Electromagnetic compatibility, an overview

A.H.M. van Roermund
Delft University of Technology
Dept. of Electrical Engineering
Mekelweg 4, 2628 CD DELFT
The Netherlands

1 Introduction

Electro-magnetic compatibility, or the way two or more systems can "live" together without introducing intolerable disturbances, is gaining increased attention in the micro-electronics business, see e.g. [Paul1992][Goedbloed1992]. Although not everyone might be familiar with the concept of EMC, or the concept of EMI -electromagnetic interference- he certainly is well acquainted with the fact that systems can interfere via electromagnetic coupling.

Some examples are: interference occurring in the reception of radio broadcasting programs, which results in, for instance, cross-modulation, the reception of a program at the modulation frequency of another program; reception of audio broadcasting channels via an audio amplifier or a compact disc player; radio music on the telephone; interference during teletext transmission, resulting in incorrect characters on the television screen; PCs that interfere with the electronics in an airplane; communication equipment that interferes with hearing aids or with hospital medical equipment; digital electronics on a PCB that interferes with the analog part; remote controls that control equipment other than the intended equipment; the controls of stereo sets that go their own way, and so on.

Such problems of interference, especially with radio-frequency signals, are not new; they were called, for instance, RFI: radio-frequency interference. However, the problem of interference has grown significantly, both with respect to the number of times problems occur, with the impact such problems can have on our society. Airplanes that crash, or people who die because medical equipment was disturbed by communication equipment ..., this cannot be tolerated. But also the chance that, let's say, normal consumer equipment does not operate properly, has increased beyond a critical level. And production costs have risen because of interference problems at the end of the production process.

There are several reasons behind this explosion of interference problems. First, the radio frequencies are used far more extensively than they were in former days. The spectrum has become more crowded. Hand-held communication equipment is conquering the market. Use in made of higher and higher frequencies, thereby enlarging the interference problem. Also digital equipment transmits signals, in this case unwanted interference signals. As digital ICs are already operating above 100MHz, the frequency components caused by the fast rise and fall times emit EM fields with a rather high efficiency. On the other hand there is a strong tendency to low power and low voltage, for battery operation, and for several other reasons. Although this has a positive influence on the radiation aspect, it also makes the equipment more sensitive to interference signals. And, of course, the total amount of electronic equipment in our society keeps escalating.

The problem of interference causing systems to function unsatisfactorily, as expressed in the concept of EMI, can also be viewed from the positive side only: the desired property of equipment functioning satisfactorily without mutual disturbance. This is the difference between the EMI view and the EMC view. And, instead of responding to problems, it is also possible to take electro-magnetic compatibility into account in an early stage of the design process.

The main obstacle, however, encountered in the EMC field is the complexity of the problem. In principle, everything can be calculated with the Maxwell laws, but, in practice, these calculations are far too complex to be used without simplifications. Research is therefore done to find simpler models, and to make better CAD. The mathematical world of the EM-field specialists has to be coupled to the world of the designers of electronic equipment. Very much remains to be done.

2 The main aspects of EMC

The formal definition of EMC, as given by the International Electrotechnical Commission (IEC) [IEC1990][IEC1992] runs as follows:

> "EMC is the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment".

The definition of EMI, given by the same commission, is:

> "EMI is the degradation of the performance of a device, equipment or system by an electromagnetic disturbance."

The main aspects of EMC and EMI are contained in these definitions.
First: there is always more than one piece of apparatus: at least one that is radiating EM-disturbances, the emitter, and there is at least one that is receiving the disturbances, the susceptor. Thus distinction is made between the two main subareas of

EMC: the electromagnetic emission (EME) - *"the phenomenon by which electromagnetic energy emanates from a source"* and the electromagnetic susceptibility (EMS) - *"the inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance."*
Second: there is a coupling path between them, somewhere in the common environment.
Third: the interference or compatibility can be considered at all levels of a system, expressed in the definition by *"device, equipment or system"*; translated this means, e.g., system, subsystem/module, print, IC package, IC interconnections, IC devices.

3 Discrimination

In the definitions given by the IEC, we find the coupling effect: electromagnetic waves that are travelling in one way or the other to the receiving system, and the aspect of proper operation, or degradation. In many EMC discussions, emphasis is laid on the coupling paths and the associated calculations based on Maxwell or simplifications thereof. However, it is emphasized here, that the susceptibility of a system not only depends on the presence of coupling paths, but also on signal-domain aspects. Of course, if there is no coupling path, there will also be no disturbance; however, if there is a coupling path, then there is not necessarily a degradation of performance. And, if there is a degradation, it cannot always be explained just by the presence of a coupling path that brings the disturbing signal into the receiving system. The aforementioned example of the reception of an audio broadcasting program by an amplifier doesn't explain how it is possible that we can hear the demodulated baseband audio signal. Obviously, susceptibility also includes such aspects as: are the interference signal and the interfered with signal in the same frequency band? If they are, they can still be discriminated, for instance by filters; if not, they are mixed and the operation of the receiving system is affected.

