The World of EMI Modeling

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INTRODUCTION

The subject of EMI modeling is beginning to appear in the technical literature with increasing frequency. Most articles identify a new feature or special model that may or may not be useful to the general EMI engineer responsible for product development. But little information is available to the potential user of EMI modeling programs other than textbooks and/or technical papers containing lots of heavy mathematics and even Maxwell's equations. To understand the current state of the art in EMI modeling and to perform accurate simulations and obtain meaningful results, an engineer does not need a Ph.D. in modeling techniques or electromagnetics.

Modeling EMI problems can truly help the typical engineer, but like any tool, before modeling can be used effectively the basics must be understood. This article will serve two levels of readers. It will serve as a basic introduction to modeling (as applied to EMI problems) for the engineer interested in getting started, and it will help the person already using modeling as a tool to become more effective in using different modeling techniques. A description of the most common EMI modeling techniques will be given. Standard problems will be presented to allow interested users to evaluate vendor software before purchase to insure that it can simulate the types of problems EMI engineers experience.

Different modeling techniques are suited to different problems.

WHY IS EMI MODELING IMPORTANT?

The main reason to use EMI modeling as one of the tools in the EMI engineer's tool box is to reduce the cost of the product. Without modeling, engineers must rely on out-of-context handbooks, equations, graphs and rules-of-thumb. These guidelines are usually based on far-field assumptions which do not apply in most computer boxes. Some guidelines are better, in that they attempt to correct for the inappropriate assumptions, but even these have severe accuracy limitations in all but the most carefully controlled circumstances. Proper modeling allows engineers to use a full implementation of Maxwell's equations (therefore a full-field solution, rather than a far-field simplification) to predict the effect on the specific product of concern.

Given the limitations that these guidelines have in most real-world problems, engineers are faced with two choices: either a conservative or a non-conservative design. The conservative designer wants to insure that the product will meet the appropriate regulatory limits the first time. This can only be assured by over-design of the EMI features. This over-design will usually meet the appropriate limits, but extra cost is added to the product. The non-conservative designer will take some reasonable chances to reduce the number of EMI features required. Depending on the engineer's experience and training, the product may or may not meet the regulatory limit. If the product doesn't meet the limit, then a panic redesign is required, most often resulting in shipping delays and extra cost due to the band-aid nature of the fixes. Modeling prevents this scenario.

Another realistic benefit of using EMI modeling is credibility. Often the product design team represents a number of different engineering disciplines such as electrical, mechanical, thermal and EMI. CAD simulation tools are commonly used in other engineering disciplines and these tools add significant credibility to the engineer's claim for whatever features are needed to be successful. These features (e.g., larger air vent openings, etc.) are often in direct conflict with the EMI engineer's design direction. However, since the EMI engineer has no simulation to rely on, the EMI engineer's recommendations are often ignored. EMI modeling tools can provide the design team with

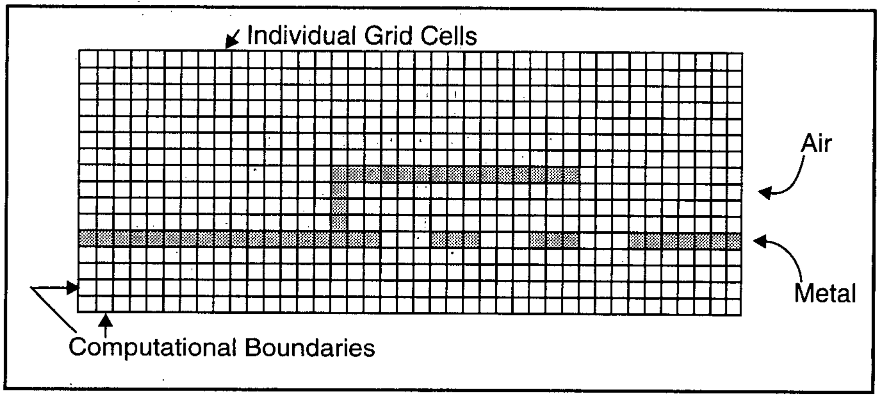

Figure 1. *FDTD 2-Dimensional Grid.*

reliable numerical results, taking the guesswork out of the design, and providing the EMI engineer with the credibility to get design recommendations seriously considered by the team.

