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Estimating Maximum Radiated Emissions From Printed Circuit Boards With an Attached Cable

Shaowei Deng, Todd Hubing, and Daryl Beetner

Abstract—The common-mode current induced on cables attached to printed circuit boards can be a significant source of radiated emissions. Previous studies have shown that coupling from electric and magnetic field sources on circuit boards can be effectively modeled by placing equivalent voltage sources between the board and the cable. The amplitude of these equivalent sources can be estimated by using closed-form equations; however, estimates of the radiated emissions from these board-cable geometries have required full-wave simulations, and full-wave simulation results depend on the exact cable length and placement, which are not normally fixed during radiated emissions testing. This paper develops a closed-form equation to estimate the maximum radiated fields from a voltage source driving a board relative to an attached cable over a ground plane. This equation is evaluated for various cable and board geometries by comparing the calculated results to full-wave simulations. The maximum radiation calculated by using the closed-form expression generally predicts the peak full-wave simulation results within a few decibels for various board sizes and cable lengths.

Index Terms—Antenna model, common-mode current, maximum radiated emissions, printed circuit board (PCB).

I. INTRODUCTION

The common-mode current induced on cables attached to printed circuit boards (PCBs) can be a significant source of unintentional radiated emissions [1]–[3]. The signal traces, integrated circuits (ICs), and heatsinks on a PCB produce electric and magnetic fields that couple to these cables inducing common-mode currents. The maximum

radiated emissions from a typical PCB with attached cables due to common-mode current can be numerically calculated using a full-wave simulation. However, this type of simulation requires extensive computational resources and does not calculate the maximum emissions, but rather the emissions expected from the precise configuration modeled. Alternately, expert system algorithms for estimating maximum radiated emissions from PCBs employ closed-form calculations that anticipate the maximum possible radiation [4], [5]. In this way, sources and coupling mechanisms that cannot contribute significantly to radiated emissions can be systematically eliminated, and attention can be focused on the features of a given design that may be the source of electromagnetic interference (EMI) problems.

Previous attempts to estimate the maximum radiation from cables attached to circuit boards with traces, ICs, and heatsinks have shown that it is possible to start with a complex board geometry that has various structures driven by differential-mode signal voltages (V_{DM}), and use relatively simple static-field modeling techniques [6], closed-form estimates [7], or transverse electromagnetic cell measurements [8] to represent that board with a simple board–source–cable model, as shown in Fig. 1. For a electric field coupling, the magnitude of the equivalent common-mode voltage source (V_{CM}) is determined by the self-capacitance of the traces or heatsinks and by the board dimensions. For magnetic field coupling, it is a function of trace or component currents, and current-loop geometries on the board [9], [10].

In order to estimate the maximum radiated emissions, it has been necessary to model the board–source–cable geometry using a full-wave technique or employ relatively crude closed-form estimates based on dipole source models. In this paper, a closed-form equation is developed to predict the maximum radiation from the board–source–cable geometries likely to be encountered in radiated emissions tests. The accuracy of the closed-form equation is evaluated for various board sizes and cable lengths.

II. MAXIMUM RADIATION ESTIMATION

Consider the simplified structure of a board with an attached cable in a typical electromagnetic compatibility (EMC) test environment, as shown in Fig. 2, where a voltage source is located between the cable and the board. The cable is 1 m long and attached to an infinite ground plane. This structure is essentially an unbalanced monopole with the source located some distance away from the ground plane. For simplicity, it is assumed that the attached cable has negligible diameter and the current distribution on the cable is sinusoidal. This is a good approximation when the cable diameter is considerably smaller than the wavelength.

The radiated field from the monopole is proportional to the peak current and also proportional to the monopole length at frequencies where the monopole is much smaller than the wavelength [11]. Due to the sinusoidal distribution of the current, the peak current in the monopole obtains its maximum value only when the effective length of the structure above the ground plane is a quarter wavelength or longer. The current at the source location is also limited by the effective length of the board. Thus, the maximum radiated electric field is significantly affected by the cable length l_{cable} and the board size, if the cable length or the effective board length is shorter than a quarter wavelength. When the cable length and/or the board size are larger than a quarter wavelength, the peak current in this antenna is capable of reaching its theoretical maximum, and so is the corresponding radiated electric field.

