Electromagnetic Frontiers in the design of connections in printed circuit board.

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Abstract: In this paper is presented a comparison between a model based on distributed parameters and a circuit model based on localized or concentrated parameters for traces Printed Circuit Board (PCB). The two models are developed from Transmission Line (TL) theory. The analysis is done from the voltage at the terminals of the conductor. The models presented had been simulated to verify the behavior of the voltage and phase when the circuit operates in a band of frequency from 800 MHz to 2 GHz. The simulation results show the amplitude and phase voltage variation as a function of the electrical length of a PCB traces.

Keywords: EMI, PCB, Integrated Circuit, Transmission Line.

1. INTRODUCTION

The electronic circuits are sufficiently susceptible to the electromagnetic interferences (EMI) that they are issues of the environment or components of one's own circuit, as shown in Fig. 1.

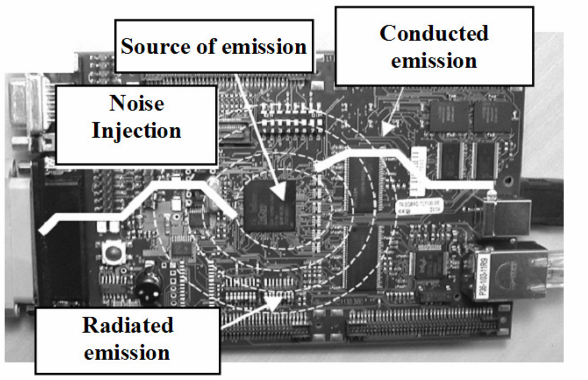

Figure 1: Possible mechanisms for coupling due EMI.

To check the caused problems from EMI, it was performed a preliminary study of the electromagnetic behavior of electronic equipments. A method of study the mentioned effects was the use of models that describes the electromagnetic behavior of the circuit. The signals transmission (analog or digital) in PCB's was performed through metallic conductors. Depending of the signal frequency's (clock for the digital signals) or the data processing rate, these conductors do not behave as ideals conductors, but as a TL. When analyzed as a TL, the signal frequency increase can cause: alterations of signal integrity, time delay and in the worst situation it can damage some component of the electronic circuit [1].

In the study of the effects of EMI were analyzed the behavior of electric, *E*, and magnetic, *H*, fields in the PCB and the currents distribution, *I*, and voltages, *V*, in their circuit. The *E* and *H* fields and the electrical quantities *V* and *I* were determined from the Maxwell's equations. There are many numerical and analytical methods for their calculations. We can enumerate some numerical methods as: the Method of Moments (MoM) [2], the FDTD [2, 3], FEM [2]. Other possibility is using the TL theory to determine the electrical behavior of a traces PCB [4, 5]. The choice of the method was made from the comparison between the length of electrical circuit and wavelength in the operation frequency of the circuit.

Based on the TL Theory it is possible to determine two models for a metallic conductor. The former representation consists to determine a circuit model with distributed parameters, in order to obtain equations of voltage and current in the conductors of the PCB. The second consists in to represent a PCB conductor through a circuit with concentrated parameters composed by passive elements: inductance, resistance, capacitance and conductance [6].

In this paper, is verified the differences between the two models, with distributed and concentrated parameters, developed with the TL theory. The system under study is analyzed, including the transition, to the frequency range from 800 MHz to 2 GHz. The theory is developed for a uni-layer PCB and it is neglected the losses. The section 2 provides the theoretical formulation used in the development of models. In section 3, is showed the simulation results and in section 4 is presented the conclusions.

2. PROBLEM FORMULATION

A simple example of the kind of connection found PCB circuits is shown in Fig. 1. Here is shown the transversal view of a PCB with a trace of metal.

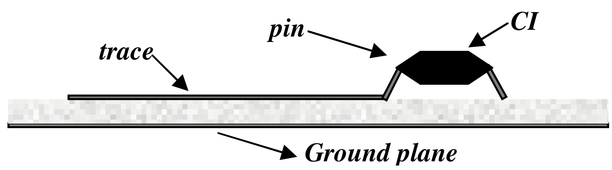

Figure 2: Transversal view of a PCB board.

From another side view of the Fig. 1 it is possible identify the real geometry of the PCB trace (Fig. 2). To determine its characteristic impedance the connection between the components of the circuit is considered a structure similar to a microstrip line (Fig. 3).