Current EMI modeling tools cannot do everything. That is, they cannot take the complete mechanical and electrical CAD files, compute overnight, and provide the engineer with a green or red light to indicate pass or fail for the regulatory standard desired. The EMI engineer is needed to reduce the overall product into a set of problems that can be realistically modeled. The engineer must decide where the risks are in the product design and analyze those areas. This means that the EMI engineer must remain an integral part of the EMI design team. Modeling will not replace the EMI engineer. Modeling is only one of the tools at the disposal of the EMI engineer. The knowledge and experience that the EMI engineer uses to create the design is critical to determine which area of the design needs further analysis and modeling.

Often the problem to be analyzed requires a multi-stage model. The results of one model simulation will provide the input to the next stage model. This allows the model to be optimized for each particular portion of the problem and for the combined results. Thus, much larger overall problems can be analyzed using this multi-stage approach than by using an approach in which the entire problem is modeled at once. Again, the EMI engineer needs to understand the problem in order to know where to break it into individual simulations.

EMI MODELING TECHNIQUES

There are three techniques that are typically used for EMI modeling problems: Finite-Difference Time Domain (FDTD), Method of Moments (MoM) and Finite Element Method (FEM). No one modeling technique will be the most efficient and accurate for every possible model needed. Unfortunately, many commercial packages specialize in only one technique and try to force every problem into a particular solution technique. The strengths and shortcomings of each package must be understood. For example, the Finite Element Method is not well-suited to long wire simulation (as in a computer with an external cable) since it requires a volume of space to be modeled around the wire (and this volume must be large enough to have the boundary in the far field). This requires a computationally inefficient model. However, the Method of Moments technique is perfectly suited to a long wire simulation since it determines the currents on conductors (surfaces and wires) and there is no need to model the volume of free space around the wires. Naturally, MoM is not well-suited to simulate other models; therefore, a set of tools that contains different modeling techniques is vital to the EMI engineer's success.

FINITE-DIFFERENCE TIME DOMAIN

FDTD is a volume-based solution to Maxwell's differential equations. Maxwell's equations are converted to central difference equations and solved directly in the time domain. The entire volume of space surrounding the object to be modeled must be divided into grids (usually into square or rectangular, and small compared to the shortest wavelength of interest) and each grid location is identified as metal, air or whatever material is desired (Figure 1). Once the grid parameters are established, the electric and magnetic fields are determined throughout the grid at a particular time. Time is advanced by one time step and the fields are determined again. Thus, the electric and magnetic fields are determined at each time step based on the previous values of the electric and magnetic fields.

Once the fields have propagated throughout the grid domain, the FDTD simulation is complete and the broadband frequency response of the model is determined by performing a Fourier Transform (e.g., FFT) of the time domain results at the specified monitor points. Since FDTD is a time domain solution, the entire frequency domain result is available from a single simulation when the source signal is a pulse.

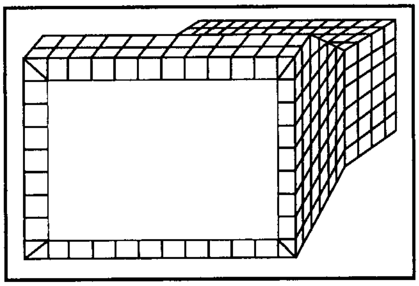

Figure 2. *Wire Frame Model of Video Monitor for MoM.*

Since FDTD is a volume-based solution, the edges of the grid must be specially controlled to provide the proper radiation response. The edges are modeled with an absorbing boundary condition (ABC). There are a number of different ABCs, mostly named after their inventors. In nearly all cases, the ABC must be distanced from the source so that the far-field assumption of the ABC holds true. Typically, a good ABC for FDTD will provide a reflection of less than -60 dB.

Naturally, since the size of the gridded computational area is determined from the size of the model itself, some effort is needed to keep the model small. The solution time increases as the size of the computational area (number of grid points) increases. FDTD is not well-suited to modeling long, thin structures, since the computational area overhead increases very rapidly with this type of structure.

METHOD OF MOMENTS

The MoM is not a volume-based technique. The structure to be modeled is converted into a series of metal plates and wires. In fact, a solid structure is often converted into a wire frame model, eliminating the metal plates completely (Figure 2). Once the structure is defined, the wires are broken into wire segments (short compared to a wavelength) and the plates are divided into patches (small compared to a wavelength). From this structure, a set of linear equations is created. The solution to this set of linear equations is the RF currents on each wire segment and surface patch. Once the RF current is known for each segment and patch, the electric field at any point in space can be determined by solving for each segment/patch and performing the vector summation.

