The Role of Simulations in Support of Measurements at High-Frequencies

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Abstract- The complexity of interactions at high-frequencies requires the full range of analytical, numerical and experimental techniques to be employed to get a thorough understanding and quantification of observations. The all too often perceived dichotomy between "theory" and "measurements" is unfortunate and does not help the serious investigator. The paper attempts to show how measurements and numerical simulations in complex systems are complementary approaches and should be used together to enhance understanding

I. Introduction

The design of modern systems is characterised by extreme complexity, very substantial costs, rapid time to market and the desire that the design is "right first time". Many markets, such as PCs and mobile phones, dictate a very rapid design turn round time which precludes extensive redesign and experimental optimization. The consequence of these trends is that traditional iterative experimental design techniques are being replaced by computer-aided design (CAD) methods. The question then arises how valid, accurate, and representative of real things these methods are. There is a culture of believing that a measurement in a laboratory is the ultimate representation of reality and that a simulation is somewhat lesser artificial and an ersatz approach. A better approach is to accept that there are good and bad measurements as there are good and bad simulations. No one can legitimately claim that one approach is better under all circumstances. The skilful designer uses a combination of measurements and simulations to gain the best possible understanding of the inherent complex interactions in real systems. In the electrical field, and in the area of high-frequency electromagnetics in particular, the difficulties of doing accurate representative measurements are considerable and the need to supplement them by carefully considered numerical models and simulations is obvious. The aim of this paper is not to show that simulations are "better" or "more accurate" but rather to explain how and under what circumstances they can complement with benefit other approaches such as measurements. This is done by addressing a number of issues of importance in engineering design.

II. The Limitations of Modelling

Excluding analytical approaches where the use of infinitesimal calculus allows us to approach, in the limit, continuous time and space variables, most engineering level calculations are based on a numerical technique where space and time are discretised. Analytical approaches are only possible for a restricted number of canonical problems. They are ideal for understanding trends and for validating other techniques such as those based on numerical methods. Inherent to numerical modelling is the idea that physical laws are imposed not on every point in space but on a grid of points spaced a distance $\Delta\ell$. This is essential for computation by a digital computer since if $\Delta\ell$ tended to zero this would require the storage of quantities at an infinite number of points i.e. a computer with infinite memory. This is irrespective of the physical size of the problem studied. Similarly, physical laws are imposed at discrete time intervals Δt. This interval Δt cannot be made zero as this would require an infinite computation time even for finding the response of a system over a short interval of time. We see therefore that a numerical calculation is necessarily and fundamentally approximate by virtue of the fact that time and space are discretized. Numerical calculations are subject to many other errors but the discretization errors can only be reduced at the expense of longer computation time and a larger computer-they cannot be brought down to zero. A good numerical model uses a space discretization length which is much smaller that the shortest wavelength of interest. A typical upper limit is $\lambda_{min}/10$. Using a numerical model above this limit will result to uncontrolled errors and a very poor approximation to the phenomena studied. Similarly, the time discretization must be much shorter than the shortest period or time constant of interest. Very high frequency studies are therefore computationally expensive until the optical limit is reached and different, geometrical, techniques can be used. Users of numerical methods must be aware of these limitations [1,2].

Another area of considerable difficulty is the mapping the geometrical details of features onto the numerical grid (mesh) described above. Whilst a spatial resolution of a tenth of the wavelength may be sufficient to describe signals it fails in many cases to resolve fine geometrical details. A typical example is the modelling of wires where in most cases the wire diameter is much smaller than $\lambda/10$. These are described as multi-scale problems meaning that we have in the same problem features which are electrically small (e.g. wire diameter) and electrically large (e.g. wire length). These are very challenging modelling problems as they require fine resolution to accommodate the electrically small features and coarse resolution elsewhere to economise on computer storage and runtime. Such a numerical mesh is described as a multi-grid mesh and is difficult to construct and operate accurately and efficiently. An attractive alternative is to separate the description of the fine features from the global mesh by embedding local solutions for the fine features into the mesh [3, 4]. Users of numerical solvers should be sensitive to these issues and be aware of the level of approximation inherent in the model. In may cases commercial solvers introduce approximations in the description of fine features (to speed up computation and fit the problem in the available computational resource) which may result in substantial errors.

