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Prediction of Radiated Electromagnetic Emissions from PCB Traces Based on Green Dyadics

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Abstract

Because it costs to solve ElectroMagnetic Compatibility (EMC) problems late in the development process, new methods have to predict radiated electromagnetic emissions at the design stage. In the case of complex Printed Circuit Boards (PCBs) containing embedded microstrips and a large number of nets, a tradeoff between accuracy and simulation time must be found for this evaluation. In this paper the basic algorithm used within a new emissions predictive analysis tool: ElectroMagnetic Interferences Radiated (EMIR) is presented. It is able to take accurately into account the actual crossection between the metal plane and the air for each PCB trace. It is compared to theoretical formulas for validation. The effects of superstrate (cover) on a dipole radiation are described.

1. Introduction

The problem that designers of electronic circuits face today is not just to make sure that products work by themselves but they must also make sure that their products fit into a large community of electronic systems. The issue is Electromagnetic Compatibility (EMC). In particular, norms that limit the radiation of commercial equipments have been in use for many years in various nations (e.g. FCC, CISPR, VDE 0871-B, ...) and in 1996 the European Norms will be in operation. In many cases electronic equipment is mostly composed of Printed Circuit Boards (PCBs), so PCB's manufacturers will have properly to limit the radiation of the boards they produce. Currently, the most common method of handling ElectroMagnetic (EM) emissions is through compliance testing of the first prototype, already implemented.

In the case of a PCB it would be necessary to have the first board made by the manufacturer, and if it does not pass the tests, repeat again all the manufacturing processes. And this may delay the product's completion date and increase the unit cost of the product because the designer has not as many options available for correcting an EMC problem late in the development process. A solution to avoid this possible iteration is to predict the EM Field at the design stage, thanks to a computer-oriented analysis of EM radiated Interferences (EMI).

This proposal seems to be quite hard to solve because of the number of factors that influence the radiated EM field. But among these factors the microstrip structures that compose the nets play a major role especially in the frequency bands of the norms. The purpose of this article is to show how an algorithm used within a new emissions predictive analysis tool: ElectroMagnetic Interferences Radiated (EMIR) integrated in a powerful post-layout simulation environment is able to compute the EM field radiated by PCB traces.The algorithm that we will discuss is especially well suited to PCB having a complex crossection and many nets. Various approaches can be used for this problem. Using the Hertzian Radiating Dipoles Method the radiating conductors are divided into segments that can be considered as elementary Hertzian radiating dipoles. Provided that the length of each dipole is a fraction of the concerned wavelength, the current for each segment of the conductor may be assumed as constant. The current's value may be taken to equal the current at the center of the segment. In these conditions we can use the classical formulation for the E and H fields associated with an hertzian dipole placed at the origin. This method is quite quick but it assumes that each dipole is in the air with or without a ground plane. In reality there is one (or several) dielectric layer(s) between the conductor and the ground plane and there could be also dielectric covers above the conductor. This method suffers for a lack of accuracy for PCBs which have a complex crossection (embedded microstrips),

because it does not take into account for each microstrip structure the actual medium existing between the metal plane and the air.

Full wave approaches such as the Method Of Moments (M.O.M), or the Finite Element Method (F.E.M) can be utilized to provide near-exact numerical results. Their accuracy is essentially limited only by the computation power available. They can be used to simulate the radiation of generic structures including effects of box, enclosures. However, these methods are computationally too expensive if we consider complex PCBs with a large number of nets. A method that gives a good approximation of reality without taking too much time is needed. In fact the algorithm has to repeat the calculation of the field for all the critical radiating traces that can be a considerable number.

To predict the EM field radiated by PCBs having a complex crossection and a large number of nets it is necessary to find a tradeoff between accuracy and simulation time.

2.Electromagnetic formulation

The present method [1] utilizes the dyadic Green's function of the actual PCB medium that accurately takes into account the description of the PCB crossection.

