in Fig. 4 for the normal incidence. The agreement is quite good. For the gridded-square array, over 20-dB attenuation is achieved at the second harmonic (4.9 GHz), and for the double-square array, over 10-dB attenuation are achieved at both the second (4.9 GHz) and third harmonics (7.35 GHz). The insertion loss at 2.45 GHz for both the gridded- and double-square arrays is less than 0.5 dB. The gridded-square array was also tested with a rectenna array. The efficiency of the rectenna decreases approximately 1% when the FSS is added, and the second-order harmonic (4.9 GHz) from the rectenna array is reduced approximately 10–15 dB, depending on the distance between the rectenna and FSS arrays. There are two ways to simultaneously suppress the second- and the third-order harmonics. One is to use two gridded-square arrays with their center frequencies at 4.9 and 7.35 GHz, respectively, and another is to merely use a double-square array. Taken into account the reduction of the rectenna efficiency, due to the insertion loss of the FSS at 2.45 GHz, it may be better to merely use a double-square FSS array for suppressing both the second- and third-order harmonics.

The frequency response of a gridded-square array for oblique incidence were also measured. The measured frequency response are shown, in Fig. 5 for oblique incidence of a TE- or TM-polarized plane wave, and in Fig. 6 for oblique incidence when the transmitter is a circularly polarized conical-spiral antenna and the receiver is a linearly polarized horn antenna. As expected from the theory, the response are sensitive to the incident angle for a TE- or TM-polarized incident wave, but relatively insensitive for a circularly polarized incident wave. Thus, for effectively suppressing the harmonics radiation by the FSS array, it is hoped that the circularly polarized wave is used for microwave power transmission.

IV. Conclusions

By using an equivalent-circuit model, the gridded- and double-square FSS arrays have been designed and measured for microwave power transmission systems, where the pass of 2.45 GHz and the rejection of 4.9 and/or 7.35 GHz are required. When the FSS was added, over 10 dB of attenuation of the second harmonic (4.9 GHz) radiated from the rectenna array is obtained and the conversion efficiency of the rectenna decreases approximately 1%. It is also found that, for a combination of TE- and TM-polarized waves or a circularly polarized wave, the angular sensitivity of the FSS arrays could be improved.

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[1] T. K. Wu and S. W. Lee, “Multiband frequency selective surface with multiring patch elements,” *IEEE Trans. Antennas Propagat.*, vol. 42, pp. 1484–1490, Nov. 1994.
[2] J. Shaker and L. Shafai, “Removing the angular sensitivity of FSS structures using novel double-layer structures,” *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 324–325, Oct. 1995.
[3] J. O. McSpadden, T. Yoo, and K. Chang, “Theoretical and experimental investigation of a rectenna element for microwave power transmission,” *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2359–2366, Dec. 1992.
[4] G. Zarrillo and K. Aguiar, “Closed-form low frequency solutions for electromagnetic waves through a frequency selective surfaces,” *IEEE Trans. Antennas Propagat.*, vol. AP-35, pp. 1406–1417, Dec. 1987.
[5] J. Jin and J. L. Volakis, “Electromagnetic scattering by a perfectly conducting patch array on a dielectric slab,” *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 556–563, Apr. 1990.
[6] R. J. Langley and E. A. Parker, “Equivalent circuit model for arrays of square loops,” *Electron. Lett.*, vol. 18, pp. 294–296, 1983.
[7] ——, “Double-square frequency selective surfaces and their equivalent circuit,” *Electron. Lett.*, vol. 19, pp. 675–676, 1983.
[8] C. K. Lee and R. J. Langley, “Equivalent-circuit models for frequency-selective surfaces at oblique angles of incidence,” *Proc. Inst. Elect. Eng.*, vol. 132, pt. H, no. 6, pp. 395–399, June 1985.
[9] M. I. Sobhy, M. H. A. El-Azeem, K. W. Royer, R. J. Langley, and E. A. Parker, “Simulation of frequency selective surfaces (FSS) using 3D-TLM,” in *Proc. Comput. Electromag.*, Apr. 1996, 352–357.
[10] I. Anderson, “On the theory of self-resonant grids,” *Bell Syst. Tech. J.*, vol. 54, no. 10, pp. 1725–1731, Dec. 1975.
[11] M. J. Archer, “Wave reactance of thin planar strip gratings,” *Int. J. Electron.*, vol. 58, pp. 187–230, 1985.

