# A NEW APPROACH TO SIGNAL REFLECTIONS ANALYSIS ON PCB TRANSMISSION LINES TERMINATED ON NONLINEAR IMPEDANCES

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**Abstract: A novel approach for analyzing signal reflections on transmission lines terminated on non-linear impedances is presented. The starting point of this new method is the Bergeron diagram method. The results obtained by the well-known method are used as input data for the new approach. This new method is implemented in MatLab and is suitable for both linear and non-linear impedances, and also for driving signals having rise/fall times of any value. This is the novelty of this approach compared to the Bergeron method which is valid only for fast command signals. The results are compared and they show good agreement with the ones obtained by experimental measurements performed with a high-performance digital oscilloscope.**

***Keywords:*** *signal reflections, transmission line, non-linear impedance, time domain measurements*

## I. INTRODUCTION

The purpose of this paper is to describe a method that can be used for analyzing the signal reflections on transmission lines (t-lines) terminated on non-linear impedances. Having in mind the advantages and the drawbacks of the well-known methods that were investigated, we have come to the conclusion that in order to analyze signal reflections the following parameters must be considered:

- characteristic impedance of the transmission line - $Z_0$
- propagation delay introduced by the line - TD
- V-I characteristics of the ICs connected to the t-line
- the parameters of the signal applied at the input of the driver circuit - $t_r$, $t_f$, $V_H$, $V_L$.

As none of the methods takes all these parameters into account, it was necessary to find a way to modify the previously used methods to obtain results that are based on a more complex set of input data, in this way being closer to the real case.

The intention is not to prove that the well-established methods that are used as standard analysis methods are not good or do not provide correct results. Rather, the intention is to find a way of *estimating* the behavior of the ICs interconnected by a PCB track with given geometrical parameters. The results should be close enough to the reality so that a decision can be taken whether the signal reflections are in the acceptable limits or the transmission media must be redesigned. As mentioned before, the target is to develop a *simple* tool that can be used to *estimate* the waveforms at the extremities of the t-line. Thus, we have tried to find a way of combining the advantages of each method and implement an algorithm that is fast, simple and gives a good approximation of the signals that will appear on the transmission line.

The methods that can be applied for linear resistances are based on calculating the reflection coefficient. These will remain constant during the calculation. In [9] and [12] is presented the lattice diagram method, which is an easy way to predict the effect of reflections on a signal. The drawback of this approach is that the line terminations are considered linear. Also, the driving signal characteristics do not appear in the calculations; hence, the obtained waveforms have a "stair-step" appearance no matter the dV/dt of the applied signal. Under these assumptions, the analysis of transmission lines appears to be straightforward, but the drivers' and the receivers' impedance values are dynamic and depend on many variables. In digital systems, almost all transmission lines are driven and terminated by nonlinear devices. A comprehensive explanation of the way the input and output characteristic curves of typical integrated circuits from various logic families are determined, is given in [10]. In [13], few buffer types were chosen and the piece-wise linear graphical technique was applied to the V-I characteristics provided by the manufacturer. In this way, simplified models were derived for the driver and receiver circuits. Using these piece-wise linear V-I characteristic, the analysis could be extended to non-linear terminations. In [9] and [11], another method for analyzing signal reflections is presented – the Bergeron diagram method. This graphic method is based on the real line's characteristics ($Z_0$, TD) and the characteristics of

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the driver/receiver. It can be used for non-linear terminations, and the V-I characteristic do not have to be simplified by piece-wise linearization techniques. An implementation of the method and the results that it returns can be found in [8]. Depending on the characteristic impedance of the transmission line, the intersection points of the V-I traces can appear in different segments of the V-I characteristics, different segments can have different slopes, meaning the input/output resistance is changing during the transition from one steady-state to the other. Thus, the reflection coefficients are not constant during the transitions.

Among all these methods, the Bergeron method takes into account most of the parameters mentioned before. The only parameters that are not considered by this method are the parameters of the applied signal. But, the manufacturers of the ICs provide the typical values for voltage levels and transition times in the datasheet, and these values could be used to describe the driving signal. The well-known method has proved to be very efficient for fast driving signals. The results returned by the algorithm are the voltage levels at the input/output of the transmission line at multiples of TD. The questions that arose were:

- Could these levels be used to determine the changing of the reflection coefficients?
- How could these be used to compute the signal levels taking into account the speed of variation of the driving signal?

## II. MatLab IMPLEMENTATION OF THE METHOD

The first step was to implement an algorithm that determines the waveforms at the input and output of a t-line considering the characteristics of the applied signal. Because this was a new element introduced in the analysis, the rest of the setup was simplified as much as possible in order to be able to focus on the influence of the new parameters and to validate the results against known results obtained for exactly the same setup (e.g. the ones provided by PSpice simulator).

The setup that was considered in the beginning is presented in Figure 1. The transmission line is described by its characteristic impedance $Z_0$ and the propagation delay TD. For simplification, the ICs were replaced by resistors, in this way the V-I characteristics are considered linear. As stated before, the Bergeron method is suitable and provides good results for input signals with very fast transition times. So, this should be the starting point for this method too. The falling and rising times of the applied signal were reduced to hundreds of picoseconds. For this setup, the signal levels at the input and output of the t-line (denoted $V_{in}$ and $V_{out}$) at time moments equal with multiples of TD had to be determined.

