Bandwidth Optimisation of a Planar Inverted-F Antenna using Genetic Algorithms

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***Abstract*- The gain and bandwidth performances of an antenna are directly related to its dimensions in relation to the wavelength. This paper presents the optimisation of a simple PIFA (Planar Inverted-F Antenna) antenna in order to achieve a large bandwidth in the 2 GHz band, using the genetic algorithms optimisation tool. During the optimisation process, the different PIFA models, with the same overall dimensions, have been evaluated using the finite-difference time domain (FDTD) method.**

I. Introduction

Owing to the increase of wireless communications, the frequency band of 2 GHz is finding more and more demand. With this ever wide-spreading technology, the requirements placed on antenna design are increasingly stringent. The Planar Inverted – F Antenna (PIFA) is the most widely used antenna for the purposes mentioned above owing to its low profile, ease of fabrication and high efficiency.

In the design process, electric and magnetic fields have to be analysed in order to evaluate the performance of the antenna. Various techniques exist for the analysis of electromagnetic fields and microwave propagation. To gain a better-detailed understanding of electromagnetic interaction and fields, numerical simulation techniques are favoured against approximate analysis methodologies. A variety of three-dimensional full-wave methods are available to account for the electromagnetic propagation in space.

The aim of this study is to optimise a PIFA antenna to work in the 2 GHz band. To evaluate the performance of the antenna and observe the three-dimensional propagation of the electric and magnetic fields, the Finite Difference Time Domain (FDTD) method has been chosen.

The optimisation tool utilised in this work, is based on natural genetics and is known as the Genetic Algorithms (GA) optimising tool. The GA is a very powerful search and optimisation tool which works differently compared to classical search and optimisation methods. GA is nowadays being increasingly applied to various optimising problems owing to its wide applicability, ease of use and global perspective.

II. Basic Concepts

A. Maxwell's equations

In order to study electromagnetic waves propagation in space and time, laws governing time varying electromagnetic fields need to be studied. Maxwell developed a collective set of equations expressing all the laws of electromagnetism. These equations basically represent four fundamental laws, namely Faraday's law of induced electromotive force (emf), Ampere's circuital law, Gauss's law of electric field, and Gauss's law of magnetic field. These laws may be written in time-domain, respectively as:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1a}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \sigma \vec{E} \tag{1b}$$

$$\nabla \cdot \vec{D} = \rho \tag{1c}$$

$$\nabla \cdot \vec{B} = 0 \tag{1d}$$

where ρ is the electric charge density and σ is the electrical conductivity of the medium. Equation (1b) can be transformed and re-expressed to obtain an equation that can be used in FDTD,

$$\nabla \times \vec{H} = \varepsilon' \frac{\partial \vec{E}}{\partial t} + \sigma_{eq} \vec{E} \tag{1e}$$

Similarly, equation (1a) can be re-expressed as

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{1f}$$

It is assumed that the materials present have no magnetic losses.

B. The 2GHz band

The frequency band between 1 and 2 GHz is finding increasing application for satellite and land mobile services. In antenna technology it lies in a crossover region, in which techniques which are used at frequencies in the very high frequency (VHF) and ultra high frequency (UHF) bands merge with microwave designs.

The various types of antennas working in the 2 GHz band are mentioned below:

- Low-directivity Antennas
- Medium-directivity Antennas
- High-gain Antennas

Some reports of the International Bureau concerning the frequency band of 2 GHz band show that the 2 GHz band is still not a fix-allocated frequency band [1].

The PIFA has proved so far to efficient in the 2 GHz band. Among these services, the two services which are most prone to be allocated the 2 GHz frequency spectrum are the Mobile Satellite Services (MSS) and the third generation (3G) of terrestrial mobile system namely the UMTS or IMT-2000.

