Prediction of Radiated Emissions from High Speed PCB Traces using Travelling Wave Antenna Model

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***Abstract*—The ever-increasing clock speeds of printed circuit board (PCB) have imposed many challenges on the circuit designers, one of which is to pass the electromagnetic compatibility compliance testing for radiated emissions. It is essential to predict PCB radiated emissions prior to a compliance test with the aim to save cost and time. For high-speed PCBs, their traces are electrically long and thus making them efficient radiators. In this paper, a prediction model is developed based on travelling wave antenna model to predict Differential Mode (DM) radiated emission from a high-speed PCB traces above a ground plane while Common Mode (CM) radiated emission is predicted based on monopole antenna model. Two closed-form expressions were derived to describe DM and CM radiated emissions for electrically long PCB traces. The obtained results, based on the aforementioned models, were validated through comparison with other models and good agreements were achieved. These developed closed-form equations can be employed to develop a software tool that can characterize and quantifies radiated emissions at the design stage.**

***Keywords*—Printed Circuit Board; radiated emission; travelling wave antenna**

I. INTRODUCTION

The ubiquitous proliferation of high-speed digital devices has imposed many challenges to the circuit designers of these modern devices [1,2]. These devices must be electromagnetically compatible with mandatory governmental regulatory requirements to be sold legally and globally. One of these requirements is to comply with the Radiated Emission (RE) regulatory requirement standards to ensure effective and legal marketing. Commonly, the compliance test is carried out through RE testing of the first prototype. However, this method is an iterative and time-consuming. Alternatively, full-wave solvers can be employed to predict the RE of electronic products. Unluckily, it is not a convenient option due to the complexity of modern high speed electronic devices. Therefore, early prediction of RE using analytical method can reduce the cost drastically[1,3].

Printed Circuit Board (PCB) is known as a major source of radiated emissions from electronic products [2,4]. Naturally, the radiated emissions of these PCBs are attributed to both Differential-Mode (DM) and Common-Mode (CM) currents. The DM current is the wanted (functional) current that is responsible for differential-mode radiation while the CM current is the unwanted current (displacement current) that flows between the circuit and its environment. The CM current is typically much less than the DM current, however, the CM current is the major contributor to the total radiated emission [3,4].

Although there are numerous sources of RE on PCB, the PCB traces are considered a conspicuous contributor to the total RE. However, the PCB traces are not significant source of RE in the frequency range where the traces length (l) are electrically short. Nevertheless, A prediction model was developed in [2] to estimate the maximum RE of electrically short traces ($l<\lambda/10$), which obviously is inaccurate for electrically long traces. Additionally, an analytical model is developed for estimating the maximum RE of PCB trace. However, fair agreement had been shown for the case of realistic dielectric [5].

In another study [6,7], closed-form expressions are developed based on transmission lines theory with the aid of green functions for estimating the radiated emission of PCB microstrip signal traces. However, it is not appropriate for higher frequencies where the trace length is multiples of the wavelength. Therefore, it is important to evaluate the maximum radiated field on different spherical angles due to the complexity of the radiation pattern. In [8], different modeling techniques based on transmission-line theory and simulation programs are investigated to predict the radiated emissions up to 10 GHz from microstrip PCB trace. However the analytical method is limited to quasi-TEM mode signal propagation on the PCB trace. Later, the researchers C.Zhu and T.Hubing had developed closed-form equation for predicting DM RE [9,10]. However, it cannot be used when the trace length exceeds one tenth of the wavelength. Therefore, in this paper, closed-form equations had been developed and used to predict the DM RE of electrically long traces (Typically $l>>\lambda$) based on travelling wave antenna model while the CM RE is estimated using monopole antenna model.

