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# TLM Modeling of Emissions from Printed Circuit Board of Power Amplifier Matching Circuits

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*Abstract*— **The paper considers an electromagnetic (EM) emission from a printed circuit board (PCB) representing impedance matching circuits on microwave amplifier. The analysis is based on Transmission Line Matrix (TLM) method including the basic physical features of the input and output impedance matching circuits realized using the microstrip. The ports are described through the TLM wire compact model while a simple equivalent transistor model based on S parameters is applied to account for the connection between the PCB elements. Since a rectangular metallic enclosure is typical closed environment for microwave amplifier, the EM emissions inside and outside the enclosure with aperture are compared with respect to engineering purposes.**

***Keywords - EM emissions, PCB, Enclosure, Power Amplifier, Aperture, TLM method***

## I. INTRODUCTION

In recent years, a great effort has been dedicated to development and utilization of advanced digital techniques for information processing and transmission. A number of complex components and devices, usually in high-density packaging, can be found in modern communication systems resulting in a very challenging electromagnetic (EM) field environment. Therefore, electromagnetic compatibility (EMC) [1] has become one of the major issues in design of these systems, especially some of their parts such as printed circuit boards (PCBs) and integrated circuits (ICs).

Clock rates that drive PCBs are now in the GHz frequency range in order to increase dramatically processing speed. Therefore, consideration of even a few higher harmonics of clock rates takes design of such circuits well into the microwave regime. PCBs are increasingly becoming more complex and, consequently, 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, high-density packaging, widely applied to the PCB design, could cause a significant level of EM interference (EMI) between neighbors PCBs, particularly when they are placed in an enclosed 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 the equivalent principle [4], providing simplified equivalent dipole models to accurately predict radiated emissions without reference to the exact details of the PCB has been recently proposed [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 a dielectric body, both very important in closed environment. However, when such model is incorporated into conventional calculation algorithms of FD-TD or TLM methods, it can be very complex and time consuming.

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 an additional one-dimensional transmission line network running through a tube of regular nodes or in the form of an equivalent lumped element circuit, allowing to account for EM presence of fine features without applying a very fine mesh around them. Compared to the conventional approach, these models yield a dramatic improvement in computer resources required. Similar compact model could be developed for the PCB allowing for an efficient implementation into the TLM algorithm procedure and accurate representation of EM emissions and coupling of the PCB. Development of such model has assumed that an extensive full-wave analysis has to be conducted in order to fully characterize EM presence of the PCB either in the free space or in an enclosed environment.

Numerical TLM results of EM emissions from basic L-shaped PCB board inside the enclosure are verified with reference results based on equivalent dipole simulations and measurements [5,9,10]. In this paper, we consider the PCB consisting of two L-shaped microstrip tracks placed on FR4 substrate, representing the input and output impedance matching circuits of single stage power amplifier operating at 1GHz [11]. The ports at the ends of tracks are realized through the wire elements while the transistor is represented by an equivalent model based on S parameters at the operating frequency. PCB is placed in a rectangular metallic enclosure as a typical closed environment for a power amplifier. In addition, an aperture on the top enclosure wall is also taken into account. The impact of radiated emission of this PCB structure on EM field distribution is investigated. Numerical TLM results of EM field at resonances are compared with corresponding results inside enclosure based on simulations and measurements [5]. Also, the EM field patterns inside and outside the enclosure at amplifier operating frequency are analyzed in terms of radiated EM emissions from PCB elements.

## II. TLM MODELING

In the TLM method, 3D EM field distribution in a PCB structure in an enclosure is modelled by filling the space with a network of transmission lines and exciting a particular field component in the mesh by a voltage source. EM properties of substrate and the air in the 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 an 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.

In the TLM compact wire model, wire structures are considered as new elements that increase the capacitance and inductance of the medium which they are placed in. 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 the TLM network must be devised to simulate coupling between the EM field and the wire.