C. Planar Inverted F - Antenna

The PIFA has proved to be the most widely used internal antenna for commercial wireless systems of both the Mobile Voice and Radio Frequency (RF) data communications. In many research publications pertaining to the PIFA technology, the thrust has been on optimal performance despite the miniaturization in the sizes of both the antenna and the ground plane [2].
The conventional geometry of the PIFA, similar to that in [2], is shown in figure 1

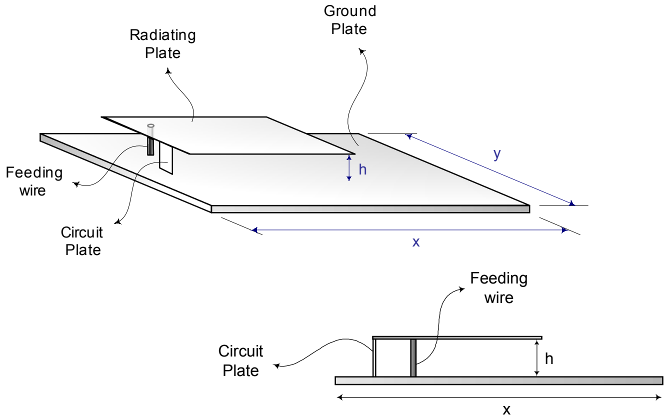

Fig. 1. Geometry of the PIFA

There is a large degree of variations as regards to the constraints on the sizes of radiating element, ground plate as well as on the choice of preferred placement of the PIFA within the communication device. The location, the size (height and width) and the relative orientation of the parasitic with respect to the radiating element control the tuning performance of antenna.

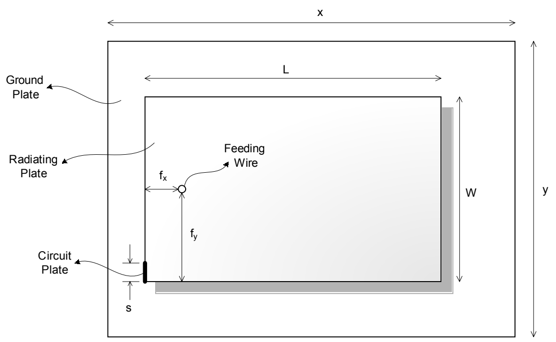

Fig. 2. Top view of the PIFA

As it may be seen in figure 2, the PIFA antenna has several parameters which may be varied to adjust the performance of the antenna. The most important parameters are the heights *h* of the radiating plate, the feeding wire position f_x and f_y, the radius r_o of the feed wire.
Owing to large computational time involved in the design of the antenna, all the case studies considered herein deal with varying heights of the radiating plates and the location of the feeding wire only, whilst the fixed parameters are the width and length of both the radiating element and the ground plate, to find an optimum performance of the PIFA.

III. Finite Difference Time Domain Method

Finite-Difference Time Domain (FDTD) is a popular and among the most widely used electromagnetic numerical modelling technique. This method belongs in the general class of differential time domain numerical modelling methods. This section describes briefly the FDTD method used throughout the project.

A. FDTD Theory

When Maxwell's differential form equations are examined, it can be seen that the time derivative of the E field is dependent on the Curl of the **H** field. This can be simplified to state that the change in the E field (the time derivative) is dependent on the change in the **H** field across space (the Curl). Using mathematical expressions for the curl of a vector, equations (1e and 1f) can be expressed in rectangular coordinates as a system of six coupled partial-differential equations.

$$\mu \frac{\partial H_x}{\partial t} = \left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right) \tag{2a}$$

$$\mu \frac{\partial H_y}{\partial t} = \left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right) \tag{2b}$$

$$\mu \frac{\partial H_z}{\partial t} = \left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right) \tag{2c}$$

$$-\varepsilon' \frac{\partial E_x}{\partial t} = \left(\frac{\partial H_y}{\partial z} - \frac{\partial H_z}{\partial y} \right) + \sigma_{eq} E_x \tag{2d}$$

$$-\varepsilon' \frac{\partial E_y}{\partial t} = \left(\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial z} \right) + \sigma_{eq} E_y \tag{2e}$$

$$-\varepsilon' \frac{\partial E_z}{\partial t} = \left(\frac{\partial H_x}{\partial y} - \frac{\partial H_y}{\partial x} \right) + \sigma_{eq} E_z \tag{2f}$$

