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Corso di Laurea in Ingegneria Elettronica e Telecomunicazioni

DESIGN OF OMNIDIRECTIONAL CIRCULARLY POLARIZED ANTENNA

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KEY WORD

Electric field

Farfield (ff)

Axial ratio

Electric and magnetic (Eh,Es,Hh,Hs)

Current density (J)

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"Any sufficiently advanced technology is indistinguishable from magic"

Arthur C.Clark

CHAPTER 1

SUMMARY

In this thesis work, the design of circular polarized antenna able to transfer power to some receiving tags is performed. After an investigation of the state-of-the-art, deep focus has been given to study of the antenna characteristics and geometrical parameters, carried out through electromagnetic simulations. Subsequently the entire syste, including both the antenna and the tags, is simulated to quantify the system performance in terms of power transferred.

CHAPTER 2

Introduction

In this project, a circular polarized antenna performing wireless power transfer at 2.4 GHz is designed. Circularly polarized (CP[1]) antennas are a types of antennas with circular polarization. Due to the features of circular polarization, CP antennas have several important advantages compared to antennas using linear polarizations, and are becoming a key technology for various wireless systems including satellite communications, mobile communications, global navigation satellite systems (GNSS), wireless sensors, radio frequency identification (RFID), wireless power transmission, wireless local area networks (WLAN), wireless personal area networks (WPAN), Worldwide Interoperability for Microwave Access (WiMAX) and Direct Broadcasting Service (DBS) television reception systems. Lots of progress in research and development has been made during recent years.

The wireless power transmission is the transmission of electrical power from a power source to an electrical load without wires.
The wireless power transmission has many problems; the most important is the loss during the transmission, around 26 %. One of the main causes of these losses is the resistance of wires used in the grid.
On the other hand, several benefits need to be taken into account: It is efficient, fast, reliable and it can be used for short and long distances and low maintenance cost. The wireless power transmission solves the problems of the cord clutter and eliminates the physical limitations of connectors.

The most common form of power transmission to use direct induction and the resonant magnetic induction; there are other methods of wireless power transmission such as microwaves or beam of light technology.

In my project I designed an omnidirectional circularly polarized antennas to be used as illuminator in wireless power transmission applications, the power has to be transmitted to some tags places in electromagnetic harsh environments. In the *figure 1* shows a schematic representation of wireless power transfer system. We can see the two antennas (Transmitter and receiver) with the power source and the electrical load.
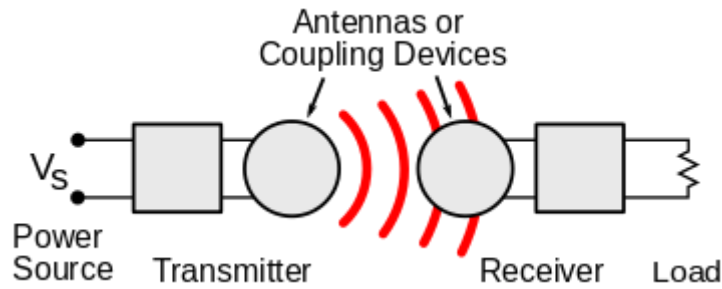
ADVANTAGES AND DISADVANTAGES OF WPT

Thanks to the WPT there is no need of cables, towers and substations transmitting high power between generators and consumers; moreover, Wireless power transmission will reduce the costs for transmission and distribution, also for the consumers, in terms of electrical energy.it

Another benefit provided by the Wireless Power transmission is that it can reach places where cables are not able to reach and losses are almost negligible, therefore the efficiency of this method is greater. This technique is able to use the energy contained in the rectenna while the Wireless power transmission works.

There are also some disadvantages such as the realization costs needed to implement this technology and the possible interferences caused by the use of microwaves.

Another thing that must be taken into account is related to the environmental impact, the possibility of radiation by microwaves, although the level of radiations is low, the use of microwaves can possibly imply the increase of EM radiations, and for this it need to be regulated.

COMPONENTS OF WIRELESS POWER TRANSMISSION

- **Transmitting antenna**

  Usually slotted waveguide antennas, microstrip patch antennas and parabolic antennas are used; the most suitable antenna for the WPT is the slotted waveguide antenna.

- **Rectenna**

  The rectenna is a passive element, it is an antenna composed of a rectifier circuit with a low pass filter between the antenna and the rectifier diode. The most efficient antenna is the patch dipole because it has achieved the highest efficiency. The type of diodes used are Schottky which are used because the recovery time is faster and has a lower voltage drop and good RF characteristics.

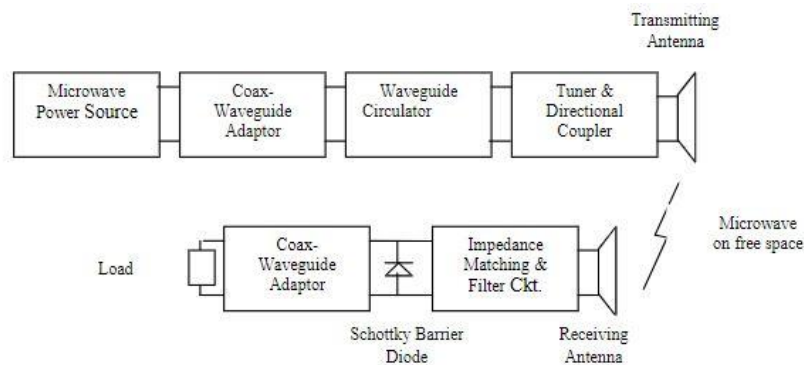The following image shows a complete scheme of the components that make up the WPT.

Figure 2: Scheme of the components

ANTENNA PARAMETERS [2]

Polarization is one of the characteristic parameters of the antenna, it is a property of the electric field vector which defines the variation in direction and magnitude over time. In the case that we observe the field in a plane perpendicular to the direction of propagation in a fixed location in space, the final point of the arrow is the one that represents the instant of the magnitude of the electric field. The curve described by the magnitude of the electric field is usually an ellipse that can be characterized by the axial ratio (AR described below). When we refer to the direction of propagation we are talking about how the vector of the electric field rotates, if the vector rotates clockwise it is designated as RH (Right polarization) and if it rotates counter clockwise LH (left polarization).

To produce circular polarization, two orthogonal components of electric fields in the farfield region are required the electrical field radiated by an antenna can be written as:

$$\vec{E}(\theta, \varphi) = \vec{\theta} E_\theta(\theta, \varphi) e^{j\phi_1} + \vec{\varphi} E_\varphi(\theta, \varphi) e^{j\phi_2}$$

The directivity is defined as the ratio of the radiation intensity of the antenna in a specific direction in space over the intensity of an isotropic source; an isotropic source is one that radiates the same power in all directions.

There are cases in which the term directivity is used to refer to its maximum value.

The gain of an antenna is related to the directivity, but the gain takes into account the losses as well as directional capabilities.

The efficiency of an antenna is the relationship between directivity and gain. It takes into account all power losses

before radiation. These losses can be caused by a mismatch in the input terminals, conduction losses, dielectric losses and overflow losses.

The Effective Isotropically Radiated Power (EIRP) is a figure of merit for the net radiated power in a given direction. It is equal to the product of the net power accepted by the antenna and the antenna gain.

The input impedance is the impedance presented by the antenna at its terminals or the relationship between voltage and current at its terminals. In case the antenna is not adapted to the transmission line a stationary wave is induced along the transmission line.

The relationship between the maximum voltage and the minimum voltage is called the voltage standing wave ratio (VSWR).

Bandwidth and resonant frequency [3] usually an antenna is designed to operate within a specified frequency range. The bandwidth of an antenna is usually determined by the frequency range within which the key parameter of the antenna satisfies a certain requiremen.Often the resonante frequency is chosen as the centre of the frequency bandwidth of an antenna. The bandwidth of an antenna can be calculated by using the upper and lower edges of the achieved frequency range:

$$BW = \frac{f_1 - f_2}{f_0} \times 100$$

f_1 is the lower edge of the achieved frequency range

f_2 is the upper edge of the achieved frequency range

f_0 is the centre frenquency of the range

CHAPTER 3

Description of the coordinate axis

COORDINATE FRAME [4]

A coordinate frame is composed of 3 specific points; the first point is the origin for the new coordinate frame. The second point is used to define the z-axis. A vector is calculated from the origin (first point) to z (second point). In the next picture we can see the two points over the plane.
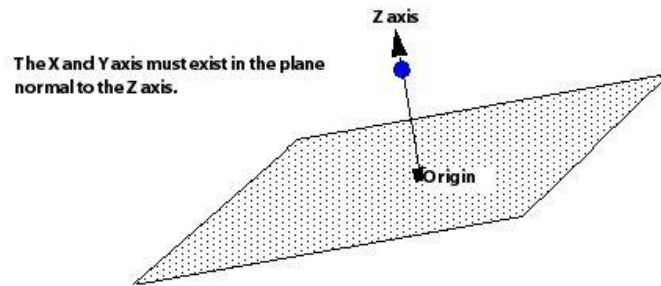
Z axis

The X and Y axis must exist in the plane normal to the Z axis.

Origin

Figure 3: Define the z-axis

The third point is necessary to define the location of the X and Y axes in the plane normal to Z axis. The location of the X-axis must be the intersection between the X-Z plane and the normal plane of the Z-axis.
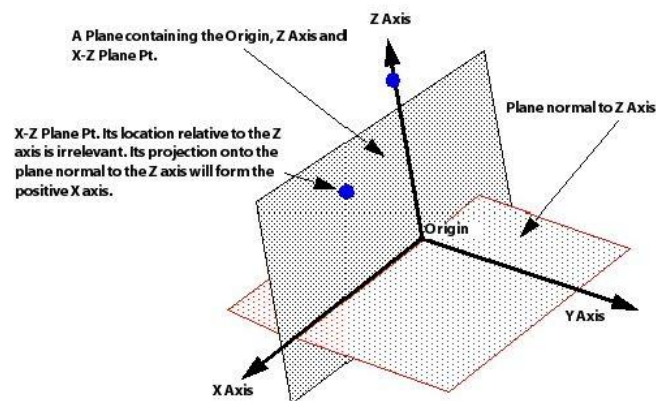
A Plane containing the Origin, Z Axis and X-Z Plane Pt.

Z Axis

Plane normal to Z Axis

X-Z Plane Pt. Its location relative to the Z axis is irrelevant. Its projection onto the plane normal to the Z axis will form the positive X axis.

Origin

Y Axis

X Axis

Figure 4: Define Z-axis, Y-axis and X-axis

Finally, because the Y axis must be perpendicular to both the X axis and the Z axis, its positive direction is determinate by the right hand rule.

For the antennas I have defined two coordinate system (Rectangular system and spherical system) that will be able to give us the gain, but exist three coordinate system Rectangular, spherical and polar system.

Each system is defined by two angles, azimuth and elevation, that are measured relative to the antenna body axes.

RECTANGULAR COORDINATE SYSTEM

The azimuth angle is the one between the projection of the direction vector on the zx plane and the z-axis, the positive azimuth is measured towards the positive x-axis, the range of the azimuth angle goes from -180 degrees to 180 degrees.

The elevation angle is the angle between the projection of the direction vector on the zy plane and the z axis, with the positive elevation measured towards the negative axis and negative elevation towards the positive axis. The range of the elevation angle is from -180 degrees to 180 degrees.
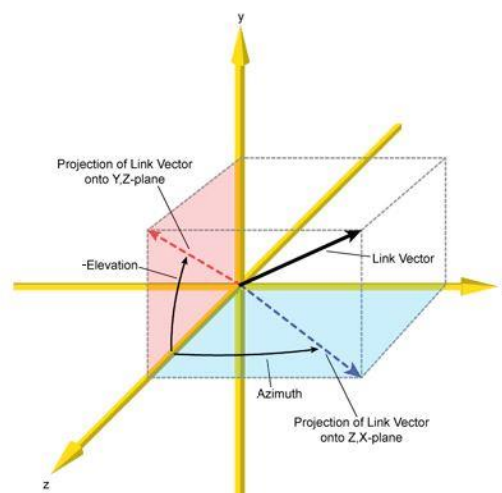

Figure 6: Complete coordinate frame

SPHERICAL COORDINATE SYSTEM

The azimuth angle is defined as the angle measured from the z-axis to the projection of the direction vector into the zy plane. The azimuth angle can range from -180 degrees to 180 degrees, with positive azimuth measured from the z-axis toward the positive y axis and negative azimuth measured from the z-axis toward the negative y-axis.

