Progress In Electromagnetics Research M, Vol. 33, 17–29, 2013

AN IMPROVED MODEL FOR ESTIMATING RADIATED EMISSIONS FROM A PCB WITH ATTACHED CABLE

Jia-Haw Goh, Boon-Kuan Chung*, Eng-Hock Lim, and Sheng-Chyan Lee

Universiti Tunku Abdul Rahman, Malaysia

Abstract—Common mode current induced on cable attached to a PCB has been a well-known source of unintentional radiated emissions. The coupling mechanism of the common mode current to the cable can be divided into two types: voltage-driven and current-driven. In voltage-driven mechanism, the common mode current is induced by electric field that couples from traces on PCB to the cable. Previous work showed that these radiated emissions can be estimate based on the self-capacitance of the trace and the signal return plane but the method is only reasonably accurate at lower frequency. This paper develops a model which gives an extended frequency range up to 800 MHz. The formulation for the equivalent common-mode voltage source is improved by taking into account the driving point impedance of the cable which behaves as a wire antenna. The radiated emissions estimated by the improved model match well with the values from 3D electromagnetic simulation of the original PCB with attached cable. It represents an improvement compared to earlier model by 11 dB at 400 MHz to 16 dB at 700 MHz for board size of 10 cm $\times$ 16 cm and cable length of 3 m. Similar improvements are obtained for other combinations of board size and cable length. The results show that the cable length is an important factor, in addition to the board area as suggested by earlier work, in determining the magnitude of the equivalent common-mode voltage source. Resonant of the wire antenna affects not only the radiated electromagnetic field but also the common-mode voltage source magnitude due to varying antenna impedances.

Received 11 June 2013, Accepted 7 September 2013, Scheduled 13 September 2013

* Corresponding author: Boon-Kuan Chung (chungbk@utar.edu.my).

1. INTRODUCTION

Cable attached on a PCB is a well-known source of unintentional radiated emissions due to its large dimension relative to the PCB [1]. The study on this kind of structure has gained a lot of interest as it is one of the most commonly seen setup of electronic equipment. There are a few recent papers on the study of EMC effect of attached cable and simplified models are proposed to estimate radiated emission from such structure [1–7]. These studies showed that the electromagnetic field coupling of noise sources from PCB traces to the attached cable can be modelled as an equivalent board-cable model driven by a common-mode source. Shim and Hubing showed that the magnitude of this common-mode noise source generated through voltage-driven mechanism was related to the capacitance of the PCB trace and signal return plane [2]. Based on this, Deng et al. proposed that if the magnitude of the common-mode voltage source of such model was known, a closed-from equation can be used to estimate the maximum radiated E field at resonant frequency of such model [3]. Similar approach was taken by Wang et al. to investigate the maximum radiated E field of PCB with attached cable whereby the PCB was shielded with a conducting enclosure [4]. The enclosure and attached cable were modelled as an asymmetrical dipole instead of a monopole as in Deng's method. However, the noise coupling mechanism in an actual product is usually too complicated to be described by a simple equation due to multiple noise sources and coupling paths. Park et al. presented an alternative to circumvent this problem by combining the measured common-mode current on the attached cable and simulation of the Radiation Transfer Function to predict the radiated emission of a box-source-cable model [8].

In a typical board-source-cable model, unintentional radiated emissions are usually caused by common-mode current induced on the cables by differential mode sources located on the PCB. There are two mechanisms by which this common mode current can be induced on the cable: current-driven (magnetic field coupling) and voltage-driven (electric field coupling) [1]. The current-driven mechanism is associated with the magnetic field that wraps around the finite width of the signal return plane (e.g., ground plane). An effective voltage drop exists across the signal return plane due to its finite impedance and this drives a common-mode current on the cable. This mechanism can be a source of radiated emissions if the impedance of the signal return path is significant; i.e., the width of the signal return path is narrow or the signal frequency is very high [2].

