INTEGRATING NETWORKS CHARACTERIZED BY MEASURED S-PARAMETER DATA INTO SWEC

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Integrating Networks Characterized by Measured S-Parameter Data into SWEC

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We have designed and implemented a technique that allows the user of a circuit simulator that operates in the time domain to include two-port network components that are described in a complete set of measured s-parameter data. This capability enables the circuit designer to simulate any components that do not have a closed form model, such as transmission lines with nonuniform electric properties. The technique has been incorporated into our timing simulator SWEC, which already handles transmission lines with the uniform RLGC model by a recursive convolution method. Inverse Fourier transform was used to transform s-parameter data from frequency domain into time domain in order to interface properly with the rest of the circuits to be simulated. Simulation based on direct convolution was devised to compute voltages and currents of nodes of interest at arbitrary time points from transformed s-parameter data. Several test circuits containing uniform transmission lines were used to compare our new simulator with SPICE and the original SWEC. The results show that electric behaviors in all test cases match well among the three. Moreover, our new simulator still enjoys a two orders of magnitude speedup over SPICE.

1 Introduction

In 1992, transmission line simulations were successfully integrated into the timing simulator SWEC [1][2] by using a recursive convolution method with linear complexity in time. Extensive tests using industrial examples and comparison with current circuit and interconnect simulators have convinced us that SWEC will play a major role in future IC, MCM, and PCB design. SWEC solves Telegrapher Equations based on the uniform transmission line model, namely, the uniform RLGC model. However, in microwave applications or high speed digital circuits, RLGC parameters for transmission lines cannot be easily obtained and the lines may not be uniform. Instead, engineers and researchers are accustomed to using scattering-parameters to characterize networks or transmission lines because of the ease of measurement [8]. Therefore, it is necessary and practically meaningful to have a tool that can simulate networks based on measured s-parameter data. The purpose of this paper is to describe our approach to integrating networks characterized by measured s-parameter data into SWEC.

Issues of integrating simulation based on measured or tabulated s-parameter data have drawn attention recently. Sanaie, Chiprout, Nakhla and Zhang[3] considered linear time invariant circuits based on a moment matching method. The network, excluding the measured subcircuits, is represented by a small set of data points similar to the measured subcircuits. Numerical inverse Fourier transform is then performed. Silveira, Elfadel, White, Chilukuri and Kundert [4] developed a sophisticated rational approximation method. But it does not consider a general 2-port which may include non-uniform lines specified by its measured scattering matrix.

In this paper, we will first briefly review the scattering formulation and the inverse Fourier transform of measured s-parameter data. Afterwards, we will derive the equations for convolution simulation and discuss some of the implementation issues. The inverse Fourier transform and the convolution simulation have been combined into an s-parameter processing module and incorporated into the latest version of SWEC, SWEC2.1.

The new version of SWEC, called SWEC2.s, can handle any two-port networks described in measured s-parameter data. Simulations of several test circuits show an excellent match with SWEC2.1 and SPICE3 runs with transmission lines replaced partly or totally by blocks described in s-parameter data. In terms of execution time, we have obtained a speedup of two orders of magnitude over SPICE3.

2 S-Parameter Representation of Two-Port Networks

Generally, s-parameters describe the ratios of reflection and transmission waves of a network under a given loading situation. Assuming a two-port network[1] in Figure 1,

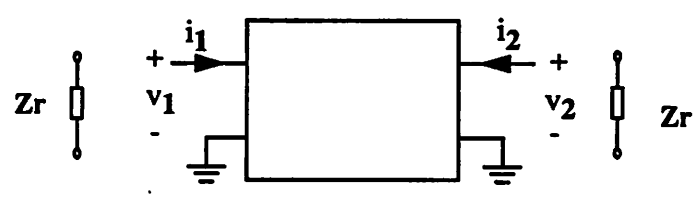


Figure 1. a two port representation

where (v_1, v_2) and (i_1, i_2) are port voltages and currents respectively, and z_r is the reference impedance, the variables that describe the reflection and transmission waves a and b at these two ports are defined as [6]

$$
\begin{aligned}
a_1 &= \frac{1}{2\sqrt{r}}(V_1 + z_r I_1)\,, & a_2 &= \frac{1}{2\sqrt{r}}(V_2 + z_r I_2) \\
b_1 &= \frac{1}{2\sqrt{r}}(V_1 - \bar{z}_r I_1)\,, & b_2 &= \frac{1}{2\sqrt{r}}(V_2 - \bar{z}_r I_2)
\end{aligned}
\qquad (1)
$$

where r is the real part of the reference impedance z_r and $\bar{z}_r$ the conjugate of z_r. The s-parameters describe the relationship of variables a and b in the following manner,

$$
\begin{aligned}
b_1 &= S_{11}a_1 + S_{12}a_2 \\
b_2 &= S_{21}a_1 + S_{22}a_2
\end{aligned}
\qquad (2)
$$

1. A large variety of networks in microwave circuits are two-port networks and most equipment that measures s-parameters is for two-port networks.

where S_{11} and S_{22} are the scattering reflection coefficients, and S_{12} and S_{21} are the scattering transmission coefficients of the network.