The elevation is defined as the angle between the zy plane and the direction vector. The elevation angle can range from -90 degrees to 90 degrees, where positive elevation is measured toward the positive x-axis
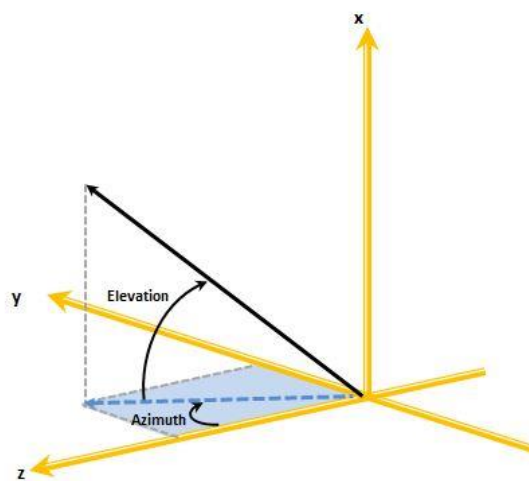

Figure 7: Elevation and azimuth

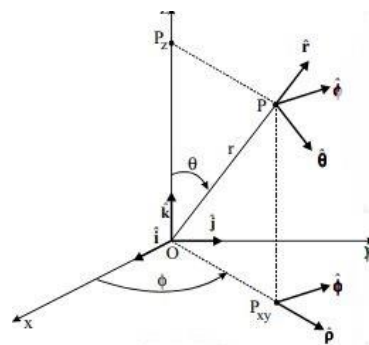# MATHEMATICAL DEVELOPMENT OF SPHERICAL COORDINATE

Figure 8: Spherical coordinate

In order to calculate the complex electromagnetic field sustained at a point, it is convenient to make use of the spherical coordinates. If we consider a Cartesian system originated in a point O whose coordinates are i,j,k. An alternative is to use the three spherical coordinates r,θ, ϕ, defined according to the Cartesian coordinates with the following relationships in which the field of variability indicated by θ, ϕ, are the integral part of the definition. The radial coordinate r has a physical dimension of one length (it represents the euclidean distance from the point P to the origin), while the angular coordinates, θ, ϕ, are dimensionless and are interpreted as angles measured in radians. The angle θ is said to be the colatitude of P and the angle ϕ is its longitude. If we look at equation 3 by default x=y=0 i.e. at the point of the z-axis. At this point the coordinate ϕ is not defined, while by equation 1 and 2 it has r=|z| and θ=0 (if z>0) or θ=π (if z<0). The geometry of the coordinates is shown in the figure above.

$$r = \sqrt{x^2 + y^2 + z^2} = |P - O| \qquad\qquad \text{II.1.1}$$

$$\cos\theta = \frac{z}{r}$$

$$\text{II.1.2}$$

$$0 \leq \theta \leq \pi$$

$$\sin\phi = \frac{y}{\sqrt{x^2+y^2}} \quad \cos\phi = \frac{x}{\sqrt{x^2+y^2}} \qquad\qquad \text{II.1.3}$$

$$0 \leq \phi \leq \pi$$

For a more in-depth investigation of the spherical coordinate system, the expression (II.1.1/II.1.3) is used.

$$\hat{r} = \frac{\nabla_r}{\|\nabla_r\|}$$

$$\hat{\theta} = \frac{\nabla_\theta}{\|\nabla_\theta\|} \qquad\qquad \text{II.1.4}$$

$$\hat{\phi} = \frac{\nabla_\phi}{\|\nabla_\phi\|}$$

Of the first equation (II.1.1) and the first expression of the fourth equation (II.1.4).

$$\nabla_r = \frac{1}{r}\left(x\hat{\imath} + y\hat{\jmath} + z\hat{k}\right) = \hat{r} \qquad \text{II.1.5}$$

$$\nabla_r = 1$$

$$\rho = \sqrt{x^2 + y^2} \qquad \text{II.1.6}$$

Can be written

$$\hat{r} = \frac{x}{\rho}\frac{\rho}{r}\hat{\imath} + \frac{y}{\rho}\frac{\rho}{r}\hat{\jmath} + \frac{z}{r}\hat{k} \qquad \text{II.1.7}$$

And so, being for a reason (II.1.2),(II.1.6)

$$\sin\theta = \frac{\rho}{r} \qquad \text{II.1.8}$$

If you have pure

$$\hat{r} = \sin\theta\cos\phi\,\hat{\imath} + \sin\theta\sin\phi\,\hat{\jmath} + \cos\theta\,\hat{k} \qquad \text{II.1.9}$$

Calculating the gradient of the two members of the (II.1.2) is obtained

$$-\sin\theta\,\nabla_\theta = \frac{1}{r^2}(r\nabla_z - z\nabla_r) = \frac{1}{r}(\hat{k} - \cos\theta\,\hat{r}) \qquad \text{II.1.10}$$

From which, being for the (II.1.9) $\hat{k}\bullet\hat{r} = \cos\theta$

$$\|\nabla_\theta\|^2 = \frac{1+\cos^2\theta - 2\cos\theta\,\hat{k}\bullet\hat{r}}{r^2\sin^2\theta} = \frac{1}{r^2} \qquad \text{II.1.11}$$

Using the (II.1.10),(II.1.11) in the second of the (II.1.4) you get

$$\hat{\theta} = \frac{\cos\theta\,\hat{r} - \hat{k}}{\sin\theta} \qquad \text{II.1.12}$$

And so for the (II.1.9)

$$\hat{\theta} = \cos\theta\cos\phi\,\hat{\imath} + \cos\theta\sin\phi\,\hat{\jmath} - \sin\theta\,\hat{k} \qquad \text{II.1.13}$$

Calculating the gradient of the two members of the second of the (II.1.3) we have

$$\cos \phi \nabla_\phi = \frac{1}{\rho^2}\left(\rho \nabla_y - y \nabla_\rho\right) = \frac{1}{\rho}(\hat{j} - \sin \phi \hat{\rho}) \qquad \text{II.1.14}$$

In which the versore has been used

$$\hat{\rho} = \nabla_\rho = \frac{1}{\rho}(x\hat{i} + y\hat{j}) = \cos \phi \hat{i} + \sin \phi \hat{j} \qquad \text{II.1.15}$$

Since (II.1.14), being for the (II.1.15) $\hat{j} \bullet \hat{\rho} = \sin \phi$, it is deduced

$$\left\|\nabla_\phi\right\|^2 = \frac{1+\sin^2 \phi - 2\sin \phi \hat{j} \bullet \hat{\rho}}{\rho^2 \cos^2 \phi} = \frac{1}{\rho^2} \qquad \text{II.1.16}$$

So from the third of the (II.1.4) you get

$$\hat{\phi} = \frac{\hat{j} - \sin \phi \hat{\rho}}{\cos \phi} \qquad \text{II.1.17}$$

Using the (II.1.15) you finally have

$$\hat{\phi} = -\sin \phi \hat{i} + \cos \phi \hat{j} \qquad \text{II.1.18}$$

At the points of the z-axis the (II.1.3) and (II.1.18), as well as the (II.1.15), fall into defect because the angle ϕ is not defined, and therefore the versors $\hat{\theta}, \hat{\phi}, \hat{\rho}$ are not defined. Instead, passing to the limit in the (II.1.9) for $\sin \theta \to 0$, or using directly the (II.1.5), we recognize that in these points is $\hat{r} = \hat{k}$ $(if\ z > 0)$ or $\hat{r} = -\hat{k}$ $(if\ z < 0)$.

From the (II.1.9), (II.1.13),(II.1.18) the reports are deduced immediately

$$\hat{r} \bullet \hat{\theta} = 0$$

$$\hat{\theta} \bullet \hat{\phi} = 0 \qquad \text{II.1.19}$$

$$\hat{\phi} \bullet \hat{r} = 0$$

CHAPTER 4

CHARACTERISTICS OF THE ANTENNA

The antenna is a wideband circularly polarized antenna performing omnidirectional radiation in the wider azimuth plane. It is an omnidirectional antenna used in the high speed mobile and rotating communications systems due to the omnidirectional radiation characteristics and CP (Circularly polarized) properties.

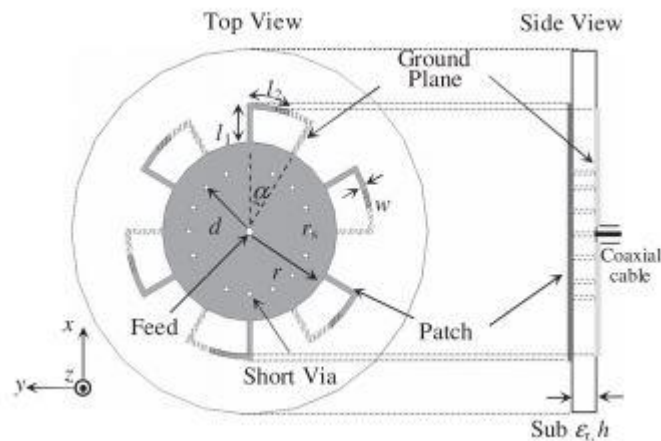*Figure 2* shows the antenna that I designed in this project by means the program CST SUITE 2018.

Figure 9: Circularly Antenna

Configuration of antenna

The antenna consists realized on a substrate (characteristics of substrate $\varepsilon_r = 4.4$, $tan\delta = 0.02$, $h = 6.4\ mm$), the patch presents six curved branches and circular radiator with a radius of r. The curved branches are located along the edge of the circular radiator and oriented in the clockwise direction to generate fields to the right sense. The ground plane is oriented in the anticlockwise

direction, this plane is connected to the circular radiator with N (N=16) shorting vias (with radius r_s uniformly distributed along the circle of radius d. In the center of circular radiator there is a coaxial cable that feeds the antenna. The circular radiators and curved branches can excite the vertically polarized electric field E_θ and the horizontally polarized electric field E_φ. This antenna is designed around half a wavelength at 2.4GHz to meet 90º phase difference between E_θ and E_φ.

Figure 9 showed the configuration of circular antenna.

Figure 10 shows the table of values of the antenna configuration.

r=35.2
rs=0.4
l1=15
l2=17.4
d=24.6
w=2
α=30º
h=6.4
N=16

Figure 10: Table of values

Design of antenna with CST STUDIO 2018

First of all I have designed the antenna with the software CST STUDIO 2018; this program offers accurate and efficient solutions for electromagnetic design and analysis.

For the design of antenna I needed to choose the material of the substrate, in this case I created a new material with the correct characteristic of the substrate ($\varepsilon_r = 4.4$, $tan\delta = 0.02$, $h = 6.4\ mm$) after creating the substrate put the circular antenna with cupper material which dimension is defined in the figure 9. Inside the subtrate I had to put sixteen vias uniformly distributed that connect both faces of the antenna across the substrate to know the position of the vias I had to do theoretical calculations.
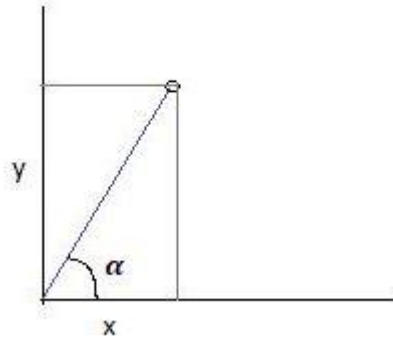
$y = \sin \alpha$

$x = \cos \alpha$

x	d	-d	0	0	9.414	-9.414	-9.414	9.414
y	0	0	d	-d	22.72	22.72	-22.72	-22.72

x	22.72	-22.72	-22.72	22.72	17.39482	-17.39482	-17.39482	17.39482
y	9.414	9.414	-9.414	-9.414	17.39482	17.39482	-17.39482	-17.39482

Theoretical calculations

To finish the design of antenna I had to do the patch this to complete the antenna design I created the patch on both sides of the substrate and the position of the branches are accurately derived by geometrical calculations.The antenna presents a symmetry on both sides which allows to easily replicate the exact shape on the other side of the substrate.When designing the geometry of the whole antenna, all the geometrical values are parametrized which allows to dynamically simulate the performance.The antenna is fed though a coaxial cable placed in the center of the patch.

The final design can be seen in the *figure 12 and 13*.
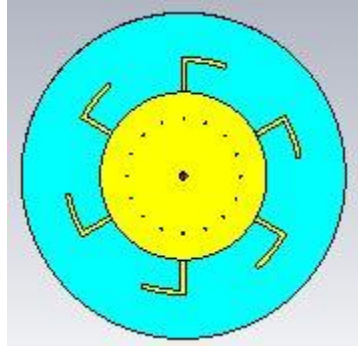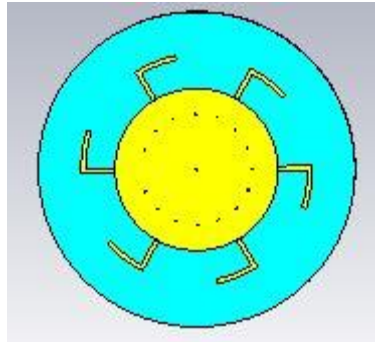
Design simulation with CST SUITE 2018

The first electromagnetic simulation brought some results which were not in accordance with the specifications.To overcome this issue a parameter sweep on the radious calue is perfomed with the aim of finding the correct resonant frequency. I had to test the antenna radius until I found the radius that gave me the approximate values. *Figure 14* shows the sweep of the radius.
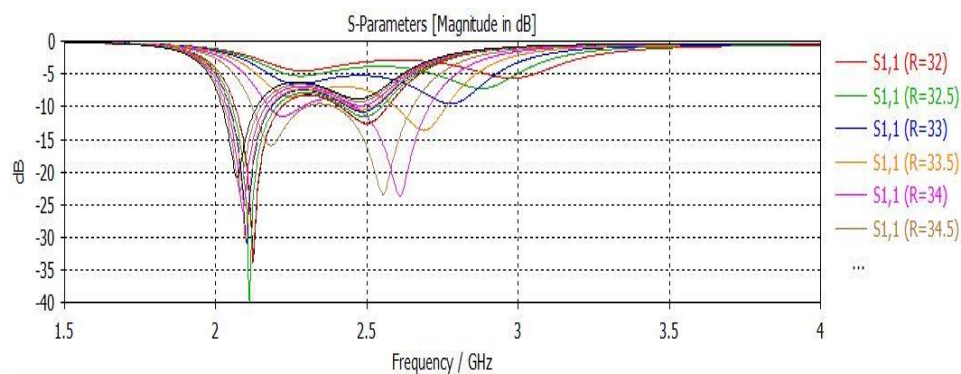

Figure 14: Test of radius

To do the tests I did a sweep of the radius from 32mm to 35.7mm (*Figure 14*), If we look at *figure 14* we can see that as the radius grows the parameter S11 (representing the resonance of antenna) reduces in terms of absolute value, meaning a worse result because the resonance is bigger, but the result closest to the specifications is found when the radious is around 34.5mm (Brown curve). S-parameter describes the input-output relationship between ports in an electrical system.