The starting point was the lattice diagram analysis, which was used for determining the transmission line step response. The voltage source $V_S$ is supposed to be of the

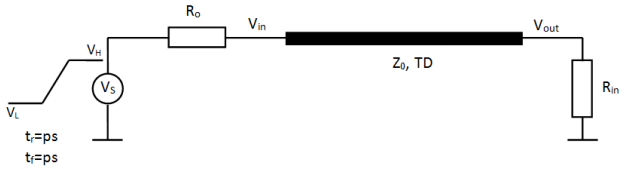



*Figure 1. The starting setup*

form $V_L$ jump to $V_H$, or $V_H$ jump to $V_L$. The results obtained using the lattice diagram are saved in two vectors, Vi and Vo. The solution converges to the steady-state voltage levels. The results obtained by applying the Bergeron diagram method represent also the voltage levels at moments equal with *nTD* and are saved in two vectors, which will be the input data for the new analysis method.

$V_i = [V_{i0} \quad V_{i2TD} \quad \dots \quad V_{i2nTD} \quad V_{isteady}]$
$V_o = [V_{oTD} \quad V_{o3TD} \quad \dots \quad V_{o(2n+1)TD} \quad V_{osteady}]$

The launch voltage and the steady-state ('DC') voltage levels were computed depending on the input/output resistances.

$$V_{init} = V_S \cdot \frac{Z_0}{Z_0+R_o} \qquad V_F = V_S \cdot \frac{R_{in}}{R_{in}+R_o} \quad (1)$$

For the LOW-to-HIGH transition:

$$V_{init} = V_{DCL} + (V_H - V_L) \cdot \frac{Z_0}{Z_0+R_o} \quad (2)$$

For the HIGH-to-LOW transition:

$$V_{init} = V_{DCH} + (V_L - V_H) \cdot \frac{Z_0}{Z_0+R_o} \quad (3)$$

The steady-state voltages are:

$$V_{DCL} = V_L \cdot \frac{R_{in}}{R_{in}+R_o} \quad (4)$$

$$V_{DCH} = V_H \cdot \frac{R_{in}}{R_{in}+R_o} \quad (5)$$

*Example:*
$V_L$ = 0, $V_H$ = 3.6V, $R_O$ = 25Ω, $Z_0$ = 50Ω, TD = 0.4ns, $R_{in}$ = 200Ω
The results obtained for this setup are:
$V_i$ = [2.4, 3.36, 3.168, 3.2064, 3.1987, 3.2, 3.2, 3.2, 3.2]
$V_o$ = [3.84, 3.072, 3.225, 3.1949, 3.201, 3.2, 3.2, 3.2, 3.2]

As expected, the solution converges to the steady-state voltage level.

Having the two voltage vectors, it's possible to determine the reflection coefficients at every *nTD*. To determine the reflection coefficients, the difference between the steady-state levels and the voltage levels determined above (Vi, Vo) was calculated and divided to the voltage change of the driving signal. The reflection coefficients at every multiple of TD were obtained, and saved in two vectors. The coefficients are computed as shown below.

For the LOW-to-HIGH transition the reflection coefficients at the input and output of the line respectively are:

$$coef_i = \frac{V_i - V_{DCL}}{V_H - V_L} \qquad coef_o = \frac{V_o - V_{DCL}}{V_H - V_L} \quad (6)$$

For the HIGH-to-LOW transition:

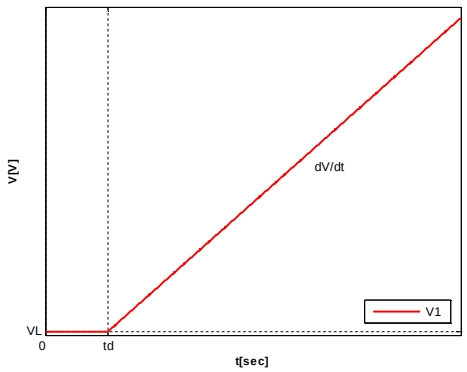
$$coef_i = \frac{V_{DCH} - V_i}{V_L - V_H} \qquad coef_o = \frac{V_{DCH} - V_o}{V_L - V_H} \quad (7)$$

The coefficients for the H-L transition are negative because of the voltage change towards a lower level, indicating a voltage decrease.

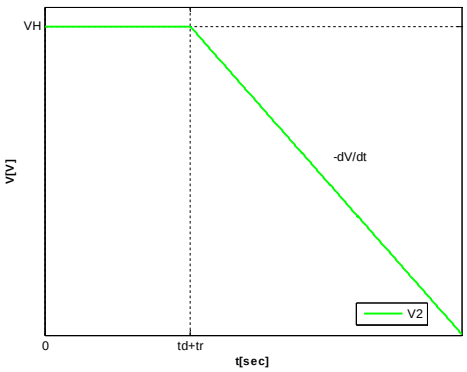
The next step is to use these coefficients in the case a slower signal is launched on the t-line. Due to the fact that the value of the rising/falling time ($t_r$/$t_f$) of the driving signal might not always be a multiple of the time delay TD introduced by the line, we came to the conclusion that the correct approach would be to apply two signals of opposite variation speed (±dV/dt), so that they cancel each other after $t_r$ (or $t_f$). Otherwise, the calculations will return erroneous results at the end of the transition, as the change of speed might happen between the calculation moments which are multiples of TD. Thus, the driving signal was expressed as the summation of two signals with opposite slopes.

