Electrical and Electronics Engineering
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Desing of a circularly polarized patch antenna array

Student: Pablo Suárez Reyero

Supervised by: Anja Skrivervik
Teaching Assistant: Germán Augusto Ramírez Arroyave

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Microwave and atenna group
EPFL

Abstract

Circularly polarised patch antennas are widely used today, due to their potential. Circular polarisation allows us to work with signals that will always work regardless of the angle at which the emitter moves with respect to the receiver. For this reason, circularly polarised antennas have become the standard for many designs, and this project is no exception.

It is worth knowing that both gain and directivity as well as frequency and size have driven the design, due to their correlation and influence. This antenna is meant to achieve a high directivity in free space and a radiation frequency of 868-869 MHz. Since the frequency is low the design ended up with larger aperture, and therefore, higher dielectric losses. The latter is the reason why I have chosen an antenna array, in order to solve/mitigate the problem of free space losses.

To carry out the design of this antenna I have used ANSYS ELECTRONICS software, but the design can also be extrapolated to other simulation programs such as CST. These simulators are very versatile and powerful, which has allowed me to implement any idea as far as the antenna design is concerned.

Contents

1 Introduction

The purpose of this project is to develop, test, and construct a small directional antenna for usage in the frequency band of 868 MHz. The antenna has to be highly directive, and the minimum gain has to be 15 dB. It should be mentioned that, a smaller size (in comparison with the current helix antenna) has to be achieved. This antenna will be placed in the ground operations of the Rocket Team, and it will replace the current helicoidal antenna.

The main motivation, that led to an updgrade of the current antenna in the ground segment, is its size. Helicoidal antennas are quite big in terms of size and sometimes cumbersome and difficult to operate (see images 1 and 2).

The development of new manufacturing techniques and new communications schemes have allowed me to choose the type of antenna, its polarisation and materials with a greater degree of freedom, as the options are greater.This is a good thing, but it introduces a new difficulty, which lies in the art of knowing how to choose well and filter out concepts or parameters that are not relevant to our design. This is what the design process of this antenna is mostly about.

After doing a research and comparing different topologies, the best suited antenna because of its simplicity and potential is a micro-strip antenna. Microstrip antennas are widely used nowadays especially for commercial operations. A metallic patch on a grounded substrate makes up a microstrip antenna.

The metallic patch can be arranged in a variety of ways. Rectangular and circular patches, on the other hand, are the most common due to their simplicity of analysis and manufacture, as well as their appealing radiation characteristics, particularly low cross-polarization radiation. Microstrip antennas have a low profile, can conform to planar and nonplanar surfaces, are simple and inexpensive to manufacture using modern printed-circuit technology, and are mechanically durable when mounted on hard surfaces. Image 3 shows an example of a square patch antenna.

Figure 1: Current helix antenna size

Figure 2: Current helix antenna size [BIS]

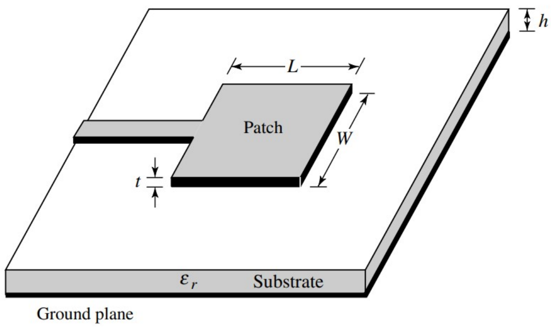


Figure 3: Microstrip patch antenna (taken from Balanis)

2 Challenges and main problems to overcome

The challenges that a design like this can pose can be divided into many branches, but since they are all related between each other, at the end of the day, one will affect the other either directly or indirectly, so each of them is described separately.
The aim of this section is to summarize the main challenges to be faced or already faced involving the design process as well the future testing process.

2.1 Rocket Trajectory

The trajectory of the rocket is just as relevant and of equal importance as any other parameter within the antenna design. Knowing the rocket trajectory and the distances involved, let us estimate some parameters, such as: path losses, gain at a certain distance, and directivity.

It is known that a functional rocket, follows a parabola, but why is that?; *"The explanation is that as they fly, they cover distance both horizontally and vertically, but only the latter is affected by the force of gravity, which bends the path of the projectile into a parabola."*(see reference 5.). The following image illustrates the rocket trajectory;

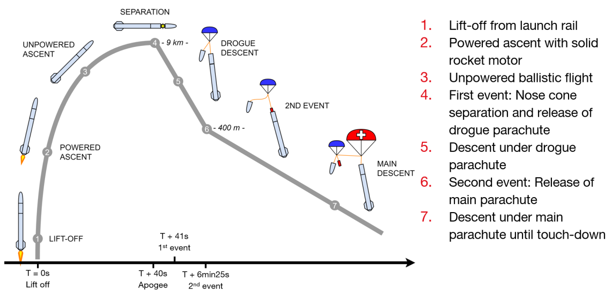


Figure 4: Rocket trajectory

In order to be capable of receiving information from the rocket, the antenna will be mounted on a 30-35mm tube perpendicular to its main axis, so a jaw at the rear end of the antenna will be provided in order to be able to clamp it on this tube. The bracket where the antenna will be placed will move the antenna up and down, this movement is given by the reception of correct co-ordinates, and it will make the antenna to move in the correct direction of the y axis, hence pointing to the correct point, allowing it to receive the information from the transmitter antenna mounted on the rocket.
Image 5 illustrates an example of how the bracket is (do not pay attention to the mounted antenna).

Figure 5: Mounting structure of the antenna (do not pay attention to the type of the antenna)

2.2 Polarization

The antenna has to have circular polarization, as opposed to linear polarisation, changes have to be made in the design to achieve it.