FDTD starts by discretising a three-dimensional space into rectangular cells, which are called Yee Lattice [3]. The Yee lattice is specially designed to solve vector electromagnetic field problems on a rectilinear grid. The grid was assumed to be uniformly spaced, with each cell having edge lengths Δx, Δy and Δz equal to 2 mm. It was then labelled using discrete indices (i, j, k), where the physical coordinates $(x, y, z) = (i\Delta x, j\Delta y, k\Delta z)$. Within each cell, six possible components of **E** and **H** fields were evaluated at distinct space and time points.

Figure 3 shows the positions of fields within a Yee cell. Each **E** component is surrounded by four circulating **H** components. Likewise, every **H** component is surrounded be four circulating **E** components. In this way, the curl operations in Maxwell’s equations can be performed efficiently.

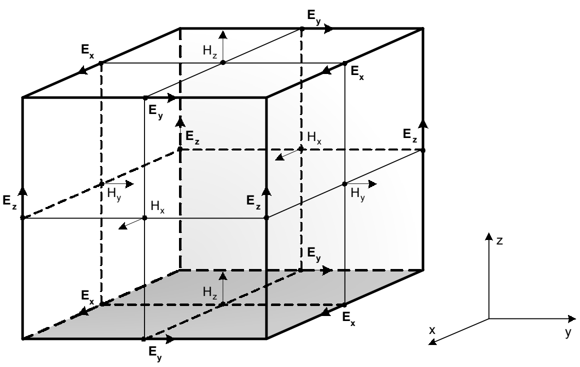

Fig. 3. The FDTD cell showing the position of the E and H fields components

A system of six difference equations for the six components of **E** and **H** fields can be obtained by evaluating the time and space derivatives of the fields using central difference equations [3]. Electric fields are sampled at integer multiples of time step $t = n\,\Delta t$, where Δt is the time step. Magnetic fields are sampled at half-integer multiples of time steps $t = (n + ½)\,\Delta t$.

The partial space derivative of a vector field $V(i,j,k,n)$, at spatial point (i,j,k) and time point $n\Delta t$, with respect to x is discretised as

$$\frac{\partial V(i,j,k,n)}{\partial x} \approx \frac{V^{n}\left(i+\frac{1}{2},j,k\right) - V^{n}\left(i-\frac{1}{2},j,k\right)}{\Delta x} \tag{3}$$

The derivatives with respect to y and z have similar expressions to equation (3). The partial time derivative of $V(i,j,k,n)$ at the fixed space point (i,j,k) is expressed as V

$$\frac{\partial V(i,j,k,n)}{\partial t} \approx \frac{V^{n+\frac{1}{2}}(i,j,k) - V^{n-\frac{1}{2}}(i,j,k)}{\Delta t} \tag{4}$$

Therefore, using discretisation of the calculus operators in equation (4) results in a set of algebraic time-stepping relation which may be written as

$$H_x^{n+\frac{1}{2}}(i,j,k) = H_x^{n-\frac{1}{2}}(i,j,k) - \frac{\Delta t}{\mu}\left[\frac{E_z^{n}\left(i,j+\frac{1}{2},k\right) - E_z^{n}\left(i,j-\frac{1}{2},k\right)}{\Delta y}\right] + \frac{\Delta t}{\mu}\left[\frac{E_y^{n}\left(i,j,k+\frac{1}{2}\right) - E_y^{n}\left(i,j,k-\frac{1}{2}\right)}{\Delta z}\right] \tag{5a}$$

