# SIMULATION OF RADIATION FROM A MICROSTRIP ANTENNA USING THREE-DIMENSIONAL FINITE-DIFFERENCE TIME-DOMAIN (FDTD) METHOD

W.J. BUCHANAN, N.K. GUPTA AND J.M. ARNOLD
WJ Buchanan and Dr NK Gupta are with the Department of Electrical, Electronic and Computer Engineering at Napier University, Edinburgh, UK.
Dr JM Arnold is with the Department of Electronics and Electrical Engineering at University of Glasgow, Glasgow, UK.

## 1. INTRODUCTION

Many electrical engineering problems can be easily formulated and expressed using Maxwell's equations. These equations define exactly the propagation of all electrical signals but their exact solutions are complex and tedious. There are, however, some approximate methods that are easier and more widely used. Three well-established methods for approximate solutions are:

- Finite-Difference Method;
- Variations Method;
- Finite-Element Method.

The next generation of computers will bring a revolution by maximising the use of parallel processing in computation. With this technology full time-domain solutions will be possible and frequency information can be extracted using Fast Fourier Transform techniques. The most relevant method for parallel systems is the Finite-Difference Time-Domain Method.

Finite-Difference Time-Domain Method is a novel method in that it provides for a direct solution to Maxwell's equations without much complexities. Also this method takes all fields (electric and magnetic) in a three-dimensional model into account; other empirical analytical methods do not.

Three-Dimensional Finite-Difference Time-Domain (3D FDTD) method has been successfully applied to structures such as Microstrip [1-6,9,10] and waveguides [7] to determine characteristics such as input impedance and scattering parameters. The FDTD method has also been applied to other applications such as the study of electromagnetic pulse (EMP) interaction with targets, radar cross section (RCS) calculations and to biological applications. Although there has been extensive research and many applications of the FDTD method to electromagnetic scattering problems, little has been reported on its application in modelling of radiations from antennas.

Taflove [6], Railton and McGeehan [8] have successfully applied FDTD method to predict cross-talk within high speed circuits and substrates. The authors have used FDTD method to model and predict the radiation patterns from a microstrip antenna.

One problem in modelling microstrip antennas is that these structures are highly resonant. The authors in this paper have described techniques to reduce this problem and have also given methods to improve accuracy and to reduce run-times. These methods include sub-gridding around discontinuities and parallel processing.

The authors have carried out modelling on three computer systems (an HP400, a 486-based PC and a 386-based PC with a transupter array) and they conclude with their opinion that the 3D FDTD method is an efficient and accurate technique to model microstrip antennas.

## 2. FINITE DIFFERENCE TIME-DOMAIN (FDTD) METHOD

With increasing power and memory storage of modern computers it is possible to simulate concepts in the time domain rather than analysing them in the frequency domain. Another change in techniques has been to convert continuous equations into discrete forms. These discrete forms are usually much easier to implement on a digital computer. A good example of the use of time-domain simulation using a discrete equation is in the Finite-Difference Time-Domain Method [12,13]. This technique also determines the frequency response over a wide spectrum of frequencies, whereas other methods would require different models and/or techniques for different frequency spectra.

### 2.1 Application of 3D FDTD method

For uniform, isotropic and homogeneous media Maxwell's curl equations can be simplified as below:

$$\mu \frac{\delta \mathbf{H}}{\delta t} = -\nabla \times \mathbf{E}$$

$$\varepsilon \frac{\delta \mathbf{E}}{\delta t} = \nabla \times \mathbf{H}$$

In order to find an approximate solution to this set of equations, the problem is made discrete over a finite three-dimensional computational domain with appropriate boundary conditions imposed on the source, conductors and mesh walls. Taking an example of the first equation in the i direction:

$$\mu \frac{\Delta H_x}{\Delta t} = \frac{\Delta E_y}{\Delta z} - \frac{\Delta E_z}{\Delta y}$$

In order to obtain discrete approximations the central difference approximation is used on both the time and space first-order partial differentiations; this gives:

$$\mu \frac{H^{n+1/2}_{xi,j,k} - H^{n-1/2}_{xi,j,k}}{\Delta T} = \frac{E^{n}_{yi,j,k} - E^{n}_{yi,j,k-1}}{\Delta z} - \frac{E^{n}_{zi,j,k} - E^{n}_{zi,j-1,k}}{\Delta y}$$