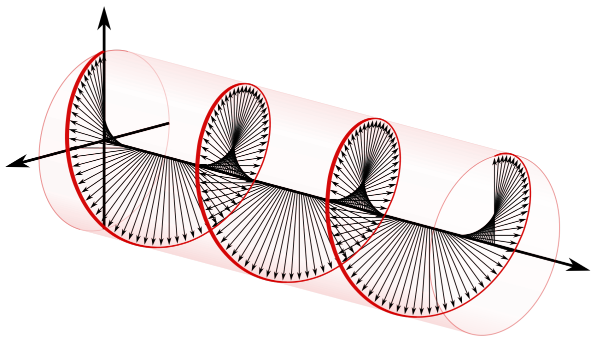
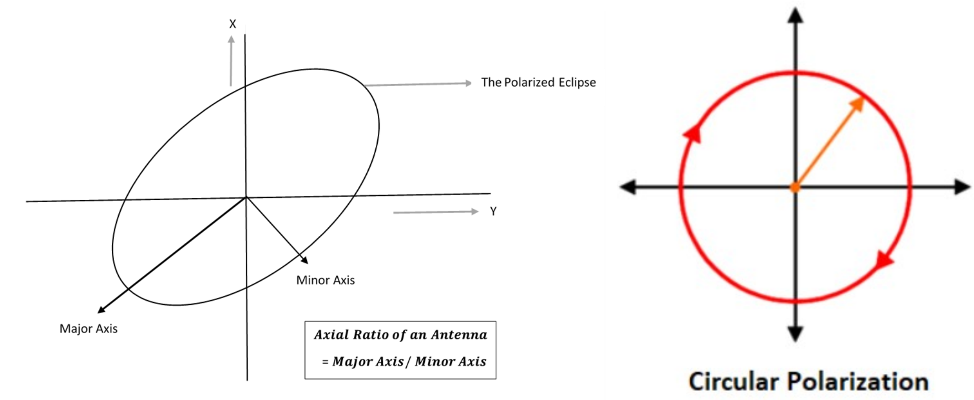


Figure 6: Circularly polarized wave

It is of considerable importance to know how good the desired polarisation of an antenna is. The concept that describes this, is the axial ratio, in Balanis, the axial ratio is defined as; *The ratio of the major axis to the minor axis*, and is given by the following expression:

$$AR = \frac{major\_axis}{minor\_axis}, \quad 1 \leq AR \leq \infty \tag{1}$$

This concept can be better understood graphically:



(a) Axial Ratio of an elliptically polarised antenna (b) Axial Ratio of a circularly polarised antenna

Figure 7: Axial Ratio

Since I'm designing a circularly polarized antenna, the value of the AR at the operating frequency and its surroundings has to be 0 dB $\equiv 1$ (natural units), or at least below 3 dB, because the *major axis* has the same shape as the *minor axis* (see 7b).

The most common way to achieve this type of polarisation in not very complex designs is by cutting two corners of opposite diagonal ends. The image 8 illustrates a simple design of a circularly polarized patch antenna.

Another common way to achieve circular polarization is using a multi-feed technique with a 90° phase delay. Note that this technique results in a bigger antenna in comparison with

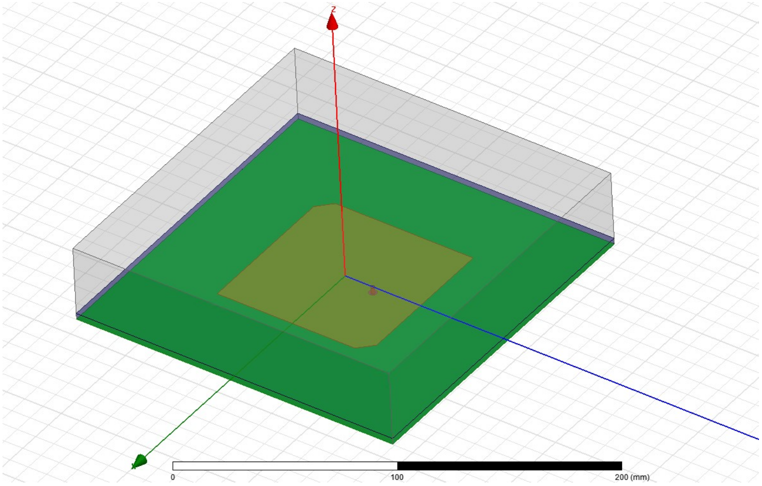


Figure 8: Design of a single patch in HFSS

the single-feed antenna, since there has to be extra space for the power divisor and the multiple feeding lines. In the other hand this technique increases the bandwidth, which is very interesting, but in comparison with the amount of space it will take, I think is not worth it.

2.3 Position on ground

Even though this is not a challenge faced during the design process it is important to note it.

This antenna will be on the ground, constantly receiving data and information from the rocket, so its directivity has to be high. The pointing angle plays a very important role during transmission as it lets directivity do its job. Settling a dgood pointing angle can avoid potential reflections, that could interfere the communication between the rocket antenna and the ground segment.

But it is not all about free space and "looking up", the ground can play a trick on us in practical terms. There could be reflections on objects and many other things regarding the free-space and the propagation.

2.4 Efficiency

The efficiency of the antenna is determined by the ratio between the radiated power and the power delivered to the antenna terminals. (see the following expression).

$$\eta = \frac{P_{rad}}{P_{in}} \tag{2}$$

In equation 13 the efficiency is written as a function of both directivity and gain. Both 2 and 8 are valid but they are general expressions, since this efficiency is characterised by the elements that make up the antenna.
It will be more correct to express the efficiency, as the product of all the efficiencies associated to the dielectric, conduction and reflection, this efficiencies exist because there are losses in dielectrics as well as in the processes of wave reflection and conduction,(see the following expression):

$$\eta = \eta_r \eta_c \eta_d \tag{3}$$

Where:

- Efficiency related to the reflection, $\eta_r = 1 - |\Gamma|^2$

- Efficiency associated to the conduction losses, η_c

- Dielectric efficiency, η_d

Being Γ the reflection coefficient:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{4}$$

In 4, Z_0 is the characteristic impedance of the line, in my case; $Z_0 = 50\,\Omega$. Ideally one would like to achieve $Z_{in} = 50\,\Omega$ by adapting the impedance, which will result in a $\Gamma = 0$, but of course this is not realisable, therefore the only thing we can do is decrease its magnitude to the minimum value.
Meanwhile, η_c and η_d are usually computed experimentally due to its complexity to compute it by hand.
In the best scenario an antenna has an efficiency of 100%, but in most practical cases an antenna has an efficiency of 50% $\sim$ 60%, in section 4, the efficiency of the 2×2 array antenna is plotted.

2.5 Gain

The gain of an antenna is is defined as; *"The ratio between the power density radiated in one direction and the power density that an isotropic antenna would radiate at equal distances and power delivered to the antenna."*(see reference 5).

The gain is an useful tool that describes the performance of an antenna. *"Although the gain of the antenna is closely related to the directivity, it is a measure that takes into account the efficiency of the antenna as well as its directional capabilities. Remember that directivity is a measure that describes only the directional properties of the antenna, and it is therefore controlled only by the pattern."*(see reference 5)

As it has been said many times before, the gain in this design has to be at least 15 dB, this data has been given by the Rocket Team, after several tests with different designs. It is of special interest to keep in mind that apart from achieving a compact size in the design we should also try to improve some other parameters, in this case, doing so with the gain would be a good thing.