$$H_y^{n+\frac{1}{2}}(i,j,k) = H_y^{n-\frac{1}{2}}(i,j,k) - \frac{\Delta t}{\mu}\left[\frac{E_x^{n}\left(i,j,k+\frac{1}{2}\right) - E_x^{n}\left(i,j,k-\frac{1}{2}\right)}{\Delta z}\right] + \frac{\Delta t}{\mu}\left[\frac{E_z^{n}\left(i+\frac{1}{2},j,k\right) - E_y^{n}\left(i-\frac{1}{2},j,k\right)}{\Delta x}\right] \tag{5b}$$

$$H_z^{n+\frac{1}{2}}(i,j,k) = H_z^{n-\frac{1}{2}}(i,j,k) - \frac{\Delta t}{\mu}\left[\frac{E_y^{n}\left(i+\frac{1}{2},j,k\right) - E_y^{n}\left(i-\frac{1}{2},j,k\right)}{\Delta x}\right] + \frac{\Delta t}{\mu}\left[\frac{E_x^{n}\left(i,j+\frac{1}{2},k\right) - E_x^{n}\left(i,j-\frac{1}{2},k\right)}{\Delta y}\right] \tag{5c}$$

$$E_x^{n}(i,j,k) = \alpha E_x^{n-1}(i,j,k) + \beta\left[\frac{H_z^{n-\frac{1}{2}}\left(i,j+\frac{1}{2},k\right) - H_z^{n-\frac{1}{2}}\left(i,j-\frac{1}{2},k\right)}{\Delta y}\right] - \beta\left[\frac{H_y^{n-\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right) - H_y^{n-\frac{1}{2}}\left(i,j,k-\frac{1}{2}\right)}{\Delta z}\right] \tag{5d}$$

$$E_y^{n}(i,j,k) = \alpha E_y^{n-1}(i,j,k) + \beta\left[\frac{H_x^{n-\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right) - H_x^{n-\frac{1}{2}}\left(i,j,k-\frac{1}{2}\right)}{\Delta z}\right] - \beta\left[\frac{H_z^{n-\frac{1}{2}}\left(i+\frac{1}{2},j,k\right) - H_z^{n-\frac{1}{2}}\left(i-\frac{1}{2},j,k\right)}{\Delta x}\right] \tag{5e}$$

$$E_z^{n}(i,j,k) = \alpha E_z^{n-1}(i,j,k) + \beta\left[\frac{H_y^{n-\frac{1}{2}}\left(i+\frac{1}{2},j,k\right) - H_y^{n-\frac{1}{2}}\left(i-\frac{1}{2},j,k\right)}{\Delta x}\right] - \beta\left[\frac{H_x^{n-\frac{1}{2}}\left(i,j+\frac{1}{2},k\right) - H_x^{n-\frac{1}{2}}\left(i,j-\frac{1}{2},k\right)}{\Delta y}\right] \tag{5f}$$

where $\alpha = \dfrac{\dfrac{\varepsilon'}{\Delta t} - \dfrac{\sigma_{eq}}{2}}{\dfrac{\varepsilon'}{\Delta t} + \dfrac{\sigma_{eq}}{2}}$ and $\beta = \dfrac{1}{\dfrac{\varepsilon'}{\Delta t} + \dfrac{\sigma_{eq}}{2}}$

From the equations (5a) to (5f), it can be seen that a new value of the components of **E** at $t = n\Delta t$ can be evaluated from their value at $t = (n - 1)\,\Delta t$ and the values of two nearby **H** field components at $t = (n - 1/2)\,\Delta t$. Using similar equations, (5a) to (5c), the sample values of the **H** field component at one point in time can also be evaluated explicitly from the **E** and **H** fields sampled at a previous point in time.

Equations (5) are called the FDTD field advance equations or the Yee field advance equations [6]. They are explicit and second-order accurate. Using these equations, FDTD proceeds by sequentially evaluating first the magnetic fields over the entire solution space at a time step, and then the electric fields over this space at the next half-time step. The equations are solved in a leap-frog manner; that is, the electric fields are solved at a given instant in time, then the magnetic fields are solved at the next instant in time, and the process is repeated over and over again for the entire time history of interest and produces time-marching solutions of the fields within the entire solution space.

