Transient Model Using Cascaded Ideal Transmission Lines for UWB Antennas for Co-simulation with Circuits

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***Abstract* — An effective and accurate model is presented for co-simulation of circuits and UWB antennas in the time-domain, which can be used in SPICE simulators. An arbitrary UWB antenna is represented by cascaded ideal transmission lines characterized by S-parameter data. Using this model, we can efficiently simulate the entire system of circuits and UWB antennas, together, for transient analysis. Numerical analysis and computer simulations show this model is highly accurate, compact, stable and derivable**

***Index Terms* — Co-simulation, SPICE, transient analysis, UWB antennas, ideal transmission lines, S-parameter..**

I. Introduction

Co-Simulation of antennas and circuits is becoming more and more important for integrated circuit design. In general there are two approaches for the co-simulation of antennas and circuits. The first is to represent the antenna by equivalent-circuits [1], but this kind of model cannot take into account phenomena such as crosstalk, radiative, or packaging effects. The alternative approach is using full-wave solution of Maxwell's equations to simulate the entire structure of circuits and antennas. For example, finite-difference time-domain (FDTD) method has been established to embed nonlinear circuits into Yee-cells [2]. Although full-wave solution is comparatively accurate, this method is quite time-consuming since EM simulations are involved.

In this paper a transient model represented by cascaded ideal transmission lines has been reported for the co-simulation of antennas and circuits in the time-domain. Firstly the antenna is treated as a one-port linear, time-invariant network and represented by modified impulse responses derived from the frequency-domain S-parameters of the antenna [3]. Then cascaded ideal transmission lines are used to represent the antenna according to the modified impulse response. This model can be directly used for transient analysis of antennas and circuits in the time-domain for the circuit analysis program (SPICE). It will be shown in this paper that UWB antennas can be represented by this model with high accuracy in transient analysis. This model is easily derived and simulation time is highly efficient. Several examples are given to validate the accuracy and speed of this model at the end of this paper.

II. REPRESENTATION OF S-PARAMETERS OF ANTENNAS IN TIME-DOMAIN

In general, S-parameters of antennas can be obtained through EM simulation or direct measurement. These S-parameters are often non-periodic signals due to the limited frequency bands of interest. Therefore a "window" function is used to discard the information outside the band of interest. However, this always leads to discontinuities and serious inaccuracies in time-domain when converting S-parameters from frequency-domain to time-domain.

In order to overcome this problem, a non-uniform discrete-time technique can be used to obtain representations of antennas' S-parameters in the time-domain [3]. According to this technique, S-parameters of an arbitrary antenna can be expressed as a Hermitean function by equation (1), where $S_{11}^r(f)$ and $S_{11}^i(f)$ are the real part and imagine part of $S_{11}(f)$, respectively, and f_m is the maximal frequency.

$$S_{11}(f)=\begin{cases} S_{11}^r(f)+j\cdot S_{11}^i(f) & (0\le f\le f_m) \\ S_{11}^r(f)-j\cdot S_{11}^i(f) & (-f_m\le f<0) \end{cases} \tag{1}$$

Obviously phase discontinuities of S-parameters will cause further discontinuities during the Fourier transform process. To avoid this kind of discontinuity equation (2) has been created:

$$F_{11}(f)=[S_{11}(f)-K]\cdot e^{-j2\pi f\tau} \tag{2}$$

where K and τ are unknowns to ensure $F_{11}(f)$ is continuous. Therefore the following two conditions must be satisfied simultaneously [3]:

(1) Im[$F_{11}(f_m)$]=0. For a Hermitean function this is sufficient to avoid a discontinuity in $F_{11}(f)$ at $f=f_m$. $F_{11}(f)$ is thus continuous and periodic in complex-values sense and may be represented efficiently by a discrete time sequence of impulse responses separated by $\Delta tir = 1/(2f_m)$.

