Design Support of Printed Circuit Boards  
Concerning Radiation and Irradiation Effects (EMI)  
Using an Extended EMC–Workbench  

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Abstract

Due to the increasing frequencies of analog and/or digital signals and a higher package density on Printed Circuit Boards (PCB), problems occur concerning reflection, crosstalk, radiation, and irradiation. New design methods have to consider the analysis of the expected radiation behaviour already in the design phases of a PCB. Then violations of the legal requirements (radiative limits - FCC, CISPR) can be recognized and removed at low costs. Furthermore, the design cycle of prototyping PCB or electronic systems can be reduced.  
In this paper especially design problems due to radiation effects and their solution using the extended EMC–Workbench are discussed. The integration of the radiation tool COMORAN (COMputation Of RADiation) into the EMC–Workbench is described. The problem of radiation is formulated in terms of an integral equation approach, which is solved with the method of moments. Numerical results are validated by comparison with TEM approaches.

1 Introduction

Compliance with the legal requirements (VDE 0871-B, FCC, CISPR, ...) is principally a problem of the system design, where influence on the radiation–behaviour of an electronic system can already be taken into consideration during the PCB–design.

Concerning the functioning, even radiated electromagnetic fields of low magnitudes may already cause failures because of the usage of highly sensitive sensors in todays electronic systems (e.g. for automotive applications). Therefore, it seems important to support the electronic– and layout–designer with an appropriate tool providing the possibility of characterising the radiation– and irradiation behaviour of PCB.

The EMC–problem can be divided into conductive and radiative noise–effects. Thereby, reduction of one kind of interference can have opposite effects on the other type of interference, and vice versa. The use of line–terminations can for example reduce the voltage– and undershoots due to reflections on the lines, but on the other hand an increased magnitude of the current distribution and consequently an increased radiation at lower frequencies could be the result. Therefore, an EMC–adequate design often can only be achieved by compromise.

Interference may not only occur due to the sources on the PCB (‘internal EMC’) but also because of the irradiation of transient electromagnetic fields (‘external EMC’). So, the excitation can either be defined by voltage sources positioned at the output of digital circuits and/or by arbitrarily polarized irradiated plane waves. In this paper examples which clarify the influence of discrete sources as well as the effects of impinging plane waves on the current– and voltage signalforms on the traces of PCB will be presented.

The computer–oriented analysis of radiation problems is a topic of various publications. Often transmission lines are modelled by elementary magnetic dipoles. Thereby, the electromagnetic coupling of multiple wire–loops, the influence of dielectric regions, and the local dependency of the current distribution are ignored. Other publications are taking the local dependencies of the current–distribution into account by using the transmission line theory. Then the far field is determined via the magnetic vector potential. This kind of analysis is only valid for simple geometries, and again the electromagnetic coupling with other transmission lines is ignored.
Furthermore, the radiation analysis can be performed exactly by analyzing Maxwell’s equations. Often, these equations are transformed into integral equations which have to be solved numerically. Here the Method of Moments (MOM) is in widespread use [1]. A lot of computer programs have been developed, whereby the transmission lines are often described by the ‘filamentary current model’. In this case the dielectric layers are ignored usually.

A refined and already implemented concept for an adequate PCB-design with respect to ‘internal’ EMC-phenomena was presented in [2]. In this paper the extension of the EMC-Workbench by the tool COMORAN will be discussed. Due to this extension the EMC-Workbench is able to take all relevant EMC-phenomena into consideration on PCB as well as on system level. Examples will be given which clarify that COMORAN is able to give a decisive contribution to the whole design process.

![Figure 1: Concept of the EMC-Workbench](image)

2 Extension of the EMC-Workbench

The extended concept of the EMC-Workbench is shown in Figure 1. Based on a given layout design, critical subnets may be extracted with the Layout Data Extractor and the Layout Data Analyser (LDE/LDA) by using appropriate rules. All geometrical and electrical informations are transformed into an adjusted description for the simulators FREACS (Fast Reflection and Crosstalk Simulator) [3] and COMORAN with the help of the Simulator Input Generator (SIG). The simulation results can be represented graphically, e.g. by use of the tool AnaRes (Analyse Result), or by listings or plots. Call upon the results of the performed analysis, proper design changes can be introduced in order to abolish or at least to minimize the ascertained effects and their impact.

Because all the geometrical information has to be accepted by the LDE from different layout systems, the setup of interfaces to these layout systems is a very important task. Commonly, the offered interfaces are based on the ASCII format. In order to equip the EMC-Workbench with an universal input interface to external ASCII data files, the SULTAN language (Standard Universal Layout Information Transport Language) was developed. The SIG is able to read all relevant geometrical data directly from a SULTAN-format.

