High-Speed EMC/EMI Correlation Study- 3D EM Model versus Anechoic Chamber Test

Peerouz Amleshi, Molex Inc.  
Peerouz.Amleshi@Molex.com

Shahriar Mokhtarzad, Brocade  
Smokhtar@Brocade.com

Xin Wu, Molex Inc.  
Xin.Wu1@Molex.com

Martin Schauer, CST of America,  
Martin.schauer@cst.com
Abstract

As data rates are increasing in communication channels, EMI issues become more important and the task of emission suppression becomes more challenging. Consequently, the need for effective numerical tools and methodologies to predict and suppress the EM emission from communication equipments has become very critical.

The purpose of this study is to use a 3D simulation tool to predict EM emission. This tool will be validated by correlating measured results with the model. This study is done in two phases, 1) far field emission correlation between the model and test results for a fabricated antenna (emission source) and 2) correlation between the model versus test results with the emitter enclosed in a metallic chassis.

Author(s) Biography

Peerouz Amleshi is an electrical engineering director in Connector Product Division at Molex Inc. His team’s primary focus is in design and characterization of next generation high-speed backplane and I/O components and systems. In his previous position as Senior Optical Engineer at Molex Fiber Optics Division, he was involved in design and characterization of planar polymeric and dielectric optical integrated devices and interconnects. Dr. Amleshi holds eleven issued and two pending US patents in the fields of optical and electrical interconnects. He received his Ph.D. in the area of electromagnetics within the Electrical Engineering discipline from the University of Illinois at Chicago.

Shahriar Mokhtarzad is an electrical engineering manager in Brocade Inc. His team’s primary focus is in design and characterization of next generation high-speed backplane and daughter card for networking systems. He received his MS. in Physics and Mathematics from the University of California at Irvine.

Xin Wu is a senior electrical engineer in Connector Product Division at Molex Inc. His industry experiences include electromagnetic simulation/EDA software development, EMC/EMI engineering, Signal Integrity analysis, RF system/Antenna engineering, and wireless networking technology development. At Molex, his focus is on high-speed interconnects signal integrity engineering and EMC/EMI. He received his Ph.D in the area of computational electromagnetic from the University of Maryland, College Park. He also received his entrepreneurial training certificate from Haas Business School, UC Berkeley.

Martin Schauer received the Dipl.-Ing. degree in Electrical Engineering from the Technische Universität Darmstadt, Germany in 1999. In the same year, he joined the Computational Electromagnetics Laboratory (TEMF) for Theory of Electromagnetic Fields, where he earned his Ph.D. in 2005. Since 1999 he is with Computer Simulation Technology (CST), where he developed 3D electromagnetic simulation software until 2005. Currently he is working as an engineering manager for the western region for CST of America in the San Francisco Bay area. His main interests are numerical methods and their application towards low and high frequency electromagnetic problems.
1. Introduction

As data rates in communication channels increase, EMC/EMI issues become increasingly more important and the task of emission suppression becomes more challenging. This trend goes hand-in-hand with increasing system complexity, adding another challenge for the EMC systems engineers to isolate cause and effect. There is a need to integrate EM numerical tools and methodologies in the design cycle since currently EMI/EMC issues are predominantly addressed late in the design cycle by trial-and-error. Demand for shorter design cycles motivates the implementation of a robust and proven workflow for prediction of compliance and suppression of emissions.

This paper will fill the methodology gap in predicting EM emission by means of an effective fullwave 3D simulation technique for the next generation communication systems of 25 Gbps and beyond. The simulation will be validated by correlating measured results with the simulation model. This study is undertaken in two phases:

I. Far-field emission correlation between the model and test results for a fabricated antenna (emission source) fed by a transmission line.

This scenario represents EMI measurement/simulation set-up to avoid interference with other devices in the same system. This approach also allows the reduction of EM emissions by a root-cause analysis during early design stages. This paper will focus on frequency domain emission correlation to create the frame work for future work on prediction of emissions from time-domain signals generated from on-board 25+ Gbps transceiver chips. High power long haul 25+ Gbps transceiver chips are on their first generation phases [1] and soon will be widely implemented and become available for system EMI evaluations. Meanwhile, time-domain transformation of test/model data in frequency domain will be utilized to analyze and predict time-domain emission characteristics of transmitting bit patterns and their relationship to FCC compliance standard which is defined as emission limits within a frequency range. We will also discuss the emission characteristics differences between a radiation source close to the transmitter versus one closer to the receiver. Due to the transmission characteristic of a lossy transmission line, the rise time of the pulses typically slow down as it propagates along the trace. In the frequency domain, this translates to less high frequency content available for emission.