Comparison of the Transmission-Line Matrix and Finite-Difference Time-Domain Methods for a Problem Containing a Sharp Metallic Edge

Neil R. S. Simons, Riaz Siushansian, Joe LoVetri, and Michel Cuhaci

***Abstract*— We compare Yee’s finite-difference time-domain (FDTD) and symmetric condensed-node transmission-line matrix (SCN–TLM) solutions for a cavity containing a metallic fin. Differential equation-based numerical methods are known to produce inaccurate results for this type of problem due to the rapid spatial variation of the field distribution in the vicinity of the singularity at the edge of the metal fin. This problem is relevant to the analysis of structures of practical interest such as microstrip and coplanar waveguides. Based on simulations, it is determined that for identical discretizations, SCN–TLM is more accurate than FDTD for this problem. We interpret this result as an indication that the symmetric condensed representation of fields (used within the SCN–TLM) lends itself to a more accurate algorithm than the distributed representation used by Yee. We estimate that the FDTD method requires 3.33 times more cells for a given three-dimensional problem than the transmission-line matrix (TLM) method (1.49 times more cells per linear dimension of the problem) in order to achieve the same accuracy. If we consider the requirements to update and store a single TLM or FDTD cell, we find the SCN–TLM algorithm is more efficient than the Yee FDTD algorithm in terms of both computational effort and memory requirements. Our conclusions regarding computational effort and memory requirements are limited to problems with homogeneous material properties.**

***Index Terms*—Electromagnetic fields, electromagnetic transient analysis, FDTD methods, finline, transmission-line matrix methods.**

I. Introduction

The finite-difference time-domain (FDTD) and symmetric condensed-node transmission-line matrix (SCN–TLM) methods are numerical techniques capable of determining an approximate solution of time-dependent Maxwell’s equations in the presence of complex environments [1], [2].

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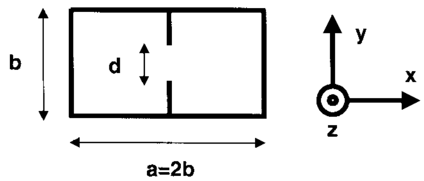

Fig. 1. Cross section of a perfectly conducting cavity possessing sharp metallic edges.

In this paper, we investigate the relative accuracy of the Yee FDTD and SCN–TLM [3] methods for problems that contain sharp metallic edges. The accuracy of solutions to this problem is relevant to practical applications such as the modeling of microstrip and coplanar-waveguide structures. The specific problem we examine is a perfectly conducting cavity with metal fins. For this problem, the transmission-line matrix (TLM) method is known to shift the frequency-domain characteristics of the solutions [4]–[6]. As will be shown in this paper, these errors also occur in FDTD simulations. These errors are due to the inability of both methods to accurately model the rapid spatial variation of the field distribution in the vicinity of the singularity at the edge of the metal fin. Both TLM and FDTD are second-order methods. Although the geometry of this problem is simple, it isolates the error caused by the metallic edge, referred to as *coarseness error,* from other sources of error. Dispersive errors have been investigated in [7], where a comparison of different finite-difference algorithms is provided.

Methods have been proposed for overcoming the inaccuracies described above. In [4], the structure was analyzed for a few different mesh sizes, and the resultant solutions extrapolated to the limit of an infinitely fine mesh. In [5], a local mesh modification scheme is provided that eliminates the error from the solution. In [6], a comparison of local mesh modifications and mesh refinement using a graded mesh are presented. Other approaches include the use of an unstructured mesh in order to increase the physical discretization in the region surrounding the metallic edge. This allows the second-order approximation to be applied over shorter physical lengths and, therefore, obtain a more accurate fit to the field distribution. The FDTD [8, Ch. 11] and TLM [9] methodologies are compatible with unstructured meshes. Higher order algorithms would more accurately predict the rapidly varying field distribution [10]–[13].

Given that FDTD and TLM do not solve this problem accurately, an opportunity exists to compare their relative accuracy for problems containing sharp field discontinuities. The purpose of this paper is, therefore, to quantitatively determine the relative accuracy of the two methods and, based on this quantitative assessment, compare computational resources.

