Challenges of time domain measurement of field-field correlation for complex PCBs

C Smartt, D W P Thomas, H Nasser, M Baharuddin
The George Green Institute of Electromagnetics Research
University of Nottingham
Nottingham NG7 2RD, UK
e-mail: chris.smartt@nottingham.ac.uk

G Gradoni, S C Creagh, G Tanner
School of Mathematical Sciences
University of Nottingham
Nottingham NG7 2RD, UK

Abstract—**Measurements of field-field correlation in the time domain can be used to characterize stochastic broadband emissions from complex sources. A two-probe scanning measurement system is developed and used to sample the stochastic emissions in the near-field of two such sources: a reverberation chamber with a rectangular aperture and a generic printed circuit board (PCB). We show that measured field data can be utilized in numerical wave propagation schemes to predict the stochastic fields in and radiated from a packaged device.**

Keywords—near field scanning; printed circuit boards; time domain measurement; field correlation function

I. INTRODUCTION

Realistic sources of EM radiation are very complex. The radiated field of a device may be composed of intentional sources i.e. transmitters used for communication with other devices as well as other, unintentional sources of radiation due to the distribution of currents in the device as a result of its normal operation. Modern digital communication systems operate in a manner such that the intentional sources of radiation may vary in frequency, they may only radiate packets of data in discrete time windows and the amplitude of the radiated field may also be adapted so as to minimise the power required to establish a communication channel. A significant contributor to unintentional emissions of a device is often the power supply systems using electronic power converters. Power converter emissions are largely deterministic however the amplitude and frequency of emissions may be modulated to some extent by the load on the system. An additional contribution to EM emissions may arise from the operation of digital circuits in which the currents giving rise to the emissions are due to the digital signals within a system. These signals depend on the operating mode of the device and the data being processed [1]. The common factor in these emissions processes is their random nature.

The prediction of the behaviour of a system when packaged in its operating environment, possibly in the presence of other equipment is useful in the assessment of the potential for interference between systems.

Deterministic modelling techniques such as TLM or FDTD may provide useful information in EMC analysis, however, these methods do not readily provide information regarding statistical measures of the fields, which may be of significance in the analysis of performance.

One approach to deal with the difficulty arising from the complexity of random sources is to use a statistical description of electromagnetic field sources. Recently approaches to the analysis of stochastic RF emissions which operate on field-field correlation functions [2] rather than the fields themselves have been introduced. The algorithms for propagating the statistical properties of electromagnetic fields are based on Green"s function techniques [3] and a Wigner function approach [4,5].

These statistical field propagation methods rely on a characterisation of the source field-field correlation which may be obtained in practice by a near field scanning technique[6].

Fig. 1 shows a complex microcontroller PCB [7] with a near field scanning grid superimposed. Near field scanning of a source by mechanical means is a time consuming process. The determination of the field-field correlation function requires the simultaneous measurement of fields at every combination of pairs of points in the scan plane i.e. for N scan points it is an order N^2 process. It is recognized that a fine resolution two probe scan of a system is not a practical proposition hence the motivation to study the field-field correlation of realistic sources. The study of the form of the correlation function for realistic sources and its variation with distance away from the source will aid us in developing the most efficient strategy for the measurement of the field-field correlation characteristics of complex systems.

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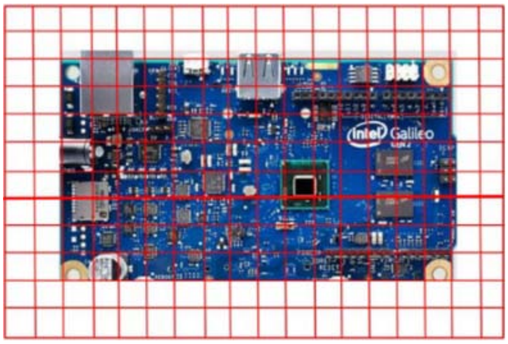


Fig. 1. PCB and 2D scanning grid, the thick line indicates the 1D scan line used for measurement of the field field correlation matrix in section IV.

