A Method to Assess the Radiated Susceptibility of Printed Circuit Boards

G. Kevin Zhu, Werner Thiel, and J. Eric Bracken
Ansys, Inc.
2600 Ansys Drive
Canonsburg, Pennsylvania 15317
Email: {kevin.zhu, werner.thiel, eric.bracken}@ansys.com

***Abstract*—Printed circuit boards (PCB) are subject to external electromagnetic interference. A validation tool to efficiently predict the worst-case induced voltages and currents is invaluable in the process of making PCB designs pass the immunity test for electromagnetic compliance. This paper proposes to use a 2.5-D hybrid finite-element-method (FEM) solver to characterize the radiated far field and use the reciprocity-based method to calculate the induced port voltages and currents due to an incident plane wave. This method can be used to analyze any full-size PCB. Good agreement with the results from a 3-D full-wave FEM is obtained at low frequencies, where the 2.5-D assumption for the fields in the PCB applies. Furthermore, the calculation time and memory consumption are significantly reduced.**

***Index Terms*—Electromagnetic interference, printed circuits, immunity testing**

I. Introduction

Printed circuit boards (PCB) are subject to electromagnetic interference. Ambient electromagnetic energy is coupled to the metallic geometries, such as traces, vias, planes, etc., inducing unwanted noise and degrading signal quality. International standards [1] have been established to ensure electronic systems withstand such interference and function properly. Validation tools to quantitatively predict the amount of electromagnetic energy coupled to electronic systems including PCB and integrated circuit packages are invaluable in the system design process. Designs evolving with frequent validation are likely to pass the immunity test and meet the standard.

One way to assess how susceptible a PCB design is to electromagnetic interference is to find the port voltages and currents induced by an incident plane wave. The PCB may contain very complicated geometry leading to computationally prohibitive problems for full-wave electromagnetic calculations. In addition, an electromagnetic susceptibility analysis often requires running multiple calculations to cover all possible sources of interference and identify the worst-case scenario.

In this paper, we take a circuit approach to calculate the induced port voltages and currents. We use a 2.5-D hybrid FEM solver [2] to compute the radiated far field due to an exciting circuit port. The radiated far field at a particular angle is related to the voltage at the plane-wave port. The circuit port and the plane-wave port form a two-port network. We use the reciprocity theorem to find the voltages and currents at the circuit port induced by the plane wave coming from this angle [3].

Complicated PCBs, impossible to analyze with full-wave 3-D solvers, can be analyzed with our method. Simple PCBs can be analyzed at a reduced calculation time and memory consumption. Parametric sweeps over all incident directions and all polarizations can be quickly set up to search for the worst-case scenario, making this method attractive for the susceptibility analysis of PCB designs.

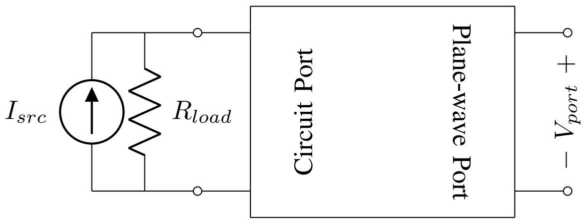
II. Method

A PCB includes metallic geometries to deliver power to electronic components and route signals among them. Three common geometries of PCB are planes, traces, and vias. Due to the high conductivity of metal planes and the absence of higher-order modes at low operating frequencies, electric fields between planes are assumed to only have the vertical components. This effectively reduces the vectorial Helmholtz's equation as a function of the fields to the scalar Helmholtz's equation as a function of the potentials on the planes. Traces are modeled as transmission lines, and vias are considered electrically small and modeled with equivalent circuits. Circuit laws relate the voltages and currents associated with the geometries and lead to a system of equations, which can be solved to yield the voltages and currents everywhere in the PCB.