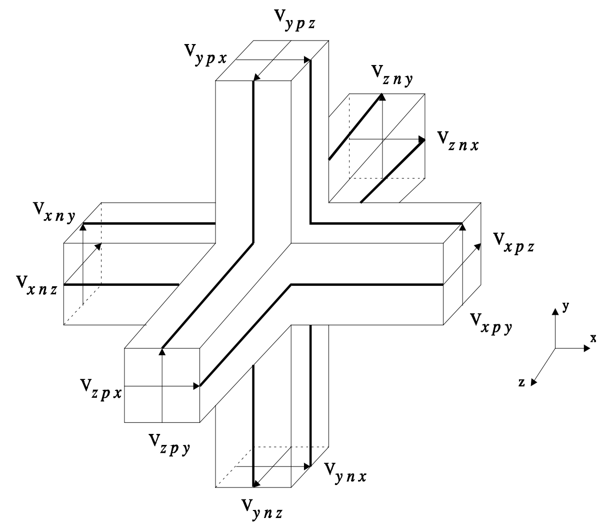

Figure 1. Symmetrical condensed node

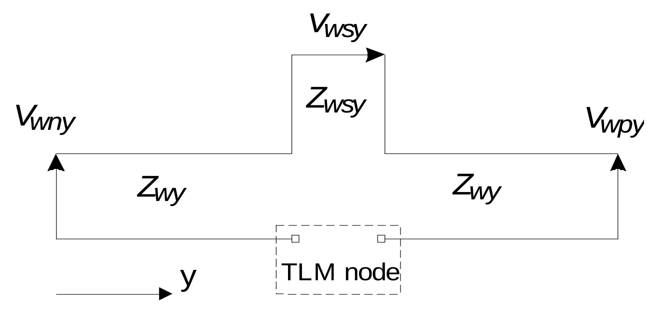

Figure 2. Wire network

In order to model wire elements, wire network segments pass through the center of the TLM node. In that case, coupling between the field and the 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 wire segments.

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].

## III. RESULTS AND ANALYSES

TLM simulations are carried out to determine the EM emissions from input and output matching circuits of a single stage amplifier, in form of microstrip lines printed on the dielectric substrate and placed in a metallic enclosure with an aperture. The layout of matching circuits is designed for single stage power amplifier based on LDMOSFET operating at 1GHz [11].

The PCB representing matching circuits of single stage power amplifier consists of two L-shaped microstrip tracks, placed on one side of a $PCB_x \times PCB_y \times PCB_z$= $(250\times150\times1.5)\text{mm}^3$ board made from FR4 substrate with relative permittivity $\varepsilon_r$ =4.2. The width of tracks is $w$ = 3.1mm, while lengths are calculated in order to achieve the impedance matching ($l_{in,1}$ = 78.2mm, $l_{in,2}$ = 31.6mm, $l_{out,1}$ = 84.7mm, $l_{out,2}$ = 27.7mm). LDMOSFET is represented by model based on S parameters at 1GHz ($S_{11}=0.841e^{-j143°}$, $S_{21}=6.01e^{j76°}$, $S_{12}=0.018e^{j11°}$, $S_1 =0.728e^{-j64°}$). The PCB is powered by external RF signals via probe (with diameter of 0.5 mm) placed at one end of microstrip track representing the input circuit. Following the design of the amplifier powered by external RF signals via SMA connectors in practice, numerical characterization of input and output ports can be done by introducing wire ports.

The PCB is mounted on the bottom of an enclosure in the form of rectangular metallic box with dimensions $a \times b \times c = (284 \times 204 \times 75)\ \mathrm{mm}^3$. In this structure, the enclosure walls are modeled through setting reflection coefficients, while coax ports are described by using the compact wire model and applying generator and loads in TLM wire ports at the ends of microstrip track. Also, the aperture with dimensions $a_1 \times b_1 = (250 \times 10)\ \mathrm{mm}^2$, placed on the top wall of the enclosure above the PCB, is incorporated into the TLM model. The geometry of the PCB representing power amplifier matching circuits in the enclosure is shown in Fig. 3.