(2) The impulse response calculated as a result of condition (1) at time=0 is forced to be exactly zero.

Taking these conditions into account, two equations can be derived to determine values of K and $\tau \in [0,1/(2f_m)]$ such that:

$$\sum_{n=1}^{N-1} 2 \cdot \begin{Bmatrix} (S_{11}^r(n\Delta f) - K) \cdot \cos(2\pi n\Delta f) \\ + S_{11}^i(n\Delta f) \cdot \sin(2\pi n\Delta f) \end{Bmatrix} + S_{11}^r(0) - K$$
$$+ (S_{11}^r(f_m) - K) \cdot \cos(2\pi f_m \tau) \quad (3)$$
$$+ S_{11}^i(f_m) \cdot \sin(2\pi f_m \tau) = 0$$

and

$$K = S_{11}^r(f_m) - S_{11}^i(f_m) / \tan(2\pi f_m \tau) \quad (4)$$

where Δf is the interval of samples in frequency-domain, and S-parameters are specified at N equally-spaced samples within the range $[0, f_m]$.

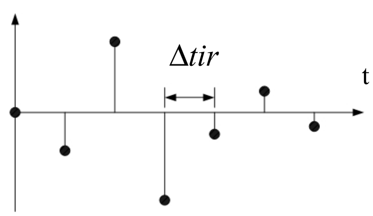

Fig. 1 Time-domain representation of $F_{11}(f)$

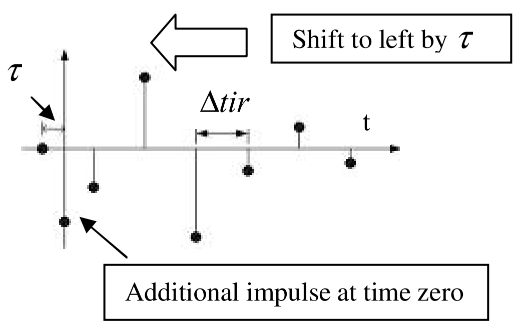

Fig. 2 Time-domain representation of Scattering Parameter $S_{11}(f)$ derived from response in Fig. 1

The resulting time-domain representation of $F_{11}(f)$ and $S_{11}(f)$ may resemble that shown in Fig. 1 and Fig. 2, respectively. Here, Fig. 2 is derived through shifting Fig. 1 to left by τ and adding an additional impulse K derived from (4)

III. TRANSIENT MODEL USING CASCADED IDEAL TRANSMISSION LINES FOR UWB ANTENNAS FOR CO-SIMULATION WITH CIRCUITS

To obtain a transient model for SPICE, consider the S-parameter equation in the frequency-domain:

$$S_{11}(f) = \frac{V(f)/I(f) - Z_0}{V(f)/I(f) + Z_0} \quad (5)$$

where Z_0 is the reference impedance , typical value is 50Ω. $V(f)$ and $I(f)$ are the voltage and current at the input point of the antenna. Therefore, the convolution equation in the time-domain can be derived from (5) as follows:

$$h_{11}(k\Delta t) \otimes [v(k\Delta t) + Z_0 \cdot i(k\Delta t)] = v(k\Delta t) - Z_0 \cdot i(k\Delta t) \quad (6)$$

where $h_{11}(k\Delta t)$ is the representation of $S_{11}(f)$ in time domain, and Δt is the time interval for convolution and is often shorter than Δtir. Suppose the first interval ($\Delta tir - \tau$) of representation of $S_{11}(f)$ is $p\Delta t$ and the subsequent uniform interval (Δtir) is $q\Delta t$, where $q > p$. Equation (6) can be written as an explicit equation such that:

$$i(k\Delta t) = \frac{1 - h_{11}(0)}{Z_0(1 + h_{11}(0))} v(k\Delta t)$$
$$- \frac{1}{Z_0(1 + h_{11}(0))} \sum_{n=1}^{N-1} \{h_{11}(n) \cdot [v([k - p - q \cdot (n-1)]\Delta t) \quad (7)$$
$$+ Z_0 \cdot i([k - p - q \cdot (n-1)]\Delta t)]\}$$

where N is total number of samples of the representation of $S_{11}(f)$. Note that while $k - p - q \cdot (n-1) < 0$, values of $v([k - p - q \cdot (n-1)]\Delta t)$ and $i([k - p - q \cdot (n-1)]\Delta t)$ should be zero, since the voltage and current are zero before time zero.