The maximum possible radiated electric field for this board–source–cable antenna model can be estimated by comparing the emissions from this structure to the emissions from a thin-wire monopole above an infinite ground plane. The radiated electric field strength from this

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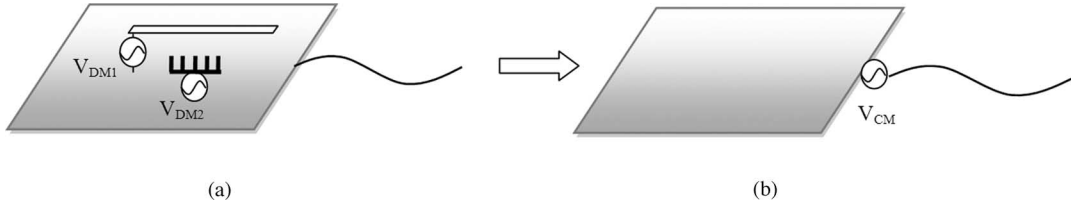


Fig. 1. Board and attached cable configuration.

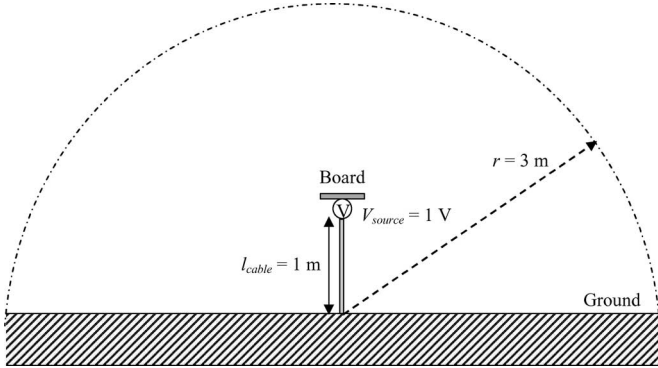


Fig. 2. Board-source-cable geometry.

structure is given by [11]

$$E_{\theta} = j\eta_0 \frac{I_0 e^{-jkr}}{2\pi r} \left[\frac{\cos(kl \cos \theta) - \cos(kl)}{\sin \theta} \right] \quad (1)$$

where I_0 is the current maximum at the voltage source in the monopole, l is the monopole length above the ground, r is the distance from the monopole to where the electric field is investigated, θ is the zenith angle in the spherical coordinate system, k is the wavenumber ($k = 2\pi/\lambda$), and η_0 is approximately $120\pi \Omega$. The magnitude of the radiated electric field (in volts per meter), 3 m from the source, can be expressed as

$$\begin{aligned} |E_{\theta}| &= \eta \frac{I_0}{2\pi r} \times \left| \frac{\cos(kl \cos \theta) - \cos(kl)}{\sin \theta} \right| \\ &= 120\pi \times \frac{I_0}{2\pi \times 3} \times f(\theta, k) = 20 \times I_0 \times f(\theta, k) \end{aligned} \quad (2)$$

where

$$f(\theta, k) = \left| \frac{\cos(kl \cos \theta) - \cos(kl)}{\sin \theta} \right|. \quad (3)$$

Here, θ is a variable between 0 and $\pi/2$ and k is a variable proportional to the frequency. The maximum value of $f(\theta, k)$ as a function of θ and frequency when l is 1 m (and the maximum frequency of interest is 500 MHz) is 2.76.

