Which Electromagnetic Simulator Should I Use?

Dave Morris[*] (david_morris@agilent.com)

*Agilent Technologies, Lakeside, Cheadle Royal Business Park, Stockport SK8 3GR

Abstract

Driven largely by ever high levels of circuit integration and complexity, the use of electromagnetic (EM) field solvers is becoming increasingly important to many RF/Microwave Designers and High Speed Digital Designers. Whilst commercial computer aided design (CAD) tools are widely used in the industry for analysing circuits using a circuit theory approach the use of EM field solvers is less pervasive and for many, EM simulation is regarded as something of a 'Dark art'.

Several key EM simulation technologies have emerged over recent years, these include the Method of Moments (MoM), Finite Element (FEM) and Finite Difference Time Domain (FDTD) solutions. Although in principal these technologies could be used to solve the same problems there are often good practical reasons why one particular simulator is better suited to solving a particular problem type. This paper will outline three of the key EM simulation technologies and attempt to compare and contrast the relative merits of each.

1. Introduction

Although it seems hard to believe, the use of computer aided design tools specifically developed for RF and Microwave circuit analysis has only been part of mainstream design processes for around 25 years. During this time significant technological developments have taken place, not least of which has been the emergence of the computer platform from early mainframe machines to today's highly specified PC's. This dramatic improvement in computer power has been leveraged by CAD tool developers and has resulted in today's designers having access to unprecedented levels of simulation capability. This is especially true in the field of computational electromagnetics where the problem sizes associated with solving Maxwell's equations can be huge.

Early microwave CAD tools provided designers with a primitive text based entry method for creating a representation of a design (a so-called 'netlist') and the ability to perform only linear (s-parameter) circuit analysis. By contrast modern tools provide designers with much more convenient design entry mechanisms with schematic and layout design entry supported. This ease of design entry is combined with a host of analysis methods ranging from basic linear circuit analysis right through to advanced non-linear frequency domain simulation, time domain simulation, hybrid frequency/time simulation methods (so-called 'envelope' simulation) and of course electromagnetic simulation.

Before diving into the details of electromagnetic simulation, it's worth stating that the factor which often limits the usefulness of modern simulation tools is not the capability of the simulation engine in terms of speed, capacity or robustness; rather it is a limitation with the accuracy or availability of the models used within the simulation. Generally speaking the component parts of a typical RF/Microwave or High Speed Digital design can be divided into 'Active' devices and 'Passive' devices. In a perfect world all active devices would be represented in simulation by 'nonlinear' models which would exhibit identical performance characteristics in both simulation and measurement domains (over the full range of possible operating conditions). Similarly, all passive components would be represented in simulation by 'linear' models which were accurate over the full range of possible operating conditions. Sadly we don't yet live in such a utopian world but thankfully a number of practical solutions do exist which significantly aid the design process. For example nonlinear device models for simulation have been developed for many years based upon the use of mathematical descriptions of the devices (Compact Models) and more recently a number of nonlinear measurement based models such as X-parameters, S-functions and the Cardiff Model have started to gain popularity within the industry.

It could be argued that modelling passive devices is a much simpler proposition due to the fact that passive devices are linear by nature and as such their behaviour is generally independent of external factors such as bias & RF drive level. For the purpose of high frequency design, passive components can be sub-divided into discrete (lumped) passive components such as R's, L's & C's and distributed components such as microstrip transmission lines. Within most microwave CAD tools, lumped component models are generally readily available as either basic primitives in 'generic' component libraries or may be provided as parts in specific 'vendor' libraries. These vendor models are often extracted from measurement. Microwave CAD tool providers typically incorporate libraries of standard building blocks for distributed components such as microstrip element libraries, stripline element libraries etc. The behaviour of these distributed component models is usually described as a closed form analytic model (based upon a mathematical description). These models provide a very useful starting point for a new design and are adequate for many design purposes. It is important however to understand some of the limitations of such models. For example it is important to realise that each model is calculated in isolation and does not take into account any interaction (electromagnetic coupling for example) with other parts of a design. To illustrate this point consider Figure 1 below which shows a 0.5 inch long 50 ohm microstrip meander line intended for fabrication on 10mil Alumina.