It is shown in Fig. 3 a cross section of a microstrip, where H represents the distance between the connection of microstrip and the ground plane, T represents the thickness of the metal and W its width.

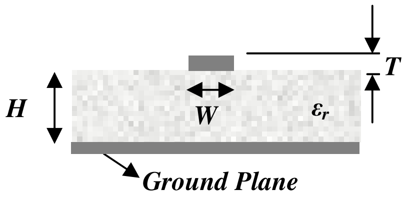

Figure 3: Transversal view for a microstrip line.

For first glance, we can without lost of generality consider $T = 0$, because its size is much smaller than W and the length of the connection.

According to what is presented in [1], the expressions used to calculate the value of the characteristic impedance, Z_C, of a microstrip, considering $T = 0$, is:

$$Z_C = \frac{60}{\sqrt{\varepsilon_r'}} ln\left[\frac{8H}{W} + \frac{W}{4H}\right], \quad \frac{W}{H} \leq 1 \tag{1}$$

$$Z_C = \frac{120\pi}{\sqrt{\varepsilon_r'}}\left[\frac{W}{H} + 1,393 + 0,667 ln\left(\frac{W}{H} + 1,444\right)\right]^{-1}, \quad \frac{W}{H} > 1 \tag{2}$$

with,

$$\varepsilon_r' = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2}\frac{1}{\sqrt{1 + 10\frac{W}{H}}} \tag{3}$$

where, ε_r is the relative dielectric permittivity constant.

In the Fig. 4 is presented a representation for a circuit with concentrated parameters.

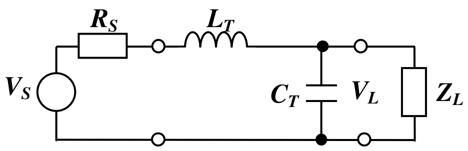

Figure 4: Representation of a Circuit with Concentrated Parameters.

where, L_T is the total inductance, C_T is the total capacitance, R_S is the resistance of the source, V_S is the voltage source, Z_c is the characteristic impedance of the connection and Z_L is the load impedance.

Using the value of Z_C can be determined the values of L *(H/m)* and C *(F/m)* and then calculate L_T and the C_T that compose the circuit with concentrated parameters, shown in Fig.4.

The expressions that express Z_C, L e C are:

$$L = \frac{Z_C}{v} \tag{4}$$

,

$$C = \frac{1}{vZ_C} \tag{5}$$

and,

$$v = \frac{v_0}{\sqrt{\varepsilon_r'}} \tag{6}$$

Where,

v is the waves propagating velocity's.

v_0 is the velocity of light.

The capacitance and inductance total (L_T e C_T) are calculated from the producer between L and the length of the connection, l, and between l and C, respectively. However, to study the parameters, L and C will be calculated according to their electrical length, i. e., according $l_e = l/\lambda$.

For the circuit shown in Fig. 3, the voltage in the resistive load is:

$$V_L = \frac{Z_1}{Z_1 + Z_2} V_S \tag{7}$$

where, Z_1 is the impedance equivalent for X_{CT} and Z_L and Z_2 are the impedance equivalent for X_{LT} and R_S.

Another form to represent the structure in study is presented on the Fig.5. In this case, the conductor is represented through two asymmetric parallels TL.

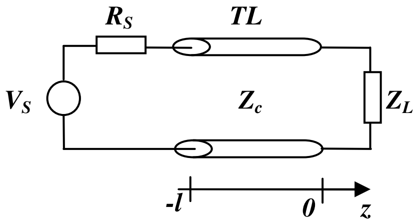

Figure 5: Representation of a Circuit with Distributed Parameters.

Considering that the wave is propagating in the z axis, the equations of voltage and current in a section of the TL can be write as[6]:

$$\frac{\partial^2 V(z,t)}{\partial z^2} - LC\frac{\partial^2 V(z,t)}{\partial t^2} = 0 \tag{8}$$

and

$$\frac{\partial^2 I(z,t)}{\partial z^2} - LC\frac{\partial^2 I(z,t)}{\partial t^2} = 0 \tag{9}$$

where, LC is the waves propagating velocity.