When a PCB is placed inside an enclosure, it is of particular interest to investigate the behavior near the resonant frequencies of the enclosure. The impact of the aperture is not critical for resonances when its dimension is much smaller than the volume of the enclosure, thus not disturbing EM field distribution inside the enclosure. Since the PCB causes differences in frequency values and peak field magnitudes, the modeling of PCB elements is essential in enclosed environment simulations. Therefore, numerical results of resonant frequencies in the modeled closed environment structure with the PCB are analyzed. Fig. 4 presents the TLM simulation results of resonant frequencies obtained from the vertical electric field sampled above the PCB, at point $z = 35$mm, corresponding to the center of the aperture in $xy$ plane ($x = 142$mm, $y = 75$mm). In order to illustrate effect of a presence of a PCB representing amplifier matching circuits, obtained results of resonances, in Table I, are compared with corresponding values based on simulations and measurements of basic L-track PCB in the same enclosure [5].

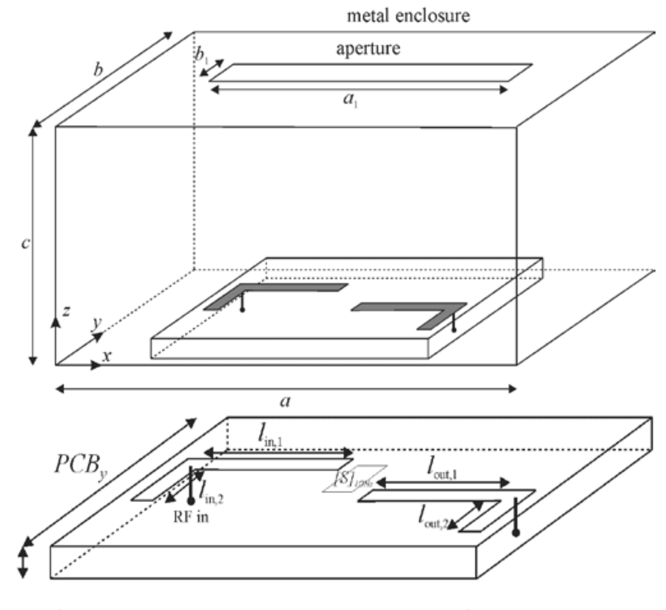

Figure 3. TLM model of basic test PCB in enclosure with aperture

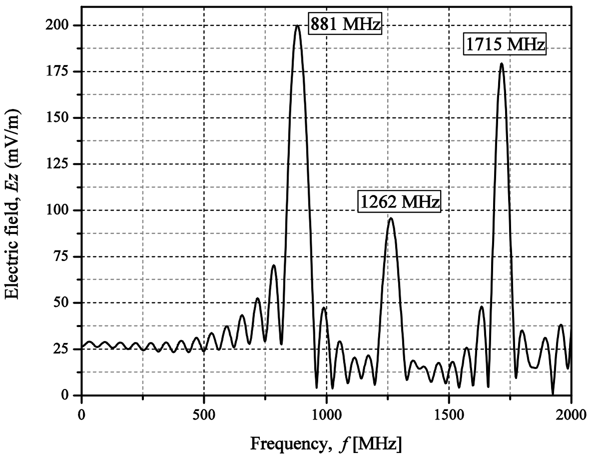

Figure 4. TLM numerical results of vertical component of electrical field from power amplifier PCB in enclosure with aperture

Fig. 5 shows the patterns based on the simulation results of an vertical electric field component at enclosure resonances, in horizontal $xy$ plane, sampled at $z = 35$mm above the PCB representing EM emissions inside the enclosure. The obtained results illustrate change of EM field distribution of an enclosure due to the physical presence of the PCB elements, in respect to corresponding results based on equivalent dipole simulations and measurements [5].

Besides enclosure resonances, an attention is particularly put on EM emissions at the power amplifier operating frequency. Fig. 6 shows the simulation results of electric field component at 1 GHz frequency, in vertical $xz$ plane, sampled at $y = 142$ mm (corresponds to aperture position) representing EM emissions inside and outside enclosure. Also, results of the vertical field component at the operating frequency are sampled in horizontal $xy$ plane, at 15 mm above the aperture, representing EM emissions outside enclosure at 1 GHz. Since the results of the vertical field component at the operating frequency are sampled inside and outside the enclosure, TLM mesh is extended to the space above the enclosure top wall.

