Performing 3-D FDTD Simulations in less than 3 Seconds on a Personal Computer and its Application to Genetic Algorithm Antenna Optimization

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Abstract — FDTD simulations generally require significant computational resources and time. This paper systematically reduces the number of time steps and the grid size to determine the shortest simulation time that returns results with tolerable error for microstrip antenna simulations and their optimization of insertion loss with the genetic algorithm. Although the error would generally be unacceptable for traditional antenna simulations, it is sufficiently small to optimize their design. Simulations in less than 3 seconds on a P4 2.8 GHz processor were shown to be usable, with error approximately equal to manufacturing tolerances. A dual band 'waffle' antenna is designed that has better performance than the traditional dual band "F" antenna.

I. Introduction

The finite difference time domain (FDTD) method [1], has become a mainstay of electromagnetic computation. It has been applied to a seemingly endless array of applications, with little limitation of geometry, frequency band, materials, etc. FDTD has an advantage over the method of moments which is also commonly used to model antennas [2], because it can simulate a fully heterogeneous antenna or antenna environment, however this does come at a significant cost. Computer simulation time and memory requirements are inherently large in heterogeneous simulations of this type, and FDTD is no exception. This computational cost has a serious impact on the numerical optimization of antennas, such as is often done using the genetic algorithm (GA) [3]. The GA will create a "population" of many (in our case 16) antennas, run their simulations (an individual FDTD simulation for each antenna), reject the poor performers, mutate/cross-over the good performers, and repeat this for many (50-100) generations resulting in 800-1600 FDTD simulations. A simple pioneering FDTD simulation with a grid size of 20x20x40 took over 38 minutes to run 600 time steps [4]. Since that time, much larger simulations have been run requiring days and even weeks [5].

This paper focuses on ways to reduce the overall time required by reducing the time for each FDTD simulation. Many efforts have been made to reduce the time required to run FDTD simulations. Methods to make FDTD run faster include: subdividing the problem and running on multiple computers or processors in parallel [5-10], using an initially smaller grid that expands with time [11], efficient processing of fields to extract useful information [12], using variable cell sizes [13], and exploiting symmetry to reduce the model size [14, 15 and others] to name a few. Dedicated hardware has also been developed specifically for FDTD to circumvent the limitation of general purpose processors [16]. A single FDTD simulation can now readily be done for most if not all field analysis applications of interest. When multiple simulations are required, however, the computational requirements can become prohibitive.

Researchers have used the GA to optimize antennas, but have generally relied on methods other than FDTD [2, 17]. Some researchers have used GA-FDTD schemes, but found computational constraints to be a limiting factor [18, 19]. They have limited the GA search to a small set of parameters, thereby limiting its usefulness as an optimization method. This paper shows that with the proper selection parameters, FDTD simulations can be run quickly enough on a personal computer to be used to design a dual band antenna using the GA in a very short period of time. Unlike typical numerical solutions where we need excellent accuracy and precision, it was found that relatively "sloppy" FDTD simulations, while not perfectly accurate, can yield results that are sufficient to determine the relative performance of similar antennas, and hence the design of optimal antennas.

Section II describes a traditional dual band monopole antenna that is used for comparison and simulation purposes. Section II also introduces QFDTD, an FDTD program well suited to use with genetic algorithms. Section III analyzes the how reducing the run time of the FDTD algorithm affects accuracy. The number of time steps is reduced, and the FDTD grid is reduced in a systematic manner while error is measured. Section IV applies the results from Section III to the design of a dual band antenna using the genetic algorithm. Section V gives instructions on how to apply these methods generally, and Section VI draws conclusions from the results.

