

Multiconductor Transmission Line Modeling with VHDL-AMS for EMC Applications

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Abstract—A multiconductor transmission line (MTL) model for the time domain considering losses, incident fields and skin-effects for the modeling language VHDL-AMS was developed. The model is based on the FDTD method. It can be extended by various VHDL-AMS circuit files and used for linear and non-linear time domain simulations. Modern standardized modeling languages like VHDL-AMS have the important advantage that growing model libraries permit fast creation of large simulation models. Exchange of models and extension of models is easily possible. After a short introduction to VHDL-AMS and presentation of the MTL- and FDTD-theory used for modeling, examples are shown. The developed model is compared to calculation results gained with other simulation methods. The validity of the implemented VHDL-AMS model is proved.

I. INTRODUCTION

Multiconductor transmission lines (MTL) play an important role in many technical areas. An important application is the automobile cable harness, in which bundles with many unshielded cables are used even for applications requiring very high safety. Reliable data transmission also under influence of strong electromagnetic fields is essential. Using simulation models, a statement about the signal integrity and immunity against external electromagnetic fields can already be made in early phases of development.

For applicable simulation results, precise models of multiconductor transmission lines are needed. C. R. Paul gives an extensive description on many MTL modeling issues in [1].

Based on [1], a transmission line model for signal integrity and EMC analysis has been developed. The presented MTL model supports an arbitrary number of conductors and time domain analysis. Furthermore the model includes excitation of the line by an homogeneous electromagnetic field.

Various methods were developed during the last years to cover coupling of electromagnetic fields to transmission lines in the time domain. A good overview can be found in [2]. The model described in this paper is based on the finite difference-time domain (FDTD) method. Other interesting approaches can be found in [3] and [4].

With the FDTD model, skin effect and other losses can be taken into account. Various geometrical structures can be simulated by using the per-unit-length parameter matrices R , C , L and G as input parameters.

VHDL-AMS [5] was selected as the modeling language to make the model usable for practical applications. During the last years, the VHDL-AMS modeling language became more and more famous in the automotive industry. It can be easily edited and extended. Models can be encapsulated as devices interfacing with their environment only via well defined terminations. This makes it very easy to use the MTL-VHDL-AMS-model in combination with other termination models like bus transceivers. Complex structures of realistic automotive cable harness/electronic control unit configurations can be built and investigated.

II. VHDL-AMS

VHDL was developed in the 1980s to describe and simulate digital systems. The modeling language VHDL-AMS (Very High Speed Integrated Circuit Hardware Description Language – Analog and Mixed Signal) is an extension of VHDL for analog systems. It was standardized by an IEEE working group (1076.1-1999) [5]. VHDL-AMS is well suited for describing digital, analog, and mixed analog/digital systems, which are based on differential algebraic equations.

Important advantages of the hardware description language are a high abstraction potential and great flexibility, which result from the equation-based structure of the language. Complex calculations can easily be integrated into a model and formulated transparently in VHDL-AMS.

Furthermore the available and continuously growing libraries are an important advantage. A considerably large library is available from the German Association for Research in Automobile Technology in the Association of the Automotive Industry [6]. In the near future it can be expected that libraries for typical electronic devices will be available, enabling some basic EMC simulation.

A VHDL-AMS model is divided into two sections: the entity that defines the interface of the model to its surrounding structures and the architecture where the behaviour of the model is described. Different architectures can use the same entity. Furthermore, packages allow bundling frequently used functions and procedures.

Besides the possibility to implement complex equations directly, modules in higher levels of abstraction can be connected via nodes similar to a network. In addition VHDL-AMS supports various sequential statements including loops and branches.