The dispersion parameters are the reflection and transmission coefficients between the incident wave and reflected wave. These parameters fully describe the behaviour of a device under linear conditions in a given frequency range. Each parameter is characterized by magnitude, gain or loss in decibels and phase

- **S11** the reflection coefficient of the input port voltage

- **S12** is the gain of the reverse voltage

- **S21** is the gain of direct voltage

- **S22** is the reflection coefficient of the output port voltage
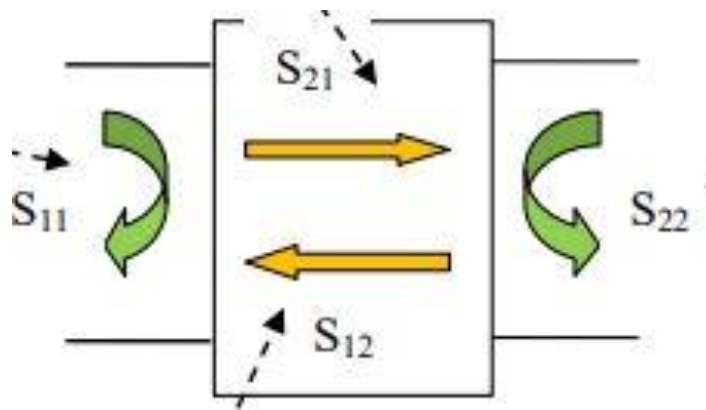
Figure 15: Parameter S

Comparison of the results obtained with the specifications

Once the radius has been selected (34.5mm) the antenna is simulated for that specific value of the radious and the results in terms of S11 are compared with the specificacion of the paper.
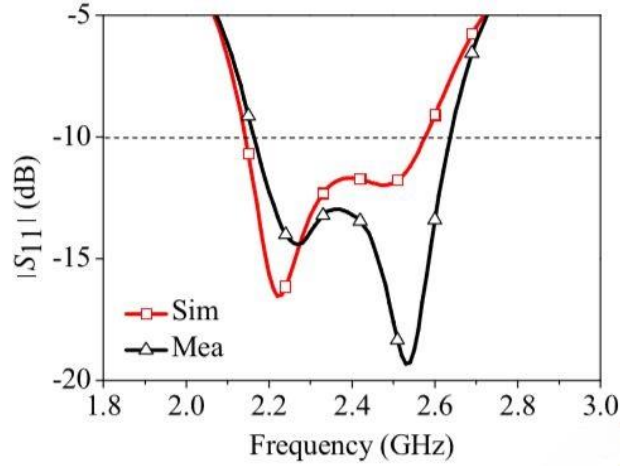

Figure 16: Result of specification parameter S11

If we look the *Figure 16* (The result of specification parameter S11) we have two curves red and black, these curves represent the parameter $|S_{11}|$ for differents values of θ: the curve red for $\theta = 50^\circ$ and the curve black for $\theta = 70^\circ$. In my simulation I need to find some values that are he best approximation of the specification ones. In *Figure 16* for $\theta = 50^\circ$ the lowest peak is at the frequency 2.21 GHz for which the S11 parameter is -16 dB approximately and at the frequency 2.55 the value of the parameter is -12.5 dB in contrast for the black curved $\theta = 70^\circ$ the parameter change a lot for the frequency 2.25GHz the parameter take the value -15 dB approximately and for the frequency 2.57 take the lowest peak -19 dB. The best resonance condition occurs when the S11 peak has a low negative value, the better resonance, because the resonance is when reflection occur.

The resonance of an antenna has to do with the intensity of the wave radiated by that antenna, depending in turn on the dimensions of the antenna and the intensity of current that we apply at its feeding point and that flows through it.

Now I am going to explain the results obtained with the simulator, in the *Figure 15* we can see the parameter S11 correspondingto a patch antenna of radious 34.5 mm. I found this optimum radious sarting from a value of 35.2

and decreasing of 0.7, obtaining a good approximation of the results given by the reference design.

In *figure 17 and figure 18* I show the simulation of parameter S11 for radious equals to 34.5 mm, the value of two lowest peaks correspond to the lowest resonance values where the antenna should work properly. In *figure 16* the peak take a value the -15.155 dB for the frequency 2.1852 GHz, in the paper the first peak has a value of -15dB at the frequency of 2.25 GHz the difference between the simulation and the paper is very small, this may be because the antennas are not exactly the same but really the difference is negligible.
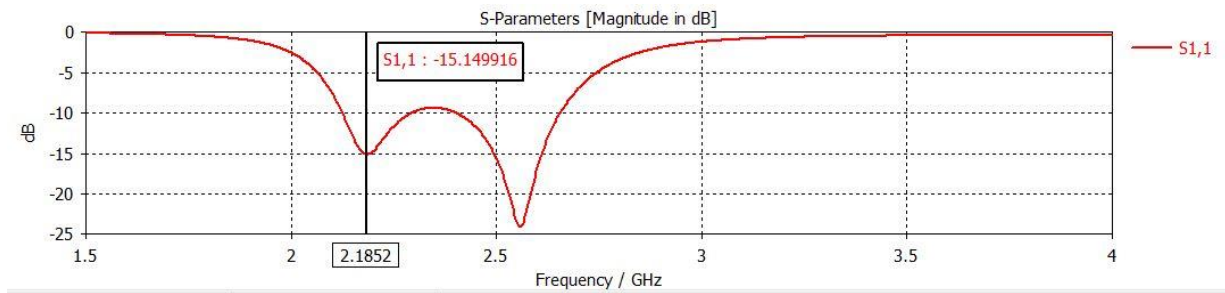
Figure 17: First result of parameter S11

Figure 18 shows the lowest peak of resonance is -24dB for the frequency 2.56 GHz, between paper and simulation is greater than in the first case.
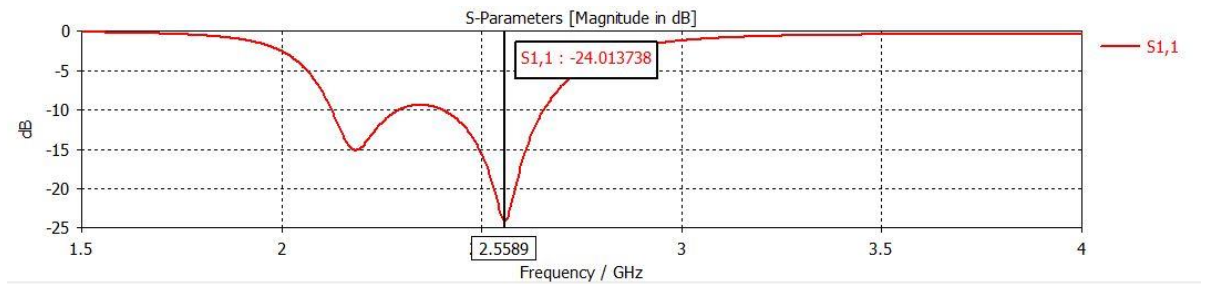
Figure 18: Second result of parameter S11

After deriving those value I permed another simulation in order to calculate the antenna performance in the far-field, the surface current and the H-field.

CHAPTER 5

FARFIELD AND AXIAL RATIO ANALYSIS

FAR FIELD (FRAUNHOFER) REGION [5]

The far-field is the region far from the antenna. The radiation pattern doesn't change shape with distance. Also, this region is dominated by radiated fields; with the E-field and H-field orthogonal to each other and the direction of propagation as with plane waves.

Three conditions must be met to satisfy the far field:

1.1.1 $R > \dfrac{2D^2}{\lambda}$

2.1.1 $R \gg D$

3.1.1 $R \gg \lambda^1$

The first and second equation above ensures that the power radiated in a given direction from distinct parts of the antenna is approximately parallel. This helps ensure the field in the far field region behave like plane waves.

DEFINITION OF FAR RADIATION ZONE [6]

$$A(P) = \frac{\mu^2}{4\pi} J_i(P_0) dV_0 \frac{\exp(-j\beta|P - P_0|)}{|P - P_0|}$$

---

[1] Wavelength is the spatial period of a periodic wave, the distance over which the waves shape repeats.
[2] Permeability the degree of a material in response to a magnetic field

- **Radiation vector**

$$\mathcal{M} = J_i(P_0)dV_0$$

The radiation vector gives the intensity, the orientation in the space and the polarization of the electric source.

- **Electric vector potential**

The currents create the vector potential in the same directions of the current flow. The result of the electric field is constructed from the potential part that is perpendicular to the direction of propagation.

$$A(P) = \frac{\mu}{4\pi}\mathcal{M}\frac{\exp(-j\beta|P - P_0|)}{|P - P_0|} = \frac{\mu}{4\pi}\mathcal{M}\frac{\exp(-j\beta r)}{r}$$

- **EM field**

$$E(P) = \frac{\eta}{2\pi}\left(1 - j\frac{\lambda}{2\pi r}\right)\frac{\exp(j\beta r)}{r^2}\mathcal{M}_r\hat{r} - j\frac{\eta}{2\lambda}\left(1 - j\frac{\lambda}{2\pi r} - \frac{\lambda^2}{4\pi^2 r^2}\right)\frac{\exp(j\beta r)}{r}\hat{r} \times \mathcal{M} \times \hat{r}$$

$$H(P) = -j\frac{1}{2\lambda}\left(1 - j\frac{\lambda}{2\pi r}\right)\frac{\exp(j\beta r)}{r}\hat{r} \times \mathcal{M}$$

For radio links it is interesting to evaluate the EM field far for the source ($r \gg \lambda$).

- **Farfield**

$$E(P) = E(r, \theta, \phi) = -j\eta\frac{\exp(-j\beta r)}{2\lambda r}\hat{r} \times \mathcal{M} \times \hat{r}$$

$$H(P) = H(r, \theta, \phi) = -j\frac{\exp(-j\beta r)}{2\lambda r}\hat{r} \times \mathcal{M}$$

- **Magnetic radiation vector**

$$\mathcal{N} = M_i(P_0)dV_0$$

- **The superposition of both electric and magnetic source**

 The far-field is useful because it provides the exact evaluation of the active power radiated by the source.

  $$E(P) = E(r, \theta, \phi) = -j \frac{\exp(-j\beta r)}{2\lambda r} [\eta \hat{r} \times \mathcal{M} \times \hat{r} + \mathcal{N} \times \hat{r}]$$

  $$H(P) = H(r, \theta, \phi) = -j \frac{\exp(-j\beta r)}{2\lambda r} [\hat{r} \times \mathcal{M} + \frac{1}{\eta} \hat{r} \times \mathcal{N} \times \hat{r}]$$

- **The lossless medium**

  The following equations are the result of the lossless medium of permeability (e) and permittivity (**μ**).

  $$\mathcal{M}(\theta, \phi) = \int J_i(P_0) \exp(j\beta w \bullet \hat{r}) dV_0$$

  $$\mathcal{N}(\theta, \phi) = \int M_i(P_0) \exp(j\beta w \bullet \hat{r}) dV_0$$

  $\mathcal{M}(\theta, \phi)$ and $\mathcal{N}(\theta, \phi)$ Have a dependence on the angular coordinates

The final result of the far-field taking into account the lossless medium is:

$$E(P) = E(r, \theta, \phi) = -j \frac{\exp(-j\beta r)}{2\lambda r} [\eta \hat{r} \times \mathcal{M}(\theta, \phi) \times \hat{r} + \mathcal{N}(\theta, \phi) \times \hat{r}]$$

$$H(P) = H(r, \theta, \phi) = -j \frac{\exp(-j\beta r)}{2\lambda r} [\hat{r} \times \mathcal{M}(\theta, \phi) + \frac{1}{\eta} \hat{r} \times \mathcal{N}(\theta, \phi) \times \hat{r}]$$

First of all The simulation results in terms of far field characteristics are analysed for different frequencies through the polar, Cartesian and 3D diagrams.

POLAR

Figure 19: Polar farfield 2.18 GHz

Farfield Gain Abs (Phi=0)
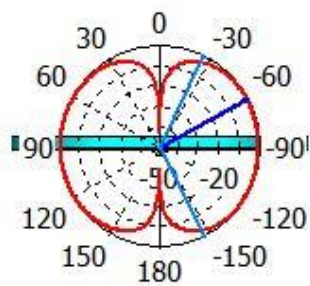
Theta / Degree vs. dB

farfield (f=2.18) [1]

Frequency = 2.18 GHz
Main lobe magnitude = -0.866 dB
Main lobe direction = -62.0 deg.
Angular width (3 dB) = 128.3 deg.