3-meter anechoic chamber emission testing and lab based emission characterization of the fabricated test vehicle will be conducted up to 40GHz. The measured data will be used to validate the numerical simulation prediction of the far field emission and the correctness of the modeled near-field distribution which will be utilized in the model decomposition approach for system level emission modeling and simulation performed in phase 2.
In order to achieve meaningful emissions for a wide range of frequencies, the emitter was chosen to be a planar ultra-wideband antenna tuned to cover the fundamental frequency up to the forth harmonic of the communication system. This antenna was fabricated on a typical PCB. With this methodology, the emission intensity is increased and better controlled. Increasing the emission across the intended frequency range should result in more meaningful data by increasing the margin between emission intensity and background noise. Better control of emission pattern should improve the cause and effect analysis.

II. Correlation between the simulation and test results with the emitter enclosed in a metallic chassis.

The second phase of this study aims at the system level, where the mechanical, thermal and electrical constraints for an enclosure must be considered. An enclosure for the PCB used in phase I study, with typical features of rack based high-end switches is tested. A simulation model of the enclosure including the source is also created. For the data rates/frequencies under consideration, such a system simulation model can be complex due to intricate features within an electrically large enclosure in the range of 50 wavelengths. This paper deals with both complexity and size problems. In order to speed up the simulation, complexity can be reduced by means of a near-field source equivalent approach. The solved PCB is used to compute the near-fields around the PCB. These near-fields are placed as a source in the enclosure instead of the detailed PCB model, effectively decomposing the model into two parts. Electrical size is addressed ideally with sectional models, the appropriate solver choice, and by making use of available high performance computing options. Furthermore, required resources and accuracy compared to the full model is discussed.

Throughout the paper, the correlation of measurement and simulation are provided and discussed and best engineering practices are highlighted. This effectively enables the reader/audience to reproduce similar results using the developed methodologies.
2. Design of the emission source (Antenna)

Based on the requirements for this paper, we investigated different emission sources to be able to perform the correlation studies in a controlled environment. In order to integrate the source with a transmission line and to easily manufacture the test vehicle, we decided to use a stripline fed planar circular disc monopole. This particular antenna was previously suggested in microstrip design for ultra-wide band transmission [2]. With its typical performance bandwidth of up to 4:1, it is well suited for our emission study up to 40GHz.

In the first design stage, we used Antenna Magus [3] and the parameters illustrated in figure 1 to tune the antenna to our operation frequency. Antenna Magus provides an excellent initial estimate of the parameter values.

![Figure 1. The design parameters of the elliptical monopole](image)

Further optimization of the antenna with its launch structure comprising of a high bandwidth coaxial connector and microstrip transmission line and its integration within an 8 layer PCB were performed in CST MICROWAVE STUDIO software [6]. Due to the very high bandwidth requirement of operation, we introduced the following features:

1) The transmission line is connected to a 2.4mm SMA connector (Molex Part # 73387-002) which provides acceptable match and low return loss up to 50GHz.
2) At desired operation frequencies of 40GHz, via stub effect will produce large signal reflections. Therefore, we back-drilled the signal via to minimize the effects.
3) To minimize the antenna radiation energy coupling back into the PCB board, stitching vias (via fences) were implemented around the reference plane cut-outs and the perimeter of the board outline.
Additionally, we incorporated a pair of mounting through holes on the PCB surface. The influence of this additional drill hole was studied in the design phase using simulation. The effect of the clearance distance of the mounting hole on the radiated emissions is illustrated in Figure 2. From this study we concluded that the mounting holes are not critical for the proposed design primarily due to the via cage placed around the antenna.

![Figure 2](image.png)

Figure 2. Mounting hole and distance parameter definition (left) and maximum radiated E-Field emission as a function of frequency and parameter (right).

PCB stack-up used in design of the antenna was selected to resemble a realistic daughter card applied in high-speed backplane systems. The stack-up and a 3D rendering of the PCB are shown in figure 3.

![Figure 3](image.png)

Figure 3. PCB based antenna (left) and its stack-up table (right).
The signal trace from SMA connector through the signal via is routed on layer 3. On layer 3, the via connects to a transmission line, which then leads to the antenna at the end. All other PCB layers are left unused. As seen in figure 3, the main radiation element is without ground plane (ground planes have cut-outs where the circular disc is present).