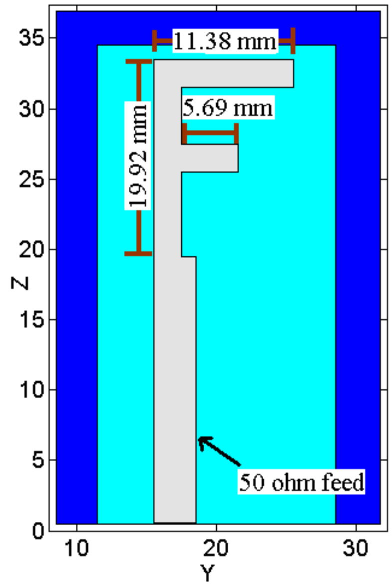

Fig. 1. Model of dual band 2.4/5.2 GHz "F" antenna as created by the authors. ΔX = 0.762 mm, ΔY=ΔZ= 1.423 mm. A ground plane on the back of the substrate extends from Z=1 to the end of the 50 ohm feed at Z=19.

II. Antenna Model and FDTD

In [20], a dual band monopole "F" antenna is designed on a microwave substrate at 2.4/5.2 GHz. In this paper, we optimize the design of a similar antenna structure shown in Fig. 1. The antenna is designed to have low insertion loss at 2.4 and 5.2 GHz as shown in Fig. 2. The FDTD model cell size is 0.762 x 1.423 x 1.423 mm^3. The microwave substrate is 0.060 inches (1.524 mm) thick and has a relative dielectric constant of 2.6. The cell dimension X is chosen to be half the substrate thickness, and the Y-Z dimension is chosen to simulate a 50 Ω microstrip feed. This antenna model is used in section IV to determine key FDTD simulation parameters.

FDTD models Maxwell's equations in a spatial grid consisting of electric and magnetic field components, which are alternately computed as the algorithm steps through time. Each cell in the grid contains six orthogonal electric and magnetic field components. Because the cells in the grid must be a minimum of $\lambda/10$ for numeric accuracy and are typically $\lambda/20$ to $\lambda/60$, the grid can be very large for many structures, including antennas. As an example, a 100x100x100 grid that can model roughly a λ^3 antenna has six million field components that need to be updated with each of about 2000 time steps.

The major sources of error in FDTD calculations are due to numerical dispersion, reflections due to imperfect absorbing boundary conditions (ABCs), and poor modeling because of a discrete rectangular grid. Numerical dispersion can be minimized by reducing the cell size. When the grid sampling density is 10 points per free-space wavelength, the numerical dispersion is approximately 1%, which is considered the minimum special sampling rate for accurate simulations [21]. By increasing the grid sampling density to 20 points per wavelength, the dispersion is reduced to 0.2% (and the grid size increases by a factor of 8). This paper uses a spatial sampling frequency of about 35 points per wavelength to accurately model the feed, reducing dispersion errors to negligible levels.

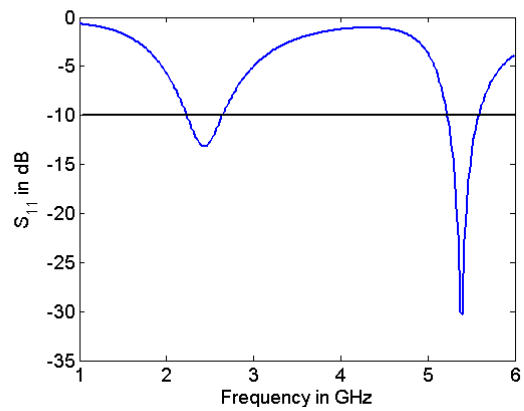

Fig. 2. Insertion loss of "F" antenna with 50 ohm feed. Note that the "F" antenna is frequency shifted at 5.2 GHz due to the course grid requirements of FDTD.

An in depth review of analytical boundary operators are covered by [22]. This review explains that the approximations used to create ABCs cause them to be imperfect. Waves traveling normal to the 2nd order Mur boundary are absorbed well. As the angle of incidence increases, the reflection coefficient increases. By increasing the grid size (and the computation time), the maximum angle of incidence is reduced, reducing reflections. Also, fewer waves will reflect back onto the antenna, because the antenna is located further from the boundary.