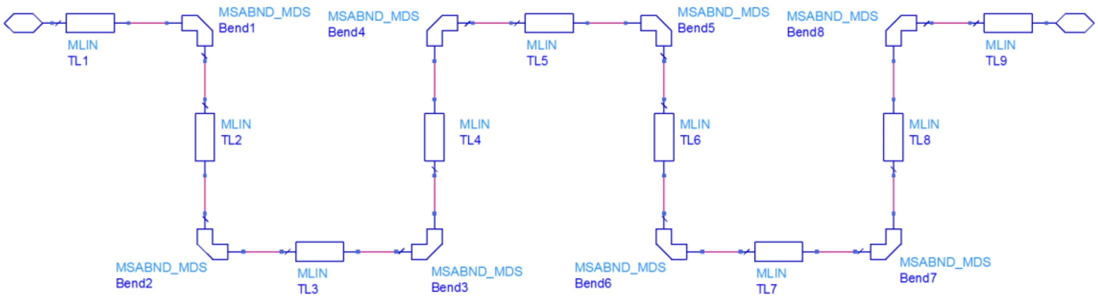

Figure 1: Schematic Representation of 500mil long 50Ω microstrip meander line

In the schematic circuit simulation of this design each of the microstrip components is modelled independently and is simply cascaded with neighbouring components through the nodal connections defined in the schematic. The models to not take into account any unintentional electromagnetic coupling between components – for example in this case the schematic analysis does not consider coupling between components TL2 and TL4. As we will see, this may or may not have a significant impact on simulation accuracy, depending upon the aspect ratio of the meander line.

Figure 2 illustrates three very different physical layout implementations that could be used to realise a 0.5 inch long 50 ohm microstrip line. Intuitively we would expect that of the three layout implementations presented, the unintentional coupling between sections of the 'Compressed Meander' would be greatest thus leading to the largest discrepancy between the schematic simulated response and the measured response (or in this case EM simulated response). We would also expect the 'Straight Line' schematic simulated response to match most closely with measured data.

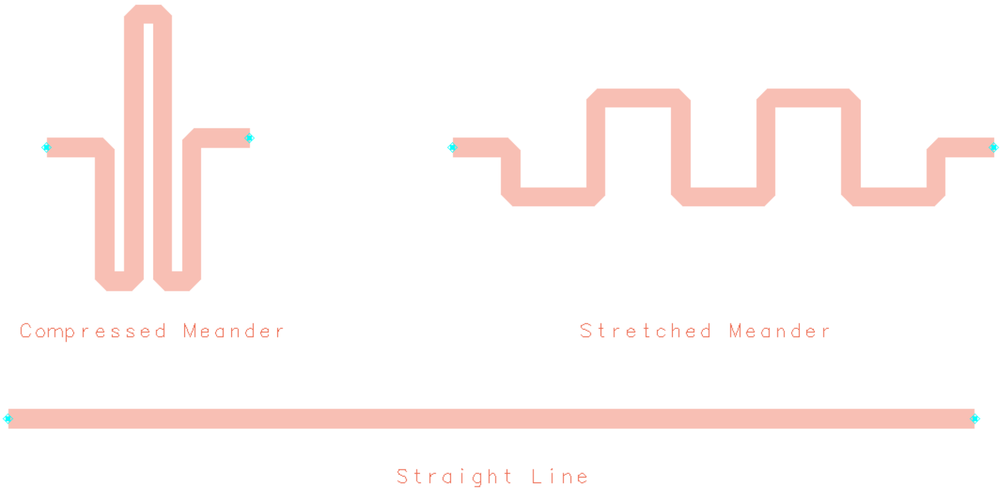

Figure 2: Three alternative layouts of 500mil long 50Ω microstrip line

Each of these three test cases has been simulated using schematic model representations and EM extracted models from the physical layout. Figure 3 shows the simulated S(1,1) results and compares the schematic model response (blue traces with symbols) with the EM extracted response (red traces). These results confirm the intuitive view that as the meander line is 'stretched' the unintentional electromagnetic coupling is reduced and the 'Schematic Model' and 'EM Model' responses converge.