For a monopole above an infinite ground plane, the maximum current is achieved when the monopole is a quarter wavelength long, and the corresponding input resistance is about 37Ω [11]. Thus, the maximum current (in amperes) on the monopole when driven by a 1-V source is

$$I_{0(\max)} = \frac{V}{R_{\min}} = \frac{1V}{37\Omega} = 0.027 \text{ A}. \quad (4)$$

The maximum radiated electric field (in volts per meter) due to a source voltage, V_{CM} , is,

$$\begin{aligned} |E|_{\max} &= 20 \times I_{0(\max)} \times f_{\max}(\theta, k) \\ &= 20 \times 0.027 \times V_{CM} \times 2.76 \\ &= 1.49 V_{CM}. \end{aligned} \quad (5)$$

When the length of the monopole is much smaller than a quarter wavelength, the maximum radiated electric field is determined by the cable length. Approximating the current distribution in the cable as sinusoidal, the highest current that actually exists on the cable, I_{peak} , is related to the maximum current $I_{0(\max)}$ by

$$I_{\text{peak}} = I_{0(\max)} \sin\left(\frac{2\pi l_{\text{cable}}}{\lambda}\right). \quad (6)$$

$I_{\text{peak}} = I_{0(\max)}$ only when the monopole (mostly cable) is at least a quarter-wavelength long. Thus, a simple radiation factor can be defined to account for the limiting effect that the finite cable length has on the maximum field at low frequencies

$$\text{cable_rad_factor} \equiv \begin{cases} \sin(2\pi l_{\text{cable}}/\lambda) & \text{when } l_{\text{cable}} \leq \frac{\lambda}{4} \\ 1.0, & \text{otherwise.} \end{cases} \quad (7)$$

If the cable length is equal to or larger than a quarter wavelength, then the maximum current may be limited by the board size (which is usually much smaller than the cable length). Similarly, approximating the current distribution on the board as sinusoidal, the peak current on the board occurs at the source and can be related to the maximum current. The peak current achieves its maximum value only when the effective board length is a quarter wavelength or longer. Thus, another radiation factor can be defined to account for the limiting effect of a small board size as

$$\text{board_size_factor} \equiv \begin{cases} \sin(2\pi l_{\text{board}}/\lambda) & \text{when } l_{\text{board}} \leq \frac{\lambda}{4} \\ 1.0, & \text{otherwise} \end{cases} \quad (8)$$

where l_{board} is the effective length of the board. Simulations conducted for this paper have shown that the diagonal length is a good approximation for the effective length of rectangular boards.

The maximum radiation accounting for the finite cable length and the finite board size can then be estimated by combining (5), (7), and (8) as

$$|E| = |E|_{\max} \times \text{cable_rad_factor} \times \text{board_size_factor}. \quad (9)$$

III. VALIDATION

The estimation (9) was evaluated by comparing estimates to full-wave simulation (Computer Simulation Technology (CST), CST Microwave Studio 5.1) results. Fig. 3 shows a plot of the closed-form estimate and simulation results as a function of frequency for a 5-cm square board and a 7 cm \times 1 cm rectangular board attached to a 1 m cable. The closed-form expression is a function of the board's diagonal length, but is independent of the board's shape. Therefore, the same closed-form estimate applies in both cases.

The peak emissions from the board-source-cable are predicted within a few decibels at every resonant frequency. Fig. 4 shows a similar plot for a 50-cm square board and a 70 cm \times 10 cm rectangular board. Even though this board is no longer very small relative