The voltage-driven mechanism is due to electric field coupling

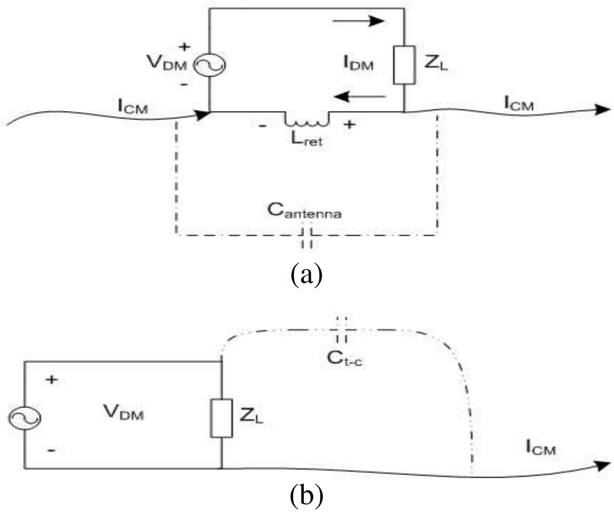

Figure 1. (a) Current-driven and (b) voltage-driven mechanism [2].

directly from the PCB trace to the attached cable, thus induces a common mode current on the cable. The magnitude of common-mode current induced is directly proportional to the magnitude of the differential-mode voltage source that drives the PCB trace. Referring to the model in Figure 1, it can be seen that the voltage-driven model drives a current through objects referenced to ground against the load connected to the PCB trace. This implies that the voltage-driven emissions can be significantly large when the signal trace capacitively couples to other large conductive object, such as heat sink. When there is no large ungrounded object on the PCB, the voltage-driven emission is less apparent and hence little attention is given to the study of this mechanism. However, Shim and Hubing showed that voltage-driven mechanism can be a significant source of radiated emissions when a cable is attached to the PCB, and a model for estimating voltage driven common-mode current was developed [2]. It was further proved that the voltage-driven mechanism is significant even for the case where the PCB trace is terminated by a matched load. The work of Kayano et al. also showed that even with a terminating load of 49 Ω, the coupling mechanism is predominantly voltage-driven type at lower frequency [5].

The board-cable model driven by a common-mode source developed by Shim and Hubing [2] has a limitation that the estimated radiated emission is only valid at frequencies below 300 MHz. The attached cable was modelled as a wire antenna and its radiation characteristics with respect to frequencies were considered but the influence of the varying antenna driving point impedances on the magnitude of the induced common-mode voltage was neglected. As a consequence, the common-mode voltage was assumed to be constant over all frequencies and its magnitude was only affected by the PCB board size. This paper is set out to correct this shortcoming and extend the applicability of the board-source-cable model to higher frequencies and yield better accuracy in estimating the EMC radiated emissions. This paper is organized as follows. Section 2 examines the voltage-driven mechanism and limitation of the simplified board-source-cable model introduced by Shim and Hubing. Section 3 introduces an improved method to model the voltage-driven mechanism and shows the derivation of the formula. In Section 4, validations are made to show the improved accuracy in estimating the radiated emission compared with Shim and Hubing method. Section 5 examines the relationship between PCB board area, length of attached cable and the resulting wire antenna driving point impedance, Z_{drive}. A simple equation to approximate the value of antenna driving point impedance is developed by mean of a curve-fitting method using the simulation results of Z_{drive} under different board areas and cable lengths. Section 6 shows the validation of the approximation equation under different conditions. Lastly, some conclusions are made in Section 7.

2. VOLTAGE DRIVEN SOURCE MODEL

Shim and Hubing proposed that a voltage-driven coupling to an attached cable can be represented as an equivalent wire antenna model where the differential-mode voltage source driving the PCB trace (as shown in Figure 2(a)) was converted to an equivalent common-mode voltage source connected between the attached cable and the

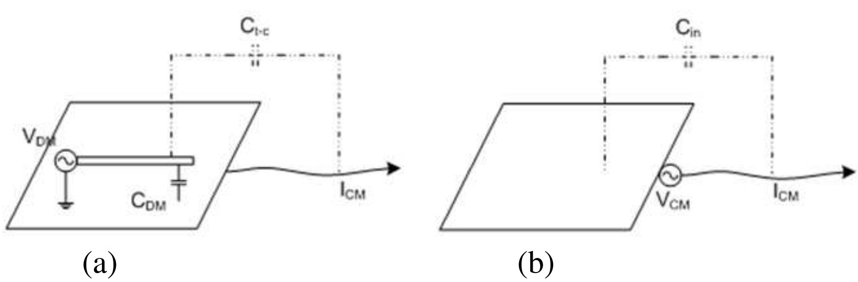

Figure 2. (a) Voltage-driven coupling to attached cable and (b) equivalent wire antenna model [2].