The key point is the determination of the actual current distribution along each trace. The method just needs the knowledge of the voltage and the current on one of the two extremities of each rectilinear trace. This information is given in Time Domain by PRESTO [2] [3] [4] (Post-layout Rapid Exhaustive Simulation and Test of Operation) environment. A Fast Fourier Transform (FFT) is performed to obtain these information in Frequency Domain. Then the current waveform at any abscissa x on the trace is determined by means of the Transmission Line Theory (TLT) assuming that only the quasi-Transverse Electric Magnetic (TEM) mode is present along the trace. Then, the radiated EM field can be calculated using dyadic Green's functions.

Because of the lack of space, only the key points of the theory that determines the radiated EM field will be presented here. The electric and magnetic fields radiated from a surface current distribution are obtained by means of the Green Dyadic $\ddot{G}(\vec{r},\vec{r}')$ which can be interpreted as a transfer function between the surface current distribution $\vec{J}_\varepsilon$ and the electric field as shown in the following:

$$\vec{E}(\vec{r}) = -j\omega\mu_o \iint \ddot{G}(\vec{r},\vec{r}').\vec{J}_\varepsilon(\vec{r}')d(\vec{r}')$$

and

$$\vec{H}(\vec{r}) = \iint \nabla x\ddot{G}(\vec{r},\vec{r}').\vec{J}_\varepsilon(\vec{r}')d(\vec{r}')$$

where:

- r is the coordinate of the point where the electric field is computed (e.g. the measuring antenna position)
- r'is the coordinate of a point situated on the rectilinear trace.

In general, $\ddot{G}(\vec{r},\vec{r}')$ and $\nabla x\ddot{G}(\vec{r},\vec{r}')$ do not admit to a close form expression. However, with the assumption of being in far field conditions, the Green Dyadic can be substantially simplified. Specific measurements [5] made on PCBs proved that the far field condition can be used for frequencies above 30 MHz also for field calculation at 3 meters of distance, which justify the use of far field Green's functions.

Because it is difficult to calculate directly the electric field due to the current density of a segment buried in dielectric layers, the far field method applies the same current source on the observation point where the EM field has to be calculated and exploits the theory of reciprocity [6].

It assumes that the field arriving at the air/dielectric interface is a plane wave which can be divided into two components, the transverse electric (TE) and transverse magnetic (TM) modes. It then applies the Transmission Line Theory (TLT) to the propagation of these two modes in the embedded microstrip structure and produces two transfer functions for the real medium between the metal plane and the air. The following expression of the Electric field in far field conditions is obtained for any rectilinear radiating trace as shown in the Figure 1.

$$\vec{E}(\vec{R}) = -j\frac{Z_o}{2R\lambda_o}e^{-jk_oR}e^{jk_ohcos\theta}\{P_{ex}(\theta,\varphi)\vec{x}+P_{ey}(\theta,\varphi)\vec{y}+P_{ez}(\theta,\varphi)\vec{z}\}$$

where:

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = \text{wave impedance in the air}$$

$$K_o = \frac{2\pi}{\lambda_o} = \text{propagation constant}$$

λ_o = wave length in the air

h = distance between the metal plane and the conductor.

$P_{ex}(\theta,\varphi)$, $P_{ey}(\theta,\varphi)$ and $P_{ez}(\theta,\varphi)$ are essentially plane-wave transfer functions of the dielectric layered medium [1], that combine TE and TM plane-wave modes. They depend on:

- the spherical coordinates of the measuring antenna position in the local reference system of the trace.
- the spatial Fourier Transform of the current density on the trace.