For fast FDTD simulations, care needs to be taken to ensure accurate simulations, while keeping the grid to a minimal size. In addition, the boundary conditions need to be computationally efficient. The commercial software package QFDTD uses simple update equations that assume a non-dispersive media. It also uses the computationally efficient Mur 2nd order boundary condition. It is written in FORTRAN90, allowing the user to modify it and port it to any desired platform. Additionally, it uses text files for all input-output operations, allowing the GA to easily create new models and access output data [23]. QFDTD runs two simulations to analyze a structure. The first simulation

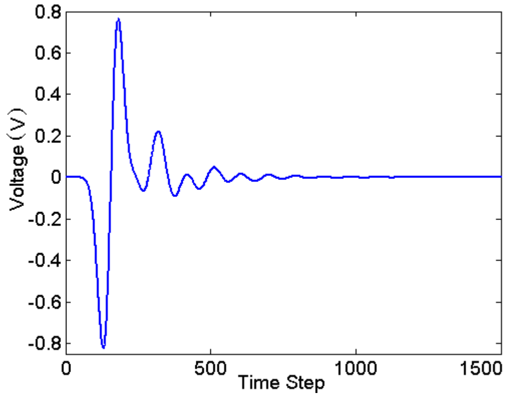

Fig. 3. Voltage on microstrip feed versus time.

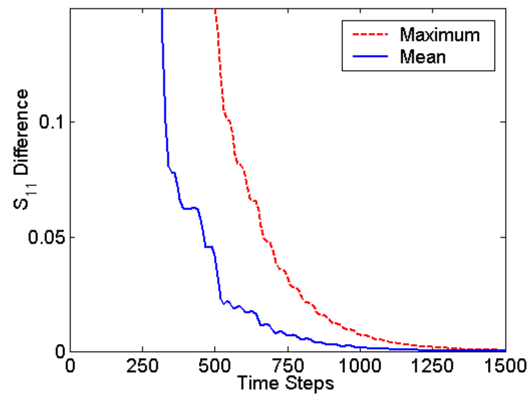

Fig. 4. Difference in insertion loss power over 1-6 GHz frequency band when number of time steps is reduced, compared to a simulation running 5000 time steps.

measures the incident signal at the microstrip feed. The second simulation measures the total signal. By subtracting the incident signal from the total signal, the scattering parameters are calculated over a wide frequency range. This two-simulation setup can be exploited with GA optimization. If the feed doesn't change, the first simulation results can be used for all subsequent simulations, and its contribution to overall computation time is negligible.

III. Simulations Speed and Accuracy

Well known ways to reduce FDTD simulation time include reducing the number of operations by reducing the model size and/or running fewer time steps. However, there are fundamental limits on how much reduction in size and time can be done before inaccuracies are introduced. This section of the paper assesses the impact of each time reduction method on the accuracy and speed of the program.

A. Run for fewer time steps

Perhaps the most obvious method to speed up the FDTD simulation is to reduce the total number of time steps in the simulation. The "F" antenna model was simulated for a long time, to determine the minimum number of time steps needed for transients to die down to a sufficient level as shown in Fig. 3. Then S_{11} is calculated from 1-6 GHz in 0.1 GHz increments. The simulation is then repeated many times stopping at 300 to 1500 time steps. S_{11} is calculated for each simulation, and the change in reflected power is computed at each frequency increment. The maximum and average change in reflected power is given in Fig. 4. Simulations show that S_{11} changes very little after 1500 time steps. Fig. 4 shows that if the number of time steps is reduced to 900, the error is relatively small, but the computation time is almost cut in half. Reducing the number of time steps below 600 creates significant errors, especially in the higher frequencies.

The number of time steps required is also dependent on the size of the discrete time step. Generally, Δt should be the maximum value that meets the Courant stability criterion unless lossy or active components are embedded into the FDTD grid [23]. Using the highest stable value of Δt will avoid unnecessary time steps. QFDTD and other commercial FDTD programs used by the authors automatically calculate the correct value for Δt.