III. MULTICONDUCTOR TRANSMISSION LINE MODELLING

The presented approach is based on the telegraph equations in matrix form for multiconductor transmission lines.

$$\frac{\partial V(z,t)}{\partial z} + RI(z,t) + L \frac{\partial}{\partial t} I(z,t) = 0 \quad (1)$$

$$\frac{\partial I(z,t)}{\partial z} + GV(z,t) + C \frac{\partial}{\partial t} V(z,t) = 0 \quad (2)$$

$V(z,t)$ and $I(z,t)$ are vectors of the voltages and currents of every single line.

The matrices R , C , L and G are composed of the different per-unit-length parameters of each line. They describe the characteristics of every single conductor as well as the interaction between them so that the model considers crosstalk. Because of the matrix structure of the per-unit-length parameters, the model supports both common and differential mode. The advantage of this general approach is that nearly no aspects are disregarded.

A. Considering Incident Fields

The influence of an incident field on the line is described by extending the right hand side of the MTL-Equations

$$\frac{\partial}{\partial z} V(z,t) + RI(z,t) + L \frac{\partial}{\partial t} I(z,t) = \frac{\partial}{\partial t} \begin{bmatrix} \int_a^{a'} \vec{B}^i \cdot \vec{a}_n \cdot d\vec{l} \\ \vdots \\ -\frac{\partial}{\partial z} \int_a^{a'} \vec{E}_i^i \cdot d\vec{l} + (E_i^i(i\text{-th conductor}, z, t) - E_i^i(\text{ref conductor}, z, t)) \\ \vdots \end{bmatrix} \quad (3)$$

$$\frac{\partial}{\partial z} I(z,t) + GV(z,t) + C \frac{\partial}{\partial t} V(z,t) = -G \begin{bmatrix} \int_a^{a'} \vec{E}_i^i \cdot d\vec{l} \\ \vdots \\ -\frac{\partial}{\partial t} \int_a^{a'} \vec{E}_i^i \cdot d\vec{l} \\ \vdots \end{bmatrix} \quad (4)$$

where $\vec{B}^i \cdot \vec{a}_n$ is the incident magnetic induction normal to the direction of the conductor and can be expressed in terms of the electrical field. \vec{E}_i^i is the transversal incident electrical field and $E_i^i(m\text{-th conductor}, z, t)$ is the longitudinal incident electric field along the position of the m -th conductor when it is removed [1].

To consider the line in different environments, different calculations for the incident field are needed. For example, the line above a metallic plane is not only exposed to the incident electrical field but also to its reflection from the plane.

For a better structured modeling, the right sides of the MTL-equations are divided into functions named $E_T(z,t)$ and $E_L(z,t)$ for the transversal and longitudinal components of the electrical field and $V'_F(z,t)$ and $I'_F(z,t)$ for equivalent voltage and current sources.

$$\frac{\partial V(z,t)}{\partial z} + RI(z,t) + L \frac{\partial}{\partial t} I(z,t) = -\frac{\partial}{\partial z} E_T(z,t) + E_L(z,t) + V'_F(z,t) \quad (5)$$

$$\frac{\partial I(z,t)}{\partial z} + GV(z,t) + C \frac{\partial}{\partial t} V(z,t) = -\frac{\partial}{\partial t} CE_T(z,t) + I'_F(z,t) \quad (6)$$

B. FDTD-Formulation for MTL

For the FDTD method, the currents and voltages are spatially discretized for incremental transmission line sections as shown in Figure 1 ($N_{DZ} = k\Delta z$). Furthermore, they are interleaved in time with voltage nodes placed at times $t = n\Delta t$, and current nodes are placed at times $t = (n + 0.5)\Delta t$. Using the usual first-order central difference approximations for the time derivative, the MTL equations become

$$\frac{1}{\Delta z} (V_{k+1}^{n+1} - V_k^{n+1}) + \frac{1}{\Delta t} L \left(I_k^{n+\frac{3}{2}} - I_k^{n+\frac{1}{2}} \right) + \frac{1}{2} R \left(I_k^{n+\frac{3}{2}} + I_k^{n+\frac{1}{2}} \right) \quad (7)$$