B. Absorbing Boundary Conditions

Bounded boundaries were easily implemented using Perfect Electric Conducting (PEC) walls where $\sigma_{eq} = \infty$, to reflect back the incident waves. However, since the PIFA structure is an open region problem, to solve for unbounded boundaries in a finite computation space, an auxiliary boundary condition was be introduced to effectively absorb all electromagnetic energy impinging on these boundaries. It is noted that the absorbing boundary condition should not produce extraneous reflections back into the region of interest or else these reflections will introduce errors in the solution.

The following absorbing boundary conditions (ABCs) that were tested:

- Dispersed Boundary Condition
  It does not require knowledge of the fields adjacent to the cells, which at the boundaries are unknown. Moreover, the Dispersive boundary condition does not require the tangential fields to be continuous. It is even capable of absorbing any linear combination of plane waves incident on the boundaries and propagating with two different velocities. However, despite the various advantages mentioned, the DBC is not a suitable boundary condition for the FDTD mesh in this work since it does not perform well at low frequencies. Moreover, the DBC requires special treatment at the corners of the FDTD space and thus more computational time.
- Higdon Boundary Condition
  The Higdon Boundary Condition provides good absorption of the fields and minimum reflection. However it does not provide significant attenuation over the frequency range of interest in late time. [4]
- Second-Order Mur's ABC
  The Mur's Absorbing Boundary Condition fit perfectly the requirement of the project. The mesh was truncated in a manner that the exterior boundary effective looks like an unbounded system. The Mur's ABC matched the exterior region to the interior region. It also provided reflectionless boundary over broad spectrum, and for all angles of incidence and polarisation. Moreover, it achieved minimal in computational cost and memory requirement. [5]

The absorbing boundaries were at more than 20 cells away from the antenna in all directions. It is noted that the larger the FDTD mesh size, the longer is the computational time. As a result, the space size were chosen to be not too large but not too small as well so as to prevent considerable interference with reflected waves incident on the boundaries.

C. Source Excitation

The conventional method of exciting PIFAs when using FDTD methods, is using a Gaussian point source.
To excite the PIFA with a wide range of frequencies, the Gaussian pulse was implemented as soft source. This excitation is given by the expression

$$E(t) = cos(\omega t)\, e^{-\frac{t^2}{2\tau^2}} \tag{6}$$

where ω is $2\pi f$ and f is the frequency of the pulse
t is $[(N\Delta t) - t_o]$ and N the number of time steps, Δt is the time step, t_o is the time at which the pulse reaches the peak value of 1.
τ control the width of the pulse

D. Bandwidth calculation

The Voltage Standing Wave Ratio (VSWR) is the key to obtaining the bandwidth of the PIFA. VSWR represents another way of expressing how close a component's characteristic impedance is to the ideal 50ohms (for this study).
In order to obtain the VSWR, the input impedance of the PIFA was first determined. The generalised input or line impedance can be simply calculated as

$$Z(\omega) = \frac{V(\omega)}{I(\omega)} \tag{7}$$

where $V(\omega)$ and $I(\omega)$ are the line voltage and current, respectively, at a fixed point on the transmission line, and are found by Fourier transforming the time-dependent voltages and currents.

After having obtained the input impedance, a scattering parameter, particularly the S_{11} which is the reflection coefficient, was calculated. The scattering parameter or *S*-parameter is a convenient characterisation of a microwave circuit device.

To compute the S_{11} parameter, the expression below is used:

$$S_{11} = \frac{Z - Z_o}{Z + Z_o} \tag{8}$$

where Z is the input impedance of the line
Z_o is the characteristic impedance of the line

This work involved a coaxial line as the input line and the characteristic impedance used for this purpose was 50ohms. Finally, using the S_{11} parameter, the VSWR may be calculated using the following equation

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|} \tag{9}$$

The bandwidth of the antenna is determined, from a graph of VSWR against frequency, by the range of frequencies where the VSWR is less that 2.