As we all know, voltage waves always propagate along ideal transmission lines without any distortion. So ideal transmission lines can be used to realize time delays whose values are $p\Delta t$ and $q\Delta t$. Therefore, a model using cascaded ideal transmission lines derived from (7) is shown in Fig. 3.

In Fig. 3 CCVS and VCVS are current controlled voltage source and voltage controlled voltage source, respectively. According to (7), CCVS is controlled by i($k\Delta t$) and its output is Z_0i($k\Delta t$), and VCVS is controlled by v($k\Delta t$) and its output is just v($k\Delta t$), where i($k\Delta t$) and v($k\Delta t$) are the voltage and current at the input point of antenna. Therefore, the output voltage wave of SUM is v($k\Delta t$)+Z_0i($k\Delta t$), which then propagates along N-1 lossless transmission lines by different delays. Delay of every ideal transmission line equals $q\Delta t$ except for the first transmission line, T1, whose delay is $p\Delta t$. Each VC(n) corresponds to the nth voltage controlled voltage source whose output is the product of its incoming delayed voltage wave and its nth gain term, h11(n). Finally a voltage controlled current source VCCS sums the voltages at the output of every VC(n) and outputs a current back to the circuits with a gain of $1/[Z_0(1+h_{11}(0))]$. Z11 represents the equivalent resistor derived from (7) and its value is given by

$[Z_0(1+h_{11}(0))]/(1- h_{11}(0))$. Therefore, model in Fig. 3 can exactly represent (7) and can be used for transient analysis in the circuit analysis program (SPICE).

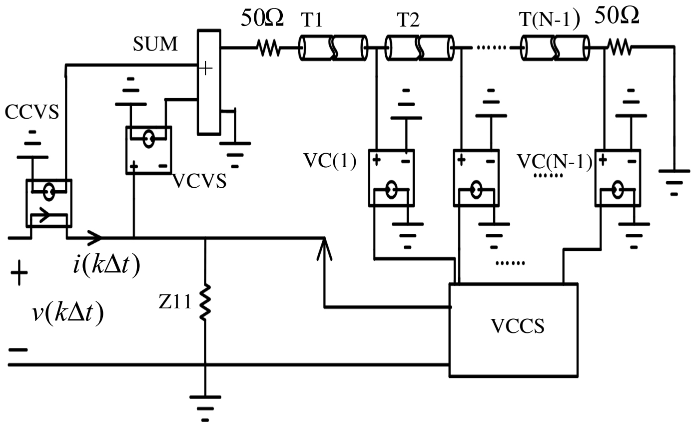

Fig. 3 Transient model of UWB antenna using cascaded transmission lines

IV. VERIFICATION

To verify this model, an UBW antenna is presented in Fig. 4 [4]. Defective ground, two slots and tapered connection between feed line and rectangle patch can enhance the working bandwidth effectively. Its S-parameters, 3.5GHz~10GHz, are shown in Fig. 5. The time-domain representation of $S_{11}(f)$ can be calculated by (3) and (4), which is shown in Fig. 6. Sixteen samples are enough to represent the S-parameters, as after the sixteenth sample, values of the representation are very small and can be treated as zeros. Therefore, fifteen ideal transmission lines are enough to represent the UWB antenna as shown in Fig. 3. In Fig. 6 the time intervals are 41.667ps except for the first time interval which is 10.14ps. Hence the first transmission line delay is 10.14ps, and subsequent transmission line delays are 41.667ps.