$$= \left(-\frac{\partial}{\partial z} E_T(z,t) + E_L(z,t) \right) + \frac{1}{2} \left(V_{Fk}^{n+\frac{3}{2}} + V_{Fk}^{n+\frac{1}{2}} \right)$$

$$-\frac{\partial}{\partial z} E_T(z,t) + E_L(z,t) = \left[\frac{1}{v_z} \underbrace{(e_x x_k + e_y y_k)}_{A_T} - \underbrace{\left(\frac{x_k}{v_x} + \frac{y_k}{v_y} \right)}_{A_L} \right] e_z \frac{\partial}{\partial z} E_0 \left(t - \frac{z}{v_z} \right)$$

$$\frac{1}{\Delta z} \left(I_k^{n+\frac{1}{2}} - I_{k-1}^{n+\frac{1}{2}} \right) + \frac{1}{\Delta t} C (V_k^{n+1} - V_k^n) + \frac{1}{2} G (V_k^{n+1} + V_k^n) \quad (8)$$

$$= -\frac{\partial}{\partial t} CE_T(z,t) + \frac{1}{2} (I_{Fk}^{n+1} + I_{Fk}^n)$$

$$-\frac{\partial}{\partial t} CE_T(z,t) = -C \underbrace{(e_x x_k + e_y y_k)}_{A_T} \frac{\partial}{\partial t} E_0 \left(t - \frac{z}{v_z} \right)$$

Rearranging these equations and setting $R=0$ and $G=0$, the voltages and the currents for lossless lines can be written in iterative form:

$$V_k^{n+1} = V_k^n - \frac{\Delta t}{\Delta z} C^{-1} \left(I_k^{n+\frac{1}{2}} - I_{k-1}^{n+\frac{1}{2}} \right) \quad (9)$$

$$- A_T \left(E_0 \left(t^{n+1} - \frac{(k-1)\Delta z}{v_z} \right) - E_0 \left(t^n - \frac{(k-1)\Delta z}{v_z} \right) \right)$$

$$I_k^{n+\frac{3}{2}} = I_k^{n+\frac{1}{2}} - \frac{\Delta t}{\Delta z} L^{-1} (V_{k+1}^{n+1} - V_k^{n+1}) \quad (10)$$

$$+ L^{-1} \left(\frac{1}{v_z} A_T - A_L \right) \left(E_0 \left(t^{n+\frac{3}{2}} - \frac{(k-\frac{1}{2})\Delta z}{v_z} \right) - E_0 \left(t^{n+\frac{1}{2}} - \frac{(k-\frac{1}{2})\Delta z}{v_z} \right) \right)$$

With the terminal conditions the voltages can be divided into three parts:

$$k=1$$

$$V_1^{n+1} = V_{S00}^n - 2 \frac{\Delta t}{\Delta z} C^{-1} \left(I_1^{n+\frac{1}{2}} - 0 \right) + \frac{\Delta t}{\Delta z} \cdot C^{-1} (I_{SS}^{n+1} + I_{SS}^n) - A_T (E_0(t^{n+1}) - E_0(t^n)) \quad (11)$$

$$k = 2 \dots N_{DZ}$$

$$V_k^{n+1} = V_k^n - \frac{\Delta t}{\Delta z} C^{-1} \left(I_k^{n+\frac{1}{2}} - I_{k-1}^{n+\frac{1}{2}} \right) - A_T \left(E_0 \left(t^{n+1} - \frac{(k-1)\Delta z}{v_z} \right) - E_0 \left(t^n - \frac{(k-1)\Delta z}{v_z} \right) \right)$$

$$k = N_{DZ} + 1$$

$$V_{NDZ+1}^{n+1} = V_{NDZ+1}^n - 2 \frac{\Delta t}{\Delta z} C^{-1} \left(0 - I_0^{n+\frac{1}{2}} \right) + \frac{\Delta t}{\Delta z} \cdot C^{-1} (I_{LL}^{n+1} + I_{LL}^n) - A_T (E_0(t^{n+1}) - E_0(t^n))$$

The above equations can be solved in a “bootstrapping” fashion. At each time step n , the voltages along the transmission lines are computed in terms of the previous voltage and current values. Afterwards, the currents along the transmission line are evaluated for the next section. The final step is the incorporation of terminal conditions, which present the relations between voltages and currents in the first and in the last section of the lines.