In addition to the discrete spatial and temporal sampling mentioned earlier the response in time is truncated after a finite period of time. Application of Fourier Transforms gives then results in the frequency domain, if desired. However, as a result of the truncation, numerical artefacts may be introduced which contaminate the true response. Again this is an area where proper windowing of the time-domain data can lead to improvements. Users must consider these issues before accepting results at face value.

It is worth saying that we cannot model and simulate the entire world. Every model is an approximation. We throw away things which we consider insignificant to our investigations. That is how models should be. As simple as possible but not too simple. In this way we focus on the essence of what we are studying and we do not dissipate effort on insignificant matters. A good modeller should be able to de-feature a problem (removes aspects which are not essential). But this is a high level task requiring deep understanding and fine judgement. Simulation is not simply running computer programmes! Only by understanding what our problem is and what our models can do may we do useful simulation work. Simulation gets a lot of bad publicity because users of models do not pay sufficient attention to their limitations.

It is inevitable that at the present time we cannot model accurately all potential situations and thus we may be tempted to say that “simulation is useless as it cannot solve my problem exactly”. It is unreasonable to expect that by pressing a key on a computer a complete solution to any problem is available. Even if we cannot simulate a problem in its entire complexity we should be able to get a long way in answering a number of crucial questions and get pointers to a good design. So what can a good numerical model do for us?

III. What if Studies

A powerful way in which numerical models can be used is in performing ‘what if’ studies. In many complex applications intuition fails and we are unable to foresee trends in design. A good model, even if it is not a very accurate one, can tell us what would happen if a design parameter is modified. This then can inform the design without the expense and complexity of constructing prototypes and performing measurements. In many cases even a small modification to a physical model and subsequent measurement can be prohibitively expensive especially if it is followed by a number of similar trials in order to find an optimum solution. In contrast, once the basic numerical model is developed, these operations are straightforward and inexpensive by simulation.

Another area where a numerical model offers a distinct advantage is in assessing the impact of the change of a single parameter in a design. This cannot be done easily, if at all, by physical modelling and measurement. This is either because of cost or simply due to the impossibility in practice of changing one parameter in isolation. This facility, unique to numerical modelling, can offer a very useful insight into what factors impact on the design and therefore lead to innovations in new material developments and design practices.

IV. Optimization

A numerical model, even if it cannot match exactly all aspects of a practical configuration, can be used to advantage in running through a number of scenarios over a large parameter space to seek optimum solutions. This can be done either by user choice or by suitable search algorithms. An example is the optimum placement of radiation absorbing material (RAM) on the inner walls of a chamber to reduce reflections. The ideal solution is the complete lining of the metallic walls of the chamber with RAM to totally eliminate resonances. Then the test environment inside the chamber will resemble that of free space. Such a room is called an anechoic room. Alternatively, the floor can be left unlined thus giving an open-area test site (OATS)[5].Two difficulties arise with this approach. First, RAM is not equally effective at all frequencies. At low-frequencies, traditional carbon loaded pyramidal RAM needs to be comparable in height with the wavelength and this implies a significant reduction in the working space of the room. An alternative is to use ferrite slabs of of approximately 1 cm in thickness which are effective at low frequencies but less efficient at high frequencies. A combination of pyramidal RAM and ferrites is the best compromise to cover a wide frequency operating range as required in EMC application (typically dc to 100 GHz). Second, the cost of lining a large room suitable for entire vehicle testing is prohibitive (of the order of 3 Meuro). The question therefore arises whether we can partially line a screened room (thus reducing costs and maximising working space) but still maintain the anechoic nature of the chamber. The quantity used to assess the quality of a test site is the normalised site attenuation (NSA) defined as,

$$NSA = \frac{20\log\left|\frac{V_1}{V_2}\right|_{\min}}{AF_T AF_R}$$

Where the ratio $|V_1/V_2|_{\min}$ is measured as the receiving antenna is scanned over height h_2 as shown in Fig 1 and AF_T, AF_R are the antenna factors for the transmitting and receiving antennas respectively.