This brings us to a more general view: as long as signal and noise can be discriminated, we do not necessarily have a degradation of performance. This discrimination can take place in three domains:

- spatial domain
- signal domain
- carrier domain

Here, discrimination in space means: the paths that are used by the signal and the noise are separated in the 3D spatial domain, for instance because they are transferred via different cables. Theoretically, following Maxwell, an EM wave extends to all positions in a 3D spatial domain; however, in the case of guided waves, for instance, we see that the waves diminish rather fast with distance, so that cables that are not too close to each other can be seen as separated paths. Aspects such as shielding, and transmitting EM waves via transmission lines or wave guides, are examples of discrimination in the spatial domain. This discrimination can be impaired, leading to a nonreparable mingling of the signals, for instance if we draw holes in a shielding case.

An example of discrimination in the signal domain is the way several programs are broadcast at different carrier frequencies; the signals traverse the same spatial domain, but they are not mixed because of the frequency multiplex used. Nonlinearities in a receiver, however, can destroy the frequency separation, and thus the discrimination, and the result is merged signals. The signals are all intentionally created by ourselves, as in the situation of broadcasting, we can take measures to ensure enough frequency discrimination; if the interfering signal is a parasitic noise signal, we normally have no influence on the spectrum used by that signal: it can be anywhere in the spectrum. However, for radiating conductors that transport digital signals, we are able to restrict the spectrum of the emitted interference signal by extending the rise and fall time of the logic as much as is permissible within the bounds of a proper functional behaviour of the logic.

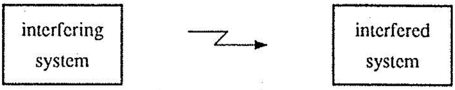
Discrimination in the signal domain does not necessarily imply discrimination in the frequency domain. Selectivity can also be obtained in the time domain: signals that are not continuous in time can be transmitted in a time-multiplexed way. Discrete-time systems are examples of this, such as switched-capacitor circuits, in which the intended signal samples can be placed at time moments different from the time moments of the interfering signals coming from the logic, by intentionally applying a phase shift between the sampling clock and the logic clock.

There is, in principle, a third way to discriminate signals, and that is by using separation in the amplitude domain: amplitude multiplexing. For intended signals, this is done, for instance, in a video signal where different signals, such as luminance, synchronisation, and black level, are combined in one signal. However, in the situation of interference signals, this can only be used in a limited way, as one is only sure of the amplitude domain covered by the intended signal, and not of that of the interference signal. This means that all signals that are outside the amplitude region of the intended signal can be marked as being interfering signals, and thus be suppressed by amplitude discrimination means, like diodes, varistors and spark gaps. Spark gaps are used, for instance, in high-voltage power lines to conduct the currents induced by lightning.

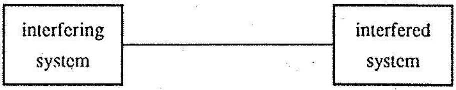
Finally, discrimination can be applied by using differential-mode signal transfer and processing, and taking care (and hoping) that all interference signals will appear as common-mode signals. This is a well-known method of discriminating between signals and interferences. In fact, in this application, we have neither spatial discrimination nor signal-domain discrimination; that discrimination is nevertheless possible because of the fact that two signal paths are used to transfer and/or process one signal, and that the combination of the signals of both paths determines whether we have to deal with the intended signal or with the interference one. Degradation of this kind of discrimination is mainly due to a kind of asymmetry, for instance spatial (one of the two conductors is closer to the reference plane), or in impedance level.

4 A global model for spatial coupling paths

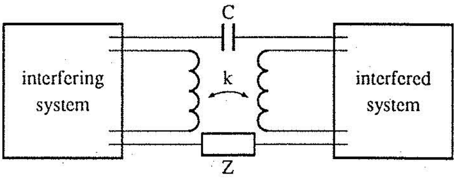
To get a grasp on an EMI problem, it makes sense to have a good model of the specific situation. A first step to this is made to make distinction between field radiation, field conduction and crosstalk, see figure 1. Although in all cases we have to deal with EM fields, this distinction makes sense, as the simplifications that can be used are different.



a) field radiation



b) field conduction



c) crosstalk

Figure 1: Distiction between field radiation, field conduction and crosstalk.

Radiation must be tackled with Maxwell laws which state, if we translate them in a popular way, that a change in time of one field component (electric field or magnetic field) is associated with a derivative in space for the other field component. For instance: shunting an output port of an interfering system doesn't mean that we have got rid of the interference; the signal currents in the loop that has been created this way cause time-variant magnetic fields which can cause inductive coupling to another loop in its neighbourhood, or emission of an EM field, thus radiating coupling to any receiving "antenna" further away. An open port, however, causes an electric field in the neighbourhood and an EM wave farther away in space.

Therefore, in the case of radiation we really need Maxwell, but in the case of field conduction with transmission lines we can make use of the simplified transmission line equations; the reason why such a simplification is allowed, is that the conductors influence the field transport in such a way that, under some assumptions, the field can be seen as a transverse EM field (a TEM wave). This takes place if we have interference coupling via antenna cables, supply cables or signal cables between different parts of a system.