The gain can be computed as follows:

$$G(\theta, \phi) = \frac{U(\theta, \phi)}{\frac{P_{in}}{4\pi}} \tag{5}$$

Where:

- $P(\theta, \phi)$ denotes the radiation intensity in any direction contained in the electric field.

- P_{in} denotes the total input power accepted by the antenna.

3 Design parameters

3.1 Overview of parameters

As mentioned in the introduction and abstract sections above, this design is based on four fundamental parameters, frequency, directive gain, size and polarisation. The desired frequency ranges from 868 MHz to 869 MHz, this can give a general idea of how large the patch can be. It is a low frequency compared to the average frequency at which mobile and satellite communications operate today, we are talking about GHz versus MHz, therefore this has been a challenge when designing the antenna.

The directive gain, also called directivty, plays a very important role in this design, since the antenna must maintain a continuous communication with the rocket throughout the entire journey, this means that communication between the rocket and the antenna must not be lost or interrupted under any circumstances, therefore the integrity of the rocket also depends on this specific parameter.

Since one of the main objectives of the project is to reduce the size of the antenna, I have decided to design an array of patches, as it allows to achieve a good gain and it helps reducing the losses in the free space, nevertheless, this will be discussed in more detail later on.

The following table summarizes the main design parameters:

$f_0[MHz]$	$G_{rx}[dB]_{min}$	$Size[mm]$	$Polarization$	$P_{rx}[dBm]$	$D[km]$
868-869	15	$\sim 81,66$	Circular (LHCP)	-130	11

Table 1: Main parameters.

3.2 Frequency and its influence

As mentioned before the operating frequency is 868 MHz. The resonant frequency of this antenna is low and this directly affects the size of the antenna patch. The relationship between these two parameters is inversely proportional, which means that as the frequency decreases, the size of the radiating element increases: $f_{operation} \propto (\sigma_{patch})^{-1}$, where σ_{patch} is the surface of the patch. This also happens with the gain and directivity.

It is important to note that at this frequency, the gain has to be maximum, and at least 15 dB, and the antenna has to be fully matched, this means that we have to achieve an impedance of approximately $Z = 50\,\Omega$.

3.3 Directivity

The directivity of an antenna is defined as the ratio of the power density radiated in one direction, at one distance, to the power density that would be radiated at the same distance by an isotropic antenna, at the same total radiated power.

$$D(\theta, \phi) = \frac{\frac{P(\theta,\phi)}{W_r}}{4\pi r^2} \tag{6}$$

If no direction is specified, then we take the direction in which the power is maximum:

$$D(\theta, \phi) = \frac{\frac{P_{max}}{W_r}}{4\pi r^2} \tag{7}$$

For directional antennas, with a single main lobe and secondary lobes of negligible level, an approximate directivity can be obtained by considering that uniform radiation is produced in the solid angle defined from the beam-widths at -3dB in the two main planes of the radiation pattern.

$$D = \frac{4\pi}{\Omega_e} = \frac{4\pi}{\theta_1 \theta_2} \tag{8}$$

In equation 8, Ω_e denotes the solid angle, which is illustrated also in the figure below (see image 10).

One term that is strictly related with the directivity is the HPBW *(Half Power Beam-Width)*,

the *IEEE* defines it as; *"In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam."*.
In other words, the HPBW is the angular separation at which the magnitude of the radiation pattern decreases by $50\% \equiv -3dB$ from the peak of the main beam. Since the directivity has to be high, θ_1 and θ_2 have to be low, (see equation 8).

In equation 8 it can be noted the angles that appear inside the main lobe in figure 10. The following image illustrates the concept of half power beam-width.

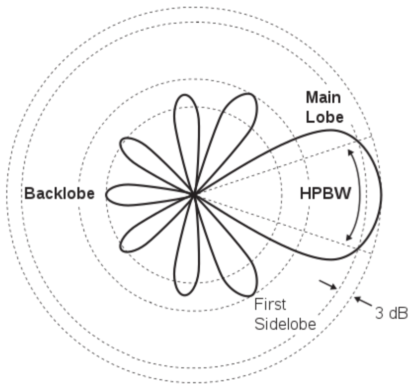


Figure 9: Illustration of the Half Power-Beamwidth

3.4 Array Factor

In this section the Array Factor is explained, therefore the number of elements are computed here.

In order to calculate the total size of the array it is necessary to know the number of elements that will make up the array, this can be calculated as follows:

$$D_0 \approx \pi \cdot \frac{2Md_x}{\lambda} \cdot \frac{2Nd_y}{\lambda} \cdot \cos\theta_0 \tag{9}$$

In equation 6

- M denotes the number of row elements in the array.
- N denotes the number of column elements in the array.
- d_x denotes the distance between elements in the x axis of the array.
- d_y denotes the distance between elements in the y axis of the array.
- λ denotes the wavelength.
- θ_0 denotes the beamwidth between nulls:

In order to avoid coupling effects, I set $d_x = d_y = \frac{\lambda}{2}$.
For simplicity it can be assumed that the array to be designed is a square array, therefore; $M = N$. For simplicity I suppose that $\theta_0 = \frac{\pi}{2}$.

It should also be taken into account, the expression that relates gain and directivity:

$$G(\theta, \phi) = D(\theta, \phi) \cdot \eta \tag{10}$$

In equation 13, η denotes the efficiency, for an initial estimation, I take an efficiency of 80%, which is very optimistic in practical terms, but it can be seen after the calculation of the array factor, that changing this value won't make a big difference in the final design.

In equation 13, I also assume that $G(\theta, \phi)|_{dB}$ is the minimum gain which is 15 dBi, therefore, in natural units: $G(\theta, \phi) = 10^{\frac{15}{10}} = 31,62$.
Then:

$$D(\theta, \phi) = \frac{31,62}{0,7} = 39,53$$

The obtained directive gain in dB's will be; $D|_{dB} = 10 \cdot log_{10}(45,17) = 16.55\,\text{dB}$. Since I am designing a planar array of directive antennas, I took into account, equation 8 in section 3.3.
Then the following can be said:

$$D_0 = 39,53 = \frac{32,40}{\theta_1\theta_2} \quad \therefore \quad \theta_1\theta_2 = 0,821 \tag{11}$$

Putting everything together, and simplifying terms substituted in equation 4:

$$\frac{32,40}{\theta_1\theta_2} = MN \cdot \pi \cdot \cos(\theta_0) \tag{12}$$

$$M \cdot N = \frac{32,40}{\theta_1\theta_2\pi \cdot \cos(\theta_0)} \tag{13}$$

Since $M = N$, I can easily estimate the value as follows;

$$M = N = \sqrt{\frac{32,40}{\theta_1 \theta_1 \pi \cdot \cos(\theta_0)}} = \sqrt{\frac{32,40}{0,821\pi \cdot \cos(\frac{\pi}{2})}} = 3,54 \tag{14}$$

Then I will need $M = N = \lceil 3,54 \rceil = 4$, this means that the array will have a dimension of 4×4.