3. PCB Test Coupon

To study the effect of transmission loss on the emission property of the radiator (antenna), three different trace lengths were included in fabricated test coupon. For characterization purpose, in addition to the antenna, we also included through and terminated lines of the same lengths as the three transmission lines used with the antennas. As a result, the test coupon contains a total of 9 structures (devices). To minimize any spurious effects on the antenna during test, all 9 devices are mechanically separable by incorporating break-away tabs. A layout screen shot identifying all 9 devices and a picture of the actual fabricated test coupon are presented in figure 4. The figure also shows a table identifying all 9 different devices by their numerical labels.

<table>
<thead>
<tr>
<th>TL Length\Feature</th>
<th>Antenna</th>
<th>Through</th>
<th>Terminated</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 mil</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>3 inch</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5 inch</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 4. Layout (top), fabricated coupon (middle), and reference table (bottom) describing the fabricated devices and their organization on the PCB.
4. Enclosure

To study the effect of enclosure and its shielding effect on the emission from the radiator, we used a 1U box style rack commonly applied in the industry. A picture of this enclosure box is shown in figure 5. At this preliminary stage of our study, to minimize complex field interactions with internal structures and details within the box, we removed most of metallic and plastic subcomponents and mounting fixtures. The basic metallic enclosure box includes a beehive style air vent structure on its back side. To further control unwanted path ways to outside emission, we made sure all metal seams, gaps, and holes are covered with copper tapes. As our correlation study evolves, we will add functional details to create more complex structures. The challenge is to be able to establish a comparison reference to understand and characterize the EM effects caused by any particular mechanical perturbations.

Figure 5. Metallic enclosure used in the study showing the side dimensions and beehive style air vent apertures.

The dimensions of the beehive style apertures are shown in figure 6. To increase the shielding effectiveness of this enclosure, the size and density of these apertures can be decreased. This solution is often not very practical since it also limits the air flow through the box, consequently, minimizing the effectiveness of cooling mechanism. Thermal management usually becomes more challenging at higher data rates due to an increase in transceiver chip heat dissipations; therefore, a comprehensive study on shielding effectiveness is necessary for 25+Gbps system designs.

Figure 6. Pattern and dimensions of air vent apertures used in the enclosure.
In this study we positioned the antenna inside the enclosure in two different configurations. In the first configuration (Configuration A shown in figure 7), the antenna is placed with the surface of PCB parallel to the base of the enclosure and the long side of the PCB parallel to the long side of the enclosure. In this position the SMA connector is pointing upward as shown in the picture.

Figure 7. The geometry of antenna located inside an enclosure (Configuration A).

The antenna is accessed by providing a small access hole (0.5”), right on top of SMA through the top cover. The antenna is also held tightly in its location using a plastic fixture.

In the second configuration (Configuration B shown in figure 8), the antenna is placed with the surface of PCB parallel to the front/back side of the enclosure. In this position the SMA connector is pointing toward the front side of the enclosure.

Figure 8. The geometry of antenna located inside an enclosure (Configuration B).
The relative position of the antenna inside the box for “Configuration B” is shown in figure 9 which also shows how the antenna is held stationary using a plastic based holding fixture.

Figure 9. Interior view of “configuration B” enclosure showing the antenna and holding fixture.

5. Shielding Effectiveness

In this section of the paper, we focus on one particular aspect/feature of the enclosure: the honeycomb vent apertures. Similar studies have been performed in the past for rectangular apertures [4, 5]. We are particularly interested in the Shielding Effectiveness (SE) of the enclosure front, which has an array of honeycomb apertures embedded. The electric and magnetic shielding effectiveness in a point \( q \) is defined as:

\[
SE_e|_q = 20 \log_{10} \frac{|E_e|_q}{|E_t|_q}
\]

\[
SE_m|_q = 20 \log_{10} \frac{|H_e|_q}{|H_t|_q}
\]

In order to evaluate the shielding effectiveness of the test enclosure we first study a unit cell out of the large array. The unit cell model can be set-up to simulate the shielding effectiveness of an infinite periodic array of apertures quickly.