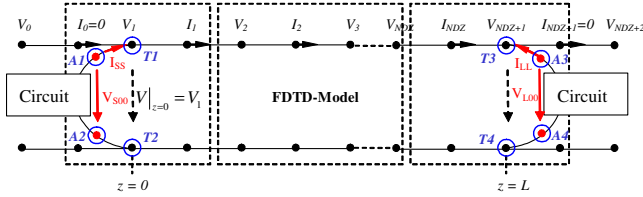


Figure 1: FDTD-Model

C. Skin Effect

Conductor losses at higher frequencies are functions of the square root of the frequency \sqrt{f} due to the skin effect. The total loss can be written as

$$r = \begin{cases} r_{dc} & f \leq f_0 \\ r_{dc} \sqrt{\frac{f}{f_0}} & f \geq f_0 \end{cases} \quad (12)$$

r_{dc} is the dc resistance and f_0 is the frequency where the resistance transitions from its dc value to its \sqrt{f} dependency. The loss is transformed into the time domain with the help of the Laplace transform. The result is a convolution integral in the time domain.

$$R(t)I(t) = r_{dc}I(z,t) + \frac{1}{\sqrt{\pi}} \frac{r_{dc}}{\sqrt{\pi \cdot f_0}} \left(\int_0^t \frac{1}{\sqrt{t-\tau}} \frac{\partial}{\partial \tau} I(z,t-\tau) d\tau \right) \quad (13)$$

The convolution integral can be approximated in the following manner, where $F(t)$ is the time derivative of the line current and may be approximated as being constant over the Δt segments:

$$\int_0^t \frac{1}{\sqrt{t-\tau}} F(t-\tau) d\tau \cong \int_0^{(n+1)\Delta t} \frac{1}{\sqrt{t-\tau}} F((n+1)\Delta t - \tau) d\tau \cong \sqrt{\Delta t} \sum_{m=0}^n F^{n+1-m} Z_0(m) \quad (14)$$

With Prony's method [7,8] $Z_0(m)$ can be simplified:

$$Z_0(m) = \int_m^{(m+1)} \frac{1}{\sqrt{\zeta}} d\zeta \cong \sum_{i=1}^N a_i e^{m\alpha_i} \quad (15)$$

Because the resistance appears only in conjunction with the current, the current for the lossy transmission lines will be changed as follows:

$$I_k^{n+\frac{3}{2}} = F^{-1} \left(L \frac{\Delta z}{\Delta t} - r_{dc} \frac{\Delta z}{2} + \frac{r_{dc}}{\sqrt{\pi \cdot f_0}} \frac{\Delta z}{\sqrt{\pi \Delta t}} Z_0(0) \right) I_k^{n+\frac{1}{2}} - F^{-1} \frac{r_{dc}}{\sqrt{\pi \cdot f_0}} \frac{\Delta z}{\sqrt{\pi \Delta t}} \sum_{i=1}^{10} \Psi_i^n - F^{-1} (V_{k+1}^{n+1} - V_k^{n+1}) \quad (16)$$

$$+ F^{-1} \left(\frac{1}{v_z} A_T - A_L \right) \frac{1}{\Delta t} \left(E_0 \left(t^{n+\frac{3}{2}} - \frac{(k-\frac{1}{2})\Delta z}{v_z} \right) - E_0 \left(t^{n+\frac{1}{2}} - \frac{(k-\frac{1}{2})\Delta z}{v_z} \right) \right) + F^{-1} \frac{V_{fk}^{n+\frac{3}{2}} + V_{fk}^{n+\frac{1}{2}}}{2}$$

$$F = L \frac{\Delta z}{\Delta t} + r_{dc} \frac{\Delta z}{2} + \frac{r_{dc}}{\sqrt{\pi \cdot f_0}} \frac{\Delta z}{\sqrt{\pi \Delta t}} Z_0(0)$$

$$\Psi_i^n = a_i e^{\alpha_i} \left(I_k^{n+\frac{1}{2}} - I_k^{n-\frac{1}{2}} \right) + e^{\alpha_i} \Psi_i^{n-1}$$