For the LOW-to-HIGH transition, a signal of positive slope is applied first, starting from the $V_L$ voltage level of the driving signal $V_S$ (Figure 2a). The second signal to be applied has negative slope, the starting level being the $V_H$ level of $V_S$. The decrease of this signal begins after $t_r$ – rising time (Figure 2b). The applied signal is: $V_S=V_1+V_2-V_H$ (Figure 2c).

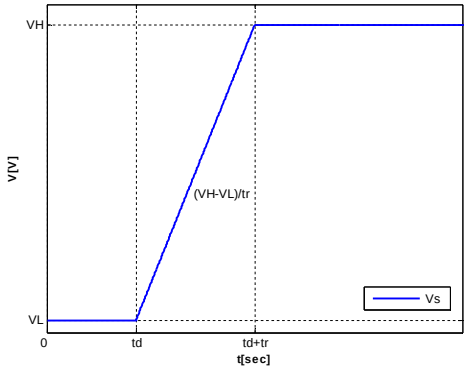
For the HIGH-to-LOW transition, the negative slope signal is $V_1$ – starting from $V_H$ voltage level of the driving signal $V_S$. The signal $V_2$ has positive slope, the starting level being the $V_L$ level of $V_S$. The increase of this signal begins after $t_f$ – falling time. The applied signal is: $V_S = V_1+V_2-V_L$




a)




b)




c)

*Figure 2. The applied signal*

*Example:*

The applied voltage source has the following parameters: $V_L$' = 0.15V, $V_H$' = 3.75V, td = 1.5ns, $t_r$ = 2ns, $t_f$ = 2ns

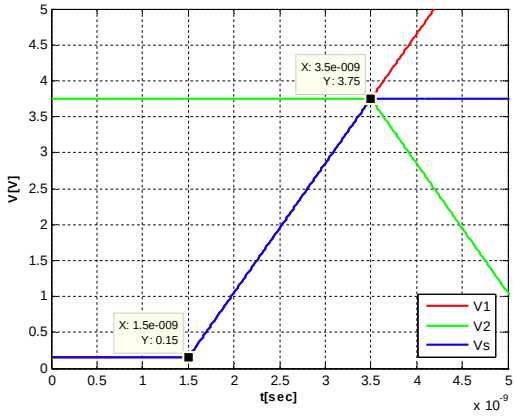



*Figure 3. The applied signal corresponding to the example*

Knowing the low and high levels of the applied signal, $V_L$ and $V_H$, the corresponding steady-state levels were computed.

*Example:*

$V_L$ = 0.15V => $V_{DCL}$ = 0.133V

$V_H$ = 3.75V => $V_{DCH}$ = 3.33V

The reflection coefficients were then used to calculate the change that appears in the speed of the signal transmitted over the line (the new slope of the signal).

The slope of the driving signal is:

$$slope = \frac{V_H - V_L}{t_r}$$ , for the LOW-to-HIGH transition (8)

$$slope = \frac{V_L - V_H}{t_f}$$ , for the HIGH-to-LOW transition (9)

The new speed of variation of the signals at the input and output of the line respectively, is computed according to the reflection coefficients as shown below:

$$new\_slope_i = slope \cdot coef_i$$ (10)

$$new\_slope_o = slope \cdot coef_o$$ (11)

Knowing the delay introduced by the line and the new slope, the voltage level that was reached after every TD was determined.

For the LOW-to-HIGH transition, the signal with positive slope ($V_1$) is applied first. The signal levels at the input/output of the line ($V_{in1}$ and $V_{out1}$) are computed as shown below:

$$V_{in1}(t) = new\_slope_i(t) \cdot 2TD + V_{in1}(t - 2TD)$$
$$\text{with} = 2n \cdot TD\ ,\ V_{in1}(1) = V_{DCL} \quad (12)$$
$$V_{out1}(t) = new\_slope_o(t) \cdot 2TD + V_{out1}(t - 2TD)$$
$$\text{with} = (2n + 1) \cdot TD\ ,\ V_{out1}(1) = V_{DCL} \quad (13)$$

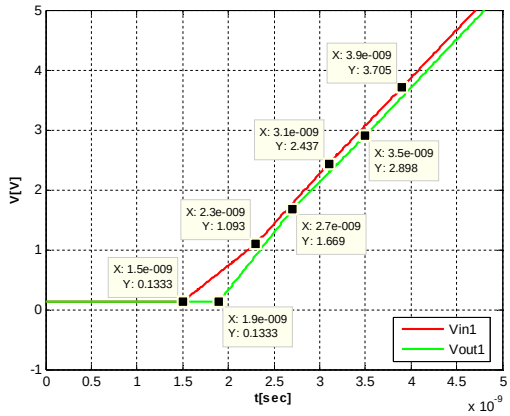



*Figure 4. The results obtained by applying $V_1$*

A similar procedure is then used for the case when the signal having the opposite slope ($V_2$) is applied. The signal levels at the input/output of the line ($V_{in2}$ and $V_{out2}$) are computed as shown below:

$$V_{in2}(t) = V_{in2}(t - 2TD) - new\_slope_i(t) \cdot 2TD$$
$$\text{with} = 2n \cdot TD\ ,\ V_{in2}(1) = V_{DCH} \quad (14)$$
$$V_{out2}(t) = V_{out2}(t - 2TD) - new\_slope_o(t) \cdot 2TD$$
$$\text{with} = (2n + 1) \cdot TD\ ,\ V_{out2}(1) = V_{DCH} \quad (15)$$