The flowchart of the FDTD process is shown in figure 4.

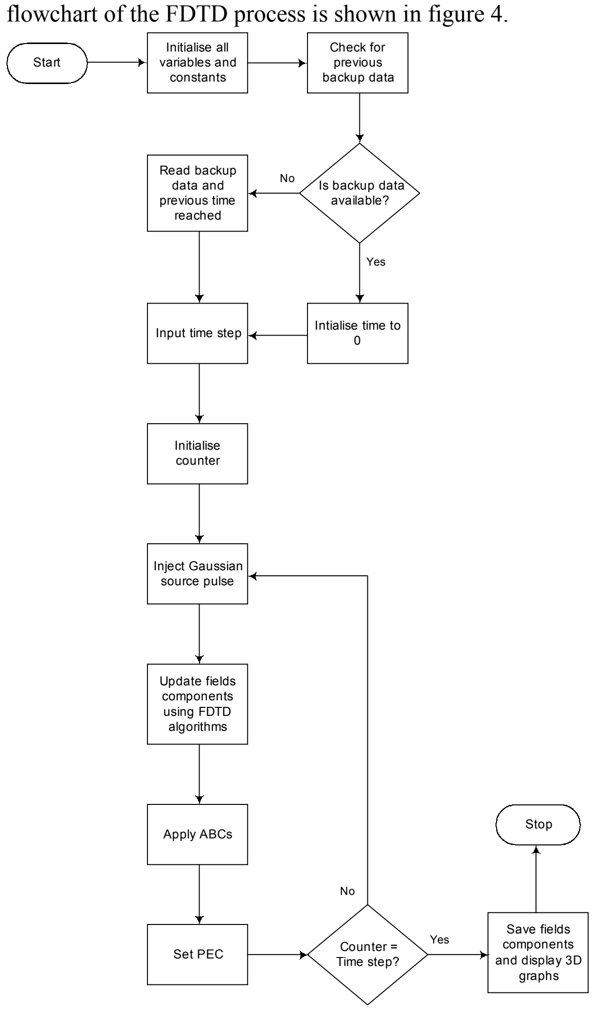

Fig. 4. Flowchart of the FDTD process

IV. GENETIC ALGORITHMS

The GA is a search and optimisation method which works by mimicking the evolutionary principles and chromosomal processing in natural genetics. Every solution is assigned a fitness which is directly related to the objective function of the search and optimisation problem. Thereafter, the population of solutions is modified to a new population by applying three operators similar to natural genetic operators, that is, reproduction, crossover and mutation operators [6]. The GA works iteratively by successively applying these three operators in each generation until a termination criterion is satisfied [7].

For this study, the set of solutions was coded in binary string structures. The working principle mentioned above is simple and GA operators involve string copying and substring exchange and occasional alteration of bits. The basic block of the genetic algorithm is the chromosome. Each chromosome is composed of genes described as a binary sequence of zeros and ones. Each gene is associated with a parameter to be optimised. For the PIFA dealt in this project, three parameters were used: the coordinates of the feeding wire, 'f_x' and 'f_z', and the height 'h' of the radiating plate (Figure 2). For the parameters f_x and f_z, only four discrete possible values were assigned to them and thus, only 2 bits were used to represent each of them. For the height h, only two discrete possible values were assigned to it and thus only 1 bit was enough to quantify it. Hence, 5 bits represent each chromosome associated with the PIFA in this project and in any case, each chromosome describes a particular geometry. It is to be noted that the small length of the string is due mainly to the fact that only a few source locations on the PIFA and only 2 different heights of the radiating plate were considered. However, more source locations and more different heights would result in very long simulation time.