There is no need for an ABC in MoM since there are no boundaries of the computational space. The currents on all conductors are determined, and the remaining space is assumed to be air. This allows MoM to be very efficient in solving problems with long thin structures such as external wires, cables, etc. Since MoM finds the currents on the conductors, it models metals and air very efficiently. However, dielectrics and other materials are difficult to model in MoM with standard codes.

MoM is a frequency domain solution technique. If the solution is needed at more than one frequency, the simulation must be run for each frequency. This is often required, since the source signals within the typical computer have fast rise times and wideband harmonic content.

The size of the model, in segments and patches, determines the amount of time required to obtain a solution. As the number of segments grows, the solution time increases proportionately to the cube of the total number of segments.

FINITE ELEMENT METHOD

FEM is another volume-based solution technique. The solution space is split into small elements (usually tetrahedral shaped) and is referred to as the finite element mesh. The field in each element is approximated by low-order polynomials with unknown coefficients. These approximation functions are substituted into a variational expression derived from Maxwell's equations, and the resulting system of equations is solved to determine the coefficients. Once these coefficients are calculated, the fields are known (in an approximate sense) within each element.

As in the above techniques, the smaller the elements, the more accurate the final solution. As the element sizes become small, the number of unknowns in the problem increases rapidly, thus increasing the solution time. Since FEM is a volume-based solution technique, it must have some boundary condition at the edge of the computational space. Typically, FEM boundaries must be a few wavelengths away from the structure being analyzed and must be spherical in shape. This restriction results in a heavy overhead burden for FEM users, since the number of unknowns is increased dramatically over other computational techniques. Recent technical literature has described new ABCs, which after accuracy analysis will probably be implemented.

TIME DOMAIN ANIMATION

Computer simulation can be a great help to engineers, but everyone should be concerned that the simulation really models the right problem. "Garbage in, garbage out" applies to EMI modeling as well as to any computer-based computation. One way to make sure that the results are representative of the problem that was to be modeled is to view a time-domain animation. The FDTD solution procedure is a time-domain technique, so the fields of interest within the computational area can be saved and displayed sequentially, forming an animation. This type of display not only serves to help the engineer verify that the model ran correctly and simulated the intended geometry, but it also helps the

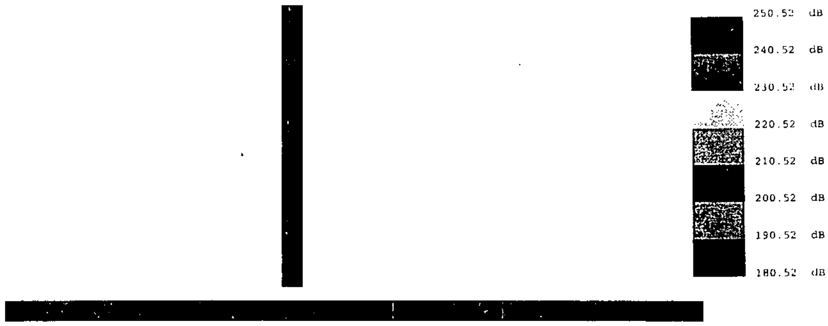

Figure 3a. Modeled Geometry.

Figure 3b. FDTD Animation at Time Step = 240.

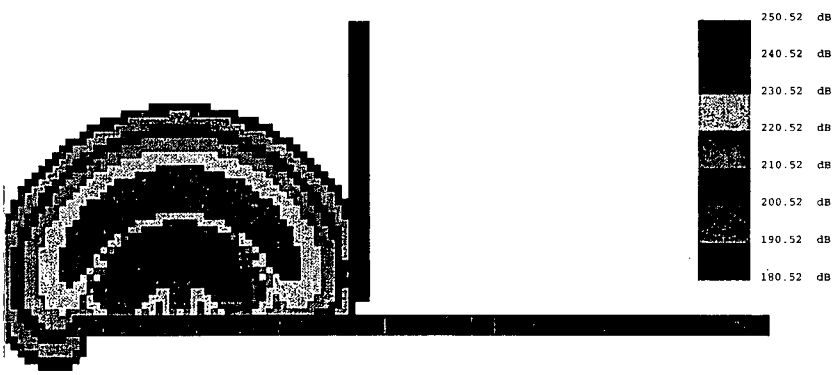

Figure 3c. FDTD Animation at Time Step = 270.

