Modelling of Printed Circuit Boards in Closed Environment Using TLM Method

Bratislav Milovanović, Nebojša Dončov and Jugoslav Joković

Abstract - In this paper, possibilities and effectiveness of Transmission Line Matrix (TLM) method for modelling of electromagnetic emissions from a printed circuit board (PCB) in closed environment are considered. The method is applied to account for the interactions between the PCB and enclosure by including the basic physical features of the PCB. A basic test board, placed in enclosure, is modelled in configurations where feeding and terminations are realized through TLM wire ports. Also, effects of wire monitoring probe and aperture used in experimental setup are considered. Comparison with reference results based on measurements and Method of Moments (MoM) simulations, confirms the validity of the numerical model.

Keywords – Printed circuit board, wire, enclosure, TLM method.

I. INTRODUCTION

The rapid development and utilization of advanced digital techniques for information processing and transmission in modern communication systems have led to a further evolution of semiconductor technology to nanometre regime. A number of complex components and devices, usually in high-density packaging, can be found in today's communication systems resulting in a very challenging electromagnetic (EM) field environment. Therefore, electromagnetic compatibility (EMC) [1] has become one of the major issues when designing these systems, especially some of their parts such as printed circuit boards (PCBs) and integrated circuits (ICs)

Clock rates that are driving PCBs are now in the GHz frequency range in order to increase dramatically processing speed. Therefore, considering even a few higher harmonics of clock rates takes design of such circuits well into the microwave regime. PCBs are becoming increasingly more complex and as a consequence quantifying their EM presence is more difficult. In the microwave frequency range, PCBs have dimensions of the order of several wavelengths and thus become efficient radiators and receivers of EM energy. In addition to that, high-density packaging, widely applied to PCB design, could cause a significant level of EM interference (EMI) between neighbours PCBs, particularly when they are placed in closed environment. These effects in combination with the driving down of device switching voltage levels are making signal quality/integrity and emission/ susceptibility critical EMC issues in next generation high-speed systems.

Differential numerical techniques, such as the finite-difference time-domain (FD-TD) method [2] and the transmission line matrix (TLM) method [3], are common tools for computational analysis of numerous EM and EMC problems. However, a full-wave three dimensional (3D) numerical simulation to accurately reproduce the EM field around a PCB usually requires substantial computing power and simulation run-time. Therefore, one efficient technique based on equivalent principle [4], providing simplified equivalent dipole models to accurately predict the radiated emissions without reference to the exact details of the PCB has been recently proposed in [5]. The model has been deduced from experimental near-field scanning and it includes not only the excitation but also physical features of PCB such as its ground plane and dielectric body, both very important in closed environment. However, such model can be very complex and run-time consuming when incorporating it into conventional calculation algorithms of FD-TD or TLM methods.

For some of the geometrically small but electrically important features (so-called fine features), such as wires, slots and air-vents, few enhancements to the TLM method have been developed [6-8]. These compact models have been implemented either in the form of additional one-dimensional transmission line network running through a tube of regular nodes or in the form of equivalent lumped element circuit, allowing to account for EM presence of fine features without applying a very fine mesh around them. Compared with the conventional approach, these models yield a dramatic improvement in computer resources required.

Similar compact model could be developed for PCB allowing for efficient implementation into TLM algorithm procedure and accurate representation of EM emissions and coupling of PCB. In order to develop such model, an extensive full-wave analysis has to be conducted in order to fully characterize EM presence of PCB either in free space or in closed environment. In this paper, we consider the basic test PCB placed in rectangular enclosure as typical closed environment for PCBs. It consists of L-shaped microstrip track on FR4 substrate [5]. The impact of radiated emission of this simple PCB structure, with wire feed and terminated probes at its ends, on EM field distribution inside the enclosure is investigated. In addition,

Bratislav Milovanović, Nebojša Dončov and Jugoslav Joković are with the Department of Telecommunications, Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, E-mail: {bata, doncov, jugoslav}@elfak.ni.ac.rs.

a monitoring probe, used in practice to sample the EM field interaction between PCB and enclosure as well as an aperture on one enclosure wall (e.g. used for outgoing or incoming cable penetration from and to PCB) are also taken into account. TLM method, enhanced with the compact wire model is used to carry out this investigation while the simulation results are compared with reference results based on measurements and Method of Moments (MoM) simulations [5].