In the case of crosstalk we have to deal with radiation and reception with two "antennas" in each other's near field, which makes it valid to use a network description (capacitive and inductive crosstalk); this reduces the complexity significantly. Further on, we will come back to the description models and their validity.

Thus far we have talked about the distinction between the three types of coupling paths. Apart from this, we can make distinctions between the various parts of a total coupling path between an interfering system and an interfered with system, as shown in figure 2. In this figure, we see at the left the interfering system, with the interference source in it, and on the right the interfered with system, with between them the "external coupling" via the common environment. Except for these external couplings we also distinguish between the out-coupling and in-coupling. The reason for this differentiation is that for these parts of the total coupling path there are big differences in description, in approach, and in the influence you can exert. In the case of interference caused by a radio channel transmitted by a broadcaster, for instance, you only have influence on the in-coupling of fields; with an interfering magnetron, you can influence the out-coupling (shielding of the source); if you want to do very accurate measurements that are not to be influenced by interferences, you use a Faraday cavity; if you have to counteract all external transmission paths except for the direct one, you do so by putting the equipment under test in an anechoic room.

Apart from the previously mentioned parts of the total coupling path, we see the block called "signal-path coupling". It shows the coupling that is responsible for the fact that a disturbance that has already entered the equipment, and that is, for instance, present on the power supply lines, penetrates the signal path itself. This can be due to radiation, field conduction and crosstalk, as discussed previously, but often it is a consequence of nonideal behaviour of electronic circuits. In a differential amplifier design, for instance, there will be no coupling from power lines to output in the ideal situation; in practice, however, such a circuit will not be ideal, and the

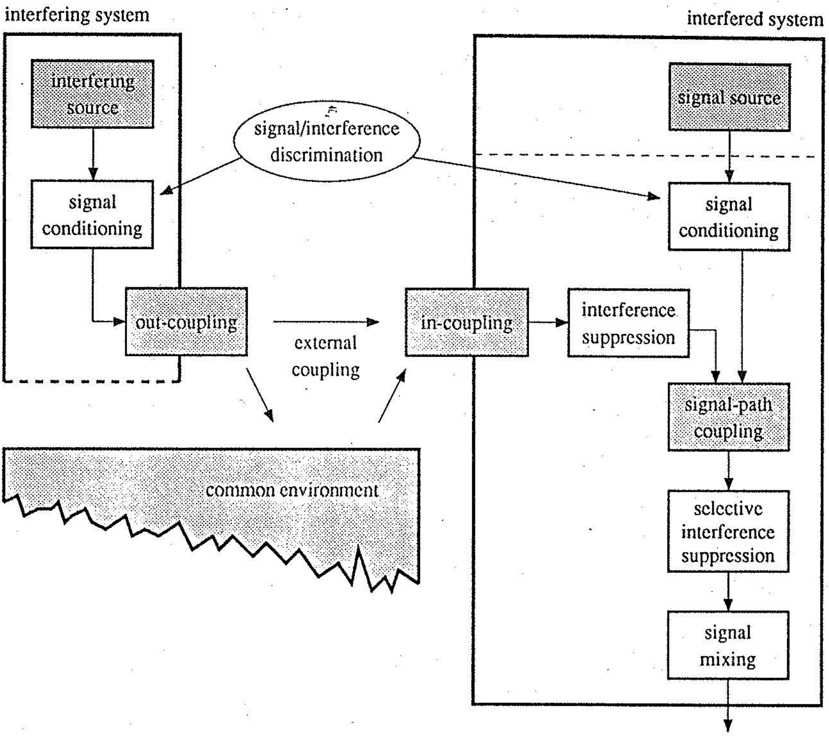


Figure 2: Total coupling path between an inteferring system and an interfered with system.

power supply rejection will be restricted to a finite value. As the example shows, the signal-path coupling will often be an electronic design problem in contradiction to the incoupling in the system. To emphasize this, these two parts of the total coupling path have been mentioned separately.

5 Extended model for signal-domain coupling

The figure shows the aforementioned intermediate steps in the total path from interfering source to output of the interfered with system. It provides a framework that can be used for the analysis of an EMC problem. However, we have already seen that we can also discriminate between the intended signal and the interference signal in the signal domain. We can influence this signal-domain discrimination at several points in the total coupling path. Therefore, figure 2 shows extra signal-processing blocks in between.

If possible, we can take care that the interfering source only shows components in those parts of the frequency or time domain where our signal is not present; we can also take care that the intended signal is shifted out of the disturbed parts of the frequency spectrum or time domain; these actions are referred to as signal conditioning. Nonselective suppression of the disturbances is possible as long as signal and disturbances are not on the same path, thus before the signal-path coupling. As soon as signal and disturbances are on the same path, we can only use selective suppression to diminish the interference signal. Having used all these possibilities, we are then left with the mixing of the remaining interference signal and the intended signal.