Figure 20: Polar farfield 2.4GHz

Farfield Gain Abs (Phi=0)
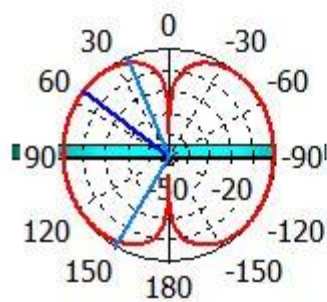
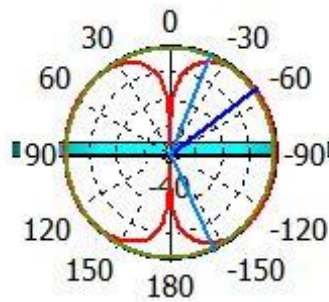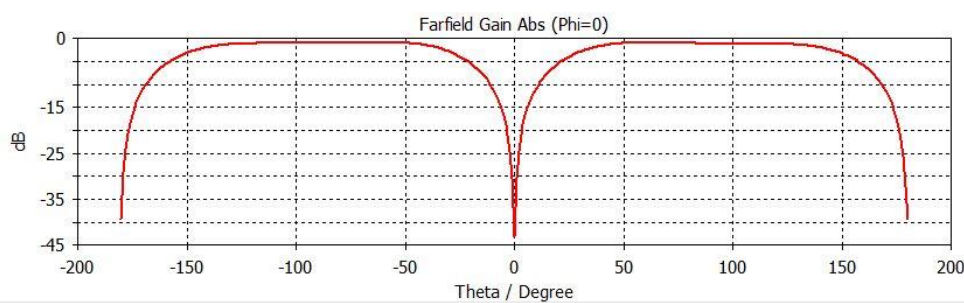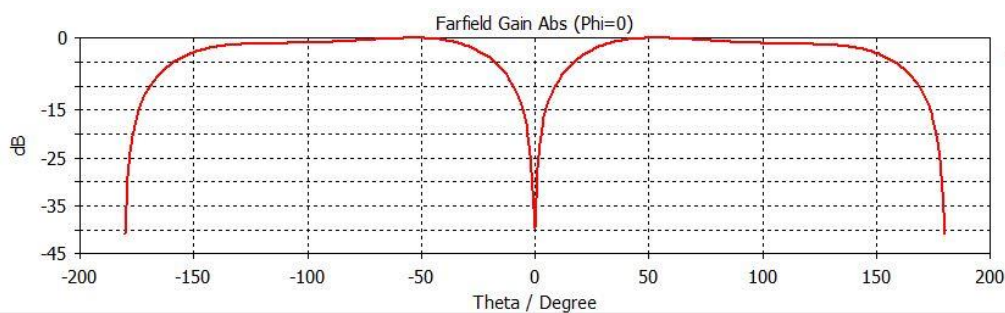Theta / Degree vs. dB

farfield (f=2.4) [1]

Frequency = 2.4 GHz
Main lobe magnitude = -0.0381 dB
Main lobe direction = 53.0 deg.
Angular width (3 dB) = 126.3 deg.

29

Farfield Gain Abs (Phi=0)

farfield (f=2.55) [1]

Theta / Degree vs. dB

Frequency = 2.55 GHz
Main lobe magnitude = -0.558 dB
Main lobe direction = -53.0 deg.
Angular width (3 dB) = 132.9 deg.
Side lobe level = -0.5 dB

Figure 21: Polar farfield 2.55GHz

CARTESIAN

Farfield Gain Abs (Phi=0)

farfield (f=2.18) [1]

Frequency = 2.18 GHz
Main lobe magnitude = -0.866 dB
Main lobe direction = -62.0 deg.
Angular width (3 dB) = 128.3 deg.

Figure 22: Cartesian farfield 2.18GHz

Farfield Gain Abs (Phi=0)

farfield (f=2.4) [1]

Frequency = 2.4 GHz
Main lobe magnitude = -0.0381 dB
Main lobe direction = 53.0 deg.
Angular width (3 dB) = 126.3 deg.

Figure 23: Cartesian farfield 2.4GHz
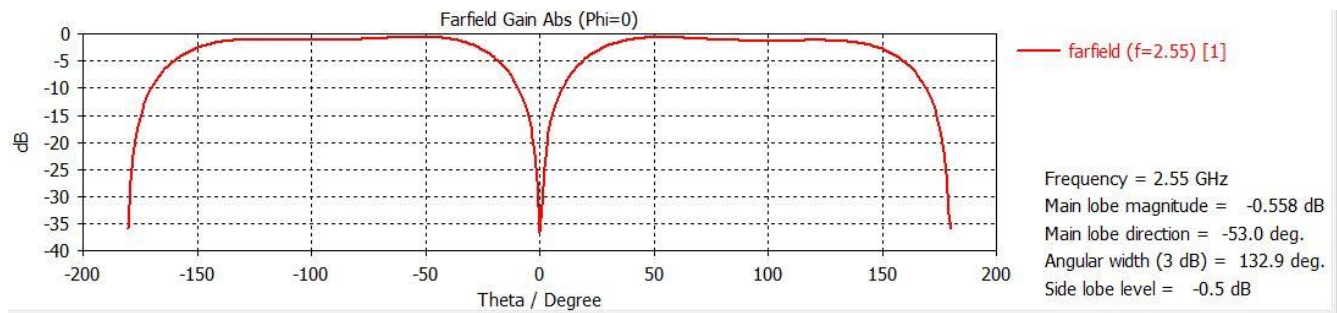
Figure 24: Cartesian farfield 2.55GHz

3D
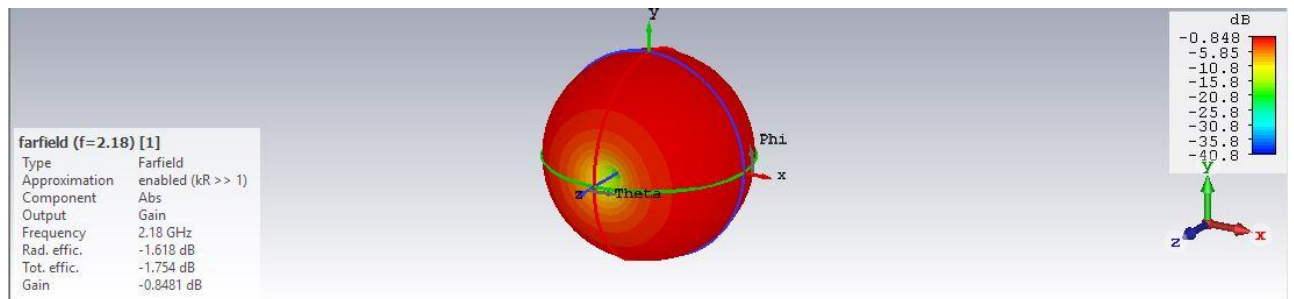
Figure 25: 3D farfield 2.18GHz
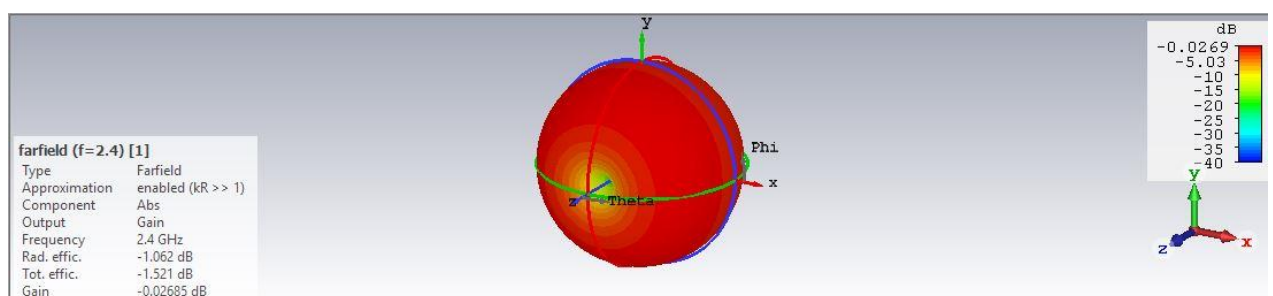
Figure 26: 3D farfield 2.4GHz

farfield (f=2.55) [1]
Type   Farfield
Approximation enabled (kR >> 1)
Component   Abs
Output   Gain
Frequency   2.55 GHz
Rad. effic.   -1.227 dB
Tot. effic.   -1.247 dB
Gain   -0.5257 dB

dB
-0.526
-5.53
-10.5
-15.5
-20.5
-25.5
-30.5
-35.5
-40.5
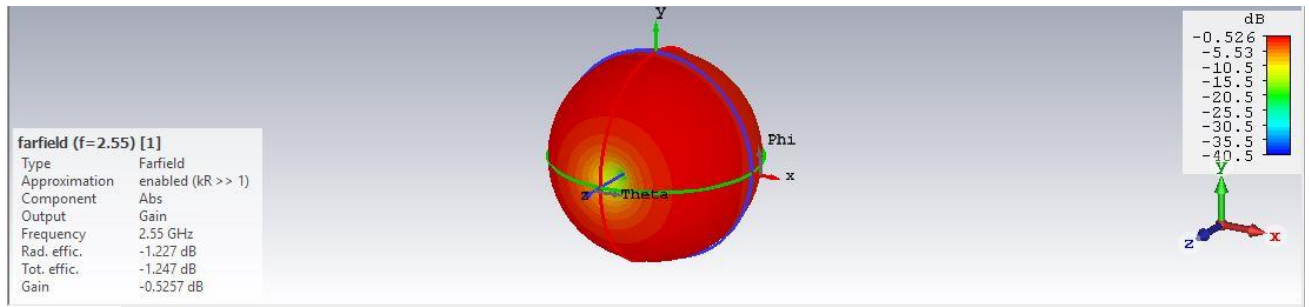
Figure 27: 3D farfield 2.55GHz

In the images you can see that the antenna I designed does not emit radiation on the Z axis, it only emits circular radiation on the X-axis and on the Y-axis. It is interesting to put markers in the maximums of the farfield because it is where we will have the best radiation and this is related to the axial ratio. Once explained the axial ratio, I will show the graphs to see how it is related

Axial ratio[3]

The axial ratio is the ratio of orthogonal components of an E-field. A circularly polarized field is made up of two orthogonal E-field components of equal amplitude (and 90 degrees out of phase). Because the components are equal magnitude, the axial ratio is 1 (or 0 dB)

The ideal value of the axial ratio for circularly polarized fields is 0 dB. In addition, the axial ratio tends to degrade away from the main beam of an antenna, for an antenna as follows: Axial Ratio: <3 dB for ±30 degrees from main beam. This indicates that the deviation from circular polarization is less than 3 dB over the specified angular range.

The axial ratio is defined as a ratio of the major to the minor axis of the polarization ellipse.

---

[3] http://www.antenna-theory.com/definitions/axial.php
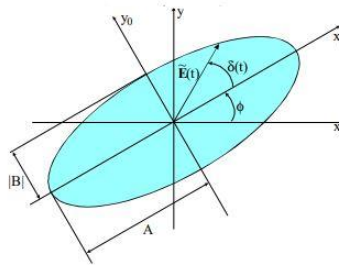
The axial ratio of the ellipse is:

$$AR = \frac{A}{|B|}$$

	Right handed	Right handed elliptical	Linear	Left handed elliptical	Left handed
	B=-A	B<0	B=0	B>0	B=A
AR(dB)	0	>0	∞	>0	0

In the simulation the results of the axial ratio for values where the resonance is lower (2.18 and 2.55 GHz) and the frequency that works the antenna is the following (figure 13, figure 14 and figure 115):

POLAR
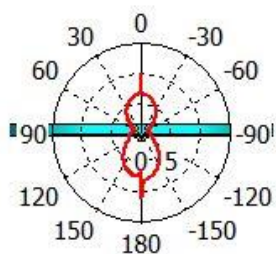
Frequency = 2.18 GHz
Main lobe magnitude = 10.7 dB

Figure 28: Axial ratio (2.18 GHz)
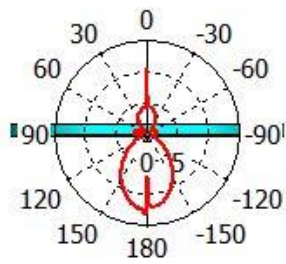
Figure 29: Axial ratio (2.4 GHz)
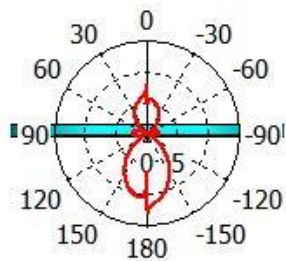
Figure 30: Axial ratio (2.55 GHz)

In the previous figures the axial ratio is shown in polar coordinates, to appreciate it better I will show it in Cartesian.
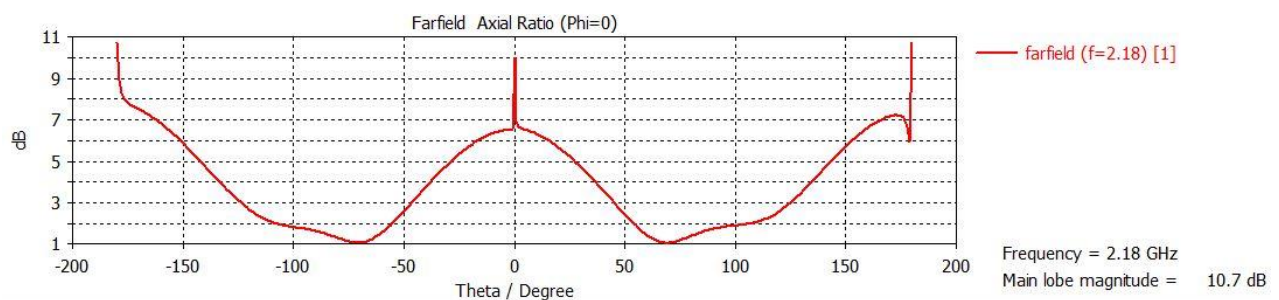
CARTESIAN