This paper describes the measurement of field-field correlation functions in two different scenarios. The first is a frequency domain measurement with the purpose of providing data for the validation of the field-field correlation propagation algorithm based on the Wigner function technique [2,3]. The second scenario is the measurement of a microcontroller PCB, a realistic complex source. This source is used to study the characteristics of the field-field correlation function and the most efficient way in which the correlation function of such sources can be characterised by measurement.

II. TECHNIQUES FOR THE ANALYSIS OF STOCHASTIC ELECTROMAGNETIC FIELDS

We can define the field-field correlation function $C_\Phi(x_1,x_2,\tau)$ of the field $\phi(x,t)$ as

$$c_\Phi(x_1,x_2,\tau)=\lim_{T\to\infty}\frac{1}{2T}\int\Phi_T(x_1,t)\Phi_T(x_2,t-\tau)dt \qquad (1)$$

Where ϕ_T denotes the time field windowed function which is zero for $|t|\geq T$. The Fourier Transform of the correlation function gives the correlation spectrum:

$$\Gamma_\Phi(x_1,x_2,\omega)=\int_{-\infty}^{\infty}c_\Phi(x_1,x_2,t)\exp(-j\omega t)dt. \qquad (2)$$

The correlation spectrum may be obtained directly from time domain fields by

$$\Gamma_\Phi(x_1,x_2,\omega)=\lim_{T\to\infty}\frac{1}{2T}\left\langle\Phi_T(x_1,\omega)\Phi_T^*(x_2,\omega)\right\rangle \qquad (3)$$

Where $\langle\ \rangle$ denotes a suitable ensemble average.

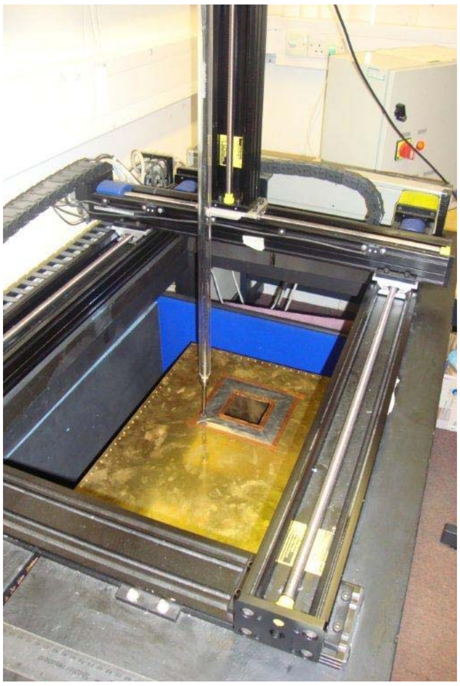
Knowledge of the near field correlation spectrum allows propagation algorithms to be applied which can evaluate the correlation spectrum anywhere in space. Propagation algorithms may be based on a Green‟s function formulation as in [1]. Alternatively an approach based on the Wigner distribution function [3,4] can be employed, in which the correlation function is Fourier transformed into phase space, the phase space density propagated using a Wigner function propagator and subsequently transformed back into real space. The correlation spectrum is useful in that it directly gives the spectral energy density.

III. MEASUREMENT OF FIELD-FIELD CORRELATION BY MECHANICAL SCANNING

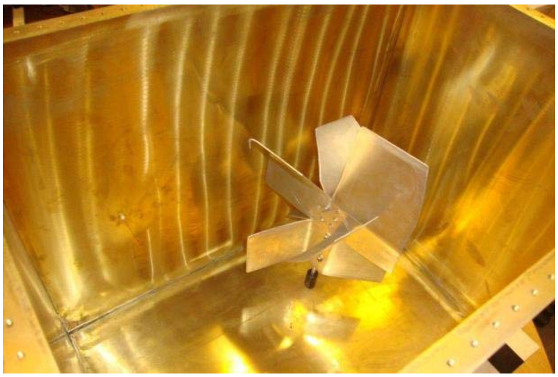
In order to apply the field-field correlation analysis in a practical scenario we need to characterise the source of radiation by measurement. In the work described here we describe frequency and time domain techniques which we have applied to the challenging task of gathering field-field correlation data for real systems.