After knowing how many elements the array will host, the dimensions of the final array, can be computed, but since the latter dependens on the dielectric, in the next section the dielectric topic is introduced, thus the size of the patch is also discussed.

3.5 Dielectric

The choice of the dielectric in this project was not difficult, since the design is not very complex. While choosing a dielectric it is really important to enumerate all the aspects as well as the associated pros and cons. The following list summarizes what my choice is based on:

- Prize
- Operating frequency
- How common it is
- Losses (i.e: $\tan(\delta)$)
- Relative permitivity (i.e: ε_r)

The difficult part of choosing a dielectric is to understand the trade-off between all of its specifications, and how each parameter can get influenced by another. It is fundamental to go deeper into the technical aspects that are directly related to the design, (e.g tangent of losses, frequency). After doing a research I noted that not every dielectric is suited for any frequency, so filtering in this case is a must. The following table summarizes the most famous dielectrics for low frequencies.

Material	ε_r **(1GHz)**	$\tan\delta$ **(1GHz)**	**Manufacturer**
RO3003	3	0,0013	Rogers Corporation
RO3006	6,15	0,0013	Rogers Corporation
RO3010	10,2	0,0013	Rogers Corporation
RO4003	3,38	0,0022	Rogers Corporation
TLC-32	3,2	0,0030	Taconic Plastics
HT-2	4,3	0,0033	Hewlett-Packard
Polyguide	2,32	0,0005	Shawinigan Research
Epoxy/Glass (FR4)	4,4	0,01	—

Table 2: Micro strip patch antenna dielectrics for low frequencies.

Perhaps, the most known dielectric among the ones shown in table 2, is the FR4-epoxy. This dielectric is cheap and it has high strength characteristics, excellent electrical properties and chemical resistance not only at room temperature but also under wet or humid conditions.

From section 3.4 we already know the dimensions of the final array (i.e. 70 mm), so it is a big surface. So the final decision variables in this case, are the size and the prize, this two are directlproportional, the bigger the array, the more expensive the dielectric gets. The dielectrics from the manufacturer: *Rogers Corporation* are quite expensive when size increments notably, so they are not a realistic choice, and among the other ones, the *FR4-Epoxy* is the most famous and used one.

For my design the *FR4-Epoxy* is the best one, since it is cheaper than the others, it has good electrical properties and it gives good experimental results in terms of gain, even though its tangent of losses is one order of magnitude higher than the others. The standard FR4 can have a thickness inside this range: $thickness \in \{0'2, ..., 3'2\}$ $[mm]$, this value is discussed later on in the results, since changing it, gave different results and it may improve them.

3.5.1 Patch size

The size of the patch is determined by two fundamental elements: the frequency and the thickness of the dielectric, (see section 3.5). Since I chose the *FR4-Epoxy*, the relative permeability, will be: $\varepsilon_r = 4,4$, which has a direct relation with the dimensions of the patch, which can be computed with the following equations taken from Balanis:

First, the expression that determines the width of the patch:

$$W = \frac{c}{2 \cdot f_0 \sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{15}$$

The variable c in equation 15, denotes the speed of light in vacuum, f_0 denotes the resonant frequency, and again ε_r denotes the relative permeability of the chosen substrate.

The length of the patch can be computed as follows:

$$L = \frac{c}{2 \cdot f_0 \sqrt{\varepsilon_{eff}}} - 0,824h \left(\frac{(\varepsilon_{eff} + 0,3) \cdot (\frac{W}{h} + 0,264))}{(\varepsilon_{eff} - 0,258) \cdot (\frac{W}{h} + 0,8)} \right) \tag{16}$$

Where $\varepsilon_{effective}$ denotes the effective permeability of the *FR4-Epoxy* and it has the following form:

$$\varepsilon_{effective} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \left[\frac{1}{\sqrt{1 + 12 \left(\frac{h}{W}\right)}} \right] \tag{17}$$

Note the importance of $\varepsilon_{effective}$, this permittivity is introduced when more than 1 different medium influence the dielectric, e.g: air in the top, copper in the bottom, and the dielectric in between.

Knowing that:

- The speed of light in the vacuum; $c = 3 \cdot 10^8 m/s$
- The resonant frequency; $f_0 = 868\,\mathrm{MHz}$
- The relative permitivity of *FR4-epoxy*; $\varepsilon_r = 4.4\,\frac{\mathrm{C}^2}{\mathrm{N \cdot m}^2}$
- The permitivity with respect to the vacuum is denoted by $\varepsilon = \varepsilon_r \varepsilon_0$
- ε_0 denotes the permitivity in vacuum and $\varepsilon_0 = 8,85 \cdot 10^{-12}\ \frac{C^2}{N \cdot m^2}$
- The thickness of the substrate; $h = 3.2\,\mathrm{mm}$

Expressions 15 and 16, yield the following values:

$$\begin{cases} W = 105.1\,\mathrm{mm} \\ L = 81.75\,\mathrm{mm} \end{cases}$$

For simplicity, the array will be square, this will prevent currents of different magnitudes, resulting in a better value for the axial ratio, therefore a better circular polarization will be obtained.

$$W = L = 81.75\,\text{mm}$$

3.5.2 Single element size

In order to manufacture the antenna array in the EPFL workshop, the size of a sub-array 2×2 has to be about 30×30 cm. To achieve an approximate size and to respect a $\lambda/2$ spacing from the center of a patch to the rest, the unit cell size has to be $\lambda/2$. This also means that, a value of $\lambda/4$ is taken from the centre of the patch to the end of the unit cell substrate (drawing a straight line), see the following image.