Combine Equations 1 and 2 by substituting variables a and b, we obtain the relations of s-parameters with port voltages and currents,

$$\begin{aligned} (S_{11}-1)V_1 + S_{12}V_2 + z_r(S_{11}+1)I_1 + z_rS_{12}I_2 = 0 \\ S_{21}V_1 + (S_{22}-1)V_2 + z_rS_{21}I_1 + z_r(S_{22}+1)I_2 = 0 \end{aligned} \tag{3}$$

where it is assumed that the reference impedance is a resistor, i.e.,

$$\bar{z}_r = z_r .$$

Equation 3 characterizes the behavior of two-port networks described by s-parameters in the frequency domain. The central task is to incorporate the two equations in (3) into the circuit equation of the rest of the circuit, which is established based on KCL and KVL. Since SWEC solves the circuit equation in the time domain, we have to transform the relations in Equation 3 into the time domain,

$$\begin{aligned} & s_{11}(t)^*v_1(t) - v_1(t) + s_{12}(t)^*v_2(t) + z_rs_{11}(t)^*i_1(t) + z_ri_1(t) \\ & \quad + z_rs_{12}(t)^*i_2(t) = 0 \\ & s_{21}(t)^*v_1(t) + s_{22}(t)^*v_2(t) - v_2(t) + z_rs_{21}(t)^*i_1(t) \\ & \quad + z_rs_{22}(t)^*i_2(t) + z_ri_2(t) = 0 \end{aligned} \tag{4}$$

where * denotes convolution, $s_{11}(t)$, $s_{21}(t)$, $s_{12}(t)$, and $s_{22}(t)$ are the time domain functions of S_{11}, S_{21}, S_{12}, and S_{22}, and $v_1(t)$, $v_2(t)$, $i_1(t)$, and $i_2(t)$ are the time domain functions of V_1, V_2, I_1, and I_2, respectively.

Therefore the problem of integrating networks described by s-parameters is to solve Equation 4 together with the circuit equations of the remaining circuit. In the following sections, we will discuss how to transform s-parameters into the time domain based on measured data in the frequency domain and present the convolution simulation method.

3 Inverse Fourier Transform

For electronic circuits and systems, the inverse Fourier transforms (IFT) of s-parameters in the time domain are real-valued functions. This simple fact is central to the way we transform measured s-parameter data into time domain.

Let $F(\omega)$ be the Fourier transform of $f(t)$. From well-known properties of Fourier transform, only the real part of $F(\omega)$ is needed to obtain a real, even function $f(t) = f(-t)$. For convolution purpose to be discussed in the next Section, $f(t)$ for $t < 0$ is ignored.

The measured s-parameter data are sampled data in a limited band of frequencies (e.g. 300KHz - 6GHz [8]). Both extrapolation and interpolation may be necessary to obtain correct and accurate time response. Certainly the value at zero frequency must be available for IFT. As to the high end, a rule of thumb which is useful for determining the needed maximum frequency is

$$f_{max} \geq \frac{1.2}{\Delta t},$$

where Δt is the approximate rise time of the signals at the ports of the two-port network.

4 Convolution Simulation

From Equation 4, we know that to simulate the networks characterized by s-parameters we must compute the convolution of $s_{11}(t)$, $s_{21}(t)$, $s_{12}(t)$, $s_{22}(t)$ and appropriate variables $v_1(t)$, $v_2(t)$, $i_1(t)$, $i_2(t)$. Without loss of generality, let us look into one convolution

$$s_{11}(t)^* v_1(t) = \int_0^t v_1(t-\tau)\, s_{11}(\tau)\, d\tau. \qquad (5)$$

Our plan is to perform trapezoidal approximation to obtain the integration. Let T be the time interval of IFT, which is equal to $\frac{1}{f_{max}}$. Suppose that the current simulation time point is t_n. We first discretize the interval $[0, t_n]$ into LT segments, where L is the quotient of t_n divided by T. (Refer to Figure 2.)

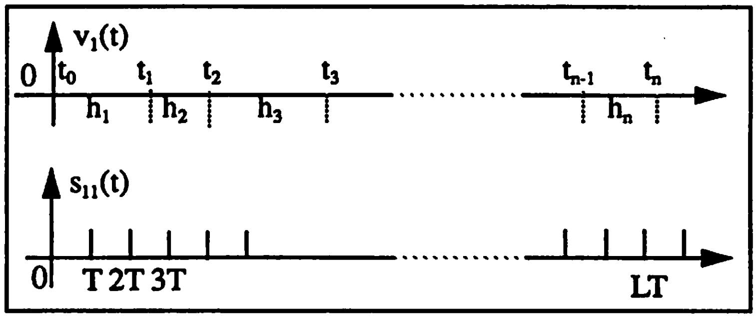


Figure 2. discretization of time axises

T is the time interval of IFT, L is the quotient of t_n divided by T, $h_1, h_2, \ldots, h_n$ represent integration intervals between consecutive time points, and $t_0, t_1, \ldots, t_n$ are the time points.

Equation 5 can be rewritten as

$$s_{11}(t)^* v_1(t)\Big|_{t_n} = \sum_{i=1}^{L}\left[\int_{(i-1)T}^{iT} v_1(t_n-\tau)s_{11}(\tau)\,d\tau\right] + \int_{LT}^{t_n} v_1(t_n-\tau)s_{11}(\tau)\,d\tau \tag{6}$$

The first term corresponds to the integration over the LT segments and the second term is the residual segment between LT and t_n. By trapezoidal approximation,

$$\int_{(i-1)T}^{iT} v_1(t_n-\tau)s_{11}(\tau)\,d\tau = \frac{1}{2}T\left[v_1(t_n-(i-1)T)s_{11}((i-1)T) + v_1(t_n-iT)s_{11}(iT)\right] \tag{7}$$

and

$$\int_{LT}^{t_n} v_1 (t_n - \tau) s_{11} (\tau) d\tau = \frac{1}{2} (t_n - LT) [v_1 (t_n - LT) s_{11} (LT) + v_1 (0) s_{11} (t_n)] \tag{8}$$