In Section II, we describe the specific geometry investigated, and our approach to obtaining a benchmark solution to the problem. In Section III, we compare the accuracy of the TLM and FDTD methods and, in Section IV, perform a detailed comparison of the computational resources for this problem. A discussion and conclusions follow in Section V.

II. A Benchmark Solution

The cross section of the geometry of the problem is provided in Fig. 1. This cross section lies in the x–y-plane. The boundaries are perfectly conducting, with free-space material assumed within the cavity $(\varepsilon_o, \mu_o, \sigma = 0)$. We consider the specific case $a = 32$ mm, $b = 16$ mm and various gap sizes d. Solutions for the cutoff frequency of the waveguide defined by the cross section of Fig. 1 are examined. The fields do not vary in the z-direction at cutoff and, therefore, magnetic walls are placed on the minimum and maximum z surfaces.

TABLE I
TLM and FDTD Solutions for the Ratio b/λ for the Various Gap and Cell Sizes

Gap Size, d (mm)	Δl (mm)	TLM	FDTD
12	1.0	0.242158	0.241394
12	0.5	0.243048	0.242621
12	0.25	0.243225	0.243198
12	0.125	0.243603	0.243501
10	1.0	0.233557	0.232428
10	0.5	0.234811	0.234224
10	0.25	0.235278	0.235085
10	0.125	0.235526	0.235569
8	1.0	0.221736	0.220270
8	0.5	0.223341	0.222639
8	0.25	0.224134	0.223799
8	0.125	0.224283	0.224354
6	1.0	0.206632	0.204856
6	0.5	0.208656	0.207795
6	0.25	0.209766	0.209254
6	0.125	0.210492	0.209866
4	1.0	0.187707	0.185391
4	0.5	0.190297	0.189144
4	0.25	0.191564	0.190952
4	0.125	0.192104	0.191843

TABLE II
TLM and FDTD Prediction of b/λ for $\Delta l \to 0$ and the Benchmark Solution for Various Gap Sizes

Gap Size, d(mm)	TLM ($\Delta l \to 0$)	FDTD ($\Delta l \to 0$)	Benchmark Solution
4	0.192791	0.192794	0.192792
6	0.210921	0.210648	0.210784
8	0.224782	0.224959	0.224870
10	0.235851	0.236001	0.235926
12	0.243742	0.243806	0.243774

In the simulations, a few cells are used to model the z-direction of the problem; the solution being independent of the number of cells. This specific geometry has been previously investigated in [4]–[6].

In order to obtain benchmark solutions for the resonant frequency for various gap sizes, we analyze the problem using both methods on increasingly finer meshes. We consider cubical mesh sizes of $\Delta l = 1.0, 0.5, 0.25$, and 0.125 mm for both the x- and y-directions. The simulations for these mesh sizes run for 8000, 16000, 32000, and 64 000 time steps, respectively. The FDTD algorithm is run at the limit of stability. The predictions for b/λ, where λ is the wavelength corresponding to the first resonance of the cavity, for all of the above mesh sizes are provided in Table I. For each gap size, we fit a linear function, using a least-squares linear regression, to the data points corresponding to the values of b/λ versus cell size. The y*-intercept* of these linear functions is an estimate of the solution for b/λ as $\Delta l \to 0$, an infinitely fine discretized problem. Higher order curve fitting to these data points was also performed, where only a slight change in the predicted $\Delta l \to 0$ solutions was observed. Shih and Hoefer have utilized a similar strategy [4]. These estimated values are provided in Table II. We found that the difference between the $\Delta l \to 0$ solution provided by the TLM and FDTD simulations is less than 0.16% for all cases. We chose the benchmark solution to the problem as the average of the TLM and FDTD estimates. For the two specific gap sizes common to both our investigation and that of Shih and Hoefer [4], our benchmark solution is identical to that provided by the transverse resonance method [4] (data in [4] is provided for four significant figures).