IV. DISCUSSION OF MODELING

The FDTD-Model is implemented for the lossless and lossy parallel multiconductor transmission lines and incorporates the effects of incident electromagnetic field. The code hierarchy is shown in Figure 2.

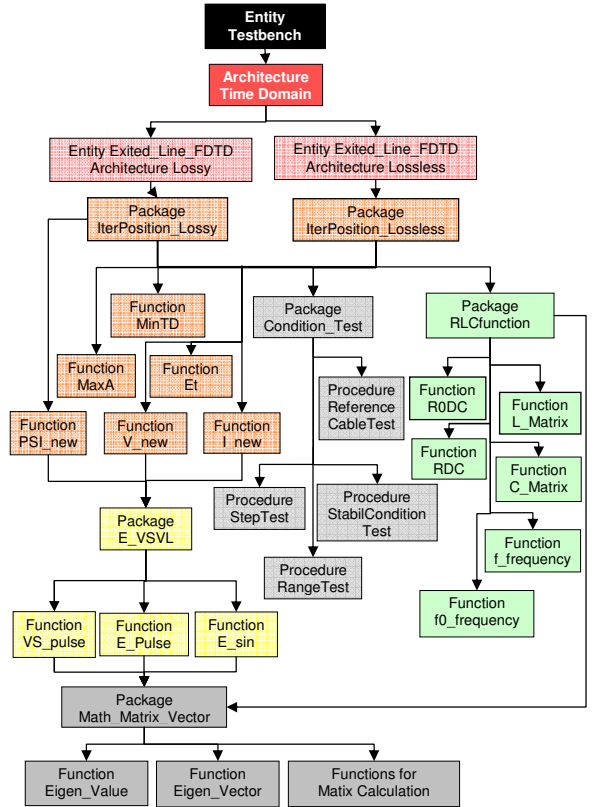


Figure 2: VHDL-AMS code hierarchy of FDTD-Model

A. Interaction

At first several tests are executed before the calculation starts. For example it is tested if the condition for the current set of recursive relations is stable, which means the time step must not be greater than the propagation time of each segment.

Then the voltages and currents are solved by iterating k for a fixed time and then iterating time. The initial values of the voltages and currents are zero. All the calculated voltages and currents are *signals* in VHDL-AMS, which are used as discrete values. Afterwards, the voltages (or currents) of the last segments of the lines are assigned to the circuit as *quantities*, which represent continuous values. The corresponding currents (or voltages) of the circuit are used to update the voltages of the transmission lines at the next time step.

B. Ringing

If the time and length discretizations conform to

$$\Delta t = \frac{\Delta z}{v}$$

the solution will be exact with no approximation error even if the line is only divided in very few sections. If the time step is reduced, “ringing” is observed on the leading edge of each transition. In order to eliminate the “ringing”, Δz must be reduced further. The faster the pulse sources of the transmission lines, the smaller Δz needs to be divided and the simulation time increases considerably.

C. VHDL-AMS Simulator-Specific Issues

The FDTD model was tested intensively with SMASH from Dolphin [9] and System Vision from Mentor Graphics [10]. When the circuit contains only resistors, reasonable results could always be gathered. If the circuit contains capacitors or inductors, a problem of convergence occurs, which stems from the continuous derivatives of discontinuous quantities of voltage or current. There are two ways to solve the problem.

