

## DesignFeature

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# Sorting Through EM Simulators

Matching an electromagnetic simulator to a particular application requires an understanding of the different simulation technologies at the heart of these software tools.

**E**LECTROMAGNETIC (EM) simulation software has become an almost essential tool for high-frequency/high-speed circuit designers, helping provide accurate predictions of real-world performance before a design is fabricated. EM analysis programs vary widely, based on a number of different underlying technologies. Each simulation technology offers particular benefits which can often lead to one particular type of EM simulator being better suited to solve a specific problem type. What follows is an outline of the three main EM simulation technologies found in commercial design tools today along with an outline of how they compare for different types of problems and applications.

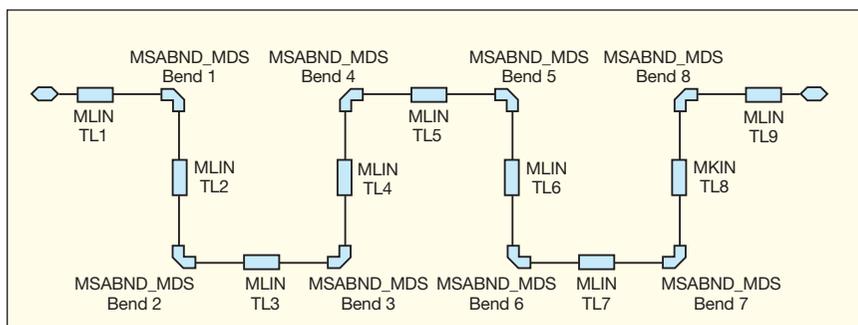
A number of different EM simulation technologies have emerged over the years, including those based on the method of moments (MoM), finite-element method (FEM), and finite-difference-time-domain (FDTD) approaches. In principle, these technologies could be applied to solve the same problems, although there are practical reasons why one approach is better suited for solving a particular problem type. By reviewing these three key EM simulation technologies and comparing the relative merits of each, it may be possible to clarify those applications where an EM simulation based on one technology might be a better choice than software employing one of the other two EM simulation technologies.

The use of computer-aided-engineering (CAE) software developed specifically for RF and microwave circuit analysis has only been part of mainstream design processes for around 25 years, although such tools are now a much-relied-upon part of the high-frequency-circuit design process. Of course, computers have grown in power over that time, to currently efficient and powerful personal computers (PCs) capable of running compute-intensive CAE programs with fast processing speed. This dramatic improvement in computer power has been leveraged by CAE tool developers, resulting in today's designers having

access to unprecedented levels of simulation capability. This is especially true in the field of computational EM analysis, where the problem sizes associated with solving Maxwell's equations can be quite large.

Early microwave CAE tools employed primitive text-based data entry, creating representations of circuit designs by building netlists. They were limited in their analysis capabilities, performing calculations only of linear scattering (S) parameters. In contrast, modern CAE tools provide designers with much more convenient design entry mechanisms that support schematic and layout design entry. This ease of design entry is combined with a host of analysis methods ranging from basic linear circuit analysis to advanced nonlinear frequency-domain simulation, time-domain simulation, hybrid frequency/time simulation methods (so-called "envelope" simulations), and EM simulation.

What limits the usefulness of a CAE simulation tool is generally not the speed or robustness of the simulation engine, but the accuracy or availability of the models within the simulation. Most microwave and high-speed digital designs can be divided into active or passive components or devices. Ideally, active devices would be represented by nonlinear models and passive devices by linear models. Of course, nothing is ideal—and even passive components such as cables and connectors exhibit nonlinear behavior—so complex models are often needed. Fortunately, nonlinear models have been in development for some time, with those based on X-parameters or the Cardiff model gaining popu-



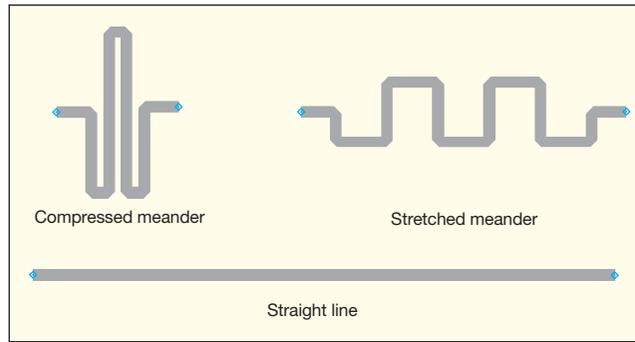
1. This is a schematic representation of a 500-mil-long, 50-Ω microstrip meander line.