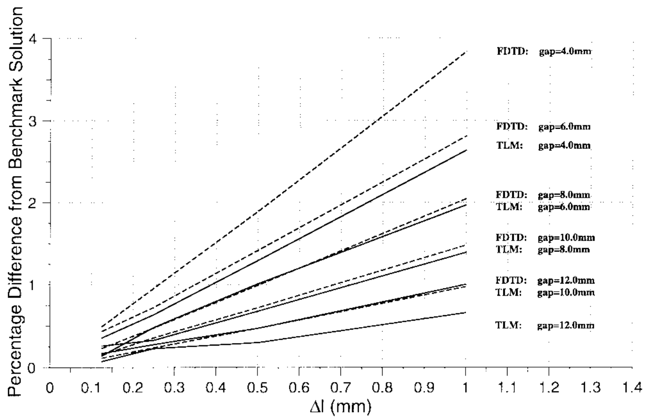

Fig. 2. Comparison of the percentage difference of TLM and FDTD solutions for b/λ from the benchmark solutions versus mesh discretization Δl. Data provided for various gap sizes d. TLM (FDTD) data points are connected with solid (dashed) lines.

TABLE III
SLOPES OF THE LINES OF FIG. 3 FOR VARIOUS GAP SIZES

Gap Size, d(mm)	$SLOPE_{TLM}$	$SLOPE_{FDTD}$	$SLOPE_{FDTD}/SLOPE_{TLM}$
4	0.3282	0.4788	1.458
6	0.2573	0.3422	1.330
8	0.1671	0.2601	1.557
10	0.1196	0.1893	1.583
12	0.0802	0.1233	1.539

Average value of $SLOPE_{FDTD}/SLOPE_{TLM}$=1.49

III. COMPARISON OF FDTD AND TLM SOLUTIONS

A comparison of the FDTD and TLM solutions with the benchmark solution will allow a measure of the relative accuracy of the methods to be determined. The goal of this comparison is to determine the Δl required by both methods in order to achieve the same accuracy. In Fig. 2, the percent difference between the FDTD and TLM solutions and the benchmark solutions are provided versus Δl for various gap sizes. It is noticed that error decreases as gap size increases. For large gap sizes, the problem approaches that of a simple two-dimensional waveguide cross section. For the case of a simple two-dimensional waveguide cross section, the error in the solution is due only to numerical dispersive errors. The inverse of the discretization ratio $\lambda/\Delta l$ is always greater than 64 in our calculations and, therefore, these errors are minimal.

For all Δl considered, TLM is more accurate than FDTD since the percent error in the TLM solution is always less than that of the FDTD solution. The curves for the smaller gap sizes (corresponding to the larger error) appear to be linear. In order to obtain a relative measure of the TLM and FDTD accuracy, we fit a straight line to these curves using a least-squares linear regression, and compare the slopes of the fitted lines. The slopes of these lines represent the increase in solution error for a given increase in Δl. The slopes along with their ratios are provided in Table III. The slopes are greater for the FDTD method, indicating a larger increase in solution error for the same increase in Δl. Note that the data points, as presented in Fig. 2, are connected with straight line segments. The lines obtained from the linear regression are not provided. The y-intercepts of the fitted linear functions are very small for all gap sizes (less than 0.066). This indicates the fitted linear functions intersect the point (0, 0), indicating the error reduces to zero as $\Delta l \rightarrow 0$.

The ratio of the slopes is equivalent to $\Delta l_{\rm FDTD}/\Delta l_{\rm TLM}$, the ratio of cell sizes required by each method to obtain the same accuracy of solution. We expect these ratios to be indicative of the relative accuracy of the two methods for problems containing sharp metallic fins and, therefore, independent of specific problem details such as gap size. As shown in Table III, the ratios do not vary from the average value by more than -11% to $+6\%$. The average value of the ratio is 1.49, indicating the FDTD method requires $(1.49)^3$ or 3.33 times more cells for a given three-dimensional field problem than the TLM method (1.49 times more cells per linear dimension of the problem).

TABLE IV
COMPUTATIONAL REQUIREMENTS OF THE TLM AND FDTD ALGORITHMS, AS GIVEN IN [8, pp. 64–71] AND [14]

	TLM*	FDTD
Add/Subtract	24	24
Multiplication	6	6
Stored Coefficients	0	0
Real Variables	12	6

*not including overhead required for the transfer operation (see discussion in Section IV)

IV. COMPARISON OF FDTD AND TLM COMPUTATIONAL REQUIREMENTS

Following [8, pp. 70–71] and [14], the computational requirements of the two algorithms for a homogeneous problem are provided in Table IV. We require a modification of the computational resources from [14] to include the computational costs of the TLM transfer operation. Numerical simulations using our TLM simulation program on the geometry under study indicate an 11% central processing unit (CPU) time cost for the transfer event. Therefore, the relative number of operations is given by $N^T_{\rm OPS} = 1.11 N^F_{\rm OPS}$. The TLM algorithm requires two times the number of real variables per cell, $N^T_{\rm BYTES} = 2N^F_{\rm BYTES}$. These per-cell comparisons along with the data in Table III enable a comparison of the resources of the methods as they are applied to a problem possessing sharp metallic edges.