TABLE I
SUMMARY OF CLOSED-FORM ESTIMATE VERSUS FULL-WAVE SIMULATION RESULTS

Board Length (cm)	Board Width (cm)	Cable Length (cm)	Estimate/simulation difference in dB			
			1 st resonance	2 nd resonance	3 rd resonance	4 th resonance
5	5	100	0	+1	+1	+1
7	1	100	+3	+3	+3	+4
10	10	100	0	+1	+2	+3
14	2	100	+3	+4	+4	+3
15	15	100	0	+2	+3	+2
21	3	100	+3	+4	+3	+2
20	20	100	+1	+2	+2	+2
28	4	100	+3	+4	+2	+2
25	25	100	+2	+3	+3	+1
35	5	100	+3	+4	+2	+1
30	30	100	+3	+3	+2	+1
42	6	100	+4	+4	+2	+1
35	35	100	+3	+3	+2	+1
49	7	100	+4	+3	+2	+2
40	40	100	+2	+3	+2	0
56	8	100	+5	+2	+2	+5
45	45	100	+3	+3	+2	0
63	9	100	+5	+3	+2	+8
50	50	100	+3	+2	+2	0
70	10	100	+3	+2	+2	+5
10	10	80	0	+2	+2	NA
10	10	160	+2	0	0	+2

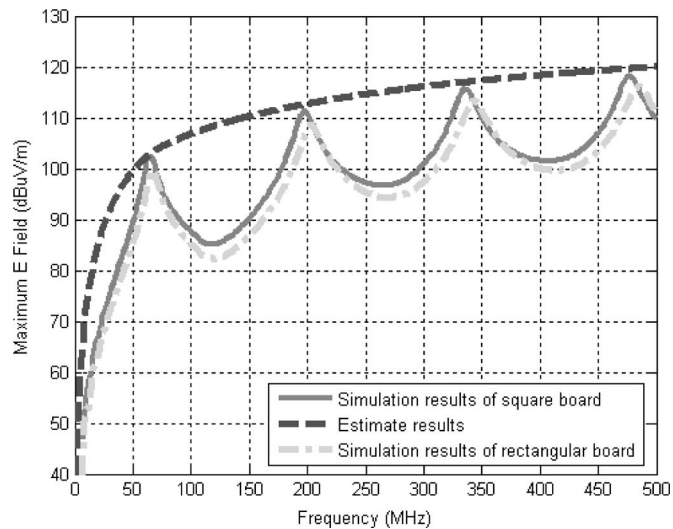


Fig. 3. Maximum radiation for a 5-cm square board and a 7 cm \times 1 cm rectangular board (1-m cable).

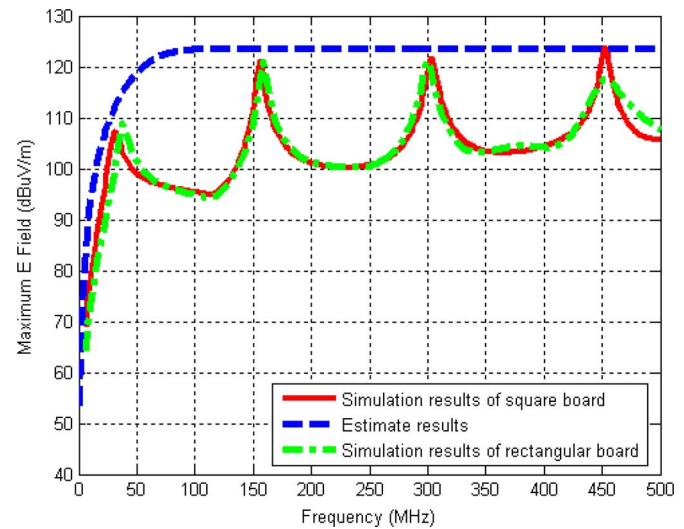


Fig. 4. Maximum radiation for a 50-cm square board and a 70 cm \times 10 cm rectangular board (1-m cable).

to the cable length, the closed-form estimate does a reasonable job of estimating the maximum emissions.

Table I lists various board–source–cable configurations that were evaluated during this research. The difference between the estimate and the simulation in decibels is reported at each of the resonant frequencies between 30 and 500 MHz. In most cases, the closed-form estimate predicted the maximum emissions at resonances within a few decibels, and it never underestimated the emission peaks. Although there is no room to plot all the results here, plots corresponding to each of the configurations in Table I can be found in [12].

The simulation results in the previous figures were performed with the source connected to the bottom center of the circuit board plane. However, the peak emissions are relatively independent of the connection point to the board. To illustrate this point, a 100-cm-long cable was

connected at the edge of a 10-cm square board instead of the center. The change in the radiated emissions was less than 1 dB at all frequencies evaluated (30–500 MHz).