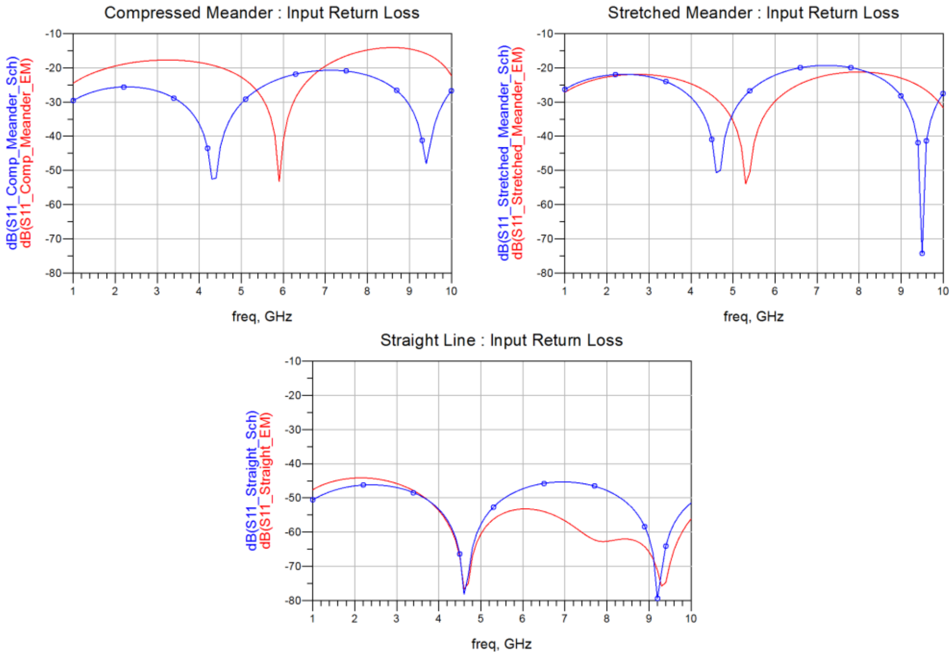

Figure 3 : Schematic & EM Results Converge as EM Coupling Reduces

Although the meander line example is rather artificial, it does serve to illustrate that as interconnect densities on PCB's and IC's increase, the possibilities of unintended electromagnetic coupling between parts of the design may also increase. Worse still is that unless post-layout EM simulation is used to extract a model for interconnects then these unexpected problems may not be detected until the design has been fabricated and is being tested.

2. Generalised Electromagnetic Simulation Process

The main purpose of an electromagnetic simulator is to find an approximate solution to Maxwell's equations that satisfy a given set of boundary conditions and initial conditions. Over the last twenty or thirty years, several technical approaches have been developed to address this requirement. Considering the huge range of problems designers may wish to analyse, from the 'micro scale' parasitic inductance of a bond wire through to 'macro scale' radar cross section of a fighter aircraft, it perhaps isn't surprising that no one solution method fits all application areas perfectly.

In recent years three key solution technologies have found favour in commercial CAD tools, these are based upon Method of Moments (MoM), Finite Element Method (FEM) and Finite Difference Time Domain (FDTD) techniques. In general terms these simulation methods use a similar approach to solving a particular problem [1]. The key steps in the simulation process include :-

- Creation of the Physical Model
    - This step will usually involve the creation of the layout geometry together with the definition and assignment of material properties to objects contained within the layout geometry.
- EM Simulation Setup
    - This step will usually include defining the extents of the simulation and the boundary conditions, the assignment of ports and specific simulation option settings.
- Performing the EM Simulation
    - The physical model (layout geometry) must be discretised using 'mesh cells'. The field/current across the mesh cell is then approximated using a local function (often referred to as an Expansion or Basis Function). The function coefficients are adjusted until the boundary conditions are satisfied.
- Post-processing
    - Calculation of S-parameters, Far Field Radiation Patterns etc....

Whilst the general solution process is quite similar for MoM, FEM and FDTD there are some important differences which ultimately lead to certain solvers being better suited to particular applications.