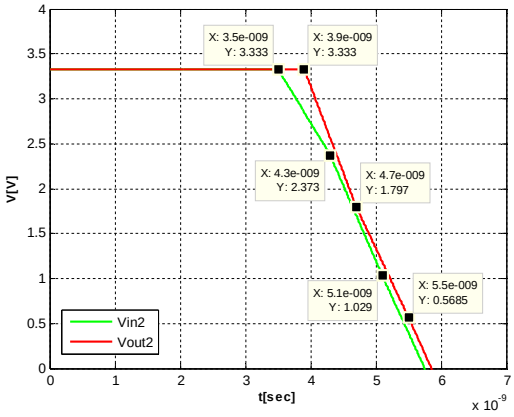



*Figure 5. The results obtained by applying $V_2$*

By adding the results obtained in the two cases, it was possible to determine the signals at the input/output of the line when a driving signal with any value of the rising/falling edge is applied.

For the LOW-to-HIGH transition, the reconstruction of the signals is done by:

$$V_{in}(t) = V_{in1}(t) + V_{in2}(t) - V_{DCH} \quad (16)$$
$$V_{out}(t) = V_{out1}(t) + V_{out2}(t) - V_{DCH} \quad (17)$$

For the HIGH-to-LOW transition, we used the same procedure, with the difference that $V_1$ is the signal with negative slope and $V_2$ the one with positive slope. The reconstruction of the signals is done by:

$$V_{in}(t) = V_{in1}(t) + V_{in2}(t) - V_{DCL} \quad (18)$$
$$V_{out}(t) = V_{out1}(t) + V_{out2}(t) - V_{DCL} \quad (19)$$

The results obtained are shown below in Figures 6-7.

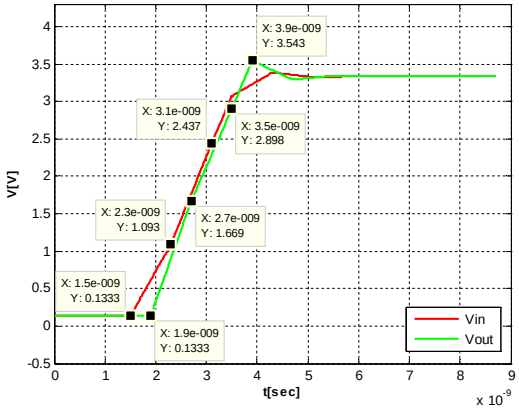



*Figure 6. The results obtained by applying $V_S$ (L-to-H)*

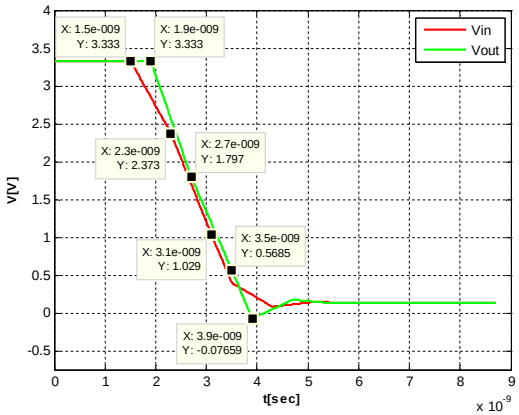



*Figure 7. The results obtained for the H-to-L transition*

In order to prove that the algorithm returns correct results, these were compared with the ones indicated by Orcad/PSpice simulator. A number of 30 cases were analyzed. The parameters that were varied are: $R_{in}$, $R_O$, $Z_0$, TD, $t_r$, $t_f$. The results were identical.

**Non-linear impedances**

The same algorithm can be applied for the case when ICs are connected at the extremities of the t-line. First, the Bergeron method for fast driving signals is used. The input data are the characteristic impedance of the t-line $Z_0$ and the V-I characteristics of the IC family that is analyzed. The voltage levels obtained at *nTD* time moments are saved in two vectors Vi, Vo. The steady-state voltages $V_{DCL}$ and $V_{DCH}$ are the first and last (or vice-versa) values in the vectors - the Bergeron method

starts from the regime point before transition and the solution converges to the new steady-state reached after transition. These levels are specific for each IC family. The reflection coefficients are computed in the same way as described before. The parameters of the driving signal ($V_H$, $V_L$, $t_r$, $t_f$) are chosen according to the typical values indicated by the manufacturer in the datasheet of the ICs.