II. PREDICTION OF HIGH SPEED PCB DM RE

The maximum possible radiated electric field due to DM current $\left|\hat{E}_D\right|_{\max}$, and CM current, $\left|\hat{E}_C\right|_{\max}$ for electrically short traces can be given as [11]:

$$\left|\hat{E}_{D,\max}\right| = 1.316\times10^{-14}\left|\hat{I}_D\right| f^2\, l\, s \big/ r\,, \qquad (1a)$$

$$\left|\hat{E}_{C,\max}\right| = 1.257\times10^{-6}\left|\hat{I}_C\right| f\, l \big/ r\,, \qquad (1b)$$

where f is frequency, l is the length of the trace, r is the observation point of the radiated electric fields and s is the separation distance between the signal trace and return trace and I_D denotes the DM current of the signal.

Eq. (1a) & (1b) are derived with the assumption that the current is uniform along the trace based on the concept of hertzian dipole antenna. Therefore, the phase delay can be neglected whereas in high speed PCBs, the traces are electrically long; thus the DM current is not uniform along the trace as assumed in the electrically short traces. Consequently, the trace and its image are modeled as travelling wave antenna to predict the DM RE while CM RE is modeled based on monopole antenna.The circuit board trace configuration to be analysed is depicted in Fig. 1.

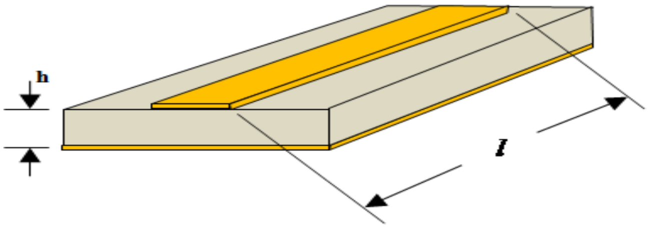

Fig. 1. Printed circuit board trace above a ground plane.

The trace length, l is located above a ground plane that carries the return current. The dielectric layer has a thickness of *h*. The differential-mode signal on the trace is terminated with a resistive load. Although (1a) and (1b) provide good estimation for DM and CM radiated emissions, their applications have been limited to electrically short traces [1],[2]. The trace length has to be less than one tenth of the wavelength of interest to be employed in (1a) and (1b). As a result, the authors had developed closed-form equations that can predict the RE of that traces with length greater than one tenth of wavelength and less than one wavelength. Therefore, for electrically long traces, the maximum possible DM radiated emission of electrically long PCB traces can be written as

$$\left|\hat{E}_{D,\max}\right| = 2.52\times10^{-6}\,\frac{I_D}{r}\, f\, h\left(1-\cos\left(\pi l \big/ \lambda_0\right)\right) \qquad (2a)$$

For measurement in a 3-meter Semi Anechoic Chamber (SAC), equation (2a) becomes

$$\left|\hat{E}_{D,\max}\right| = 8.4\times10^{-7}\, I_D\, f\, h\left(1-\cos\left(\pi l \big/ \lambda_0\right)\right) \qquad (2b)$$

where λ_0 is the wavelength of interest.

In this paper, eq. (2b) was employed to estimate the maximum possible DM radiated emission of electrically long PCB traces while the maximum CM radiated emission of electrically long PCB traces ($\lambda/10 \le l \le \lambda$) can be written as

$$\left|\hat{E}_{C,\max}\right| = 120\,\frac{I_C}{r}\left[1-\cos\left(\pi l \big/ \lambda_o\right)\right] \qquad (3a)$$

For r =3 meters, eq. (3a) becomes

$$\left|\hat{E}_{C,\max}\right| = 40\, I_C\left[1-\cos\left(\pi l \big/ \lambda_o\right)\right] \qquad (3b)$$

For electrically long traces, the circuit board in Fig. 1 can be represented as travelling wave antenna model as shown in Fig. 2. Thus, the radiated electric fields of travelling wave antenna model as illustrated in Figure 2 is given as [11]