One of the solutions to Eq. 8 to the voltage source is sinusoidal is in the form:

$$V(z,t) = V^+ e^{-j\varpi z} - V^- e^{j\varpi z} \tag{10}$$

where, V^+ e V^- are constants and represent the amplitude of the voltage waves incident and reflected, respectively.

The voltage at the point z = - l is given by:

$$V_{in} = V(-l,t) = V^+ e^{-\gamma l} - V^- e^{\gamma l} \tag{11}$$

That can be written:

$$V_{in} = V(-l,t) = V^+ (e^{-\gamma l} - \Gamma_L e^{\gamma l}) \tag{12}$$

where, Γ_L is the load reflection coefficient.

The voltage V^+ can be calculated by:

$$V^+ = \frac{V_{in}}{e^{\gamma l} + \Gamma_L e^{-\gamma l}} \tag{13}$$

The impedance and the voltage source can be calculated from Eq. 14 e 15.

$$Z_{in} = Z_C \frac{Z_L + Z_C \tan(\beta l)}{Z_C + Z_L \tan(\beta l)} \tag{14}$$

$$V_{in} = V_S \frac{Z_{in}}{Z_{in} + R_S} \tag{15}$$

where, $\beta = 2\pi/\lambda$ is the constant phase propagation. The factor βl is equal to $2\pi l/\lambda$.

To determine the value of the voltage V_L function the l/λ is replaced by l_e in Eq. 14. Using the Eq. 13-15 is possible to calculate the voltage at the terminals of the load, according to l_e, from:

$$V_L = V(0,t) = V^{+}(1+\Gamma_L) \qquad (16)$$

3. SIMULATION

The two models presented were simulated to verify their behavior. The simulation was developed was used the circuits shown in Fig. 4 and 5. These circuits were simulated based on the formulation shown in section 2. It was admitted that $V_S = 1$ V, $R_L = 300\ \Omega$ and $R_S = 100\ \Omega$ and considered the PCB trace as a microstrip line with $W = 0.1$ mm, $H = 1$ mm and $\varepsilon_r = 5$.

The simulation was performed with different values for the physical length of PCB trace (l). It was chosen as physical length of reference the value of 15 cm. It was chosen this value because it is equivalent to the wavelength for a frequency of 2 GHz. The two others values that were used to the physical length to the PCB trace were 1,5 cm and 0,15 cm, that corresponds to a physical length 10 and 100 times smaller than the reference value's. It was utilized the voltage in the load to verify the behavior of the two models developed for the PCB trace.

The Magnitude and Phase calculated for the voltage at the load terminals R_L for the physical length of the 15 cm is shown in Fig. 6.

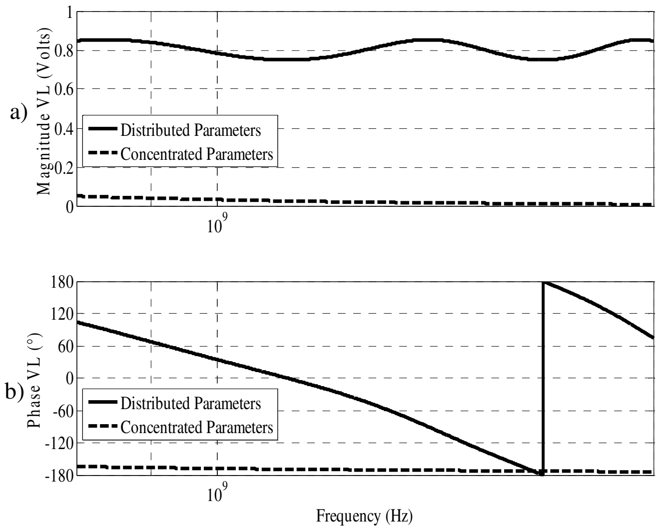

Figure 6: Comparison between the voltage amplitude and phase variation at the load, RL, as a function of frequency, for l = 15 cm.

It can be viewed, in Fig. 6a, that the magnitude voltage's at the load present different results. The voltage magnitude of the circuit with distributed parameters is approximately 0.8 V and the voltage magnitude of the circuits with distributed parameters is less than 0.2 V. From the Fig. 6b, it is seen that the phase for the model with distributed parameters varies 360° while the phase for the model with concentrated parameters is almost constant. As expected, the model with concentrated parameters fails to describe the behavior of the conductor when its physical length is close to the wavelength to the signal's operation.