3. Method of Moments Simulation Summary

The MoM simulation method is often referred to a '3D planar' solver and is one of the most difficult to implement EM simulation methods because it requires the careful evaluation of Green's functions and coupling integrals [2]

The key practical advantage of the MoM technique is that it is only necessary to discretise (mesh) the metal interconnects in the structure being simulated due to the fact that the current distribution on the metal surfaces emerge as the core unknowns. This is in contrast to other techniques which typically have the electric/magnetic fields (present everywhere in the solution space) as the core unknowns. The direct consequence of this is that the ‘planar’ MoM mesh is much simpler and smaller than the equivalent ‘3D volume’ mesh required for FEM/FDTD simulation. An efficient MoM mesh will be conformal (Mesh cells are only created on the metal interconnects) and will typically consist of rectangles, triangles and quadrilateral shaped mesh cells.

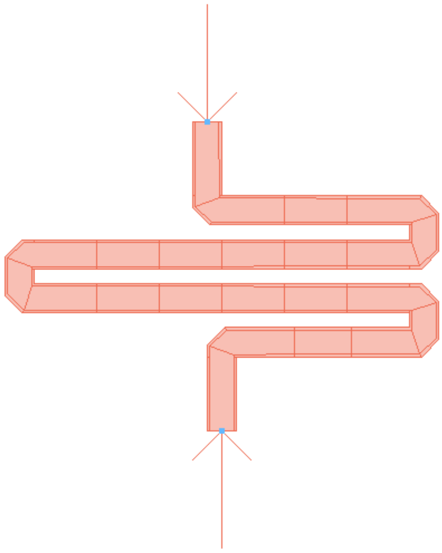

Figure 4 : Typical Conformal Mesh used in MoM Simulation

A reduced number of mesh cells leads to fewer unknowns and an extremely efficient simulation. This makes MoM well suited for the analysis of complex (layered) structures. Another benefit of the MoM technique is that only one matrix solve is required for all port excitations, in other words there is no significant time penalty associated with simulating designs requiring a large numbers of ports.

To balance the efficiency benefits of MoM we also have to consider some of the potential limitations and it is important to recognise that MoM is not applicable for general 3-dimensional structures. As already stated MoM relies upon the computation of Greens functions which are only available for free space or for structures that fit in a layered stack up. This in turn means that the structures being simulated must be ‘planar’ in nature and fit within the layered stack up (drawn in the x-y plane) or be planar objects (drawn in the x-y plane) which are extruded vertically (along the z-axis) through the layered stack up. Fortunately for many RF/Microwave technologies this limitation is not significant because the technology is often planar in nature. Think of a multi-layer PCB or a MMIC structure, this typically consists of a layered stack up (substrate dielectric layers) and interconnects (metal traces). The interconnects are printed in the x-y plane at various interface locations in the substrate and via contacts between metal layers can be considered 2D objects (cross sections) extruded vertically through the substrate layers.

A typical application well suited to MoM analysis might be the ‘extraction’ of a detailed multi-port s-parameter model representing all of the interconnects on a PCB. The example shown in Figure 5 illustrates a relatively simple layout which could be characterised using MoM and the resulting s-parameter model combined with the models representing the discrete components for a simulation of the complete PCB [3].

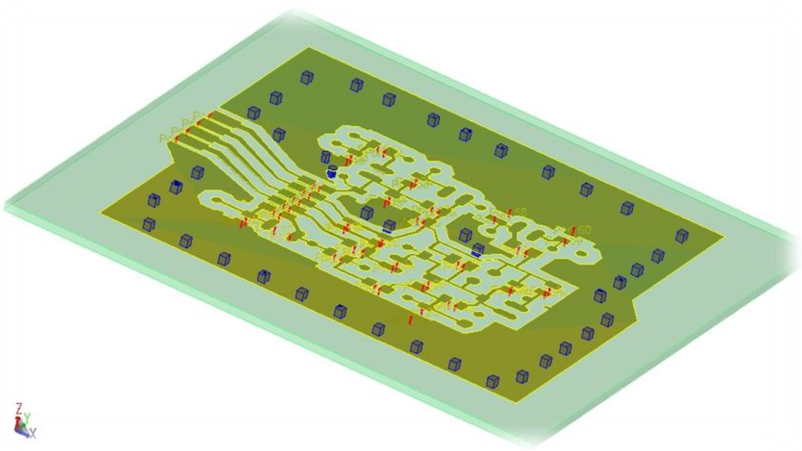

Figure 5 : PCB layouts can typically be solved using MoM Simulation

4. Finite Element Simulation Summary

The FEM simulation method is a true 3D field solver which has the advantage over MoM in that it can be used to analyse arbitrary shaped 3D structures and is not confined to a layered stack up.