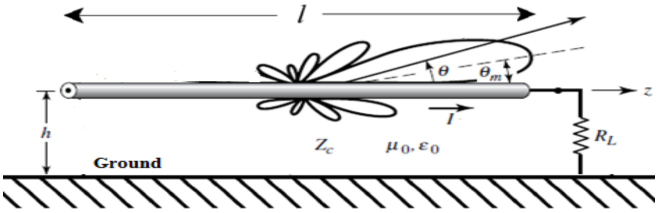

Fig. 2. Equivalent model of PCB above ground plane with radiation pattern

$$\left|\hat{\mathrm{E}}_{\mathrm{D,max}}\right| \cong \left[j\eta_0 k\, l\, I_D \exp(-jkr)/4\pi r\right]\exp(-j(kl/2)(P-\cos(\theta)))\,D \qquad (4)$$

where

$$D = \sin(\theta)\,(\sin(M)/M) \qquad (5)$$

$$M = (\sin[(k\,l/2)\cos(\theta)-P])/[(k\,l/2)\cos(\theta)-P] \qquad (6)$$

$$P = k_z/k \qquad (7)$$

k_z represents phase constant of the wave along the transmission line and k represents phase constant of the wave in free-space while the parameter η_0 denotes the intrinsic impedance of free space.

Assuming a perfect electric conductor for the ground, the total field for Fig. 2 is obtained by multiplying each of by the array factor $\sin[k\,h\,\sin(\theta)]$. For simplicity assume $P=1$ which implies $k = 2\pi/\lambda$ and let the observation point, $r=3$. As a result the maximum total RE can be computed as

$$\left|\hat{\mathrm{E}}_{\mathrm{D,max}}\right| = \left[\frac{120\pi}{4\pi\times3}\times2\pi/\lambda\right] l\, I_D\, F(\theta)\,\sin(kh\sin(\theta)) \qquad (8)$$

$$F(\theta) = \exp[\,j\,(\pi l/\lambda)(\cos(\theta)-1)\,]\sin(\theta)\,(\sin(B)/B) \qquad (9)$$

$$B = (\pi l/\lambda)\,[\cos(\theta)-1] \qquad (10)$$

The separation between the trace and the ground plane is very small. Therefore, the angle is almost same as its sin. So equation (9) & (10) respectively can be written a

$$\left|\hat{\mathrm{E}}_{D,\max}\right| = (20\pi/\lambda)\, l\, I_D\, F(\theta)\, kh \qquad (11)$$

$$F(\theta) = \exp[\,j\,(\pi l/\lambda)(\cos(\theta)-1)\,]\sin^2(\theta)\,(\sin(B)/B) \qquad (12)$$

By expressing the wavelength in form of frequency, equation (11) becomes

$$\left|\hat{\mathrm{E}}_{D,\max}\right| = (20\pi/3\times10^8)\, f\, l\, I_D\, kh\, F(\theta) \qquad (13)$$

$$= (20.93\times10^{-8}\times f\, l\, I_D\, (2\pi/\lambda)\, h\, F(\theta) \qquad (14)$$

$$=(20.93\times10^{-8}\times f\,l\,I_D\ (2\pi f/3\times10^{8})\,h\ F(\theta) \qquad (15)$$

$$=43.813\times10^{-16}\, f^{2}\, l\,I_D\ h\ F(\theta) \qquad (16)$$

The ground reflected wave needs to be accounted so the above expression needs to be multiplied by two so it becomes

$$\left|\hat{E}_{D,\max}\right| \cong 8.8\times10^{-15}\, f^{2}\, l\,I_D\ h\ F(\theta) \qquad (17)$$

$$F(\theta)=\exp[j\,(\pi l/\lambda)(\cos(\theta)-1)]\sin^{2}(\theta)\ (\sin(B)/B) \qquad (18)$$

The angle (θ) at which the maximum RE is obtained can expressed as

$$\theta_{\max}=\cos^{-1}(1-\frac{0.371\lambda}{l}) \qquad (19)$$

III. PREDICTION OF HIGH SPEED PCB CM RE

Common-mode current is usually smaller than differential-mode current. However, the CM RE is typically much greater than DM-RE [2]. Basically, common-mode current cannot flow on a PCB with an infinite ground-return plane, as the plane acts like a mirror to generate another circuit that makes the structure perfectly balanced. However, the finite ground-return plane of an actual PCB produces an imperfect image that causes the ground-return plane itself to radiate. The trace above a finite ground plane produces a voltage drop on the ground plane directly under the trace. This voltage drop, denoted by V_{CM} , is related to the effective inductance (L_{gnd}) associated with the ground plane by the relation $V_{CM}=j\omega L_{gnd}\,\hat{I}_D(\omega)$ where $\hat{I}_D(\omega)$ the signal or functional current which can be computed using the transmission line model.