6 Typical interference signals

From the signal domain discussion, it will be clear that it is important to know the type of interference signal: its frequency spectrum; its time domain behavior; its amplitude range. The most well-known interference signals are:

- transients caused by logic
- transients caused by switching
- electrostatic discharges (ESD)
- lightning
- corona
- nuclear electromagnetic pulse

Transients caused by logic are found in all digital circuits. Logic causes pulses with fast rise and fall times and transient current peaks at the switching moments. The pulses can be modeled with trapezoidal functions. The envelope of the spectrum of a symmetrical trapezoid with rise time of t_r and width t_w shows two 3dB break points, located at $1/\pi t_w$ and $1/\pi t_r$, see figure 3. The emitted spectrum can be very broad and cause severe interference problems, especially with the high clock frequencies employed today.

Transients caused by switching are found in, for instance, switched-mode power supplies and relays. The energy in the transient signals can be rather high, and with fast switching the emitted spectrum can be very broad. It can be modeled

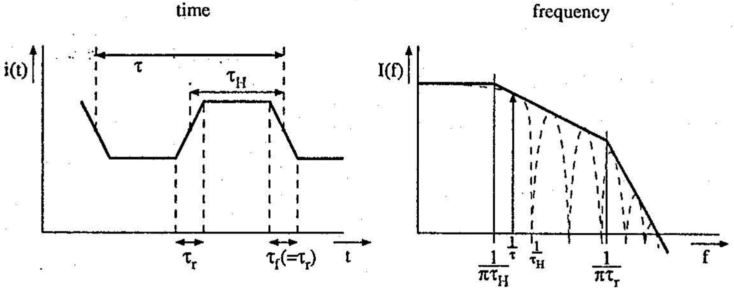


Figure 3: Spectrum of a symmetrical trapezoid with rise time of t_r and width t_w.

with a double-exponential pulse, with parameters for pulse height, rise time and pulse width. The IEC 801-4 standard prescribes a test signal for relay switching; it has 5ns rise time and 50ns fall time and an amplitude of some kilovolts; the spectrum shows a first roll-off at about 2.2 MHz and a second roll-off at about 70 MHz.

Electrostatic discharges are produced by friction between two materials, of which at least one is an insulator. This causes transfer of charges, and therefore charge accumulation. A notorious example is that of a charged human being, charged up to tens of kilovolts by walking over a carpet, and discharged via sensitive electronics. Especially CMOS circuits with their high-impedance gates can easily be disrupted by ESD. Good protection at the bonding paths of ICs are therefore of vital importance. This phenomenon can be modeled with two double-exponential pulses. The test setup can be built up of a capacitor of 150pF (human being), in series with an inductor of some micro-henrys and a resistor of 1kohm. Discharge of furniture shows a more oscillatory character and can be modeled by using a lower resistance.

Lightning is caused by a separation of negatively and positively charged rain drops in clouds, leading to an electric field, followed by an amplification by the avalanche effect. A discharge is attended by currents starting with some hundreds of amperes and rising up to several tens of kiloamperes, and that several times in succession. With respect to EMC, the di/dt of the current at the wave front is especially important: it causes high EM fields and high induction currents in wires. The standardised lightning interference signal shows an exponential increase with a half-value time of 1.2 microseconds and an exponential decay time of 50 microseconds. It can be modeled with a double-exponential pulse.

Coronas are found at power lines and pylons, in TV sets at the high-tension plug, in X-ray equipment, etc. The manifestation can be audible as a crackling noise, caused by a local crossing of the maximum field strength in air at corners and edges. The intefering signal is inhomogeneous, has a stochastic nature, rise and fall times in the order of nanoseconds, and it causes radio interferences up to the UHF-frequency range.

The nuclear electromagnetic pulse is caused by a nuclear explosion, via the gamma radiation. Collisions of gamma quants with gas molecules free high-energy Compton electrons that in their turn give rise to thousands of ionisations. The result is a strong transient EM field that can disrupt electronic equipment over a large area, especially if the explosion is accomplished at a height of a few hundred kilometres. Here again, the double-exponential pulse can be used as a model, with a rise time of about 2.5 nanoseconds and a fall time of about 270 nanoseconds.

7 Modeling and simulation

There are several ways to model an EMC situation. Of course, a description based on the Maxwell relations is the most complete one, but it is also the most complex and time-consuming one. Sometimes using so much detail cannot be avoided, but in many cases it is permissible to simplify the model. In many cases the simulation complexity even forces us to go for simpler modeling. Much of the research accomplished now in the field of EMC is related to the problem of simulation. Further on I will come back to this point.