The Figure 1(b) shows a crossection with two dielectric layers but the theory can take into account an arbitrary number of layers.
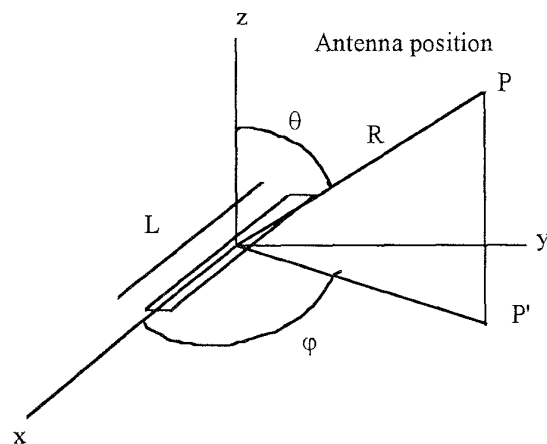
Figure 1(a): Representation of a rectilinear radiating trace, L: net length, R: "antenna" position where the EM field is computed
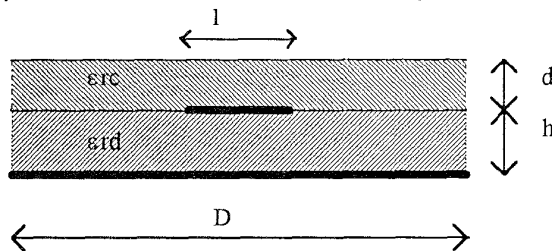

Figure 1(b): Crossection view, D: metal plane length, trace width

3. EMIR: a tool integrated into a post-layout framework

This formulation takes into account, for each PCB trace, the presence of dielectric layers between the metal plane and the air. And it does not need a discretisation of each trace. This algorithm has been integrated into the PRESTO environment. It is a high performance post-layout quality check software that performs accurate electrical simulations of entire systems (PCBs, MultichipModules (MCM), interconnections) to evaluate Signal Integrity (SI), as well as EMC problems like crosstalk, power and ground distribution noise, susceptibility to conducted noise due to internal or external sources. This integration allows to take advantage of the potential of SPRINT [7] (Simulation Program of Response of Integrated Network Transients) simulator engine embedded in PRESTO. In fact all nets can be analysed in one single run so that all the parasitic effects (reflections, crosstalk, mismatches, package and board ground bounce, actual VCC/GND effects) are simultaneously taken into account. Modelling capabilities available in PRESTO can use Time Domain

Reflectometry (TDR) measurements to obtain very accurate electrical models for both passive and active components. This is a very important issue especially for high speed systems like Telecom apparatus [8] and for EMC predictive analysis like conducted noise propagation.
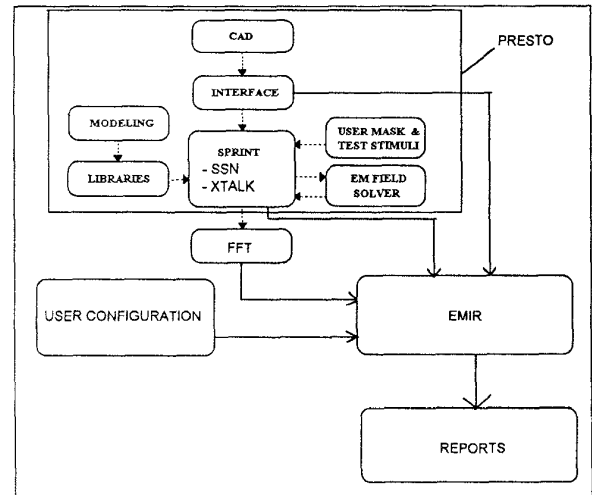

**Figure 2: EMIR integrated into a framework**

First of all, EMIR takes the geometrical and topological data of each rectilinear segment that composes the nets from PRESTO environment (Figure 2). PRESTO executes a Signal Integrity simulation of all the board and produces the actual current distributions on the nets, in the time domain. A Fast Fourier Transform (FFT) is performed in order to obtain voltage and current waveforms in the frequency domain. Finally EMIR calculates the radiated EM field for each segment and sums all these contributions in order to find the total radiated EM field. According to the user configuration (antenna position, chosen norm) EMIR displays the frequency spectrum of radiated emissions per single nets, groups of user-selected nets or for the entire board versus the FCC, VDE, CISPR, VCCI or user-specified limits at user specified distances.

4. Numerical validations and results

Although the dyadic Green's method can be used for an arbitrary set of traces on a multilayers PCB, we will employ EMIR for the analysis of two simple structures for which the radiation patterns are well known, in order to validate the approach and the implementation.