ground plane (as shown in Figure 2(b)). Based on this model, the relationship between the differential-mode voltage source and the equivalent common-mode voltage source was developed by assuming the charge induced on the attached cable in both cases were the same. The resulting equation was expressed as [2]

$$V_{CM} = \frac{C_{t-c}}{C_{in}} V_{DM} \tag{1}$$

where C_{t-c} represents the effective mutual capacitance between the trace and the attached cable and C_{in} the input capacitance of the wire antenna model. The equation can be further simplified if the cable length is much longer than the board dimension. The input capacitance of the wire antenna model is approximated as predominantly the self-capacitance of the PCB board, C_{board}. Also, the effective mutual capacitance, C_{t-c} is approximated as predominantly the self-capacitance of the signal trace, C_{trace}. Hence, the simplified equation is expressed as

$$V_{CM} = \frac{C_{\text{trace}}}{C_{\text{board}}} V_{DM} \tag{2}$$

However, there is one drawback with this method, i.e., it models the driving point impedance of the wire antenna as a purely capacitive one. This is relatively accurate when the wire antenna is being driven at the frequencies lower than its first resonant frequency. When the

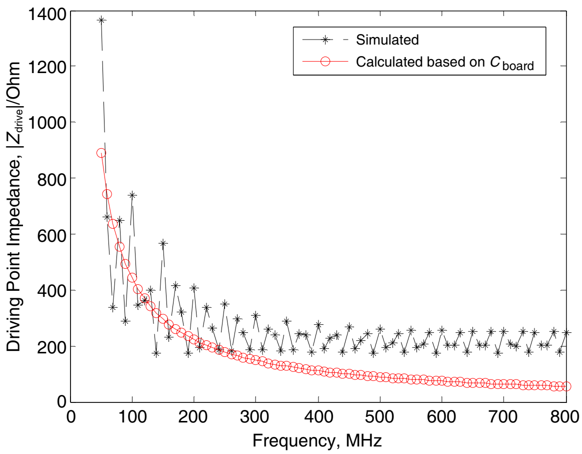

Figure 3. Comparison between simulated Z_{drive} and antenna input reactance calculated using Shim and Hubing method (Board size: 10 cm × 8 cm; Cable length: 6 m).

frequency increases beyond the resonant frequency, the driving point impedance will start to shift due to the inductance of the antenna, as shown in Figure 3. The simulated Z_{drive} is obtained by running a CST Microwave Studio simulation on a 10 cm × 8 cm board attached with a 6 m cable.

It is noted that although the calculated antenna input reactance based on C_{board} does not exhibit the sinusoidal oscillation characteristic of the CST simulated Z_{drive}, its value is close to the average value of the simulated Z_{drive} from 50 MHz to about 200 MHz. Beyond 200 MHz, error in the calculated input reactance starts to increase gradually with frequency. This same characteristic is evidenced in the error between the radiated E-field from CST simulation and the E-field estimated using Shim and Hubing method which will be shown in Section 4. Nevertheless, the varying Z_{drive} suggests that the equivalent common-mode voltage will not be a constant over all frequencies. Instead, it shall oscillate with the similar pattern as Z_{drive}.