A. Single probe, frequency domain measurement

The development of novel field-field correlation propagation analysis algorithms requires data for validation of the methods and their implementation. This requirement has driven us to develop a validation measurement which is relevant to the study of the propagation of electromagnetic field propagation from random sources in a feasible and well controlled manner. The source of random fields consists of a cavity with an 8cm×8cm aperture in the lid as shown in Fig. 2. The source is a monopole inside the cavity, fed from the outside of the cavity through a bulkhead connector. The electromagnetic field radiated from the aperture is randomised by a paddle within the cavity, driven by a stepper motor. We use a vector network analyser (Agilent E8362B) to perform the measurement. Port 1 of the network analyser is connected to the monopole within the cavity and port 2 to a magnetic field probe which is scanned mechanically over a 30cm×30cm area centred on the aperture.



2a) Mode stirred cavity with an aperture scan under way.



2b) Cavity with the aperture panel removed to show the monopole antenna and rotating paddle

Fig. 2. Single probe scanning measurement on a mode stirred cavity aperture.

A frequency domain measurement of both magnitude and phase of coupling between the monopole and the field probe (S_{21}) at each point on the scan plane is performed for a large number of different paddle positions. This set of measurements for different paddle positions constitutes the ensemble of data required for the field-field correlation calculation, Eq. (3). The vector network analyser provides us with a phase reference for the electromagnetic field source in the measurement. Since we have a stable phase reference we can calculate the correlation spectrum via Eq. (3) from measurements obtained by scanning a single probe over the source plane.

At a given angular frequency, ω, a two dimensional scan over an (x,y) plane gives rise to a 4 dimensional correlation dataset $\Gamma_{\Phi}(x_1, y_1, x_2, y_2)$. This provides some difficulty in the visualisation of the correlation data. Figure 3 shows a part of this dataset gathered from a scan of the cavity aperture. The figure shows a visualisation of the magnitude of the correlation of the field over the whole scan plane with the field measured at the centre of the aperture i.e. $\Gamma_{\Phi}(x_1, y_1, 0, 0)$ i.e. a 2D subset of the full correlation dataset.

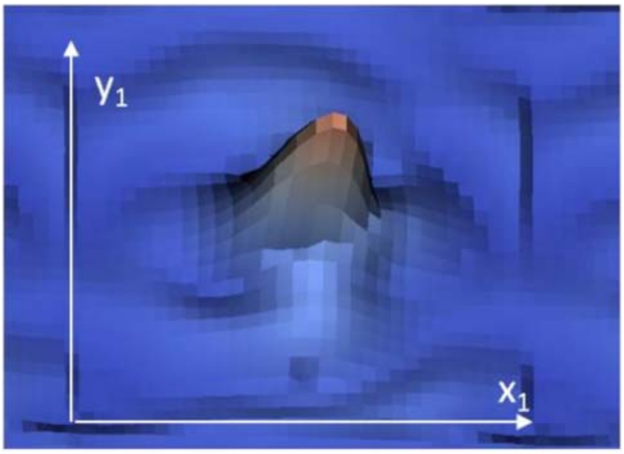


Fig. 3. Field-Field Correlation function $\Gamma_{\Phi}(x_1, y_1, 0, 0)$ for the aperture in a mode-stirred cavity.

The measured correlation data decribed for the mode-stirred cavity aperture is suitable for validation of the statistical field propagation techniques, however the analysis of real world systems throws up considerable challenges as we cannot necessarily obtain the stable phase (for frequency domain measurement) or time reference required for a single probe scan.