Generally, the patterns representing EM emissions inside an enclosure are dominantly determined by positions of wire ports and microstrip tracks. It can be seen from Fig. 6. that emissions outside of the enclosure are much smaller compared to corresponding levels inside the enclosure. Also, the emissions from lines representing output matching circuits are much higher than input, due to the level of a signal amplified by the transistor. Besides wire elements and microstrip lines, emissions outside the enclosure are also determined by the aperture position.

TABLE I. RESONANCES OF PCB IN THE ENCLOSURE

| **PCB in enclosure** | **Measured Basic PCB [5]** | **TLM simulation** | |
|---|---|---|---|
| | | *Basic PCB* | *Amplifier PCB* |
| Resonant frequencies (MHz) | 900 | 903 | 881 |
| | 1290 | 1285 | 1262 |
| | 1740 | 1749 | 1715 |

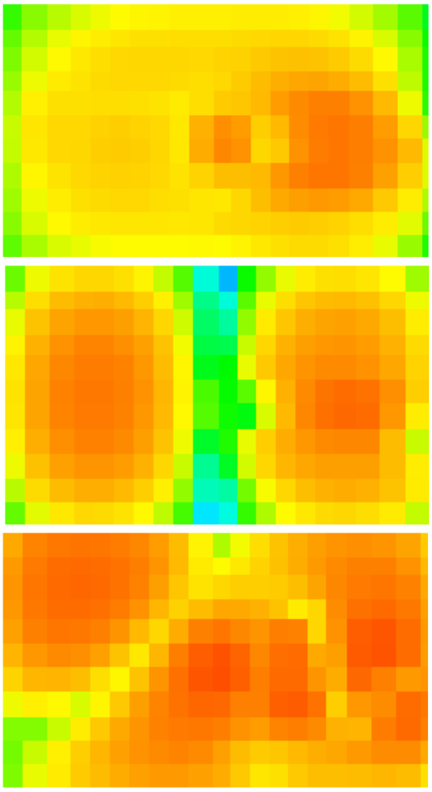

Figure 5. Patterns of Ez given by the TLM simulation of power amplifier PCB, at resonances of enclosure

## 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 EM emissions from a PCB structure representing power amplifier matching circuits. The coax ports and transistor model are used to account for the interactions between the physical presence of the PCB elements. Also, an enclosure should be taken into account when outdoor emission EMC compliance test of PCB is conducted. A method applied to determine radiated emissions from a PCB is based on the TLM model of a board placed in an enclosure with an aperture.

The impact of presence of particular elements of PCB in an enclosure with an aperture is analysed through comparing values of resonances obtained using TLM simulation with reference values of enclosure resonances. The patterns of EM emissions at the amplifier operating frequency inside and outside the enclosure with the aperture are presented and an impact of particular elements on EM emissions is analysed.

The simulation results of basic amplifier boards show that the inclusion of basic features, such as the microstrip track of matching circuits and wire ports, in addition to transistor model, enables accurate prediction of emitted fields, inside the enclosure, that interacts with the PCBs inside. In overall, it is demonstrated that the TLM method have the potential to characterize emissions from PCB structures in realistic environments such as enclosures with an aperture and making it possible to perform system EMC studies.

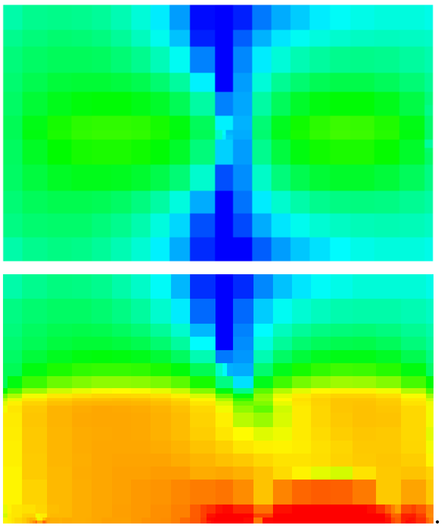

Figure 6. Patterns of Ez given by the TLM simulation of PCB in the enclosure with the aperture, at the operating frequency: a) in a horizontal plane outside the enclosure b) in a vertical plane

## ACKNOWLEDGEMENT

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