FEM simulation requires that the objects being simulated are placed into a 'box' which truncates space and defines the simulation domain. The entire volume of the simulation domain is discretised, usually using tetrahedral mesh cells with a denser mesh being created around the geometric model being simulated.

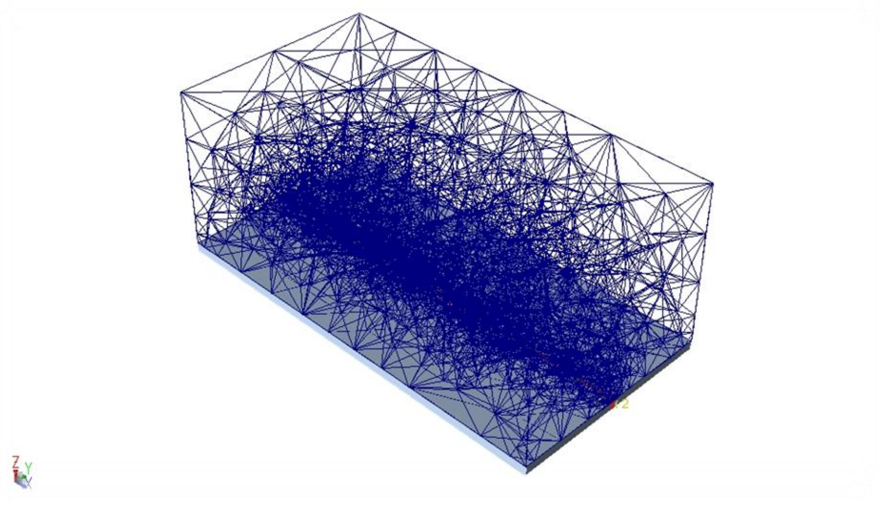

Figure 6 : Typical Tetrahedral Mesh used in FEM Simulation

The core unknown quantity in FEM analysis is usually a field quantity. The field is approximated over each tetrahedron as a sum of known expansion functions with unknown coefficients. The resulting sparse matrix is solved to determine the expansion function coefficients. Like MoM only one matrix solve is required for all port excitations, in other words there is no significant time penalty associated with simulating designs requiring a large numbers of ports.

A typical application well suited to FEM analysis is the characterisation of the parasitics associated with packaging RF/Microwave IC's. The example shown in Figure 7 illustrates how FEM could be used to characterise the interconnect path right through from PCB launch to the bond pads on a MMIC device encapsulated inside a QFN package. The package/interconnect model could then be combined with the MMIC circuit to assess the impact of the packaging on the MMIC performance

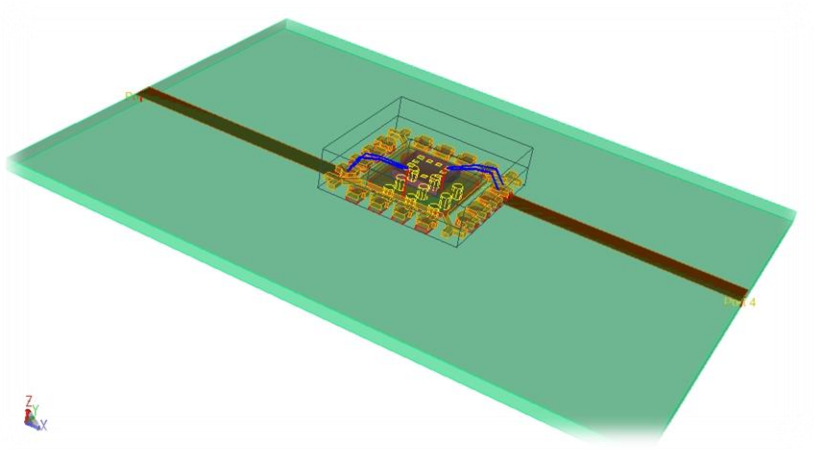

Figure 7 : Typical Tetrahedral Mesh used in FEM Simulation

Arguably FEM provides the most flexible EM analysis method, allowing designers to simulate most arbitrary 3D geometries however for geometrically complex and/or electrically large structures, the mesh can become very complex with many tetrahedral mesh cells. This in turn leads to huge matrices to solve which can require very large amounts of computer memory.