One of the drawbacks of the currently models in the design a particular PCB circuit is not to know the real validation limit of the model. To check it, two others simulations changing the physical length were made. In the first simulation the physical length of the trace is equal to 1.5 cm, and in the second one the physical length of the conductor was considered equal to 0.15 cm.

The magnitude and phase of the simulated voltage, for the first case (1,5 cm), at the load terminals R_L are presented in Fig. 7.

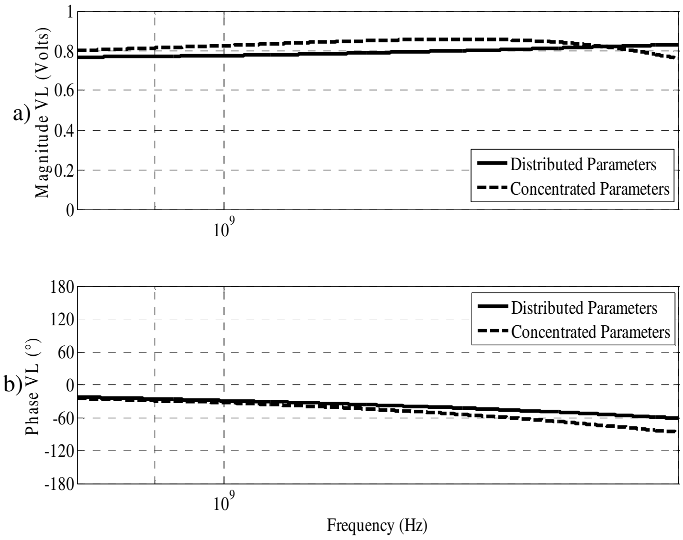

Figure 7: Comparison between the voltage amplitude and phase variation at the load, RL, as a function of frequency, for l = 1,5 cm.

The results for the second case, the magnitude and phase in the voltage at the load terminals R_L for a conductor with physical length of 0.15 cm, are shown in Fig. 8.

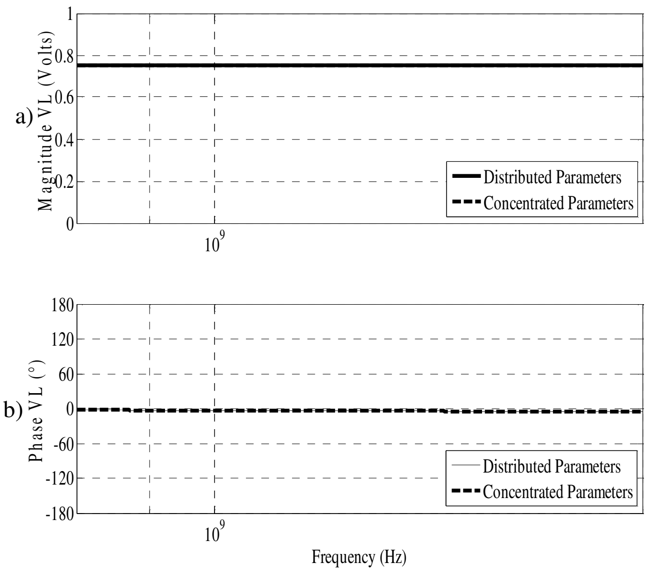

Figure 8: Comparison between the voltage amplitude and phase variation at the load, RL, as a function of frequency, for l = 0,15 cm.

When the physical length becomes smaller than the wavelength the magnitude and phase behavior of the voltage in the load, calculated for the two models, are very similar (Fig. 7 and Fig. 8).

To put in evidence the differences found in the load voltage, it was made a comparison between the responses calculated for the two models as a function of the electrical length (l_e). The considered range to l_e in the simulation was from 0.01 to 10. Fig. 9 shows the Magnitude and Phase voltages calculated at the terminals of the load R_L.