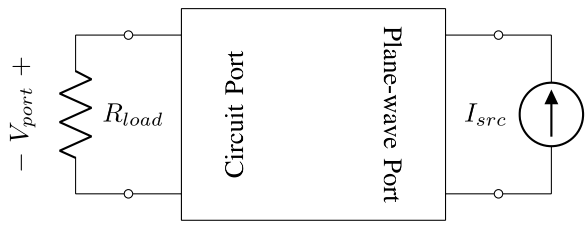
We use a hybrid of modified nodal analysis and 2-D finite elements to formulate the system of equations that describes the voltage-current relationship in the PCB. We excite each circuit port with a current source I_{src} in parallel with a resistor R_{load} and leave all other ports terminated with load resistors. We solve for the branch voltages everywhere in the circuit and calculate the surface currents of the PCB from the branch-voltage solution and the connectivity of the circuit. Convolving these surface currents and the Green's function gives the radiated far field due to the port excitation.

We follow the work in [3] to use the reciprocity theorem to find the induced voltage at the circuit port. The circuit representation of the forward radiation problem is shown in Fig. 1a, which is solved by the hybrid solver. The voltage V_{port} at the plane wave port of length L is given by [4]

$$V_{port} = -\int_{-L/2}^{L/2} \frac{e^{-jkr}}{r} \left(r\vec{E}_{rad} \right) \cdot \vec{l}dl \ , \qquad (1)$$



(a)



(b)

Fig. 1. Circuit diagram of (a) the forward radiation problem and (b) the reverse problem.

where r denotes the radial distance, $\left(r\vec{E}_{rad}\right)$ denotes the radiated far field at a particular angle, and $\vec{l}$ denotes the orientation of the port perpendicular to the radial vector. The circuit representation of the reverse problem is shown in Fig. 1b. A Hertzian dipole of length L with the same constant current I_{src} excites the plane-wave port and its radiated field at the circuit port is given by

$$\vec{E}_0 = \frac{k\eta}{j4\pi} I_{src} \frac{e^{-jkr}}{r} L\vec{l}\ . \tag{2}$$

By reciprocity, the voltage at this circuit port induced by the Hertzian dipole in the reverse problem is equal to the voltage at the plane-wave port in the forward problem. Combining (1) and (2) eliminates the dipole length L and gives the final equation

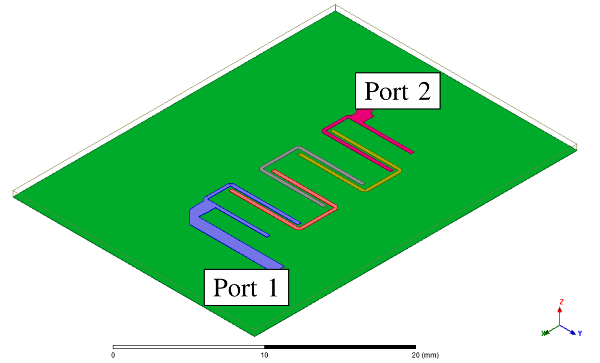
$$V_{port} = \frac{4\pi}{jk\eta I_{src}} \vec{E}_0 \cdot \left(r\vec{E}_{rad}\right)\ . \tag{3}$$

The direction of propagation of the incident plane wave is stored in $r\vec{E}_{rad}$. The magnitude and polarization of the incident plane wave is stored in $\vec{E}_0$.

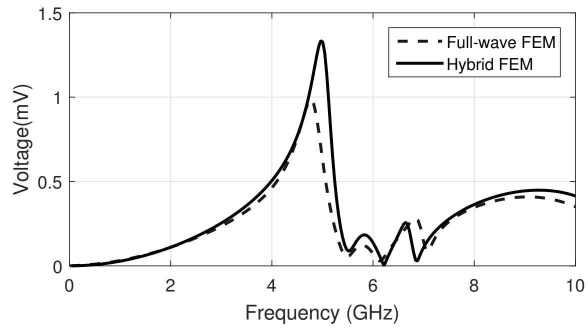
One solution to the system of equations gives the radiated far field at all angles due to the exciting port. Permuting different incident directions, field polarizations, and field magnitudes and applying (3) gives the induced voltage. The induced current is found from Ohm's law. The largest induced voltage at this port is the worst-case scenario due to plane waves. This process is iterated through the remaining ports and we find the induced voltages at all ports due to plane waves.