4. Finite Difference Time Domain Simulation Summary

Like FEM, the FDTD simulation method is a true 3D field solver which can be used to analyse arbitrary shaped 3D structures. Whilst the MoM and FEM algorithms solve Maxwell's equations implicitly through the solution of a matrix, FDTD algorithms solve Maxwell's equations in a fully explicit way.

FDTD analysis requires that the objects being simulated are placed into a 'box' which truncates space and defines the simulation domain. The entire volume of the simulation domain is discretised, usually using hexahedral mesh cells (often referred to as 'Yee' cells [4]). FDTD uses a time stepping algorithm which updates the field values across the mesh cell time-step by time-step, thereby explicitly following the electromagnetic waves as they propagate through the structure.

One of the significant benefits over the FEM method is that FDTD technique does not require a matrix solve and thus very large problems can often be addressed using surprisingly small amounts of computer memory. FDTD also lends itself extremely well to parallelisation, meaning that the processing capabilities of modern GPU's (Graphics processors) can be leveraged to 'accelerate' simulation speeds.

To balance these benefits are a number of less desirable features of FDTD simulation. Firstly it is important to realise that a single simulation has to run for each port placed onto the geometry, so an

N-port design would require N simulation runs. This makes FDTD less attractive for analysing designs with high port counts.

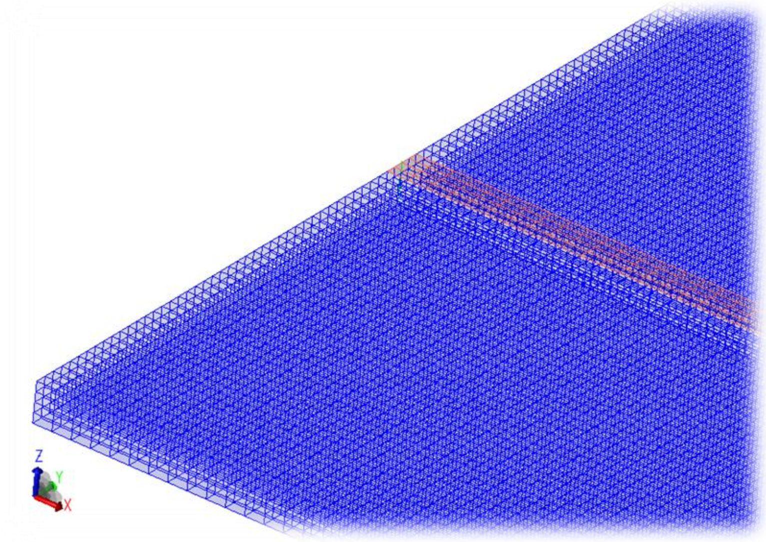

Figure 8 : Typical Hexahedral Mesh used in FDTD Simulation

A typical application well suited to FDTD analysis is the characterisation of an antenna embedded inside a mobile phone. The antenna(s) can become detuned when embedded in a handset or when the handset is in close proximity to the human body and early evaluation of these effects and the assessment of additional legal requirements such Specific Absorption Ratio (SAR) and Hearing Aid Compatibility (HAC) is extremely useful.