Substituting Equations 7 and 8 in Equation 6, we obtain

$$\begin{aligned} s_{11} (t)^* v_1 (t) \Big|_{t_n} &= \frac{1}{2} T v_1 (t_n) s_{11} (0) + \sum_{i=1}^{L-1} T v_1 (t_n - iT) s_{11} (iT) \\ &+ \frac{1}{2} [t_n - (L-1) T] v_1 (t_n - LT) s_{11} (LT) + \frac{1}{2} (t_n - LT) v_1 (0) s_{11} (t_n) . \end{aligned} \tag{9}$$

We calculate $v_1 (t)$ at time $t_n - iT$ by linear interpolation based on its nearest neighboring values at simulation time points. That is,

$$v_1 (t_n - iT) = \frac{t_n - iT - t_{k-1}}{h_k} v_1 (t_k) + \frac{t_k + iT - t_n}{h_k} v_1 (t_{k-1}) , \quad \text{for } k \text{ satisfying } t_{k-1} < t_n - iT \le t_k . \tag{10}$$

For the special case when $k = n$, Equation 10 can be written as

$$v_1 (t_n - iT) = \frac{h_n - iT}{h_n} v_1 (t_n) + \frac{iT}{h_n} v_1 (t_{n-1}) , \text{ for any } i \text{ such that } i \le \frac{h_n}{T} . \tag{11}$$

Likewise $s_{11} (t_n)$ is also obtained by linearly interpolating adjacent known values.

Referring to Figure 2, $t_0, t_1, \ldots, t_n$ are simulation time points. At the time we are calculating $v_1 (t_n)$, we have already obtained all the values $v_1 (t_i)$ for $i = 0, 1, 2, ! \ldots, (n-1)$. Likewise, $s_{11} (iT)$ are available, for $i = 0, 1, \ldots, \frac{N}{2}$, where N is the number of points used in IFT. Substitute these values and Equations 10 and 11 into Equation 9 and collect all terms that involve $v_1 (t_n)$, we can put the convolution into the following form

$$s_{11}(t) * v_1(t)\Big|_{t_n} = C_{11} v_1(t_n) + R_{11, v_1} \tag{12}$$

where C_{11} is the coefficient for the $v_1(t_n)$ term and R_{11, v_1} is the remaining term.

By the same technique, we can obtain the following equations for the convolutions in Equation 4,

$$\begin{aligned} s_{jk}(t) * v_k(t)\Big|_{t_n} &= C_{jk} v_k(t_n) + R_{jk, v_k} \\ s_{jk}(t) * i_k(t)\Big|_{t_n} &= C_{jk} i_k(t_n) + R_{jk, i_k} \end{aligned} \qquad (j = 1, 2\ ;\ \mathrm{k} = 1, 2) \tag{13}$$

To evaluate Equation 4 at time t_n, we use the formula in Equation 13 to obtain

$$\tilde{A}_c \tilde{X}_c = \tilde{b}_c \tag{14}$$

where

$$\tilde{A}_c = \begin{bmatrix} C_{11} - 1 & C_{12} & z_r(C_{11} + 1) & z_r C_{12} \\ C_{21} & C_{22} - 1 & z_r C_{21} & z_r(C_{22} + 1) \end{bmatrix} \tag{15}$$

$$\tilde{b}_c = -\begin{bmatrix} R_{11, v_1} + R_{12, v_2} + z_r R_{11, i_1} + z_r R_{12, i_2} \\ R_{21, v_1} + R_{22, v_2} + z_r R_{21, i_1} + z_r R_{22, i_2} \end{bmatrix} \tag{16}$$

$$\tilde{X}_c = \begin{bmatrix} v_1(t_n) & v_2(t_n) & i_1(t_n) & i_2(t_n) \end{bmatrix}^T \tag{17}$$

Equation 14 are the two 2-port equations in terms of the port voltages and currents. Together with the rest of the circuit equations, SWEC obtains the simulation results. When integrating our technique into SWEC, we retain SWEC's partitioning algorithm [1]. We regard the measured blocks as strongly coupled components.

5 Experimental Results

In this section, several examples have been tested and compared with SWEC2.1 and SPICE3. All of them are run on DEC 5000.

In order to make comparison with SWEC2.1 and SPICE3, for which only uniform transmission lines modelled by RLGC parameters are acceptable, the measured data have been generated using the RLGC model before simulation. Our technique works equally well for any two-port networks.

5.1 Circuit 1

Circuit 1 is simply a resistor and a transmission line connected to an inverter as shown in Figure 3. The transmission line was replaced by generated s-parameter data in the frequency range 300Hz - 3GHz when the circuit is simulated by SWEC2.s.