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larity among CAE users.

Modelling passive components and devices should be simpler than modelling active devices, since passive devices tend to be linear by nature and their behavior is typically independent of external factors, such as bias and RF drive level. For high-frequency design and modelling, passive components can be subdivided into discrete or lumped components [such as those formed of separate resistors ( $R_s$ ), capacitors ( $C_s$ ), and inductors ( $L_s$ )] and distributed components (such as those formed of microstrip transmission lines).

Lumped component models are generally available within most microwave CAE tools as either generic component libraries or as vendor libraries, based on specific commercial parts. Vendor models are often extracted from measurements.

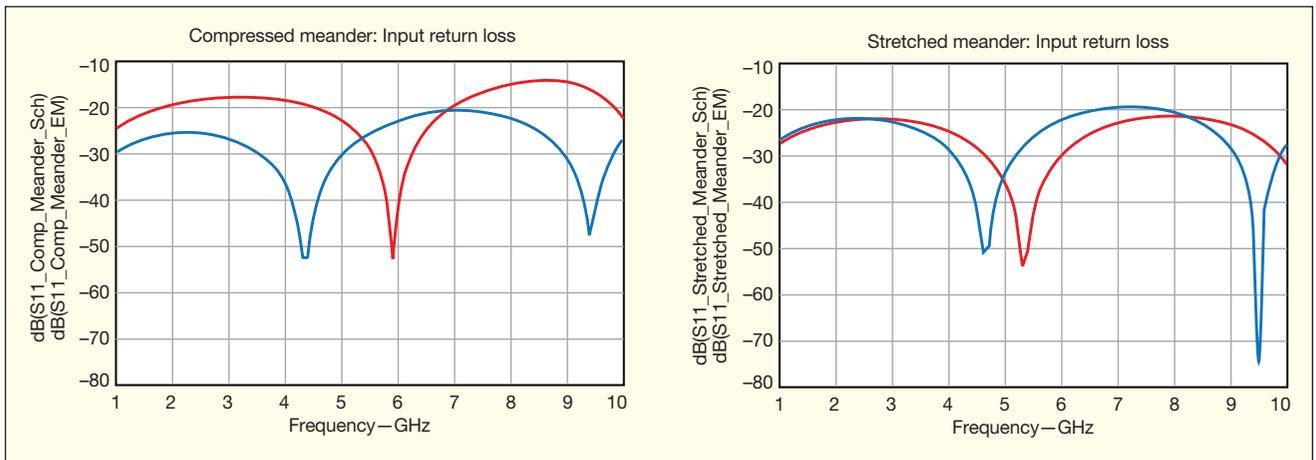


2. These three layouts represent alternative versions of the 500-mil-long, 50- $\Omega$  microstrip meander line.

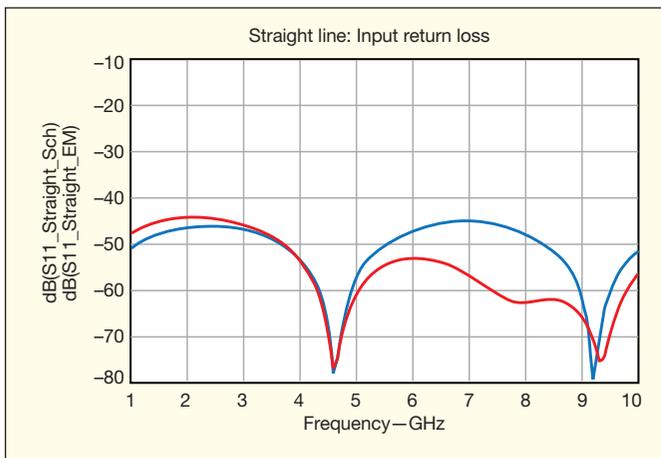
These component libraries also include models of standard building blocks for distributed components, such as microstrip and stripline elements. These distributed component models are typically closed-form types based on mathematical descriptions. They provide a useful starting point for a new design, but may be limited for some applications. Each of these distributed component models is

calculated in isolation, without taking into account interactions (such as EM coupling) with other components in a circuit design. To illustrate this point, consider Fig. 1 which shows a 0.5-in.-long 50- $\Omega$  microstrip meander line intended for fabrication on 10-mil-thick alumina substrate.

In a schematic circuit simulation of Fig. 1, each of the microstrip components is modelled independently and cascaded



3. The results from schematic model representations and EM extracted models converge as unintentional EM coupling is reduced.



with neighboring components through nodal connections defined in the schematic. Unintentional EM coupling between components, such as between TL2 and TL4, is not taken into account in the modelling process. Depending upon the aspect ratio of the meander line, this may or may not have a significant impact on the simulation accuracy.