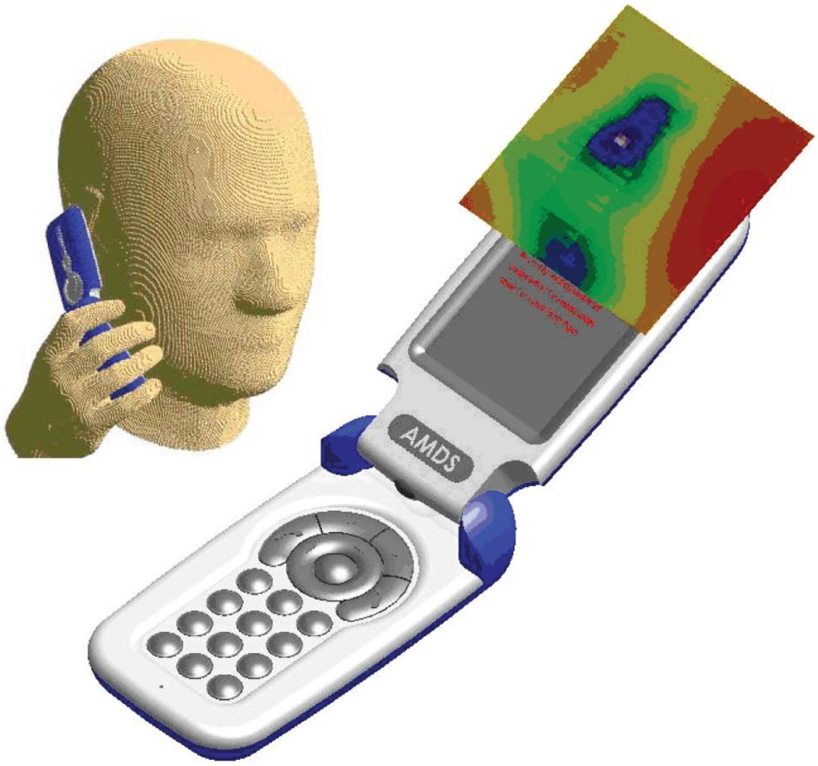

Figure 9 : Evaluation of Mobile Phone Antenna using FDTD Simulation

5. Selecting the 'Right' Simulation Method for the Job

There are many considerations to take into account when assessing the suitability of a particular EM analysis tool. Of course some of these considerations go beyond simply comparing simulation algorithms and typically might include important factors such as the design flow efficiency.

- How easy is it to create the geometric model?
- Does the EM simulation environment link easily with the circuit simulation tools?
- Do you need to be an 'EM guru' to run the tools?

Answering these types of questions is beyond the scope of this paper and soon becomes very subjective. Instead we will focus on some of the key factors designers should consider when assessing which simulation method, MoM, FEM or FDTD will best suit their applications.

The first major consideration is whether the geometry can be considered 'Planar' in nature or whether it is genuinely '3D'. For 'Planar' structures, MoM provides the most efficient simulation method and for that reason generally MoM would be recommended for the analysis of PCB interconnects, On-chip Passives and interconnects and planar antenna's. Whilst for true '3D' structures such as Transitions (Coax-Microstrip, Coax-Waveguide etc), Connectors, Packages, Cavities, Waveguides, or 3D antennas, then either FEM or FDTD will usually be more appropriate.

Another important consideration is the circuit response type. Both MoM and FEM solve natively in the frequency domain, this makes them more appropriate than FDTD for the analysis of 'High Q' circuits. Examples falling into this category might include the analysis of Filters, Cavities, Resonators etc. On the other hand FDTD solves natively in the time domain which means that it can be very useful for performing Time Domain Reflectometry (TDR) analysis on Connector Interfaces & Transitions. Typically TDR is a technique which is employed more in the High Speed Digital / Signal Integrity world than in traditional RF / Microwave analysis.

Assuming the geometry is truly '3D' in nature, the complexity of the geometry and the problem size (Size of the mesh and number of ports) also needs to be taken into account. FEM provides the most efficient solution to problems with large numbers of ports. Examples of such structures which frequently require many ports include IC packages and Multi-Chip Modules. On the other hand if the geometry contains only a small number of ports but is electrically large then FDTD provides the most memory efficient simulations. Applications better suited to FDTD simulation include the likes of antenna placement on vehicles / aircraft and the analysis of antenna performance in the presence of detailed human body models.

6. Summary & Conclusions

This paper has attempted to demonstrate that as levels of integration and packing densities increase, a reliance on closed form analytic models in simulation will not always provide designers with sufficient accuracy. A practical solution to address this problem early in the design phase is to utilise EM simulation to extract more accurate models for the passive interconnects. A review of three key EM simulation techniques has been undertaken and it is clear that no practical 'one size fits all' solution exists today. An attempt has been made to highlight the types of application best suited to each of the EM simulation methods.

References

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