- Using the attribute *last_value* in VHDL-AMS approximates the discrete derivatives. The differences between consecutive values of the signals are calculated and then divided by the time step used in the simulation:

$$A' \text{ dot} = \frac{(A - A' \text{ LAST_VALUE})}{\Delta t}$$

Decreasing Δt leads to a more exact solution.

- A discontinuity is indicated by using a *break* statement in VHDL-AMS. Each time a *break* statement executes, it signals to the analog solver that a discontinuity has occurred at the current simulation time. The analog solver in a VHDL-AMS simulator can solve model equations for quantities that are piecewise continuous.

For the first method the problem of convergence is only solved under the condition that the capacitance or inductance is lower than 1 pF or 300 nH respectively. This limitation doesn't exist when using the second method, but then the results differ

from those calculated with PSpice. It has to be taken into account that not all compilers support the *break* statement, e.g. System Vision 5.0.

Due to the derivative problem it is difficult to get a satisfying result for a circuit including capacitors and inductors. Future work will investigate the FDTD-model more deeply in different VHDL-AMS simulators, find the origin of the deviation and try to get a more exact solution.

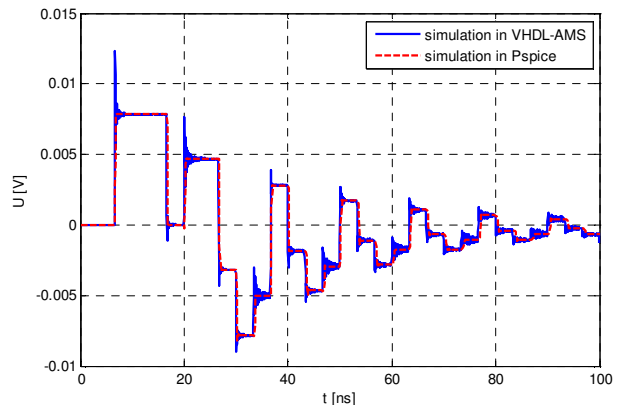


Figure 3: Simulation results for a square pulse on a two-conductor-configuration with two inductances of 1 nH in SMASH and in PSpice

V. RESULTS – VERIFICATION OF METHOD

The developed simulation model was tested intensively to confirm applicability. Several configurations were created for different simulation methods for comparison. The following methods were applied for verification:

- Method of Moments (MoM) Frequency Domain code in EMC Studio, Time Domain results were created with EMC Studio internal FFT features
- MTL lumped element code combined with Method of Moments in EMC Studio, Time Domain results were created with EMC Studio internal FFT features
- Lossy MTL model based on matrix diagonalization implemented in VHDL-AMS
- MTL model in PSpice

The Method of Moments can be seen as a very accurate method as long as the distance between wires is larger than the wire diameter. By carefully selecting time and frequency steps it is possible to get accurate time domain results from MoM.

A. Cross Talk

In automotive applications cross talk can be a serious threat to data bus systems. A data bus configuration shown in Figure 4 was investigated. An UTP CAN-Bus wire with a conductor radius of 0,33 mm in a distance of 5 cm from a ground plane with the following MTL parameters was used:

$$\mathbf{C} = \begin{bmatrix} 4,9p & -49p \\ -49p & 4,9p \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} 1,13\mu & 0,91\mu \\ 0,91\mu & 1,13\mu \end{bmatrix}$$

A pulse generator fed a transient pulse into one wire, the pulse coupled to the second wire. The bus terminations were modeled by simple linear susceptibility models. The transmission line was split into 450 elements for FDTD modeling. 10000 time steps were simulated. Results are shown in Figure 5. VHDL-AMS simulations were compared to MTL simulations based on the matrix diagonalization method and PSpice simulations.