B. Two probe scanning measurement

Without a stable phase or time reference available for synchronisation, a single probe measurement is not possible and it is necessary to perform a full two port measurement. If the scan plane has N observation points then (since the correlation spectrum matrix is Hermitian) we require ½N×(N-1) two probe measurements for the cross-correlation (off diagonal) correlation matrix elements and N single probe measurements for the autocorrelation elements on the leading diagonal of the correlation matrix. For even a modest spatial resolution scan this measurement scheme with order N^2 pairs of measurements will be very demanding in terms of the time taken to complete a scan within. In order to be a viable technique for EMC and EMI studies we need to be able to reduce the number of individual measurements required to characterise a device down to a realistic number. With this in mind it is the purpose of the initial measurements presented in this paper to investigate the structure of the spectral correlation matrix so as to try and design an efficient means of characterising the field-field correlation spectrum of real devices by measurement. Thus, it is judged to be sufficient to measure field-field correlation data over a 1D scan line above a PCB and analyse the dataset arising from it in order to draw conclusions regarding the form of the full correlation matrix.

The lack of a phase (time) reference suggests that it is most appropriate to perform the measurements of the field-field correlation in the time domain using a multi-channel digital oscilloscope. Since we are interested in the correlation of fields in our two probe measurement, it is vital that the transfer functions of the two measurement channels are identical i.e. both the magnitude and the phase response of the measurement channels (probes, amplifiers if used, and cables) should be the same. Since the correlation of the fields is related to the phase difference, we are not necessarily interested a full time domain calibration of the probes. It is sufficient to have the magnitude of the probe performance factor ($V_{received}/H_{probe}$) to be able to relate the correlation matrix of the received voltages to the correlation matrix of the magnetic fields being measured.

Two identical Langer EMV-Technik RF R50-1 magnetic field probes are connected to two ports of an Agilent MSO8104A digital time domain oscilloscope. Fig 4 shows the two probe scanning measurement in progress for the Arduino Galileo board pictured in Fig. 1.

An important consideration in the characterization of a complex PCB is what processes should be running on the board whilst the measurement is taking place. In order to investigate this aspect on the measurement we have measured the magnetic field at a number of points close to the PCB and analyzed the response using a time-frequency analysis. For this study measurements were taken with a number of different processes running on the board. The processes tested included the following:

1. A largely null process in which an on board LED was switched on of, with a waiting process in between
2. A memory intensive process in which a large array was allocated (significantly larger than the on-board cache) and filled systematically with random numbers
3. A process in which a large array was allocated and random elements were filled with random numbers.

The random elements of the processes were deliberately introduced to mimic the processing of real data. It was found that the measured magnetic field was significantly different in character when the PCB was running the quiet LED flashing process to when it was running the memory intensive process. Clearly the process running has a significant impact on the measured field.

A time-frequency plot of a single component of magnetic field measured at a point close to the memory chips is shown in Fig. 5 when running the second process outlined above. It is important to note that the measured field is not stationary i.e. its characteristics are a function of time. Much of the field spectrum is constant over time or with a seemingly predictable modulation however the plot does show an event which produces a field of a very different character, a broad band response which is present for only a few percent of the total observed time. It may be that this is associated with the transfer of CPU cache memory to the memory chips as a part of the function of the process running on the PCB although there are other processes going on which are not necessarily in the control of the user and this has not yet been confirmed. The time frequency response raises questions as to how to characterize such a complex, time dependent system. It may be that significant emission events occur quite sporadically over a short time period. In order to characterize the field-field correlation function in a meaningful and useful manner in order to analyze the potential for EMI, it may be necessary to identify and trigger time domain measurements related to specific events or processes occurring as part of the normal operation of the system.

