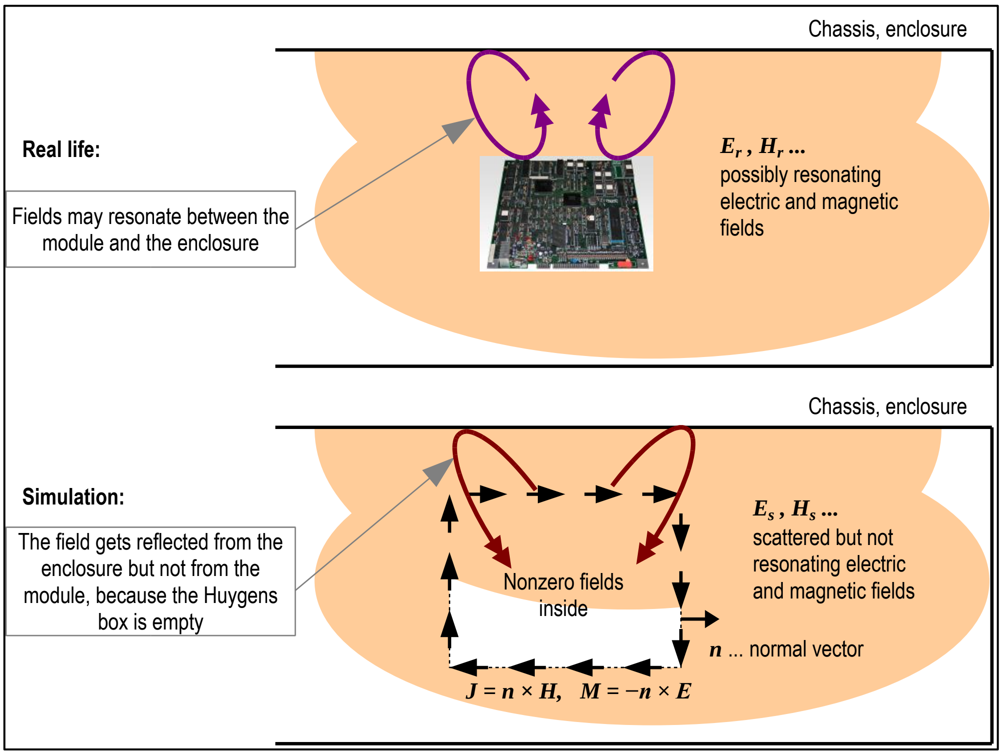


Figure 31. Dissimilarity of the fields inside an enclosure.

Remedy to the above described problem lies in offering the fields a ‘scatterer’ to reflect from inside the Huygens box. This ‘scatterer’ should represent the main features of the module, for example a substrate with ground plane in case of a PCB. The resonance will then be re-established, together with the correct radiation (figure 4).

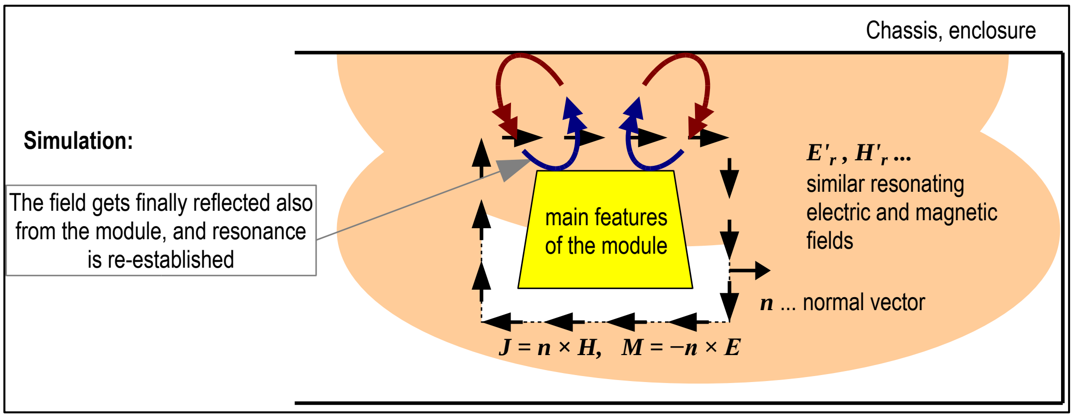


Figure 32. Re-establishment of the resonances inside an enclosure.

It is quite clear that in order to correctly simulate the reflections and resonances with the ‘scatterer’ approach, we need to start with empty Huygens box, and therefore need both electric and magnetic field. If measurement data is available for only one set of fields, the procedure described in figure 30 is necessary.

3.2.4 Summary

- The concept of Huygens box allows us to use the near-field scan of a module as a source in simulations, without the need to create the full model of the module.
- Only two tangential components of one set of fields, electric or magnetic, are needed in order to fully recover the emission.
- A chassis or enclosure may hinder correct prediction of internal fields and emission – a remedy is to include main features of the module inside the Huygens box.

3.2.5 References

[1] C. A. Balanis, Advanced Engineering Electromagnetics. Wiley, 1989.

[2] O. Franek, M. Sørensen, H. Ebert, and G. F. Pedersen, 'Near-field characterization of a printed circuit board in the presence of a finite-sized metallic ground plane,' In Progress in Electromagnetics Research Symposium, Apr. 2012, pp. 1146–1149.

[3] O. Franek, M. Sørensen, H. Ebert, and G. F. Pedersen, 'Influence of nearby obstacles on the feasibility of a Huygens box as a field source,' in IEEE International Symposium on Electromagnetic Compatibility, Aug 2012, pp. 600–604.

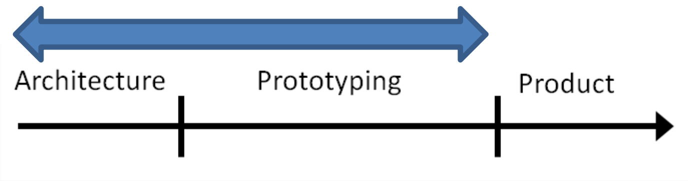
[4] O. Franek, M. Sørensen, H. Ebert, and G. F. Pedersen, 'On the applicability of the surface equivalence theorem inside enclosures,' In International Conference on Electromagnetics in Advanced Applications (ICEAA), Sep. 2012, pp. 946-948.

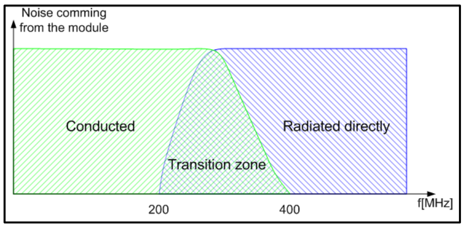
3.3 Simulation – PART I

3.3.1 Introduction to the method (a few hints to simulation)

Ondrej Franek, Aalborg University

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: entire frequency range

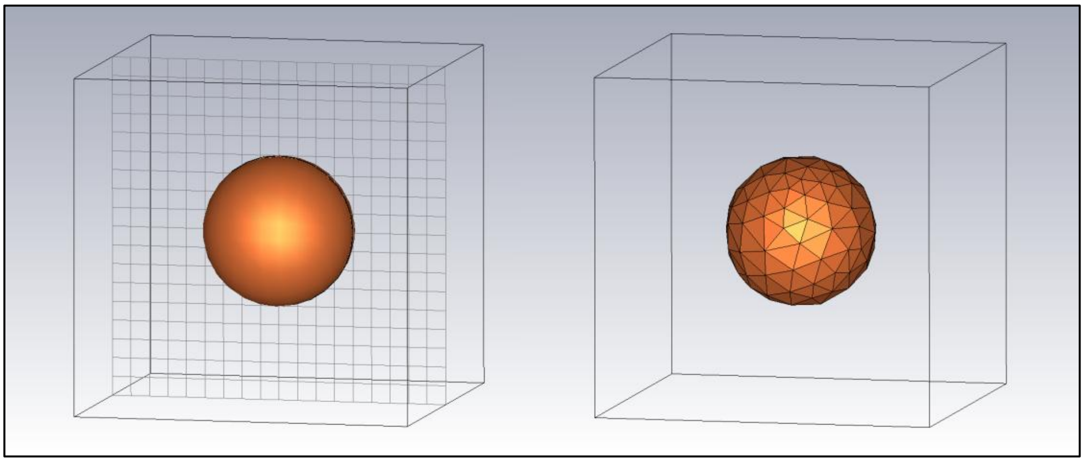


Figure 33. Volumetric (left) and surface (right) mesh types

3.3.2 Introduction

This section provides basic information on simulation tools, criteria of their selection, and a few hints on how to use them.

3.3.3 EMC Challenge

We would like to know how a designed device will behave in terms of EMC, before it is actually manufactured. We can get quite a good approximation of that by mathematically modeling the underlying physical phenomena – making a simulation. Just like with any other undertaking there are some tradeoffs involved:

1. Selecting the right method for simulation
2. Making a very detailed model helps to achieve high accuracy, but increases computation time and computer hardware requirements.

3.3.4 Procedure

3.3.4.1 Selection of the right numerical method and simulation tool

The principal numerical methods for electromagnetic (EM) analysis can be divided into two groups according to domain in which the problem is discretized (meshed): a) volumetric meshing, and b) surface or line meshing.

The first group, which is represented by the FDTD and FEM methods (see below), discretizes partial differential equations in volume and allows for modeling of inhomogeneous material bodies. On the other hand, the second group utilizes Green's functions to calculate EM interactions and discretizes only material boundaries, as in MoM, which is very efficient for large-scale simulations of mostly homogeneous objects and materials. In the following, the main methods used in EM are briefly introduced and their characteristics discussed.

3.3.4.2 Finite-Difference Time-Domain Method (FDTD)

This is the most popular of larger group of finite difference methods. It is based on the efficient and accurate Yee algorithm, which discretizes Maxwell's equations in differential form (alternatively also in integral form) on a spatially staggered grid and with leap-frog update scheme in time domain. However, the finite difference system can be solved also in frequency domain, which gives an advantage in narrow band simulations.

Advantages and disadvantages:

+ Suitable for basically any geometry, very general, close to underlying physics (*ab initio* principle)
+ The time-domain algorithm provides results over wide frequency range within single simulation
− For large structures, the memory requirements can be prohibitive

Examples of FDTD Software (with vendor): CST Studio Suite (CST)*; XFDTD (Remcom); SEMCAD (Schmid & Partner Engineering); EMPIRE XCcel (IMST GmbH); Fidelity (Zeland Software); APLAC (AWR, formerly Aplac Solutions); Concerto (Vector Fields); EM.Cube FDTD.module (Emagware); QuickWave (QWED); EMPro (Agilent); Sim3D_Max (Nonlinear Control Strategies); etc.

* CST uses the finite integration technique (FIT), which is closely related to FDTD.

3.3.4.3 Finite Element Method (FEM)

Here, the volume of the computational domain is discretized into finite element mesh, formed by typically tetrahedrons, and the underlying differential form of Maxwell's equations is solved by minimizing variational functional. This results in a matrix equation to be solved.

While this method is highly popular in the fields of structural analysis, thermodynamics and fluid dynamics, it is less perspective for solving electromagnetic problems. It has higher complexity and computational demands than FDTD, but no significant advantages. Historically, this method was favored over FDTD because of better treatment of irregular or curved boundaries, and its inherent ability to refine mesh in selected regions. However, these are not competitive advantages any more, since FDTD software has recently introduced conformal techniques and sub gridding, achieving basically the same abilities.

Advantages and disadvantages:

+ Can be good for multiphysics computations, coupled with mechanical or thermal solver
− Higher computational demands, need to generate the often irregular mesh
− Higher complexity

Examples of FEM Software (with vendor): HFSS (Ansoft/ANSYS); ANSYS (ANSYS, Inc.); COMSOL Multiphysics (COMSOL); Opera, Concerto (Vector Fields); EMPro, ADS (Agilent); etc.

3.3.4.4 Method of Moments (MoM)

Uses Green's functions to describe interactions between elements of mesh, which is present only at boundaries between homogeneous material areas. This method is actually a special case of boundary element method (BEM) with sub sectional base functions and Dirac delta functions as weighting functions. The method of moments has been traditionally implemented in frequency domain only (calculating single frequency at a time); time domain formulations are still largely experimental.

Advantages and disadvantages:

+ Efficient for low surface / volume ratio of the problem
+ Could be ideal for empty spaces between the modules
− Frequency-domain only, wideband results difficult

Examples of MoM Software (with vendor): CST Studio Suite (CST); FEKO (EM Software & Systems); NEC-2 (public domain); NEC-4 (Lawrence Livermore National Laboratory); SuperNEC (Poynting Software); IE3D (Zeland Software); WIPL-D; Concerto (Vector Fields); EM.Cube Metal3D.module (Emagware) – wire models only; EM.Cube Planar.module (Emagware) – 2.5D solver, for microstrip planar structures only; ADS (Agilent) – planar structures only; Sonnet Suites (Sonnet Software) – planar structures only; Xpatch/FISC (SAIC); Concept-II (Technical University Hamburg-Harburg); etc.

3.3.4.5 Other Methods and Extensions

There are also other methods and techniques for solution of EM problems, however these have not achieved such widespread use as the ones mentioned above, and. Examples may include: Multilevel fast multipole method (MLFMM), Transmission line matrix (TLM), Geometrical optics (GO), Physical optics (PO), Uniform theory of diffraction (UTD), Partial element equivalent circuit (PEEC), and many others -- many of them serve for special purposes not compatible with the EMC problem.

3.3.4.6 Few hints about the FDTD method

The FDTD method appears to be the most flexible method for simulation of most possible scenarios that can arise in EMC. Therefore it has been adopted in the First Time Right consortium as the reference method. In our experiments, we have used both the in-house FDTD code developed at Aalborg University as well as the commercial software package CST Studio Suite, which uses the finite integration technique (FIT), a variant of FDTD method, and is one of the most widespread tools in the industry sphere. A few remarks on the usage of the method follow:

1. The cell size should always be smaller than one tenth of a wavelength (λ/10), preferably (λ/20).
2. Making the cell size smaller increases accuracy, but also increases computation time and memory requirements. Remember that by cutting the cell size down to one half the simulation time increases 16x! (2^3 = 8× more cells in the same volume, times 2× more time steps, since the time step is bound to the cell size)
3. If we want to simulate the electronic device in free space (as if in anechoic or semi-anechoic chamber), we need to turn on the absorbing boundary conditions (usually PML) that will facilitate reflection less termination of the mesh.
4. Try to avoid too wideband simulations – unwanted resonances might be excited and spoil the results. On the other hand, too narrowband excitation pulse makes the simulation run longer.
5. Always keep in mind that although the simulated structure as well as any displayed fields might look smooth and 'pretty' in the visualization window of the software, they are in fact discretized into small but not negligible cells and what you see is mostly interpolation.

3.3.5 Investment

The cost of commercial simulation software varies greatly from vendor to vendor, and the prices are largely subject to negotiations. Approximate values span from $4.000 to $40.000. In any case, it is advised to contact the local reseller for detailed information.

3.3.6 Summary

For simulation of arbitrary modules, the FDTD method seems as the most suitable choice for its versatility. MoM will likely be faster if there are free space and large electrical distances between parts of the apparatus.

3.3.7 References

[1] D. B. Davidson, *Computational Electromagnetics for RF and Microwave Engineering*. Cambridge, UK: Cambridge University Press, 2005.

[2] D. Poljak, *Advanced Modeling in Computational Electromagnetic Compatibility*. Hoboken, NJ: John Wiley & Sons, 2007.