Figure 10 illustrates the structure under test as well as the periodic setup. For the infinite periodic simulation, we assume that the incident field can be described as Floquet modes. The Floquet mode analysis also allows us to consider incident fields with an arbitrary angle with respect to the apertures, see figure 10 for the definition of the angles theta and phi.
When an angle of incident is considered, the polarization of the field becomes important, even for symmetric apertures. We distinguish between a TE case with the electric field transversal to the apertures and a TM case with the magnetic field transversal to the apertures. Figure 11 illustrates the results of the parametric study of varying angle of incidence $\theta$ as well as the frequency via discrete curves at 5GHz, 15GHz, 30GHz and 40GHz.

We notice a decreasing trend of the SE as the frequency increases, which is certainly expected. The other interesting point is that TE and TM mode behave differently for
different angles of incidence. The apertures provide higher SE to the TE mode as the angle of incidence increases. For an angle theta=0 the SE of TE and TM mode are within the numerical accuracy for this example. The SE of the TM mode on the other hand decreases as the angle of incidence increases. This means the lowest SE is provided for the highest frequency with a TM field polarization and at the highest angle of incidence. This remarkable result has the consequence that for practical applications the study of normal angles of incidence is not sufficient because a) the position and orientation of the emission source with respect to the apertures is unknown and b) at very high frequencies the enclosure will act as a high quality resonator and the fields can be reflected off the walls many times before hitting the apertures at arbitrary angles.

While the unit cell simulation is extremely useful in the early design stage, it does not apply to the final real world application, where the honeycom vent apertures are embedded in an enclosure.

For these finite sized, but still geometrically complex arrays of many apertures we would like to introduce a simulation concept called compact model. The idea of the compact model is to replace the fine geometry details without losing accuracy of the emission prediction. This can be achieved by means of reflection and transmission within a mesh cell, which behaves as the microscopic details. In the simulation software used [6], this is implemented in a user friendly way, such that the user only has to specify the geometric details instead of drawing the full details or generating the equations for the compact model. Figure 12 illustrates the comparison of full model to compact model for a single unit cell. The results between both agree with a few dB’s and due to the lower shielding effectiveness of the compact model it is safe to use it for emission predictions even with low safety margins. The big advantage of the compact model is the reduction in mesh cell count, hence required computer resources and a reduction in the simulation time. We will provide more of this data in the next chapter.

![Figure 12. Shielding effectiveness simulation of the honeycomb unit cell model and its equivalent compact model approach.](image)

### 6. Antenna RL- Model vs. Test Correlation

As a first step in verifying the accuracy of EM modeling to predict the radiated emission, it is useful and informative to examine the antenna return loss correlation. To accomplish this, a detailed 3D geometry of the shortest antenna (devices 7 in figure. 4) was generated...
and modeled. To ensure the modeling accuracy, modeling best practices highlighted in [7] were closely followed.

The antenna RL was measured (figure 13) using a 50 GHz PNA and model and test results were compared (figure 14).

Figure 13. VNA based antenna and TL characterization.

As shown in figure 14, the degree of correlation between model and test result is impressive. It is a good indication that these models can be used reliably in emission prediction.

Figure 14. Plots of Return loss comparing test versus model.
In figure 15, we have plotted the return loss test results for all three antennas where the differences are primarily due to the trace lengths.

Figure 15. Graphs of RL test results comparing three different trace lengths, 0.6” (red), 3” (blue), and 5” (green).

In figures 16 and 17, we have presented the step and impulse responses, respectively, for all three transmission lines by transforming the 40 GHz frequency domain results to time domain.

Figure 16. Time domain plots characterizing the effect of TL lengths on signal step response degradation.
As seen in these plots, a high-speed signal degrades substantially within the 5” transmission line. To be sure that the emission source (antenna) produces sufficient radiation at high frequencies, we decided to use the shortest transmission line for the antenna emission characterizations. However, long transmission lines will be used in next phases of this study where we focus on time domain analysis using 25 Gbps chip sets. To conduct such studies, self running, long haul 25+ Gbps test chips with PRBS signal output capabilities are needed.

7. Emission Characterization

7.1. Emission Scan

Most suited for simulating test is a so called cylinder scan. The far-field is projected onto a cylinder. The radius of the cylinder corresponds to the distance device-under-test to receiving antenna. As far as radiated emission standards are concerned the radius is typically given as 3 or 10m.