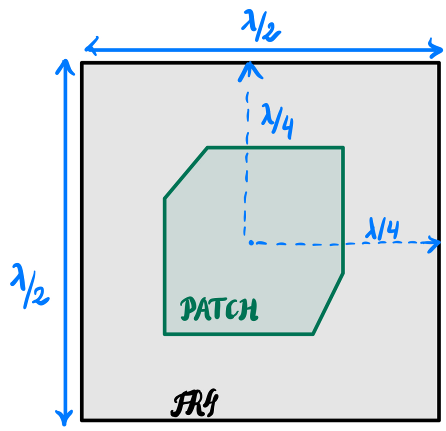


Figure 10: Illustration of the single patch dimensions

3.5.3 Array and sub-array dimensions.

Now that the dimensions of the single element are known, the dimensions of the final array can be estimated.
If every patch has a length of $d = \lambda/2 \sim 172.81\,\text{mm}$, thus a dimension of $\frac{\lambda}{2} \times \frac{\lambda}{2}$, and the total array contains 4×4 elements, then the dimensions of the total array will be of about; $2\lambda \times 2\lambda \sim 691,24 \times 691,24$ mm. Since the design can accomplish a maximum value for the length of $70\,\text{cm} \times 70\,\text{cm}$, therefore the implemented design will have a dimension of $70\,\text{cm} \times 70\,\text{cm}$.
It is important to note, that in this proyect I'm only simulating a sub-array of 2×2 elements (see figure 11), due to the little time left.

3.6 Link budget

It is important not to lose the perspective of the design, since a link budget is established thus, specific values have to be achieved, in order to respect the margin that this budget establishes.
During the design process, not only the parameters concerning the ground segment antenna have been taken into account, the designed antenna complies with a pre-established link budget, which, although it limits the margin of freedom when designing the antenna, it helps to steer the design in the right direction, in order to comply with the specifications concerning not only the designed antenna but also the antenna mounted on the rocket.
The mounted antenna in the rocket is a linearly polarized antenna, this will introduce some losses, since the polarization is not the same.
The link budget is summarized in the following table:

Note that in 3 for L_{path}, D is the distance of the transmission.

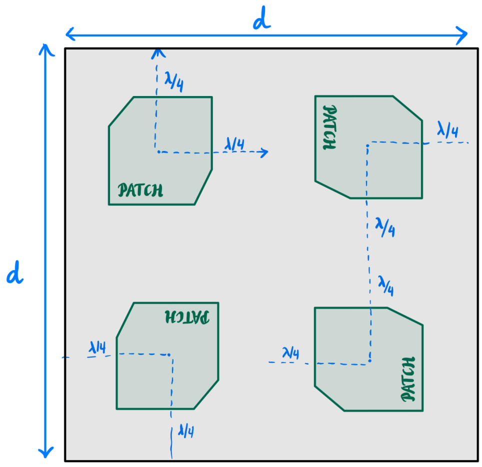


Figure 11: Scheme of the 2×2 subarray

Variable	Description	Value
P_{rx}	Received Power	$-130\,\mathrm{dBm}$
$G_{rx}\|_{min}$	Gain of the ground antenna	$15\,\mathrm{dB}$
L_{path}	Losses due to the free space $\Rightarrow 20\ \log_{10}(\frac{c}{4\pi\cdot D\cdot f})$	-112 dB
L_{pol}	Losses due to the different polarization	$-3\,\mathrm{dB}$
$L_{pointing}$	Losses due to pointing	$-20\,\mathrm{dB}$
$L_{mismatch}$	Losses due to the mismatch	$-20\,\mathrm{dB}$

Table 3: Main parameters.

4 Design Process and Simulations

In this section, schemes and figures regarding the simulations of the first, intermediate and final design will be shown chronologically.

4.1 First patch design

The first design that was carried out taking into account the calculated dimensions as well as the chosen dielectric, is pictures in the following image;

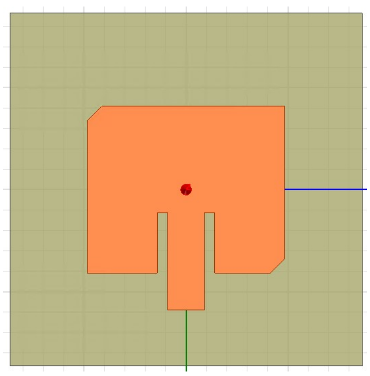


Figure 12: First designed patch.

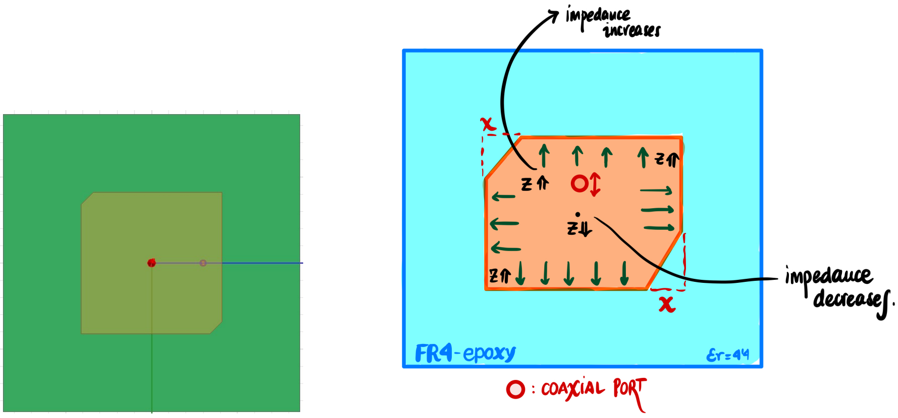
The results obtained from this first design were not good, the gain was not enough and the axial ratio value was too high at the operating frequency, this gave me a clue about how bad the circular polarization was. If one goes back to the section 2.2, in equation 1, one realizes that this high value for the axial ratio, means that the larger lobe is much larger than the smaller lobe which ends up producing a shape nowhere near being circular which is what is wanted because it would mean that the larger and smaller lobes are equal.

The lateral slots help to adapt correctly the impedance, in order to see $50\,\Omega$ at the input, this can be achieved by varying its length, but this has a repercussion in the AXIAL RATIO, thus in the polarization of the antenna. Because the lengths within the patch are not the same, this will produce currents of different magnitude, since they will have to flow through spaces of different length.