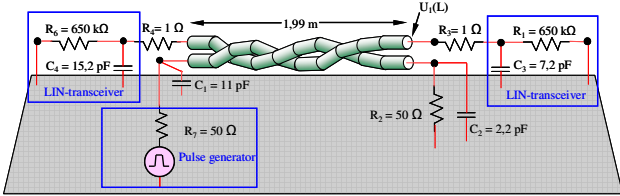


Figure 4: Cross talk configuration

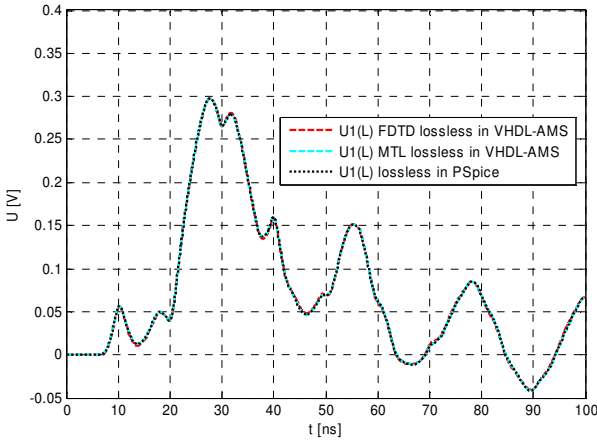


Figure 5: Results for cross talk configuration

B. Field Excited MTL

In Figure 6 the investigated field excited MTL is shown. Two wires are placed over a PEC (perfect electrical conductor) ground plane. The length of the MTL is 2 m. The transmission line is excited by a field pulse propagating along the line. The E-field is oriented perpendicular to the ground plane. The H-field penetrates the loop area between the MTL and ground plane. The copper wires have a radius of 0,28 mm and are terminated with 50 Ohm resistance. If not otherwise stated the resistance is only determined by the resistive copper losses. Figure 7 shows the shape of the E-field of the exciting pulse. The MTL was split into 133 segments (N_{DZ}). The simulation time of 100 ns was separated into 2000 (N_{DT}) time steps.

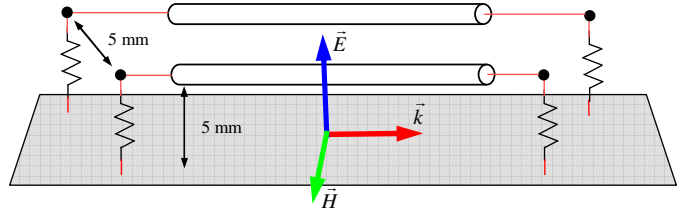


Figure 6: Field excited MTL

Figure 8 shows the voltage across the 50 Ohm resistor at the beginning of the wire 1. The VHDL-AMS FDTD result is compared to a Method of Moment result transformed into the time domain. It can be seen that both results are in good agreement.