III. Numerical Examples

The following examples were first solved by our 2.5-D hybrid FEM solver [5], then by our 3-D full-wave FEM solver [6] for comparisons. All calculations were run on a Dell Precision T5600 workstation with an Intel Xeon E5-2687W processor and 128 GB memory. All calculations used 16 cores.



(a)



(b)

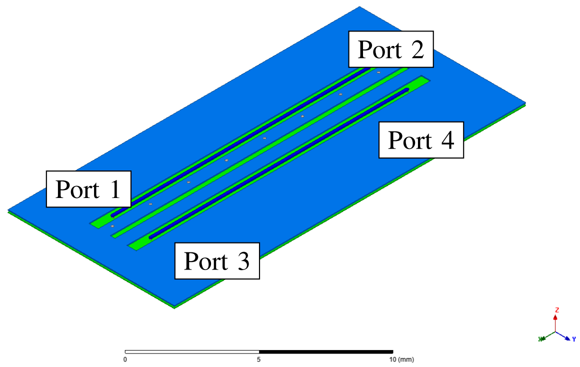
Fig. 2. (a) A microwave filter illuminated by a 1-V/m plane wave polarized in the +X direction propagating in the -Z direction, (b) voltage induced at Port 1.

A. Microwave Filter

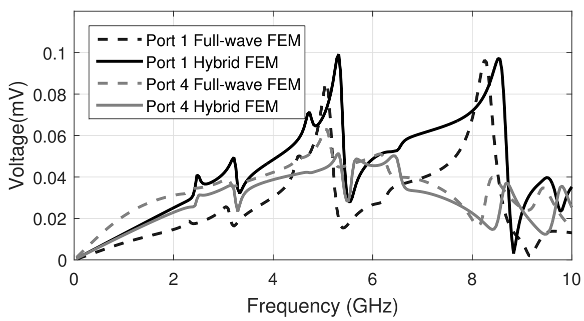
The first example is a 30 mm×22 mm microwave filter shown in Fig. 2a, which is illuminated by a 1-V/m plane wave polarized in the +X direction propagating in the -Z direction. All ports are terminated with 50-Ω resistors. The induced voltage from 50 MHz to 10 GHz at Port 1 is shown in Fig. 2b. The voltages at the terminated ports obtained by the hybrid solver are comparable to those obtained by the full-wave solver at the frequencies below 4 GHz. The models in our hybrid solver match better at low frequencies. As the frequency is raised, they do not capture the 3-D coupling effect. The accuracy of the hybrid solver is gradually lost and so is the calculated voltages. In this case, 3-D full-wave calculations are necessary to accurately characterize the PCB. In this example, our hybrid solver takes 86 ms for each frequency point, and the maximum memory consumption is 155 MB. Our 3-D full-wave solver takes 2.98 s for each frequency point, and the maximum memory consumption is 328 MB.

B. Grounded Co-planar Waveguides

The second example includes two parallel grounded co-planar waveguides separated by a via fence over a 18.8 mm×9 mm substrate shown in Fig. 3a. The structure is illuminated by a 1-V/m plane wave polarized in the $\vec{\theta}$ direction with an oblique incident direction of $\phi = 45°$, $\theta = 30°$. All ports are terminated with 50-Ω resistors. The induced voltages

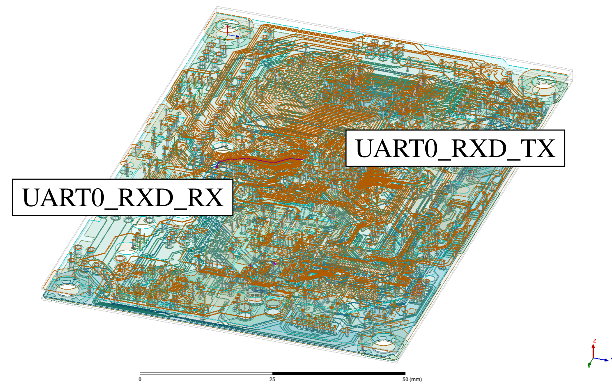


(a)