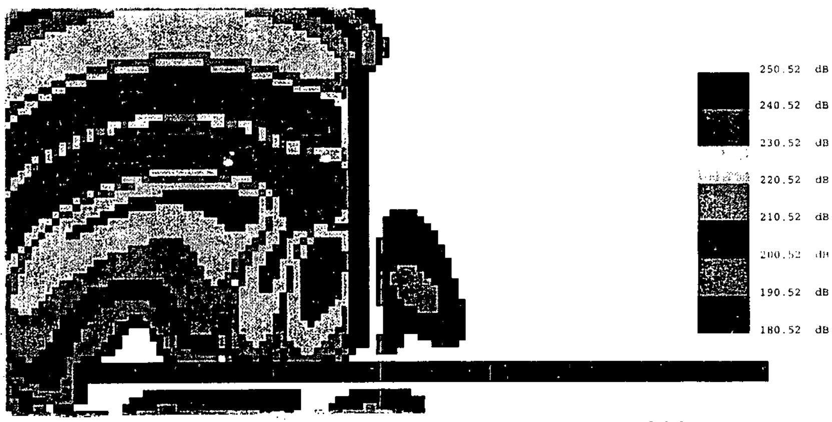

Figure 3d. FDTD Animation at Time Step = 320.

***Figure 3**. Animation Steps.*

engineer better understand what is really happening.

An example of such a time-domain animation is shown in Figure 3. Figure 3a shows the basic geometry modeled. A printed circuit board (PCB) is modeled as the mother board from a typical personal computer. A second PCB (possibly a memory board) is perpendicular and provides some amount of internal shielding. The two boards are connected only by a few connector pins. An engineer might wish to determine if the second board will provide much (if any) shielding and if increasing the size of the board, or the number of connector pins, will increase the shielding.

In this case, the 3-dimensional simulation was run using a time-domain animation. The electric fields in a 2-dimensional plane were saved for the animation display. Figures 3b through 3d show the fields at different time steps (only a few are displayed here) and the leakage points above and below the memory board can be easily seen, proof that the model ran correctly. Experience has shown that these animation displays are used extensively when available, since they provide the engineer with a lot of information about the simulation in a visual format.

STANDARD MODELING PROBLEMS

In order to better discuss EMI modeling in a consistent manner, standard EMI modeling problems have been created. These problems are discussed here to help the reader understand the kinds of problems that can be modeled and how to organize a product into pieces that can be modeled. Before any serious modeling can be accomplished, the engineer must identify the major parts of the model, and determine if multiple models will be necessary to accomplish the overall goal.