4.2 Design of a single patch

After realising that the first design was not correct, since achieving a good AR and a good adaptation of the impedance at the same time was not possible. I went for a simpler design (see image 13)

In order to avoid the problem described in the last paragraph of the last subsection, I designed a simple square patch. After this, instead of feeding the patch with a line and a lumped port at the edge of the substrate, I went for a coaxial port. This helped me a lot while adapting the impedance of the patch, since moving the port around the y-axis results in a different Z since the impedance in a radiant patch increases while approaching the limits of the substrate, and decreases while approaching the center of the patch, the next picture illustrate the latter said:



(a) Second patch 1

(b) Z variation 2

Figure 13: Second design

But since this antenna has to achieve circular polarization, the edges have to be cut (x in the picture above). I simulated for some values of the cut of the edges as well as for the port position, in order to find which value gives best results in terms of Axial Ratio and impedance (see the images 14 and 15)

The best results for the *cut_ edge* and the *port_position*, are the following:

$$\begin{cases} port\_position = 30\ mm \Rightarrow Z(\Omega) = 44,32\ \Omega \\ cut\_edge = 12\ mm \Rightarrow AR(dB) = 2.4\ dB \end{cases}$$

As we can see from figures 14 and figure 15, the best achievable impedance is not exactly 50 Ω, and even though the axial ratio is bellow 3 dB (2,4 dB at f_0), it is not a very robust value, since the major lobe is close to be 2 times bigger than the minor lobe, and this is not good.

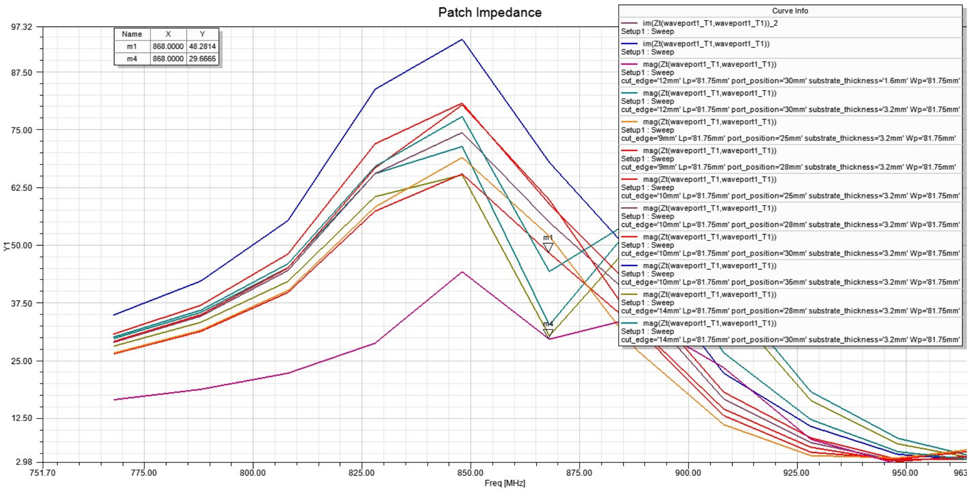


Figure 14: Sweep of values for the $Z(\Omega)$.

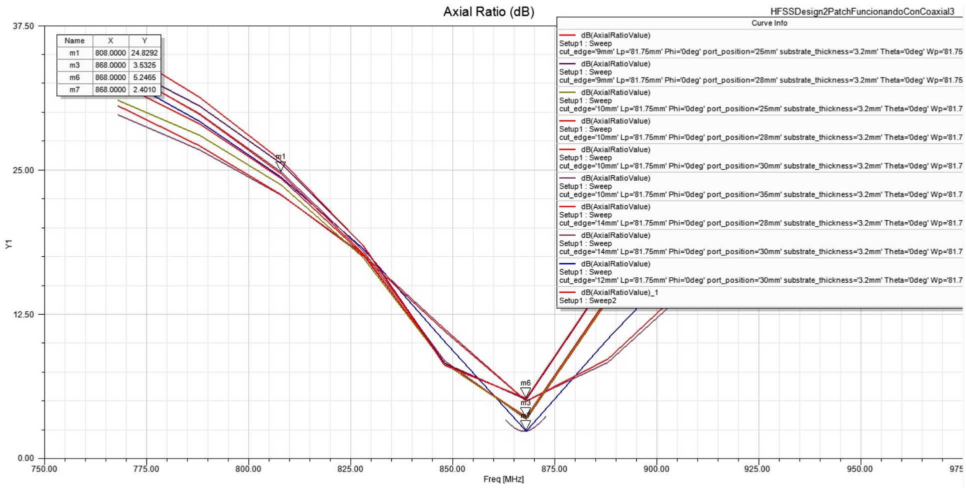


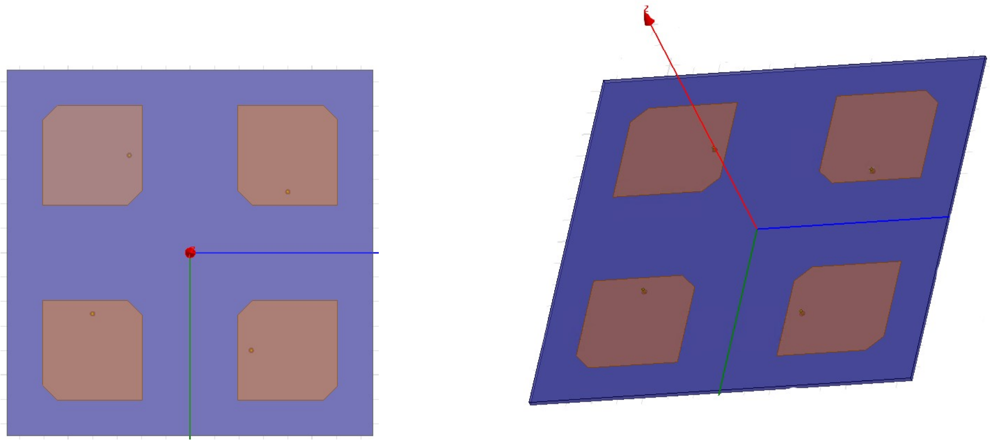
Figure 15: Sweep of values for the $AR(dB)$.

4.3 Design of 2×2 patch array

After finding the best results for the *cut_edge* and the *port_position* I designed the sub-array of 2×2 elements, see the image 16.
In figure 16 it is important to know that each patch is rotated 90°, this is in order to improve the value of the axial ratio. For the simulations of this sub-array I respected all the already mentioned values regarding the size and thickness of the dielectric.

In the next page the results of the simulations are shown. Taking a look at image 17, surprisingly, the value of the axial ratio got decreased by a lot, and it is almost 0 dB. This is a good thing, and it will be due to the placement of multiple elements.