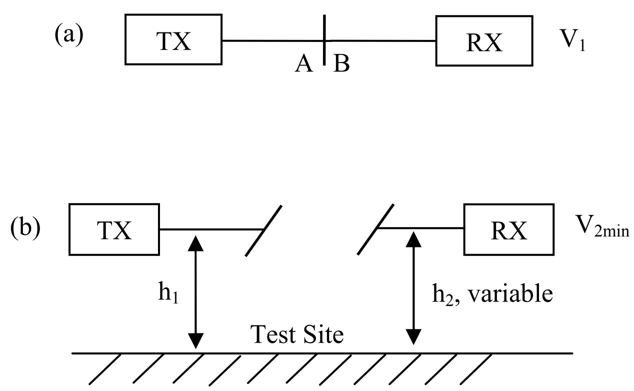

Figure 1. Schematic showing arrangements for measuring V_1 (a) and V_{2min} (b). In (b) RX is height scanned.

An experimental optimization study would therefore require configuring different RAM/ferrite arrangements and doing height scans at all frequencies to obtain the NSA and compare with the theoretical value for an ideal site. Such an investigation is practically impossible as it would require incur enormous material and testing time costs. An attractive alternative is to use a numerical model for optimization. A model based on the TLM CEM technique was employed [1, 2] to study the NSA in a partially lined room of dimensions 4.9x7.1x4.8 m^3 [6, 7]. Typical results are shown in Fig 2 and 3. It is clear that the numerical simulation describes very well the experimentally obtained results and therefore can be used with confidence for 'what if' and optimization studies.

V. A Virtual Laboratory

Modern time-domain electromagnetic techniques such as FDTD and TLM offer unparalled access to all aspects of the evolution of EM fields in complex electromagnetic environments. Not only is a complete picture of all values of field components available everywhere and at all times but through the techniques of animation the propagation of pulses along tracks and through vias or around bends can be followed showing with clarity reflections and emissions as shown in Fig 4 and 5 [8, 9] .