Maxwell describes an EM field in the three-dimensional space and in time, with the well known Maxwell relations [Maxwell1873], supplemented already with the constitutive relations that describe the electric-conduction properties, the dielectric properties, and the magnetic properties of the medium:

$$-\underline{\nabla} \times \underline{H} + \sigma \underline{E} + \varepsilon \delta_t \underline{E} = -\underline{J}^e,$$

$$\underline{\nabla} \times \underline{E} + \mu \delta_t \underline{H} = -\underline{K}^e.$$

Herein E and H are the electric and magnetic field strengths; J^e and K^e are the volume source densities representative of, respectively, the action of an electric current source and an electric voltage source; and σ the electric conductivity, ε the permittivity, and μ the permeability of the medium. The field and source vectors are functions of position (with as argument the vector r or the three coordinates x,y and z). The medium is far from homogeneous of course; in the case of a printed circuit board, for instance, we have capacitances (ε), inductances (μ) and conductances (σ) varying strongly with position. Moreover, we can recognize several sources in actual EMC situations. This all makes EMC calculations so complex. However, several simplifications can be made, depending on the situation.

Normally, the medium is time invariant. Therefore ε, σ, and μ are functions only of the vector r (or the coordinates x, y, z) and not of time. In some situations also some parameters can be taken constant (e.g. μ=1) or even neglected (σ=0). In many cases, the constitutive parameters σ, ε and μ are only position dependent in a plane (PCB, IC, thin wires, thin planar conductors); outside that plane they are constant.

A further reduction of complexity can now be achieved in several ways, but we can make a main distinction between on the one hand reduction of the complexity of our model c.q. description, and on the other hand a reduction of calculation complexity (increasing numerical efficiency). Modeling reduction can be seen as a preprocessing that is only done once, whereas the real simulations must be done for several positions, and time or frequency points. Therefore model reduction is of primary importance.

Starting with the 3D-field descriptions, we can replace the differential equations with the integral relations. Instead of the local differential formulation that provides information for each point in the domain, we then work with a global formulation that provides integral information for a given subdomain (for instance for a given spatial object, or for a period in time). Moreover, we can perform transformations: a Laplace transformation on the time variable and/or a Fourier transformation on the space dimensions. These formulae can be found in textbooks on EM fields [Cheng1983][Paul1987]. Implicitly, we make use of the fact that all EM fields are transient: they start somewhere and they will end; and that the systems are causal and time invariant. This makes further calculations much simpler. Then, the resolution can be decreased for all dimensions as much as is permissible. For instance, the grid used in the spatial description of connectors can be enlarged, thus resulting in a simpler description.

However, we can go much further in many cases: instead of using a larger grid, we can even ignore, under certain conditions, one, two, or even all three spatial dimensions. That brings us to the plane-wave description, the transmission line description, and the network description. In transmission-line and network descriptions, the concepts of voltage and current are valid and can greatly simplify the simulations. If, and to what extent it is permissible to use these descriptions, depends on what is called the electrical dimensions of the circuit. EM waves propagate through a medium with a speed that depends on the medium parameters (the constitutive parameters). Together with the frequency of the EM waves, this leads to a certain wavelength. If the dimensions of the circuit or of a part of the circuit are far smaller than the wavelength, the field vectors will have almost the same value everywhere in that (part of) the circuit at a given time moment. That means that we can ignore the dependence on the spatial parameter(s). As for higher frequencies the wavelength will be shorter, it is not the real spatial dimensions of a body that are relevant, but the electrical dimensions, expressed in wavelengths.

If a body is too large to satisfy these conditions, we can still split it up into smaller segments that do fulfill the requirements, so that these segments can each be translated to a lower-dimension model. Thus we can model a 3D-field with a combination of transmission lines; this is called the transmission line method (TLM); or a transmission line with a distributed RLC network; or a 3D-field directly with a large network of interconnected subcircuits. Interconnection systems on PCBs, for instance, are simulated that way [MSS1994][Scott1994][CMW1994]. The problem is that with a direct translation with a network generator, the networks are typically very large. In [MSS1994] a theoretical basis is given of a method to reduce greatly the number of components in the circuit, so that it can then be handled efficiently enough by a network simulator. Recall that such a network compression algorithm has only to be performed once, whereas the network simulator has to perform a tremendous number of calculations.

It is not necessary to translate the whole circuit to one and the same description domain; parts of the total circuit might be expressed in terms of field expressions, parts in terms of transmission lines, and parts in terms of networks.

Finally, the model must be evaluated for all relevant frequency points and or time moments. Here, research is done to reduce the calculation complexity, or put differently: to enhance the numerical efficiency. We can mention here, for instance, the (well-known) finite difference method [Marvin1991] which adapts the resolution during calculation, depending on the simulation results obtained; the finite integral method [Dawson1991], which is similar, but now applied to integral descriptions; the finite element method with optimization to minimal energy; the method of moments, as applied, for instance, in the Boundary Element Method [CMW1994].

8 Interference reduction

Most research in the field of EMC is done, as explained previously, on simulation of the physical coupling path. However, this relates to analysis and therefore serves to estimate how much interference we can expect. The other point is: how can we prevent or reduce that interference, either during design or afterwards? As pointed out earlier, discrimination can be realized both in the spatial domain and in the signal domain.

8.1 Transmission lines and shielding

In the spatial domain, interference reduction means the reduction of parasitic coupling paths, both on the emission side, during transport, and on the receiver side, see figure 2. Typical examples are the use of transmission lines for signal transport, and the use of shielding layers or shielding metallic cases for the suppression or bypassing of EM fields.