As a first example the radiation analysis of a short rectilinear trace above a metal plane will be discussed. We will compare EMIR results with the theoretical

ones for an Hertzian dipole, in order to see how the Green-Dyadic based algorithm follows a variation of the distance between the metal plane and the radiating dipole. The crossection of the structure is shown in Figure 3. The "antenna position" is as shown in the Figure 1(a).
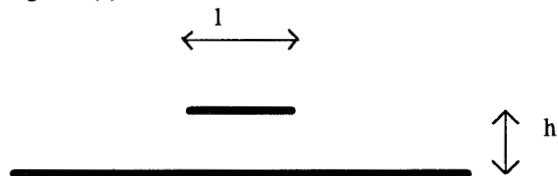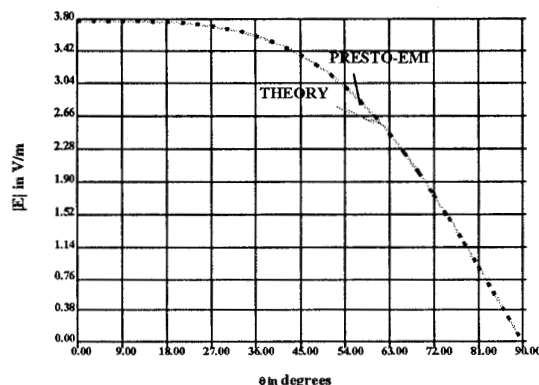

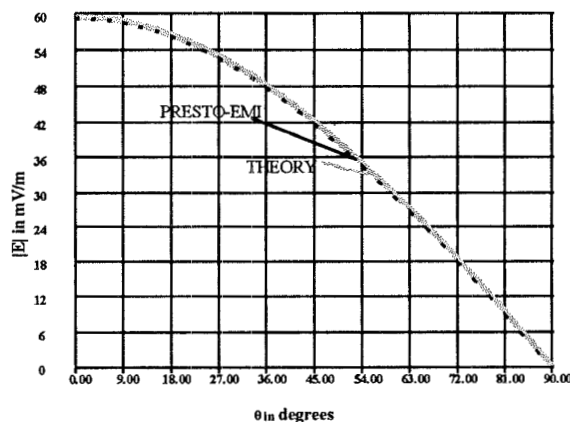**Figure 3: Hertzian dipole above a metal plane**
We took:
- l (dipole width) = 1mm
- L (dipole length) = 0.4 m
- f = 75 MHz => λ = 4 m
- I (current intensity) = constant = 1 A
- R ("antenna position") = 10 m

Notice that $l \ll L$ and $L \ll \lambda$. The results can be tested against the classical approach [9] of an array of two identical vertical Hertzian dipoles.


Figure 4(a): H-plane pattern for an Hertzian dipole above a metal plane (h = 1m)

The patterns of Figure 4 show the comparison of the two methods for the H-plane (θ from 0 to 90 degrees and φ = 90 degrees) in two cases: h = 1 m (a) and h = 1 cm (b). We can see a good conformity between EMIR and the used classical formula. The dyadic Green's method approximates the theoretical results with a precision of 1 E -3. The more the radiating dipole is closed to the metal plane, the less it radiates because of the influence of the image dipole. When the observation point is placed on the metal plane, |E| becomes equal to zero respecting the interface condition.

Figure 4(b): H-plane pattern for an Hertzian dipole above a metal plane (h = 1 cm)
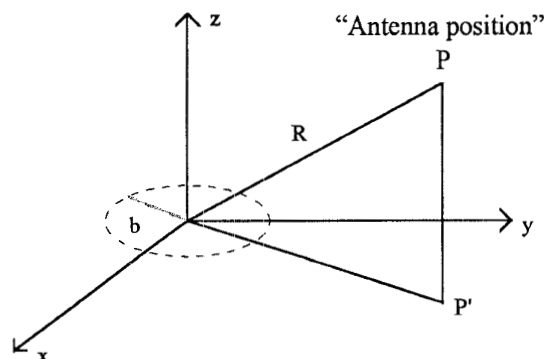
Figure 5: Radiating loop antenna made of 16 electrically small dipoles connected together in the xy plane.

