Cyclostationarity in EMI Assessment of PCBs

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***Abstract*—Printed circuit boards (PCBs) are a source of radiated electromagnetic interference (EMI). Signal data transfer occurring on digital circuits can be considered in EMI modeling as a random process with cyclostationary properties. Electromagnetic fields originating from random or quasi-random source processes with stationary Gaussian probability distribution can be characterized by field-field correlations. For cyclostationary processes, the analysis procedure needs to be extended. In this contribution, we discuss the exposure of cycostationarity in the context of near field correlation analysis.**

I. Introduction

Modeling of electromagnetic (EM) field emissions originating from printed circuit boards (PCBs) based on near field scanning data and correlation analysis can significantly enhance modeling accuracy. Given the increasing number of wireless and mobile electronic devices, increasing data rates and the required low power operations, there is a strong need for efficient EMC aware CAD techniques for computer aided fabrication of circuits.. Electromagnetic emissions stemming from Gaussian noise can be fully characterized by field-field correlations, i.e. using second order moments of the EM field data [1], [2]. For noise emission originating from digital circuit boards, cyclostationarity should be considered [3]–[7]. The characterization of the near-field electromagnetic emissions from an electronic device can be achieved by two-probe time-domain measurements by using high speed real-time digital oscilloscopes along with an automated sequential scanning system for the near-field probes, as illustrated in Fig. 1. By removing the periodic sample mean function, the hidden cyclostationarity of a data transferring process on the device under test is exposed.

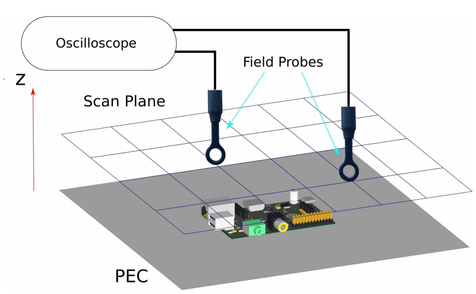

Fig. 1. Device under test in a two field probe measurement setup

In this contribution, we discuss near field correlation analysis and, for this purpose, the exposure of cycostationarity.

II. Stochastic EM fields and Cyclostationary

Cyclostationary signals are non-stationary signals which, however, exhibit a periodicity in their statistics. Consider two real valued signal vectors $\boldsymbol{s}_i(t)$ and $\boldsymbol{s}_j(t)$, then their time shifted time-domain correlation matrix is obtained as

$$\boldsymbol{c}_{ij}(t,\tau) = \left\langle \boldsymbol{s}_i(t-\tau/2)\boldsymbol{s}_j^T(t+\tau/2)\right\rangle . \quad (1)$$

The superscript ^{T} denotes the transpose vector. For a stationary process, dependence on the global time t vanishes, and for a cyclostationary process, the time dependence of the statistic expectation values becomes periodic with a period T_0, i.e. we find

$$\langle c_{ij}(t+T_0,\tau)\rangle = \langle c_{ij}(t,\tau)\rangle . \quad (2)$$

Upon determining the period T_0, we define the so-called cycle frequencies $nf_0 = n\omega_0/2\pi$, and use those to perform a Fourier series expansion of the correlation function, i.e.

$$\boldsymbol{c}_{n,ij}(\tau) = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} \boldsymbol{c}_{ij}(t,\tau)\mathrm{e}^{-\jmath n\omega_0 t}dt\,, \quad (3)$$

where $\boldsymbol{c}_{n,ij}(\tau)$ are the cyclic autocorrelation functions [3], [7]. By Fourier transformation of the cyclic correlation functions we obtain the cyclic correlation spectrum

$$\boldsymbol{C}_n(\omega_1) = \int_{-\infty}^{+\infty} \boldsymbol{c}_n(\tau)\mathrm{e}^{\jmath\omega_2\tau}d\tau\,. \quad (4)$$

The two-dimensional spectral power density matrix can thus be given in a series expansion of cyclic correlation spectra

$$\boldsymbol{C}(\omega_1,\omega_2) = \iint_{-\infty}^{+\infty} \boldsymbol{c}(t_1,t_2)\mathrm{e}^{-\jmath(\omega_1 t_1-\omega_2 t_2)}dt_1 dt_2 = \sum_{n=-\infty}^{+\infty} \boldsymbol{C}_n(\omega_1)\delta(\omega_1-\omega_2-n\omega_0)\,. \quad (5)$$

This leads to a compact formulation for a transformation of the signal correlation matrix for a vector of input signals to the correlation matrix for the signal on the output ports of a linear network, as discussed in [3].