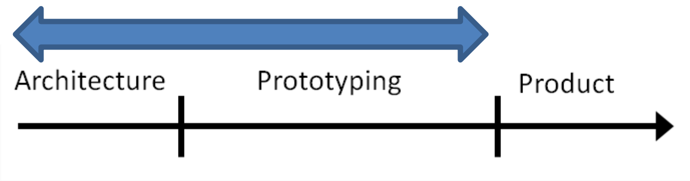
[3] J. Jin, *The Finite Element Method in Electromagnetics*, 2nd ed. New York: John Wiley & Sons, 2002.

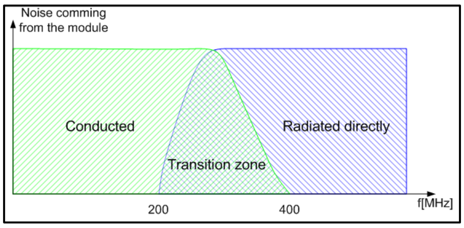
3.4 Simulation – PART II

3.4.1 Examples and everyday use of simulations

Morten Sørensen and Kim Jensen, Bang & Olufsen

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: Above approx. 100 MHz

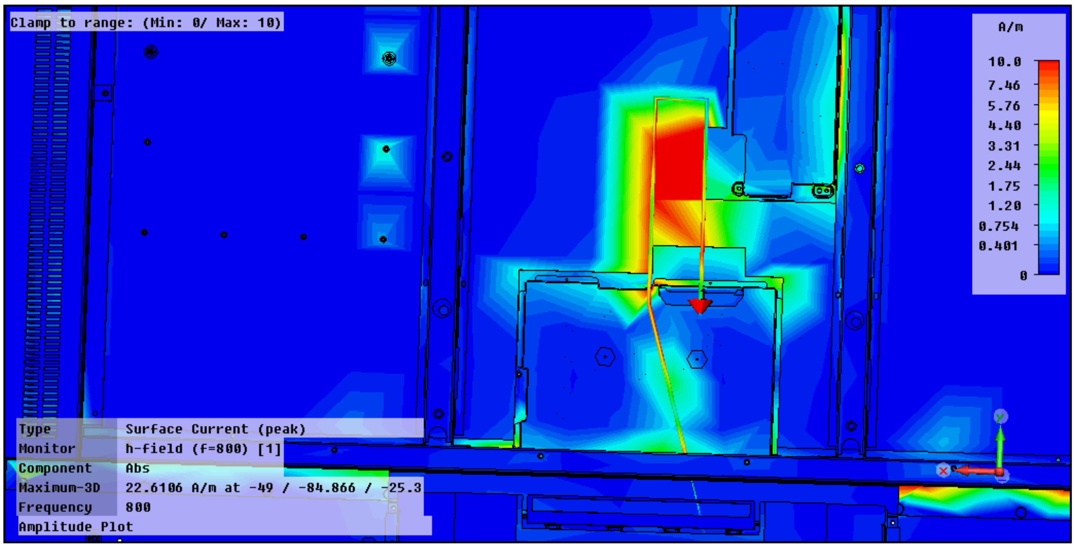


Figure 34. Surface current simulation on a product

3.4.2 Introduction

Simulations have the last decade increasingly been an important tool when working with EMC, signal- and power integrity. Simulations are often faster and cheaper than many measurements, mock-up building etc. Simulations give more insight compared to measurements alone because you can study the electromagnetic fields involved in the problem.

Simulations give us the possibility to take examined decisions early in the projects.

3.4.3 EMC Challenge

Simulations can be a very important tool within many EMC challenges and the best way to illustrate this is to show a few examples.

3.4.4 Proactive learning

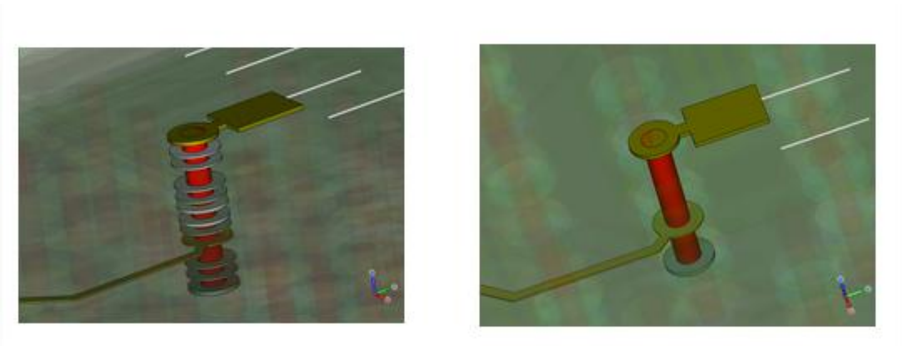
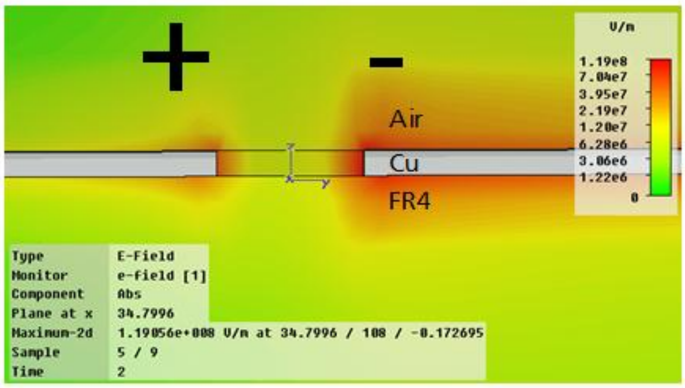
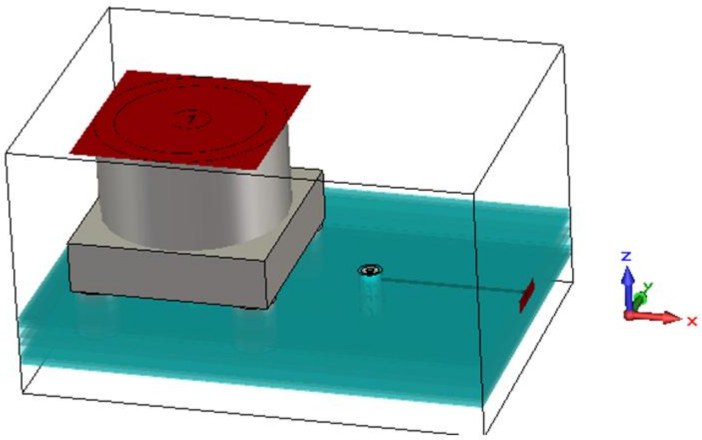
<table>
<tr><td></td><td>Simulation of via impedance depending on the via design</td></tr>
<tr><td>
</td><td>Design of printed atmospheric spark gaps</td></tr>
<tr><td></td><td>Simulations of trace and via impedance – TDR measurements.</td></tr>
</table>

Figure 35. Examples of circuit input models for simulation tools.

3.4.4.1 Simulations of simple structures early in the project

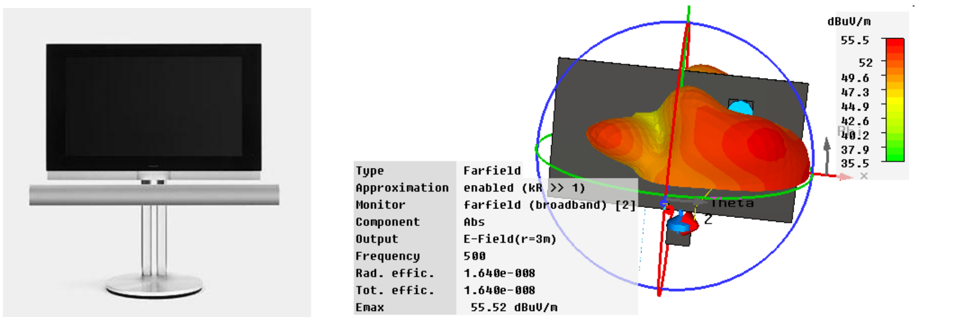
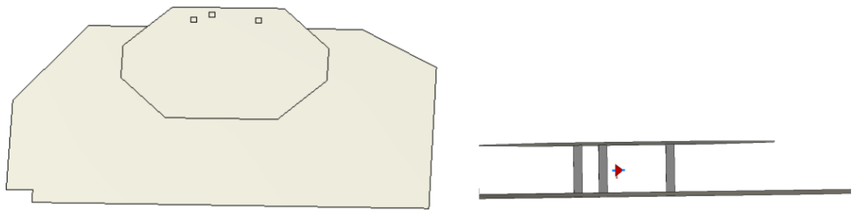
<table>
<tr><td>
</td><td>Investigation of EMC architecture very early in the project.</td></tr>
<tr><td></td><td>Looking for resonances between two PCBs</td></tr>
</table>

Figure 36. Examples of investigation of EMC design using circuit modeling.

3.4.4.2 Full product import later in the project

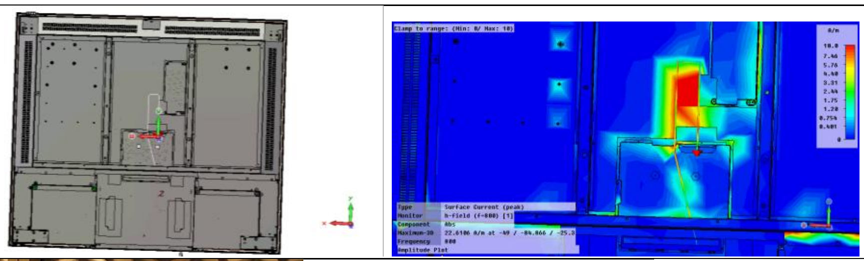
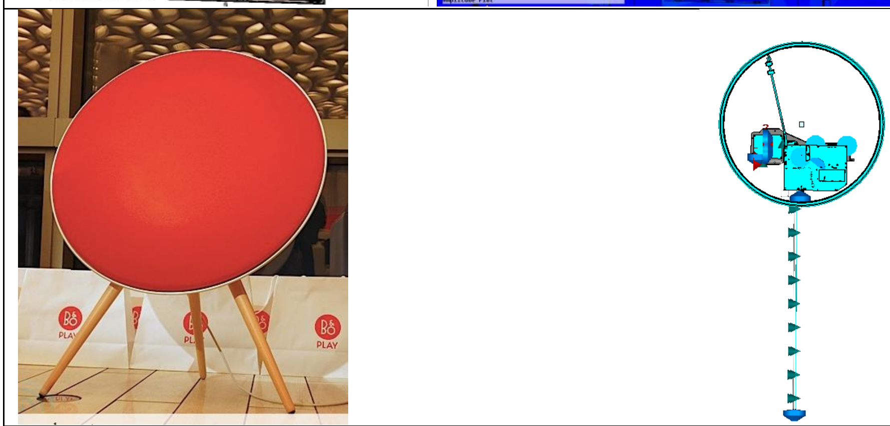
<table>
<tr><td></td><td>Investigation of return currents</td></tr>
<tr><td></td><td>Investigation possible cable resonances</td></tr>
</table>

Figure 37. Examples of investigation of EMC design using circuit modeling.

3.4.4.3 Other applications

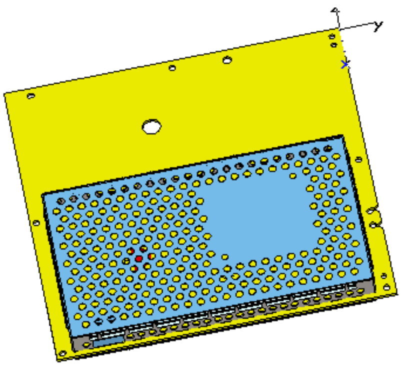
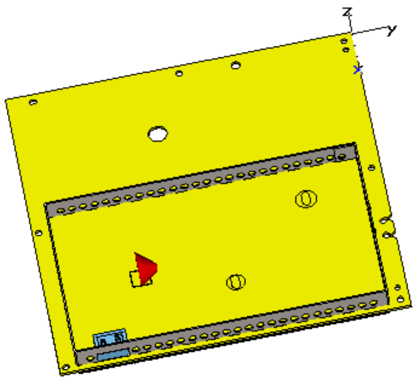
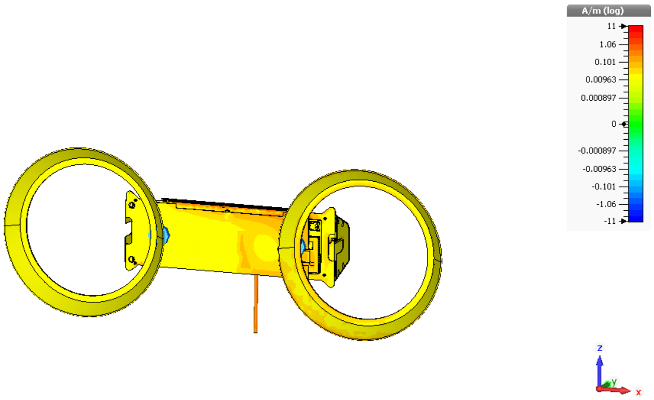
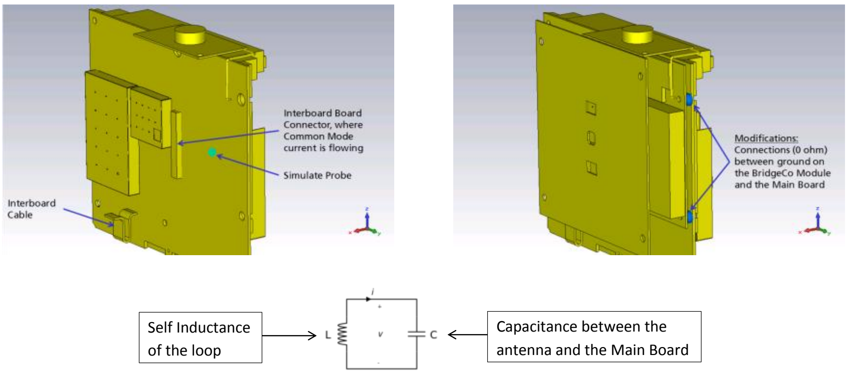
 	Evaluation hole size in shielding boxes
	ESD currents in product

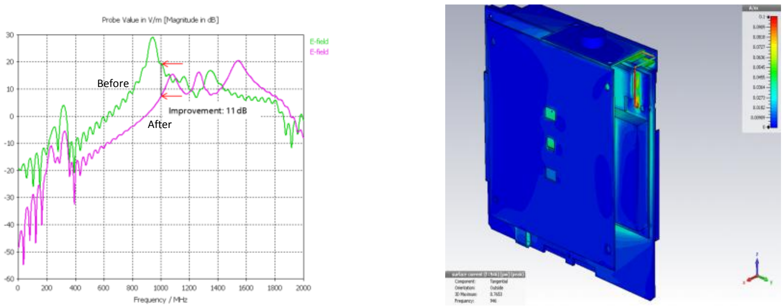
Figure 38. Examples of investigation of EMC design using circuit modeling.

3.4.4.4 Visualisation of resonances

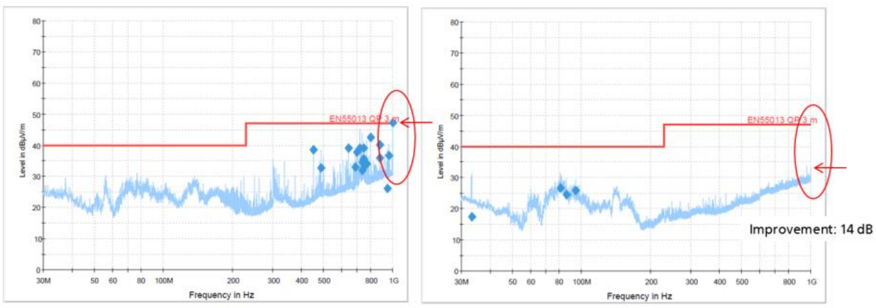
The resonance is found by stimulating the structure with a plane wave and measuring the electrical field with a probe.