Different sources can be connected to the antenna to verify the model presented in this paper. The UWB antenna was represented by the transient model using cascaded ideal transmission lines, and source impedance Zs is 50Ω.

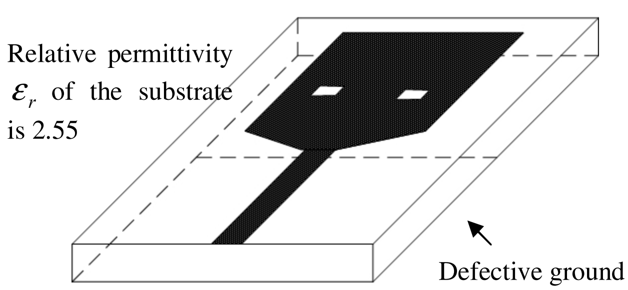

Fig. 4 UWB antenna [5]

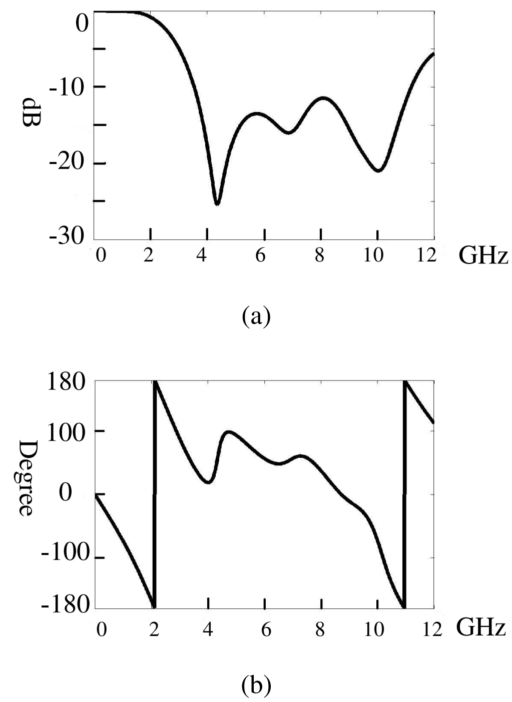

Fig. 5 $S_{11}(f)$ of UWB antenna. (a) Magnitude of Scattering Parameter in dB. (b) Phase of Scattering Parameter

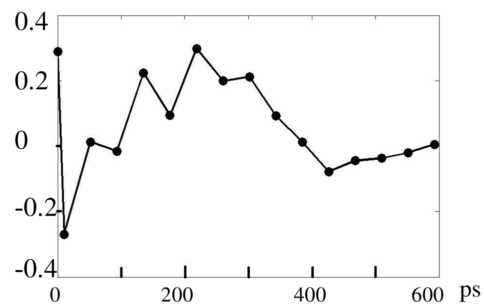

Fig. 6 Representation of $S_{11}(f)$ of UWB antenna in time-domain

First verification was a 6GHz sine-wave voltage source of magnitude 1V. From the S-parameters of the antenna, the input impedance is $58.82 + j \cdot 21.01\Omega$, corresponding to a series 58.82Ω resistor and a $0.56nH$ inductor. Therefore a practical simulation result can be got by using this lumped elements representation of the UWB antenna in ADS at 6GHz. The comparison between the transient analysis of the transient model presented in this paper and ADS is shown in Fig. 7. It indicates a very good agreement.

Second verification used a 10GHz sine-wave voltage of magnitude 1V. For this case, lumped elements including a series 52.01Ω resistor and a $1.79pF$ capacitor represented the antenna in ADS at 10GHz. The comparison between the transient analysis of the transient model presented in this paper and ADS is shown in Fig. 8. It shows a very good agreement in both the transient and steady state time-domains.