Transmission lines are two or more coupled conductors, in which the fields have a transversal electromagnetic structure: they have only field components perpendicular to the conductors. The field components are coupled as the conductors are (electrically seen) close to each other; in the ideal case the fields are 100% coupled, and there will be no outflow nor inflow of fields. The coupling is expressed in the coupling factor k, where $k=1$ means ideal coupling. The leakage of fields is expressed in terms of the transfer impedance, showing the ratio of induced emf in one line to the current in the other. For higher frequencies, coupling becomes more problematic, as the wavelengths become smaller and the electrical dimensions relatively larger. The analysis is well known from transmission line theory.

Shielding means suppression of EM fields or bypassing of EM-field transport. Suppression is based on currents induced in a highly conductive shield; bypassing of magnetic flux, so that it doesn't enter the critical circuit, is achieved with high-permeability shields (magnetostatic shielding).

Theory on shielding is already known for micro-wave circuits. Shielding is analyzed with the Maxwell relations or with the Schelkunoff method [Schelkunoff], also called the impedance concept, derived from transmission line theory. This last method is frequently used and mentioned in literature, but often incorrectly, as the assumptions made are not satisfied. It is assumed that the fields can be represented as plane TEM waves and that the impedance of the transmission line just before and just behind the shield are the same. In [Nishikata93] it is shown that especially the last simplification is impermissible.

Measurements of shielding efficiency, which is defined as the ratio of the magnitude of the electric (magnetic) field that is incident on the shield to the magnitude of the electric (magnetic) field that is transmitted through the shield, can be performed in a direct way if the shield is large or if it forms a completely closed box. For smaller parts, measurements are performed in a TEM cell: two parallel coaxial cables, of which the concentric shields are locally expanded and connected to each other, see figure 4. A hole is made in the region where the concentric shields are merged, forming a leakage hole for EM fields from one coax to the other. The cables are loaded in a characteristic way; on coax is excited by a source, while the fields through the other are measured. The transfer impedance between the lines is measured in this way. By placing the shield material at the position of the hole, the shielding effectiveness can be derived from the transfer impedance measurements.

Research focuses primarily on a more sound analysis of shielding, see e.q. [Quack] and on new and better shielding materials, especially on plastic materials, which have interesting properties from the production point of view.

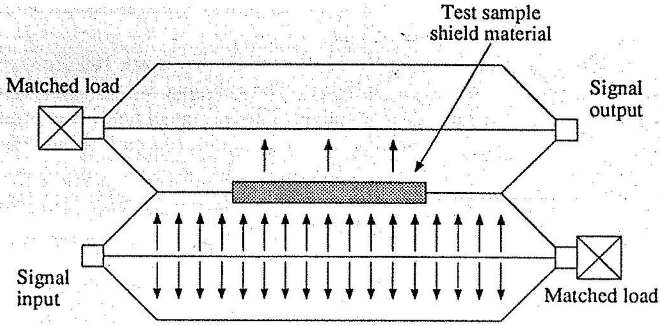


Figure 4: A TEM-cell for shielding measurements.

8.2 Signal-domain interference reduction

In the signal domain, interference reduction means: increase discrimination between intended and the interference signals in the signal domain, and guard against mixing.

Digital circuits form an important source of interference. Their currents exhibit a broad spectrum, as explained earlier. The emitting interconnection lines on ICs and PCBs can be modelled as (combinations of) electric and magnetic dipoles. For the far-field region, the fields of these dipoles can be approximated with plane waves and their strengths can be derived from the general emission formulae for dipoles, which finally results in:

$$|E_{FF,electr.}| = \frac{6.3 \cdot 10^{-7} f I}{r}.$$

$$|E_{FF,magn.}| = \frac{1.32 \cdot 10^{-14} \cdot f^2 A I}{r};$$

where f is the frequency of the excitation current I, A the area of the magnetic loop, l the length of the electric dipole, and r the distance to the dipole. Note the linear frequency relation for the electric dipole and the square-law relation for the magnetic dipole. Translating now the earlier-discussed spectrum to the field strength, we see that the emitted spectrum for an electric dipole is flat between the first and second time constants and that for a magnetic dipole the spectrum is flat starting from the second time constant, see figure 5. From this it will be clear that emission from digital circuits can extend to very high frequencies. In most cases the electric radiation is dominant, but at very high frequencies also the magnetic radiation can play an important role. To reduce the effect of the electric radiation, it is of utmost importance to decouple power lines, and to use strongly coupled lines with differential-mode currents for signal transmission, so that the total current through the two lines acting as one radiator is kept as small as possible. This means that common-mode currents must be kept small. Recalling that the second time constant is related to the rise time of the digital pulses, it will be clear that radiation can also be decreased by decreasing the rise times as much as is permitted for proper functional behavior of the circuit. In other words: don't use faster logic than is strictly necessary.