From the impedance plot (figure 18), it can be seen that the impedance is not $50\,\Omega$, but as mentioned before, this is normal, since it is very rare and almost impossible to see an input impedance with that exact value. For all the 4 patches I obtain an average value for the impedance of $Z(\Omega) = 44\Omega$



(a) Sub-array of 2 × 2 elements (b) Sub-array of 2 × 2 elements (rotated)

Figure 16: Second design

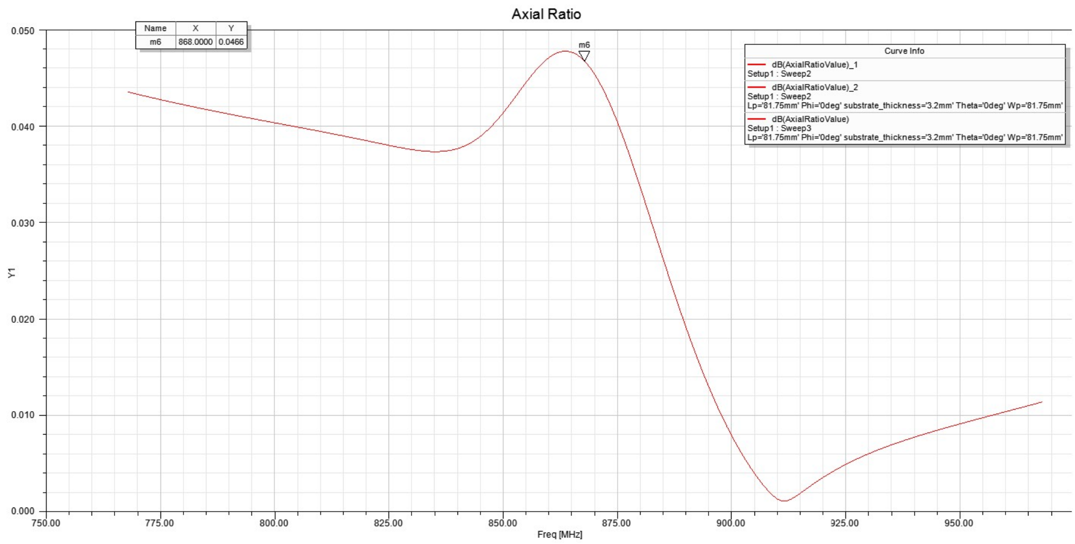


Figure 17: Axial Ratio of the sub-array

Then, I plotted the S11 in 19. As it can be noted from the figure, at f_0 I obtain a value of $-17.8\,\text{dB}$ as an average for all 4 patches, this value is bellow $-10\,\text{dB}$, so this means that the reflected wave is 10 dB lower than the incident wave. This meaning that a tiny part of the wave got reflected. From $-10\,\text{dB}$ to below, the changes are almost unnoticeable.

To see the impedance adaptation one could also plot the Smith Chart with the Z and the S parameters (see images in figure 24)
We can see from the plot that the impedance is almost adapted since it crosses the unitary circle in the Smith Chart.

After having plotted the impedance, the axial ratio and even the S parameters I plotted the radiation pattern, the directivity, and the gain.
In figure 21 the radiation pattern is shown, as well as the directivity. From the radiation pattern we can see that the antenna is not VERY directive, since θ_1 and θ_0 are not that narrow, but is directive, note that for a higher number of elements the directiity could increase, therefore when

