Evaluation of the Effective Electrical Parameters of a PCB Trace for Accurate Signal Integrity Simulations

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Abstract

Signal integrity (SI) analysis for high speed digital design on printed circuit boards (PCBs) requires to know the per unit length R, L, G, C parameters of the traces on boards. The paper presents a simple method to extract these parameters starting from simple measurements in the frequency domain. The evaluated electrical parameters are compared with the theoretical ones by means of eye diagram simulations at the end of a stripline 70 cm long.

Introduction

Due to the reduced physical dimensions of the on-chip transistors, the speed and complexity of the integrated circuits (ICs) on board increase. This trend places higher demands on the performances of the chip-to-chip interconnections. Multi-GHz signal bandwidths are involved in the high speed digital boards. Consequently signal integrity driven design has to extend beyond transmission-line based crosstalk and delay analysis to address all forms of electromagnetic interference (EMI) generation and coupling [1]. Accurate models for interconnect losses in PCB traces have to be considered: broadband interconnect characterization, frequency dependent resistance and inductance (skin effect loss), return path loss, dielectric loss are key parameters for correctly modeling the high speed signal propagation on the boards. The paper suggests a simple method for evaluating the electrical parameters of a PCB trace using effective propagation constant measurement, de-embedded by the effects of the adapters connecting the trace to the measurement instrument [2]. These parameters are used for tuning the model of the trace. Then simulations of the signal propagation along the trace are carried out, so to validate the proposed model.

Theoretical Approach

Consider an on board trace between two surface mounted adapters (SMAs), used for connecting the trace to a vector network analyzer (VNA) (Fig. 1).

Let L be the length of the trace with propagation constant $\gamma$ and characteristic impedance $Z_c$ for the dominant quasi-TEM mode of propagation. If $Z_c$ equals the normalization impedance, the $S_{21}$ parameter for the structure in Fig. 1 is:

$$S_{21}^L = \frac{S_{21}^A S_{21}^C}{1 + S_{22}^A S_{11}^C e^{-2\gamma L}} e^{-\gamma L},$$

(1)
where $S_{ij}^{A,C}, S_{ii}^{A,C}$ are the scattering parameters of the two SMA connectors A and C in Fig. 1. Consider two traces with lengths $L_1$ and $L_2$, each one with two SMAs at the ends as in Fig. 1. The traces have the same configuration and cross-sectional dimensions, while all the SMAs are assumed identical. Let $S_{21}^{L_1}, S_{21}^{L_2}$ be the forward transmission scattering parameters of the two traces as in (1). Using the VNA time windowing option to eliminate any unwanted end reflections ($S_{ii}^A = S_{ii}^C = 0$), one obtains:

$$\gamma = \frac{1}{L_1 \cdot L_2} \ln \frac{S_{21}^{L_2}}{S_{21}^{L_1}}$$

(2).

$S_{21}^{L_1}$ and $S_{21}^{L_2}$ are measured and $\gamma$ is then obtained indirectly by measurements. The real part of $\gamma$ accounts for the attenuation along the lines, while its imaginary part considers the phase shift that each line introduces.

Knowing $\gamma$, the characteristic impedance $Z_c$ of the trace with length $L$ can be evaluated as [3]:

$$Z_c = Z_o \frac{2e^{-\gamma L}}{1 - e^{-2\gamma L}} \sinh(\gamma L)$$

(3)

where $Z_o = 50\Omega$ is the reference impedance. Knowing $\gamma$ and $Z_c$ the electrical parameters of the trace can be evaluated using the equations [4]:

$$\gamma Z_c = R + j \omega L$$

(4)

$$\frac{\gamma}{Z_c} = G + j \omega C$$

(5)

The proposed procedure is general and it doesn’t require any approximations about the trace losses, whatever be the frequency into play. $R(f), G(f), C(f), L(f)$ are evaluated in the frequency range 40 MHz – 10 GHz for a stripline structure, showing the discrepancy with the theoretical values. The parameters account for all the losses in the designed structure and can be used to obtain a more sophisticated stripline model, useful for signal integrity and EMI simulations.

Experimental Approach And Simulations

The measurement setup consists of two 50 $\Omega$ single ended striplines with lengths $L_1 = 50$ cm and $L_2 = 70$ cm, laid out on a PCB with $\varepsilon_r \approx 3.8$ at 1 GHz and $\tan\delta \approx 0.007$ at 1 GHz. Both the traces are 250 $\mu$m wide and 18 $\mu$m thick. Applying the procedure in [2] and the equations (2), (3), it is possible to evaluate the effective $\gamma, Z_c$ for the two traces. Then, using the equations (4), (5), the electrical parameters of the traces in the frequency range 40 MHz – 10 GHz, where the quasi-TEM mode of propagation is dominant, are computed. Fig. 2 compares $R(f), G(f), C(f), L(f)$ evaluated from measurements with the theoretical values. The differences among the evaluated electrical parameters of the traces and the theoretical ones are evident.

The measurements highlight that the high-frequency resistance of the stripline increases as $f$. This differs from the widely held assumption that the resistance of a conductor of trapezoidal cross section, for the frequencies where the skin effect is well developed, increases as $\sqrt{f}$ [5]. It is important to note that the evaluated R(f) accounts for the lossy reference planes effects also.

The measured high-frequency conductance of the trace, looking like the theoretical value, increases as $f$. 

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A numerical evaluation of the eye diagram [6] at the end of the stripline with length equal to 70 cm can be carried out, when a pseudo random data pattern 2^{15}-1, no return to zero (NRZ) coded, at 2.5Gbps is sent at its input. The stripline is modeled using both the effective electrical parameters (Fig. 3) and the theoretical ones (Fig. 4).

Two are the appropriate metrics of the eye diagram [6]: 1) the maximum difference, at the same time instant, between points in the interior of the eye diagram, that is the maximum eye opening (MEO); and 2) its maximum eye width (MEW), that is the maximum difference, at the same voltage level, between two points in the interior of the eye diagram. These two points correspond to the decision threshold, i.e., the region of the eye diagram where the bits’ fronts intersect. The eye diagram in Fig. 3, which refers to the stripline modeled using the effective electrical parameters, has $MEO \approx 290$ mV and $MEW \approx 310$ ps, while the evaluated one in Fig. 4, referring to the stripline modeled with the theoretical electrical parameters, has $MEO \approx 385$ mV and $MEW \approx 325$ ps. As it is evident, modeling the line using its effective electrical parameters attenuates the traveling signal, reducing the duration of the transmitted bit.

![Comparison of effective and theoretical electrical parameters](image)

**Figure 2.** Comparison among the effective electrical parameters of the stripline from measurements and the theoretical ones.

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**REFERENCES**


**Figure 3.** Evaluation of the eye-diagram at the end of the stripline 70 cm long, modeled using its measured electrical parameters

**Figure 4.** Evaluation of the eye-diagram at the end of the stripline 70 cm long, modeled using its theoretical electrical parameters