The simulation result before and after the modification. Visualizing the surface current on the model.



The result of a radiated emission test (3 m SAC) before and after the modification.



The figures show how a simulation tool can be used to visualize a structure resonance making it easier to understand and solve the problem.

In this case a resonance close to 1 GHz gave a problem in the radiated emission test.

Figure 39. Examples of visualisation of resonances using circuit modeling.

3.4.5 Procedure

The simulation method is described in chapter 3.3. In this chapter we will just emphasize that a simulation tool is like a calculator. It does what you ask for, so if you input is wrong the results will also be wrong, which is illustrated in the wide used phrase: Garbage in, garbage out (GIGO). It requires an understanding of the numerical methods and electromagnetic in order to do simulations.

3.4.6 Investment

The price range for simulations tools are from free download on the internet (basic simulations with a poor user interface) up to $100.000 for more advanced commercial solutions.

3.4.7 Summary

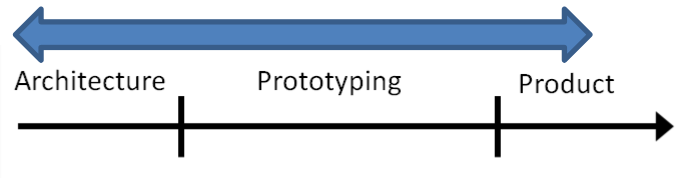
Handled with care simulations are a useful tool that often is faster and cheaper compared to measurements and mock-ups. It gives the engineer an understanding of electromagnetic involved in the problem.

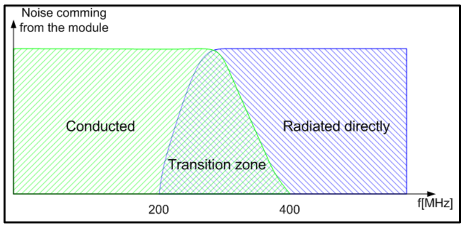
4 System integration

4.1 General system integration aspects

Per Thåstrup Jensen and Anders P. Mynster, DELTA

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: Full frequency range

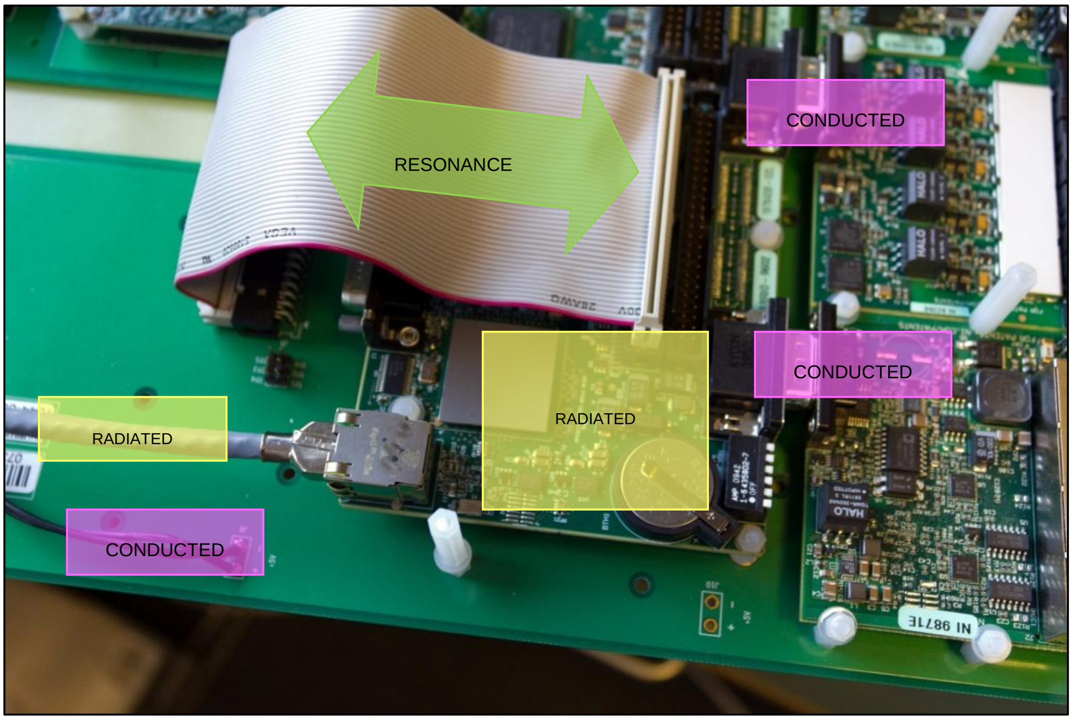


Figure 40. Radiated and conducted signal paths on a subassembly consisting of multiple PCB's

4.1.1 Introduction

The EMC First Time Right has produced a number of tools and analysis activities, which all contribute to the project goal: the design and integration of several modules into an apparatus, which will meet the EMC requirements at first glance. However it is a multi-discipline activity to manage all of the tools and techniques developed during the project period. The following chapters will provide information on the more important topics in the system design phase.

4.1.2 EMC Challenge

The challenge in EMC system design is to acquire and utilize efficient information about the EMC properties of the system components.

It is unlikely to perform an accurate estimation of the EMC properties of a system, if the accessible EMC data are not accurate, and if the data are used out of the context, in which they were obtained.

4.1.3 Procedure

A number of important topics are discussed in detail in this chapter. The descriptions are mainly text, and all subchapters contain a list of recommendations for improved EMC design. Illustrations and more details on the topics and mechanisms regarding the detailed EMC challenges are given in the remaining chapters of this report.

4.1.3.1 Power supply properties

The power supply is the connection between the mains supply network (if any) and the low voltage electronics of the construction.

The emission properties of the power supply are relevant for both the conducted emission properties and for the radiated emission properties (at least up to some hundreds of MHz).

The power supply can be an external unit, which is only connected to the mains and to the equipment via cables. Or it can be a separate PCB, a module or an area of a main PCB, which is integrated into the equipment.

EMC properties of the mains filter:

- The filter must provide low impedance between the lines and chassis. As the capacitance between the AC mains lines and the chassis can be maximum 1-5 nF due to leakage current considerations, it is important that the filter components are connected via very short leads or mechanically wide connections having a low inductance. This also applies, if a metal chassis or a ground reference plane (for instance a ground plane on the PCB) is used.
- If a non-conducting chassis is used, the EMC properties of the power supply rely solely on the common mode impedance of the power supply. This impedance is usually high in the frequency range below 10 MHz, where the galvanic isolation provides a capacitive impedance of a few nF. In order to maintain the high impedance at higher frequencies, the CM chokes in the power supply circuit must be designed to provide high impedance over a wide frequency range.
- The mains filter has influence on the conducted emission/immunity and on the radiated emission/immunity in the frequency range up to around 300 MHz.

Common mode attenuation of the power supply:

- The ability of the power supply to attenuate common mode currents relies mainly on high CM impedance.
- If the module or equipment is equipped with a metal chassis, it is possible to improve the common mode attenuation of the power supply. However, if no chassis is available, unwanted current cannot be transferred to a reference surface.
- The common mode attenuation or the common mode impedance can be estimated using the WBFC setup or a current probe setup in conjunction with an RF test generator. These tools are described in separate chapters of this guideline.
- The mains filter has influence on the conducted emission/immunity and on the radiated emission/immunity in the frequency range up to approx. 100 MHz.

Modules having direct DC power supply input:

This applies to modules or equipment that does not have a galvanic isolation barrier between the power source and the equipment/module.

- The equipment must be designed, so it meets the requirements for conducted emission/immunity directly on the DC power input terminals. There is no power supply to provide attenuation of excess conducted emission or conducted disturbances from the surroundings.
- The module must also withstand voltage transients directly on the DC power input. Arrestors or protection devices must designed for the power- and current pulses due to the transients.
- If a dedicated DC/DC power supply is used, verify if it is equipped with galvanic isolation between primary and secondary side, as this has direct impact on the common mode attenuation properties.
- The DC power input has influence on the conducted emission/immunity and on the radiated emission/immunity in the frequency range up to 100-300 MHz.
- The DC power input has influence on the immunity to transient voltages (burst, surge etc.).

Magnetic components, transformers and chokes:

Magnetic components are not ideal, and may be the source of stray magnetic radiation in the working frequency and its harmonic frequencies.

- Near-field scanning data will show where areas of high field strength levels are located. Avoid running PCB tracks, cables, cable bundles parts of other circuitry near such area (a separation distance of 30-100 mm is recommended, dependent upon the source).
- The windings of transformers can be a source of electromagnetic fields due to a high dV/dt drive signal on the windings.
- As described in the chapter on near-field scanning, the radiated magnetic field may have a very complex radiation pattern.
- The magnetic near-field usually decays very rapidly with increasing distance from the source.
- The magnetic or electrical radiation from magnetic components has influence on the field emission at frequencies below some MHz, but coupling to wires can also be the source of differential- and common mode conducted emission disturbances in the frequency range up to approx. 10 MHz.

Earth connection:

Protective earth wires (yellow/green wires) cannot be expected to have any positive impact on the EMC properties of the power supply. The wires serve only electrical safety purposes.

Ground plane on the power supply PCB:

The ground plane of the PCB is usually not a full plane, as the electrical safety requirements impose the need for a mechanical distance of some mm between primary and secondary circuit parts.

- It is important to have a ground reference plane or –surface on either side of the galvanic isolation barrier.
- It is an advantage for the EMC design to establish a low impedance connection (such as using numerous metal spacers, screws or ground connections) between low-voltage ground planes and the metal chassis parts (if such parts are available). The ground connections will reduce the risk of RF voltages between the ground plane and chassis parts.
- The risk of PCB ground plane self-resonances are greatly reduced by using more chassis connections.

- The mains filter has influence on the conducted emission/immunity and on the radiated emission/immunity in the frequency range up to approx. 100 MHz.

Heat sinks:

As part of the electrical safety requirements, heat sinks are often connected to earth via a PCB- or wire connection. However the heat sinks may still carry high, impulsive voltages due to parasitic capacitive coupling from the power components. This can result in electrical near-field radiation at the working frequency and its harmonic frequencies.

- Near-field scanning data will show where areas of high field strength levels are located. Avoid to route PCB tracks, cables, cable bundles or parts of other circuitry near such areas (a separation distance of 30-100 mm is recommended, dependent upon the source).
- The radiated emission from heat sinks is usually electrical emission, and can be regarded as capacitive coupling between the heat sink body and the surroundings.
- As described in the chapter on near-field scanning, the radiated electric field may have a complex radiation pattern. If the generated frequencies are below 100 MHz, the radiated emission from heat sinks usually does not contribute to the emission levels measured at a distance of 3 or 10 m.
- The electric near-field usually decays more slowly than magnetic near-field with increasing distance from the source.
- The electrical radiation from heat sinks has influence on the field emission at frequencies below 100 MHz, but coupling to wires can also be the source of mainly common mode conducted emission.

Overvoltage protection:

The ground plane of the PCB is usually not a full plane, as the electrical safety requirements impose the need for a mechanical distance of some mm between primary and secondary circuit parts.

- Use the guidelines or rules of thumb provided by the component manufacturers on how to design the protection.
- Simulate the protection circuits using Lt Spice or other circuit simulation software packages. Use source impedances of 50 Ω and 1-5 Ω for the disturbance transients (both for the common mode- and the differential mode impedance of the disturbance sources).
- Remember that metal oxide varistors (MOV's) and suppressor diodes may have an inherent capacitance of some nF.
- Overvoltage protection components usually do not have a strong influence on the emission properties of the equipment.

4.1.3.2 Combining EMC data from near-field scanning of modules

In the present report, near-field scan data are collected from scanning of the surfaces of electronics modules. Even subsequent to a severe data reduction, the amount of data is still very large (som GB of data). Within the project period, it was still not simple to combine emission data from several modules using EMI simulation software. Numerical solutions to the combination of several modules are not readily available. However, from the near-field scan data, useful information can be retrieved. In the following a few rules of thumb for evaluation of the near-field data are given.

Hot spot evaluation:

- Scanning at a very small distance from the module will provide field strength amplitudes that may appear high (the reactive near field region). However, by repeating the scan at larger or smaller distances will reveal if the observed emission decays slowly or rapidly. Detailed information is given in the chapter on near-field scanning.

- If the field strength changes rapidly, the field strength contribution can probably be left out of consideration. Use an initial scan distance similar to the typical distance to surrounding modules or circuit parts. Field strength levels below 1 mA/m (60 dBµA/m) usually do not contribute significantly to the emission levels measured at a distance of 3 or 10 m.
- Avoid to route cables or circuit parts through an area having large amplitudes of magnetic or electrical field strength.
- Passive module parts such as metal support structures etc. can pick up and re-radiate emission if they are placed in front of an emission hot spot.
- Heat sinks can be temporarily removed for the purpose of evaluating if they contribute to the radiated emission.

Shielding parts:

- The project has concluded that emission data from modules or equipment subparts is of more value if the emission data are recorded on the module or subpart including metal support structures or similar, as these parts may strongly change the radiation behavior of the module.
- Shielding parts that form 'an integrated part' of a module must be included in the testing in WBFC, near-field scanner or GTEM cell, in order to acquire a realistic radiation pattern.
- Cables attached to a module can have a significant influence on the emission parameters for a module. Use investigation techniques such as WBFC, near-field scanner or GTEM cell to evaluate (and minimize) the influence from cables.

4.1.3.3 Selecting shielding material between modules

The shielding properties of chassis material can in general be regarded as a 'perfect shield' if it is constructed from metal. Even thin, vacuum deposited metal layers provide a substantial shielding, at least in the frequency range starting at 10-100 MHz and up to approx. 1 GHz. The shielding performance is usually limited by junctions, seams, openings, holes in the metal shielding or cables routed through holes in the shield.

Unknown emission sources

If the source impedance of the emission source is not known, some guidance can still be given regarding the source impedance.

- In development of the PCB, prepare solder pads around critical areas for applying local shielding that can be added later on if needed.
- Use near-field scan data (manual or full scan data) for identifying potential hot spots.
- If possible, review the accessible near-field scan data, in order to estimate the source impedance of the field source.
- Use formulas and calculations matching the present configuration. Assume that only the minimum calculated shielding attenuation can be obtained in practice.
- If in doubt, assume that the field emission is magnetic field.

Electric near-field sources

Near-field scan data usually comprises only the magnetic field components. A high impedance emission source may appear weak, as only a small magnetic component is measured. If scan data are recorded at several distances, the source impedance may anyhow be estimated from the magnetic field scan data.

- A high impedance electric field source can be shielded using very thin layers of shielding material.
- A high impedance field source is often just a source of capacitive coupling to other radiating structures.

Magnetic near-field sources

Near-field scan data usually comprises only the magnetic field components. If the data are only recorded at one distance, the source impedance can be estimated using formulas comprising the distance from the field source. The field impedance increases at increasing distance from the source. The field impedance is 377 Ω in the far field distance from the source.

- Magnetic emission sources at close distance and at low frequencies can be expected to possess low field impedance.
- Thin metal shields do not attenuate the field very much, as the impedance mismatch between the low impedance source and the low impedance shield surface is small.
- Shielding low frequency magnetic fields requires the use of either very thick, conductive shielding walls or a magnetically permeable material. In either case the skin depth of the material indicates if the material will provide any shielding.
- At frequencies from some MHz and with increasing frequency, the field impedance can be expected to approach the far field impedance of 377 Ω, thus shielding using also non-permeable metal sheet is possible.
- Use available formulas or simulation software to calculate the expected shielding attenuation.