II. MODELLING PROCEDURE

A. TLM method

In TLM method, a 3D electromagnetic (EM) field distribution in a PCB structure in enclosure is modelled by filling the space with a network of transmission lines and exciting a particular field component in the mesh by voltage source placed on the excitation probe. EM properties of a medium in the substrate and enclosure are modelled by using a network of interconnected nodes. A typical node structure is the symmetrical condensed node (SCN), which is shown in Fig. 1. To operate at a higher time-step, a hybrid symmetrical condensed node (HSCN) [3] is used. An efficient computational algorithm of scattering properties, based on enforcing continuity of the electric and magnetic fields and conservation of charge and magnetic flux, is implemented to speed up the simulation process. For accurate modelling of this problem, a finer mesh within the substrate and cells with arbitrary aspect ratio suitable for modelling of particular geometrical features, such as microstrip track, are applied. External boundaries of arbitrary reflection coefficient of enclosures are modelled in TLM by terminating the link lines at the edge of the problem space with an appropriate load.

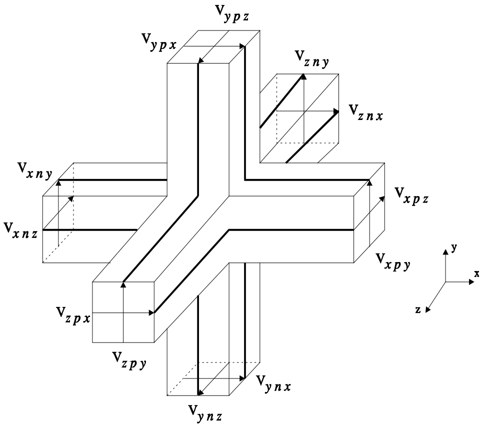


Fig. 1. Symmetrical condensed node

B. Compact wire TLM model

In TLM wire node, wire structures are considered as new elements that increase the capacitance and inductance of the medium in which they are placed. Thus, an appropriate wire network needs to be interposed over the existing TLM network to model the required deficit of electromagnetic parameters of the medium. In order to achieve consistency with the rest of the TLM model, it is most suitable to form wire networks by using TLM link and stub lines (Fig. 2) with characteristic impedances, denoted as Z_{wy} and Z_{wsy}, respectively.

An interface between the wire network and the rest of TLM network must be devised to simulate coupling between the electromagnetic field and the wire.

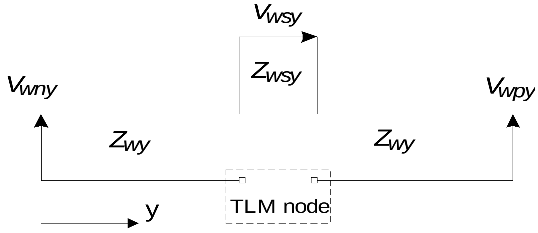


Fig. 2. Wire network

In order to model wire elements, wire network segments pass through the centre of the TLM node. In that case, coupling between the field and wire coincides with the scattering event in the node which makes the scattering matrix calculation, for the nodes containing a segment of wire network, more complex. Because of that, an approach proposed in [6], which solves interfacing between arbitrary complex wire network and arbitrary complex TLM nodes without a modification of the scattering procedure, is applied to the modelling of microstrip structures.

The single column of TLM nodes, through which wire conductor passes, can be used to approximately form the fictitious cylinder which represents capacitance and inductance of wire per unit length. Its effective diameter, different for capacitance and inductance, can be expressed as a product of factors empirically obtained by using known characteristics of TLM network and the mean dimensions of the node cross-section in the direction of wire running [6].

Following the experimental approach that using inner conductor of coaxial guide as a probe, numerical characterisation of EM field inside the cavity can be done by introducing wire ports at the interface between wire probes and enclosure walls.

III. NUMERICAL RESULTS

Results presented here illustrates possibilities of TLM method for determining the emissions from basic PCB structure in form of test board with a microstrip printed on the dielectric substrate [5]. Therefore, for verification purposes, the numerical TLM results from this board are compared with reference results based on MoM, as well as corresponding measurements [5].

The basic test PCB is a 2-mm wide L-shaped microstrip track (l_1=40mm, l_2=20mm) on one side of a $PCB_x \times PCB_y \times PCB_z = (80\times50\times1.5)mm^3$ board made from FR4 substrate with relative permittivity ε_r =4.5. The geometry of the board is shown in Fig. 3.

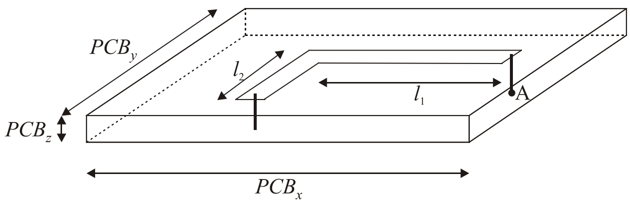


Fig. 3. Geometry of basic test PCB

The test board PCB is mounted on the bottom of an enclosure in the form on rectangular metallic box with dimensions $a\times b\times c$=(284×204×75)mm^3. PCB is powered by external RF signals via probe (with radius of 0.5mm) placed at one end of microstrip track (point A). This structure allows for an accurate modeling of enclosure through reflection coefficients of boundaries, while feed and terminated probes are modeled through compact wire model applying generator and loads in TLM wire ports at the ends of microstrip track.