Rearranging and writing all the equations gives the following:

$$H^{n+1/2}_{x\,i,j,k} = H^{n-1/2}_{x\,i,j,k} + \frac{\Delta t}{\mu \Delta z}[E^{n}_{y\,i,j,k} - E^{n}_{y\,i,j,k-1}] - \frac{\Delta t}{\mu \Delta y}[E^{n}_{z\,i,j,k} - E^{n}_{z\,i-1,j,k}]$$

$$H^{n+1/2}_{y\,i,j,k} = H^{n-1/2}_{y\,i,j,k} + \frac{\Delta t}{\mu \Delta x}[E^{n}_{z\,i,j,k} - E^{n}_{z\,i,j,k-1}] - \frac{\Delta t}{\mu \Delta z}[E^{n}_{x\,i,j,k} - E^{n}_{z\,i-1,j,k}]$$

$$H^{n+1/2}_{z\,i,j,k} = H^{n-1/2}_{z\,i,j,k} + \frac{\Delta t}{\mu \Delta y}[E^{n}_{x\,i,j,k} - E^{n}_{x\,i,j,k-1}] - \frac{\Delta t}{\mu \Delta x}[E^{n}_{y\,i,j,k} - E^{n}_{y\,i-1,j,k}]$$

$$E^{n+1}_{x\,i,j,k} = E^{n}_{x\,i,j,k} + \frac{\Delta t}{\varepsilon \Delta y}[H^{n+1/2}_{z\,i,j+1,k} - H^{n+1/2}_{z\,i,j,k}] - \frac{\Delta t}{\varepsilon \Delta z}[H^{n+1/2}_{y\,i,j,k} - H^{n+1/2}_{y\,i-1,j,k}]$$

$$E^{n+1}_{y\,i,j,k} = E^{n}_{y\,i,j,k} + \frac{\Delta t}{\varepsilon \Delta z}[H^{n+1/2}_{x\,i,j,k+1} - H^{n+1/2}_{x\,i,j,k}] - \frac{\Delta t}{\varepsilon \Delta z}[H^{n+1/2}_{z\,i,j,k+1} - H^{n+1/2}_{z\,i,j,k}]$$

$$E^{n+1}_{z\,i,j,k} = E^{n}_{z\,i,j,k} + \frac{\Delta t}{\varepsilon \Delta x}[H^{n+1/2}_{y\,i+1,j,k} - H^{n+1/2}_{y\,i,j,k}] - \frac{\Delta t}{\varepsilon \Delta y}[H^{n+1/2}_{z\,i,j+1,k} - H^{n+1/2}_{x\,i,j,k}]$$

The half time steps indicate that E and H are alternately calculated in order to achieve central differences for the time derivatives. In these equations, the permittivity and the permeability are set to the approximate values depending on the location of each field component.

### 2.2 Problem formulation

The structure simulated in this paper is a microstrip antenna. This structure is used to radiate microwave energy at a desired resonant frequency. The transient analysis to the antenna is complex as it involves multiple reflections and is highly resonant at certain frequencies. The physical structure of the antenna consists of a substrate layer, such as Duroid (dielectric constant of 2.2), and a ground plane below this layer. A copper layer is formed by etching off a portion from the top of the substrate to give the required pattern. The diagram in figure 1 shows an example of a microstrip antenna with an xyz grid superimposed on the structure.

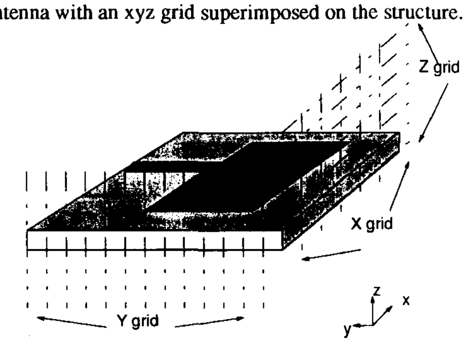


FIG.1 Microstrip antenna with grid

To analyse this structure using the 3D FDTD method the six equations of section 2.1 are used in conjunction with the following model considerations:

(1) Dielectrics-

In air, the relative dielectric constant is $\varepsilon_{r1}$; in dielectric, it is $\varepsilon_{r2}$; at the interface between the air and the dielectric, the relative dielectric constant is the average of the air and the dielectric, i.e. $\frac{\varepsilon_{r1}+\varepsilon_{r2}}{2}$

(2) Time step-

the maximum time step that may be used is limited by the stability restriction of the finite difference equations. This is shown below.

$$\Delta t < \frac{1}{c}[\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}]^{-1/2}$$

c is the speed of light (300,000,000 m/s) and $\Delta x$, $\Delta y$ and $\Delta z$ are the dimensions of the unit cell.

(3) Source- A Gaussian pulse is applied to the source. This pulse is used because its frequency spectrum is also Gaussian and will provide frequency-domain information for DC to the desired cut-off frequency by adjusting the width of the pulse. The width of the Gaussian pulse is chosen for at least 20 points per wavelength at the highest frequency represented significantly in the pulse.