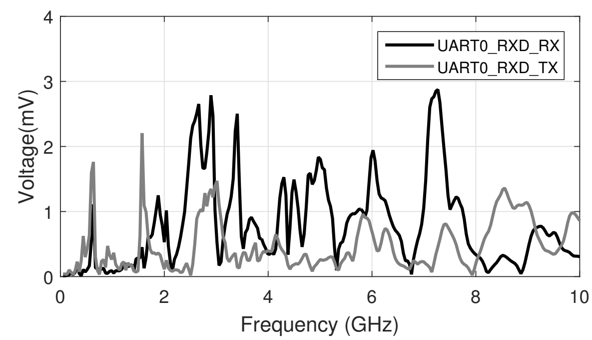


(b)

Fig. 3. (a) Two parallel grounded co-planar waveguides separated by a via fence and illuminated by a 1-V/m plane wave polarized in the $\vec{\theta}$ direction with an incident direction in $\phi = 45°$, $\theta = 30°$, (b) voltages induced at Port 1 and Port 4.



(a)



(b)

Fig. 4. (a) Intel Galileo board illuminated by a 1-V/m plane wave polarized in the $\vec{\theta}$ direction with an incident direction in $\phi = 45°$, $\theta = 30°$, (b) voltages induced at the two ports on the signal net `UART0_RXD`.

at Port 1 and Port 4 are shown in Fig. 3b. In this example, the hybrid solver takes 113 ms for each frequency point, and the maximum memory consumption is 130 MB. The 3-D full-wave solver takes 2.98 s for each frequency point, and the maximum memory consumption is 456 MB.

C. Galileo Board

The third example, shown in Fig. 4a, is the Intel Galileo board [7] illuminated by a 1-V/m plane wave polarized in the $\vec{\theta}$ direction with an incident direction in $\phi = 45°$, $\theta = 30°$. The signal net `UART0_RXD` is selected and has two ports terminated with 50-Ω resistors defined at its ends. The induced voltages are shown in Fig. 4b. The hybrid solver takes 7.24 s for each frequency point and the maximum memory consumption is 35.2 GB. This problem cannot be solved by the 3-D solver on the test machine.

IV. Conclusion

This paper presents a method to assess the radiated susceptibility of a PCB. It utilizes the 2.5-D hybrid FEM method and the reciprocity-based method to calculate the induced port voltages and currents. This is the only method to analyze any full-size PCB, and analyze simple PCB at reduced computational cost. The accuracy of this method is determined by how closely the fields in the PCB agree with the assumptions made in the hybrid FEM method. Validation tools based this method could be invaluable in the process of making PCB designs pass the immunity test for electromagnetic compliance.

Acknowledgment

The authors would like to thank Naiguang Lei and Jiuzhou Qin for constructing the examples and collecting calculation results.

References

[1] *Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test*, International Electrotechnical Commission Std. 61 000-4-3, 2006.
[2] J. E. Bracken, S. Polstyanko, S. Raman, and Z. J. Cendes, "Efficient full-wave simulation of high-speed printed circuit boards and electronic packages," in *Proc. IEEE Antennas and Propagation Society International Symposium (AP-S'04)*, Monterey, California, Jun. 2004, pp. 3301–3304.
[3] F. Vanhee, D. Pissoort, J. Catrysse, G. A. E. Vandenbosch, and G. G. E. Gielen, "Efficient reciprocity-based algorithm to predict worst case induced disturbances on multiconductor transmission lines due to incoming plane waves," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 1, pp. 208–216, Feb. 2013.
[4] P.-S. Kildal, "Equivalent circuits of receive antennas in signal processing arrays," *Microwave and optical technology letters*, vol. 21, no. 4, pp. 244–246, May 1999.
[5] *SIwave Online Help*, Ansys, Inc., Canonsburgh, PA, 2017, release 18.0.
[6] *HFSS Online Help*, Ansys, Inc., Canonsburgh, PA, 2017, release 18.0.
[7] Reference design .BRD file for Intel® Galileo. online. Intel Corporation. [Online]. Available: http://www.intel.com/content/www/us/en/support/boards-and-kits/intel-galileo-boards/000006443.html