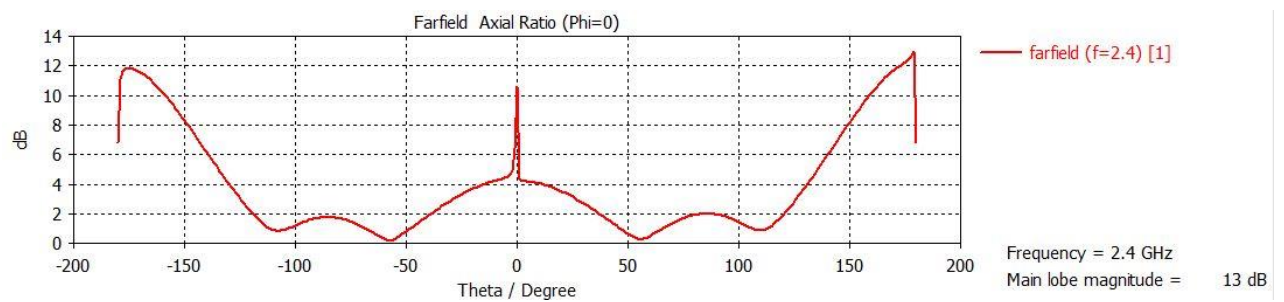Figure 31: Cartesian axial ratio 2.18GHz
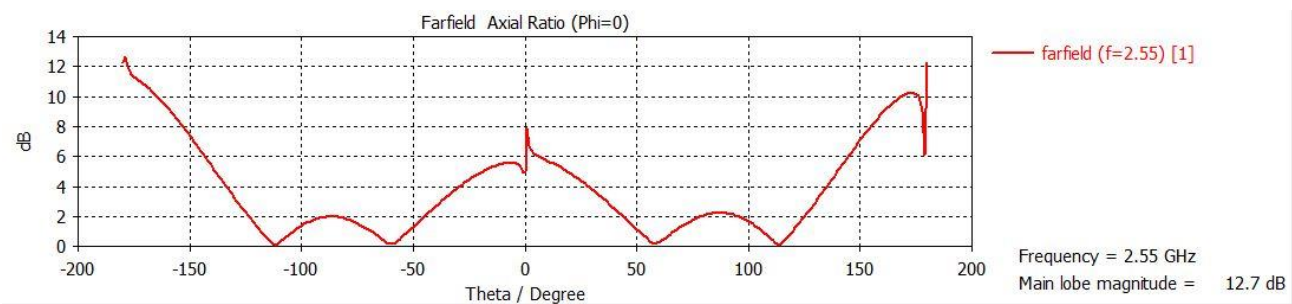
Figure 32: Cartesian axial ratio 2.4GHz

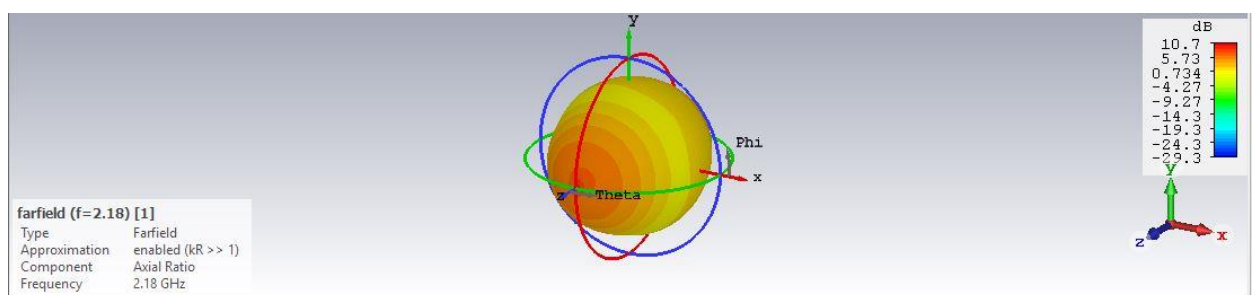**Figure 33: Cartesian axial ratio 2.55GHz**

3D
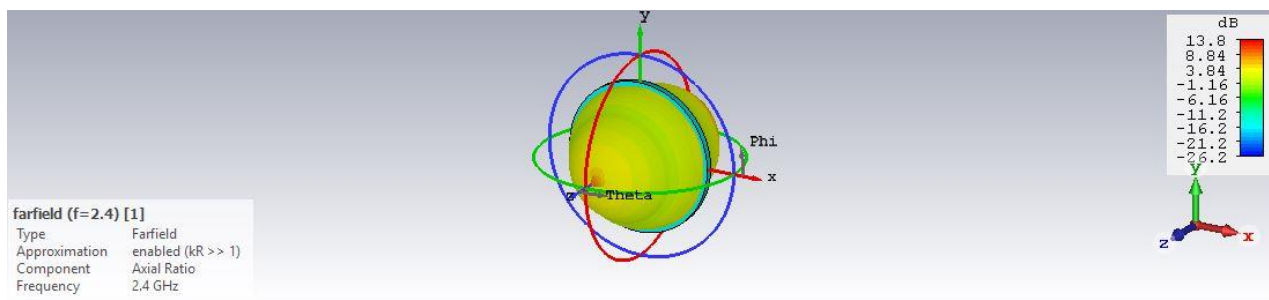

Figure 34:3D axial ratio 2.18GHz
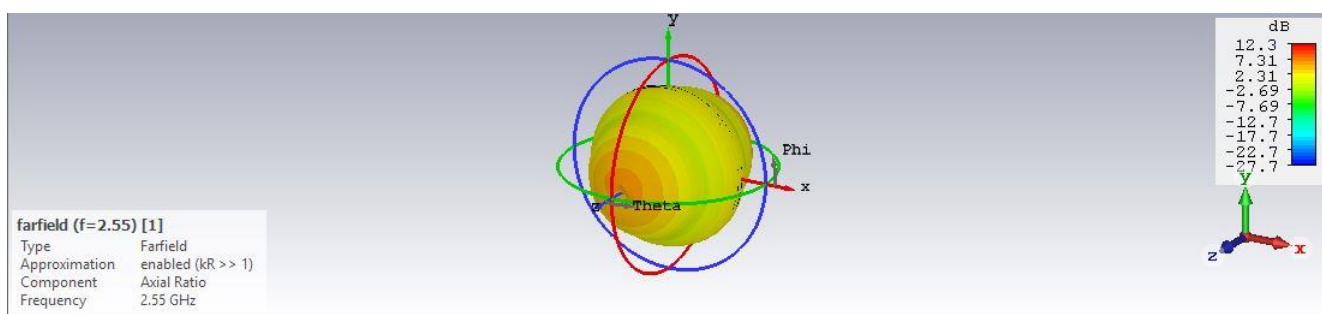
Figure 35: 3D axial ratio 2.4GHz

Figure 36: 3D axial ratio 2.55GHZ

In figures 37 and 38 I have selected the two smallest values of the axial ratio to check the values are both less than 3dB as I said earlier, in figure 37 the value is 0.29 and in figure 38 0.92 these values are good for power transmission.
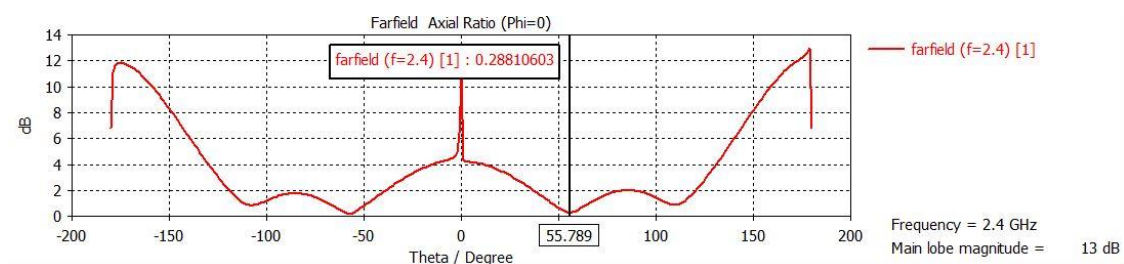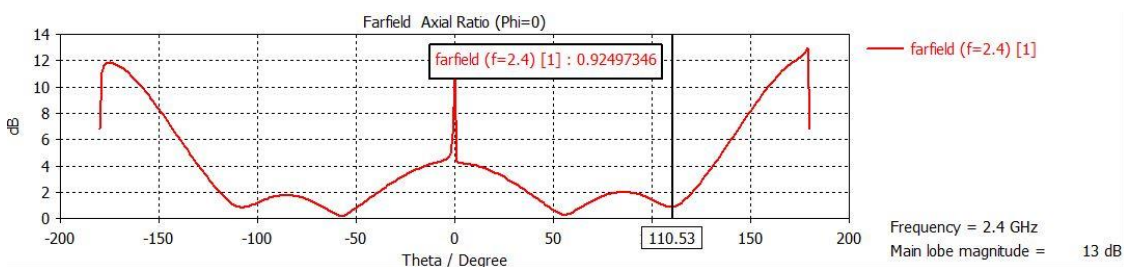

Figure 37: First mínimum axial ratio

Figure 38: Second mínimum axial ratio

RELATION GRAPHICAL AXIAL RATIO AND FARFIELD

I make the relation between the farfield and the previously mentioned axial ratio, first I place a marker in one of the minimums of the axial ratio (figure 39), the minimum value of the axial ratio that is where we have better radiation, since it must be below 3dB corresponds with the maximum of the farfield (figure 40), to check this relationship applies to the two minima of the axial ratio (figure 41) and figure 42), another observation I have made is that the graphs are symmetrical with respect to 0, is because it is an antenna that radiates circularly.
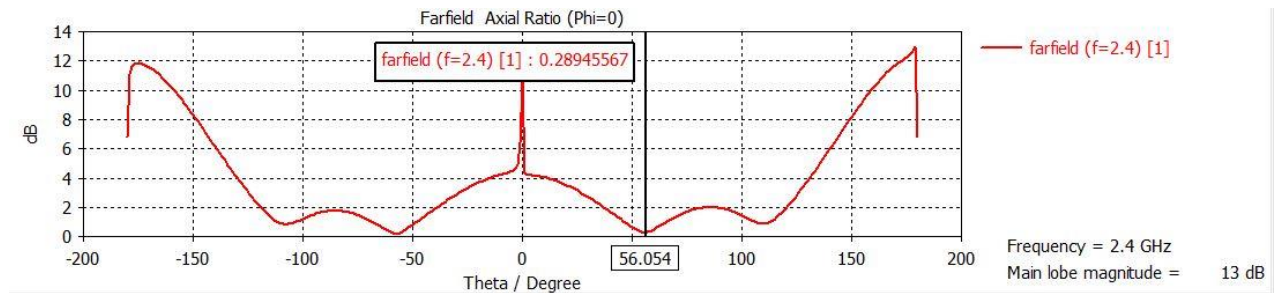

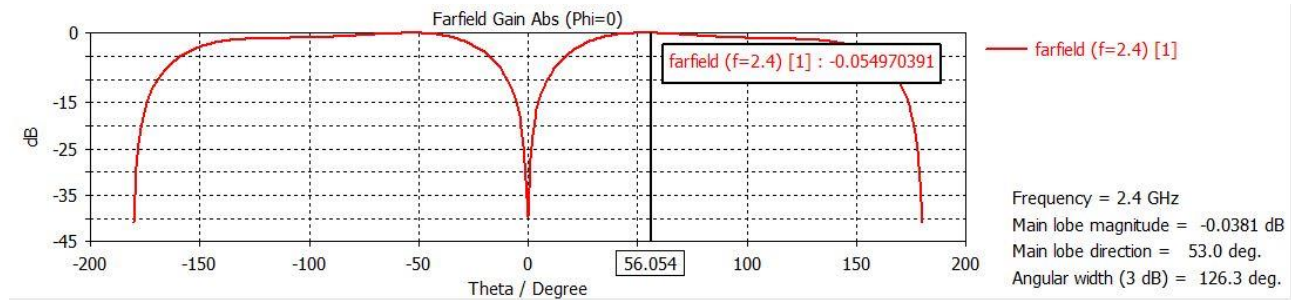
Figure 39: First mínimum axial ratio
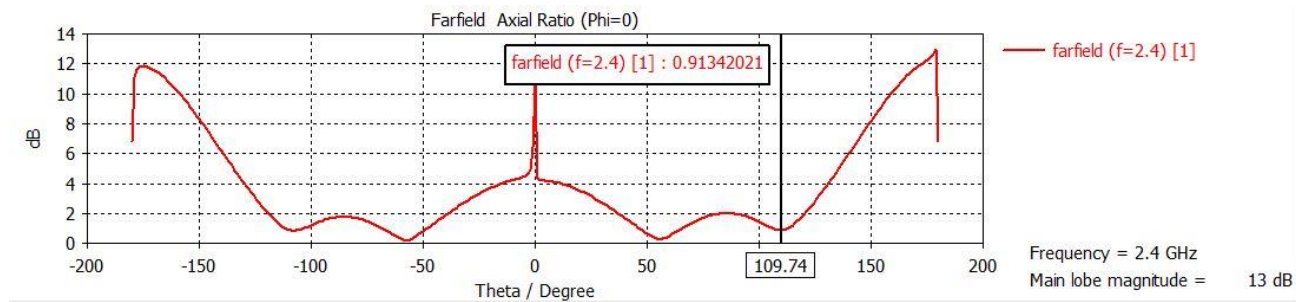

Figure 40: First máximum farfield

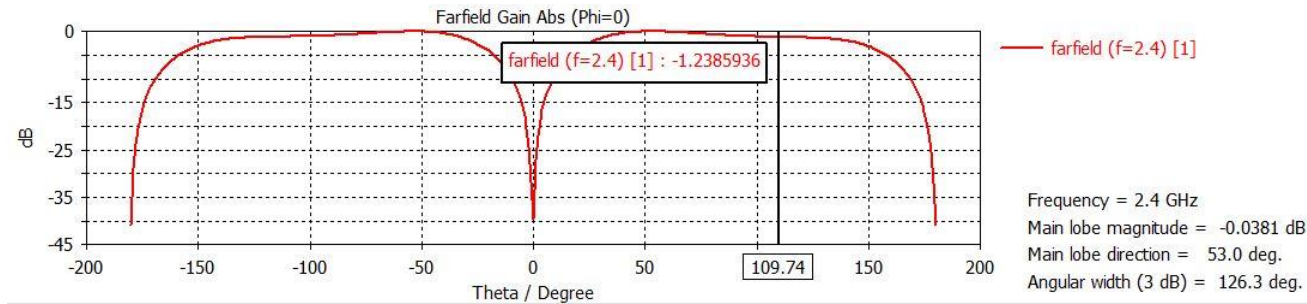**Figure 41: Second mínimum axial ratio**

Figure 42: Second máximum farfield

FULL SIMULATION

To make the complete simulation of the system, i.e., the designed antenna working as an illuminator of a receiving tag, I first have to extract a document with the data of the farfield at all frequencies.