Holes and openings in the shielding

Literature (for instance [1] and [2]) provides formulas and rules for calculation of the shielding attenuation of materials having different types of openings and holes.

- A vertically oriented slit will radiate horizontally polarized electromagnetic field, and vice versa.
- If possible, use 90 deg. Orthogonal orientation of seams and slits on faces of modules placed opposite to each other, in order to reduce the transfer of signals.
- Standard emission- and immunity requirements apply up to typically approx. 3 GHz. Keeping openings and seams shorter than 1/10 of a wavelength would require maximum 1 cm between contact points/screws etc. in order to maintain good shielding.
- In a practical cabinet or construction, the EMI suppression must be established as a combination of shielding and decoupling designs, as neither of the design solutions can be implemented in full.
- Use near-field probes to check all junctions between plates, to ensure an intact shielding.
- Surface treatment as paint, eloxation or similar can lead to non-conducting junctions even if a short distance between screw connections is established. Use a conductive surface treatment.

4.1.3.4 Avoiding cavity resonances between modules

Passive metal parts can in some cases constitute an electrical resonator, which can amplify the electromagnetic field by up to approx. 15 dB. This passive amplification occurs for field components entering the resonance structure. Identifying and eliminating the resonator can be a difficult task.

Identifying a resonance structure

A resonance structure may be present inside the equipment without imposing an EMC problem. If however the structure is excited by emission from the test object or induced electromagnetic field from an external transmitter, both emission and immunity problems can arise.

- Parallel metal surfaces such as shielding walls and PCBs separated by 10-50 mm can potentially form a resonance circuit.
- The resonance frequency can be estimated from the electrical distance between the surfaces.

- If near-field scan data are available, the presence of a resonance structure can be identified from scanning in several heights above the module surface.
- Scanning at a very small distance from the module will provide field strength amplitudes that may appear high (the reactive near-field region). However, by repeating the scan at 0.7 x the distance and 1.4 x the distance will reveal if the observed emission decays slowly or rapidly. The decay is considered slow, if the changes from 1.0 to 0.7 or from 1.0 to 1.4 times the distance shows a change in amplitude of 3 dB or less. The decay is more than 3 dB, the field decays rapidly.

Metal structures having one or more conductive support structure

- If piggy back PCBs or mechanical structures are supported by insulating spacers such as nylon- or plastic spacers, they may form a resonator with the main PCB.
- If possible use metal support connections placed in opposite corners of the PCB.
- If possible also add at least one conductive connection near the center of the PCB.
- Avoid routing of cables or circuit parts inside a potential resonator.

4.1.3.5 PCB resonances

Individual PCBs may act as resonators. Surface waves across the PCB (length- or width dimensions) can in some cases be excited, and if this is the case, decoupling components on the PCB has no effect on the direct radiation from the PCB, as the ground plane on the PCB is part of the resonance.

Identifying a resonant PCB

- If near-field scanning data are available, a resonant PCB can be identified using the same technique as described for resonant structures.
- Special attention must be directed to PCBs that have none or only one electrical contact point to other structures.
- A potential PCB resonance structure does not necessarily radiated excess electromagnetic field. The PCB must be excited by electromagnetic energy from the electronics on the PCB, before any emission is generated. If possible avoid overlap between identified resonance structure frequencies and system generated frequencies
- A potential PCB resonance can be experimentally damped by adding additional contact points between opposite PCB faces and a common structure (module chassis or another metal structure).

Elimination of PCB resonances

- As mentioned above PCB resonances can be damped by adding additional electrical connections to the PCB. As the ground plane is part of the PCB resonance, the electrical contacts can be made directly to ground areas on the PCB.
- The attachment of additional wires or grounding points can reduce the Q-factor of the resonance, or the resonance frequency can shift due to the additional wires. A frequency shift can be difficult to detect if the excitation signal is only a carrier wave at one specific frequency.
- If possible attach a comb generator producing spectral lines at 1 MHz intervals to selected PCB tracks on the unpowered module, in order to detect any PCB resonances.

4.1.3.6 Awareness on parasitic component properties

During the integration of modules into a full apparatus, it can be difficult to retrieve information about circuit component values for the parasitic interaction between several modules placed in close proximity of each other. A rough estimation of some important elements is given below:

- Regard mechanical connections, wire connections or cable bundles having a length of L mm as inductors having an inductance of 1.5 nH/mm
- Regard metal surface (also if the surfaces are irregular) placed opposite to each other as a capacitor having a capacitance *C* pF per cm^2 of surface area *A* placed at a distance *d* from each other:

$$C = \varepsilon_0 \, x \, A/d \tag{9}$$

where $\varepsilon_0 = 8{,}85 \times 10^{-12}\ \mathrm{pF/m}$. The capacitance for 1 cm^2 surfaces placed 1 mm apart is calculated to

0.885 pF (approx. 1 pF).

- Relative capacitances at other dimensions and other distances can be estimated from this reference point.
- Freeware simulation software such as Lt Spice can be used for calculations on a lumped element model of a system integration using the parasitic electrical properties.
- Using the proper cabling
  The measurement of transfer impedance of cables is described in a separate chapter of this report. The use of proper shielded cables or proper ribbon type cables having sufficiently low transfer impedance is briefly described by the following guidelines.

Shielded cables

- A shielded cable contains an outer shield and an inner 'protected' environment, where the signal wires are routed. Bear in mind that if the cable or the connectors contain openings of some mm in size (for instance at the connectors), the shielding properties are severely deteriorated.
- The shielding property is established by the electrical separation between the inner and the outer part of the cable shield.
- A shielded cable needs a reference surface at the transmission end and at the reception end, for instance of a ground plane, where the connectors shell can be properly connected to the reference surface.
- A shielded cable terminated into a wire of even 1 mm length (a pig-tail) largely deteriorates the shielding performance of the cable.
- The shielding more or less deteriorates at high frequencies (above approx. 100-200 MHz), as the small holes in the woven, braided shield material acts as openings at high frequencies. The use of shielding material with no openings (a metal pipe) is usually unrealistic for cables and connectors.
- Due to imperfections in the geometry and construction of multi-wire cables, a small amount of common mode current on the signal wires may arise from the intended, differential mode signal in the cable (The Longitudinal Conversion Loss, LCL). This occurs even if the signal pairs inside the cable are driven using a 'perfectly balanced' transceiver circuit.

Connectors

- If a connector is unshielded, or is constructed from non-conducting material, only a negligible shielding performance can be expected from shielded cables.
- In order to provide substantial shielding, the connector shell must allow for a 360 deg. electrical connection around the perimeter of the cable braid (shield) and the connector shell.
- Place all connectors on one side of the PCB, in order to avoid common mode currents slowing across the PCB (single point entry).

Coaxial cables

The guidelines for the shielding performance and the use of coaxial cables and connectors are quite similar to those for shielded cables and connectors.

Cable bundles

Cable bundles can contain control signal wires, power supply wires and serial/parallel data transmission wires.

- Cable segregation and separation must be maintained in accordance with the system requirements.
- The wires contained in a cable bundle must be chosen according to the signal transmission on the wires. Care must be taken not to route fast serial communication wires, PWM signals or similar noisy signals together with wires for sensitive analog measurements. Split the cable bundles to a number of sub-bundles, and route the bundles so segregation between source- and victim cables is obtained.

Ribbon cables

Ribbon cables consist of 10-100 or more of parallel, unshielded wires forming a flat ribbon. The cables can be used for single-ended signal connections, where signal- and return wires are typically not balanced. The cables can also be used for transmission of for instance parallel data transmission, where the wires are typically organized in balanced pairs.

- It can be an advantage to allocate signal wire pairs so they are surrounded by one or more ‘ground’ wires on each side of the wire pair.
- The transfer impedance of a ribbon cable can be measured using similar techniques as for shielded cables. The ‘ground’ wires constitute the shield, which however does not surround the signal wire pair.
- Bear in mind that only a modest electrical shielding is provided by the ‘ground’ wires in a ribbon cable. The shielding of wire pairs in a ribbon cable cannot be as high as for a shielded cable. The shielding can be regarded as more or less as relief current path, which prevents unwanted noise current from flowing on only the signal wires.
- Do not use only one ‘ground’ wire in the ribbon cable. Allocate more wires as ‘ground’ wires, and distribute these across the width of the cable.

Ferrite beads for control of common mode current

Ferrite beads can be a tool for controlling common mode currents on bundles of signal cables. The beads allow the transmission of differential mode signals, as the impedance only affects the common mode impedance of the cable passing through the bead.

- Analyze the EMC challenge, before a ferrite bead is added to the cable setup. Ferrite beads represent modest impedance of 100 Ω or in some cases up to 1 k Ω in a smaller frequency range. The impedance of most ferrite beads is less than 100 Ω in the frequency range below 100 MHz. If the common mode impedance of the cabling is already in the range 50-100 Ω, common mode current are only slightly reduced by the introduction of the series impedance formed by the ferrite bead.
- The manufacturer’s data sheets usually provide information about the impedance of the beads. At frequencies above 10 MHz, the impedance is predominantly resistive, and can be compared with a common mode series resistor added to the cable. The resistance adds a lossy circuit element to the cable, and can thus be used for damping resonances.
- Ferrite beads is not a magic tool for removing unwanted emission, but rather an easy tool for adding common mode impedance and/or loss to a cable. If the common mode emission of the cable is already very high, the ferrite bead cannot be expected to provide significant reduction of emission.

4.1.3.7 Using a shielded cabinet

A shielded cabinet can be used for very effective suppression of radiated signals between the equipment and its surroundings. However, in practically all cases the cabinet is equipped with openings, cable connections or junctions/seams between cabinet parts, which deteriorates the shielding performance by the cabinet material. In practice an overall shielding effectiveness of more than 60 dB is extremely unusual, and the shielding may be as low as 20 dB or less. At spot frequencies, the cabinet may provide no attenuation at all, if a cable resonance or an aperture resonance transfers signals from the inside to the outside of the cabinet.

- A well shielded construction requires that no weak point allow flow of signals across the shielding barrier. If the equipment is protected solely by shielding, the entire EMI suppression strategy fails if only one opening, one cable entry or one cabinet junction is weaker than specified.
- As a strategy based upon only shielding is costly and difficult to implement, a combination of decoupling on the PCB and applying a reasonably good shielding cabinet can be an optimum solution.
- Bear in mind that the use of a shielded cabinet also requires that the cable connections are equipped with either RF filtering at the penetration point, or the use of shielded cables and connectors.
- If shielded cables cannot be guaranteed (for instance if the user is likely to install the equipment using unshielded cables), it is recommended also to provide the necessary RF filtering on the cable connections.

4.1.3.8 Visualization of resonances or hotspots

It is important to identify potential emission sources, and to evaluate if the sources are compromising the EMC properties of the equipment or the apparatus. However, it is also important to be able to provide this information to other members of the design team, such as engineers responsible for the mechanical- or thermal design.

A colored plot showing the emission hotspots or the peak emission levels near a resonance structure can be extremely useful for the modification process, when the redesign is initiated. It can be hard for a mechanical designer to understand how a passive support rod or metal structure can have a strong influence on the EMC properties of the equipment. The colored plots are easily understood, although the mechanisms forming the hotspot can be somewhat more subtle.

4.1.4 Investment

This chapter describes a set of topics related with integration of PCBs and subassemblies into an apparatus. No investments are necessary for this activity. If an RF simulation tool, such as CST Microwave Studio, or similar software packages are available, they can be used for visualization of EMC topics in the system integration phase. This requires however that EMI data are available from either simulation of the circuit behavior or from near-field scanning of modules. It seems unlikely that such comprehensive tools are available solely for the system integration activity.

4.1.5 Summary

The present chapter provides a set of checkpoints or guidelines that can be useful for the system integrator and the designers of individual parts of an apparatus.

The guidelines must be used within a relevant context, in order to be useful. Several references are given to other chapters of this document that describe how to provide knowledge and data of the EMC properties of the individual subparts of an equipment or apparatus.

Design activities such as near-field scanning of PCBs or emission pre-testing are encouraged, as the integration of several modules into an apparatus is extremely complex.

4.1.6 References

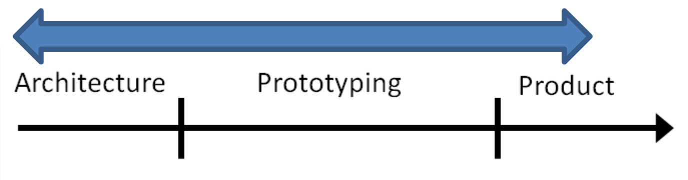
[1] *EMI Troubleshooting Techniques*, Michel Mardiguian, ISBN 0-07-134418-7, McGraw-Hill.

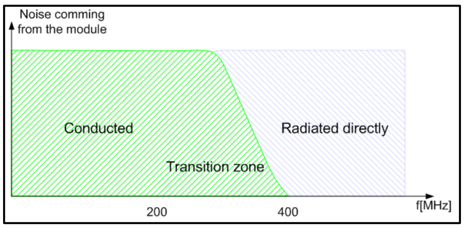
[2] *EMC for Product Designers,* Tim Williams, ISBN 0-7056-1264-9, BH Newnes.

4.2 Choosing the right cables (transfer impedance)

Søren Christensen, Bang & Olufsen

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: Below 400 MHz

Figure 41. Signal cable.

4.2.1 Introduction

The idea of this chapter is to give the reader the possibility to choose and specify the right cable for the job with respect to radiation from the product. And to have the possibility to test the cable later in the development phase to see if it can transfer the wanted signal without radiating to the surroundings.

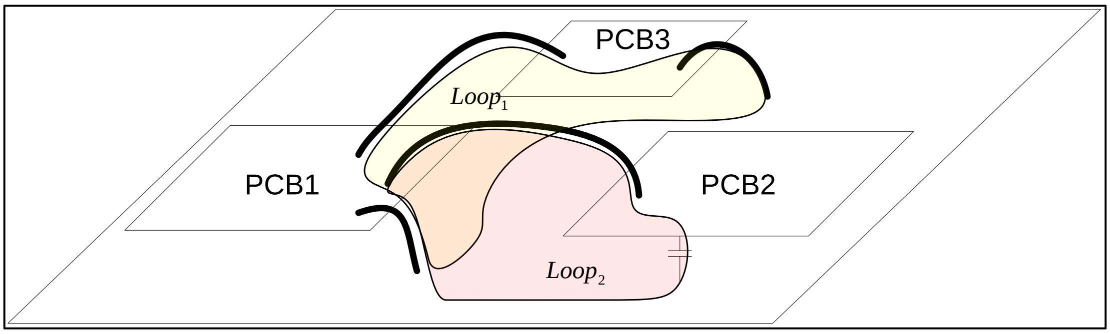


Figure 42. Current loops in the product

Do to transfer impedance in the cables the wanted signal in the cables will drive a current in the different loops inside the product. This is not a problem as long as the current are kept inside the product. If the product is not made inside a metal shield but in a plastic box our experience are that the currents in the loops inside the product have to be less than 3μA.