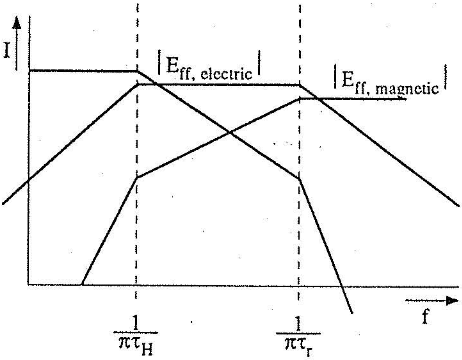


Figure 5: Current and field spectra for an electric and a magnetic dipole.

To be able to guard effectively against mixing of the interference signal and the intended signal, it is important to realize what causes the intermixing. There are several possible reasons for the intermixing of signals in the time or frequency domains. Three important ones are here briefly discussed: non-linear processing, digital processing, common-mode / differential-mode intermixing.

In non-linear circuits, a signal is treated in a non-linear way; as a consequence the frequency domain components of that signal give rise to distortion components at multiples of their original frequencies (harmonic distortion) and at all kinds of combination frequencies (intermodulation distortion). This holds both for the intended and the (unexpected) interference signals. Therefore, harmonic distortion and intermodulation distortion can shift these interference signals into the frequency range that was meant for the intended signals, thus resulting in interference that can no longer be corrected. Recall that all active circuits have nonlinear components (transistors, diodes), that are intentionally driven in the small-signal mode, but that can be driven in the large-signal mode by the interference signal with all consequences of this. Nonlinear devices cannot be precluded; therefore it is important to take care that interference signals cannot reach these nonlinear points in the circuit, and if they still do, that they are common mode for both sides of a nonlinear junction, so that the junction doesn't have an interference signal across it.

Digital circuits are sensitive for interference during the short time of a clock transition, as each gate in the logic must then take the decision for its next logic value.

This means that logic circuits sample the interference signals, which results in frequency mixing, and are therefore sensitive for interference signals over a very broad frequency range; therefore they are especially sensitive to transient signals. Moreover, logic gates have a very poor rejection ratio for noise on the supply lines: transistors are switched and couple, therefore, supply noise directly onto the signal path. Interference signals can in a worst case situation influence the logic output, but even if the noise margin is large enough to prevent this, the noise margin is decreased, so that the gate becomes more sensitive to other disturbances. If the interference signal is coupled in at the same time at the inputs of successive gates, the effect is accumulated and the noise margin will be further deteriorated. Finally, the sensitivity of logic circuits depends on their logic, as the circuitry is asymmetric, both in regard to power lines, and to impedance levels. The dependency on moment of interference, combination of interferences, temperature, logic state, etc., makes interference analysis for logic circuitry difficult, and requires a statistic approach with many of measurements.

Finally, in many circuits, interference signals can be discriminated from the intended signals by using differential-mode processing and taking care that the interference signals enter the differential signal processing path as common-mode signals. In such a case, symmetry is very important, as any unbalance in the circuit in impedance, or in the (parasitic) coupling path, will result in a differential-mode component of the interference signal, and therefore in an interference that can no longer be discriminated from the differential-mode signal.

9 Regulatory requirements

EMC requirements are coming up from many government agencies with accompanying legal regulations, and from manufacturers. As markets are becoming increasingly global, the success of products will be strongly dependent on compliance with EMC requirements. Regulations are different for commercial and military equipment. Further, distinction is made between "professional" equipment (industrial, commercial, business), called "class A" products, and "consumer" equipment: "class B".

The IEC, the International Electric Committee, with members from various countries with standardization institutes, prepares recommendations, with international agreement. These recommendations can be followed by manufacturers voluntarily. They can also be used by government agencies to formulate legal regulations that become mandatory for manufacturers. The CISPR (Comité International Spécial des Perturbations Radioélectriques), which started separately from IEC, is now one of the technical committees within IEC that is involved in EMC. TC65 and TC77 are two other technical committees. The CISPR has since its start been involved in radio emission, with radio frequencies defined as all frequencies between 9kHz and 3000GHz; and, more recently, also in immunity tests.

The European normalization institute CENELEC tunes the CISPR recommendations [Eguchi1994], to make them suited for regulatory use ("harmonisation"). The European Union (EU) drew up a directives on EMC in 1989 [89/336/EEC], with measuring methods and norm values expressed in accompanying norms. TC110 is a special technical committee within CENELEC, working since 1989 on these standards. In 1992, this EU directive became effective, and from 1 January 1996 it will be mandatory; during the transitional period, manufacturers are advised to follow the national regulations on EMC, which can deviate to a greater or lesser degree from the directive.

In the USA, the FCC is charged with the requirements for radio transmission. The status of EMC regulations can be found in [Wall1994a] [Wall1994b]. Further information on regulations can be found in e.g. [Wouters1995] [Goedbloed1992] [Paul1992].