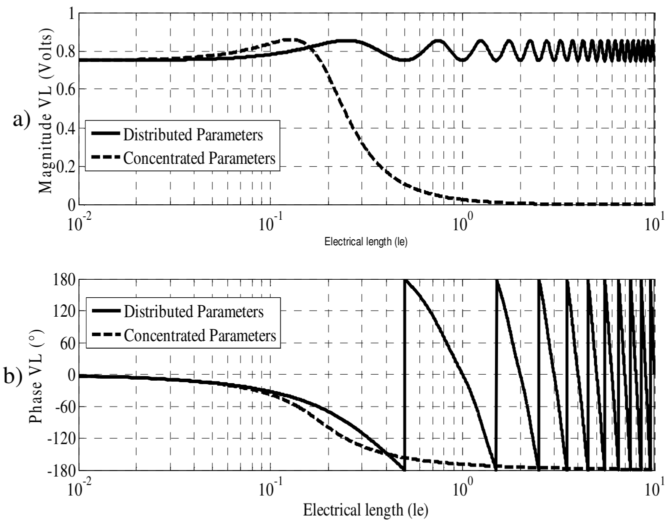

Figure 9: Comparison between the voltage amplitude and phase variation at the load, RL, as a function of frequency, as a function of le.

It is seen from Fig. 9 that the voltage magnitudes at the load terminals, calculated using the presented models, are equivalents when the l_e varies from 0.01 to 0.03. Also, it is shown in Figure 9, that the phase of voltage in the two models is equal when the electrical length varies of 0.01 to 0.1. Then, we have two different limits for magnitude and phase in the load to be considered in the circuits design.

To better observe the intervals where the values of the results are close the figure scales were increased. It is shown a detail of the voltage magnitude at the load in Fig 10 and for the voltage phase at the load in Fig 11.

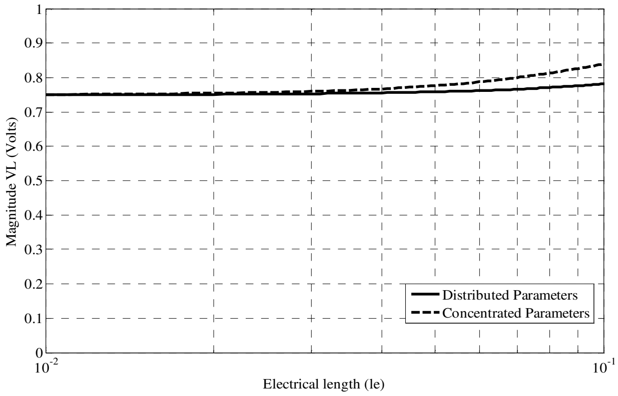

Figure 10: Detail of the magnitude voltages in the load RL.

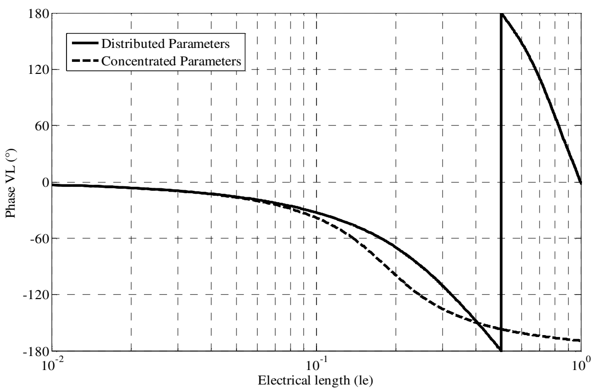

Figure 11: Detail of the phase voltages in the load RL.

As was mentioned, it is possible to see more clearly, from Fig.10 and 11, that the intervals where the two models present the same response are different. Depending on the chosen value for the l_e, it is possible to use the two models and to get the same response. However, when l_e is equal to 0.04 the models have the same response for the phase, but it presents different magnitude value for the voltage.

4. CONCLUSION

In this paper were presented the equations of the models with concentrated and distributed parameters to a metal connection of a PCB. The results of simulation were shown the variation of the magnitude and phase voltage as a function of the electrical length calculated through these two models. It was seen that the magnitudes voltages in the load for the two models are equivalents when the electrical length varies from 0.01 to 0.03 and the phase voltages are equals when the electrical length varies of 0.01 to 0.1 for the circuit presented. It follows that to applications where the electrical length of the connection is greater to 0.03 it is possible use the two models to represent the behavior of the connection. To values of the electrical length that varies of 0.03 to 0.1 the designer must choose which quantity is more relevant to the project, the magnitude or the phase voltage.

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