Determining the Maximum Allowable Heatsink Voltage to Ensure Compliance with a Given Radiated Emissions Specification

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***Abstract*—A model to estimate the minimum voltage between a heatsink and a PCB that is required to generate a given radiated electromagnetic field strength from a PCB with attached cables is introduced. The model is based on a previously introduced technique for calculating the maximum possible radiated field due to a known voltage driving a heatsink against a circuit board with attached cables. A closed-form expression is derived that can be used to determine if a measured voltage on a heatsink is capable of generating a field strong enough to exceed an FCC or CISPR radiated emissions limit.**

***Keywords*—heatsink, PCB, cable, radiated emissions, FCC limit**

I. INTRODUCTION

Common-mode currents induced on cables attached to printed circuit boards (PCBs) are a well known source of unintentional radiated emissions. The mechanisms by which intentional signals induce common-mode currents on attached cables are generally divided into two categories: current-driven and voltage-driven. The former describes coupling from the signal's magnetic field and the latter from the signal's electric field. PCB radiation due to currents induced on attached cables by a heatsink is usually voltage-driven and the source parameter of interest is the voltage between the heatsink and the top of the circuit board [1] [2].

The amplitude of this radiation depends on the level of the differential-mode voltage and the geometry of the PCB, cable and heatsink. Calculation of the exact radiated fields from any specific geometry is complicated and generally requires sophisticated numerical modeling techniques. It is helpful to have a simplified model that calculates the maximum possible EMI level attainable from a given heatsink and PCB cable geometry. A model like this is described in [4].

Conversely, suppose the maximum radiated field was the known quantity and the voltage between the heatsink and PCB was the object of the calculation. With such a model, one could estimate the maximum allowable differential-mode voltage between the heatsink and the PCB subject to a known radiated emissions limit.

Such a model is introduced in this report. With this model, the maximum allowable differential-mode voltage between a heatsink and a PCB (that guarantees the heatsink is not the source of a given radiated emissions problem) can be calculated.

II. VOLTAGE ESTIMATION MODEL

A. *Simplified heatsink-PCB-cable model.*

Most circuit board heatsinks have resonant frequencies above 1 GHz. At frequencies below the heatsink's resonance, the EMI is more likely to be dominated by the resonances of the attached cables. If the PCB is electrically small and the self-capacitance of the heatsink is smaller than that of the PCB, a simplified model can be used to estimate the radiated EMI due to the heatsink. In such a model, the original heatsink-PCB-cable configuration is replaced with an equivalent PCB-cable configuration, where the geometry of the board and the cable remains the same. In the new model, an equivalent voltage source is placed at the junction where the cable is connected to the board. The amplitude of the equivalent voltage source is calculated using the following formula [2],

$$V_{CM} = \frac{C_{heatsink}}{C_{board}} V_{DM} \tag{1}$$

where, $C_{heatsink}$ and C_{board} are the self-capacitance of the heatsink and the board, respectively; V_{DM} is the differential mode voltage between the heatsink and the PCB in the original configuration; and V_{CM} is the equivalent common-mode voltage between the cable and the board in the new configuration [3]. The self-capacitance can be calculated with 3-D static field solvers or estimated with closed-form expressions [2].

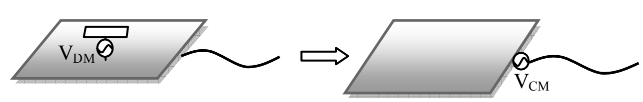

Fig. 1. Heatsink-PCB-cable model and equivalent PCB-cable model.

B. *Maximum radiated electric field calculation*

The simplified model is actually an unbalanced monopole with the source located some distance away from the ground

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plane to which the other end of the cable is connected. For such a structure, the maximum radiation is estimated under the assumption that the thickness of the cable is negligible and the current distribution on the cable is sinusoidal. This is a good assumption when the cable diameter is significantly smaller than a wavelength [3].