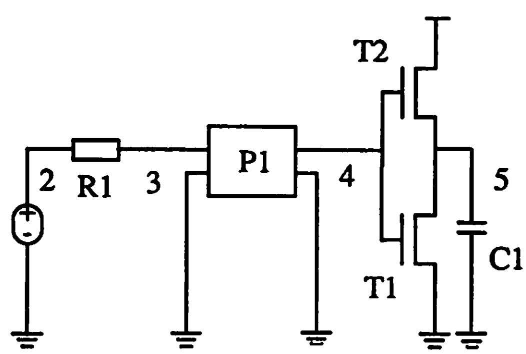
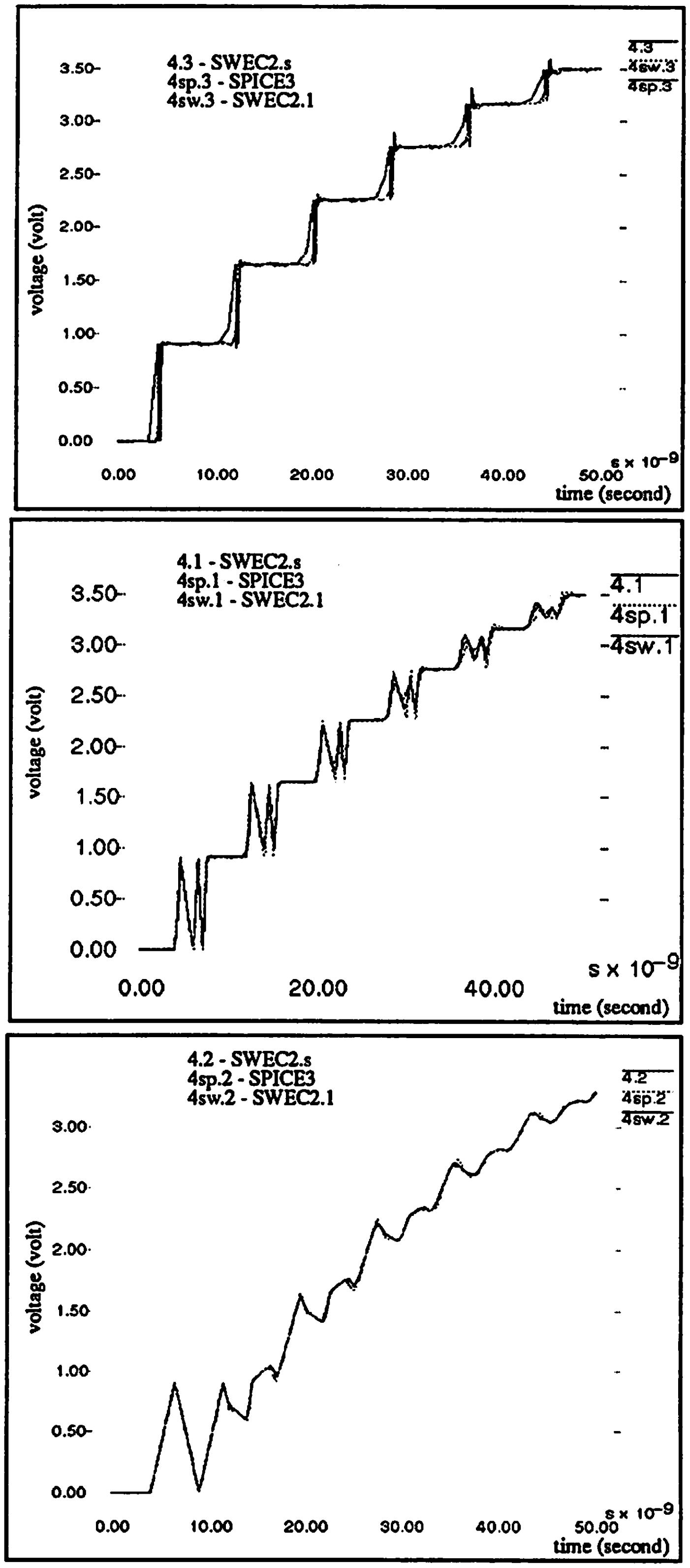


Figure 3. circuit 1

We imposed a PWL source with 5 and 0 volts as its upper and lower bounds at node 2. The waveforms obtained at node 4 when setting the ramp time of the input signal to be 0.1ns, 0.5ns, 2.5ns respectively are shown in Figure 4. In Figure 4 (b) and (c), we observe that the results from three simulators (SWEC2.s, SWEC2.1 and SPICE3) are almost identical. In (a), the slight differences are caused by insufficiency of s-parameter data at high frequencies.



(a) ramp time 0.1ns

(b) ramp time 0.5ns

(c) ramp time 2.5ns

Figure 4. waveforms at node 4 for circuit 1

5.2 Circuit 2

The second circuit tested is shown in Figure 5. We also replaced the transmission line between the two cascaded inverters with a two-port network described by generated s-parameter data, which range between 10KHz and 15GHz. We imposed a periodical PWL source at node 2, and showed the waveforms at node 4 from the three simulators in Figure 6. We can see that the waveforms agree fairly well.

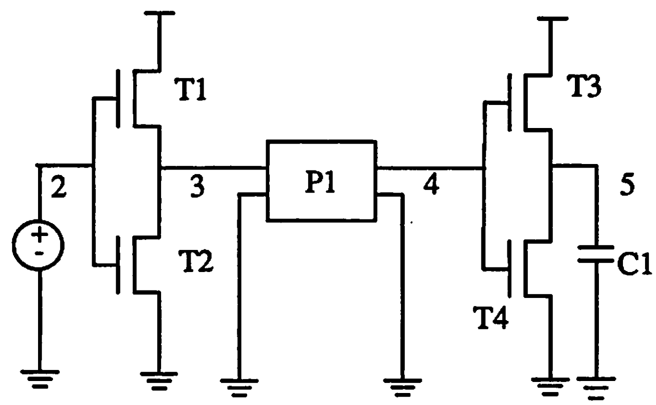


Figure 5. circuit 2

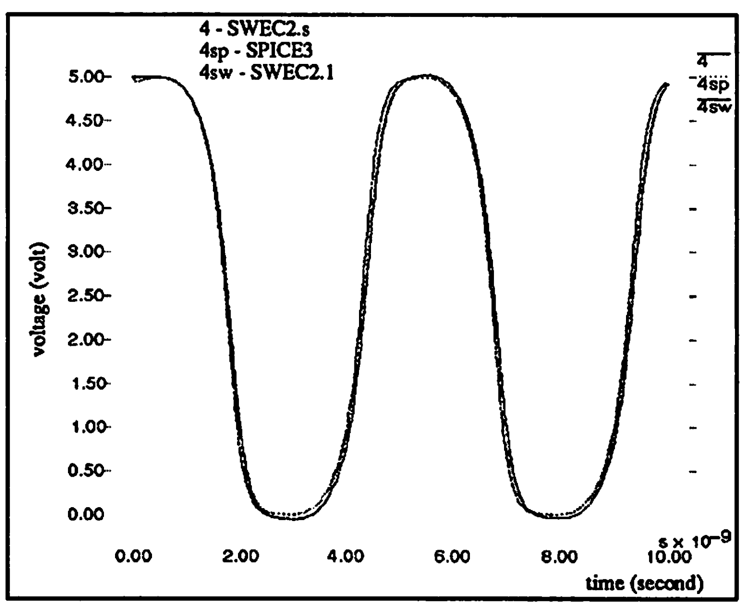


Figure 6. waveforms at node 4 in circuit 2

Table 1 displays the time statistics for the three runs.