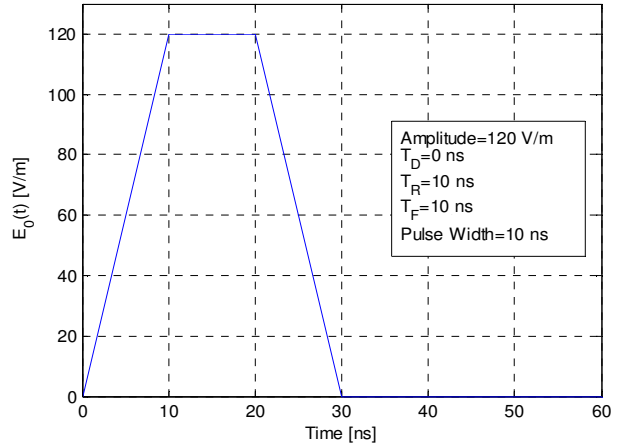


Figure 7: Shape of E-field pulse coupled into the MTL

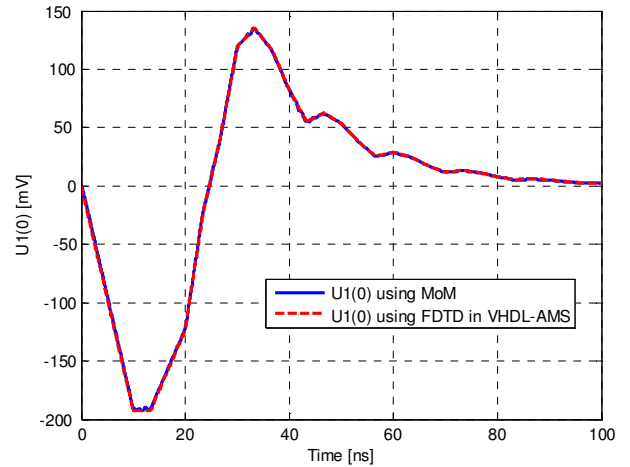


Figure 8: Termination voltage due to an incident field pulse calculated with FDTD and MoM

C. Skin Effect

To validate the skin effect model a configuration from [1] was investigated. Two PCB traces over a substrate and a ground layer were modeled and excited by a pulse shaped voltage source. Figure 9 shows details.

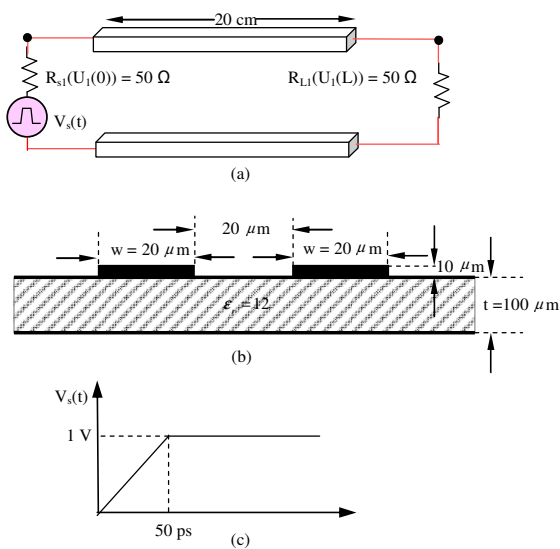


Figure 9: Model for investigating the skin-effect [1]

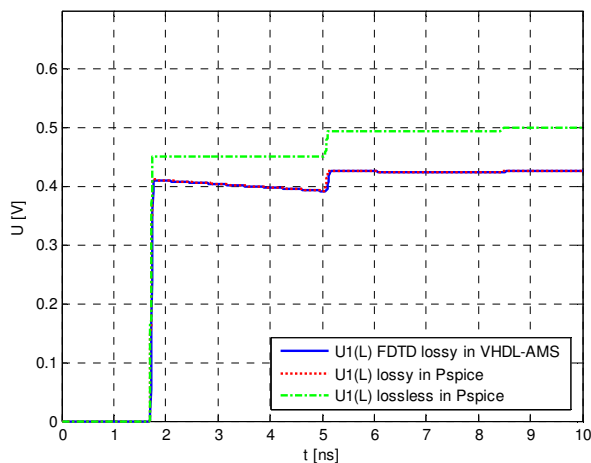


Figure 10: Far-end voltages of PCB configuration

Figure 10 shows results created with the VHDL-AMS FDTD skin effect model. The result is compared to a lossy and lossless PSpice model, considering no skin-effect. It can be seen that the amplitude is affected by losses and the VHDL-AMS and PSpice results are in good agreement.

VI. CONCLUSION

A Multiconductor Transmission Line model for transient VHDL-AMS was developed. VHDL-AMS is a modern simulation language widespread in the automotive industry. The model can handle crosstalk, incident fields and skin effect. The transmission line model can be extended using a large set of available linear and nonlinear models. Validation was done with several different simulation methods. It could be shown that the model can be used for practical applications. Nevertheless all available VHDL-AMS simulators do not support the VHDL-AMS specification completely. This can result in work-arounds limiting the accuracy. Future work will verify the model with more configurations of practical importance and more extensively investigate the available VHDL-AMS simulation programs.

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