Prediction of common-mode radiation from cables attached to PCB using imbalance difference and asymmetrical dipole antenna models

A.M. Sayegh✉ and M.Z.M. Jenu

Cables attached to a PCB can produce a significant amount of unintentional common-mode (CM) radiated emissions (REs). Therefore, it is important to predict these emissions at the design stage before the first prototype is fabricated to ensure time and cost savings. In this Letter, a novel method was proposed to estimate the CM RE from two cables attached to a PCB using the imbalance difference model and asymmetrical dipole antenna model. The proposed method consists of two steps: first, the induced CM voltages on the junctions between the cables and PCB are computed using the imbalance difference model; secondly, the CM REs are then estimated separately for each cable related to half of the ground plane using the asymmetrical dipole antenna model. The overall REs are then computed by the superposition of the RE from the two asymmetrical dipoles. The effectiveness of the proposed method has been verified by comparing the predicted results to both 3D high-frequency structure simulator simulation results and measurement results taken in a semi-anechoic chamber. A good agreement with the accuracy of more than 95% is observed for the upper bounds of the measured REs.

Introduction: Cables attached to a PCB are well-known sources of the unintentional common-mode (CM) radiated emission (RE) [1]. These CM emissions can be evaluated by the measurement of CM current as performed in [2]. However, this method is time consuming since the CM current depends on the frequency and the position of the current probe along the cable.

Alternatively, CM RE can be computed using full-wave numerical solvers. However, this method also involves intensive computational resources, especially if the attached cables are long. Therefore, a fast and accurate analytical method is necessary to estimate the CM RE. Watanabe *et al.* [3] have proposed a model to estimate a CM RE based on current division factor. According to this model, the CM voltage sources are located at the junctions between the cables and the PCB ground plane where the change in the imbalance occurs. Although the derived CM equivalent structures based on the imbalance difference model provide accurate results for CM RE [4], these emissions are estimated by simulating the equivalent structure using a 3D high-frequency structure simulator (HFSS) simulation.

Analytically, a closed-form expression is developed in [5] to estimate the maximum CM RE from a PCB with one attached cable. However, this expression cannot detect the resonant peak positions for various board and cable geometries. Zhang *et al.* [6] have proposed an analytical method for estimating the CM RE using the imbalance difference model and asymmetrical dipole antenna. However, this method has been applied to the PCB with only one attached cable. In this Letter, a novel method is proposed to predict the CM RE from two cables attached to two ends of the PCB using the imbalance difference model and asymmetrical dipole antenna model. It can be described in two steps: computing the CM voltages on the junctions between the PCB and the attached cables, and secondly by estimating the CM RE produced from each cable based on the asymmetrical dipole antenna. The total REs are then computed by superposition of the emissions of the two asymmetrical dipole models as shown in the next sections.

Estimation of CM voltages: For a simple microstrip structure with two attached cables as shown in Fig. 1*a*, the CM voltage sources were located at the junctions between the attached cables and the PCB ground plane, where the change in the imbalances occurred as shown in Fig. 1*b*. The magnitude of the CM voltage at the source point was computed based on the change in the imbalance factor (h) as [4]

$$V_{\mathrm{CM}}(s) = (h2 - h3)V_{\mathrm{DM}}(s) = h2\ V_{\mathrm{DM}}(s) \tag{1}$$

while the CM voltage at the load point was given by

$$V_{\mathrm{CM}}(L) = (h1 - h2)V_{\mathrm{DM}}(L) = -h2V_{\mathrm{DM}}(L) \tag{2}$$

where $h1$, $h2$ and $h3$ were the imbalance factors for the *cable#1* (at the load junction), microstrip PCB and *cable#2* (at the source junction), respectively. $V_{\mathrm{CM}}(s)$ and $V_{\mathrm{CM}}(L)$ denoted the CM voltages at the source and load points, respectively. For the microstrip PCB used in this Letter, the imbalance factors $h1$ and $h3$ were due to the absence of the signal trace, whereas the imbalance factor of microstrip PCB, $h2$, was calculated as [4]

$$h2 = \frac{c_{\mathrm{trace}}}{c_{\mathrm{trace}} + c_{\mathrm{board}}} \tag{3}$$

where the c_{trace}, c_{board} are the self-capacitance of the signal trace and the PCB board capacitance, respectively. These capacitances were computed in this Letter using Ansys Q3D extractor.