4.2.2 Radiation from cable

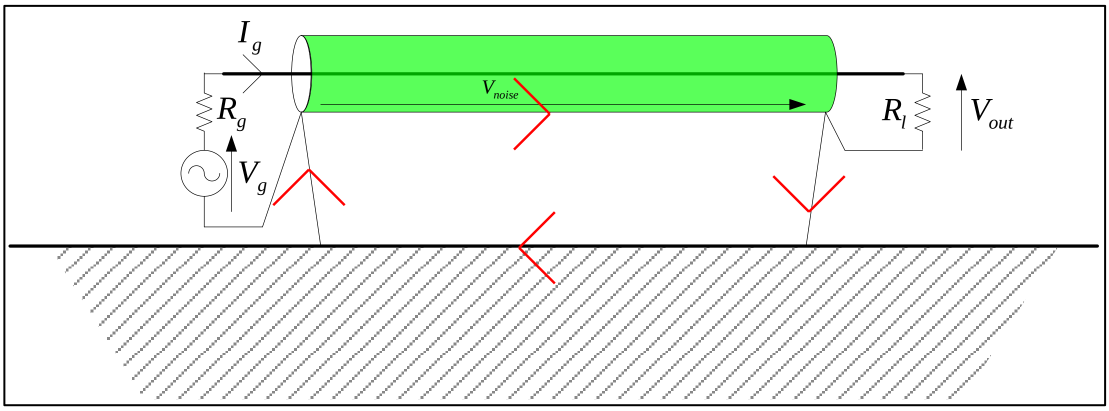


Figure 43. Noise generator in a signal cable.

In figure 2 we have a cable with the wanted signal Vg. This signal will drive a current in the ground that will give a voltage over ground. In this case this is a noise voltage that can drive a noise current in a loop in the product. The transformation from wanted signal current to noise voltage is the transfer impedance of the cable (10):

$$Z_t = \frac{V_{noise}}{I_g} \,. \tag{10}$$

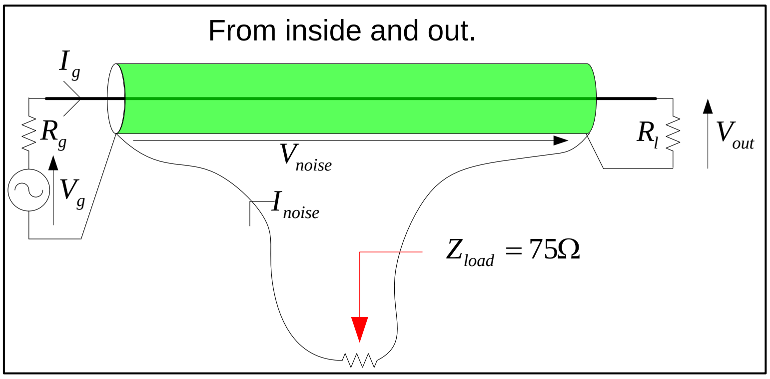


Figure 44 If the noise current 'looks into' a dipole it will 'see' a 75 Ω load.

The noise voltage V_{noise} will drive a current and if this noise current is bigger than 3µA it will radiate to much compare to CISPR 13 in the 3m chamber. We can from this set the maximum noise voltage allowed. If we know V_g , R_g, R_l and Z_{load} we also know I_{noise} .

$$Z_{t\,max} = \frac{I_{noise\_max}(3\mu A) * Z_{load}}{\frac{V_g}{(R_g+R_l)}} \tag{11}$$

So from this we can for all frequencies find the maximum allowed transfer impedance for the cable we use. And therefore very early in the project choose the right cable for the job. We just need a method to find the transfer impedance. We have not seen this from suppliers of cables.

4.2.3 How to measure transfer impedance

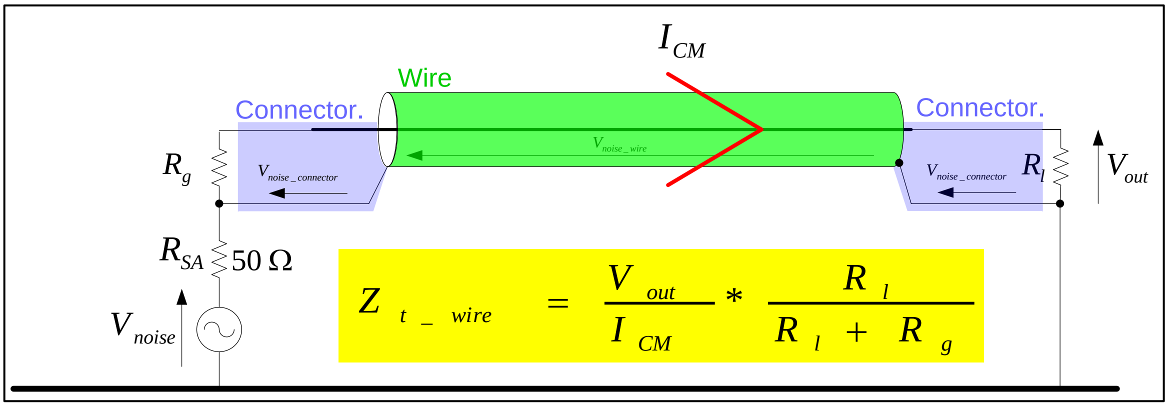


Figure 44. One possible setup for measuring the transfer impedance of a cable.

It is possible to measure the transfer impedance the other way around. We introduce a current in the ground and measure the voltage generated by this current. Remember to measure on cable together with connectors. Many times the transfer impedance of a cable assembly is limited in performance by connectors having poor performance.

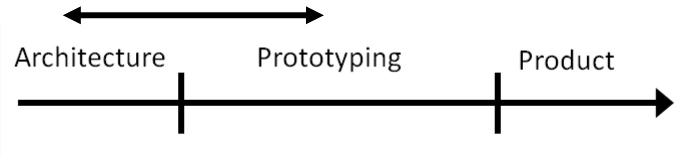
4.2.4 Guide line for cables going out of a module

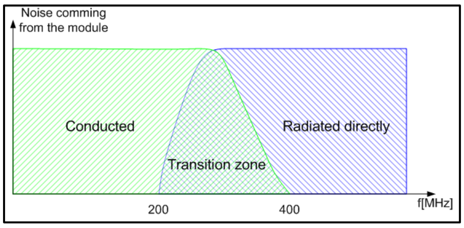
- Find the amplitude at different frequencies on the signals that you want to transfer in the cables in the products.
- From the signal in the cable find the maximum transfer impedance allowed if the maximum noise current is 3µA and is loaded with a dipole antenna of 75 Ω.
- Measure the different cables and find one that has satisfying low transfer impedance.

4.3 Transients. How to design for good burst and ESD performance

Jørgen Selmer Jensen, Bang & Olufsen

Method applicable during development phase:





Project phase: Is good for early design evaluation

Relevant frequency band: Full frequency range

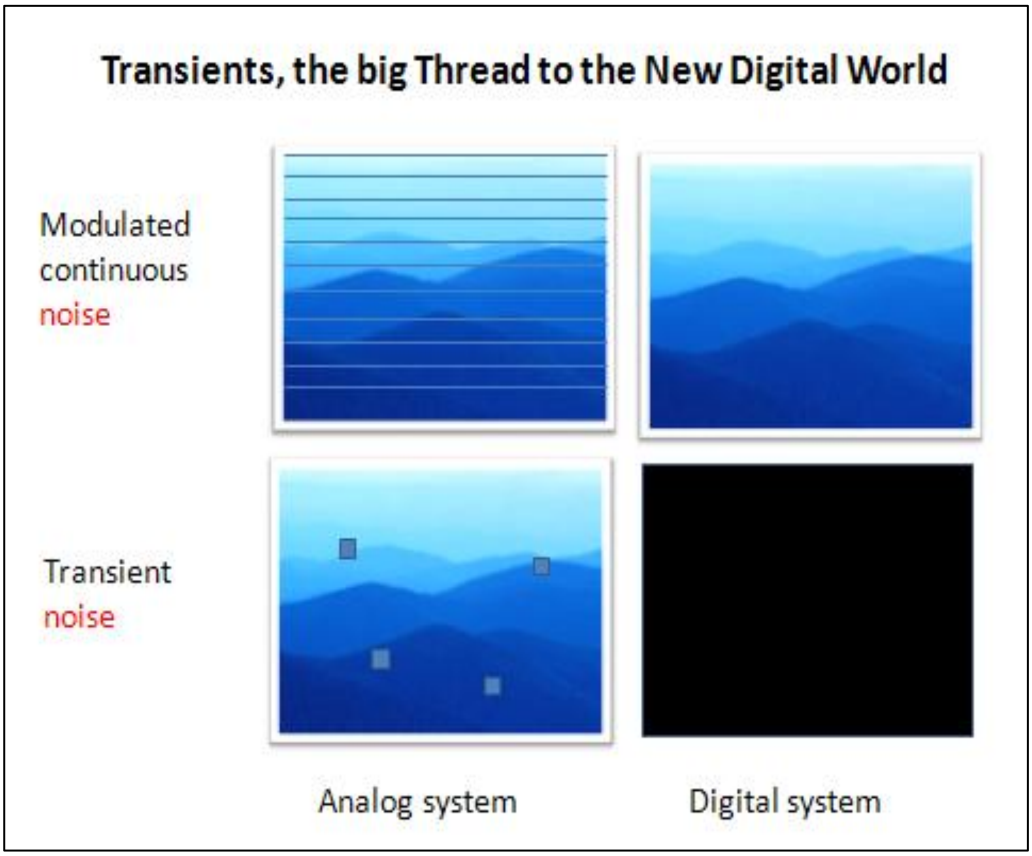


Figure 46. Transient signals may cause severe damage to digital signaling.

4.3.1 Introduction

Transients are the big thread to the new digital time age. This can be illustrated by the 4 TV pictures of the same scene on the previous page.

4.3.2 EMC challenge

In the analog time age the big thread was interference with modulated continuous noise. Of course transients also interfered, but the interference disappeared immediately the transient stopped. Digital signals are much less sensitive to continuous noise but transients can bring the data stream out of order and the result is major disrupt of picture, sound and control meaning no picture.

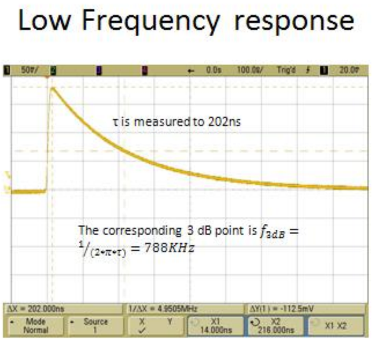
4.3.3 Procedure

The new things are:

- We can measure the transients.
- We can calculate on the stuff.
- We can make proper design in this field (architecture).

Basically this presentation deals with moving the handling of transients from the 'magic and mysterious' to a basic engineering discipline.

4.3.4 To measure using a current probe



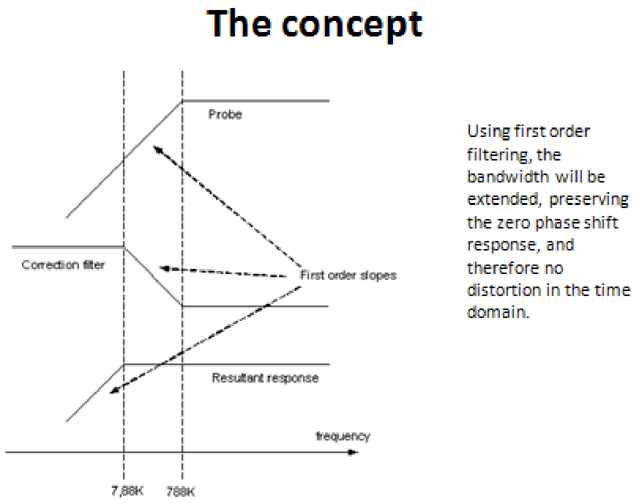
Conclusion:

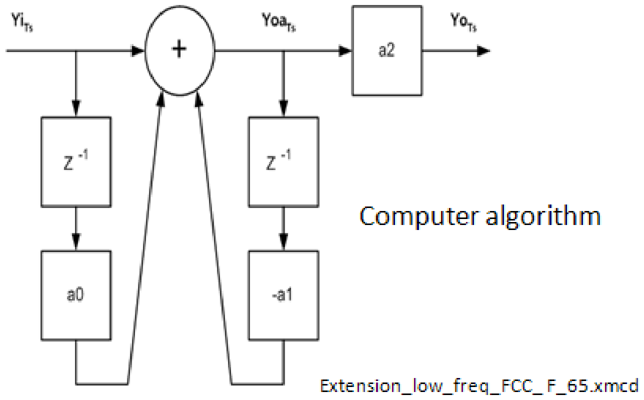
The probe exhibits properties making it suitable to real time measurements of Burst and ESD.

Figure 47. Measuring the time domain response of a current probe using a test fixture.

The probe behaves like a first order high pass filter with 3dB cut off at 788 KHz. These parameters must be considered whenever evaluating the measurements results. It would be an advantage to have a SW tool to enhance the low frequency range in order to cover the low frequency range of Burst and ESD currents whenever precise measurements are needed.

4.3.5 Extension of the low frequency range





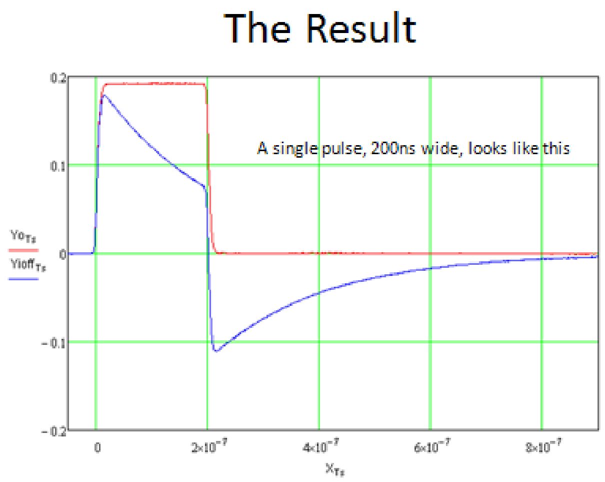


Figure 48. Correcting the low frequency current probe response using filtering algorithms.

4.3.6 Design for Burst Performance

This session takes us through the demands to bust and how to make proper design to cope with burst. But also a lot of effort is made to show that we can measure and simulate on burst. If we by simple measurements and simple simulation can describe what is going on, then we are equipped to find the 'intelligent' solutions where we get the maximum benefit for a minimum of effort.