Figure 2 shows three different layouts for a 0.5-in.-long 50- $\Omega$  microstrip line. Intuitively, it might be expected that the transmission line sections of the “compressed meander” design might result in the greatest unintentional EM coupling, leading to the largest discrepancy between a schematic simulation response and a measured or EM-simulated response. The simple “straight-line” design might be expected to most closely match the schematic simulation response to the measured or EM-

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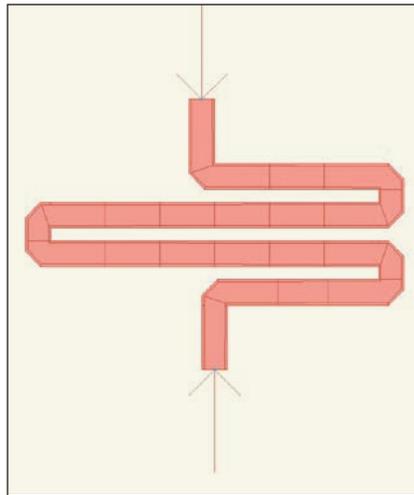
simulated response.

Each of the three transmission-line variations has been simulated using schematic model representations and EM extracted models of the physical layout. **Figure 3** shows simulated  $S_{11}$  results and compares the schematic model response with the EM-extracted response. The results confirm that as the meander line is straightened and unintentional coupling is reduced, the responses of the two model types converge.

Although the meander line example is rather artificial, it does serve to illustrate that as interconnect densities on PCBs and ICs increase, the chances for unintentional EM coupling increase. Unless post-layout EM simulation is used to extract a model for interconnects in such cases, these unexpected problems may not be detected until the design has been fabricated and is tested.

EM simulators attempt to find solutions to Maxwell's equations for different circuit problems. A wide variety of commercial EM simulators has become available over the years, based largely on three key technologies: the aforementioned MoM, FEM, and FDTD methods. In general, these simulation methods use a similar approach to solving a particular problem.<sup>1</sup> They start with creating a physical model, which involves creating a layout geometry along with defining and assigning material properties to objects within the layout. The next step is to set up the EM simulator, which usually involves defining the extents of the simulation and the boundary conditions, as well as assignment of ports and specific simulation options.

Once the first two steps have been completed, the EM simulation can be performed; this involves transforming the physical model into discrete elements by means of mesh cells. The electric field/current across the mesh cells is then approximat-



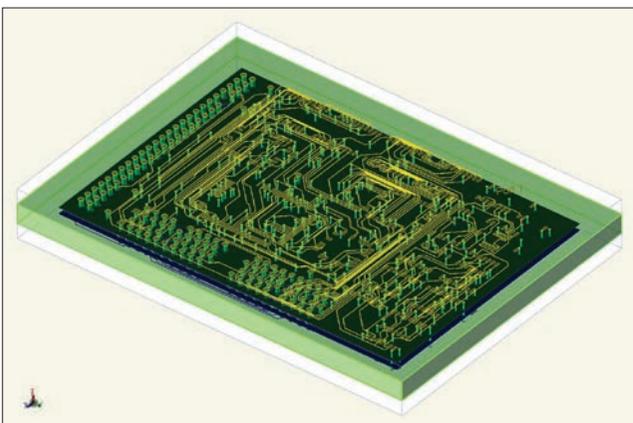
**4. This is a typical conformal mesh for MoM simulations, where mesh cells are only applied at metal interconnects.**

ed using a local function, often referred to as an expansion or basis function. The function coefficients are then adjusted until the boundary conditions of the simulation are satisfied. The step after this involves post-processing, in which information about the design, including S-parameters and far-field radiation patterns, can be calculated. This process is similar for simulators based on MoM, FEM, and FDTD approaches, although differences among those technologies make each one best suited for particular applications.