3. IMPROVED VOLTAGE-DRIVEN SOURCE MODEL

An improved equation is proposed in this paper, taking into account the said characteristic of Z_{drive}. Referring to Figure 2, we shall expect that the common-mode currents induced on the cable I_{CM}, for both cases, are the same. In the actual circuit of Figure 2(a), I_{CM} can be expressed as

$$|I_{CM}| = 2\pi f C_{t-c} |V_{DM}| \tag{3}$$

In the equivalent wire antenna model, with Z_{drive} replacing $1/\omega C_{in}$, I_{CM} can be expressed as

$$|I_{CM}| = \frac{|V_{CM}|}{|Z_{\text{drive}}|} \tag{4}$$

By equating (3) and (4), the induced common-mode voltage source, V_{CM}, can be expressed in term of the differential-mode voltage source, V_{DM} as

$$|V_{CM}| = \omega C_{t-c} |Z_{\text{drive}}| \, |V_{DM}| \tag{5}$$

where $\omega = 2\pi f$. If the cable length is much longer than the board dimension, C_{t-c} can be approximated as the self-capacitance of the signal trace, C_{trace}. Hence,

$$|V_{CM}| = \omega C_{\text{trace}} |Z_{\text{drive}}| |V_{DM}| \tag{6}$$

Previous study showed that the self-capacitance of the signal trace can be approximated using a close-formed equation [7]. Thus, the only unknown parameter left in (6) would be the antenna driving point impedance, Z_{drive}. The wire antenna model is essentially an asymmetrical dipole where the cable is driven by a common-mode voltage source against the signal return plane [9]. Ostadzadeh et al. has suggested a method to compute the driving point impedance of an isolated dipole antenna using fuzzy model [10]. However, the same method cannot be applied here as the structure of interest is an asymmetrical dipole. For the asymmetrical dipole, its driving point impedance can be computed from CST simulation.

4. VALIDATION OF THE MODEL

Figure 4 shows a model comprising a conductive ground plane that is 8 cm × 10 cm with a signal trace on top of it. The trace is 5 cm long, 1 mm wide, and 1 mm above the ground plane. The substrate between the signal trace and ground plane is air. One end of the trace is connected to the voltage source, V_{DM} and the other end that is adjacent to the attached cable is terminated with an open circuit. A 6 m cable with a radius of 0.1 mm is attached to the board.

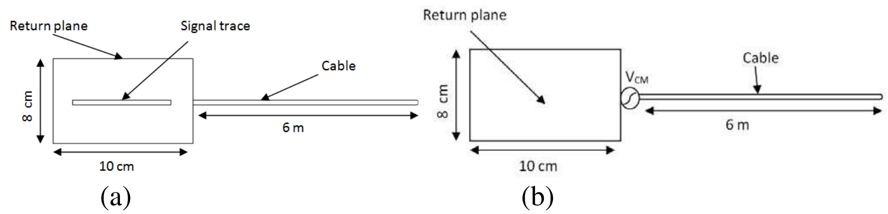

Figure 4. (a) Original configuration and (b) equivalent wire antenna model.

To validate the model, simulation is done using CST Microwave Studio to compute the driving point impedance of the wire antenna model, Z_{drive}. This Z_{drive} is used in (6) to find the corresponding V_{CM} when the model in Figure 4(a) is driven by a 1-V V_{DM}. The C_{trace} in (6) is calculated using the closed-form equation of [7] and its value is 0.025 pF. The maximum E-field of the wire antenna model at a distance of 3 m is simulated and compared with the one from the original configuration.

Figure 5 shows that the E-field simulated using Shim and Hubing method is reasonably close to the E-field simulated using the original configuration only at low frequencies. Beyond 200 MHz, the error starts to increase with frequency. At 400 MHz, the error of Shim and Hubing method is about 7 dB. At 700 MHz, the error increases to about 12 dB.

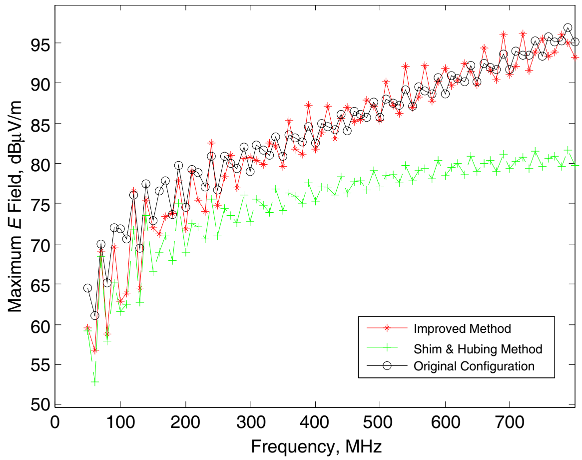

Figure 5. Simulated maximum E field using original configuration and wire antenna model.