B. Reduce grid size

Reducing the grid size can have an even greater effect on simulation time than the number of time steps. If the dimensions of a 3-D grid are halved in each direction, the number of cells is reduced by a factor of eight, but the grid size reduction effectively brings the outer boundary closer and causes reflections at the boundary to increase. To determine how much grid size affects S_{11}, the "F" antenna model was simulated on a grid with 37x48 cells in the YxZ direction and a variable number of cells in the X direction. It is first simulated on a 100x37x48 grid for comparison. After the comparison simulation is run, the X grid is reduced to 10 and expanded in the X direction with each simulation, while the antenna is held at the center of the grid. Fig. 5a shows that as the grid expands in the X dimension, the change in reflected S_{11} power is reduced.

The next test enlarged the grid in all three dimensions and compared the results to a 100x100x100 cell grid. As can be seen from Fig. 5b the difference in S_{11} continued to decrease as the grid is enlarged, but the results have not fully converged, even when the grid is a 100x100x100 cell. Expanding the grid beyond 100x100x100 cells to reduce reflections proved unreasonable. Rather a smaller grid would be implemented with a more effective, but computationally costlier, boundary condition. Thus a

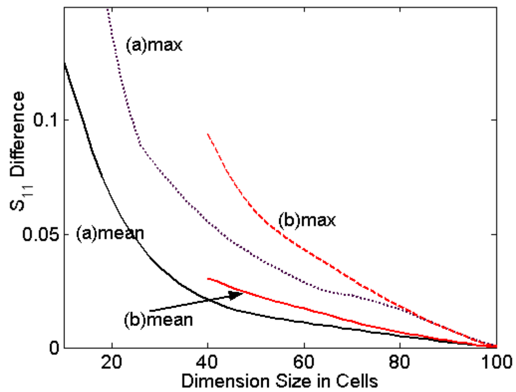

Fig. 5. Change in S_{11} power when grid size is changed. (a) YZ dimensions are 37 and 48. X dimension vary from 10-100 cells. (b) XYZ dimensions vary from 40-100 cells.

100x100x100 grid for these simulations could be considered large enough when using the Mur 2nd order boundary condition. Getting the fastest execution time precludes the use of high cost boundary conditions even for small simulations.

It is significant to note that reducing the grid size caused more error in the lower frequency part of the 1 to 6 GHz range. Reducing the grid size moves the outer boundary closer to the antenna model. Because distance to the outer boundary is relative to the wavelength, lower frequencies will be closer to the boundary than higher frequencies. It was also observed that reducing the number of time steps produced more error in the higher frequency part of the 1 to 6 GHz simulations (although we can't explain why and it may be model-dependent). From these observations we can conclude that a relatively narrow band design can be run faster. A low frequency design can run for fewer time steps, and a high frequency design can simulate on a smaller grid, while maintaining simulation accuracy.

C. Other execution speed factors

The FDTD executable needs to be optimized for speed. The authors found that different compilers and compiler settings can affect execution speed by more than 300%. Also, storing more information than necessary increase the simulation time and memory usage.

Each speed increase factor is multiplied by the next factor. Implementing all speedup factors results in a dramatic decrease in FDTD run time. This speedup makes FDTD a viable simulator for running hundreds or even thousands of simulations needed by the GA optimizer.

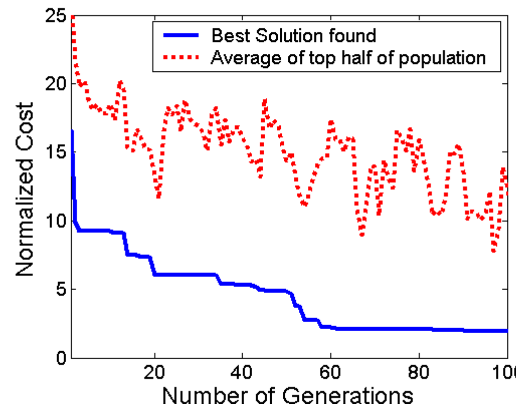

Fig. 6. Cost (or fitness) of antennas at each generation of the GA. The cost is the percentage of reflection loss over the frequency range of 2.2 – 2.6 GHz, and 5.0-5.5 GHz.