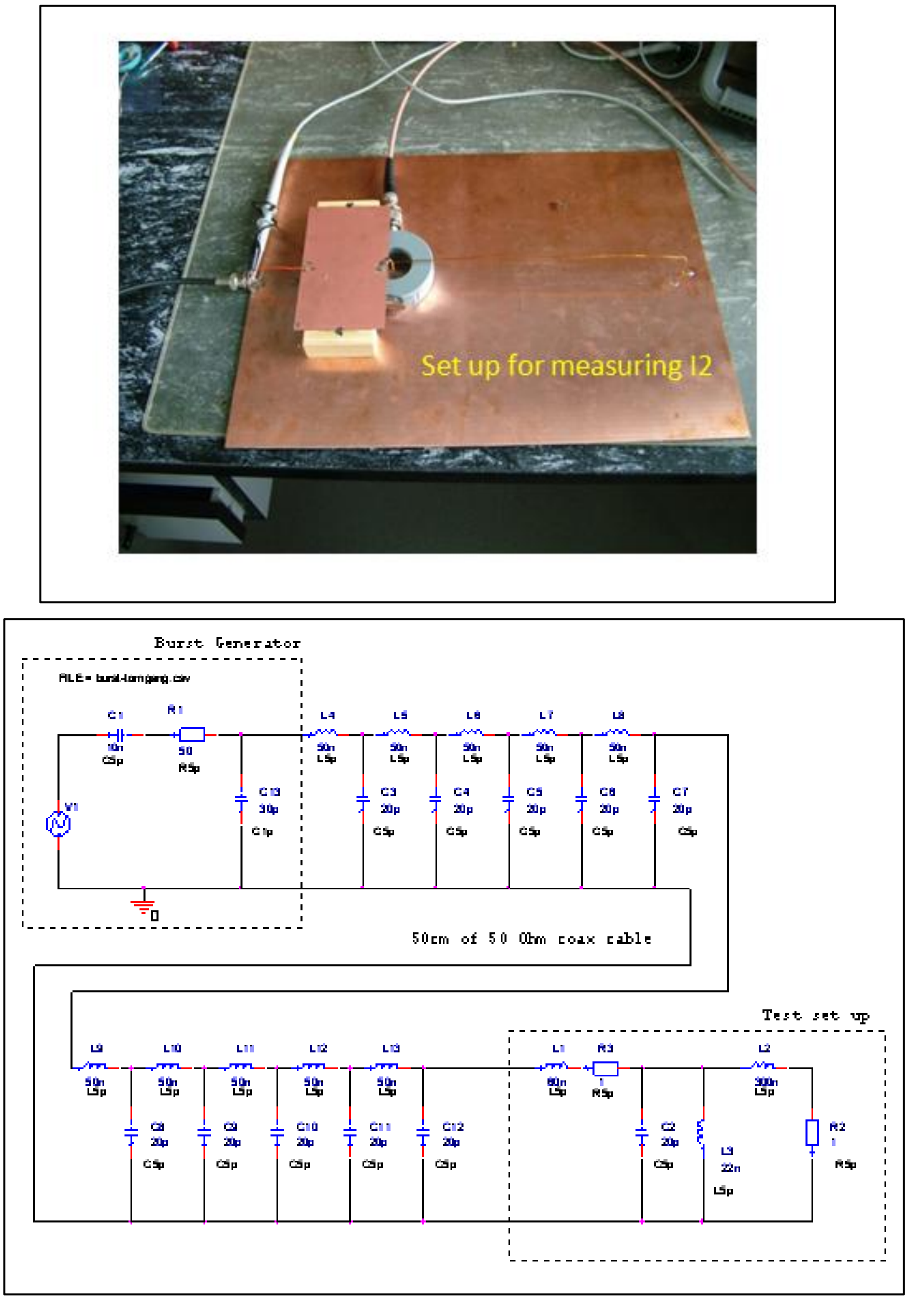


Figure 49. Setup and circuit modeling of current probe response.

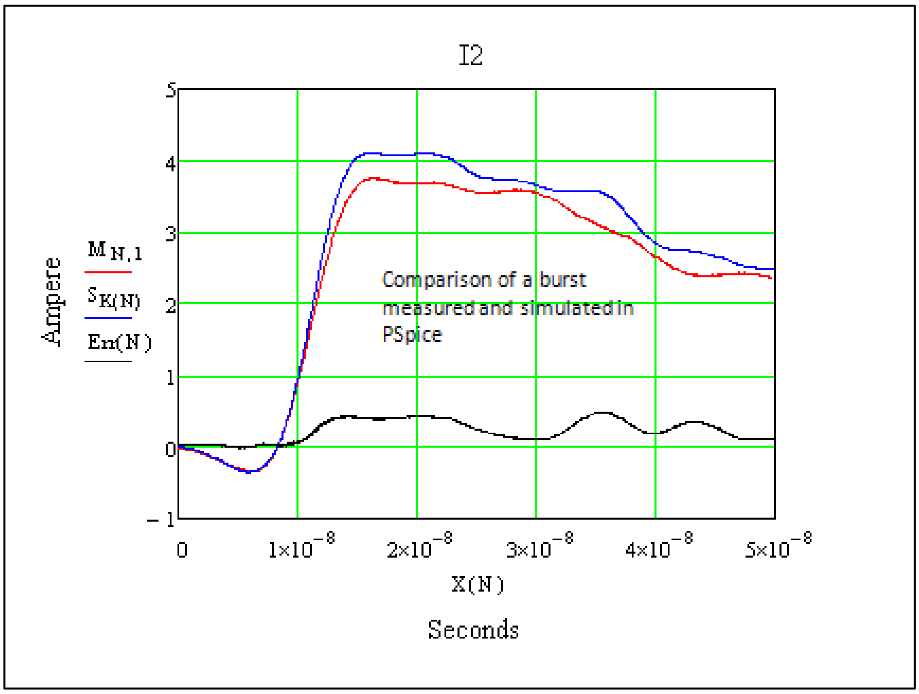


Figure 50. Setup and circuit modeling of current probe response.
The blue curve is simulated.
The red curve is measured.
The black curve is the difference between simulated and measured.

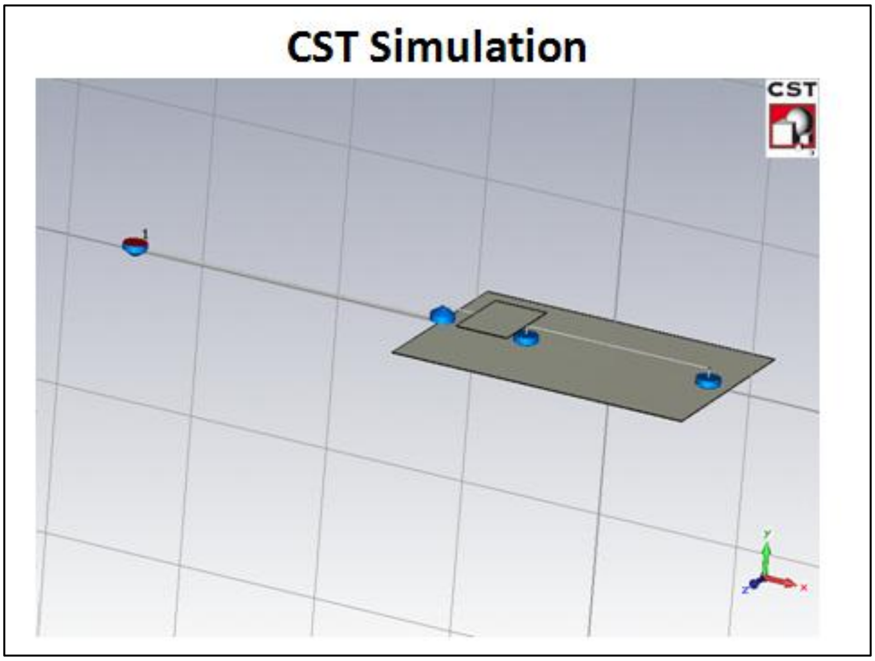


Figure 51. Model of the circuit using the CST software model.

4.3.7 The conclusion of measuring and modeling

We have a model of the burst generator usable for CST and PSpice simulation and a method for making thrust worthy simulation in both systems. Also we have a method for architectural design for bust handling. Furthermore it has been proved that we can measure the burst current by using the current probes available on our premises (B&O).

4.3.8 ESD

Using this set up we can measure that there is a difference in a positive and a negative charged ESD spark.

A needle is mounted on a large copper surface below the probe as shown.

The current from the ESD spark passes through the needle and through the probe and the probe measures the ESD current. The gain of the probe (the transducer factor) is 1 Volt per Amp (1 Ω).

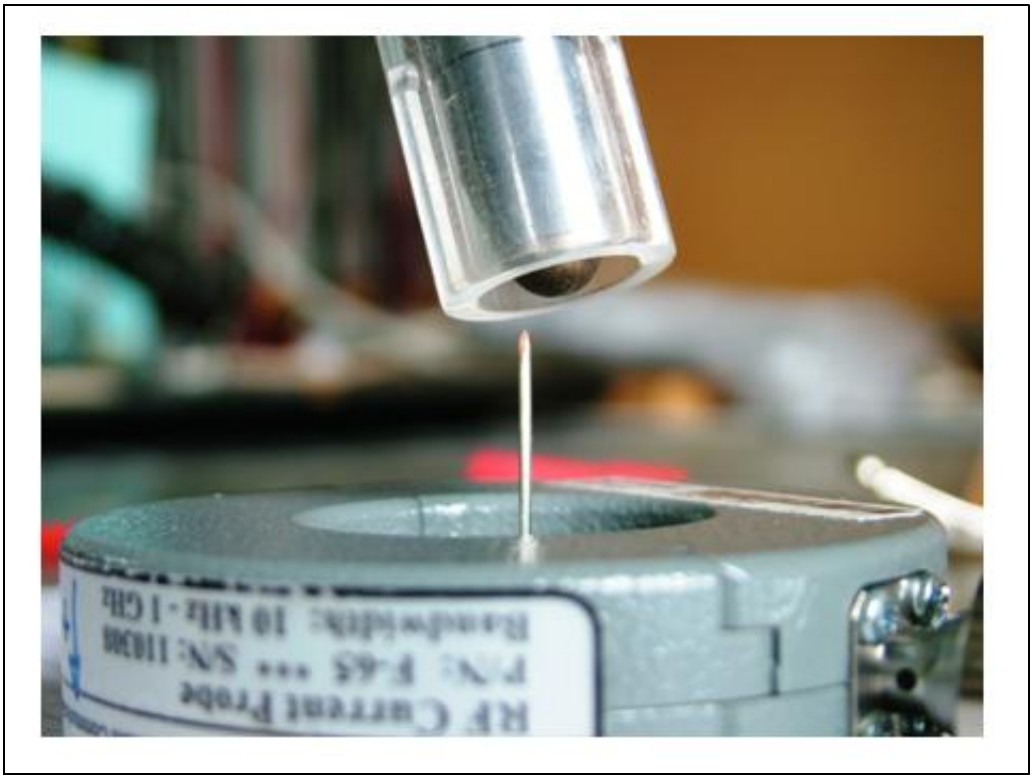
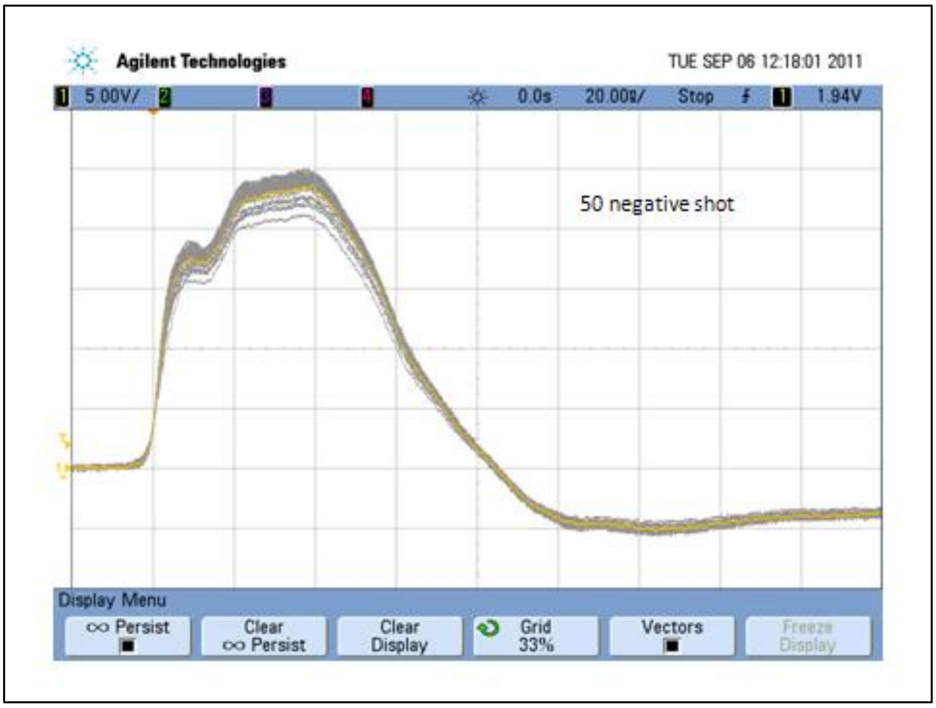


Figure 52. Practical test setup showing the tip of the ESD generator (above), the discharge pin (center)and the current probe measuring the current through the pin (bottom).



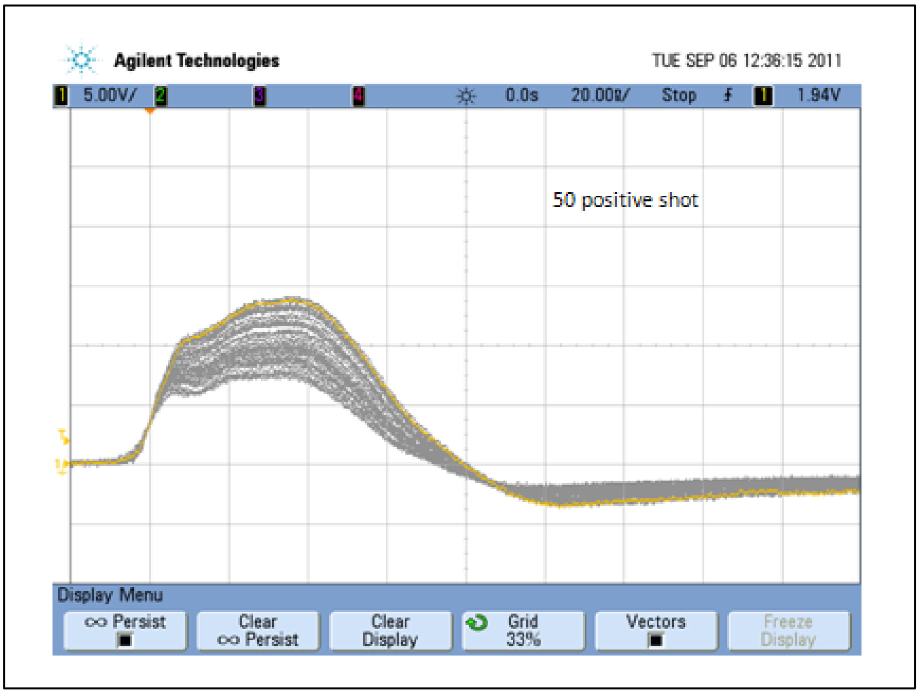


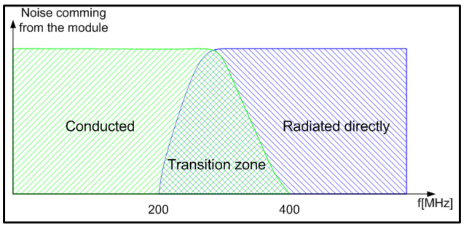
Figure 53. Curves showing the current resulting from 50 negative discharges (upper) and 50 positive discharges (lower)

4.4 EMC Expert systems, locating errors in the PCB design before the prototypes

Knud Møller, kk-electronics

Method applicable during development phase:

Project phase: Is good for early design evaluation



Relevant frequency band: Full frequency range

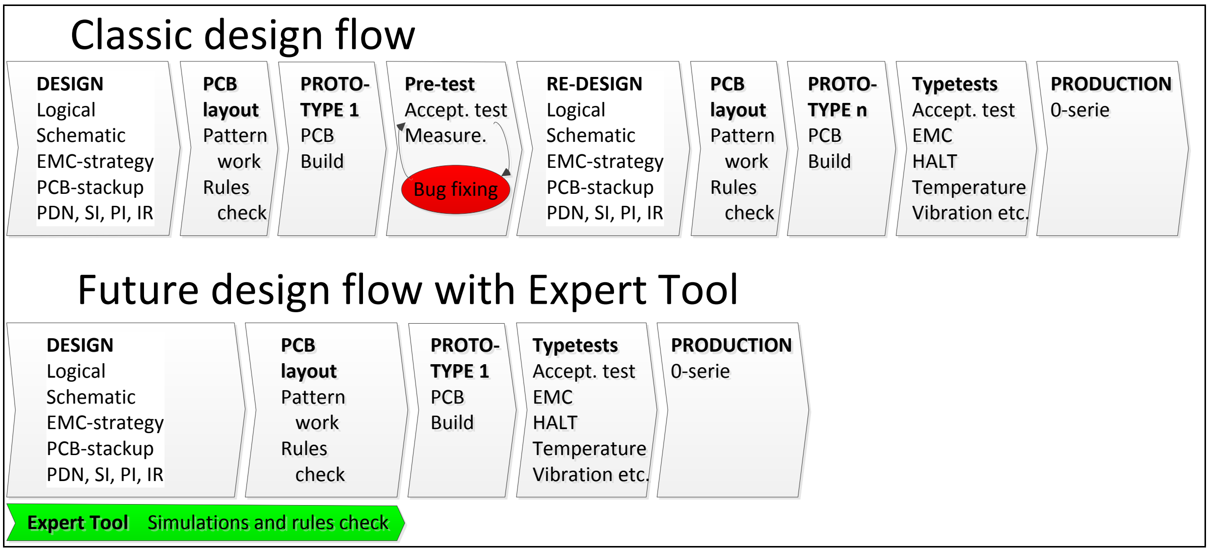


Figure 54. EMC design workflow illustrated with and without the use of EMC expert tools.