Using the improved method proposed in this paper, a good match is achieved throughout the frequencies. The error is within 2 dB from 400 MHz to 700 MHz.

5. MODELLING Z_{drive} OF WIRE ANTENNA

From the simulated result, it is observed that the driving point impedance of the wire antenna, Z_{drive} is related to the board area, A_{board} and cable length, l_{cable}. For the ease of curve fitting, Z_{drive} is multiplied with the angular frequency, ω to avoid infinitely large value of Z_{drive} at low frequency, i.e., at dc. Figure 6 and Figure 7 show the effect of different board sizes and cable lengths on ωZ_{drive}.

Figure 6 shows that the oscillation magnitude of ωZ_{drive} reduces significantly with the increase of cable length. Since the magnitude of induced common mode voltage is directly proportional to ωZ_{drive}, as suggested in Equation (6), the effect of the cable length cannot be neglected. Longer cable also gives rise to lower resonant frequency and closer spacing between subsequent harmonics.

Figure 7 shows that the board size can lower the resonant frequency but the effect is not very significant. Larger board area increases the shunt capacitance and reduces the driving point impedance.

In addition to the results in Figure 6 and Figure 7, a large number of simulations are performed to evaluate the effects of different board sizes and cable lengths on ωZ_{drive}. A curve-fitting method is used to consolidate the various results. A simple closed-form expression that fits the data collected is given by:

$$\omega Z_{\text{drive}} = \left[\left[(1.828)l_{\text{cable}}^{-0.22} - 1\right] \cos\frac{2\pi f_{\text{MHz}}}{f_{\text{resonant}}} + 1\right] \left(3\times 10^{11}\right) e^{\left(8.48\times 10^{-4}\right)A_{\text{board}}^{-0.15} f_{\text{MHz}}} \tag{7}$$

where f_{resonant} is the first resonance frequency of the cable plus board capacitance, in MHz. f_{MHz} is the frequency of interest in MHz. l_{cable} is the length of the cable in meter and A_{board} the area of the board in m^2. Since the wire antenna is similar to a half-wave dipole and the cable in a typical setup usually much longer than the board size, the effective length of the wire antenna can be approximated as the cable length, l_{cable}. For a half-wave dipole, the length of the dipole is equal to half the free space wavelength multiply with an adjustment factor, $k\left(l = \frac{1}{2}k\lambda_0\right)$. The adjustment factor is to compensate for propagation speed somewhat less than the speed of light and its value is typically around 0.95. For simplicity, k is assumed to be 1. Hence,

$$f_{\text{resonant}} = \frac{1}{2}\cdot\frac{C}{l_{\text{cable}}}\cdot 10^{-6} \tag{8}$$

The cos term in the square bracket of Equation (7) provides an oscillatory pattern which matches the resonant and harmonic characteristics of half-wave dipole as seen in Figure 6. The shorter

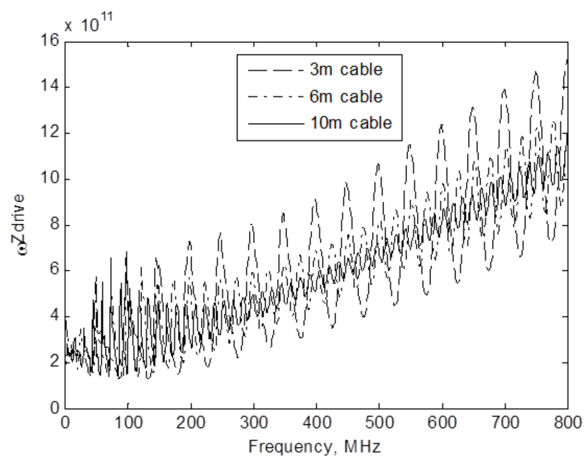

Figure 6. ωZ_{drive} with different cable lengths (Board size: 10 cm × 8 cm).