10 Conclusions

EMC is gaining increased attention, because the interference problem is increasing. The number of publications increased after 1992, when the new regulatory requirements of the European Union took effect. Also education on EMC received more attention. Most work in the EMC field focuses on better analysis methods and simulation tools, new shielding materials, and regulatory requirements. Much work must still be done to translate current EMC knowledge into useful guidelines for electronic design.

11 References

[**Paul1992**] C.R. Paul: *Introduction to Electromagnetic Compatibility*, John Wiley & Sons, Inc., 1992.

[**Goedbloed1992**] J.J. Goedbloed: *Electromagnetic Compatibility*, Prentice Hall, New York, London, 1992, .

[**IEC1990**] *Electromagnetic Compatibility, International Electrotechnical Vocabulary*, Chapter 161, IEC Publication 50(161), Geneva, 1990

[**IEC1992**] *Electromagnetic Compatibility, Application and Interpretation of Fundamental Terms*, IEC Publication 1000-1-1, Geneva, 1992.

[**Maxwell1873**] J.C. Maxwell: *A treatise on Electricity and Magnetism*, Oxford, Clarendon Press.

[**Cheng1983**] D.K. Cheng: *Field and Wave Electromagnetics, Reading*, Massachusetts, Addison-Wesley Publishing Company, (1983).

[**Paul1987**] C.R. Paul and S.A. Nasar: (1987), *Introduction to Electromagnetic Fields*, New York, McGraw-Hill Book Company.

[**Quack**] D. Quack, A.T. de Hoop: *Shielding of wire segments and loops in electrica circuits by spherical shells*, IEEE Trans. on Electromagnetic compatibility, vol. 31, no. 3, Augus 1989.

[**Milsom1994**] R.F. Milsom, K.J. Scott and P.R. Simons: *Reduced Equivalent Circuit Model for PCB*, Philips Journal of Research, 1994, Vol. 48, Nos 1-2, pp. 9-35

[**Scott1994**] K.J. Scott: Efficient Image Theory for Electromagnetic Field Modelling in PCB, *Philips Journal of Research*, 1994, Vol. 48, Nos 1-2, pp. 37-61

[**CMW1994**] R. de Cloux, G.P.J.F.M. Maas, A.J.H. Wachters: Quasi-static Boundary Element Method for Electromagnetic Simulation of PCBs, *Philips Journal of Research*, 1994, Vol. 48, Nos 1-2, pp. 117-144

[**Marvin1991**] A. Marvin: *Euro-EMC '91 Conference*, MBC Conferences, London, UK, 1991, pp.3

[**Dawson1991**] J.F. Dawson: *Euro-EMC '91 Conference*, MBC Conferences, London, UK, 1991, pp.19

[**Schelkunoff**] S.A. Schelkunoff: *Electro magnetic waves*, Princeton NJ.D., Van Nostrand Company, New York 1943.

[**Nishikata93**] A. Nishikata, S. Kiener, M. Ohtsubo, T. Shinozuka, A. Sugiura: A Rigorous Analysis for Test Methods of EM-Shielding Materials, *Journal of the Communications Research Laboratory* Japan, July 1993.

[**Eguchi1994**] T. Eguchi: IEC801/1000-4 series, *IEEE International Symposium on Electromagnetic Compatibility*, Sendai, 1994, pp. 819.

[**89/336/EEC**] Richtlijn van de Raad betreffende de onderlinge aanpassing van de wetgeving der Lid-Staten inzake elektromagnetische compatibiliteit, 89/336/EEC, *Publikatieblad van de Europese Gemeenschappen*, Nr. L 139, pp. 19-26, Brussels, May 1989

[**Wall1994a**] L.A. Wall: Recent and Potential Changes to the US EMC Regulatory Requirements, *IEEE International Symposium on EMC*, Chicago 1994, pp. 11-15

[**Wall1994b**] L.A. Wall: Update of US Regulations for Controlling Electromagnetic Compatibility, *IEEE International Symposium on Electromagnetic Compatibility*, Sendai 1994, pp. 539-543.

[**Wouters1995**] R. Wouters e.a.: *De EMC-richtlijn - Handleiding voor Produktontwikkelaars en -fabrikanten*, Ten Hagen & Stam 1995.

Biography

Arthur H.M. van Roermund (M'83-SM'95) was born in Delft, The Netherlands in 1951. He received the M.Sc. degree in electrical engineering in 1975 from the Delft University of Technology and the Ph.D. degree in Applied Sciences from the K.U.Leuven, Belgium, in 1987. From 1975 to 1992 he was with the Philips Research Laboratories in Eindhoven. First he worked in the Consumer Electronics group on design and integration of analog circuits and systems, especially switched-capacitor circuits. In 1987 he joined the Visual Communications Group where he has been engaged in video architectures and digital video signal processing. From 1987 to 1990 he was project leader of the Video Signal Processor project and from 1990 to 1992 of a Multi-Window Television project. Since 1992 he is a full professor at the Electrical Engineering Department of Delft University of Technology, where he heads the Electronics Department. The research activities of his group are accomodated in DIMES: the Delft Institute of Micro Electronics and Submicron technology, where he heads the Circuits and Systems Section.