The inductance L_{gnd} for a finite Plane can be calculated by the approximate expression [12]

$$L_{gnd}=\frac{\mu_0}{2\pi}\,l\,\ln(\frac{\pi h}{W_{gnd}}+1) \qquad (20)$$

where W_{gnd} is the width of the ground plane, and l is the length of the PCB ground plane. The identified CM voltage, V_{CM} , can drive the PCB traces to act as monopole antenna as shown in Fig. 3.

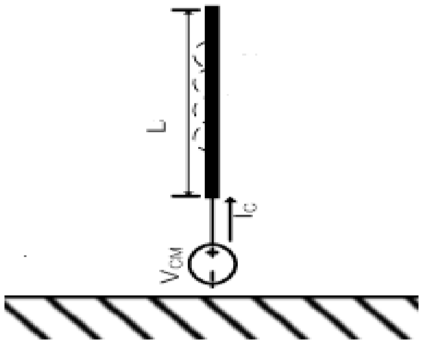

Fig. 3. Equivalent model for CM RE

The radiated electric field ($\hat{E}_C$) from monopole antenna model can be given as [11]

$$\hat{E}_C=j\eta_0\,\frac{I_{CM}\exp(-jkr)}{2\pi r}\,f(\theta,k) \qquad (21)$$

where

$$f(\theta,k)=\left[\frac{\cos(kl\cos(\theta)-\cos(kl)}{\sin\theta}\right] \qquad (22)$$

I_{CM} is the CM current in the monopole, l is the monopole length, r is the distance between the monopole and the observation point, θ is the zenith angle in the spherical coordinate system, and η_0 is approximately 120π Ω. The magnitude of the radiated electric field, when $r=3$ meters far from the source, can be expressed as

$$\left|\hat{E}_{C,\max}\right|=120\pi\frac{I_{CM}}{2\pi\times3}\times f(\theta,k)=20\times I_{CM}\times f(\theta,k) \qquad (23)$$

IV. DESCRIPTION OF SIMULATION PARAMETERS

The RE of PCB trace is simulated based on the aforementioned derived equations using Matlab software. The simulation is configured with specific parameters for all the different models. Namely, the trace length, l has the value 15 cm while the separation between the trace and the ground plane is 1.6 mm which is the thickness of FR4 dielectric material. The DM current is computed based on transmission line theory while the CM current is calculated based on monopole antenna model. Additionally, the frequency range from 30 MHz to 3 GHz has assigned to the frequency parameter. All the results are obtained in the far-field at 3 meters far away from the RE PCB source.