Figure 18 illustrates the output of the cylinder scan. We can see that in addition to a fixed cylinder radius, the scan can also be performed for a given cylinder height. Although for practical applications eventually only a given height is scanned, it is extremely valuable information to detect possible compliance violations for other heights.
In this section we will address both issues mentioned in the previous section. In order to speed up the simulation, complexity can be reduced by means of a near-field source. The solved PCB is used to compute the near-fields around the PCB. These near-fields then are placed as a source in the enclosure instead of the detailed PCB model, effectively decomposing the model into two parts. Special consideration will also be given to the detailed features of the enclosure (e.g. slots, seams and ventilation holes) and their efficient simulation handling using compact models. Electrical size will be addressed ideally with the appropriate solver choice and by making use of available high performance computing options.

First of all we would study the enclosure itself without an emission source. A full metallic enclosure is an excellent high quality resonator. A first approximation about the modes of the enclosure can be achieved by treating it as a perfectly closed box. For such a structure the eigenfrequencies are analytically known as:

$$f_{km} = \frac{c}{2\pi \sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{k\pi}{l_x}\right)^2 + \left(\frac{l\pi}{l_y}\right)^2 + \left(\frac{m\pi}{l_z}\right)^2}$$

With $l_x, l_y, l_z$, the characteristic length in $x, y$ and $z$ and $k, l$ and $m$ the integer mode indices.
Figure 19 plots the modes in a perfect unloaded box enclosure as a histogram. We notice that at low frequencies only isolated modes exist within a 200 MHz interval. As we move to higher frequencies, the mode spectrum gets very dense. Between 4 and 5 GHz, we reach intervals which support more than 20 modes within 200 MHz. Please note that 4-5GHz is only a 10$^{th}$ of the maximum frequency we are studying in this paper.

![Histogram of modes in an ideal unloaded enclosure.](image)

Simulation can also assist in prediction of the resonance frequencies. Using an eigenmode solver we will get eigenfrequencies and eigenfields as output. Table 1 compares the predicted eigenfrequencies with and without the PCB inside. We note that the eigenfrequencies of the first four modes decrease between 50 and 100 MHz.

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Frequency Unloaded / GHz</th>
<th>Frequency Loaded / GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>0.54</td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>1.04</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>1.16</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 1. Simulated Eigenfrequencies of the enclosure with and without PCB inside.

For the designer, the eigenmode analysis can be useful to predict resonances and avoid critical resonances, which could affect other components. The freedom of organizing the electronic components in the enclosure can also be used to suppress certain critical eigenmodes. Figure 20 illustrates the electric field strength of the loaded enclosure at the fourth eigenmode. Placing metallic posts from top to bottom at positions with high field intensity would reduce the strength of the mode and the coupling into this mode.
Figure 20. Electric Field Strength of the fourth eigenmode, looking into the enclosure from the top.

For the system level simulation, we do have a variety of options to speed up the simulation, reduce complexity and use compact modeling. The model 1 or baseline of course is the PCB and Enclosure modeled and simulated together in one model. This approach does not have any limitations, as it just merges the geometry of the antenna and enclosure into one mode. This model on the other hand uses the most resources of memory used and simulation time spent.

For the second case we can replace the detailed PCB model with an equivalent near-field source. This near field source is generated by a simulation of the PCB only. The near-fields around the device are captured and recorded in a file. This is then used for a subsequent simulation, where the near-field is imported into the right location in the enclosure model. The near-fields are then imprinted and model the emission of the PCB. The advantage of this approach is reduced simulation complexity of the PCB, which speeds up the simulation and needs less memory. The accuracy of this approach is normally excellent, as the equivalence principle allows this simplification if the two domains are not strongly coupled.

Finally a third model was simulated, where part of the complex geometric details are replaced with a compact vent model. The compact models are macro-models, which exhibit a similar macroscopic behavior without the need of simulating all the microscopic details of features like cables, vents, slots and seams. The compact models, therefore, do not require meshing the fine details and instead a homogeneous mesh in this region can be used. This significantly simplifies the simulation in terms of number of mesh cells, smallest mesh cell and simulation time.
Figure 21 compares the three different approaches. We can see that all of them track the general trend of the emissions very well.

![Graph comparing three different approaches for radiated emissions simulation.](image)

Figure 21. Radiated Emissions Simulation of three cases, Full 3D Model (red), PCB replaced by a field source and full Vent Model (purple), and PCB as field source and Vent as compact model (blue).

The advantage is that the field source as well as the compact model for the vent reduce simulation time and memory requirements. Table 2 documents the simulation statistics for the three different approaches.