The following figures present the results obtained in MatLab versus the ones from PSpice. In the first example (Figures 8-9) was supposed that two ICs from the Schottky family are interconnected by a transmission line having $Z_0 = 80\Omega$ and TD = 2.5ns. The rising and falling times of the input signal are 3.75ns, the high and low voltage levels are 3.75V and 0.1680V respectively.

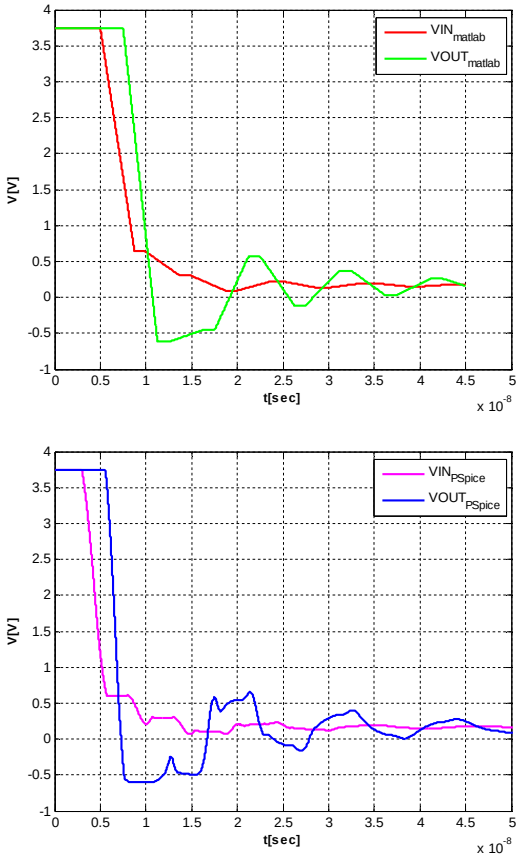
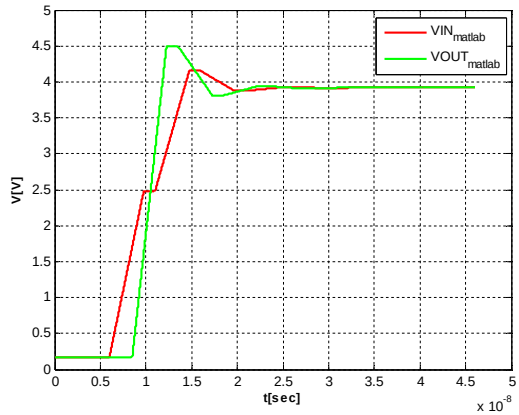



*Figure 8. H-to-L transition (74S04)*



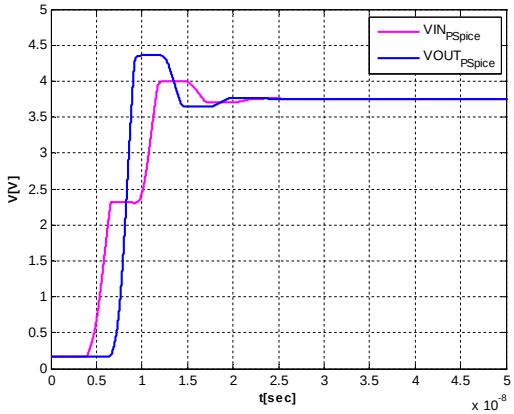




*Figure 9. L-to-H transition (74S04)*

In the second example (Figures 10-11) was supposed that two ICs from the Advanced CMOS family are interconnected by a transmission line having $Z_0 = 85\Omega$ and TD = 2.5ns. The rising and falling times of the input signal are 3.75ns, the high and low voltage levels are 5V and 0V respectively.