For example:
 2.18GHz

```
// CST Farfield Source File

// Version:
3.0

// Data Type
Farfield

// #Frequencies
1

// Position
0.000000e+00 0.000000e+00 2.200000e-03

// zAxis
0.000000e+00 0.000000e+00 1.000000e+00

// xAxis
1.000000e+00 0.000000e+00 0.000000e+00

// Radiated/Accepted/Stimulated Power , Frequency
3.338536e-01
4.845850e-01
5.000000e-01
2.180000e+09


// >> Total #phi samples, total #theta samples
```

721 361

// >> Phi, Theta, Re(E_Theta), Im(E_Theta), Re(E_Phi), Im(E_Phi):
```
  0.000    0.000  -2.91278437e-02   1.99573170e-02  1.01206440e-03   1.34572359e-02
  0.000    0.500  -1.94182321e-02   5.52349500e-02  5.84252439e-02  -2.69078687e-02
  0.000    1.000  -9.78418253e-03   9.03946906e-02  1.15665711e-01  -6.71452135e-02
  0.000    1.500  -1.35197901e-04   1.25539869e-01  1.72867239e-01  -1.07320562e-01
  0.000    2.000   9.53068770e-03   1.60664916e-01  2.30009601e-01  -1.47411078e-01
  0.000    2.500   1.92154106e-02   1.95764273e-01  2.87072629e-01  -1.87394038e-01
  0.000    3.000   2.89208796e-02   2.30832383e-01  3.44036192e-01  -2.27246806e-01
  0.000    3.500   3.86489630e-02   2.65863687e-01  4.00880307e-01  -2.66946971e-01
  0.000    4.000   4.84014936e-02   3.00852627e-01  4.57584977e-01  -3.06472212e-01
  0.000    4.500   5.81802465e-02   3.35793674e-01  5.14130414e-01  -3.45800459e-01
  0.000    5.000   6.79869652e-02   3.70681256e-01  5.70496857e-01  -3.84909838e-01
  0.000    5.500   7.78233185e-02   4.05509859e-01  6.26664877e-01  -4.23778743e-01
```

2.4GHz

// CST Farfield Source File

// Version:
3.0

// Data Type
Farfield

// #Frequencies
1

// Position
0.000000e+00 0.000000e+00 2.200000e-03

// zAxis
0.000000e+00 0.000000e+00 1.000000e+00

// xAxis
1.000000e+00 0.000000e+00 0.000000e+00

// Radiated/Accepted/Stimulated Power , Frequency
3.522478e-01
4.497782e-01
5.000000e-01
2.400000e+09

// >> Total #phi samples, total #theta samples
721 361

// >> Phi, Theta, Re(E_Theta), Im(E_Theta), Re(E_Phi), Im(E_Phi):
```
  0.000    0.000   4.22542654e-02   6.73041493e-03  -2.50586532e-02  -2.31305584e-02
  0.000    0.500   9.17485878e-02   1.84651930e-03  -5.09130694e-02  -9.47199762e-02
  0.000    1.000   1.41079754e-01  -2.93582678e-03  -7.66101778e-02  -1.66106373e-01
  0.000    1.500   1.90383509e-01  -7.72674847e-03  -1.02225929e-01  -2.37429917e-01
  0.000    2.000   2.39649370e-01  -1.25251822e-02  -1.27737254e-01  -3.08659822e-01
  0.000    2.500   2.88866907e-01  -1.73300412e-02  -1.53121248e-01  -3.79765272e-01
  0.000    3.000   3.38025659e-01  -2.21402124e-02  -1.78355157e-01  -4.50715691e-01
  0.000    3.500   3.87115240e-01  -2.69545633e-02  -2.03416437e-01  -5.21480501e-01
```

0.000	4.000	4.36125189e-01	-3.17719281e-02	-2.28282809e-01	-5.92029393e-01
0.000	4.500	4.85045135e-01	-3.65911238e-02	-2.52932221e-01	-6.62332237e-01
0.000	5.000	5.33864737e-01	-4.14109267e-02	-2.77342916e-01	-7.32358992e-01
0.000	5.500	5.82573593e-01	-4.62300964e-02	-3.01493466e-01	-8.02080035e-01

2.55GHz

// CST Farfield Source File

// Version:
3.0

// Data Type
Farfield

// #Frequencies
1

// Position
0.000000e+00 0.000000e+00 2.200000e-03

// zAxis
0.000000e+00 0.000000e+00 1.000000e+00

// xAxis
1.000000e+00 0.000000e+00 0.000000e+00

// Radiated/Accepted/Stimulated Power , Frequency
3.751877e-01
4.976666e-01
5.000000e-01
2.550000e+09

// >> Total #phi samples, total #theta samples
721 361

// >> Phi, Theta, Re(E_Theta), Im(E_Theta), Re(E_Phi), Im(E_Phi):

0.000	0.000	-3.82657424e-02	1.15567669e-02	1.72038116e-02	6.89808577e-02
0.000	0.500	-8.59130267e-03	-2.22552381e-02	-5.68520166e-02	3.78819257e-02
0.000	1.000	2.10965779e-02	-5.58644421e-02	-1.30639061e-01	6.74780877e-03
0.000	1.500	5.07771038e-02	-8.94720182e-02	-2.04323366e-01	-2.44284719e-02
0.000	2.000	8.04462060e-02	-1.23072438e-01	-2.77860641e-01	-5.56446575e-02
0.000	2.500	1.10099837e-01	-1.56660154e-01	-3.51206720e-01	-8.68983939e-02
0.000	3.000	1.39733940e-01	-1.90229595e-01	-4.24317747e-01	-1.18187211e-01
0.000	3.500	1.69344500e-01	-2.23775119e-01	-4.97150064e-01	-1.49508521e-01
0.000	4.000	1.98927462e-01	-2.57291108e-01	-5.69660366e-01	-1.80859625e-01
0.000	4.500	2.28478834e-01	-2.90771812e-01	-6.41805768e-01	-2.12237671e-01
0.000	5.000	2.57994592e-01	-3.24211508e-01	-7.13543713e-01	-2.43639678e-01
0.000	5.500	2.87470758e-01	-3.57604414e-01	-7.84832180e-01	-2.75062531e-01

Once the simulation is finished and the data are available and suitable for the power transmission, I proceed to make the complete simulation together with the tags to be illuminated in order to describe a harsh environment from the electromagnetic point of view the simulation scenario is represented by a metallic box with a smaller metallic object inside: this could represent an automatic machine. To do this, I use the box drawn below (figure 43) and the extracted data of farfield, then I place the antenna at the midpoint, at a suitable distance so that the incoming rays

bounce throughout the interior and produce a random effect for the power transmission.The purpose of this phase is to accurately estimate the power received by the illuminated tags.The tags are equipped with a standard square patch resonanting at 2.45GHz and linearly polarized.
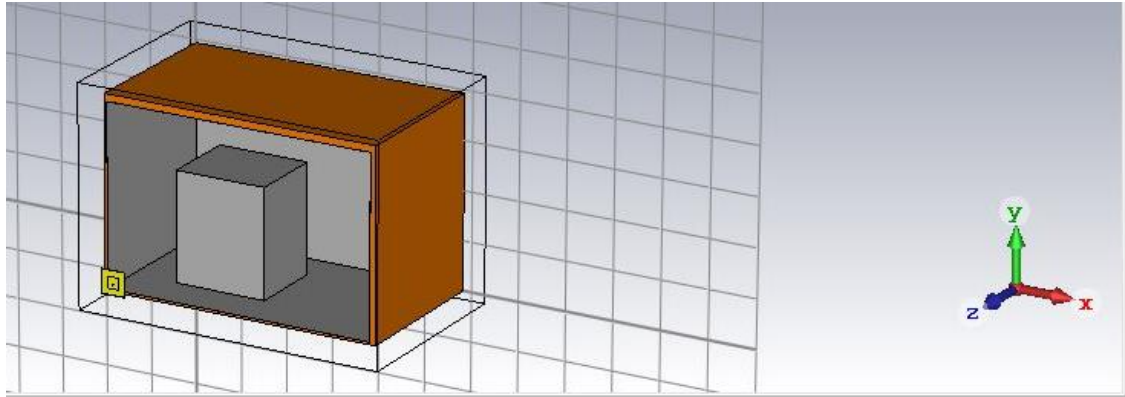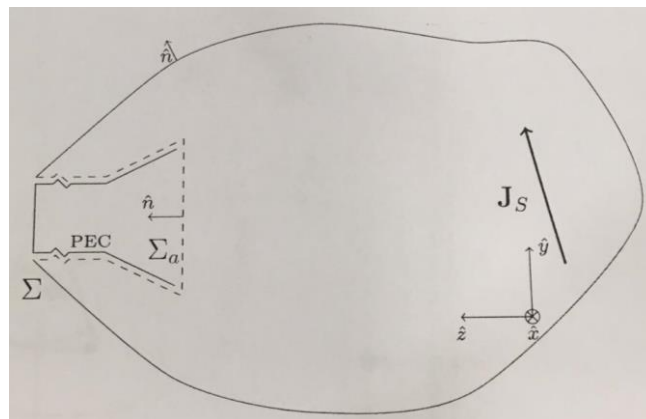

Figure 43: Box for final simulation

Figure 44: The sigma región

The circuit represented in figure 44 shows the circuit equivalent to the sigma region and explain integral equation

JS: represents the electric current density vector which substitutes the transmitting antenna and generates the field in the sigma region,part of which has to be received by the receiving tag, here represented by a horn antenna.

Jeq is the equivalent current source value (complex value) which represents the receiving antenna in reception mode Norton current genearator to be placed in parallel to the antenna admittance (Y(w)).This generator is the outcome of this procedure, because it is the circuital equivalen representation of the incoming field received by the receiving antenna of the tag.The available power received by the antenna (i.e., the power received in case of perfect matching between the antenna and the receiver

connected to it,represented by a resistance RL in figure 44 can then be given in the following way:

$$P_r = \frac{|J_{eq}|^2}{8 \times Re(Y(\omega))} \qquad (1)$$

Zr: Is the internal impedance of the receiving antenna when it behaves as transmitter (when applying the reciprocity theorem). For simplicity, we choose this value to be equal to the transmission line characteristic impedance. That is, 50 Ohm. But it could be eventually different.

Y(w): Is the antenna admittance at frequency w.

Es(Psigma): Electric field generated by transmitter taken at Point sigma of surface SIGMA between the transmitter and receiver (as shown in the figure).

Hh(Psigma): Magnetic field generated by receiving antenna (working in transmitting mode based on reciprocity theorem) taken at Point sigma of surface SIGMA between the transmitter and receiver (as shown in the figure).

Eh(Psigma): Electric field generated by receiving antenna (working in transmitting mode based on reciprocity theorem) taken at Point sigma of surface SIGMA between the transmitter and receiver (as shown in the figure).

Hs(Psigma): Magnetic field generated by transmitter taken at Point sigma of surface SIGMA between the transmitter and receiver (as shown in the figure).

The integral is evaluated on the surface SIGMA with normal vector **n** and will have a non-zero value over the receiving aperture.
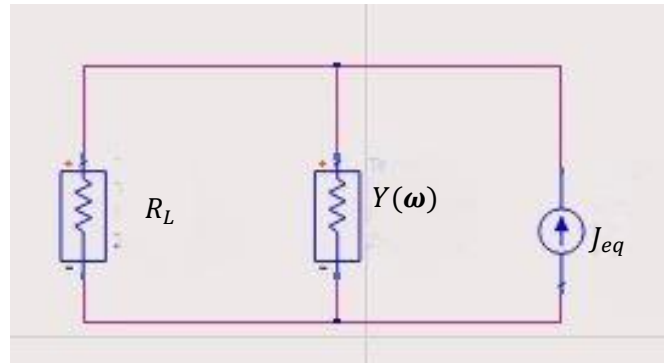

Figure 44 Schematic representation of the receiving antenna in presence of an incoming field that is responsible for the excitation J_{eq}

$$J_{eq} = \frac{1 + Z_R Y(\omega)}{U} \cdot \hat{n} \int_{\Sigma} \left[E_s(P_\Sigma) \times H_H(P_\Sigma) - E_H(P_\Sigma) \times H_s(P_\Sigma) \right] d\Sigma \quad (2)$$

The equation excludes the region of the transmitting antenna and includes the region in front of the transmitting antenna. In practice, this region extends to

infinity, in the sense that it is an infinite plane between the transmitting antenna and the receiving antenna.

To get the values of the antenna I use the equations made in Excel, for the calculation of the equivalent current generator the output power, the ratio output power / incident power.

In the following excel table the preliminary results of the first full simulation are shown, the data in the excel file can be explained as the first line there is the value of the integrand of formula (2), whereas the fourth line contains the full evaluation of (2), i.e, Jeq. Finally, in the seventh line there is the amount of power received by the tag according to (1).