To start the GA simulation, the initial population was created at random, each string was evaluated and the three GA operators were used. The operators used in this work are the proportionate selection reproduction operator, the single-point crossover operator with a probability of 1 and the bit-wise mutation operator with a probability of 0.01 [6].

Figure 5 shows the flowchart of the genetic algorithms process. The values of the parameters for the basic structure obtained from the GA optimisation tool are:

f_x = 3 cells (6 mm)
f_z = 3 cells (6 mm)
h = 4 cells (8 mm).

V. Simulation Results

While the FDTD mesh size, and boundary conditions work well, the PIFA was modelled, using different locations of the source and different heights of the radiating plate only, to evaluate its performance. The PIFA was excited using a Gaussian waveform of frequency ranging from 1.9 GHz to 2.5 GHz and the boundary condition used was the Mur's second order ABC.

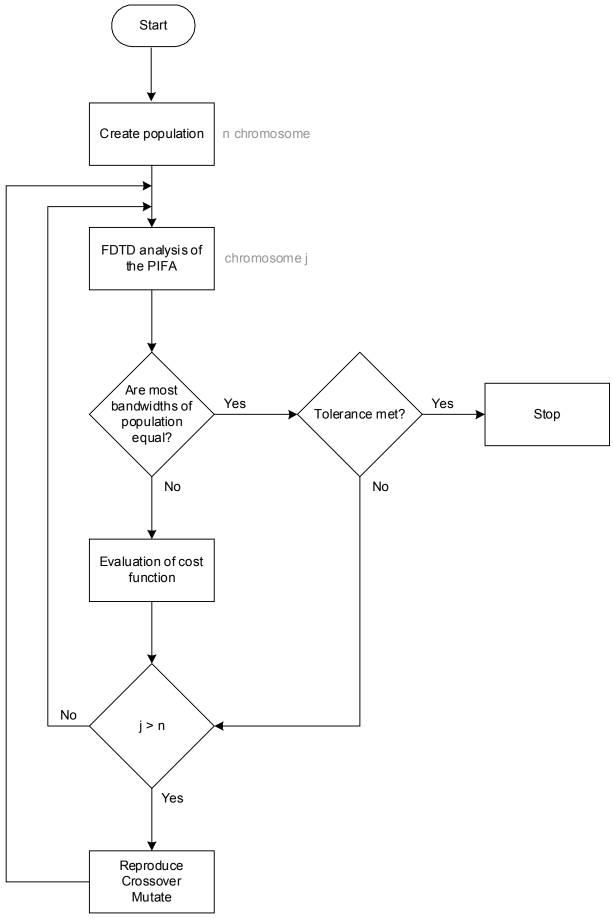

Fig. 5. Flowchart of the GA process

The optimum structure of the PIFA, that is, the feeding wire location at f_x = 3cells, f_y = 3cells and the height h = 4 cells, triggered the following E-field propagation shown in Figures 6a, b and c.