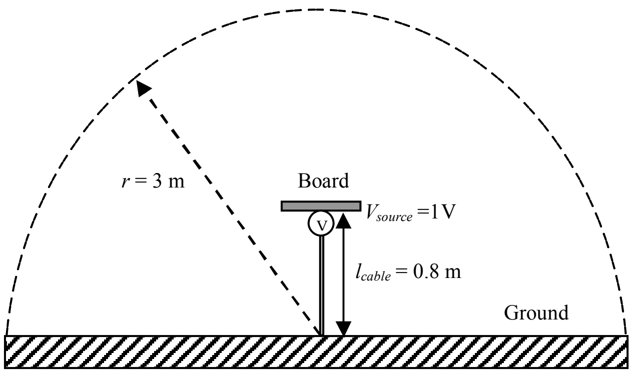

Fig. 2. The board-equivalent-source-cable geometry.

The maximum possible EMI from this structure is estimated by the following formula [3],

$$|E| = |E|_{\max} \times F_{cable} \times F_{board} \tag{2}$$

where $|E|_{max}$ is the maximum radiation for such a structure assuming the cable and board are long enough to allow the current to achieve its peak value. It is given by [3],

$$\begin{aligned} |E|_{\max} &= \frac{\eta_o}{2\pi r} \times \frac{V_{CM}}{R_{rad\_\min}} \times f_{\max}(\theta, k) \\ &= \frac{120\pi}{2\pi r} \times \frac{V_{CM}}{37} \times 2.76 \end{aligned} \tag{3}$$

where V_{CM} is the equivalent common-mode voltage at the cable-PCB junction, and r is the distance where the radiated E field is calculated. F_{cable} corrects the expression in (3) when the board is less than one quarter wavelength above the floor and is given by [3],

$$F_{cable} \equiv \begin{cases} \sin\left(2\pi l_{cable} / \lambda \right) & when\ l_{cable} \le \dfrac{\lambda}{4} \\ 1.0 & otherwise \end{cases} \tag{4}$$

where l_{cable} is the vertical distance traversed by the cable and not necessarily the overall length of the cable. F_{board} corrects the expression in (3) when the effective length of the board is less than one quarter wavelength. The definition of this factor is [3],

$$F_{board} \equiv \begin{cases} \sin\left(2\pi l_{board} / \lambda \right) & when\ l_{board} \le \dfrac{\lambda}{4} \\ 1.0 & otherwise \end{cases} . \tag{5}$$

The diagonal length is a good approximation of the effective length for rectangular boards as described in [3].

C. Estimation of the voltage between the heatsink and the PCB

Combining (1) and (2), the relation between the heatsink-PCB differential-mode voltage and the maximum radiated E field is,

$$\begin{aligned} V_{DM} &= \frac{C_{board}}{C_{heat\sin k}} V_{CM} \\ &= \frac{C_{board}}{C_{heat\sin k}} \times \frac{2\pi r(37)}{\eta F_{board} F_{cable} 2.76} \times |E|_{\max} \\ &= 0.2234 \frac{C_{board}}{C_{heat\sin k}} \times \frac{r}{F_{board} F_{cable}} \times |E|_{\max} \end{aligned} . \tag{6}$$

In this case, V_{DM} is the minimum voltage required to generate a given $|E|_{max}$ at a distance, r.

III. MODEL VERIFICATION WITH FULL-WAVE SIMULATIONS

To verify the formula obtained in the previous sections, a PCB with a heatsink and an attached cable is simulated with a full-wave EM modeling code, EMAP5, in the frequency range from 5 MHz to 500 MHz. The board is 20 cm by 20 cm; the heatsink is 5 cm by 5 cm by 1 cm and is located 1 cm above the center of the board as indicated in Fig. 5. A 0.8 meter long cable is connected to the midpoint of one of the board's edges and the other end is connected to the infinite ground plane. The field observation distance is 3 meters.

In Figure 3, three simulation curves are presented. The solid line is the radiated field strength calculated using EMAP when the voltage between the board and heatsink was set to one volt from 5 to 500 MHz. The circle-marked line is the simulation result with the equivalent common-mode voltage placed at the junction between the board and the cable. For these two simulations, the maximum E field in all directions was determined for each frequency step. The two simulation results match each other up to 500 MHz indicating that the cable radiation dominates. For frequencies above 500 MHz, the radiation directly from the heatsink dominates and the two results deviate. The dashed line is the maximum E field calculated using Equation (2). It is seen that the estimate is very close to the peaks of the full-wave simulation results up to about 500 MHz.

To further verify the formula, a longer cable was used. In this configuration, the cable was 3 meters long and the observation distance was increased to 10 meters. The simulation results in Figure 4 show that the estimate is still valid in the same 5-500 MHz frequency range.

