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Computer Aided Analysis of EMI Radiated from Printed Circuit Boards

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Abstract

In this paper, we describe a procedure for computer aided characterization of radiated emissions of printed circuit boards. Noisy electromagnetic fields are thereby modeled as Gaussian stochastic processes. From the auto- and cross-correlation functions of the fields, sampled at different locations, we obtain the spectral energy density on a plane close above the device under test. Based on a characterization by field correlations, we can assess the impact of different parts of the printed circuit board on other parts of the system due to radiated EMI.

1 Introduction

Electromagnetic interference (EMI) is omnipresent in contemporary electronic devices. Data rates for communication between different components within a device, even within the same printed circuit board (PCB) can be limited due to the EMI radiated by other digital and analog circuits. For designing communication interfaces in densely integrated environments, it is thus essential to know the mutual EMI impact of different parts of the system on each other. The actual signals transferred in such an on-board communication scenario remain in general unknown and the electromagnetic (EM) fields which they cause need to be treated as stochastic EM fields for consideration of radiated EMI [1]. We are ultimately interested in the spectral energy density at certain regions of the PCB, where other communication channels, i.e. transmission lines or wireless channels are located [2]. The spectral energy density is directly related to the auto-correlation spectra of the EM fields at each point in space [1]. Moreover, the spectral energy density at an observation point depends on the degree of correlation between multiple source signals. An approach for time-domain modeling of noisy electromagnetic fields was presented in [3]. Numerical solutions for auto- and cross-correlation functions using time-domain Green's functions have been discussed within the framework of the transmission line matrix method [4], [5].

We present simulations, investigating a PCB design with a pair of transmission lines excited. The impulse responses for the excited ports to a set of observation points above the PCB are calculated numerically using CST Microwave Studio. We excite the transmission lines with signals with different degree of correlation and monitor the spectral energy density above the whole PCB.

2 Stochastic Field Modeling and Simulations

Stochastic electromagnetic fields with Gaussian probability distribution can be described by the field auto- and cross-correlation functions. The noisy electromagnetic field close to an electronic device consists of a superposition of the radiated EMI of all quasi random signals and noisy processes within the device. Hence, signal and field correlations play an important role in the analysis of signal integrity and electromagnetic compatibility, as they are characteristics allow a description on how one part of the device influences another. The correlation function of two stationary random processes $s_i(t)$ and $s_j(t)$ is given by [6]

$$c_{ij}^{s}(\tau) = \left\langle\!\left\langle s_i(t)\, s_j(t-\tau) \right\rangle\!\right\rangle , \tag{1}$$

where the brackets $\langle\!\langle \dots \rangle\!\rangle$ denote the ensemble average. For ergodic random processes, the ensemble average can be substituted by time mean value, such that

$$c_{ij}^{s}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} s_i(t)\, s_j(\tau - t)\, \mathrm{d}t . \tag{2}$$

Let us now consider a PCB with N transmission lines, excited with either pairwise correlated, pairwise partially correlated, or uncorrelated stationary Gaussian random signals. The degree of correlation for all pairs of stochastic signals $s_i(t)$ and $s_j(t)$ is given by the correlation $c_{ij}^{s}(\tau)$. The whole PCB and the surrounding free-space region form a linear time-invariant (LTI) system, which can be described by an impulse response $Z(\boldsymbol{x},t)$, describing the propagation from each port exciting a transmission line on the PCB to all observation points summarized in the vector $\boldsymbol{x}$, located on a virtual plane close to the surface of the PCB [6]. With a CAD model of the PCB available, one can calculate these impulse responses numerically. If multiple signal lines are excited with either correlated or uncorrelated signals, we can observe the field-field correlations for all pairs of observation points specified on a mesh grid on a virtual plane above the surface of the PCB. The elements of the field-field correlation matrix for the magnetic field is given by [1]

$$c_{mn}^{H_p}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} H_p(\boldsymbol{x}_m,t)\, H_p(\boldsymbol{x}_n,t-\tau)\, \mathrm{d}t , \tag{3}$$

where $H_p(\boldsymbol{x},t)$ is the magnetic field at position $\boldsymbol{x}$ with polarization $p \in \{x,y\}$. Also field cross-polarization correlations may be considered. We evaluate the spectral energy density for a grid of observation points, based on the computed impulse responses for arbitrary signal correlations. The magnetic field at each observation point, excited by a superposition of N random signals propagating along transmission lines on the PCB, is given by the convolution [6]

$$H_p(\boldsymbol{x},t) = \sum_{i=1}^{N} \int_{-\infty}^{\infty} s_i(\tau) Z_i^{H_p}(\boldsymbol{x},t-\tau)\,\mathrm{d}\tau\,, \tag{4}$$

where $s_i(t)$ is the signal propagating along the i-th transmission line. The field-field correlations are given by

$$c_{mn}^{H_p}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \sum_{i=1}^{N}\sum_{j=1}^{N} \int_{-T}^{T}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Z_i^{H_p}(\boldsymbol{x}_m,t'')\, s_i(t) \times \times s_j(t'-t)\, Z_j^{H_p}(\boldsymbol{x}_n,\tau-t'-t'')\,\mathrm{d}t\,\mathrm{d}t'\,\mathrm{d}t''\,. \tag{5}$$