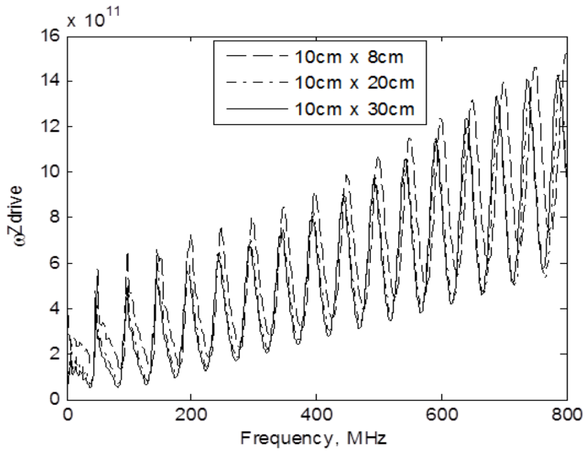

Figure 7. ωZ_{drive} with different board sizes (Cable length: 3 m).

is the cable, the higher is the resonance frequency, and the wider is the spacing between subsequent harmonics. The magnitude of oscillation in the curve of ωZ_{drive} decreases with cable length, especially at the higher harmonic numbers. For the same length of cable, the resonant and harmonic characteristics are only slightly affected by the PCB board area as seen in Figure 7. The exponential term in Equation (7) accounts for the gradually increasing ωZ_{drive} with respect to frequency in which the rate of increase dependens on the PCB board area.

Table 1. Comparison between the Shim and Hubing method and improved method ($C_{\text{trace}} = 0.025\,\text{pF}$; $V_{DM} = 1\,\text{V}$).

Board Size	Cable Length	Error in Max E-Field (dB)			
		Shim and Hubing Method		Improved Method	
		400 MHz	700 MHz	400 MHz	700 MHz
10 cm × 8 cm	3 m	2.64	5.69	0.12	0.95
10 cm × 16 cm	3 m	10.97	17.79	0.22	1.59
10 cm × 8 cm	6 m	6.79	12.17	0.89	1.07
10 cm × 16 cm	6 m	9.67	16.91	1.87	0.68
10 cm × 8 cm	10 m	2.80	5.45	0.36	0.39
10 cm × 16 cm	10 m	9.17	15.13	1.11	0.17

6. EVALUATION OF CLOSED-FORM EXPRESSION

Table 1 shows the comparison between the error in dB of the maximum E-field estimated by Shim and Hubing method and that by the improved method. The error is the difference between the maximum radiated E-field from simulation of the actual circuit and that radiated from the wire antenna models. For the Shim and Hubing model, V_{CM} is a constant as given by (2). For the improved model, V_{CM} varies with frequencies and its values are given by (6) and (7). It is noted that in the six cases that were tested, all of them show much lesser error for the improved method. The improved method has a much better accuracy than Shim and Hubing method, especially at the higher frequency range.

The radiated E-field is related to the induced common-mode current on the wire antenna. A 1.6-mm thick FR4 substrate PCB with conductive ground plane of 8 cm × 10 cm is built. The signal trace on the top of it is 5 cm long and 1 mm wide. A 1-m long wire is attached to the ground plane in a similar configuration as shown in Figure 4(a). The induced common-mode current $I_{\rm cm}$ on the wire, near the edge of the PCB, is measured using a 9119-1N RFI current probe from Solar Electronics Co. and a spectrum analyzer. RF signal is fed to the PCB trace through an SMA connector. The RF voltage is measured using an RF active probe and a LeCroy 6Zi Digital Oscilloscope. The measured common-mode current $I_{\rm cm}$ is then normalized to a 1 V RF source voltage. The measurement

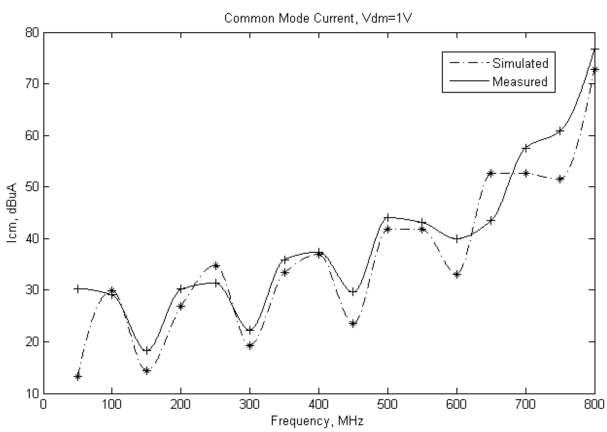

Figure 8. Comparison between measured and simulated common-mode current, $I_{\rm cm}$.