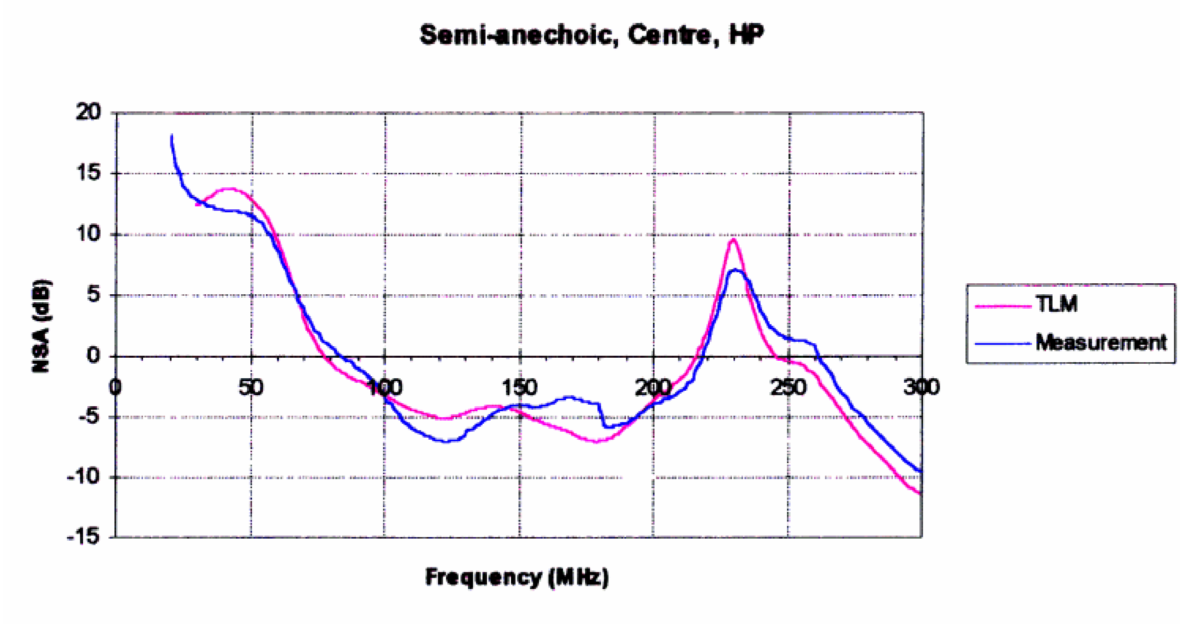

Figure 2. NSA with all surfaces tiled except the floor (Horizontal polalization).

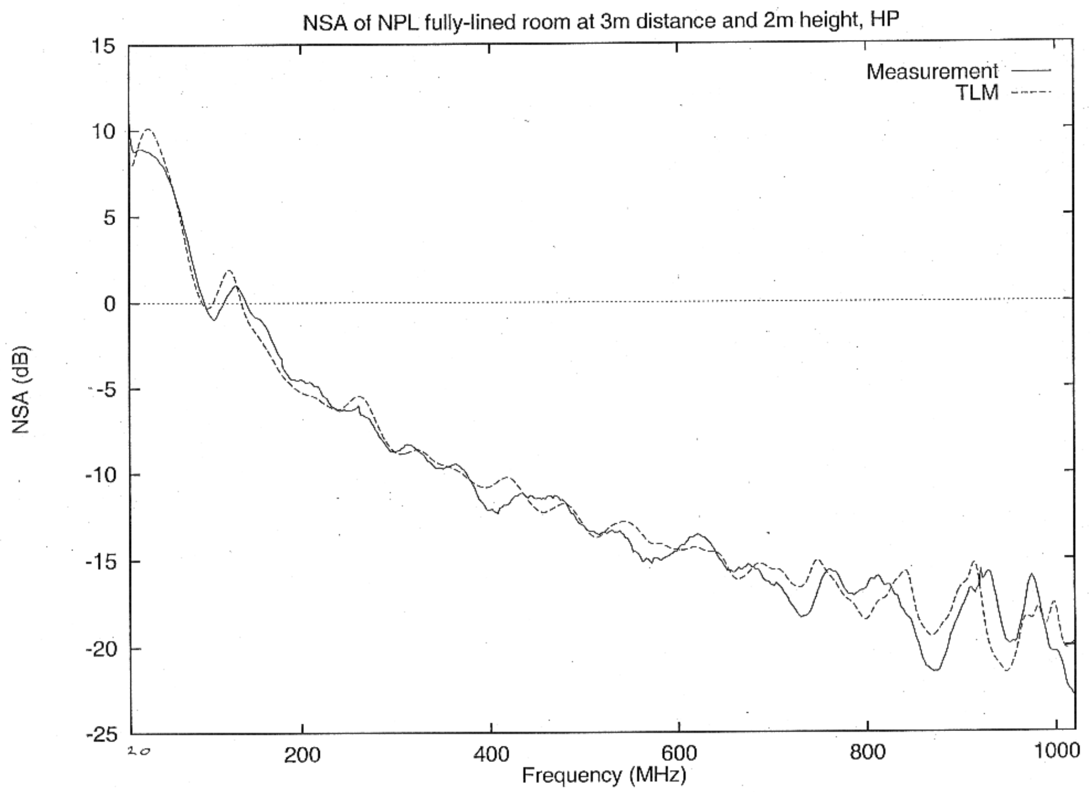

Figure 3. NSA in fully tiled room (horizontal polarization).