SWEC2.s	SWEC2.1	SPICE3	time unit
2.8	0.53	154.4	second

Table 1. time cost for circuit 2

About 0.93 seconds of the 2.8 seconds for SWEC2.s is spent on the setting up of IFT of s-parameters. This means that the transient simulation time for SWEC2.s, which uses our direct convolution simulation method for the block described by s-parameter data, is about twice of the simulation time for SWEC2.1, which depends on the recursive convolution method.

5.3 Circuit 3

The circuit shown in Figure 7 is an 8-bit full adder. Node ca is the carry out of the adder, s7 is the 8th bit of the sum, s5 is the 6th bit of the sum, and vp4 is a point at power line which is modelled by 7 transmission lines. For the ground line, there are also 7 transmission lines. We regard these 14 lines as 14 two-port networks which are characterized by generated s-parameter data in the range of frequency 100Hz-3GHz.

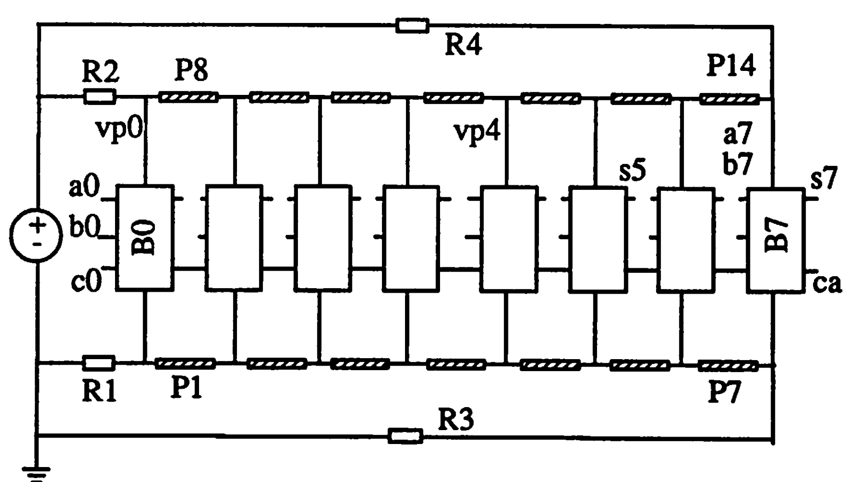


Figure 7. circuit 3 - an 8 bit full adder

Figures 8, 9, 10 and 11 display the waveforms at nodes ca, s5, s7 and vp4.