Integral results						
f= 2,4 (GHz), U = 9,052 (v), Y(w) =0,011408984(S)|_-8,83(deg), R0= 50 (Ohm)						
	P1	P1(XPD)	P2			
prt1 int(EsxHh -EhxHs, dS)	-0,0081-0,0157i	-0,0043+0,0077i	0,0110 + 0,0075i		R0 (Ohm) =	50
int (Mag)	1,76664E-02	8,81930E-03	1,33135E-02		Y(w) (S) =	0,011273731-0,0017515442i
int (Phase) deg	242,71	119,18	34,29		U (v) =	9,052
Jeq (A)	-0,00071536676977463...	-0,00165515908086611+...	0,00207081307998232+,00269360362350862i			
Jeq (Mag)	4,50845E-03	2,25068E-03	3,39761E-03		P_inc (W)=	3,52E+05
Jeq (Phase) deg	260,87	137,34	52,45			
P_out	8,8024E-04	2,1937E-04	4,9991E-04			
P_out/P_inc	-86,02	-92,06	-88,48			

Figure 45: Integral results

The three columns have the following meaning corresponds to the position of the tag quite in front of the TX antenna; P2 corresponds to the tag rotated by 90º around the vertical axis, thus exploiting the field reflected by the box; P1(XPD) corresponds to the tag in the same position as P1, but rotated by 90º in the horizontal plane, thus in cross-polarization conditions with respect to P1. The received power is always enough, despite the tag position, thanks to both the relections and the circular polarization of the transmitting antenna.
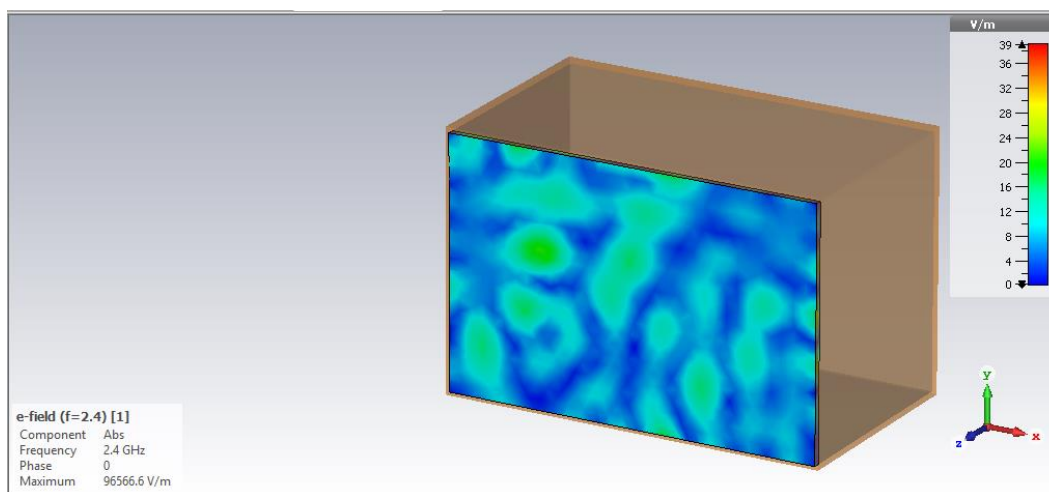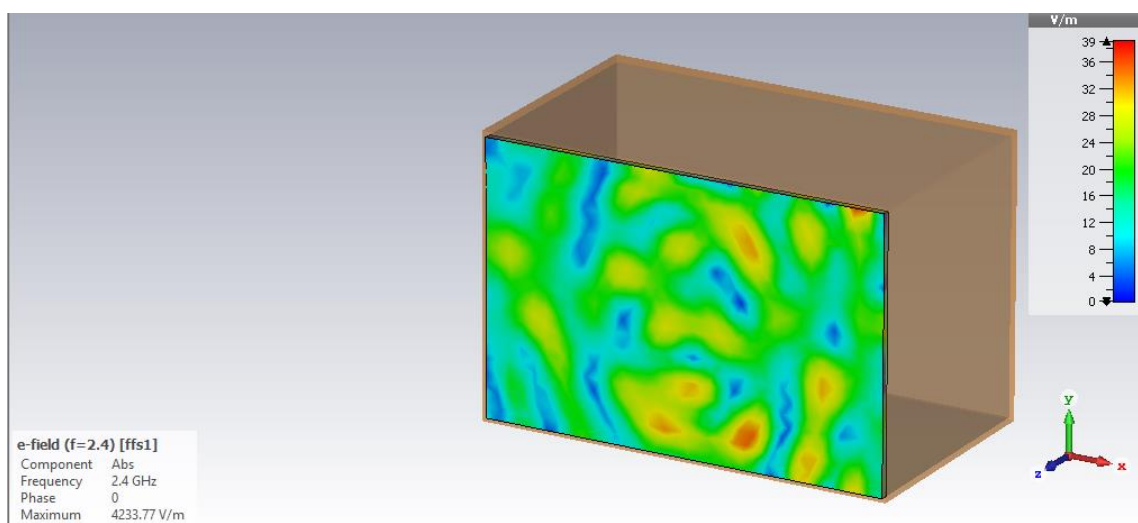
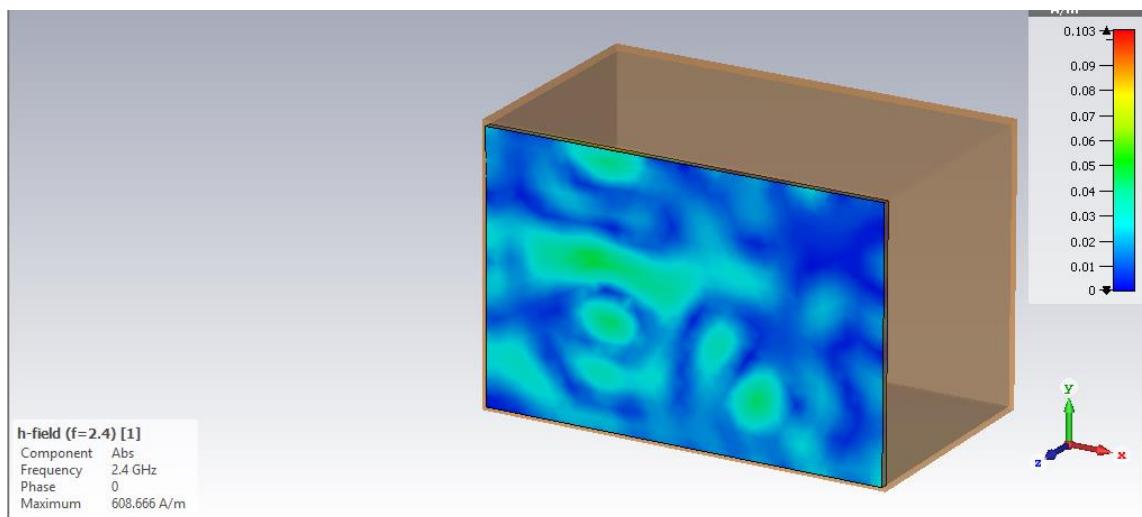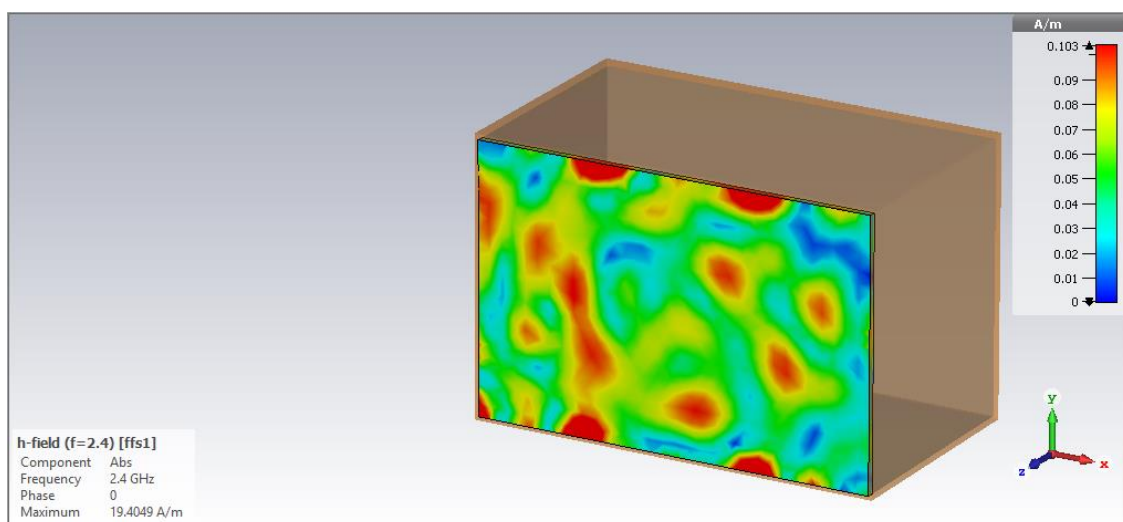**Figure 46:IE_Eh_2f4**

Figure 47: IE_Es_2f4

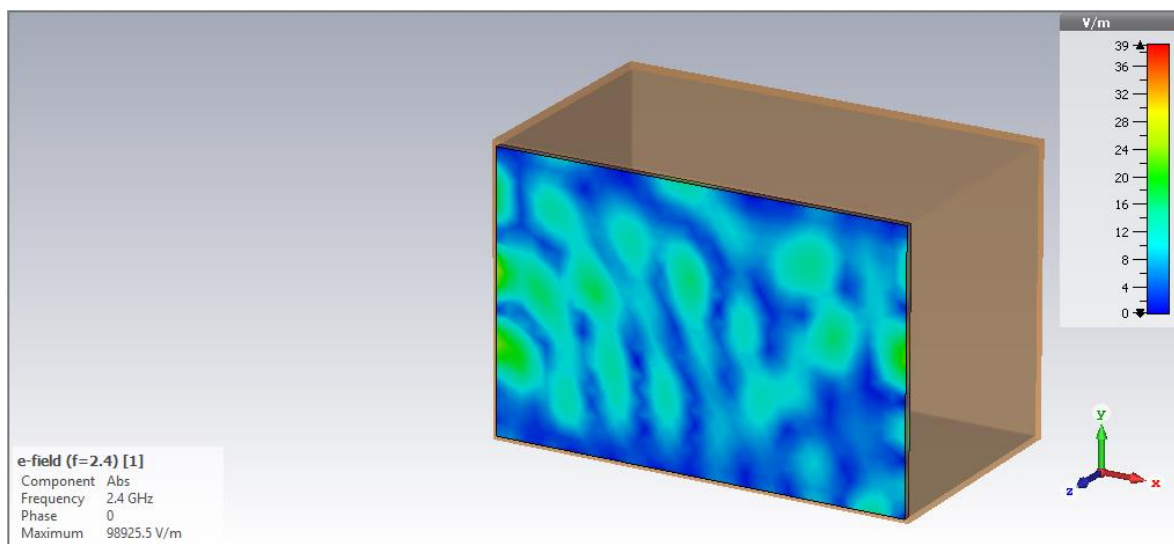**Figure 48: IE_Hh_2f4**

Figure 49: IE_Hs_2f4
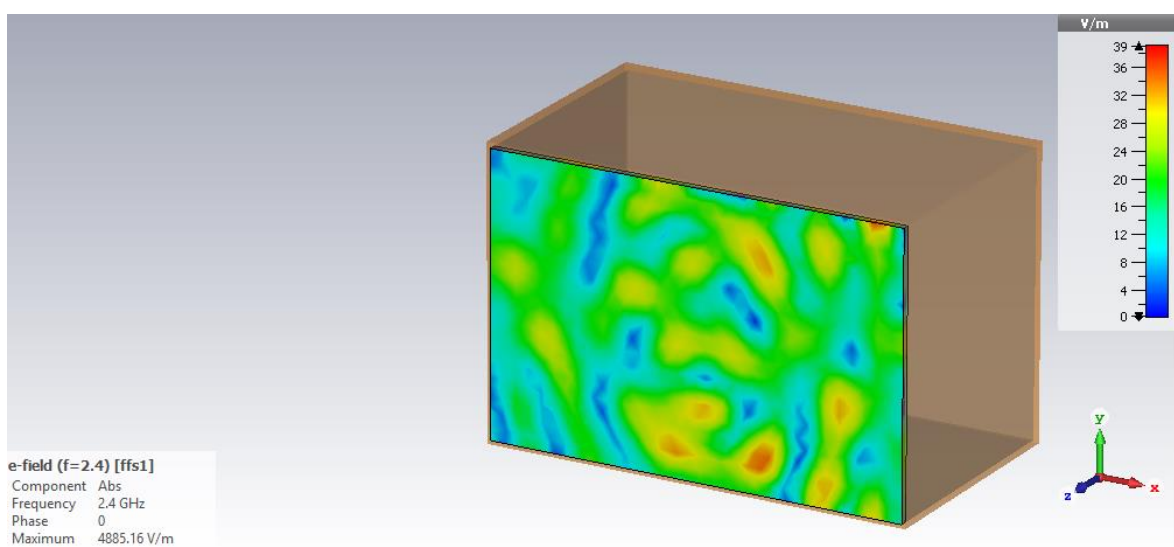
Figure 50: P2_Eh_2f4
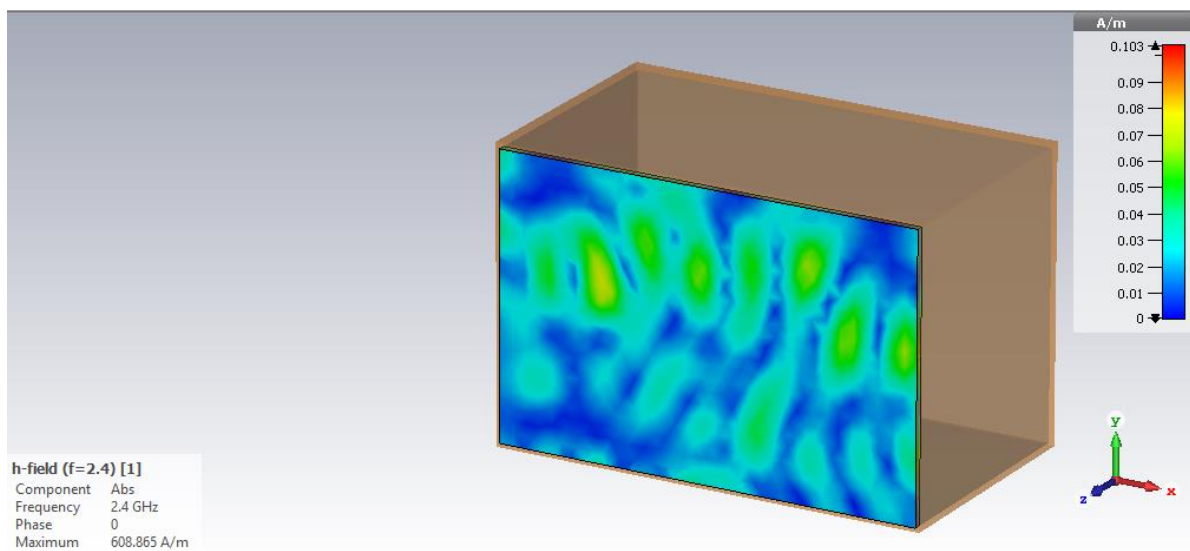