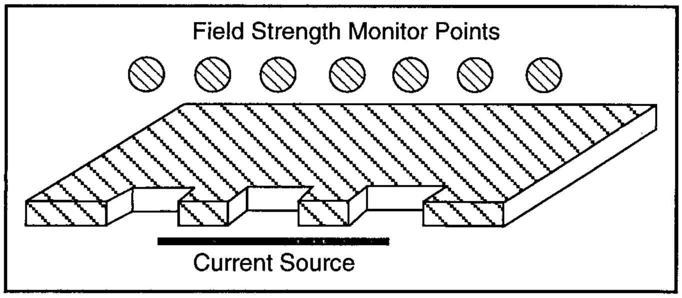

Figure 4. *Wire Source for Shield Modeling.*

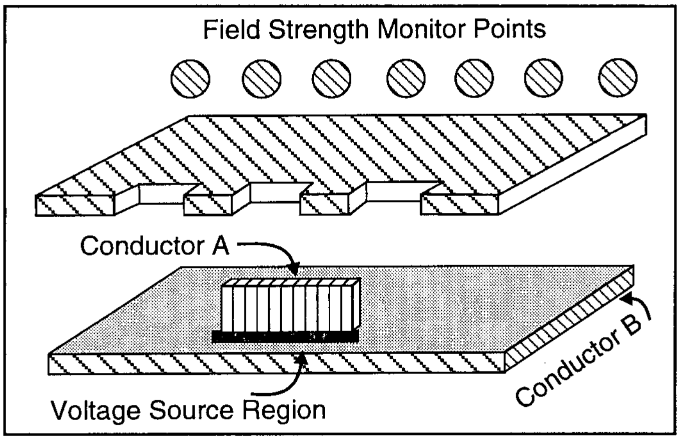

Figure 5. *Voltage Source for Shield Modeling.*

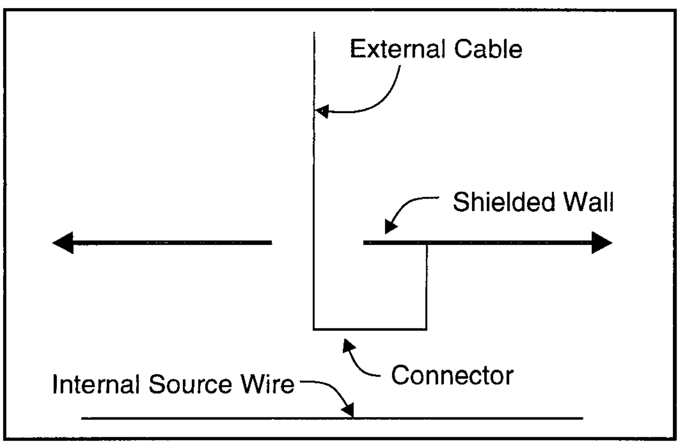

Figure 6. *Wire through an Aperture.*

These standard modeling problems can also be used by engineers to obtain comparison data from different modeling tool vendors.

PREPARING TO MODEL

When preparing to perform EMI modeling, the problem must be broken down into its component parts. The originating source of the EMI signals, the final radiating element, and the coupling mechanism between them must all be determined separately. Once these individual components are understood, then the proper modeling tool can be selected to give a correct result.

THE MODEL'S SOURCE

The originating source of the EMI signal is usually a high speed, fast rise time signal. It may be present, for example, on a bus as a current, on an internal wire as a current, or between an integrated circuit's (IC) heat sink and the PCB's reference plane as a voltage. 'Larger' sources could be the RF voltage between a PCB and the metal enclosure (due to poor bonding between them). Naturally, more than one of these sources could exist at once, but the EMI engineer can usually determine the most likely main source. The model can be run for any number of sources, as necessary.

THE MODEL'S RADIATING ELEMENT

The final radiating element is the antenna which causes the emissions to radiate from the equipment under test (EUT). Probably the most common cause of EMI emissions above the limit is the larger effective antenna size of the EUT due to common-mode RF currents on the wires and cables attached to it. These wires and cables become the model's radiating element. Other examples of this radiating element are slots or air vent openings in the EUT's metal enclosure.

THE MODEL'S COUPLING

The coupling between the source and the final radiating element can be accomplished through a variety of processes. The coupling could be through the fields internal to the shielded box, for example between the source and a connector/ wire leaving the shielded box. Another common coupling mechanism is for currents created in the reference plane by a microstrip bus to travel to another part of the printed wiring board (PWB) and be conducted onto a connector/wire. Direct radiation from an IC's heat sink through the air vent (or a nearby slot) is another possibility. Obviously, many possible coupling paths can occur. The engineer must select the most likely path and use it in the model.

SPECIFIC MODELING PROBLEMS

Although there are many different possible modeling problems, most of them can be broken down into specific classes. Six different modeling problems are presented here as representative of EMI modeling in general. It is hoped that these problems will help the engineer to understand how to reduce the overall EMI problem into elements that can be effectively modeled, and so better understand and evaluate alternative modeling approaches or tools.

STANDARD CASE #1: RADIATION THROUGH APERTURES

One of the most basic EMI problems is to accurately predict the level of attenuation

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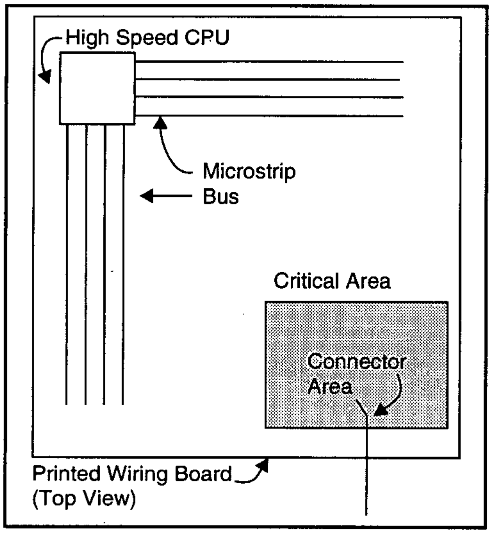