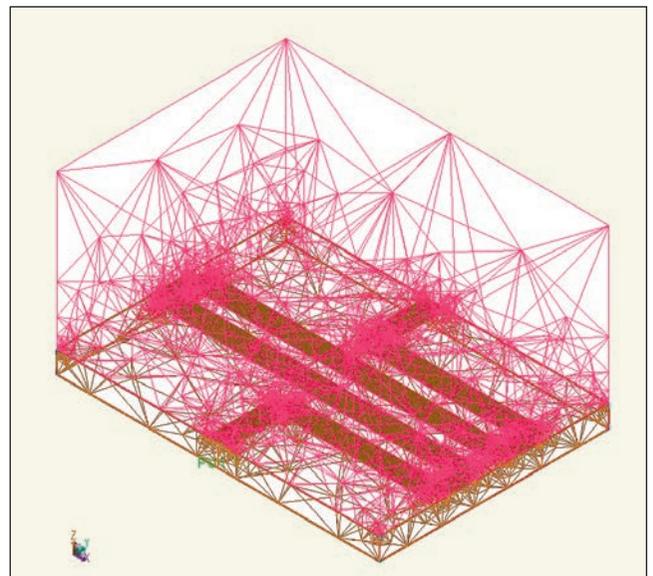
Solvers based on the MoM simulation method are often referred to as “three-dimensional planar” (3D planar) solvers. This approach is one of the most difficult to implement EM simulation methods because it requires the careful evaluation of

Green's functions and coupling integrals.<sup>2</sup>

The key practical advantage of the MoM technique is that it is only necessary to discretize (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 a “planar” MoM mesh is simpler and smaller than the equivalent “3D volume” mesh required for an FEM or FDTD simulation. An efficient MoM mesh will be conformal (mesh cells are only created on the metal interconnects) and will typically



**5. PCB layouts can typically be analyzed quite effectively by means of MoM simulation.**



**6. This is a typical tetrahedral mesh used in FEM-based EM simulations.**

consist of rectangles, triangles, and quadrilateral-shaped mesh cells (Fig. 4).

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 solution is required for all port excitations; in other words, there is no significant time penalty associated with simulating designs having a large numbers of ports.

The efficiency of MoM must be balanced with some of its potential limitations. For example, simulators based on MoM are not suitable for general three-dimensional (3D) structures. MoM simulators rely on solving Green's functions, which are only available for free space or for structures that fit within a layered stack up. As a result, structures simulated with MoM-based EM simulators must be planar in nature and fit within a layered stack up (in an x-y plane) which are extruded vertically (along the z-axis) through the layered stack up. This is not a significant limitation in many cases since many RF/microwave designs are planar in nature. Even a multilayer PCB or monolithic-microwave-integrated-circuit (MMIC) structure can be considered planar when interconnects between dielectric and metal layers are considered as two-dimensional (2D) objects or cross sections extruded vertically through the substrate layers.

An example of an MoM-based analysis is the extraction of a multiport S-parameter model for the interconnections of a high-frequency PCB. Figure 5 shows a relatively simple PCB layout that can be characterized by means of MoM. The resulting S-parameter model for that layout, when combined with the models that represent the discrete components used in the circuit, enables a simulation of the complete PCB.<sup>3</sup>

For analyzing arbitrarily shaped 3D structures, the FEM simulation method is a true 3D field solver with an advantage over MoM simulators: it can be used for any type of 3D structure and is not confined to a layered stack up. FEM simulation requires that objects being simulated are placed into a "box" which truncates space and defines the simulation domain. The entire volume of the simulation domain is converted into discrete elements, usually tetrahedral mesh cells with a denser mesh being created around the geometric model being simulated (Fig. 6).

In an FEM analysis, the core unknown 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. As with an MoM simulator, only one matrix solving procedure is required for all port excitations in an FEM analysis. There is no time penalty associated with FEM when simulating designs requiring a large numbers of ports.

An application well suited to FEM analysis is the characterization of the parasitic circuit elements associated with packaging for RF/microwave ICs. Figure 7 shows how an FEM-based EM simulator could be used to characterize the interconnect path from the PCB launch point to the bond pads on the MMIC with-

in a QFN surface-mount package. The model extracted for the package and its interconnections could then be combined with a model for the MMIC to assess the impact of the packaging on the MMIC's performance. FEM may be the most flexible EM analysis method, but for geometrically complex and/or electrically large structures, the mesh can become very complex with many tetrahedral mesh cells. This results in large mathematical matrices, and a need for massive computer processing power.

Like FEM, the FDTD simulation method is a true 3D field solver which can analyze arbitrary shaped 3D structures. In contrast to MoM and FEM algorithms, which solve Maxwell's equations implicitly by solving for a matrix, FDTD algorithms solve Maxwell's equations in a fully explicit way. For an FDTD analysis, simulated objects are placed within a "box" with defined borders, to truncate the analysis space and define the simulation domain. The volume of the simulation domain is filled by means of discrete elements, usually hexahedral mesh cells, also known as "Yee" cells (Fig. 8).<sup>4</sup> FDTD employs a time-stepping algorithm which updates the field values across the mesh cell time-step by time-step, thereby explicitly following the EM waves as they propagate through the structure.