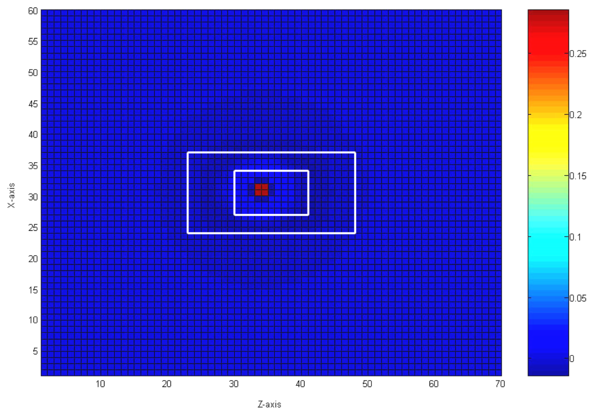

Fig. 6a. Top view of propagating E-field at time step = 40

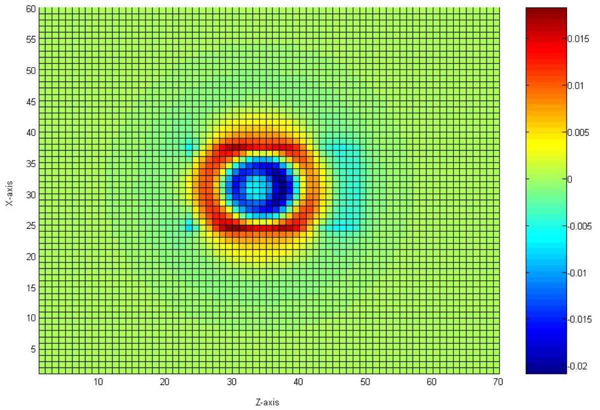

Fig. 6b. Top view of propagating E-field at time step = 50

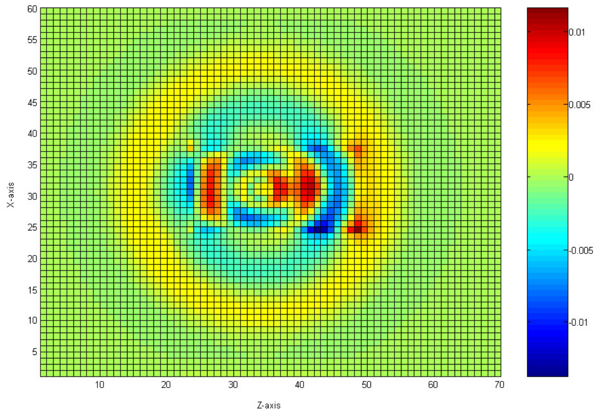

Fig. 6c. Top view of propagating E-field at time step = 70

The simulation results show how the E-fields in between the radiating plate and the ground plate are highly concentrated and how they attenuate and fade out as they propagate in the surroundings. The results also reveal that the boundary condition chosen, that is, the Mur's ABC, absorbs properly the incident fields without creating high peaks in the fields.

The aim of this project was to obtain maximum bandwidth of a PIFA while keeping its overall size unchanged. The optimisation process lead to a bandwidth of approximately 420MHz, as shown in figure 7.

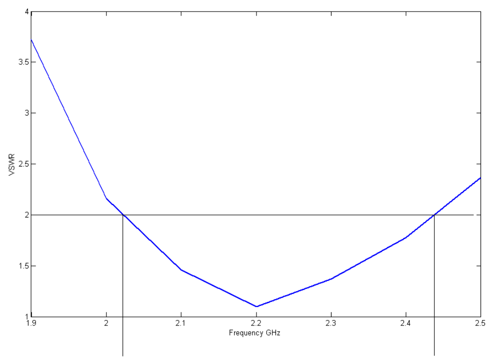

Fig. 7. Bandwidth for optimal solution

VI. CONCLUSIONS

In this paper, a PIFA antenna was optimised using an optimisation tool known as genetic algorithms. During the optimisation process, different antenna structures, with the same overall size, were modelled and their performances were evaluated using a numerical technique known as the finite difference time domain technique.

The FDTD technique is seen to be very powerful for the analysis of electromagnetic propagation. However, the FDTD method is limited by the amount of memory storage required, which depends on the complexity of the problem structure.

The genetic algorithms opted in this project considered the population of solutions in binary strings. Thus only discrete possible values were assigned to the varying parameters which affect the performance of the PIFA. The operators used in the GA process were proportionate selection reproduction, single-point crossover and bit-wise mutation. Using these operators the new population obtained at each generation was a population with more solutions of higher fitness. This implies that the GA was converging properly to an optimal solution.

As a result of the optimisation described above, a simple PIFA antenna was obtained with a bandwidth of approximately 420 MHz and VSWR equal to 1.095 at 2.2 GHz. The corresponding values of the parameters which resulted in the above mentioned bandwidth and VSWR are the *x*-position of the feeding wire, f_x = 6 mm, the *z*-position of the feeding wire, f_z = 6 mm and the height of the radiating plate from the ground plate, h = 8 mm.

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