IV. Application Example-Design of GA Antenna

To show that high speed FDTD simulations can produce useful results, the authors remove the branches from the “F” antenna model to produce a simple monopole. This simple monopole is then placed in a 25x30x42 cell grid to be simulated for 900 time steps. A rectangle with either non-metal or metal covered cells is placed over the top of the monopole model. The cells with and without metal correspond directly to the “1s” and “0s” in a binary chromosome that is controlled by the GA.

The GA creates a population of 16 antennas, and simulates them for 100 generations. Each antenna is given a cost which is based on how much insertion loss it generates over the frequency bands 2.2-2.6 GHz and 5.0-5.5 GHz. Single point crossover is used, and population decimation is used as the selection criteria. The mutation method randomly picks bits in each chromosome and replaces the previous value with a random bit. This mutation method is different than standard mutation schemes, but is necessary because it may be desirable to have a higher percentage of "1" bits. Fig. 6 shows that the GA is able to evolve an antenna with low return loss after 60 generations. Fig. 7 shows the optimized antenna model. After the GA completes optimization, the final model is simulated for 1500 time steps on a larger 100x100x100 grid for comparison.

Fig. 8 shows that the smaller model didn’t produce the most accurate results, but the optimized antenna performance is still very good. In addition, the change in S_{11} from the small to the large model is comparable to manufacturing tolerances found by previous GA antenna designers [16, 17]. The larger comparison simulation shows that the GA antenna has a

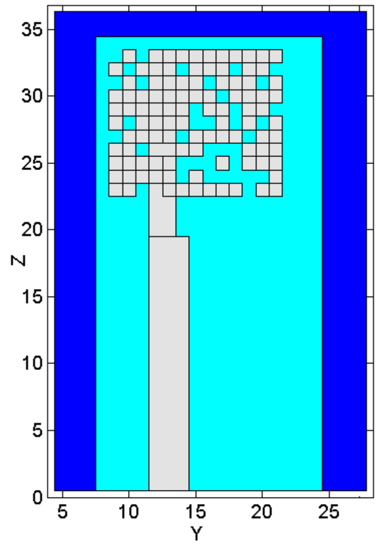

Fig. 7. Antenna design created by GA using structure similar to "F" antenna design in Fig. 1. The GA created a population of 16 structures and evolved them for 100 generations to create this final design found in the 91st generation. The substrate dimensions are 17x34 cells or 24.19mm x 48.38mm. The substrate is 1.524 mm thick.

-10 dB insertion loss bandwidth from 2 to 2.6 GHz and 5.1 to 5.7 GHz. This is better than the results obtained by the authors and [20] for the "F" antenna. It is true that the GA design shown isn't much better than the "standard" design. The point of this paper is that it can quickly be designed using the GA if a small FDTD model is used. We purposely used a simple dual band design because we are emphasizing FDTD. Once the simulation time is reduced, very wide or multiband designs can be quickly produced that would be nearly impossible to produce using conventional design techniques. We have obtained better results using smaller cells, but we wanted to step to the limits in this paper.

Our first optimization simulations took over 17 minutes. To run 1600 simulations would take 19 days, and we often had to make changes in our model starting the process over again. Using the techniques described in this paper (along with faster processors) has reduced simulation time to less than 3 seconds for the models presented here. With faster simulation times, several designs can be produced in a single day.

The entire optimization presented took only 82 minutes and ran 1600 FDTD simulations. That corresponds to 3.06 seconds for the GA to create each model, run the FDTD simulation, and evaluate its cost. The simulation was run on a Pentium 4 running at 2.8 GHz. The FDTD executable was created using the Intel FORTRAN Compiler Version 8.0 for Linux.