<table>
<thead>
<tr>
<th></th>
<th>Full Model</th>
<th>Field Source + Full Vent</th>
<th>Field Source + Compact Vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Step</td>
<td>1.857e-13</td>
<td>2.598e-13</td>
<td>7.135e-13</td>
</tr>
<tr>
<td>Mesh Cells Before Lumping</td>
<td>101.28M</td>
<td>71.52M</td>
<td>16.32</td>
</tr>
<tr>
<td>Mesh Cells After Lumping</td>
<td>24.96</td>
<td>24.60</td>
<td>15.22</td>
</tr>
<tr>
<td>Speed-up</td>
<td>1</td>
<td>1.42</td>
<td>6.07</td>
</tr>
</tbody>
</table>

Table 2. Simulation statistics for the different simulation approaches in figure 21.

We notice that the field source modeling reduces the number of mesh cells before lumping the cells together. The biggest advantage however lies in the increase in the time step for the time domain simulation, which is related to the smallest mesh step via the time integration stability criterion. In summary we get a speed-up of factor of 6 when we use the field source and the compact vent model, without a sacrifice of accuracy.

We would also like to note that this factor can increase significantly if smaller details are modeled or the emission frequency of interest is lower, e.g. factor of 50 for 0-20GHz.
7.3. **GPU computing**

In addition to the various modeling accelerations previously described, modern GPU hardware can be exploited as well. We studied the full simulation model on a regular workstation as well as the same workstation, but running the simulation off the installed GPU hardware accelerators.

Table 3 lists the results of the comparison of CPU and GPU computing. Since GPU computing is a pure acceleration technique we get exactly the same results with GPU computing than with CPU computing. Because the processing architecture is better suited for this particular computing task mainly because of the high memory bandwidth, we see a speed-up of factor 26.5 compared to CPU computing.

<table>
<thead>
<tr>
<th>Value</th>
<th>Hardware</th>
<th>Dual Xeon E5645</th>
<th>Dual Xeon E5645 + 4 Nvidia 2070</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of meshcells</td>
<td>101.28M</td>
<td>101.28M</td>
<td></td>
</tr>
<tr>
<td>Time Domain Loop [s]</td>
<td>92429</td>
<td>3493</td>
<td></td>
</tr>
<tr>
<td>Speed-up</td>
<td>1</td>
<td>26.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Comparison of GPU vs. CPU computing.

7.4. **Results**

7.4.1. **“Configuration A” Analysis**

Figure 22 shows the coordinate convention used in this study for far field referencing. This picture shows a 3D rendering of the antenna with the shortest transmission line. The origin of the coordinate is set at the center of the circular antenna embedded in dielectric material (FR408). The z-axis is along the SMA barrel (normal to the plane of antenna). Once the model is solved, a full 3D far field emission data can be obtained. Using the solution data, the emission magnitude in dB(μv/m) as a function of frequency can be plotted for any particular distance and angle. For example, a scan can be performed at θ=90° for a full range of φ variation (0-360°). We refer to this scan as “Configuration A” in this paper. “Configuration A” represents a PCB sitting flat inside an enclosure which is often the case in the real applications. For enclosure analysis related to this configuration we use the geometry depicted in figure 7 as described previously.

Since most of the radiated fields interact with the enclosure, the emission out of an enclosure follows a complex interaction between the antenna and the enclosure. For example, reflection, resonance, and polarization effects need to be considered, and they all play important roles in the overall far field emission characteristics. If the radiator has a more directional emission characteristic, or there is an angle (lobe) that the emitter
radiates more intensely, we could align that direction toward the air vent apertures (figure 6). In this case, we may see that a direct pass through (or secondary radiation from aperture) dominates the far field radiation from the enclosure.

![Coordinate convention definition used for the emission characterization of the radiation source.](image)

Antenna was modeled in both time domain and frequency domain solvers. The results have been compared and a reasonable agreement has been obtained.

### 7.4.2. "Configuration A" Test

This test was performed at a third party EMI anechoic chamber facility. The test was performed up to 18 GHz maximum frequency with 1 GHz increments and the signal generator output power was set at 10dBm. Complete angular data was collected for every 5 degrees for antenna only configuration and every 10 degrees for the antenna installed inside the enclosure. The equipment details are summarized below and the test configuration and arrangements are depicted in the pictures shown in figure 23.

- **10 Meter Chamber:** ETS-Lingren, Model DKE- 8X8 DBL
- **Horn Antenna:** EMCO, Model 3115
- **Spectrum Analyzer:** Agilent/HP, Model E4447A
- **Signal Generator:** Anritsu, Model MG3694B
Figure 23. “Configuration A” proposed test set-up (left) and the actual anechoic chamber test arrangement (right).