Figure 7. *PWB Configuration.*

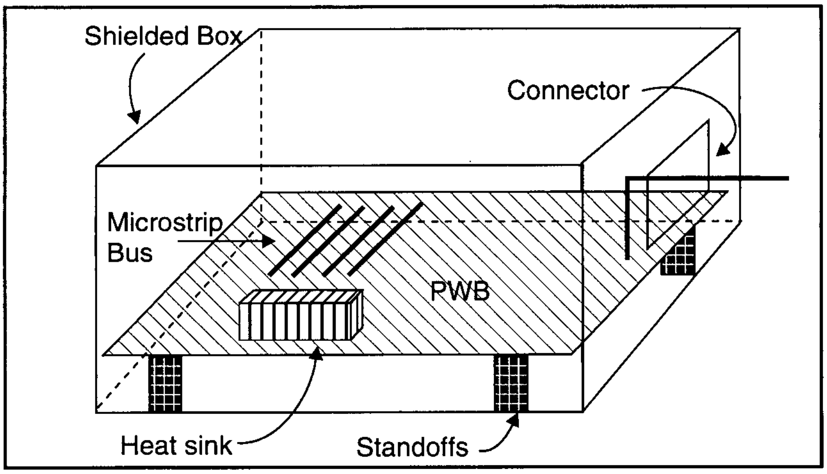

Figure 8. *Connector Common-mode Voltage Geometry.*

obtained when using an EMI shield. Far-field equations are frequently used as a starting point for this type of analysis; however, a large number of assumptions are required.

Two source types need to be considered: a current on a wire and a voltage between two conducting bodies. As the EMI shield is usually very close to the EMI energy source, far-field assumptions do not hold. The interaction of the near fields generated by both of these source types with the shield can be quite different and both need to be understood. The geometries for these cases are shown in Figures 4 and 5. While the monitor points are shown close to the shield, it is important to obtain both near- and far-field predictions. This enables the data to be used both on the bench and at a radiated test facility.

STANDARD CASE #2: WIRE THROUGH AN APERTURE

The case of a wire traveling through an aperture, as in the case of a connector through a shielded box, is an important model for problems concerned with common-mode voltages on a cable. The geometry is shown in Figure 6; an internal wire or cable is coupled via the electromagnetic fields to a separate connector, and energy is conducted to the external cable. There is no electrical connector between the internal source wire and the connector. The connector is shorted (electrically) to the shielded box wall, representing a perfect filter. Although the model in Figure 6 is not drawn to scale, the connector loop would be small (12 mm diameter) while the external cable would be long (1 m). The problem is to determine the field strength at a distant (10 m) receiving antenna, based upon the current in the internal source conductor.

STANDARD CASE #3: RF CURRENT ON REFERENCE PLANE DUE TO REMOTE SOURCE

Often the use of a high-speed (high edge rate) microstrip (or stripline) bus line creates unacceptably high RF currents on another remote part of the PWB reference plane. It is necessary to predict these currents, as they can be coupled through connectors or other enclosure openings and result in significant radiated field strength.

These currents are sometimes controlled by creating voids on the reference (ground) plane between the area where the high frequency signals exist, and the area where the high frequency signals are not desired. This requires a complete current distribution solution. Figure 7 shows the geometry for such an evaluation of the amount of RF current in a remote critical area of a PWB. As can be seen in Figure 7, the microstrip bus is in an area of the board remote to the critical connector area. Although most of the RF currents will be coupled to the reference plane directly below the microstrip lines, some amount of RF current will exist over the entire board, possibly causing coupling to the outside through the connector. Typical PWB sizes for PCs or larger products allow significant distances depending upon the application.