The electric field applied to the source has only a z component and is Gaussian.

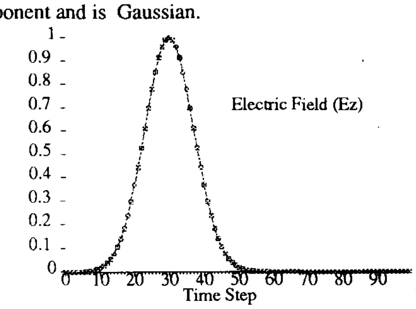


FIG.2 Gaussian pulse

Frequency information is extracted by conducting a FFT on the time response.

### 2.3 Parallel processing of 3D FDTD method

Simulation of the structure on different computer systems shows the need for a maths co-processor. A maths co-processor fitted into a PC improves run-times more than ten-fold. The next generation of computers will have an architecture which will support truly multiple processing systems, with different processes running off a unique microprocessor. These systems will be able to run many processes concurrently.

Currently transputers can be fitted into a PC or workstation and can be configured to run multiple processes, even when operating under a single user operating system such as DOS. A transputer can execute an application as a single process on one processor, but can be used with other transputers to form a large array in which each transputer communicates with its neighbouring transputers by means of point-to-point communication. A typical transputer has a 32-bit RISC processor, on-board and local memory, full 64-bit float point processing and high speed serial link to communicate with other transputers. Each transputer is equivalent to a microcomputer and can run at 30 Mips, 4.3

MFlops. It can address up to 4 GBytes of RAM and communicate at 5/10 or 20 MBits/sec. A transputer does not have the problems of segmented memory (64kByte chunks and maximum addressable memory of 1MByte) that a PC running 8086/DOS compatible code has.

To simulate the microstrip antenna of figure 1, the problem must be segmented into physical domains. Each parallel process will operate on one of these domains. An advantage of the 3D FDTD method is that the present calculations depend only on the previous time-step calculations and that no cell has to wait until the neighbouring cells have completed their calculation for input to this cell (sequential method of sweeping over a problem). The problem with any parallel processing task is that the boundary conditions need to be transmitted after each iteration. Even if these boundary conditions are transmitted at 1/5/10 or 20 MBits/sec, these communications can have a large overhead in time. Thus, for a given size of problem, the more the number of parallel processes, the more is the time spent with the inter-domain communications (transmitting boundary conditions for each domain). The actual time to compute the simulation will reduce by a factor determined by the number of transputers. The total time taken, then, will be the sum of the actual computation time and the total inter-communication time. A typical simulation for a 50x80x12 grid with 50 time steps is shown in figure 3. These simulations are based on a 1 MBit/sec inter-communication rate, assuming 4 bytes per floating point value. It can be seen from the figure that the optimum number of transputers is probably about 3 or 4. Also it can be observed that if 20 or more transputers are used, there is virtually no significant improvement in simulation time. In typical simulations, if more than 50 transputers are used, the simulation time starts to increase for increasing number of transputers.

An advantage of using transputers in a PC is that a model using more that 1 MB of memory can be simulated. However, there will be a limit on the maximum number of transputers that can be used to process the problem.

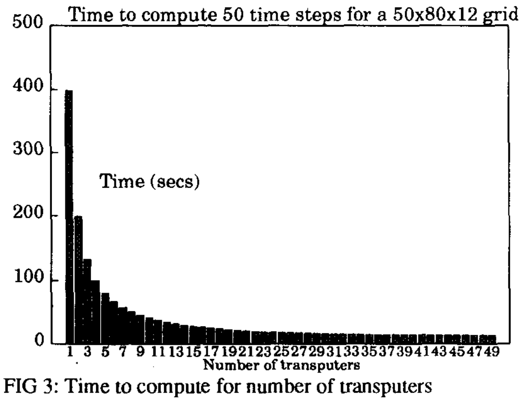


FIG 3: Time to compute for number of transputers

## 3. RESULTS

The results from a simulation using a 4-transupter array connected to a 386-based PC for a 50x100x12 grid are shown in figures 4-6. The simulated antenna has a width of 12.45mm, a length of 16.00mm and a feed width of 2.46mm, which is offset from the edge of the head of the antenna by 2.09mm. Each time step is approximately 1.25 picoseconds. The Electric Field plots show the field intensity in the z-direction and are measured just below the antenna. Results show that the antenna resonates at 7.5 GHz, as expected. and that over 90% of the incident energy is radiated at and around the frequencies of 7.5 GHz, 10 GHz, 12 GHz and 18 GHz. The simulated model assumes a match between the source and the antenna and an absorbing boundary around on the outer walls of the problem. These values will not be totally accurate since the FDTD method used does not take into account conduction or dielectric losses.