Figure 51: P2_Es_2f4
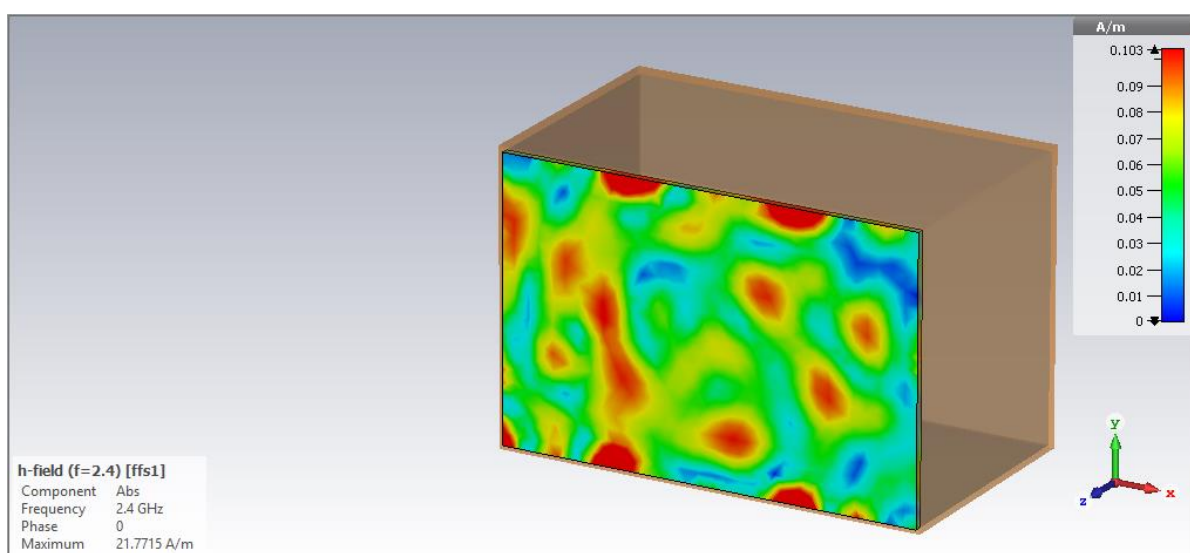
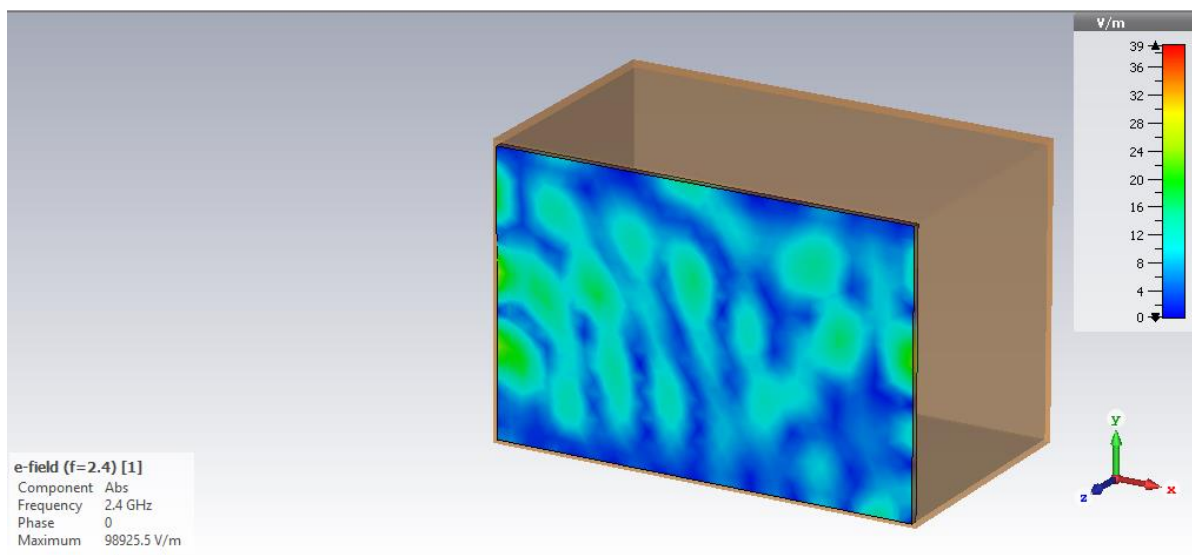**Figure 52: P2_Hh_2f4**

Figure 53: P2_Hs_2f4
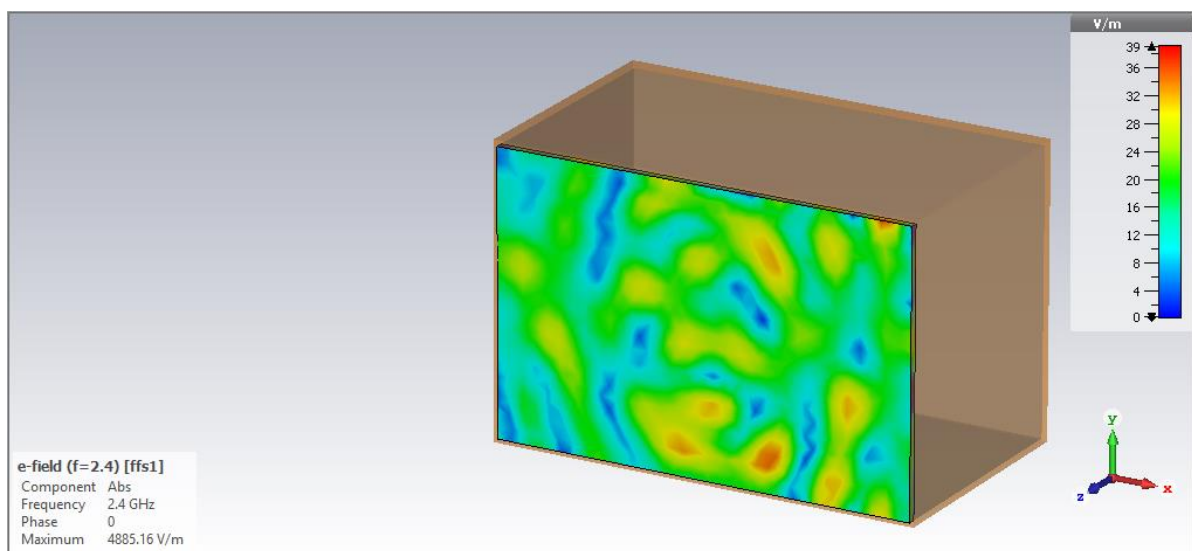
Figure 54: XPD_Eh_2f4

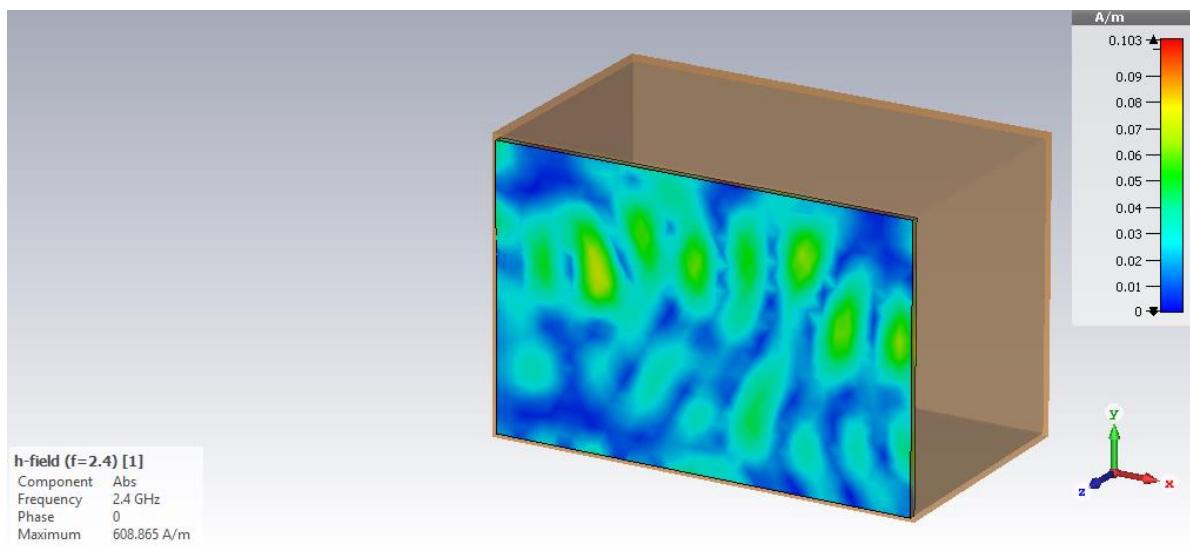**Figure 55: XPD_Es_2f4**

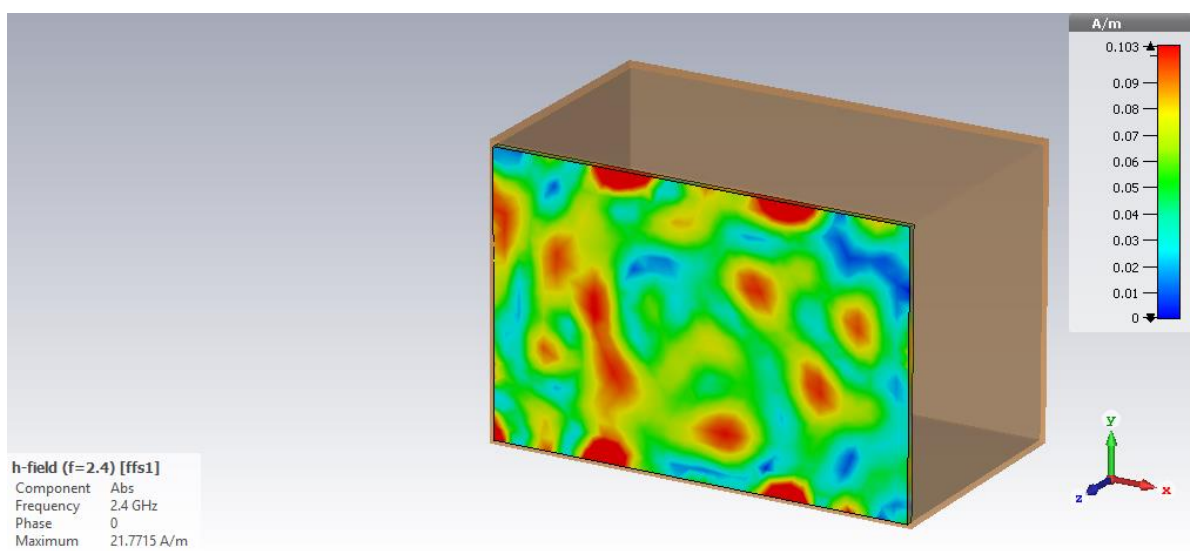**Figure 56: XPD_Hh_2f4**

Figure 57: XPD_Hs_2f4

From figure 44 to figure 57 the results of the final simulation are shown.

CHAPTER 6

CONCLUSION

To finish I will make a conclusion about the antenna, as I mentioned at the beginning the purpose of the antenna is to transmit power to illuminate the tag, the type of antenna used is a circular polarized antenna, following the design of the document we get the results seen above The antenna used is well for the transmission of power but we have to to keep in mind that only radiation at elevation angle around +-30 circularly, so we would have to take this into account when placing the elements around moreover in the z-axis does not emit radiation and a bad placement of the antenna would not make possible the transmission of power.

With respect to the values of farfield and axial ratio have adequate values for power transmission, if you look at the figure 30 the axial ratio is below 3dB optimal value for that transmission and this relates to the maximum value of farfield.

Finish by saying that the antenna is suitable for power transmission.

CHAPTER 7

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