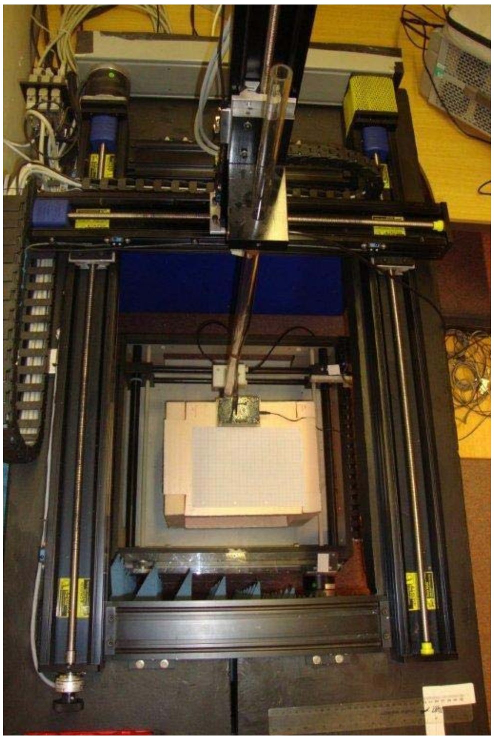


Fig. 4. Two probe scanning rig for direct field-field correlation measurement.

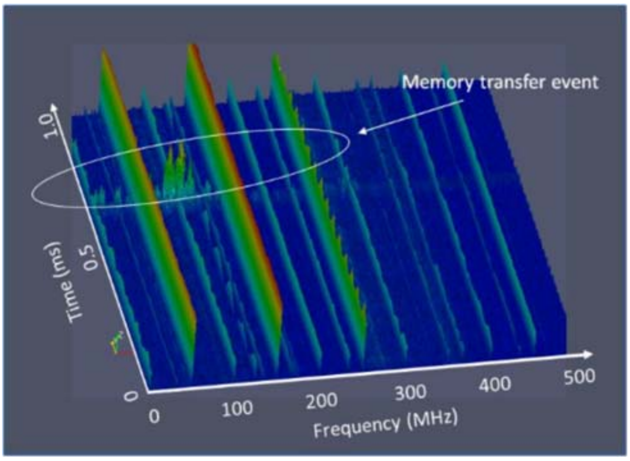


Fig. 5. Time frequency plot for a single measurement point on the PCB

IV. FIELD-FIELD CORRELATION RESULTS

In this initial study we are aiming solely to investigate the form of the field-field correlation matrix so as to gain some understanding of how the field-field correlation develops as the observation plane moves away from the source. The aim is that this will help to develop efficient measurement strategies which will allow efficient characterisation of the statistics of PCB emissions and take advantage of the associated prediction methods being developed.

Our initial scans have been performed on the Arduino Galileo PBC with the random array filling algorithm running (process number 2). The two probes are scanned over a line along the length of the board so as to gather all the measurements required to fill the correlation matrix. At each position the two probe voltages are measured as a function of time over a period of 1ms. This time period is assumed to include all the on board events and processes of significance. We are ignoring for now the specific analysis of „sporadic events“ such as that described in the earlier discussion of the time-frequency analysis. The thick line superimposed on the photograph of the PCB in fig1 shows the path of the 1D scan where the scan was performed on the other side of the board to that shown. The 1D scan line was 10cm long and divided into 20 measurement points with a 5mm separation leading to a 20×20 correlation matrix. The time domain sampling rate in the measurement was 2GSa/s and 2050000 time samples were recorded at each pair of measurement points. In the post processing of the data this time period was divided into an ensemble of 100 shorter time periods. The Fourier Transform of each of these datasets was calculated for the frequencies of interest. The correlation matrix elements were then calculated from Eq. (3) from the ensemble of frequency domain data.

Figs. 6 and 7 show the magnitude of the correlation matrix elements at frequencies of 100MHz and 233MHz respectively which have been obtained from our initial two probe measurements from a 1D scan of the Arduino Galileo PCB.