In figure 4, the pulse has entered the structure and is propagating along the feed to the head of the antenna. In figure 5, the pulse enters the head of the antenna and a negative pulse is reflected from the interface between the feed and the head of the antenna (this is because the feed has a higher characteristic impedance than the head). As seen in figure 6, a negative pulse propagates back to the feed and the pulse entering the head reaches the end of the head and is reflected back. Thus the structure continues to resonate until the pulse is either radiated or absorbed at source or the outer walls.

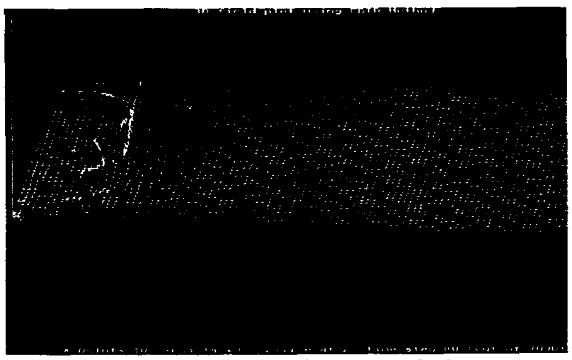

FIG 4: Pulse in launched into antenna feed

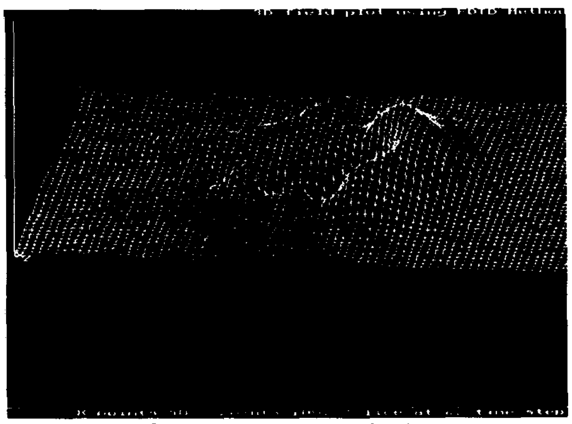

FIG 5: Pulse enters antenna head

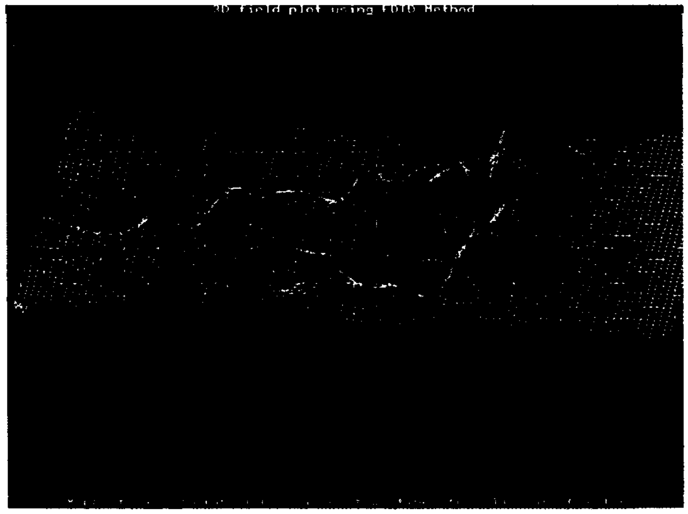

FIG 6: Pulse in head antenna showing reflected pulse

## 4. CONCLUSIONS

Although the exact solution of Maxwell's equations is complex and tedious, finite-difference time-domain method is a novel method for solving these equations with great accuracy and simplicity.

One problem with the FDTD method is that it simulates structures in the time-domain, which requires large memory storage and large run-times. However, this problem can be reduced by using modern powerful computers (such as 386/486 PCs and workstations). For very large and complex simulations the use of parallel processing will further alleviate this problem. The next generation of computers should bring a revolution in the 21st century by maximising the use of parallel processing in computation. Parallel processing reduces run time and increases grid size by segmentation of the problem.

Another problem with the method used is that it does not take into account diectric losses and assumes perfect conductors. Improved accuracy can be obtained using sub-gridding methods around discontinuties [3].

The results obtained clearly show the propagation, reflection and absorption of a Gaussian pulse appropriate to its position in the structure and time. This pulse can be used to determine all required frequency characteristics from DC to the required upper frequency with no change to the model for different frequency spectra.

The authors are convinced that parallel processing is an efficient and accurate technique for the simulation of complex structures by the method of FDTD to determine electrical parameters and can be used on limited memory computer systems (such as modern PCs) with transputer arrays.

## 5. ACKNOWLEDGEMENT

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