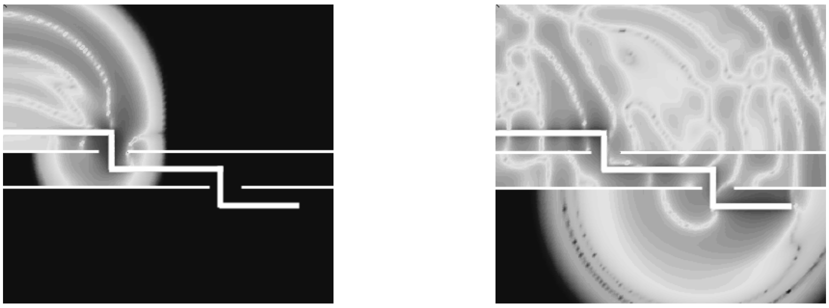

Figure 4. Magnetic field associatted with a pulse propagating through a cascade of vias.

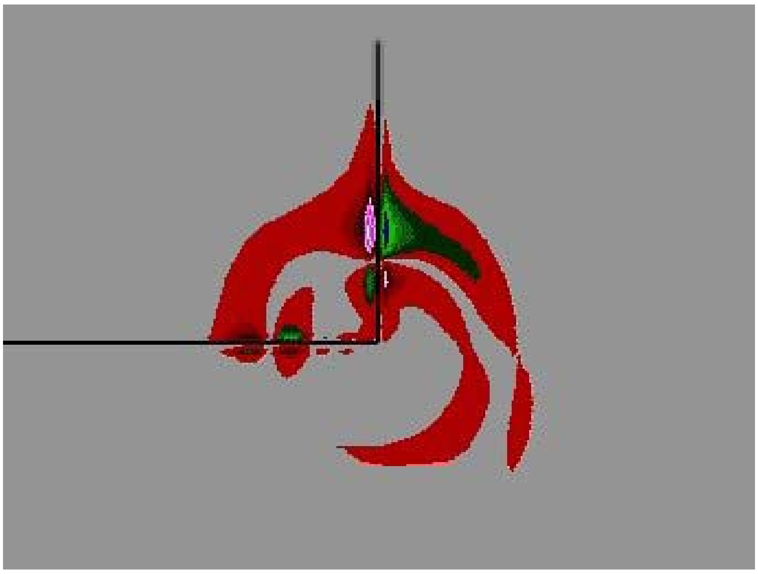

Figure 5.The field profile associated with a pulse propagating around a right angle bend.

This kind of visualization is a major help to the designer who can thus track more easily problems associated with EMC and Signal Integrity. Without this type of information from a numerical models it is nearly impossible to investigate the origin of interference and thus to devise appropriate remedies.

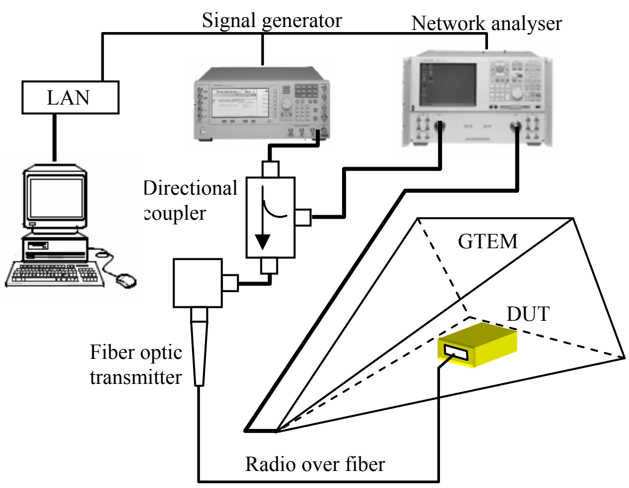

Figure 6. Experimental setup for measurements on a DUT inside a GTEM test cell.