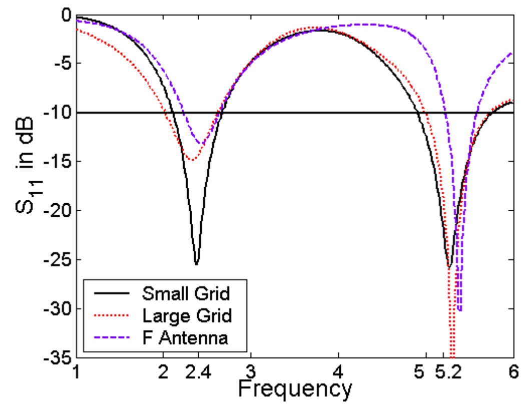

Fig. 8. Optimized S_{11} results as calculated on small grid (25x30x42 cells) for GA optimization, and large grid (100x100x100 cells) for comparison with "F" antenna. Even though the small grid introduces simulation error, the -10 dB bandwidth is very close on both simulations, justifying the use of the small grid for fast optimization.

V. General Application of Speed Increase Methods

Carefully choosing the cell and grid size is essential to fast and accurate FDTD simulations. Minimizing the grid size and number of time steps can reduce simulation time 1-2 orders of magnitude compared to poorly chosen parameters.

As explained in the introduction, the cell size should be chosen to accurately model the structures dimensions, and meet the minimum of 10 cells per wavelength at the lowest frequency. A general guideline for choosing the grid size is to have at least 1/4 wavelength between the structure and the outer boundary at the lowest frequency of interest. For the example given, the wavelength at 2.2 GHz is 136 mm and 1/4 wavelength is 34 mm. The cell size in the X direction is 0.762 mm or about 45 cells. These are similar to the dimensions used for the 100x100x100 cell grid (about 45 cells above and below the model). The problem with this approach is that each simulation takes approximately 94 seconds or almost 42 hours for a 1600 simulation GA optimization. By reducing the grid size, additional error will be introduced into the simulation. The plots in Fig. 5 give the reader a general guide to how much error is introduced, and the grid size should be chosen based on how much error can be tolerated. Again, more error will be introduced at the lower frequencies as shown in Fig. 8.

Correctly choosing the number of time steps is also critical to a fast, accurate simulation. In the example shown, a modulated Gaussian pulse is used.

After 900 time steps the reflected signal at the feed is reduced to 0.5% of the pulses maximum amplitude. For fast simulations, the reflected signal should decay to between 0.5% and 1.0%. After 1500 time steps, negligible error was introduced, and the reflected signal was 0.1% of the maximum incident pulse. Note that highly resonant structures may require much longer simulation times.

Advanced absorbing boundaries such as PML have lower reflections, but a much higher computational cost. It should therefore be possible to reduce the grid size without inducing as much error as when reducing the grid size using the Mur boundary. Optimizing using the GA on a larger grid after it has been optimized on a small grid is an excellent way to apply the results of the small grid optimization. When only a few variables are present, a hybrid GA that consists of a GA and local optimizer works extremely well and will outperform the GA alone [24]. However, a local optimizer wouldn't be appropriate in this situation because each cell is considered a variable, and local optimizers are not efficient for a large number of variables.

Several antenna prototypes have been successfully built using photo-etching techniques, and measured data has matched well with simulations [25]. Using these techniques, broad and multiband designs have been created that minimize size requirements while achieving extremely low return loss.

VI. Conclusions

FDTD is a viable solution for the GA simulator on a PC if FDTD parameters are chosen for quick simulation. Even though individual simulation results may not be extremely accurate, their relative values are sufficient for the GA to find a good solution. When the FDTD simulation is optimized for speed by running for a minimum number of time steps, using a minimal FDTD grid, and storing only necessary information, it can be fast enough to compete with other simulation techniques such as method of moments. Simulation time is no longer the limiting factor with the GA-FDTD combination, allowing for more complex designs to be generated than previously possible, including the 2.4 GHz and 5.2 GHz dual band antenna described in this paper.

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