When a PCB is inside an enclosure, it is of particular interest to investigate the behavior near the resonant frequencies of the enclosure. Therefore, numerical results of resonant frequencies in modeling closed environment structure are analysed. Fig 4 presents the resonant frequencies obtained from vertical electric field (E_z) sampled at point 35-mm above the PCB.

In Table I values of resonances obtained using TLM simulation are compared with reference values found experimentally by observing the field magnitude inside the enclosure. Comparing with measurements, the simulation results of test boards show that the inclusion of basic features, such as the microstrip track and substrate, in addition to the wires elements for feeding and terminations, permit an accurate prediction of emitted fields to be made in enclosures that have interactions with the PCBs inside. The difference in frequency is less than 10 MHz and may be because the enclosure, used for the measurements, has features not included in the numerical model, such as probe used for EM field monitoring and aperture made on one enclosure wall [5].

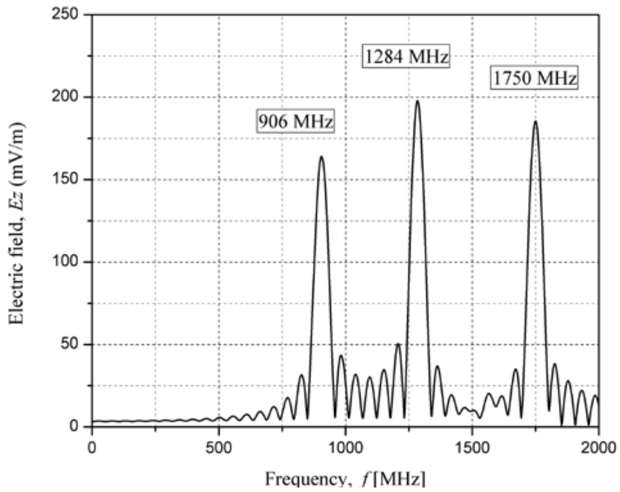


Fig. 4. TLM numerical results of vertical component of electrical field in enclosure with basic test PCB

TABLE I
COMPARISON OF MEASURED AND NUMERICAL RESULTS

Resonant frequencies (MHz)	Measured [5]	TLM
PCB in enclosure	900	906
	1290	1284
	1740	1750

Therefore, in Table II values of resonances are compared when, first, the probes used for EM field monitoring, and later the aperture, are incorporated into the TLM model together with the enclosure, to simulate the real closed environment problem (Fig 5). The 30-mm length monitoring probe is placed in vertical direction, mounted on the top wall of enclosure. It is also described by the compact wire model. Aperture with dimensions $a_1\times b_1$= (60×10)mm^2 is placed on top wall on enclosure above PCB according to experimental setup.

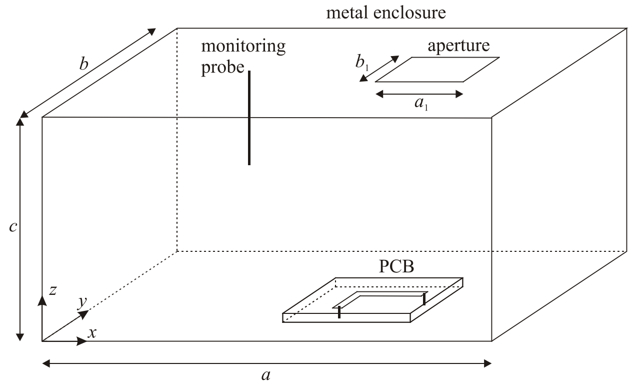


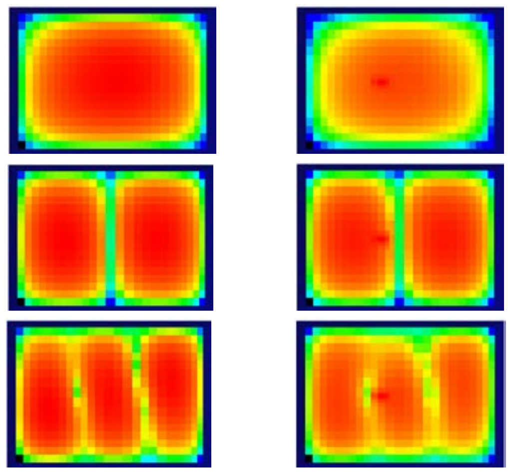
Fig. 5. TLM model of basic test PCB in enclosure with monitoring probe and aperture