Due to large cable power loss at high frequencies, the signal generator was located close to the emitter (PCB antenna). Since the signal generator is located inside the room facing the receiving antenna, its emission property was evaluated as shown in figure 24. As shown in the figure, the emission from the signal generator is negligible and very close to the system (background) noise.

Figure 24. Signal generator unintentional emission test result.

It was realized that the data at higher frequencies did not show ideal signal to background noise margin, therefore, incorporating a preamplifier may be needed to increase the accuracy of the emission data at higher frequencies. However, incorporating an amplifier may also introduce signal level variations due to limited amplification accuracy or response flatness. Without an amplifier due to the problem of high cable loss, the maximum reliable anechoic based test was limited to 18 GHz with an ideal margin up to 8 GHz. The margin may increase sufficiently if we position the antenna at $\theta=180^\circ$ direction (“Configuration B” per figure 8) which corresponds to the maximum emission intensity. To show test versus mode correlation up to 40 GHz, we performed lab based tests for 1 meter distance using “Configuration B” (figure 8) which will be discussed in details.
7.4.3. “Configuration A” Results - Antenna only

In this test, receiving antenna was a 3 meter distance away and 20 cm above the emitter. This displacement translates to an angle around 4 degrees (θ≈86°). There are also angular variations of the antenna with respect to the turntable surface. The graph in Figure 25 shows the correlation between test and model for maximum of 18 GHz for the range of 83°< θ <86°. The correlation above 7 GHz is degraded and the model predicts about 10 dB higher emission intensities.

Figure 25. Test versus model correlation results for the frequency range of 1-18 GHz.

The correlation between test and model for the maximum frequency range of 7 GHz within 83°< θ <86° range, as shown in figure 26, is reasonably good.

Figure 26. Test versus model correlation results for the frequency range of 1-8GHz.

As indicated before, an excellent correlation exists up to 7 GHz where the spectrum analyzer showed good signal to background noise margin. We will run this experiment with a low noise amplifier to see if the correlation above 7 GHz would improve.
7.4.4. “Configuration A” Results- With enclosure

In this section we present simulation and test results for the emission from the radiation source placed inside the enclosure described previously (figure 8). The test results were obtained in a similar fashion as for the antenna only case.

Correlation between test and model for the frequency span of 1-18GHz at the antenna orientation of $\theta = 86^\circ$ and $0^\circ \leq \phi \leq 360^\circ$ range is shown in figure 27. Correlation between test and model is reasonable except for the low end of the frequency range (1-2GHz) where model predicts good shielding effectiveness. A probable cause may be related to the possibility that the emission power has dropped below the system noise, therefore, masking the true emission intensity. Even in the absence of ideal level of signal to noise above 8 GHz, the correlation is practically good. It should be noted, and certainly open to discussion, that the observed similarity in the shape of response (test and model) indicates that the test data is a real emission data not background noise.

![3m Emission, Test vs.Model With Enclosure](image)

Figure 27. Test versus model correlation results for emission from antenna inside the enclosure (1-18GHz).

Another observation on this correlation data reveals a larger deviation at 6 GHz. For further investigation into this issue, it would be helpful to run the test and model at finer frequency points. Then, we may observe, if potentially, single narrow band interference may have upset the balance or there are other unaccounted effects. Finer frequency points may also reveal if there are periodic narrow resonances which can also explain this observation. Modeled and tested resonances may not line up exactly and by under sampling the frequency, the difference between the test and model result at a certain frequency point could be exaggerated.
7.4.5. **"Configuration B" Results- Antenna only**

To investigate the test and model correlation for up to 40 GHz, we considered the emission at a single angle. To improve the test accuracy, we use the direction with most intense radiation and perform the test versus modeling analysis at that angle. We also reduced the distance between the radiator and the receiving antenna to 1 meter. The angle considered for this study was set to $\theta=180^\circ$ per coordinate definition shown in figure 22. Antenna emission model can be used to produce data for all directions but in this section, we only consider the correlation for the tested angle. The antenna test set-up is depicted in the diagram below;

![Antenna test set-up diagram](image)

Figure 28. Antenna only test set-up for “configuration B” direction.