results compared with the simulation results are shown in Figure 8. A good match is achieved throughout the frequencies, although there are small discrepancies due to calibration accuracy of the measurement instruments and sensitivity of the measured common-mode current near the resonance frequency of the open-circuited PCB trace around 800 MHz. Hence, the approximate model developed through EM simulation proposed in this paper for estimating radiated emissions from a PCB with attached cable is experimentally validated.

7. CONCLUSIONS

An improved wire antenna model for estimating EMC radiated emission from a PCB with attached cable due to voltage-driven mechanism is developed and validated. The magnitude of the equivalent common-mode voltage source that drives the wire antenna is expressed in term of the self-capacitance of the signal trace and the driving point impedance of the wire antenna. The self-capacitance of the signal trace can be obtained using the closed-form equation of [7]. The driving point impedance of the wire antenna can be approximated using the closed-form equation developed in Section 5 of this paper. Simulation results show that the maximum radiated E-field from this improved model matches well with the simulation results of the actual circuit. It has a much improved accuracy compared with Shim and Hubing model and can be used to estimate maximum radiated E-field across a wider range of frequency, well beyond the first resonance of the attached cable.

ACKNOWLEDGMENT

This project is partially sponsored by Intel MSC Sdn Bhd.

REFERENCES

1. Hockanson, D., J. Drewniak, T. Hubing, T. van Doren, F. Sha, and M. Wilhelm, "Investigation of fundamental EMI source mechanisms driving common-mode radiation from printed circuit boards with attached cables," *IEEE Trans. Electromagn. Compat.*, Vol. 38, No. 4, 557–566, Nov. 1996.
2. Shim, H. W. and T. Hubing, "Model for estimating radiated emissions from a printed circuit boards with attached cables due to voltage driven sources," *IEEE Trans. Electromagn. Compat.*, Vol. 47, No. 4, 899–907, Nov. 2005.

3. Deng, S., T. Hubing, and D. Beetner, "Estimating maximum radiated emissions from printed circuit boards with an attached cable," *IEEE Trans. Electromagn. Compat.*, Vol. 50, No. 1, 215–218, Feb. 2008.
4. Wang, J., O. Fujiwara, and K. Sasabe, "A simple method for predicting common mode radiation from a cable attached to a conducting enclosure," *Proc. 2001 APMC*, 1119–1122, Taipei, Taiwan, 2001.
5. Kayano, Y., M. Tanaka, and H. Inoue, "Radiated emission from a PCB with an attached cable resulting from a nonzero ground plane impedance," *Proc. IEEE Int. Symp. Electromagn. Compat.*, 955–960, Aug. 2005.
6. Hockanson, D. M., C.-W. Lam, J. L. Drewniak, T. H. Hubing, and T. P. van Doren, "Experimental and numerical investigations of fundamental radiation mechanisms in PCB designs with attached cable," *Proc. IEEE Int. Symp. Electromagn. Compat.*, 305–310, Aug. 1996.
7. Shim, H. W. and T. H. Hubing, "Derivation of a closed-form approximate expression for the self-capacitance of a printed circuit board trace," *IEEE Trans. Electromagn. Compat.*, Vol. 47, No. 4, 1004–1008, Nov. 2005.
8. Park, H. H., H. Park, and H. S. Lee, "A simple method of estimating the radiated emission from a cable attached to a mobile device," *IEEE Trans. Electromagn. Compat.*, Vol. 55, No. 2, 257–264, Apr. 2013.
9. Cooray, G. and V. Cooray, "Electromagnetic fields of a short electric dipole in free space — Revisited," *Progress In Electromagnetics Research*, Vol. 131, 357–373, 2012.
10. Ostadzadeh, S. R., M. Soleimani, and M. Tayarani, "A fuzzy model for computing input impedance of two coupled dipole antennas in the echelon form," *Progress In Electromagnetics Research*, Vol. 78, 265–283, 2008.