First investigations for the development of a comfortable COMORAN input language were based on the examination whether the TANDEL language (TrAnsmission Line Network DEscription Language) [3] could be expanded for a COMORAN usage. It has to be considered that the amount of COMORAN input parameters is much greater than the one of a transmission line calculator. Nevertheless, as a result it can be stated that TANDEL is a good base for developing the required new COMORAN input language.

3 Mathematical Formulation

The overall electric field strength \( \vec{E}_\alpha \) in the ambient of a homogeneous body \( V \) of constitutive parameters \( \varepsilon, \mu \) excited by an incident field \( (\vec{E}^s, \vec{H}^s) \) can be described by the equation [7] (see Figure 2)

\[
\vec{E}_\alpha(\vec{r}_p) = T \cdot \vec{E}^s(\vec{r}_p) - T \cdot \frac{1}{4\pi} \int_{\partial V} \left( j \omega \mu_\alpha \vec{J}^s \cdot G_\alpha \right) d\vec{q} + \int_{\partial V} \left( \vec{M}^s \times \frac{\vec{E}_\alpha}{\varepsilon} - \frac{\varepsilon}{\varepsilon} \frac{\vec{J}^s}{\varepsilon} \cdot G_\alpha \right) d\vec{q}
\]

where \( \vec{M}^s = \vec{E} \times \vec{\eta}_\alpha \), \( T = \left( 1 - \frac{\Omega}{4\pi} \right)^{-1} \)

with

\[
\Omega = \begin{cases} 
0 & \text{if } \vec{r}_p \text{ in } V \\
2\pi & \text{if } \vec{r}_p \text{ on } \partial V, \text{ } \partial V \text{ smooth} \\
\gamma & \text{if } \vec{r}_p \text{ on } \partial V \text{ with solid angle } \gamma
\end{cases}
\]

and

\[
G_\alpha(\vec{r}_p, \vec{r}_q) = \frac{1}{4\pi} \frac{\varepsilon^{-jkr}}{r} 
\]

The symbol \( \int \) denotes the principal value integral over the surface \( \partial V \), i.e. the integral over the whole surface excluding an infinite sphere around the singularity of the Green’s function \( G \).
If the body is a very good conductor \((\kappa \to \infty)\), no equivalent magnetic sources have to be considered because of the condition \(\vec{n}_a \times \vec{E} \big|_{\partial V} = 0\). Enforcing the boundary condition
\[
\vec{n}_a \times \left( \vec{E}^i + \vec{E}^S \right) \big|_{\partial V} = 0
\]
and using the equation of continuity
\[
u^S = \frac{j}{\omega} \vec{\nabla} \cdot \vec{J}^S,
\]
the following Electric Field Integral Equation (EFIE) is obtained:
\[
\vec{n}_a \times \vec{E}^i \big|_{\partial V} = \vec{n}_a \times \left( \int_{\partial V} j \omega \mu_0 \cdot \vec{J}^S \cdot G_a(\vec{r}_p, \vec{r}_q) \right) + \frac{1}{\epsilon_\infty} \vec{\nabla} \int_{\partial V} G_a(\vec{r}_p, \vec{r}_q) \: da_q \big|_{\partial V}. \tag{6}
\]

Using the method of moments, the operator equation (6) can be transformed into a linear matrix equation [1, 5]. Hence, the unknown \(\vec{J}^S\) is given by solving a linear system of equations, where the excitation is represented by its inhomogeneous part. This method can be used for any kind of excitation, provided \(\vec{E}^i\) is given by an analytical expression or for every point on the discretized structures.

The procedures described above are implemented into the tool COMORAN, and the overall electric and magnetic field strength for arbitrary observation points can be calculated. In addition, the operator of the Magnetic Field Integral Equation (MFIE) is included, and the equivalence principle enables the prediction of radiation through apertures as well as the solution of scattering problems including dielectric bodies.

Figure 3 shows the models used by COMORAN for analyzing the electromagnetic behaviour of transmission lines [4, 5]. There is also a simplified model of the structure (b), which neglects the current component perpendicular to the lines. Due to this simplification a significant increase of computation speed without loss of accuracy is achieved. Furthermore, rules have been developed which help COMORAN to decide which transmission line model has to be used.