4.4.1 Introduction

Driven by goals as lower cost, higher speeds, higher capacity, we see die shrink, lower supply voltage and more complex electronic designs. Lower supply voltage leads to less margin left for power and signal levels. Die shrink leads typical to shorter rise and fall times. Higher complexity leads to more nets and connections in the same or less space. All these trends are typical not followed by matching lower power consumption. The trends lead to a growing set of rules and a higher number of individual rules checks necessary for meting internal functional demands and external demands (EMI and EMC).

4.4.2 EMC challenge

In complex designs, compromises is part of the game – the challenge is to find the set of compromises that leads to lowest cost and in the same time secure sufficient margins with respect to functional and legal demands.

1. Keep sufficient margins (functional and EMC) without over engineering.
2. Meet the marked in shorter time.
3. Cut risks and cost in development face.
4. Cut the number of layout cycles in development.
5. Reduce BOM.

Testing more different set of compromises in real hardware is very time and resource demanding. Tools able to answer 'What if' questions fast, not necessary 100% exact can help the engineer finding the best set of compromises with respect to BOM and margins, in a reduced timeframe. To help the engineers not to struggle in rules checks and to make smarter solutions, a demand for tools able to manage high number of constraints and able to perform fast rule checks, and ranking of discovered problems is essential. If identification of EMC problems in an early stage is possible, development time and number of prototypes can be reduced significant.

4.4.3 Procedure

4.4.3.1 Expert systems algorithms

Estimating EMC performance for a PCB board in the design phase is complex and requires huge data for describing the product (PCB). One big question: Is the existing algorithms able to predict EMC performance? To answer this question, the consortium has made some simplified tests. Algorithms, available from Clemson University are used to calculate expected maximum EMI values for a simple test board holding a generator and a single trace. By comparing estimated and measured results it is demonstrated that the algorithms is useful for predicting possible EMC problems, however no one should expect exact calculated values for radiated EMI from the apparatus.

4.4.3.2 Using expert systems

Exact Calculation related to EMI simulation requires huge data inputs and it requires CPU power. As with many other complex systems, the quality of data coming out depends on the quality of the data feed in. Even with high quality data input, do not expect exact calculated EMI values, but you should expect the opportunity to do EMI optimization at an early development stage, before investment in real prototypes. Most of the changes for EMI optimization is almost free to implement before the prototypes are made since it most involve floor planning, re-routing of traces and changing layout in ground planes power planes and the stack up. When and who do the EMI optimization in the development process?

When development is done without using expert system for EMI calculation, the hardware responsible engineer has to in a partly manual way to take care of power distribution network, power integrity, signal integrity, heat/temperature rise etc. The tasks is done before layout and includes instructions to layout, and partly again during layout and after layout is finished (often as reviews). The process includes a number of calculations and many boring time consuming checks against preselected rules. If the pre-layout work is done poorly, it may lead to redoing parts of the layout before it is send to fabrication, or a bad product if errors are not discovered before production. EMI optimization is often not finished when the first prototypes is present. Based on measurements followed by analyze, fixes is tested on the prototypes and new prototypes are build. This process may take place more times until requirements are met.

How can expert systems change the development process?

The same tasks, has to be done. After feeding a lot of data, describing the components and nets plus rules setup, the expert system is able to do the boring checks and calculations fast. The expert system also gives access to estimated values regarding radiation, power and signal integrity and heat. Possible problems, is reported and ranked.

Time from optimization idea to simulated test is short compared to building and modifying hardware prototypes. It is a more efficient way to optimize for meeting the demands in the smartest and cheapest way (This is what the expert system builder's claim).

The expert systems can help to move the engineer's effort and focus from boring rule checks to product optimization, and closer to the goal 'First time right'.

Learning how to use expert systems:

First, expert systems is a tool that can organize and perform rule check and calculate, identify and rate possible EMC, SI, PI and heat problems. Engineers cannot be substituted by any expert system, but they can have great help from it. The user must have the deep understanding of the product under development.

One way to start learning how to use an expert system, is taking one for the engineer well known product, and make the first calculations on this. A lot of data has to be collected, and you should not expect that all models are available. Modifications to existing models may be needed.

Calculated and measured signals have to be compared and modifications of component models may be necessary to archive matching simulation results. Useful EMC estimations cannot be expected before signal integrity results from calculations and measurements match.

Component database and models:

To be able to simulate/calculate EMC behavior, the model must describe the active part of integrated circuits as well as the package and bonding inside the package. Available models do often describe the component as seen from the package pins.

PCB – description:

Expert systems are able to import PCB structure data direct from layout system data files.

Some systems are able to simulate on the designs even before routing is finished. (Part of floor planning and rule setup process).

Tagging and Rule setup:

Tagging is used to describe which rules/checks have to be done on particular nets. Constraints describing frequency, max length, impedance etc. are tagged on the nets in design phase. The amount of data can be quite large. Data is typical represented as tables in *.xls. Common definition of constrains for group of net are used.

Data handling and calculation amount:

No system is able to do exact estimation even if the models and structure descriptions are very detailed, and you are ready to wait for the results. On that background, all systems do use a reduced/selected set of rules and simplified algorithms to achieve acceptable response time and results that have value compared to the effort needed for data collection and calculation.

Tools overlap:

More EDA tools for schematic and layout do already have some rule checks related to the layout process. There can be overlap with the expert systems; however the same check may be made in an earlier stage of the process if expert system is used. In some EDA tools custom checks can be programmed and thus some of the rule checks in the table below can be programmed directly.

4.4.4 Investment

The expert systems are relatively expensive compared to other tools in the business (schematic and layout tools). Due to the fact that the systems are relative young, they are still added new and improved functions, and this leads to relative high upgrade rates. Systems is offered from about $25.000 and up, including one year support and update service - annual upgrade and support is typical up to 50% of the price for the tool. (OBS – most tool vendors offers a range of 'add on' packages. Final price depends of selections. On top of the tool's investment, initial education, after education, time spend on collecting/building model and rules library can be as costly (or more) as the tool itself.

4.4.5 Evaluated expert systems

In this project we have had a look at the following systems

1. EMSAT (IBM) – Trail version tested (Sept 2010).
2. EMIStream (NEC) – Evaluation version 4.2-002 tested (Nov 2010..Jan 2011).
3. CST STUDIO SUITE 2012 – Prospect study and webinar (March 2012)
4. Cadence layout – Prospect and EDA support interview.
5. Free tools

4.4.5.1 EMSAT (IBM)

The EMSAT tool package can help, to check and verify very complex printed circuit boards (PCB's) which is buildup of many layers and nets. Such PCB's will often contain complex circuits and very fast switching signals ex. adr.-/data-buses, communication lines, oscillator lines etc. These circuits implemented in complex PCB stack-ups can be almost impossible to check 'by hand', and it is essential that the layout is made optimal to reach the targets regarding EMC demands. To check such layouts I think EMSAT will be of great help. All layout tools, holds a sort of design-rules setup and these rules can be quit complex. The EMSAT check rules can be characterized as further extension of layout rules particularly focused on EMC properties. You have to be familiar with the tool, setup and functions to get the advantage of it (as it is with most tools). One of the tasks which are quit time consumption, is to put the characteristics of the circuits/components into EMSAT, also called 'tagging'. But this tagging procedure is one of the items which will be handled and improved in the coming version. The distributor, Moss Bay EDA, Gene Garat, is very forthcoming and willing to help. He has been in the EDA business for many years.

4.4.5.2 EMIStream (NEC)

EMIStream was created by engineers at NEC facing real world EMI problems. It was started in 1994 and is still being developed. EMIStream is an EMI suppression support tool that can decrease undesirable EMI generated from PCB at an early design stage. EMI Design Rule Check scans your board against 13 rules and lists errors in order of priority allowing time efficient noise countermeasures. Power Plane Resonance Analysis shows you the hot spots on the board enabling optimized capacitor placement to reduce resonance. The tool uses Spice models for EMI estimations. EMI estimations are made individual for each net. Problem nets can be highlighted in graphic presentation. Initial EMI estimation can take place before layout – as part of floor planning process. EMIStream is not widely used in Europe. But they have customers of International Corporation, which have sites in Europe and using it.

4.4.5.3 CST STUDIO SUITE 2012

CST BOARDCHECK is at tool like EMIStream and EMSAT. The tool is one of several tools from CST. The tools are integrated into a user friendly environment, and connect well to Cadence schematic and layout tools. The tools look (from prospect and testimonials) serious. We have made no hands on test of this tool. It looks like a tool worth looking at, especially if the interest is for high end expert system. Since CST also provides 3D EM simulation, a full package of tools can be bought from one vendor.

4.4.5.4 Cadence layout

This tool holds a limited number of rules check facilities (see the table later). It is in no way an expert system but brought in just to illustrate that some of the rules handled by expert systems is part of layout systems today. EMI estimation is not part of the tool. Cadence offers other tools for Signal and Power integrity analyzes and simulation.

4.4.5.5 Free ware tools

Tools covering parts of the design process are available from electronic part vendors and from others (University's, education vendors etc.) No free tool cover the overall challenge regarding EMI radiated from PCB's, but typical one subject i.e. simplified PDN calculation. The tools can in a cheap way, lead to better understanding of what to do and not to do, regarding a specific subject. We have used PDN tool from Altera, it is easy to learn and easy to use, and deliver useful results in a simple way.

4.4.5.6 Tools Comparison

Each of the 4 tools cower a set of functions and rules check. They do not cower exact the same. We have tried to compare anyway, just to give a rough idea of the differences of the tools.

Subject	A EMIStream	B EMSAT	C CST PCB STUDIO	D Cadence Layout
A Return current Path Discontinuity	X		X	(X)
B Net crossing split		X	X	
A Reference change	X		X	X
B Net Changing Reference		X		
A Traces near Plane Edge	X			(X)
B Net Near Edge of Reference		X	X	
B Critical Net near I/O Net		X	X	
A Trace length	X			X
B Exposed Critical Trace Length		X	X	
C Net Coupling			X	
C Net Stub			X	
C Between ref plane routing			X	
A Critical Net Isolation		X	X	
C Via integrity				
C Unconnected via pads			X	
C Via clearance overlap			X	
C Via net coupling			X	
C Via Stub			X	
A Differential Signal	X		X	X
B Critical Differential Net Isolation		X	X	
B Critical Differential Net Matching		X	X	
B Wide Power/Ground Traces		X	X	
A PI-rule, 'Expert' option	X			
B Decoupling Capacitor Density		X	X	
A Decoupling Capacitor	X			
B Power Pin Capacitor Distance		X	X	
B IC Power/Ground Pin-Via Distance		X	X	
B Decoupling Cap Distance to Via		X	X	
B Power/Ground Trace Decoupling		X	X	
C Power via's			X	
C Power via Density			X	
C Decupling capacitor density			X	
A Filter	X			
B I/O Filter Distance		X	X	X
B Distance from Oscillator to Clk.Driver		X	X	
A Via Count	X			X
A Signal Guard Trace	X			X
A Estimated Radiated Emissions	X		X	
C Estimated Conducted Emissions			X	
A Signal Guard Via Spacing	X			X
A Grounding Via's Along Plane Outline	X			X
A X-Talk	X		X	X
C Power integrity IR–drop analysis			X	
C Power plane impedance analysis			X	
C Signal integrity analysis			X	
C 3D full wave post layout analysis			X	
C Tool ready for cluster and multi user			X	

Table 5 Comparison of EMC design software tool capabilities during the period of the literature study.

4.4.6 Conclusion

The Expert tools cannot be expected to be able to calculate the radiated emission accurately. However, it is the experience that most critical layout errors will be discovered, and over engineering eliminated. Since the changes do not imply significant costs the effort can be recommended. If the engineer and layouter are well familiar with the rules in the table above, little benefit can be drawn, but if this is not the case critical design rules can be broken resulting in later problems with EMC and signal integrity. Expert systems has been on the marked for some time, but not widely spread out. As the systems are further developed, and the demands for expert systems grow due to demands for higher speed and smaller dimensions, the interest from a growing number of users is expected. Useful model data is available from most component vendors, others have none or the models are simplified and not direct useful for EMC, SI, PI and IR-drop simulation. To select the right tool, no final advice can be given – you have to match your needs and ambitions with the tools on the marked. However it is recommended to spend some time in the selection process, including tests of evaluation/trail versions of the tool candidates. We see the 3 tools we had a look at as valid candidates. When an Expert System is selected it is highly recommended to do the first simulation on a well-known product. This will create confidence regarding models validity and be part of common data collection useful for the next projects.