Additionally, the radiation from a loop antenna can be compared to the classical [9] results for an elementary magnetic dipole

The structure is shown in Figure 5. Sixteen short segments are connected together in order to make a loop with an equivalent radius b = 0.01 m, with an operating frequency of 50 Mhz.

The H-plane pattern of Figure 6 shows the comparision of the two models with R (Antenna position) = 10 meters, I (current intensity) = 1A. We observe an excellent agreement between the two methods. The dyadic Green's method approximates the theoretical results with a precision of 1 E-3.

Finally, the radiation of an embedded microstrip will be analysed in order to see the effects of the dielectric cover on the radiation.
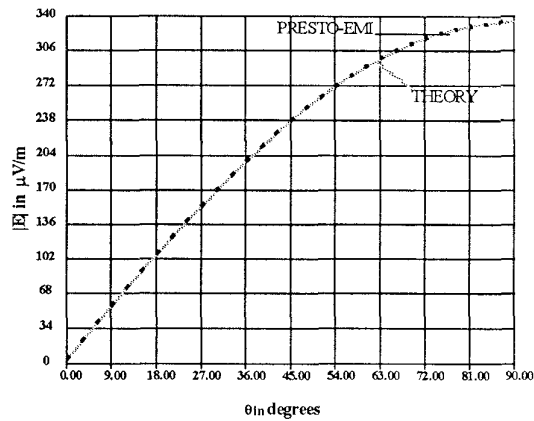
Figure 6: H-plane pattern for the loop antenna

The crossection of the structure that has been studied is shown in Figures 7. The "antenna" position is always represented in the Figure 1(a).
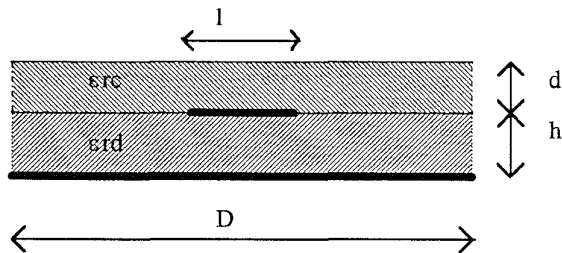

Figure 7: embedded microstrip

It is an Hertzian dipole embedded into a substrate. We will discuss the influence of the presence of a superstrate (cover) on the dipole radiation. The superstrate layer (cover) may prove beneficial or detrimental to the dipole radiation characteristics, depending on the thickness of the substrate and cover, as well as relative dielectric and permeability constants. We chose the case in which the dielectric constant in the cover is superior to that of the substrate.

The results obtained with EMIR are compared with those using Sommerfeld's method [10] [11]. This last one was used in [12] to calculate exactly the radiation of the Hertzian dipole embedded into a substrate in order to understand superstrate effects on Printed Circuit Antennas (PCA). The same geometrical data as [12] are taken:

- H-plane (θ from 0 to 90 degrees and ϕ = 90 degrees):
  - h (substrate thickness) = 0.138 λ = 0.552 m with λ = 4 m (f = 75 Mhz)
  - d (cover thickness) = 0.011 λ = 0.044

- l (dipole width) = 1mm
- εrd (dielectric constant in the substrate) = 2.1 (Teflon)
- εrc (dielectric constant in the cover) = 12.5 (GaAs)
- L (dipole length) = 0.4 m
- R ("Antenna"position) = 10 m
- E-plane (θ from 0 to 90 degrees and ϕ = 0 degrees): only one parameter changes: d = 0.0925 λ = 0.37 m
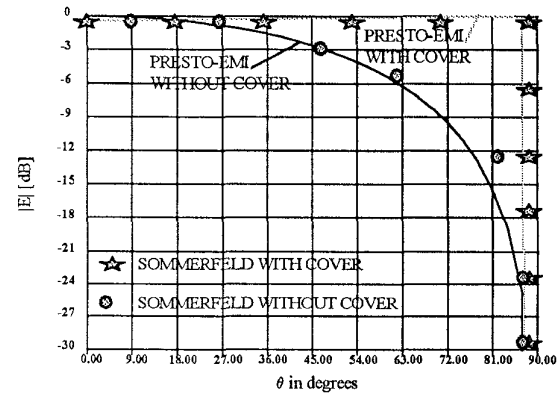