The discretisation of the lines is carried out automatically. The lines can be situated arbitrarily in the 3-dimensional space. When transmission-line nets consisting of (straight) sections of very different length have to be analyzed, equidistant segmentation schemes lead to a matrix equation of dramatically high dimension and possibly to incorrect results due to the extreme differences in the length of adjacent sections. It has to be mentioned that for example every via is very short compared to other sections of a net, and commonly they occur in great numbers on modern multilayer PCB. All these difficulties due to the equidistant segmentation can be avoided simply by employing so-called dynamic segmentation techniques. Algorithms for providing such dynamic segmentation schemes were developed and integrated into
the code, which accordingly is also capable of handling great variations of the current distribution.

4 Numerical Results

In practice the transmission line structures on PCB are very complex. The layout as well as the schematic has to be analysed in order to extract nets which might be critical with respect to radiation. Those nets can differ significantly from reflection- and crosstalk-critical nets.

As a first example the radiation analysis of the extracted nets given in Figure 5 (a) will be discussed. These structures might not coincide with lines which are reflection- and crosstalk- critical. Line 1 is driven by a clock circuit at \( s_1 = 0 \). All other transmission lines are viewed as passive scattering objects. It has to be mentioned that the lines are located in different layers with different dielectric regions (otherwise there would be artificial junctions where the lines intersect); this is also taken into account by COMORAN. In Figure 4 the shape of the clock signal is shown.

Figure 5 (b) shows the spectrum of the absolute value of the electric field component \( |E_x| \) at the observation point \( r_p = (0, 0, 10m) \). The radiated field is shown for the active line only (□) and for all scatterers depicted in Figure 5 (a) (×). It is easily seen, that in some parts of the spectrum the results differ significantly, which indicates, that in general all the scattering objects have to be taken into consideration. The difference between the calculations will even grow if an additional conductive body (e.g. a metallic enclosure of a clock circuit) is in the near ambient of the active line [6].

Additionally, a problem concerning irradiation will be discussed. Four parallel wires (bus structure) as depicted in Figure 6 (a) illuminated by an incident plane wave are investigated. The total length of each transmission line is 30 cm, and the excitation is given by

\[
\bar{E}(\bar{r}, t) = \frac{E_0}{2} + \sum_{n=1}^{\infty} E_n \vec{e}_x \cdot \exp(-j k_n \bar{r} + j \omega_n t)
\]

Figure 6 (b) shows the time dependence of the normalized incident wave function \( F(t) \) as well as the voltage at resistor R5 (dotted line). For comparison, the corresponding voltages for four straight parallel transmission lines of same length and distance is shown by the dashed line. The ratio of the amplitudes is nearby 3/2. This complies exactly with the ratio of
the x-directed straight lines of length 30cm and the x-directed sections of length 20cm of the arrangement depicted in Figure 6 (a).

Figure 6: Four parallel transmission lines (a) illuminated by an incident plane wave \(d=2\text{mm}, l1=l2=l3=10\text{cm}, R1=R2=R3 =R4=1\Omega, R5=R6=R7=R8=1\text{M}\Omega\) and the corresponding voltages (b):
- -: excitation \(F(t)\) (normalized)
- - - : voltage at resistor R5
.....: voltage at resistor R5 (straight lines)

An obvious disadvantage of a full wave analysis technique is its demand for large computer storage as well as long computation times. Therefore, it seems advisable to look for simplified but adequate geometrical model. Because the MOM transforms the integral equations into a system of linear equations, the first approach is to minimize its dimension. This could be achieved by simplifications of the transmission line geometry.

Finally a typical printed trace will be analysed. The reflection behaviour of a net with 45°-bends and stubs shown in Figure 7 (a) is compared to the one of a simplified net depicted in Figure 7 (b). The nets are driven and terminated by ACMOS devices. Both nets were analysed by the telegrapher equations (FREACS) as well as by using the EFIE (COMORAN) in order to compare these methods. The voltage drops for both configurations are depicted in Figures 8, respectively. It can clearly be observed that the results obtained from the telegrapher equations are nearly identical to those obtained from the EFIE analysis. The most important fact is obtained by comparison of the results of both, the original and the simplified net: it has to be stated that concerning reflection and radiation the simplified net shows nearly the same behaviour than the original one.
5 Conclusions

In order to solve EMC-problems within the development of electronic systems and components effectively, new CAD methods have to be applied. The question of how to deal with the problem of radiation and irradiation from/to PCB can be solved by using numerical procedures based on Maxwell’s equations. The tool COMORAN enables the prediction of the radiated and/or scattered fields by numerically solving the field integral equations based on Maxwell’s theory. This tool is integrated into the EMC-Workbench, which provides the electronic designer with a set of appropriate EMC-CAD tools. Furthermore, the EMC-Workbench is based on a framework approach so that the internal data flow and the design process is supported effectively.

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