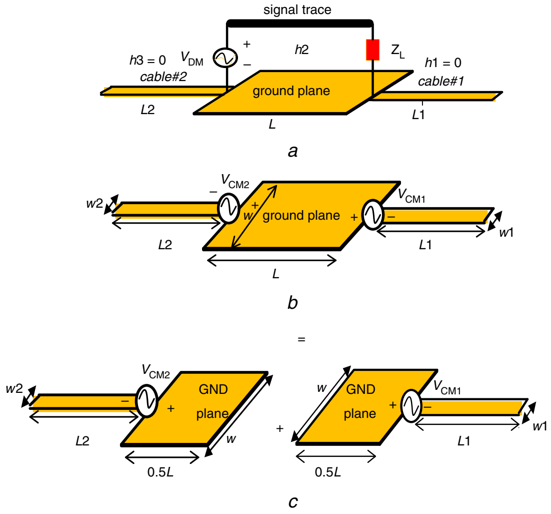

Fig. 1 *Microstrip PCB under study attached with two cables*

a Entire microstrip structure
b Equivalent CM structure using imbalance difference model
c Decomposition process of CM structure using proposed method

Estimation of maximum CM RE: The CM REs were computed analytically according to the equivalent CM structure illustrated in Fig. 1*b*. The PCB ground plane was virtually divided into two equal parts as shown in Fig. 1*c*. This was due to the existence of the CM voltages on the source/load ends of the PCB. The two parts with their attached cables were then analysed as two asymmetrical dipole antennas.

The maximum CM RE from each asymmetrical dipole is expressed as [7]

$$E_{\max} = F \times \left(\int_0^{L1} \frac{I_1(z)\mathrm{e}^{-\mathrm{j}KP_{\max}}}{P_{\max}^2}\,\mathrm{d}z + \int_{-0.5L}^{0} \frac{I_2(z)\mathrm{e}^{-\mathrm{j}KP_{\max}}}{P_{\max}^2}\,\mathrm{d}z \right) \tag{4}$$

where

$$F = 30Kr\ \sin\ \theta_{\max} \tag{5}$$

$$K = 2\pi/\lambda \tag{6}$$

K is the wave number, r is the distance between the board–cable junction to the receiving antenna which was replaced by 3 m in this Letter. $\theta_{\max}$ is the angle between the line r and the equivalent asymmetrical dipole on its length in which the maximum RE was obtained. λ is denoted as the wavelength, whereas $P_{\max}$ is the distance between the receiving antenna and any point dz along the equivalent asymmetrical dipole antenna that produced the maximum RE. It can be expressed as [7]

$$P_{\max} = \sqrt{(r^2 + z^2 - 2rz\ \cos\ \theta_{\max}\ )} \tag{7}$$

The currents $I_1(z)$, $I_2(z)$ on the equivalent asymmetrical dipole branches (board–cable structure) were given in [6, 7]. A MATLAB software was then used to simulate this analytical expression. The analytical results were compared with those results obtained from 3D HFSS simulation and measurements.

Estimated and HFSS simulated results: The effectiveness of the proposed model was verified by comparing the HFSS simulation results with that computed using (4) in the frequency range from 30 MHz to 1 GHz. A 1 V CM voltage was placed at each junction between the PCB and the cables. The estimated result of 20 cm × 4 cm of PCB with two attached cables (0.5 m × 4 mm for each cable) was illustrated in Fig. 2*a*. Fig. 2*b* shows the estimated results of a PCB with 10 cm in length and 4 cm in width attached with two 0.5 m cables, whereas

Fig. 2*c* presents the estimated result of the same PCB geometries in Fig. 2*b*, except for the lengths of the two cables, which was 0.3 m for each cable. It was clear that the analytical results agreed strongly with the HFSS simulation results. This good agreement showed that the proposed model can estimate the CM RE accurately. It was observed from Figs. 2*b* and 2*c* that the length of the cables determined the characteristics of maximum RE. Therefore, the cable length can be employed to locate the positions of the resonance peaks based on the phase constant, β, and the cables' length ($L1$, $L2$).

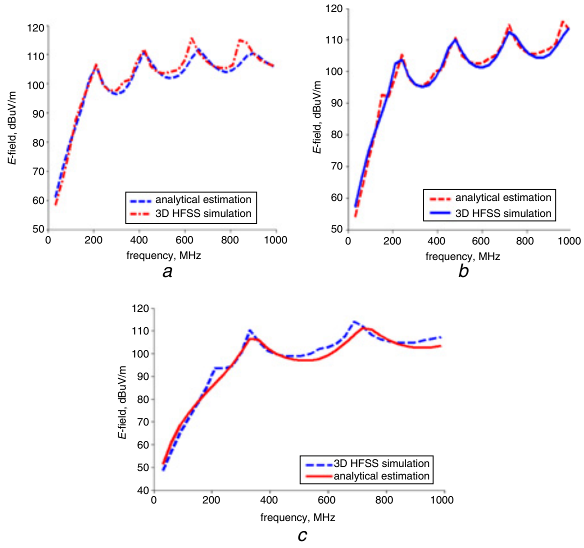

Fig. 2 *Simulated and estimated CM RE of PCB attached with two cables*

a 20 cm × 4 cm PCB with two (0.5 m, 0.5 m) attached cables
b 10 cm × 4 cm PCB with two (0.5 m, 0.5 m) attached cables
c 10 cm × 4 cm PCB with two (0.3 m, 0.3 m) attached cables