V. RESULTS AND DISCUSSION

Conceptually the total RE composes of two components. The first component is DM RE while the second is CM RE. Both the two components are predicted and simulated using Matlab software. The first part of the results describes the DM RE using (1a) comparing with (2b) and (17) as illustrated in Fig. 4. The trace length is 15cm therefore it becomes one tenth of the wavelength at 200MHz. Once the frequency slides to higher values greater than 200MHz, eq. (2) cannot provide accurate results because this eq.(2) is derived based on the concept of Hertzian dipole antenna, where the current distribution is assumed uniform. Since the trace length becomes greater than one wavelength (200 MHz point), another model is developed based on long dipole antenna model. However, this model is also limited to one wavelength of interest (2GHz point). Therefore, this model does not provide accurate results above 2 GHz where the trace length becomes multiples of wavelength. Consequently, travelling wave antenna based model is proposed to predict the DM RE for electrically long traces ($l >> \lambda$) as in Fig. 4. In Fig. 4, it is observed that at 2 GHz a resonance occurs based on (3b) while many resonance cases occurs for frequencies greater than 2 GHz based on (17). It is clearly shown that as the frequency moves to higher values, multiples resonances are obtained. On the other hand, the CM emissions in figure 6 for electrically long traces can be estimated using (1b),(3b) and (23)). Eq. (1b) can estimate the CM RE for electrically short traces. However, it can estimate the CM RE until 200 MHz ($\lambda/10$). For higher frequencies, it differs by about 40 dB compared to the electrically long traces (eq. (3b)). It shows the limitation of Paul equation for electrically long trace. Basically, eq. (1b) is derived based on the concepts of Hertzian dipole antenna while (3b) and (23) are derived based on long dipole and monopole antenna respectively. Therefore, the response behaviour of (2b) and (23) are almost same with 10dB difference as shown in fig. 5. Finally, the overall RE is predicted using the estimated DM and CM RE for the three models. The total RE of electrically short traces was computed based on Paul [2] whereas RE of electrically long traces was estimated using long dipoles and travelling wave antenna. Again, fig. 6 shows the estimated RE for all the three models. It clearly shows that our formulations have better estimation compared to that of Paul. This proved that (17) and (23) are better at estimating the RE for PCB trace for electrical length much greater than wavelength ($l >> \lambda$) .

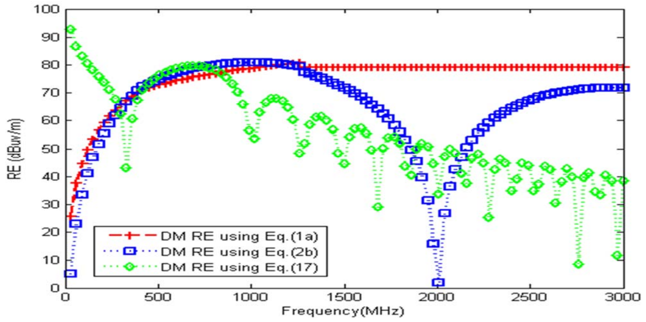

Fig. 4. DM RE prediction for PCB using three different models

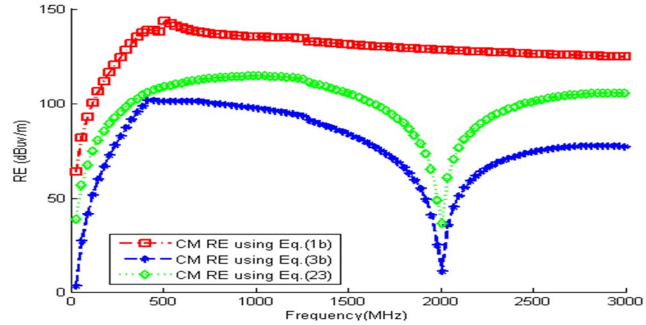

Fig. 5. CM RE prediction for PCB using three different models

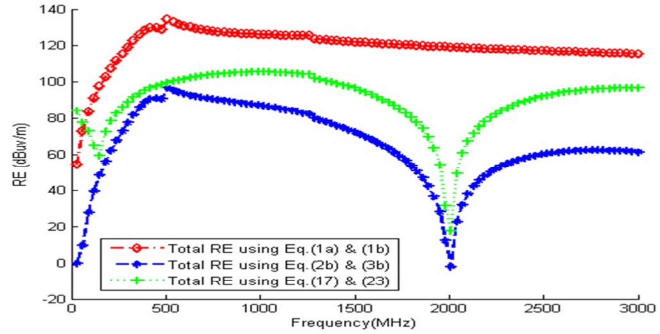

Fig. 6. Total RE prediction for PCB using three different models

VI. CONCLUSION

In this paper, closed-form equations were derived to predict the maximum radiated emissions due to both DM and CM RE of electrically long PCB traces. The theoretical results obviously show that our equations improved the limitations of the formulations for electrically short PCB traces. Good prediction were obtained for RE of a PCB. The outcomes from this work are helpful in future development of an expert system to identify PCB RE of various electrical lengths.

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