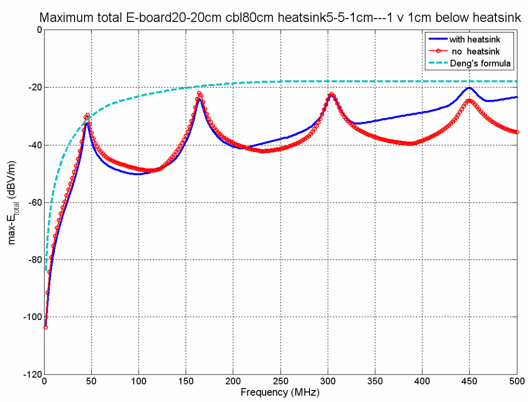

Fig. 3. Model verification results with a 0.8 meter cable.

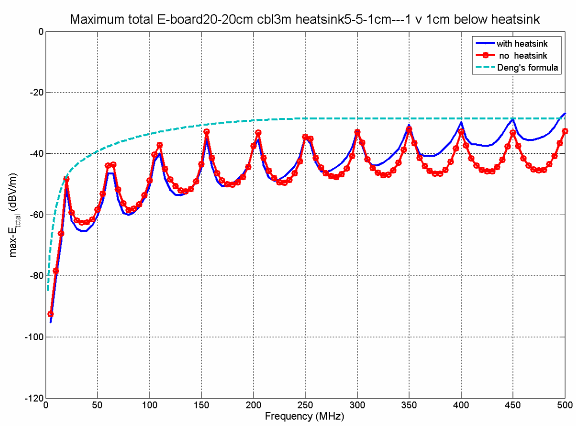

Fig. 4. Model verification results with a 3 meter cable.

IV. MODEL APPLICATION EXAMPLE

Equation (6) calculates the maximum allowable heatsink-PCB voltage that still ensures that the cable radiation will not exceed the given limits. Using the structure above, and setting $|E|_{max}$ equal to the FCC Class B limits listed in Table 1, the maximum allowable voltage between the heatsink and the board is obtained and plotted in Figure 5. In this case, l_{cable} (the height above ground) was set to 0.8 meters to be consistent with the FCC test procedure. As long as the driving voltage is below the threshold given in Figure 5, the radiation due to the heatsink driving the attached cables will be below the FCC Class B limit.

For example, for a board and heatsink of the size indicated in Figure 5, at least 3.6 mV of noise would have to appear on the heatsink at 50 MHz in order to generate a field exceeding the FCC Class B limit. At 300 MHz, 1.6 mV would be sufficient to cause a problem.

TABLE I. FCC CLASS B LIMITS ($|E|_{MIN}$).

Frequency	$\|E\|_{min}$ at 3 meters (dBμV/m)	$\|E\|_{min}$ at 3 meters (μV/m)
30 – 88 MHz	40.0	100
88 – 216 MHz	43.5	150
216 – 500 MHz	46.0	200

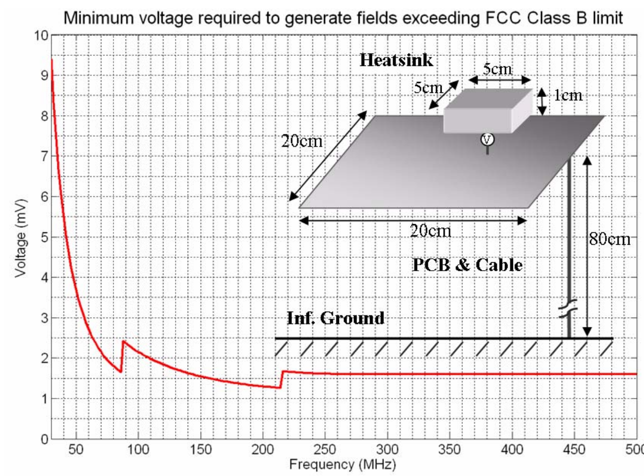

Fig. 5. Application of the formula to meet the FCC Class B limit.

V. CONCLUSIONS

A formula for estimating the minimum voltage between a heatsink and a PCB that is required to generate a radiated field above a given limit has been developed. Voltages below the minimum value are not capable of generating a field that exceeds the limit. Voltages higher than the minimum may or may not result in radiated emissions problems depending on whether board-cable geometry happens to be resonant at the particular frequency of interest.

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