VI. Numerical Simulations in Support of GTEM Measurements

An example of the way simulations based on numerical models of complex measurement systems may be used to interpret and support measurements is shown In Fig 6. This figure shows a GTEM with a DUT inside. The arrangement is used extensively for testing the EMC performance of small equipment. The environment inside the cell has been thoroughly assessed by simulation and detailed error budget was drawn up to aid in the interpretation of the measurements. Some of the results are reported in [10].

VII. Stochastic Models for EMC Problems

A difficult problem in the design of complex systems is the assessment of the impact of the variability of individual design parameters on overall behaviour. In a typical problem a material parameter e.g. the dielectric constant of part of a design is effectively a random variable descibed by a probability density funsction (pdf) with its mean value, variance and other higher statistical moments. In such a situation, the behaviour of the component where this material is present will be affected. For example, if a dielectric slab where ε_r is a random variable is part of a cavity the resonant frequencies of the cavity will be affected. The general problem is posed as follows. Let X be a random variable (e.g. representing material properties) and Y be a function of X (e.g. the resonant frequency).

$$Y = g(X)$$

It follows that Y is also a random variable. It can be shown that if $f_x(x)$ is the pdf of the random variable X then the pdf of Y is

$$f_y(y) = \frac{f_x(x)}{\left|\frac{dg(x)}{dx}\right|}$$

If the pdf of Y is not required then some of its moments can be obtained. The mean value and the variance are given by,

$$\bar{y} = g(\bar{x}) + \frac{\sigma_x^2}{2}\left[\frac{d^2 g(x)}{dx^2}\right]_{x=\bar{x}}$$

$$\sigma_y^2 = \sigma_x^2 \left\{\left[\frac{dg(x)}{dx}\right]_{x=\bar{x}}\right\}^2$$

Based on these expressions a direct simulation techniques (DST) can be embedded into numerical solver to provide statistical information very efficiently without the need for computationally expensive approaches based on the Monte Carlo technique [11]. An example of the application of DST is shown in Fig 7 for the case of a dielectric slab with a dielectric constant which is a random variable.

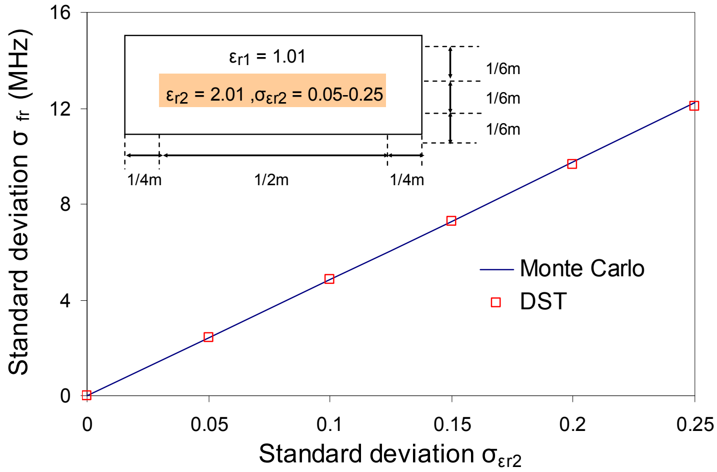

Figure 7. Standard deviation of the resonant frequency as a function of the standard deviation of the slab dielectric constant calculated with Monte Carlo and DST techniques.

Another approach is to extract the statistical moments from a small number of simulations using the Unscented Technique (UT) [12].

VII. Conclusions

Numerical simulations can add an extra dimension to experimental investigations and provide powerful alternative means for optimization and 'what if' studies. A better understanding of errors and of the impact of different design parameters is provided when measurements are supplemented by simulations. The unparalleled access to data in space and time provided by simulations is a major help to applications engineers in seeking better designs. The traditional divide between "experiment" and "theory" is a false one. A good numerical models is indeed a very practical tool !

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