TABLE II
COMPARISON OF NUMERICAL RESULTS FOR ENCLOSED PCB STRUCTURE MODIFICATION

Structure	Resonant frequencies (MHz)	Electric field (mV/m)
PCB in enclosure	906	164
	1284	197
	1750	186
PCB in enclosure with probe	897	295
	1280	421
	1738	368
PCB in enclosure with aperture	905	163
	1284	196
	1749	185

Obtained numerical results illustrate the shift in resonant frequency when additional features are incorporated particularly. It is found, as expected, that resonances appear at different frequencies if the model includes the monitoring probe. The presence of probe causes difference in frequency about 10 MHz and also leads to a change in the peak field magnitude because it becomes a secondary EM field radiator. On the other hand, impact of aperture is minimal because its dimension is much smaller than the volume of the enclosure so that do not disturb EM field distribution inside enclosure. However, aperture presence could increase the level of EM field radiated outside the enclosure which should be taken into account when emission EMC compliance test of PCB is conducted.

Fig. 6 shows the full patterns of E_z on the plane 35-mm above the bottom of the enclosure given by the TLM simulation at resonant frequencies illustrating EM field distribution of an enclosure due to the physical presence of a PCB and monitoring probe. The TLM results of PCB in enclosure simulation have very good agreement with corresponding results based on MoM simulations [5]. Obtained patterns confirms that modeling the dielectric and track of a PCB as well as wire probes is essential in enclosed environment simulations.



a) b)

Fig. 6. Patterns of E_z at resonant frequencies, given by the TLM simulation of PCB in enclosure: a) without, b) with monitoring probe

IV. Conclusion

Starting that one of the main interests in EMC tests is the intensities and distributions of the radiated fields from equipment under test (EUT), results are presented here of the emissions from basic PCB structure. A method applied to determine radiated emissions from a PCB using a model based on TLM modelling of test board in closed environments, to account for the interactions between the physical presence of the PCB and the enclosure.

According to presented results based on examples of basic test PCB in closed environments, it is found that the TLM method is very convenient for modelling of PCB structures in form of microstrip track on board made from substrate placed in enclosure. Compact wire TLM model allows modeling of wire conductors used for conections of different layers in PCB, and also probe for monitoring EM field in enclosed space. Good agreement has been achieved between results obtained by using TLM method and those obtained by using the MoM and measurements.

Generally, TLM method could also be appled for more complex multilayer PCBs, but considerations must be given to issues of computational costs, resolution and accuracy. Also, emissions from small elements in PCBs and edges due to enclosure modes will need particularly good characterization. This may require inclusion of additional parameters represented in equivalent models. Nevertheless, here it is demonstrated that the TLM method have the potential to characterize emissions from PCB structures in realistic environments and making it possible to perform system EMC studies.

Acknowledgement

This work was supported by Ministry of Education and Science of Republic of Serbia, under the project III-44009.

References

[1] Christopoulos, C., "*Principles and Techniques of Electromagnetic Compatibility*", 2nd edition, CRC Press, Boca Raton, FL, 2007.
[2] Kunz, K. S., Luebbers, R. J., "*The Finite Difference Time Domain Method for Electromagnetics*", CRC Press, Boca Raton, FL, 1993.
[3] Christopoulos, C., "*The Transmission-Line Modelling (TLM) Method*", IEEE Press in association with Oxford University Press, Piscataway, NJ, 1995.
[4] Balanis, C. A., "*Antenna Theory - Analysis and Design*", John Wiley and Sons, New Your, 1997.
[5] Tong, X., Thomas, D.W.P., Nothofer, A., Sewell, P., Christopoulos, C., "*Modeling Electromagnetic Emission From Printed Circuit Boards in Closed Environment Using Equivalent Dipoles*", IEEE Transactions on Electromagnetic Compatibility, Vol. 52, No. 2, May 2010, pp. 462-470.
[6] Wlodarczyk, A. J., Trenkic, V., Scaramuzza, R., Christopoulos, C., "*A Fully Integrated Multiconductor Model For TLM*", IEEE Transactions on Microwave Theory and Techniques, Vol. 46, No. 12, December 1998, pp. 2431-2437.
[7] Trenkic, V., Scaramuzza, R., "*Modelling of Arbitrary Slot Structures Using Transmission Line Matrix (TLM) Method*", International Symposium on Electromagnetic Compatibility, Zurich, Switzerland, 2001, pp. 393-396.
[8] Dončov, N., Wlodarczyk, A. J., Scaramuzza, R., Trenkic, V., "*Compact TLM Model of Air-vents*", Electronics Letters, Vol. 38, No. 16, 2002, pp. 887-888.