Consider a generic problem, the physical shape of which is a cube of size D_x by D_y by D_z meters, which will be simulated for D_t seconds. In the previous section, we determined that if we analyze the problem using the TLM algorithm with a cell size of $\Delta l_{\rm TLM}$, we will require a FDTD cell size of $\Delta l_{\rm FDTD} = \Delta l_{\rm TLM}/1.49$ to obtain similar accuracy. The maximum TLM and FDTD time steps are given, respectively, by

$$\Delta t_{\rm TLM} = \frac{1}{2}\,\frac{\Delta l_{\rm TLM}}{c} \quad \text{and} \quad \Delta t_{\rm FDTD} = \frac{1}{\sqrt{3}}\,\frac{\Delta l_{\rm FDTD}}{c}.$$

The number of cells, N^T_η in the η dimension $(\eta \in \{x, y, z, t\})$ required by the TLM algorithm, is $D_\eta/\Delta l_{{\rm TLM},\eta}$. The computational effort and memory required by the FDTD algorithm is given by

$$\begin{aligned} CE_{\rm FDTD} &= N^F_t N^F_x N^F_y N^F_z N^F_{\rm OPS} \\ M_{\rm FDTD} &= N^F_x N^F_y N^F_z N^F_{\rm BYTES} \end{aligned}$$

and for the TLM algorithm is given by

$$\begin{aligned} CE_{\rm TLM} &= N^T_t N^T_x N^T_y N^T_z N^T_{\rm OPS} \\ M_{\rm TLM} &= N^T_t N^T_x N^T_y N^T_z N^T_{\rm BYTES}. \end{aligned}$$

Comparing the requirements given the $\Delta l_{\rm FDTD} = \Delta l_{\rm TLM}/1.49$ ratio determined in the previous section, we obtain

$$\begin{aligned} CE_{\rm FDTD} &= \frac{\sqrt{3}}{2*(1.11)}\,(1.49)^4 CE_{\rm TLM} = 3.84 CE_{\rm TLM} \\ M_{\rm FDTD} &= \frac{(1.49)^3}{2}\,M_{\rm TLM} = 1.65 M_{\rm TLM}. \end{aligned}$$

This indicates that the TLM algorithm is more efficient than the Yee FDTD algorithm in terms of both computational effort and memory requirements for a problem involving homogeneous material properties and containing a sharp metallic edge.

V. Discussion and Conclusions

A comparison of the TLM and FDTD algorithms for the analysis of a perfectly conducting cavity possessing sharp metallic edges has been provided. The accuracy of the methods for this geometrically simple problem is relevant to practical applications such as modeling of microstrip and coplanar-waveguide structures. The shift in resonant frequency observed in the solutions to this problem is due to the inability of the methods to accurately model the rapid spatial variation of the field distribution in the vicinity of the singularity at the edge of the metal fin. We obtain a benchmark solution from which to compare our calculations by extrapolating the solutions on meshes of different cell size to the limit of an infinitely fine mesh. It is interesting to note that the convergence of both the TLM and FDTD methods for this problem appears to be first order and not second order, as would normally be expected.

Comparison of the TLM and FDTD predictions of resonant frequencies indicates that in order to achieve the same accuracy, the FDTD mesh must be 1.49 times as fine as the TLM mesh (per spatial dimension of the problem). Including the computational costs of the algorithms, the FDTD algorithm requires 1.65 times as much memory, and 3.84 times as much computational effort in order to achieve the same accuracy as the corresponding TLM simulation.

We do not interpret our result as an indication that, in general, TLM is more accurate than FDTD. It is possible to develop FDTD or TLM algorithms for a variety of different spatial cells. We interpret our results as an indication that the symmetric condensed representation of fields used within SCN–TLM is a more accurate representation than the distributed representation used in the Yee FDTD algorithm.