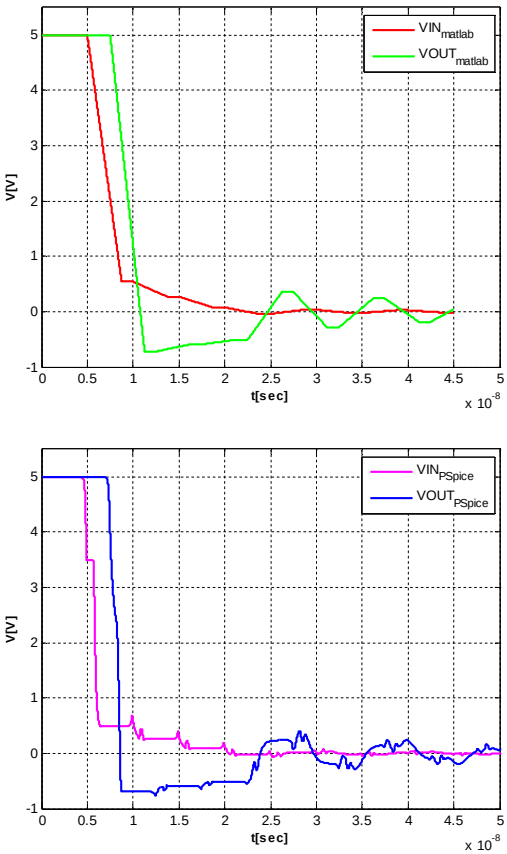



*Figure 10. H-to-L transition (74AC04)*

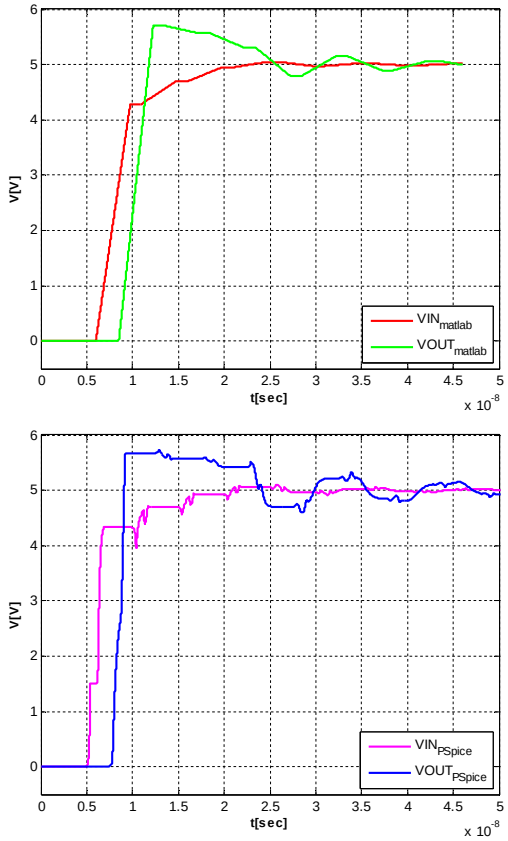



*Figure 11. L-to-H transition (74AC04)*

## III. RESULTS

This method was used to analyze the signal reflections that appear on a transmission line when ICs from different families are interconnected by structures having different geometrical parameters. Four printed circuit boards were designed and fabricated. They were successively equipped with ICs from different families. The driver and the receiver are interconnected through a microstrip. The relative dielectric constant of the 1.5748mm thick dielectric medium is 5.4. The thickness of the Copper layer is 35µm. In the followings, a comparison between measured and simulated voltage waveforms is presented. The measurements were done with a high-performance digital oscilloscope from ROHDE&SCHWARZ. The R&S®RTO1024 digital oscilloscope has 2 GHz bandwidth, 10Gsample/s sampling rate, a high-speed ASIC, deep waveform acquisition memory and a single-core A/D converter.

By comparison with the results obtained by practical experiments, we can then evaluate if the approach above is correct and might provide accurate results if further developed.

### TTL family

For a microstrip having the width w = 0.3mm and the length L = 35cm, the calculated electrical parameters are: $Z_0$ = 113Ω and TD = 2ns. If the driver and receiver are from the TTL family, the waveforms at the input and output of the line are the ones below.

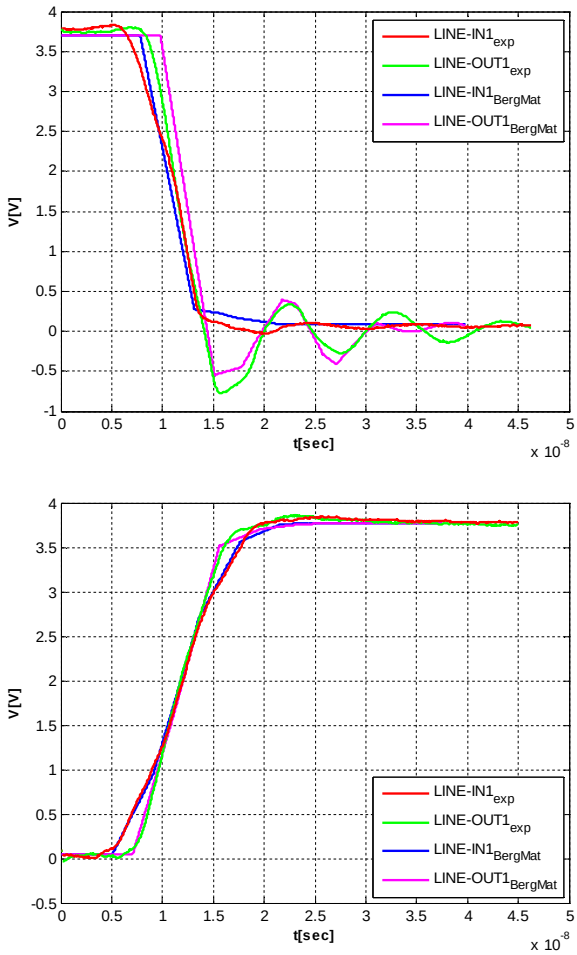
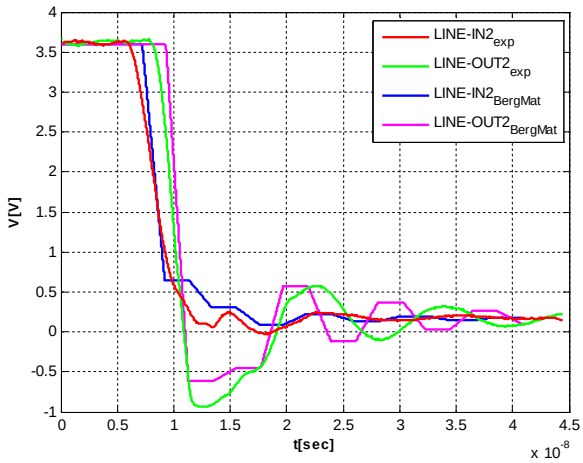



*Figure 12. MatLab simulation vs. Experimental results*

### Schottky TTL family

For w = 0.9mm and L = 35cm → $Z_0$ = 80Ω and TD = 2ns.