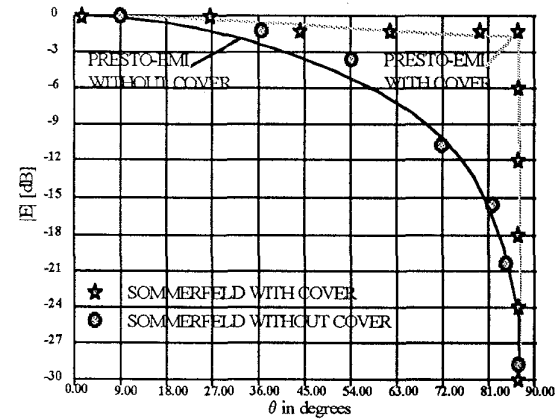**Figure 8(a): H-plane pattern for the (embedded) microstrip**

Figure 8(b): E-plane pattern for the (embedded) microstrip

The need of a comparison with another theory made the authors choose physical and geometrical data for the embedded microstrip far from those one can find in common PCBs. But the effect of the cover on typical PCB trace radiation has been also observed in the same way. The H-pattern and E-pattern of Figure 8(a) and 8(b) show the comparison of the two models. We observe a good conformity of EMIR results with Sommerfeld's method. In fact in absence of dielectrics the total field is generated by the interference between

the actual source (in free space) and its image, which results in a null field along θ = 90 degrees. In presence of dielectrics this interference is destroyed, with a resulting more omnidirectional radiation pattern; alternatively this can be viewed as the effect of the presence of waves that are partially guided between the metal plane and the air/dielectric interface. Because of the potential difference introduced by the dielectric cover, the importance of a simulation tool that correctly incorporates multilayer structures is evident.

An example is given on an actual digital PCB which contains 340 nets, 368 components and 8 layers. Radiation spectrum of 100 nets at 10 meters obtained with EMIR is given in Figure 9.
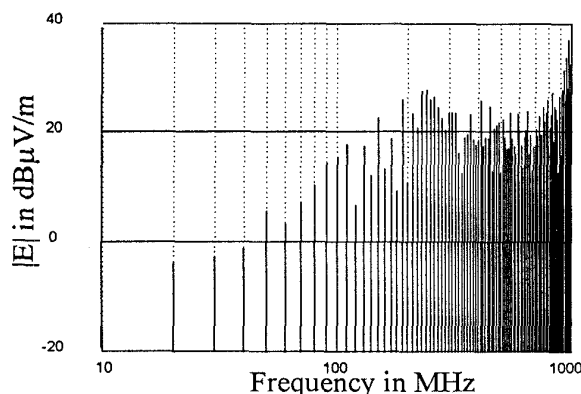
Figure 9: Radiation spectrum of 100 nets at 10 meters.

This radiation spectrum meets the requirements as specified in EN55022 norm [13] for class A equipement (commercial equipement in protected area). Timing results on a HP 750 workstation are the following:
- PRESTO simulation on all nets: 10 minutes
- FFT on 100 nets: 4 minutes
- EMIR on 100 nets: 1 minute

Radiation spectrum and SI results can be obtained on such a PCB in 15 minutes. Experimental validation of simple cases and more complex benchmarks are under way.

5. Conclusions

In order to accurately pinpoint and quantify EMI problems on complex PCBs containing a large number of nets, a tradeoff between accuracy and simulation time must be found. The algorithm used within EMIR enables the prediction of the EM field radiated by PCB traces, taking into account accurately the description of the PCB crossection by means of appropriate transfer functions based on the dyadic Green's function. It considers effects of substrate and superstrate (cover) of

the traces, effects that can have a great impact on radiation patterns. Timing results make available to simulate the radiation spectrum of all the nets of a complex PCB. The presented algorithm is opened to future developments (prediction of radiations due to common mode current, striplines, VCC/GND planes). Linked to the PRESTO environment, EMIR becomes fully integrated in a framework that checks quickly layouts from the point of view of EMC/SI.

Acknowledgements

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