4.4.7 References

EMSAT (IBM)	http://www.mossbayeda.com/EMSAT.pdf
EMIStream	http://www.nec.com/en/global/prod/emistream/index.html
CST STUDIO SUITE	http://www.cst.com/Content/Products/Products.aspx
Cadence layout	http://www.cadence.com/products/pcb/Pages/default.aspx

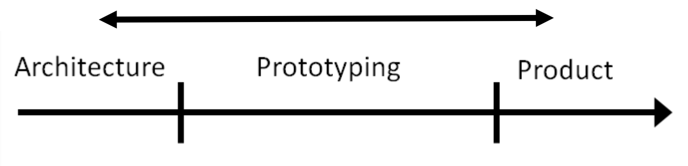
Links – freeware, other tools and homepages of interest:

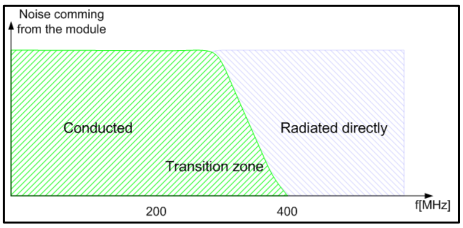
Clemson University, Links index	http://www.clemson.edu/ces/cvel/emc/index.html
Maximum Radiated Emissions Calculator	http://www.clemson.edu/ces/cvel/modeling/EMAG/maxemcalc.html
Martin O'Hara homepage, EMC consultant	http://www.tridatacom.co.uk
Consultant company	http://www.silent-solutions.com/case_studies.htm
Sigcon.com Signal Consulting Inc.	http://www.sigcon.com
Knowledge page	http://www.speedingedge.com
Consultancy and articles	http://emcesd.com
EDN.com Electronic Design strategy News	http://www.edn.com
Forum for Electronics	http://www.edaboard.com
Edaboard.com Question & answer block	http://www.edaboard.com/thread40548.html
Sigcon Newsletter & SI mailing list	http://www.sigcon.com/Pubs/newsletter.htm
Simulation and workflow	http://www.ansys.com
Istvan Novaks homepage, Signal & Power Integrity	http://www.electrical-integrity.com
EMC - EMI Simulation, SI-PI-PDN tools	http://www.sigrity.com
EMS Plus, EMC simulations tool	http://www.ems-plus.com/index.html
System level design, FPGA	http://www.synopsys.com/home.aspx
Altera PDN tool, simulation	http://www.altera.com/technology/signal/power-distribution-network/sgl-pdn.html
Xilinx PCB Checklist	http://www.xilinx.com/products/design_resources/signal_integrity/si_pcbcheck.htm
Xilinx PCB Design	http://www.xilinx.com/products/design_resources/signal_integrity/resource/si_pcb.htm
Saturn PCB Design:	http://www.saturnpcb.com/pcb_toolkit.htm
Proto express HDI tools:	http://www.protoexpress.com/hdi/hdi-tools.jsp
E-system design, EDA tools (System Integrity criteria)	http://www.e-systemdesign.com/home.html
PDN Designer, Capacitor Optimization Tool(low budget)	http://giga-hz.co.jp/en/pdn.html
PDN Expert, High-End Capacitor Optimization Tool	http://www.giga-hz.co.jp/en/index.html
tech-dream company, EDA tools	http://tech-dream.com/wp/products
EMI software homepage, EMI simulation	http://www.emisoftware.com/default.asp
EMI software, Evaluation downloads	http://www.emisoftware.com/emi-software-products_emianalyst-overview.asp
EMI Software overview	http://www.emisoftware.com/emi-software-products.asp
Polar Instruments, PCB-SI, impedance design, test and doc	http://www.polarinstruments.com
Aprel EM-I Sight, Near-Field EMI Scanner Robot	http://www.aprel.com/products/systems.html
Near-Field EMI Scanner – datasheet	http://www.aprel.com/products/EM-ISight-2011.pdf

4.5 Conducted emission (frequency range below 30 MHz)

Knud A. Baltsen, Bang & Olufsen A/S

Conducted emission EMC parameters





Project phase: Is good for prototype or design evaluation

Relevant frequency band: Above approx. 30 MHz

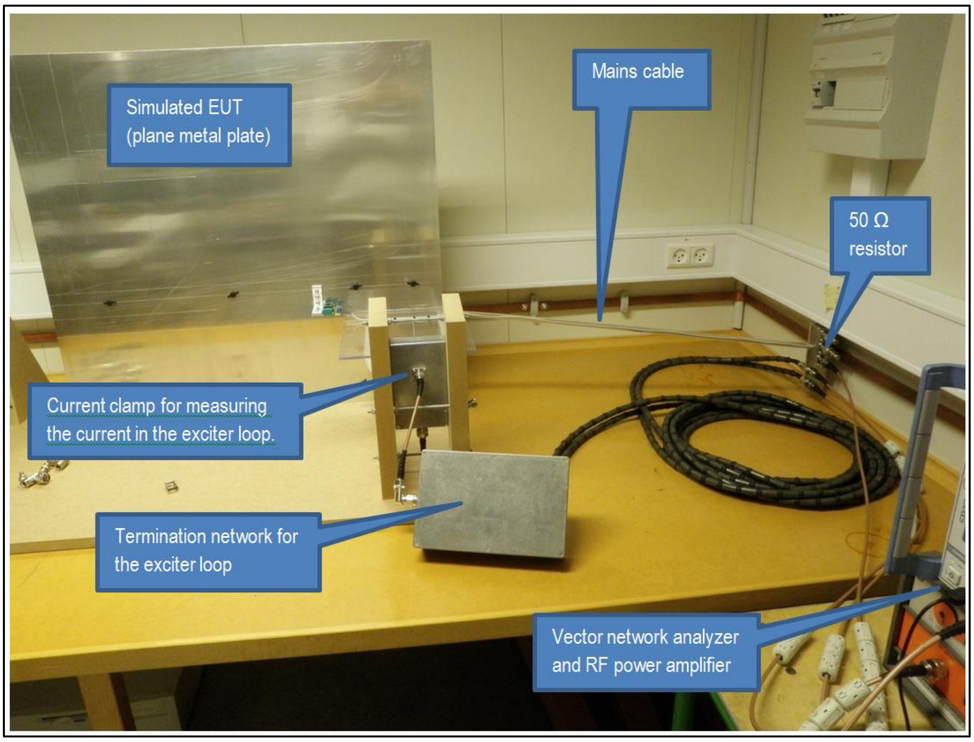


Figure 55. Setup for measuring coupling in the conducted frequency range

4.5.1 Introduction

A part of obtaining compliance with regulatory EMC requirements world-wide is to show compliance with the limits of conducted emissions from the AC mains power ports in the frequency range 150 kHz to 30 MHz. There's quite a good consensus world-wide concerning limits, measurements procedures and test set-up.

4.5.2 EMC challenge

Some of the EMC challenges regarding conducted emission are

a) Limit directly the conducted emission.
b) The resonance aspect, the influence of the test set-up on the measured emission.
c) The influence of indirectly near-field coupling from the Equipment Under Test (EUT) on the measured emission.

4.5.3 Procedure

4.5.3.1 Limit directly the conducted emission

In contrast to radiated emission the directly conducted emission can be modeled and calculated using circuit theory and for this many are available. The prerequisite for using these tools are sufficient knowledge of the equivalent circuit models of the components contributing to conducted emission. It may not be an easy and trivial task, but basically it's all circuit theory. The most difficult part is how to reach the best compromise between 1) obtaining sufficient compliance for all possible normal use conditions and 2) doing this in the most economically and space constraint way.

4.5.3.2 The influence of the test set-up on the measured emission

The test set-up as described e.g. in CISPR 13, CISPR 22 and the new CISPR 32 creates a series resonance for which the resonance frequency f_S for a large and relative flat EUT (such as a TV) can appear in the frequency range of regulation, which world-wide is from 150 kHz to 30 MHz. The series resonance is to a good degree described by the capacitive action C between the large flat EUT and the conducting wall of the screened chamber and the inductive action L of the length of mains cable, whose length due to the prescribed test set-up will end up to be 80 cm or some more. The value of the resonance frequency, f_S, can be calculated using the well know relation from circuit theory (12).

$$f_S = \frac{1}{2\pi\sqrt{LC}}. \qquad (12)$$

The values of C and L will have to be estimated based on electromagnetic theory.

If the value of the resonance frequency is placed outside the regulated frequency range, then for compliance reasons, it's of very little interest. The problem is when the created resonance frequency is within the regulated frequency band. It might seem 'un-fair', as it actually is the specified test set-up that in part creates the resonance. This seemingly 'un-fair' situation is not specific for conducted emission however, as for radiated emission testing e.g. an almost ideal metal reflecting plane is used, and this will probably not even near, be the case in actual use. One must realize, that one of the very important reasons behind specifying the test set-up's as is in CISPR 13, CISPR 22 and CISPR 32 are to provide a recognized and the simplest way of making reproducible testing.

If present, the resonance phenomenon can be mitigated e.g. by shifting the resonance frequency outside the regulated frequency range by adding additional inductance or by damping the strength of the resonance by adding resistive losses.

4.5.3.3 The influence of indirectly near-field coupling from the EUT on the test set-up

Indirect near-field coupling from the EUT to the connected mains cable contributes to the measured conducted disturbance voltage, and as such it shall be controlled. The most common near-field coupling is inductive in the form of stray fields from magnetic components in power electronic modules (e.g. switch mode power supplies (SMPS) and digital audio power amplifiers). It can be very difficult to shield against such magnetic fields, so in many cases the best way to mitigate this coupling is by increasing the distance between the magnetic component and the mains wire. But how large shall this distance be, when you're in just in the architecture phase?

Figure 56 and 57 below show a test set-up, which is aimed to investigate the influence of near-field inductive coupling from the EUT to the mains cable. Figure 58 shows the resulting disturbance as a function of the frequency.

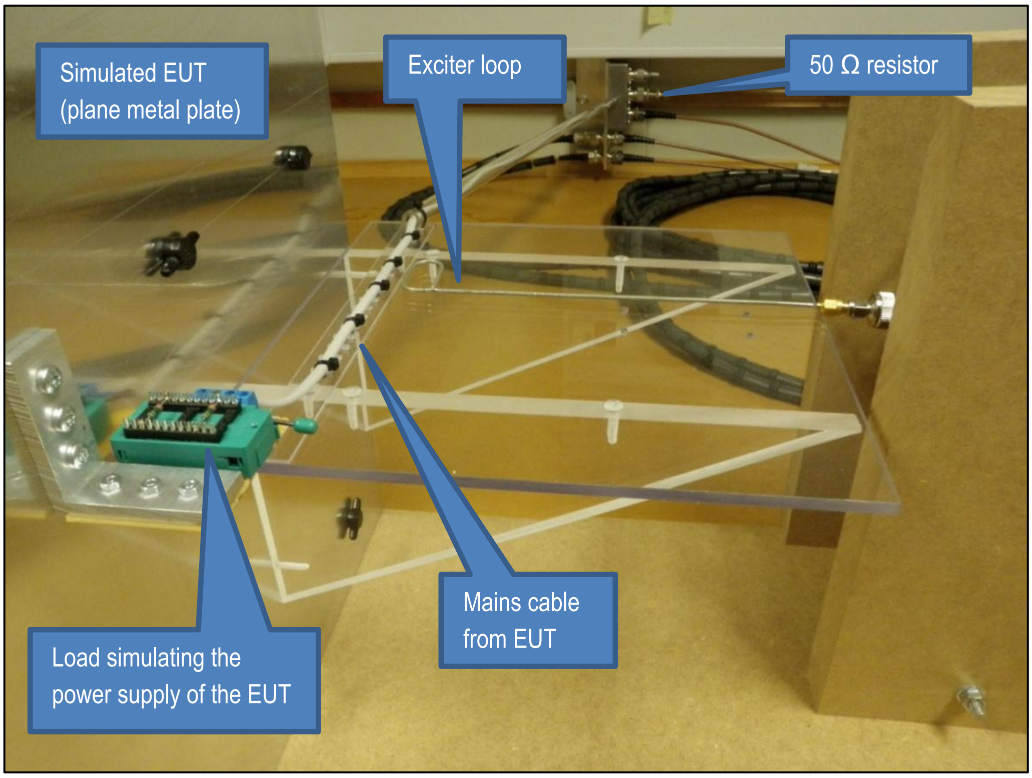


Figure 56. Photo of the test set-up for measuring the near-field (inductive) coupling to the mains cable. The cable is connected in one end to the EUT metal plate through the simulated power supply, and in the other end to a 50 Ω resistor. The 50 Ω resistor is connected to the screening wall of the chamber. The exciter loop couples inductively to the mains cable, and the resulting disturbance voltage is measured across the 50 Ω resistor. The current in the exciter loop is measured using a current clamp and is generated by a RF power amplifier fed by a vector network analyzer, which also measures the voltage across the 50 Ω resistor.

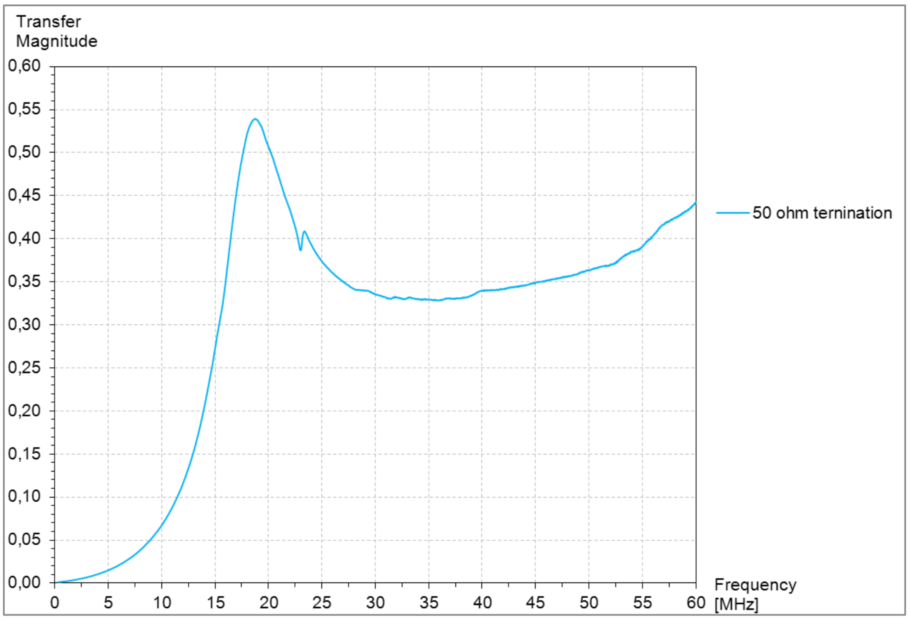


Figure 57. Graph of the measured transfer magnitude as a function of the exciter loop frequency. The transfer magnitude is a measure of the ratio of the disturbance voltage measured across the 50 Ω resistor and the current flowing in the exciter loop. The series resonance mentioned in part b) is clearly noticed at approximately 17 MHz.

It is expected the finished work will result in some kind of design rules relating a measured magnetic near-field to a compliance distance between the component generating the measured magnetic near-field and the mains cable.

4.5.4 Investment

The measurements mentioned in part c) is carried out using a vector network analyzer, a RF power amplifier, either a current clamp or a RF power attenuator and some manufacturing of the test set-up. The total price level is estimated to be in the order of $60.000 – 70.000.

4.5.5 Conclusion

It can be concluded that directly conducted emission can be modeled and calculated using circuit theory and for this many tools are available. It was found that the test set-up in itself is partly responsible for creating resonance conditions, but it's the price to pay for having simple and reproducible test conditions. Finally a test set-up is introduced with the aim to quantify a compliance distance between a magnetic component coupling inductively to a nearby mains cable, and in this way adding a disturbance voltage, which will be measured as an increased conducted voltage disturbance.

Conclusion

In this document the findings from the project EMC – first time right has been highlighted. In general the methods have improved the knowledge on both the internal and the external EMC phenomena that must be handled during product design and development to avoid costly last minute fixes.

The first chapter described the radiation mechanisms that are causing problems during the compliance radiated emission testing. The problem was primarily segmented into two parts. The common mode emission, originated from currents running on the cables to and from the module, which in the frequency range below 200-400 MHz is dominant. The radiated emission being radiated directly from the module itself, or coupled to the cables by capacitance or inductance, which in the frequency range above 200-400 MHz is dominant.

The second chapter describes how to perform test on the modular level of the currents running on the cables. The WBFC method was shown to very well suit for test on the individual module. The current probe proved useful for troubleshooting the system when assembled and somewhat on the modular level. The GTEM was only found somewhat suited in the higher frequency range and lastly and emphasis that cable termination impedance is very important when dealing with noise in the lower frequency range.

The third chapter described how to use the near-field scanner either as troubleshooting tool in the high frequency range or how to combine it with an FDTD simulation through the Huygens box principle to estimate the total direct radiation from a product. A description of the different simulation methods, and their use for EMC was described, and lastly some practical examples on, how simulation tools can be used to improve the knowledge about the specific EMC problem, and how it can be handled before the product are designed.

Lastly in chapter 4 the considerations for system integration was described and where to be cautious during assembly of many different modules. Special emphasis was put on how to choose the right cables such that problems due to transfer impedance can be avoided. Then the special case on transient propagation was covered and it was found that special care should be taken when positioning the cables internally in the product to avoid coupling of the transients to sensitive systems. Then the use of expert tools, were discussed and lastly how to make a setup that can demonstrate how conducted emission couples around the line filters of the total product.

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