With the correlation information $c_{ij}^{s}(\tau)$ of the i-th and the j-th signal from equation (2), we can simplify equation (5) and obtain

$$c_{mn}^{H_p}(\tau) = \sum_{i=1}^{N}\sum_{j=1}^{N} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Z_i^{H_p}(\boldsymbol{x}_m,t'')\, c_{ij}^{s}(\tau-t') \times \times Z_j^{H_p}(\boldsymbol{x}_n,t'-t'')\,\mathrm{d}t'\,\mathrm{d}t''\,. \tag{6}$$

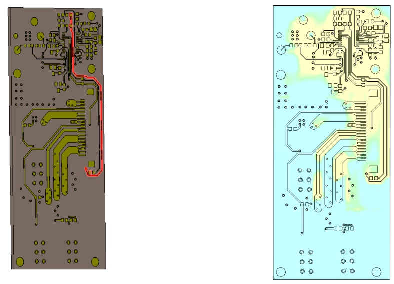
This equations relates the auto- and cross-correlation functions of the stochastic signals propagating along transmission lines on the PCB to the auto- and cross correlations of the magnetic fields at all pairs of observation points. The spectral energy density at each observation point x_m can be obtained by the Fourier transform of the auto-correlations $c_{mm}^{H_p}(\tau)$. It is given by

$$W_{\mathrm{mag}}(\omega) = \frac{\mu_0}{2} \int_{-\infty}^{\infty} c_{mm}^{H_p}(\tau)\, \mathrm{e}^{\mathrm{j}\omega\tau}\,\mathrm{d}\tau\,. \tag{7}$$

3 Numerical Example

Let us now consider an example of an actual PCB. Figure 1(a) shows a 3D model of the PCB in CST Microwave Studio. There are two high-speed signal lines close to each other which are marked in red. We are interested in the radiated EMI due to these two transmission lines, under consideration of the correlation between the stochastic data signals propagating along the lines. In Fig. 1(b), the normalized spectral energy density for a frequency of 4 GHz above the PCB is shown if only the first transmission line is excited.

Both transmission lines are excited with Gaussian pulses using discrete ports in CST Microwave Studio. The impulse responses of the magnetic fields are recorded on a rectangular 9×20 observation grid in a plane parallel to the PCB with 5 mm grid spacing in both directions. Figure 2 shows the impulse responses $Z_1^{H_x}(\boldsymbol{x}_m,t)$ for the x-polarized magnetic fields of the observation points along the line $x = 35$ mm, which is closest to the excited transmission lines. These impulse responses were obtained for only the first transmission line excited.



(a) PCB (b) SED

Figure 1. Model of PCB with transmission line for data transfer and spectral energy density.

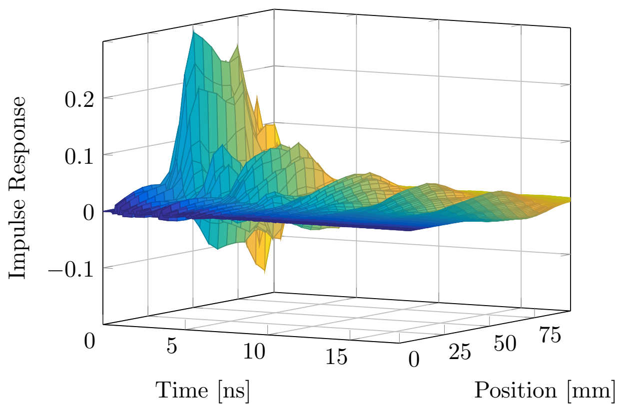


Figure 2. Impulse response over time along $x = 35$ mm for different y-positions for port 1 excited.

4 Conclusions

We presented a method for computer aided analysis of noisy electromagnetic fields on PCBs, based on evaluating field-field correlations. The field-field correlation matrix is obtained by a convolution of the correlation matrix of the signals propagating along transmission lines on the PCB and the impulse responses of the LTI system formed by the transmission line and the free-space propagation to the observation points. The impulse responses can be obtained using commercial full-wave solvers like CST Microwave Studio.

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