References

[1] K. S. Kunz and R. J. Luebbers, *The Finite Difference Time Domain Method for Electromagnetics*. Boca Raton, FL: CRC Press, 1993.

[2] C. Christopoulos, *The Transmission Line Modeling Method (TLM)*. Piscataway, NJ: IEEE Press, 1993.

[3] P. B. Johns, "A symmetrical condensed node for the TLM method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 370–377, Apr. 1987.

[4] Y.-C. Shih and W. J. R. Hoefer, "The accuracy of TLM analysis of finned rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 743–746, July 1980.

[5] J. L. Herring and W. J. R. Hoefer, "Improved correction for 3-D TLM coarseness error," *Electron. Lett.*, vol. 30, no. 14, pp. 1149–1150, July 1994.

[6] ——, "Accurate modeling of zero thickness septa with the symmetric condensed node," in *1st Int. Workshop TLM Modeling—Theory and Applicat.*, Victoria, B.C., Canada, 1995, pp. 237–240.

[7] K. L. Shlager, J. G. Maloney, S. L. Ray, and A. F. Peterson, "Relative accuracy of several finite-difference time-domain methods in two and three dimensions," *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 1732–1737, Dec. 1993.

[8] A. Taflove, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Norwood, MA: 1995.

[9] N. R. S. Simons and J. LoVetri, "Derivation of two-dimensional TLM algorithms on arbitrary grids using finite element concepts," in *1st Int. Workshop TLM Modeling—Theory and Applicat.*, Victoria, B.C., Canada, 1995, pp. 47–54.

[10] J. Fang and K. K. Mei, "A higher order finite difference scheme for the solution of Maxwell's equations in the time domain," in *Proc. URSI Radio Sci. Meeting*, 1989, San Jose, CA, p. 228.

[11] T. Deveze, L. Beaulieu, and W. Tabbara, "A fourth order scheme for the FDTD algorithm applied to Maxwell's equations," in *IEEE AP-S Int. Symp. Dig.*, Chicago IL, 1992, pp. 346–349.

[12] N. R. S. Simons and A. Sebak, "Fourth-order in space and second-order in time TLM model," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 437–444, Feb. 1995.

[13] G. Haussmann and M. Piket-May, "FDTD M24 dispersion and stability in three dimensions," in *13th Annu. Rev. Progress Appl. Comput. Electromag.*, Monterey CA, 1997, pp. 82–89.

[14] V. Trenkic, C. Christopoulus, and T. M. Benson, "Efficient computation algorithms for TLM," in *Proc. 1st Int. Workshop TLM Modeling—Theory and Applicat.*, Aug. 1–3, Victoria, B.C., Canada, 1995, pp. 77–80.

A New Global Time-Domain Electromagnetic Simulator of Microwave Circuits Including Lumped Elements Based on Finite-Element Method

K. Guillouard, M. F. Wong, V. Fouad Hanna, and J. Citerne

***Abstract*— This paper proposes an extension of the finite-element time-domain method for the global electromagnetic analysis of complex inhomogeneous microwave distributed circuits, containing linear or nonlinear lumped elements. This technique combines Maxwell's equations and circuit equations, directly using SPICE software for the lumped part. Its validation is performed through the study of a strongly coupled two-element active antenna.**

***Index Terms*— FDTD methods, finite-element method, hybrid techniques, nonlinear circuits, time-domain analysis.**

I. Introduction

Time-domain numerical methods based on Maxwell's equations have been widely used to solve transient or wide-frequency-band electromagnetic (EM) problems. Recently, efforts have been devoted to adapt these full-wave analyses to the characterization of complex and highly integrated microwave devices, including distributed as well as lumped circuits. Among these solutions, the finite-difference time-domain (FDTD) and the transmission-line matrix (TLM) extensions are the most commonly proposed [1]–[4]. These techniques depend on the types of studied lumped elements, as they have to develop the appropriate current–voltage model of the elements. Another solution consists in combining a rigorous time-domain EM simulator with a circuit software to directly take advantage of the vast choice of component models provided by the circuit software libraries [5]–[7]. However, to our knowledge, few investigations have been published concerning such an extension using the finite-element time-domain (FETD) method [8].

Thus, in this paper, a new time-domain technique combining the FETD method and SPICE software is presented. In fact, our technique extends, in the time domain, the concept of the coupling between

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