STANDARD CASE #4: COMMON-MODE VOLTAGE ON A CONNECTOR DUE TO KNOWN NOISE SOURCE

Coupling between a heat sink or microstrip bus to a connector in a shielded box is possible either through conducted RF currents (as in the previous case) or by direct electromagnetic fields. The modeling of the common-mode voltage present on the connector must take into account the shielded box, the impedance between the PWB reference plane and the shielded box, and the coupling. The geometry for this case is shown in Figure 8. Note that there is no direct electrical connection between the noise source and the connector. The common-mode voltage between

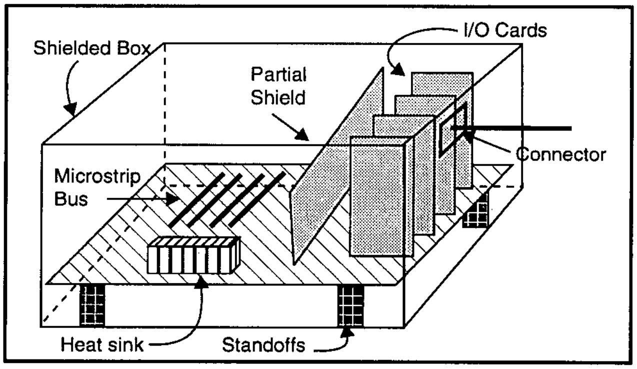

Figure 9. Partial Internal Shield Geometry.

the connector and the shielded box is found and can be used (in a separate tool) to predict the final radiated field strength.

STANDARD CASE #5: REDUCTION IN COUPLING DUE TO PARTIAL INTERNAL SHIELD

The coupling within a shielded box between the EMI source and an area sensitive to these EMI signals is of concern in many designs. The sensitivity may be due to susceptibility or may be due to a set of input/output (I/O) cards with connector/cables providing an uncontrollable escape path for the EMI signals. Figure 9 shows the geometry for this case; a partial shield is used to reduce the amount of signal strength coupled to the sensitive region with the I/O cards and connectors. This partial shield may be a special piece of metal or it might be a PWB with a solid reference plane with low impedance to the mother board.

STANDARD CASE #6: DIRECT RADIATION FROM AN UNSHIELDED PWB

Not all electronic devices require shielding in order to comply with the regulatory limits, and major cost savings can result from the elimination of unnecessary materials. To analyze these situations it is necessary to have a model that can predict the radiation that comes directly from a PWB (Figure 10).

There are many details that must be addressed for this case. While emphasis is often placed upon the signal routing and general module layout, there are other major factors in how much energy will be radiated. These include the finite size and imperfections of the reference plane, and the physical size of the connector and the components installed over it. It is important that sufficient detail is included in the PWB to fully specify the problem. Fortunately, if a module does not require shielding it is probably a relatively low-speed case and its dimensions will be small compared to the frequencies of concern.

SUMMARY

Modeling EMI problems is not a solution to replace the knowledge gained by experience, nor will it

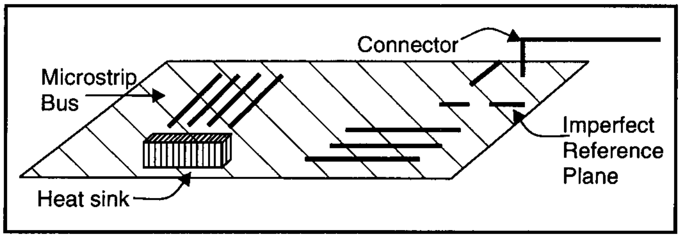

Figure 10. Direct Radiation Model.

eliminate the need for the EMI engineer to work closely with the design engineer, the thermal engineer, etc. EMI modeling is another (and certainly an important) tool that the engineer can put into his or her tool box to insure a successful design. Often there is no other way to predict the effect of emission control features because of the high-speed, high-frequency nature of the circuits involved. Old rules-of-thumb and out-of-context equations/graphs are less than useful in these cases since they provide the wrong answer to the engineer without any warning.

Careful evaluation of vendor offerings is suggested. Regardless of any sales/marketing claims, there is no one modeling technique that will be able to accomplish all modeling tasks effectively and accurately. A tool box approach where the engineer is allowed to select the appropriate modeling technique for the specific modeling task is the only way to insure success. The potential modeler should look behind the pretty graphics of some vendors' tools to insure that they can accurately predict the desired model's emissions. The "Where's the Beef?" approach can be applied by using standard modeling problems to evaluate different vendors' tools.

EMI modeling is being used by a number of companies very successfully. Reports of savings of hundreds of thousands of dollars per product, traceable to the EMI modeling, are not uncommon. Cost reduction, reducing time to market, and eliminating trial-and-error redesign loops are the main reasons to employ modeling techniques. Modeling does not require a Ph.D. in electromagnetics, nor does it require a full-time EMI modeling engineer. Some of the modeling tools available today are easy to use and have graphical interfaces that allow an engineer to use them occasionally as needed.

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