For stochastic electromagnetic fields we introduce correlation dyadics for characterizing the electric or the magnetic field, or the source current distribution, i.e. for the cyclostationary stochastic electric field with the time-windowed electric field amplitude spectrum $\boldsymbol{E}_T(\boldsymbol{x}_a, \omega)$ we introduce [1]

$$\underline{\underline{\Gamma}}_E(\boldsymbol{x}_a, \boldsymbol{x}_b, \omega_1, \omega_2) = \lim_{T\to\infty} \frac{1}{2T} \langle \boldsymbol{E}_T(\boldsymbol{x}_a, \omega_1) \boldsymbol{E}_T^{\dagger}(\boldsymbol{x}_b, \omega_2) \rangle \,,$$

where the subscript $_T$ denotes the amplitude spectrum of the field, time-windowed by a rectangular window covering the time interval $[-T, T]$. The excitation current density is described by the correlation dyadic $\underline{\underline{\Gamma}}_J(\boldsymbol{x}_a, \boldsymbol{x}_b, \omega_1, \omega_2)$. By expanding the correlation dyadics and finding their cyclic correlation spectra, analog to (3)-(5), a compact transformation of those cyclic correlation spectra can be given as [3]

$$\underline{\underline{\Gamma}}_{E,n}(\boldsymbol{x}_a, \boldsymbol{x}_b, \omega) = \iint_V \boldsymbol{G}_{EJ}(\boldsymbol{x}_a - \boldsymbol{x}'_a, \omega) \times \qquad (6)$$
$$\underline{\underline{\Gamma}}_{J,n}(\boldsymbol{x}_a, \boldsymbol{x}_b, \omega) \boldsymbol{G}_{EJ}^{\dagger}(\boldsymbol{x}_b - \boldsymbol{x}'_b, \omega - n\omega_0) d^3x'_a d^3x'_b \,,$$

where $\boldsymbol{G}_{EJ}(\boldsymbol{x} - \boldsymbol{x}', \omega)$ is the Green's dyadic relating the electric field $\boldsymbol{E}(\boldsymbol{x}, \omega)$ to the source current density $\boldsymbol{J}(\boldsymbol{x}, \omega)$.

III. Revealing Properties of Cyclostationarity

While consideration of cyclostationarity is essential for field-field correlation based characterization of radiated EMI, these cyclostationary properties are often hidden.

In the subsequent example we have generated a numerical realization of signal representing a random bit sequence with a length of 256 bit, at a bit rate of $R = 2.3$ GHz, and using binary phase shift keying. Gaussian band limited noise is added to the signal. This sample sequence s is shown in Fig. 2 and shall represent the signal captured by a magnetic near-field probe close to a signal line above a PCB serving as a device under test (DUT). Using cyclic averaging, with a period $T_0 = 9.3$ ns chosen at random, we compute the cyclic autocorrelation function (ACF) shown in Fig. 3. Isolating the cyclic ACF for $\tau = 0$ s in Fig. 4 and comparing it to the autocorrelation (AC) spectrum of the non-averaged AC of s, shows that the cyclic property due to the bit rate at 2.3 GHz is revealed clearly by the cyclic ACF only.

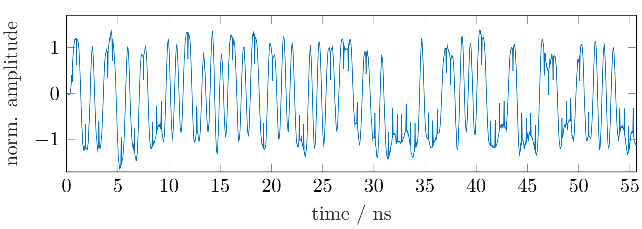

Fig. 2. Numerical realization of noisy signal.

An observer for EMI has to be able to assess a DUT without prior knowledge of its detailed operation. However, simultaneous operations of different type on the DUT, the quasi-randomness of the data being processed, various contributions of noise, and variation in clock frequencies obfuscate cycle times. Increased complexity in real life scenarios renders identification of cyclostationarity by simple inspection challenging.

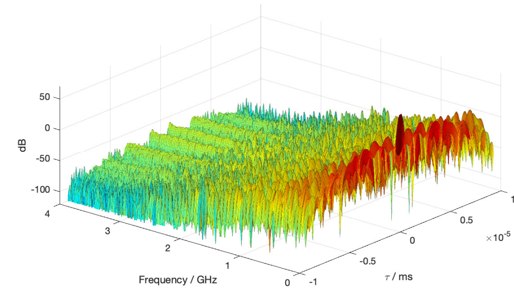

Fig. 3. Cyclic autocorrelation function of sample signal s.

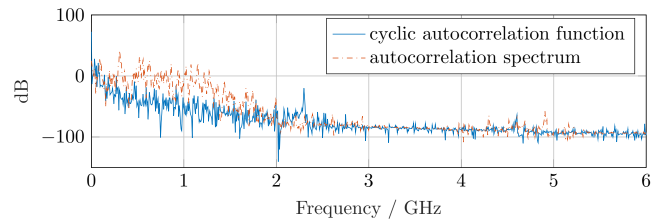

Fig. 4. Comparison of the cyclic ACF at $\tau = 0$ s and the autocorrelation spectrum of s without averaging.

IV. Conclusion

In this paper we have discussed cyclostationarity in the context for EMI assesment of PCBs. Correlation analysis provides a technique to model radiated emissions from digital circuits. However, commonly digital circuits exhibit cyclostationary processes, and hence, cyclostationarity has to be accounted for. These cyclostationary properties are often hidden from the observer in the resulting signal correlation functions and can be revealed by cyclic averaging. There is further need for devising analysis strategies to deal with arbitrary electronic devices in correlation based EMI characterization.

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