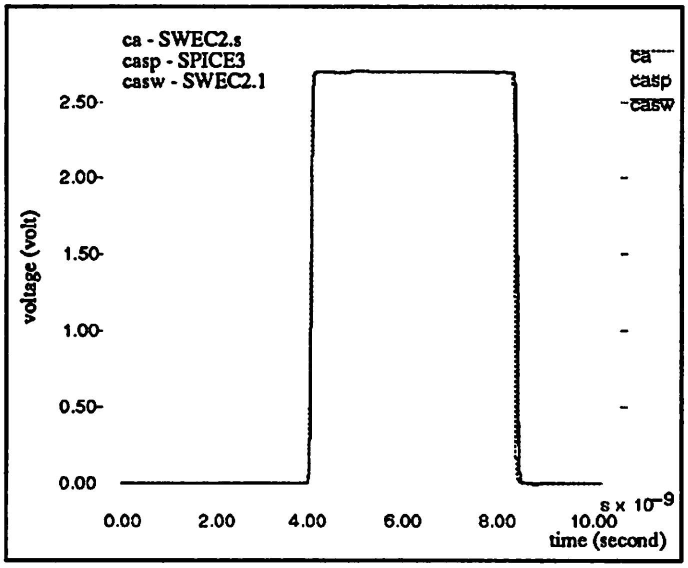


Figure 8. waveforms at node ca in circuit 3

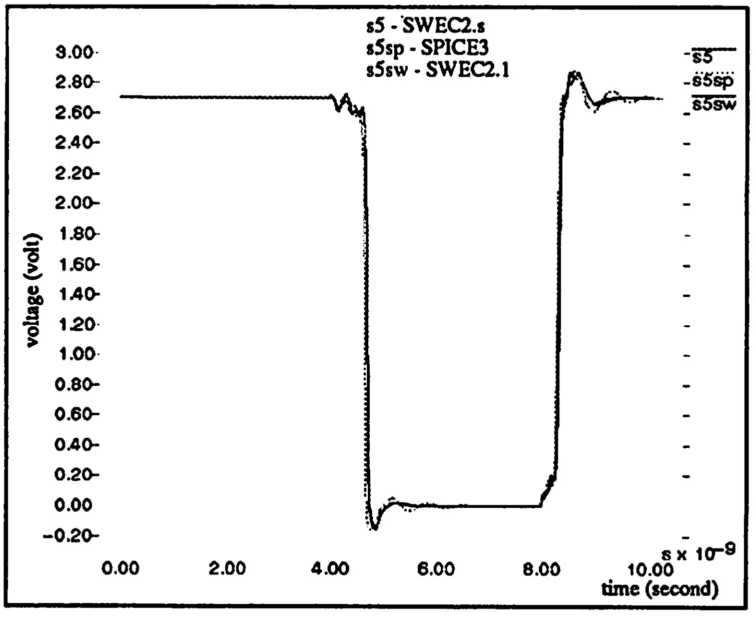


Figure 9. waveforms at node s5 in circuit 3

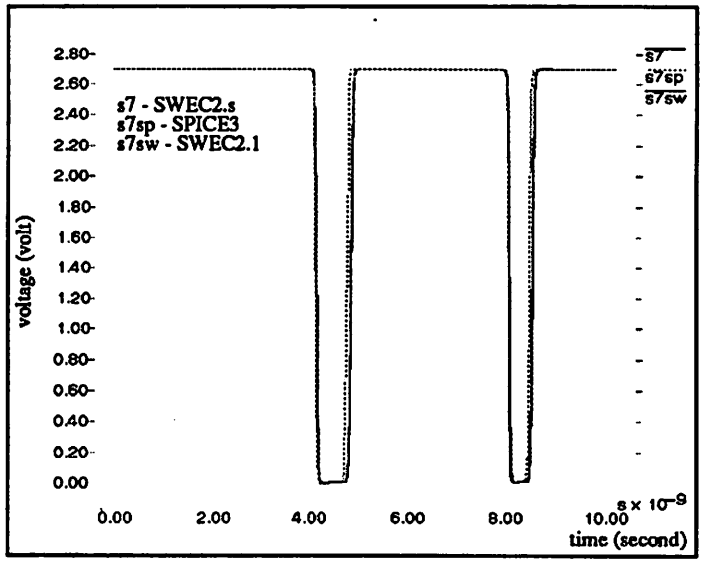


Figure 10. waveforms at node s7 in circuit 3

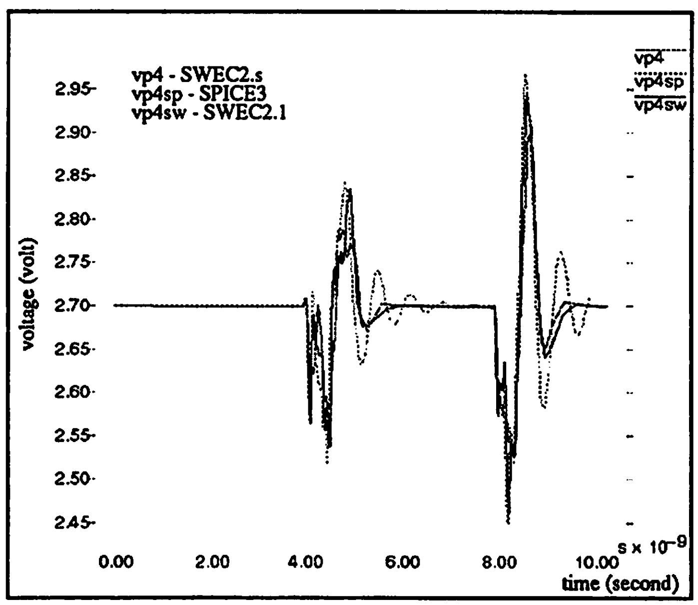


Figure 11. waveforms at node vp4 in circuit 3

The running time for this circuit is

SWEC2.s	SWEC2.1	SPICE3	time unit
89.5	35.9	157.6	second

Table 2. time cost for circuit 3

5.4 Circuit 4

Circuit 4 is shown in Figure 12. There are two coupled transmission lines and a two-port network p1 characterized by generated s-parameter data from the uniform RLGC model of a transmission line. The available data for this circuit is from 4MHz to 8GHz. We compare the simulation result with SWEC2.1 only, since SPICE3 doesn't handle coupled lines. Figure13 displays the waveforms at node B2 from both simulators. For this circuit, SWEC2.1 takes 0.45 seconds, and SWEC2.s takes 2.60 seconds, in which about 1.62 seconds was spent on IFT.