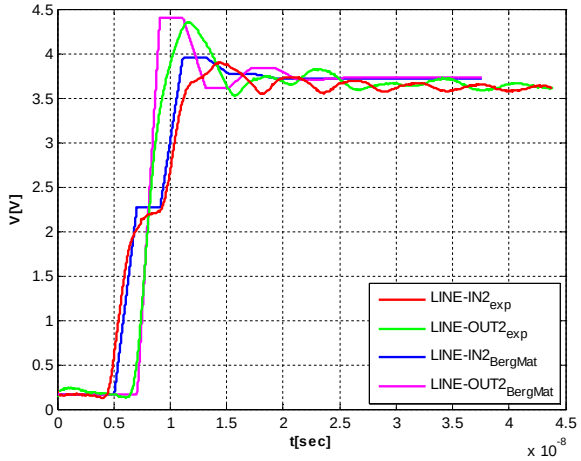



*Figure 13. MatLab simulation vs. Experimental results*

**High-speed CMOS family**

For w = 0.3mm and L=17.5cm → $Z_0$ = 113Ω and TD = 1ns.

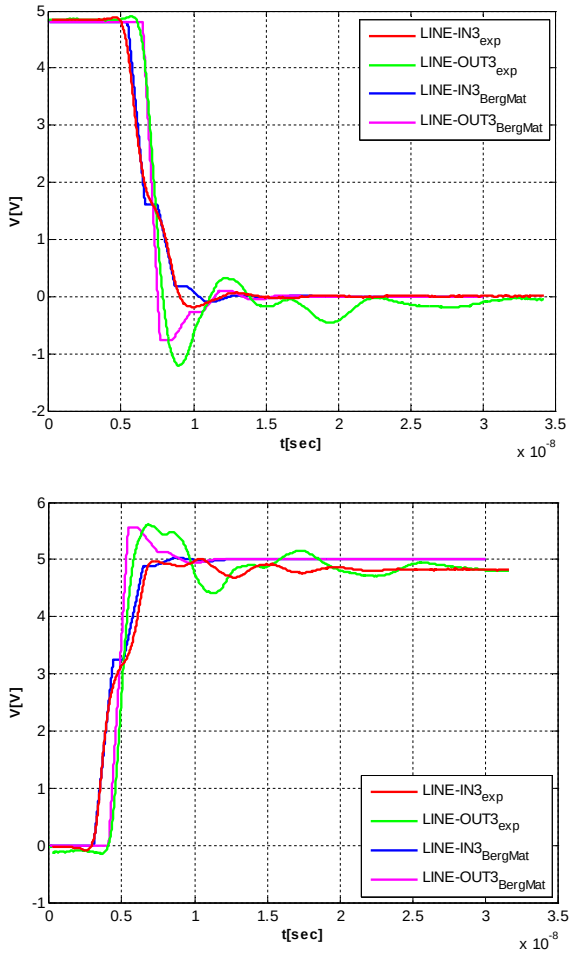



*Figure 14. MatLab simulation vs. Experimental results*

**Advanced CMOS family**

For w = 0.9mm and L=17.5cm → $Z_0$ = 80Ω and TD = 1ns.

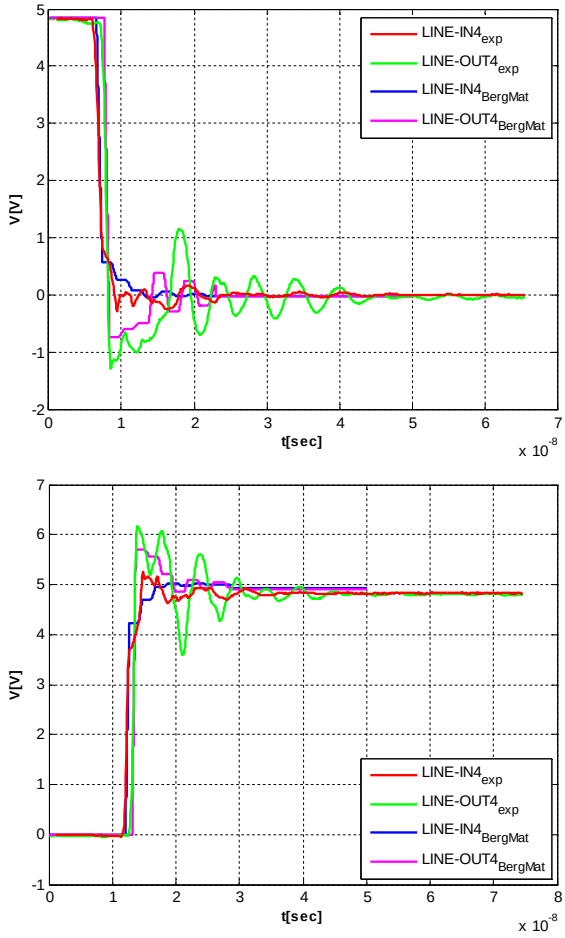
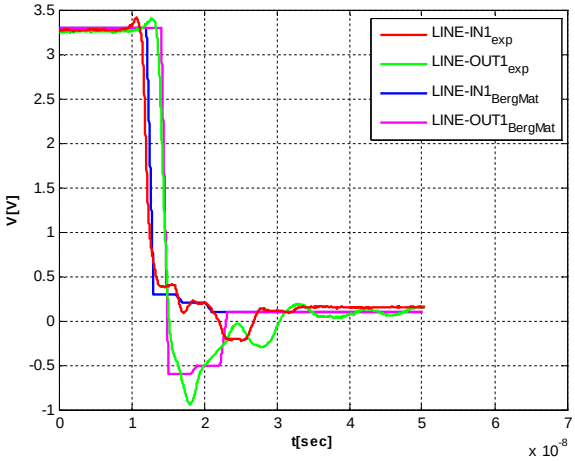