In EMI measurements of real products, the cable does not usually connect to the ground plane at the point directly beneath the circuit board. However, the maximum radiation is relatively insensitive to the total cable length or orientation. The parameters that matter most are the vertical distance traversed by the cable and the maximum current. To illustrate this, the cable length was increased and a portion of the cable was located horizontally above the ground, as illustrated in Fig. 5. The maximum radiation estimate was not affected, since the effective cable length in the closed-form equation is the vertical length. The results for various horizontal lengths of the cable, 4 mm above the ground, are shown in Fig. 6. The increase in the overall length of the cable results

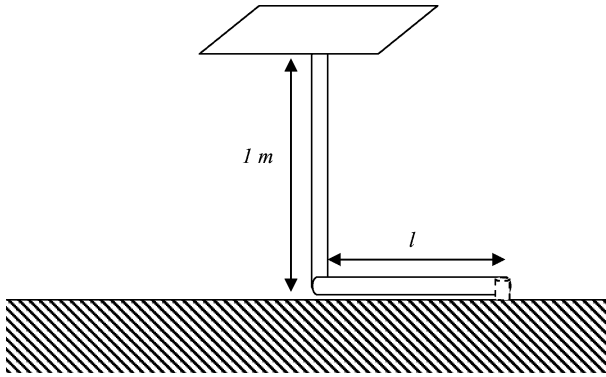


Fig. 5. Board–source–cable geometry with a portion of cable on the ground.

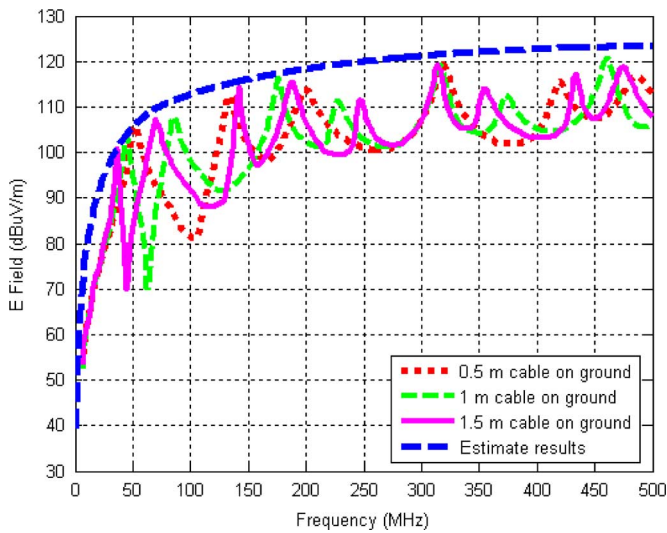


Fig. 6. Maximum E field with a portion of cable horizontal above the ground.

in a downward shift of the peak frequencies, but the magnitude of the peaks is still predicted by the closed-form estimate to within a few decibels. Similar results were obtained when the horizontal portion of the wire was 50 cm off the ground or oriented at an angle relative to the ground.

IV. CONCLUSION

A board–source–cable antenna model can be used to simplify radiated emissions estimates from circuit boards with traces, components, or heatsinks that couple common-mode currents to attached cables. This model consists of an equivalent common-mode voltage source located between the board and the attached cable. Full-wave simulations

of this structure can be used to determine the radiated field strengths; however, full-wave simulation results depend on the cable length and placement, which are not known or fixed in actual radiated emissions tests. It is often more helpful to estimate the maximum possible emissions for any attached cable than it is to calculate the emissions for a specific cable configuration.

In this paper, a closed-form equation for estimating the maximum radiation from board–source–cable structures was derived and evaluated. The closed-form expression has been shown to be reasonably accurate for various cable and board geometries. Maximum radiation estimates are generally within a few decibels of the peak amplitudes calculated by full-wave numerical models up to 500 MHz.

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