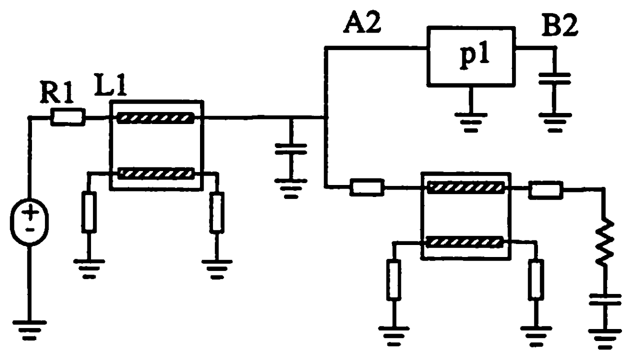


Figure 12. circuit 4

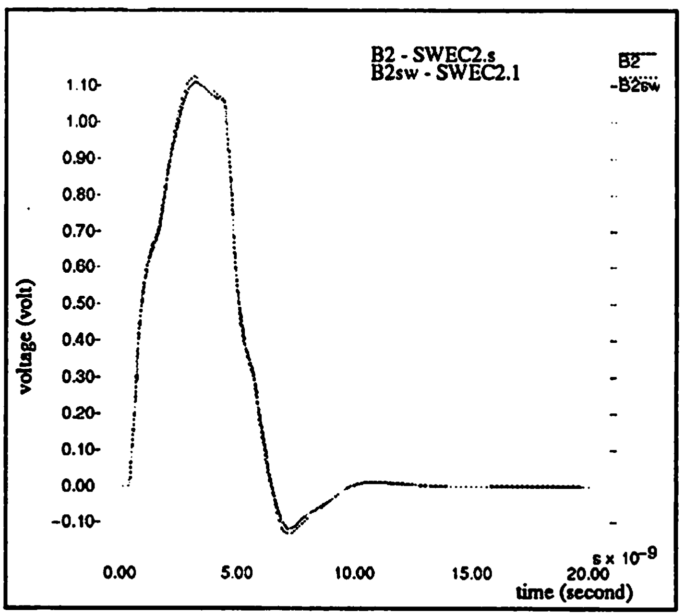


Figure 13. waveforms at node B2 in circuit 4

5.5 Circuit 5

The fifth circuit we have tested is shown in Figure 14. There is a two-port network P1 described by measured s-parameter data in the range of frequency from 4MHz to 8GHz. Again we compare the simulation results with SWEC2.1 and SPICE3 with the measured block replaced by a single transmission line. Table 3 displays the time statistics. It took about 1.58 seconds for SWEC2.s to do the setup. Compared with SWEC2.1 and SPICE3, SWEC2.s is about two times slower than SWEC2.1 in transient simulation and is more than 100 times faster than SPICE3.

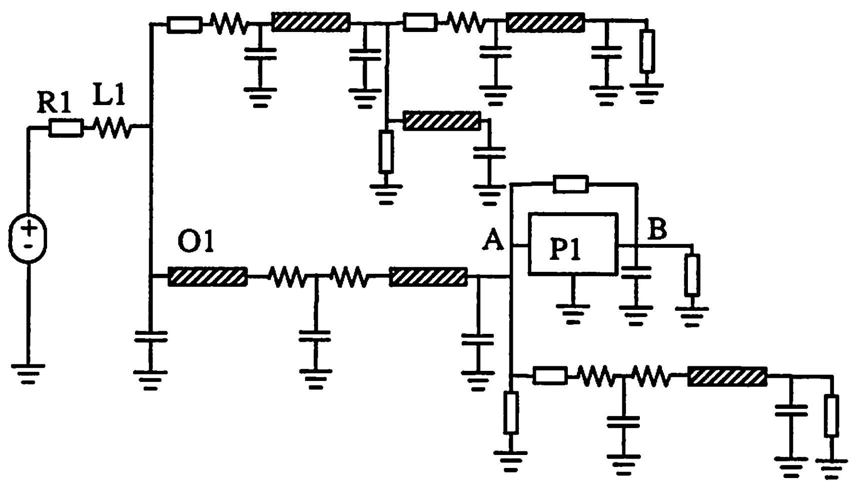


Figure 14. circuit 5

SWEC2.s	SWEC2.1	SPICE3	time unit
2.50	0.45	377.5	second

Table 3. time statistics for circuit 5

Figures 15 and 16 exhibit the waveforms from the three simulators at nodes A and B respectively.