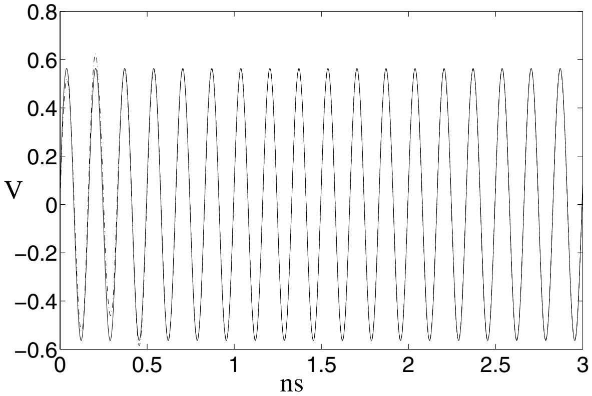

Fig. 7 Comparison between the simulation result of transient model and ADS in time domain for a sine-wave input working at 6GHz. (solid line is ADS result (-) and broken line is transient model result present in this paper (--))

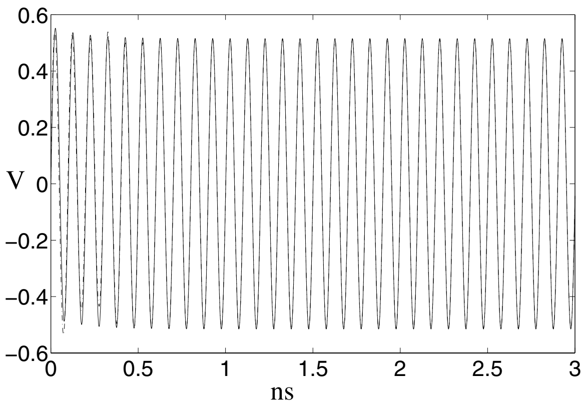

Fig. 8 Comparison between the simulation result of transient model and ADS in time domain for a sine-wave input working at 10GHz. (solid line is ADS result (-) and broken line is transient model result present in this paper (--))

For a final verification a unit wide bandwidth pulse was used, whose rising and falling times are both 0.1ns with pulse width of 1ns. It is an UWB signal, which containing frequency components from DC to 10GHz. In this frequency range the input lumped element representation of the antenna varies with frequency thus prohibiting ADS from getting the required transient results. Therefore, the convolution result derived from (7) can verify the transient model presented in this paper. The comparison between transient model and the convolution result is shown in Fig. 9, which indicates a very good agreement.

Performed on a Pentium 2.8GHz computer, the simulations above, using the transient model presented in this paper, take approximately 3 seconds to complete in a SPICE simulator. Thus highlighting the model is high computational efficiency.

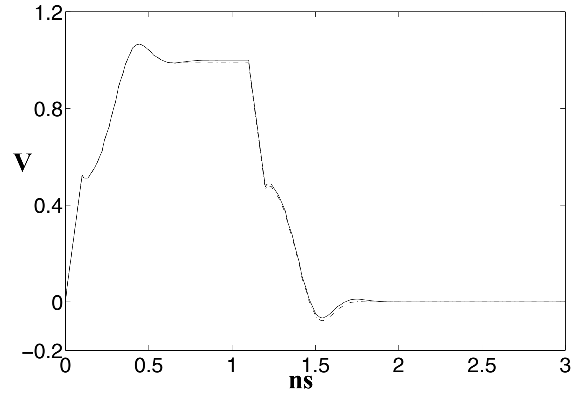

Fig. 9 Comparison between the simulation result of transient model and convolution derived from (7) for a pulse input. (solid line is convolution result (-) and broken line is transient model result present in this paper (--))

V. CONCLUSION

In this paper, a transient model, using cascaded ideal transmission lines for UWB antennas, is presented. It can be used in SPICE for transient analysis in co-simulation with circuits. The simulation results showed very good agreements have been achieved between the proposed model and ADS simulations. Furthermore, this transient model's speed and efficiency for wide bandwidth simulation over ADS has been highlighted.

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