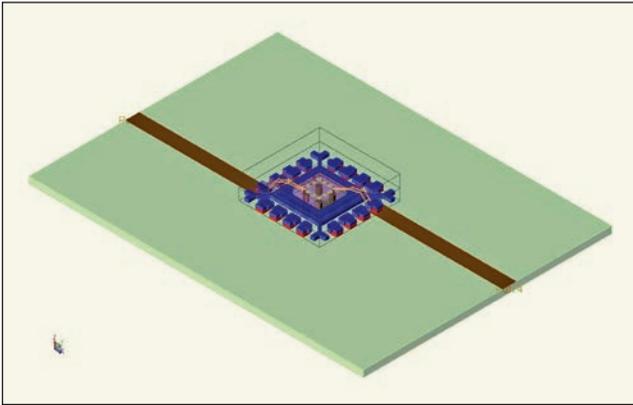
One significant benefit of the FDTD technique over the FEM method is that the former does not require a matrix solution, meaning that very large problems can often be addressed by using surprisingly small amounts of computer memory and processing power. FDTD also lends itself extremely well to parallelization, allowing modern multicore processors and graphical processing units (GPUs) to be leveraged to accelerate simulations. On the negative side, a single FDTD simulation must be run for each port placed onto simulation geometry. Since an N-port design requires N simulation runs, FDTD-based EM simulators are not ideal for analyzing designs with high port counts.

A typical application well suited to FDTD analysis is the characterization of an antenna embedded within a mobile telephone (Fig. 9). The antenna(s) can become detuned when embedded in a handset or when the handset is in close proximity to the human body. 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.

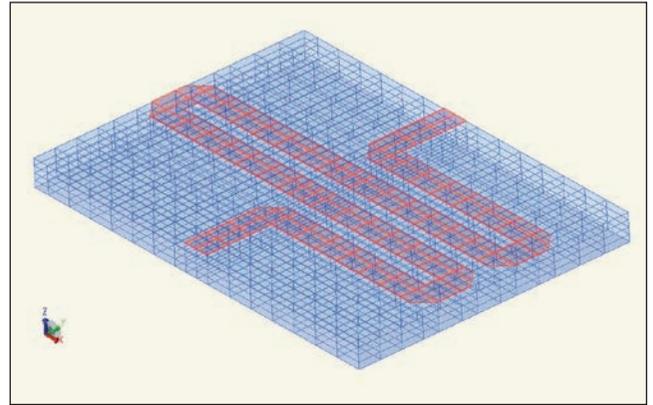
When comparing EM simulators based on MoM, FEM, and FDTD analysis methods for applications, the first consideration is whether the geometry of the design to be simulated is planar or 3D. MoM-based simulators offer the most efficient simulation method for truly planar structures. For that reason, an MoM-based simulator would be recommended for analysis of PCB interconnects, on-chip passive elements and components, on-chip interconnects, and planar antennas. Either FEM- or FDTD-based EM simulators are usually more appropriate for true 3D structures, such as transitions (coaxial-to-waveguide and others), connectors, packages, cavities, waveguide, and 3D antenna structures.

Another important consideration when selecting an EM

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7. This is a typical tetrahedral mesh used in FEM simulations.



8. This is a typical hexahedral mesh used in FDTD simulations.

simulator is the circuit response type. Both MoM- and FEM-based EM simulators solve natively in the frequency domain, which makes them more appropriate than FDTD for the analysis of circuits with high quality factor (high Q), such as filters, cavities, resonators, and oscillators. In contrast, FDTD-based EM simulators solve natively in the time domain, making them useful for time-domain-reflectometry (TDR) analysis on connector interfaces and transitions. TDR techniques are typically practiced more often in the high-speed digital domain than in RF/microwave circuit analysis.

Finally, if a structure to be simulated is truly 3D in nature, then the complexity of the structure and the problem

9. The embedded antenna in a mobile phone can be evaluated by means of an FDTD-based EM simulation.



size (the size of the mesh and the number of ports) must be taken into account when deciding whether an FEM- or FDTD-based EM simulator is more appropriate for the analysis. FEM-based EM simulators provide the most efficient solution to problems with large numbers of ports, such as IC packages and multichip modules (MCMs). For a structure that has a small number of ports but is electrically large, an FDTD-based simulator provides the most memory-efficient simulations. Applications well suited to FDTD-based simulations include analysis of antenna placement on vehicles, in addition to analysis of antenna performance in the presence of detailed human-body models. MWRF

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