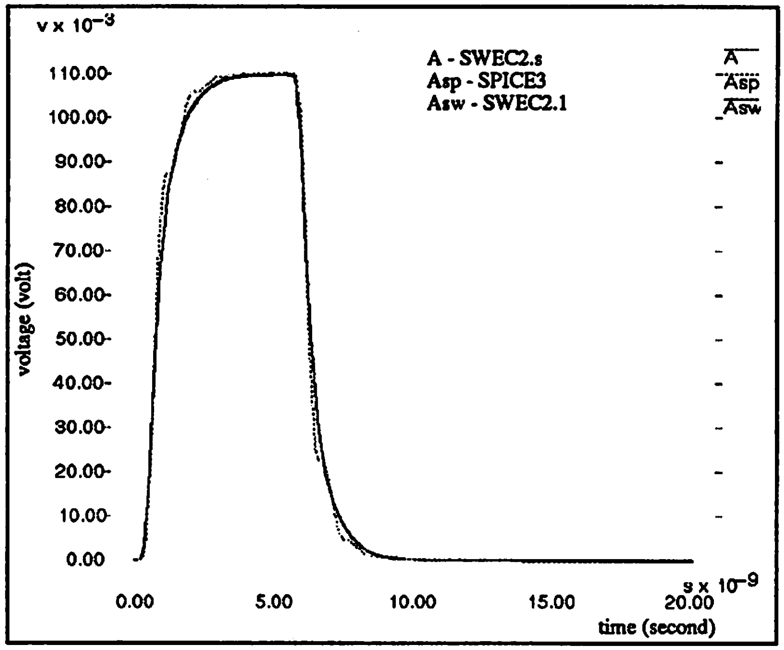


Figure 15. waveforms at node A in circuit 5

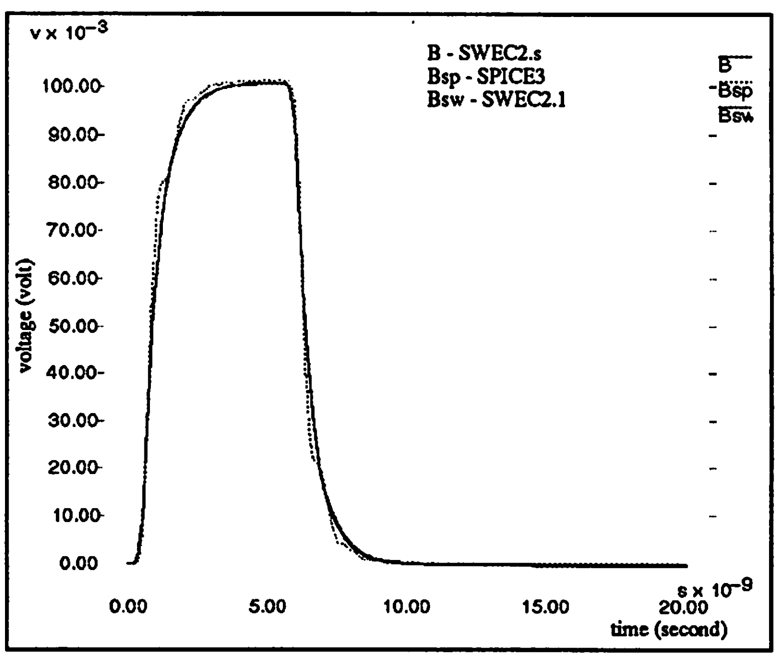


Figure 16. waveforms at node B in circuit 5

5.6 Circuit 6

The sixth circuit tested is a clock tree circuit which consists of 73 different transmission lines, nearly 3000 resistors and 3000 capacitors together with two inverters in series as the driver (Figure 17). Before simulation, we generated 73 blocks which were described by s-parameter data in frequency range 10KHz - 15GHz for each transmission line.

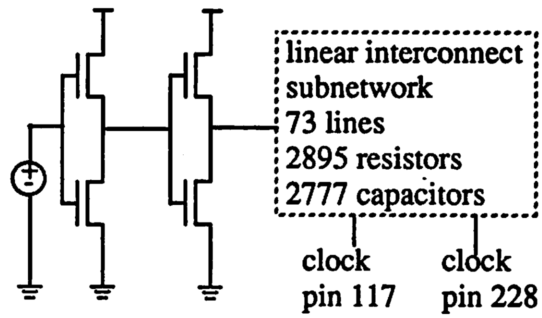


Figure 17. circuit 6 - a clock tree circuit

Figures 18 and 19 show the simulation results at two specific pins.

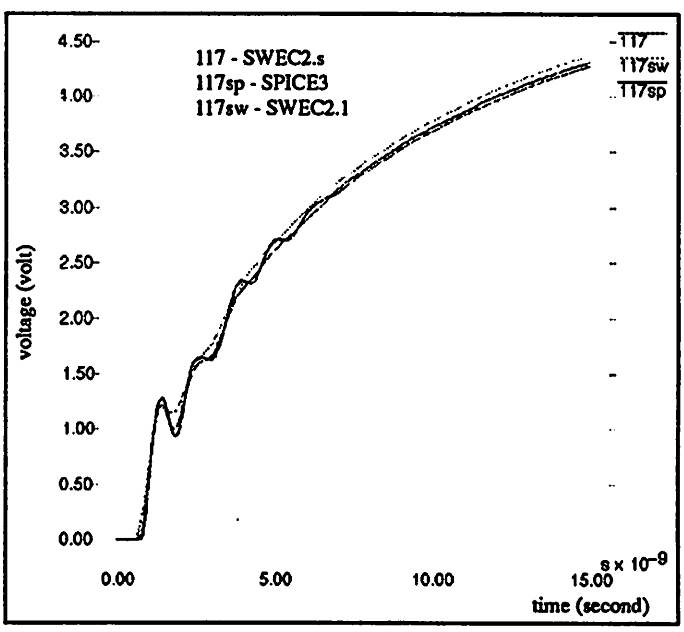


Figure 18. waveforms at pin 117 in circuit 6

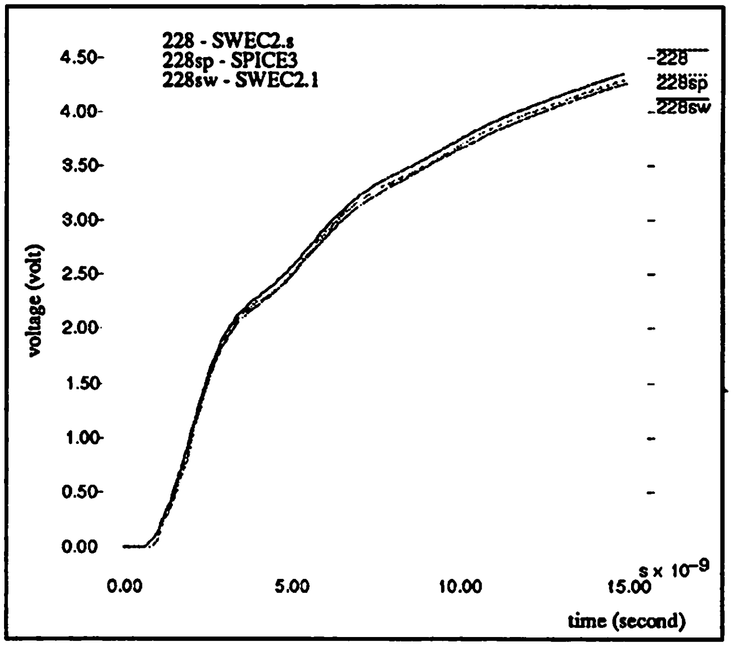


Figure 19. waveforms at pin 228 in circuit 6

Table 4 is the running time statistics.

SWEC2.s	SWEC2.1	SPICE3	time unit
184.1	69.2	5199.0	second

Table 4. time cost for circuit 4

For this circuit, SWEC2.s took about 65 seconds to perform IFT. If we omit this part of the time, SWEC2.s again is two times slower than SWEC2.1.

6 Conclusions

We have illustrated our strategy in simulating two-port networks characterized by measured s-parameters and its integration into SWEC2.1. Several test examples have demonstrated that simulation can almost reach the same accuracy as SPICE3 if the measured data at high enough frequency are available. By taking advantage of circuit partitioning of SWEC2.1, we can obtain two orders of magnitude faster speed than SPICE.

Acknowledgments

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