*Figure 15. MatLab simulation vs. Experimental results*

**Fast TTL family**

For w = 0.3mm and L = 35cm → $Z_0$ = 113Ω and TD = 2ns.



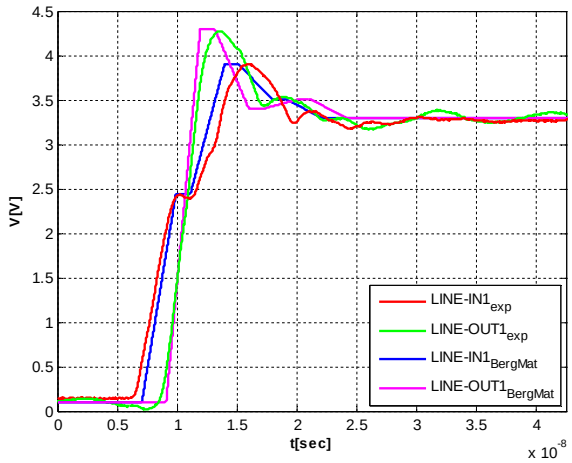



*Figure 16. MatLab simulation vs. Experimental results*

**Advanced high-speed CMOS family**

For w = 0.9mm and L = 35cm → $Z_0$ = 80Ω and TD = 2ns.

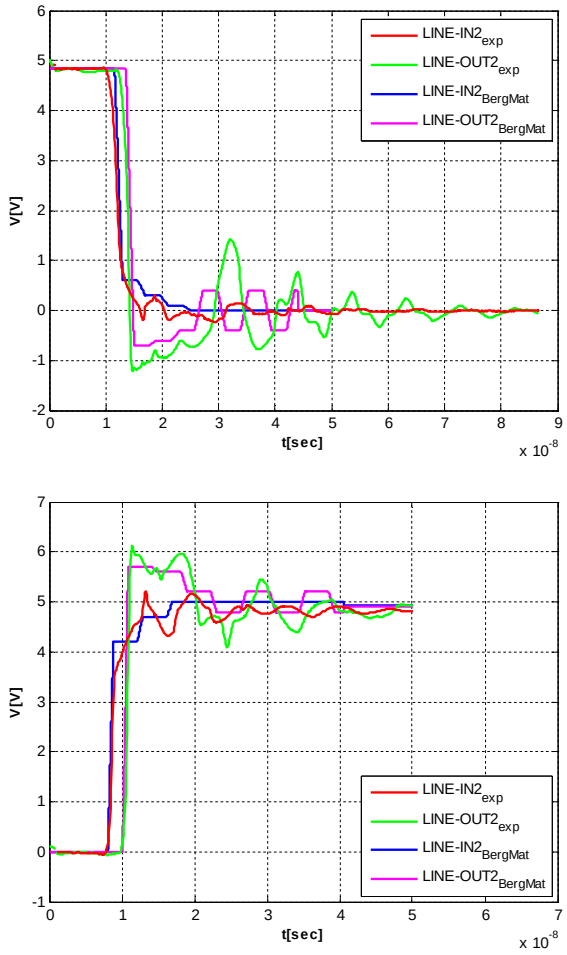



*Figure 17. MatLab simulation vs. Experimental results*

## V. CONCLUSIONS

The approach proposed in this paper returns reasonable results that are in good agreement with the ones obtained by experimental measurements. The differences that were observed between the two sets of waveforms mainly appear due to the fact that the algorithm uses as input data the V-I characteristics obtained by PSpice simulation, not the ones provided by the manufacturer of the ICs (these were not available). The results are expected to have a better accuracy if behavioral models of the devices, such as I/O Buffer Information Specification (IBIS) are used. The behavioral IBIS based models of a device provide the DC current vs. voltage curves along with a set of rise and fall time of the driver output voltage and packaging parasitic information of the I/O buffer.

One of the advantages of the method presented in this paper is that it takes into account the nonlinearity of the input/output resistance of the ICs connected to the transmission line and their switching characteristics ($V_H$, $V_L$, $t_r$, $t_f$). From the geometry of the t-line the electrical parameters are determined - $Z_0$, TD. The algorithm is simple and fast and the results are good enough to estimate if the signal's timing and shape are in the acceptable range for a specific setup.

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