The amount of data which is recorded in this measurement process is very large, even for a 1D scan; several MBytes of data for each element of the correlation matrix. The handling of large measurement datasets is one of the challenges arising from this approach.

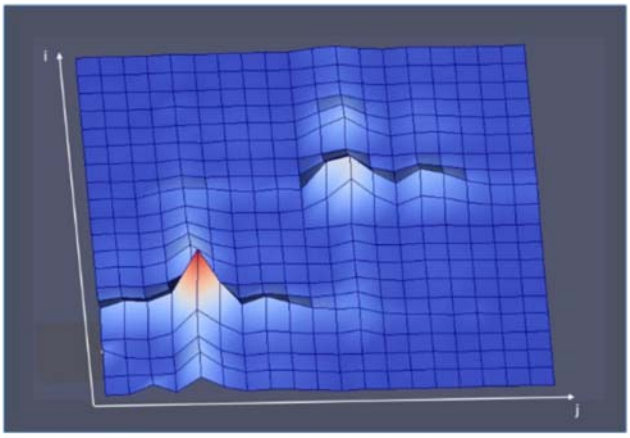


Fig. 6. Visualisation of the maghnitude of correlation matrix elements |C(i,j)| at 100MHz

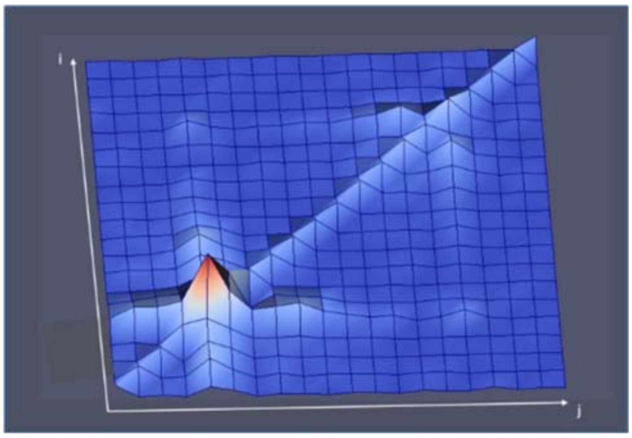


Fig. 7. Visualisation of the magnitude of correlation matrix elements |C(i,j)| at 233Mz.

The correlation matrices show definite hot spots on the leading diagonal which are due to strong field sources. C(5,5) gives the largest response and the associated row, C(i,5) and column C(5,j) of the correlation matrix show that there are fields present across the board which are correlated with this source however the correlation reduces with separation. This decay of the correlation with separation can be used to define a correlation length which will be a parameter of importance in the design of efficient correlation measurement strategies.

Away from the hotspots, the leading diagonal elements dominate the response, especially at 233MHz.

In the measurements presented here an ensemble of data was derived from subsets of a single continuous time domain measurement however we can envisage the investigation of the emissions related to sporadic events on the board by measuring an ensemble of data, the capture of each dataset in an ensemble being triggered by the event which we are interested in. This will provide a great deal more information regarding emissions and their origins than is available in more traditional measurement techniques.

V. CONCLUSIONS

The techniques outlined in this paper hold the promise of a very rigorous characterization of the emissions of complex systems through the measurement of near field correlation functions and subsequent processing by associated propagation analysis techniques. Importantly the statistical properties of the fields are dealt with directly and the use of time domain measurement gives the prospect of the analysis of sporadic events and processes in complex systems which may be significant in the analysis of EMI.

A number of practical challenges are raised by the requirements of the measurement of correlation functions. The statistical analysis underlying the measurement and associated propagation algorithms requires the capture of a very large amount of data. A full two probe near-field scan of a PCB using a mechanical scanning system as described here is not a practical proposition for anything other than research purposes due to the time taken for the measurement. The issue of identifying and characterizing sporadic emissions related to particular processes occurring within a complex system which may be significant for EMI studies is significant.

Acknowledgment

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