The list of equipments used in this test is presented below;

**Horn Antennas**: ETS-Lindgren Models 3115 (750 MHz- 18 GHz) and 3116 (18-40 GHz)

**VNA**: Agilent Network analyzer Model E8364B (10 MHz to 50 GHz)

**Amplifier**: Agilent Amplifier Model 83051A (45 MHz to 50 GHz)

Graphs of figure 29 show the test versus model comparison for maximum frequencies of 18 GHz and 40 GHz respectively. It can be seen that within 1-18 GHz, the correlation is very good but it degrades slightly for 18-40 GHz range, however, it maintains a reasonable correlation in emission resonances indicating that the test results are indeed true emission signals from the radiator and not noise.
Figure 29. Test versus model correlation results for the frequency range of 1-18GHz (top) 18-40 GHz (bottom).

The amplifier introduces power variation within the 18-40 GHz which also affects the correlation. It should be noted that a 10dBm power input has been assumed in all these analysis.
7.4.6. “Configuration B” Results- With enclosure

The “Configuration B” test arrangement for antenna inside the enclosure is depicted in figure below.

![Figure 30](image)

Figure 30. Emission test set-up for antenna inside the enclosure for “configuration B”.

In this analysis the tested emission was the y-component of the electric field, as shown in the picture below, where in the previous test, the perpendicular component of the transverse E field was measured.

![Figure 31](image)

Figure 31. Definition of emission field orientation considered for “configuration B” for antenna inside the enclosure.

Graphs in figure 32 show the test versus model comparison for maximum frequencies of 18 GHz and 40 GHz respectively. It can be seen that the correlation is reasonable but it is not as good as the correlation data from the antenna without enclosure case (figure 29).
The test result shows more resonances for the fact that data includes more frequency points ($\Delta f=0.25$ GHz) than model ($\Delta f=1$ GHz). It should also be noted that the lower frequency end of 18-40 GHz range seems to have better correlation than the high end of 1-18 GHz range (i.e., 18GHz). This may be a consequence of using an amplifier for 18-40 GHz test which suggests that the data for lower frequency end of 18-40 GHz may be more accurate than the higher frequency end of 1-18 GHz test data. Nevertheless, the overall correlation looks promising.

Figure 32. “Configuration B” test versus model correlation results for the frequency range of 1-18GHz (top) and 18-40 GHz (bottom).
8. Conclusion

In this study we used fullwave 3D simulation tools to predict EM emission from a radiation source embedded in a multi-layered PCB. For this, we designed, fabricated, and tested wide band radiation sources (antennas). The prediction accuracy of 3D EM simulation was verified for two cases, 1) antenna only and 2) antenna enclosed in a metallic enclosure.

As a conclusion to this study, it appears that if modeling is done correctly by following a set of established best practices, the correlation between test and model is satisfactory. An important factor in emission modeling accuracy relates to the physical size and fine geometrical details considerations. To manage the size and geometry complexities, advance tools with special features and effective techniques are needed. Often, however, the lack of a reasonable correlation is more indicative of a non-ideal test environment rather than modeling accuracy assuming that the modeling methodology is indeed effective and reliable. By improving test, we are primarily speaking in terms of increasing the signal (emission) to background noise margin.

Once, the modeling requirements are recognized and an effective methodology is established, simulation will provide a powerful EMC/EMI design and verification tool. Integration of this tool with all other suitable EM based design tools, such as signal and power integrity tools, can reduce the cost and complexity associated with design and development of telecom and datacom equipments. As an example, modeling and simulation of the shielding effectiveness of an enclosure showed that the internal reflections and resonances within the enclosure play important roles in the overall emission, and if these reflections are not managed correctly, shielding may not be very effective. It is within the scope of the next phases of this study to implement more detailed experiments addressing the issue of shield effectiveness at high frequencies. For example, as stated in the previous sections, we will give special consideration to the detailed features of the enclosure (e.g. slots, seams and ventilation holes) and their efficient simulation handling using compact models. Based on simulation, the individual contribution of each feature will be predicted.

Another future topic in line with this paper is the experimentation in time domain where the signal is directly generated from an on-board 25+ Gbps transceiver chips. Also, we are interested to apply recent spread spectrum techniques and making use of the time-frequency domain relationship to shift emission frequencies by introducing jitter into the system. The impact of spread spectrum on correlating measurement with simulation needs to be investigated. To complete the implementation of a robust and proven workflow for prediction of compliance and suppression of emissions, polarization and resonance dependency still need to be addressed. On the continuation of this study, we refer these remaining fundamental research tasks to our, and hopefully others, future related works.
References