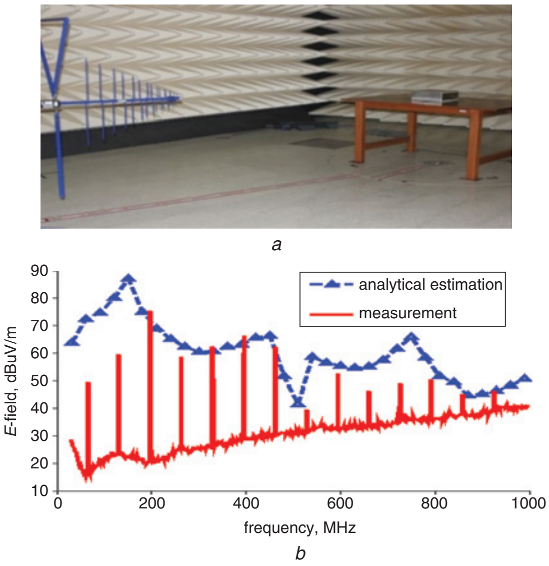

Fig. 3 *Estimation and measurement of CM RE of PCB attached with two cables*

a Measurement setup *of DUT* in *SAC*
b Estimated and measured results of CM RE of *DUT*

Estimated and measurement results: To further validate the proposed method, a 20 cm × 10 cm PCB was fabricated as a device under test (DUT) and attached with two cables with 4 mm × 0.5 m on its ends. A signal trace with 1 mm width and 15 cm length was etched on 1.6 mm FR4 dielectric material ($\varepsilon_r = 4.6$). The signal trace was fed by a 5 V DC, 66 MHz trapezoidal signal with 6 ns rise/fall time while the far end of the trace was loaded with a 75 Ω resistor. The PCB was built to be as compact as possible where a 9 V battery was used with a 7805 regulator to supply 5 V DC to the oscillator. To ensure the RE was produced from the cables only, the PCB with its power supply were placed inside a 12 cm × 30 cm × 30 cm metallic box as shown in Fig. 3*a*. The metallic box was then put on a 0.8 m wooden rotating table inside the semi-anechoic chamber (SAC). The measured results of REs agreed well with the one obtained using the proposed method for frequencies >200 MHz as shown in Fig. 3*b*. This was due to the usage of the transmission-line theory in computing differential mode voltage [1] which provided inaccurate results of electrically short traces. Generally, it can be observed from Fig. 3*a* that the proposed method can predict the CM RE from two cables attached to the PCB with an acceptable accuracy.

Conclusion: A novel method for estimating the CM RE of the PCB attached with two cables based on the imbalance difference model and the asymmetrical dipole antenna had been presented. The accuracy of the proposed method had been demonstrated by comparing the estimated results to both the HFSS simulation results and the measurement results taken in an SAC.

Acknowledgments: The authors acknowledged and expressed a sincere appreciation to the Universiti Tun Hussein Onn Malaysia (UTHM) for financing the research project under the Contract Research Grant Scheme. The support given by the Research Center for Applied Electromagnetics, UTHM by providing the facilities to perform this research is also highly appreciated.

Submitted: *30 December 2015* E-first: *14 March 2016*
doi: 10.1049/el.2015.4534
One or more of the Figures in this Letter are available in colour online.

A.M. Sayegh and M.Z.M. Jenu (*Research Center for Applied Electromagnetics, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia*)

✉ E-mail: ahmed_su2008@yahoo.com

References

1 Paul, C.R.: 'Introduction to electromagnetic compatibility' (Wiley Interscience, NJ, 2006, 2nd edn)
2 Wang, J., Sasabe, K., and Fujiwara, O.: 'A simple method for predicting common-mode radiation from a cable attached to a conducting enclosure', *IEICE Trans. Commun.*, 2002, **E85-B**, (7), pp. 1360–1367, doi: 10.1109/APMC.2001.985316
3 Watanabe, T., Wada, O., and Miyashita, T.: 'Common-mode current generation caused by difference of unbalance of transmission lines on a printed circuit board with narrow ground pattern', *IEICE Trans. Commun.*, 2000, **E83-B**, (3), pp. 593–599
4 Su, C., and Hubing, T.H.: 'Imbalance difference model for common-mode radiation from printed circuit boards', *IEEE Trans. Electromagn. Compat.*, 2011, **53**, (1), pp. 150–156, doi: 10.1109/TEMC.2010.2049853
5 Su, C., and Hubing, T.H.: 'Improvements to a method for estimating the maximum radiated emissions from PCBs with cables', *IEEE Trans. Electromagn. Compat.*, 2011, **53**, (4), pp. 1087–1091, doi: 10.1109/TEMC.2011.2165217
6 Zhang, N., Kim, J., Ryu, S., *et al.*: 'Prediction of common-mode radiated emission of PCB with an attached cable using imbalance difference model', *IEICE Trans. Commun.*, 2015, **E98-B**, (4), pp. 638–645, doi: 10.1587/transcom.E98.B.638
7 King, R., and Harrison, C.W.: 'The distribution of current along a symmetrical center-driven antenna', *Proc. IRE*, 1943, **31**, (10), pp. 548–567, doi: 10.1109/JRPROC.1943.233034