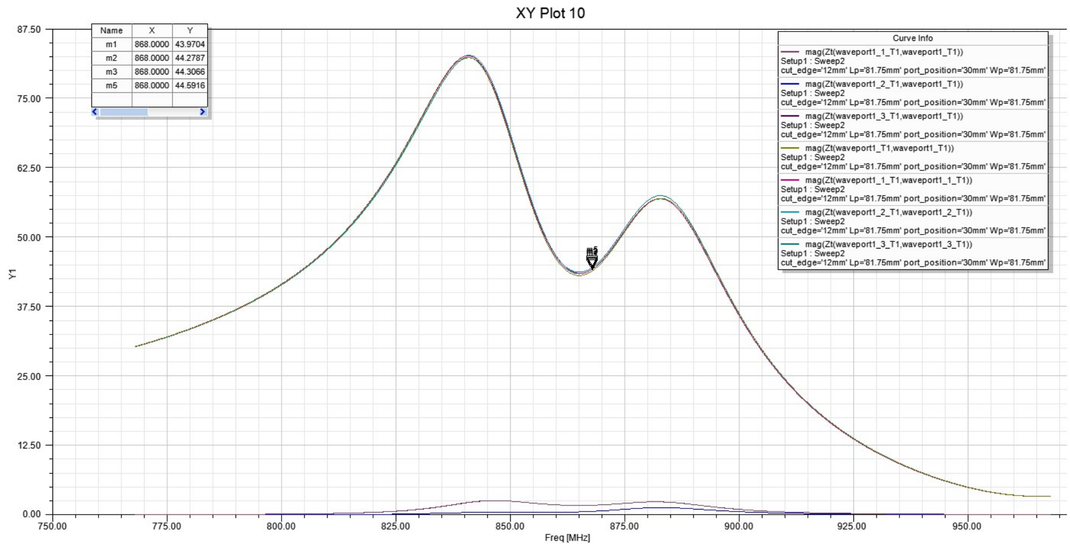


Figure 18: Impedance of each patch

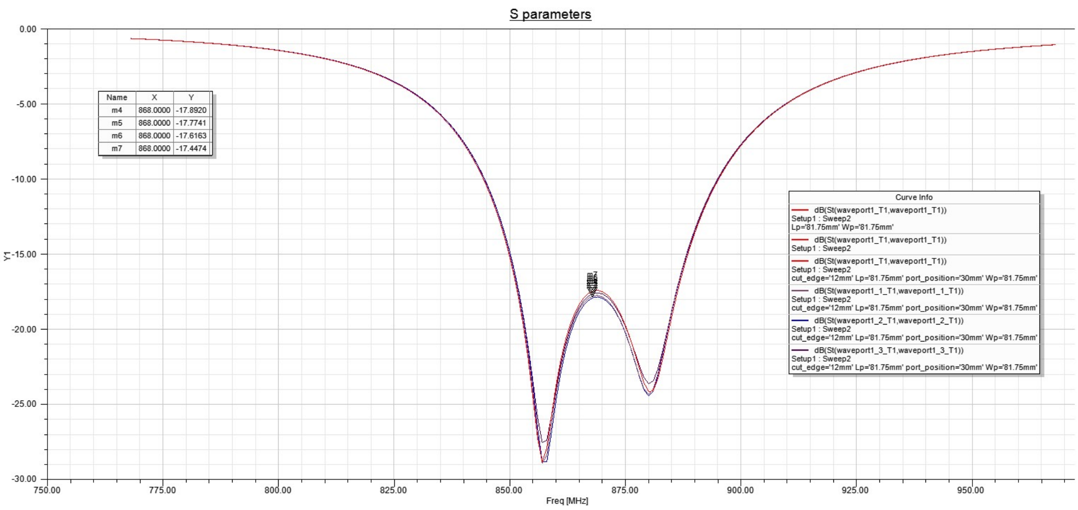
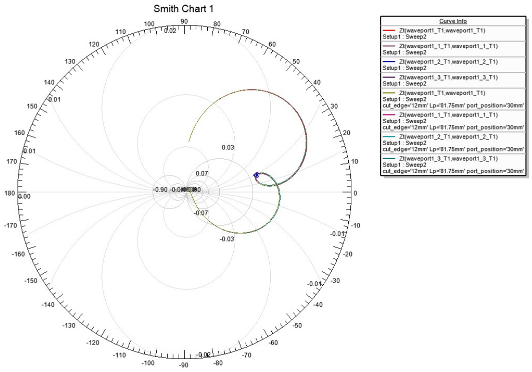
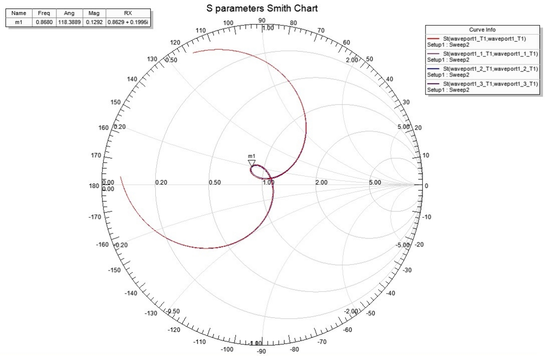


Figure 19: S parameters



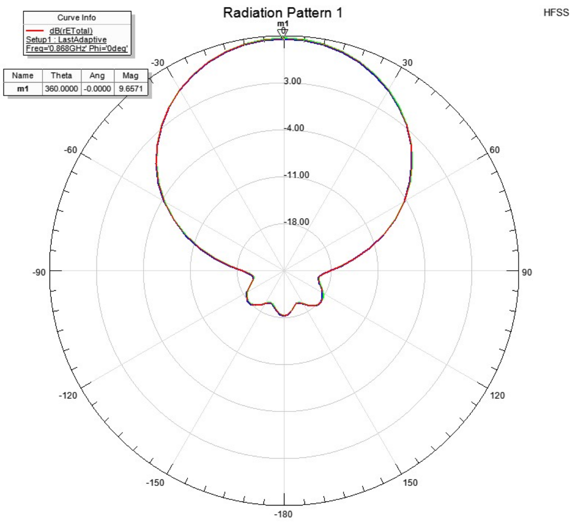
(a) Z in the smith chart.



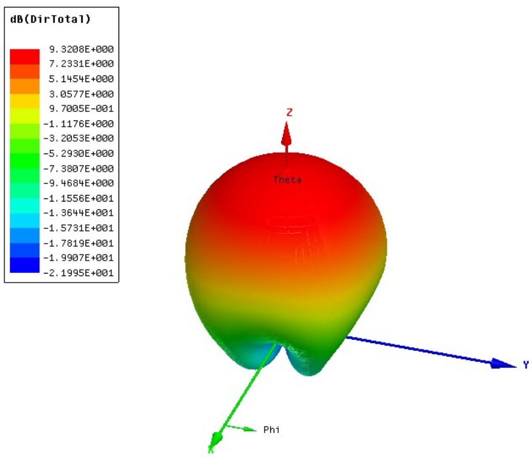
(b) S parameters in the Smith Chart 2

Figure 20: Second design

simulating the final array (4×4) I should obtain a higher directivity.



(a) Radiation Pattern. chart.



(b) Total directivity of the array.

Figure 21: Radiation pattern and directivity

Finally but not less important, the total gain of the antenna. This, tells us about the performance of the antenna. In this case the gain is of about $9\,dB$, note that this value is for

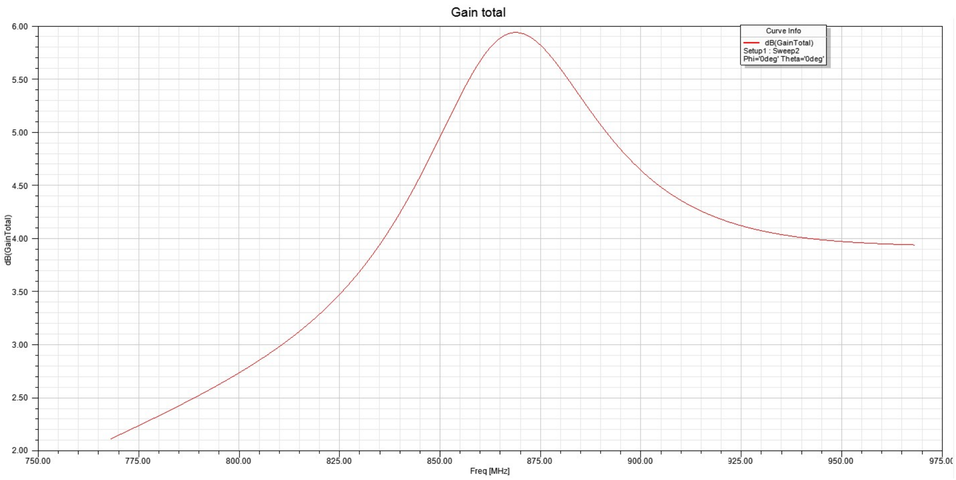


Figure 22: Total gain of the array.

the sub-array and not for the final array where I have to achieve 15 dB as my minimum gain.

*The gain of the final array of 4×4 dimensions, should be 4 times the one plotted in 22.

4.4 Design of a new feeding system

Since in the second design each patch inside the array is being fed by a coaxial cable, I had to change the feeding system to make it more efficient and realistic. In reality in an array of antennas, the total array is fed by one coaxial cable, and then a feeding system takes care of driving the current to all 4 antennas. But one should note the following regarding the feed lines:

- Introduce degradation on the radiation pattern.

- The lines introduce losses when feeding the patch.

- The use of high Z elements in the feed network further reduce:

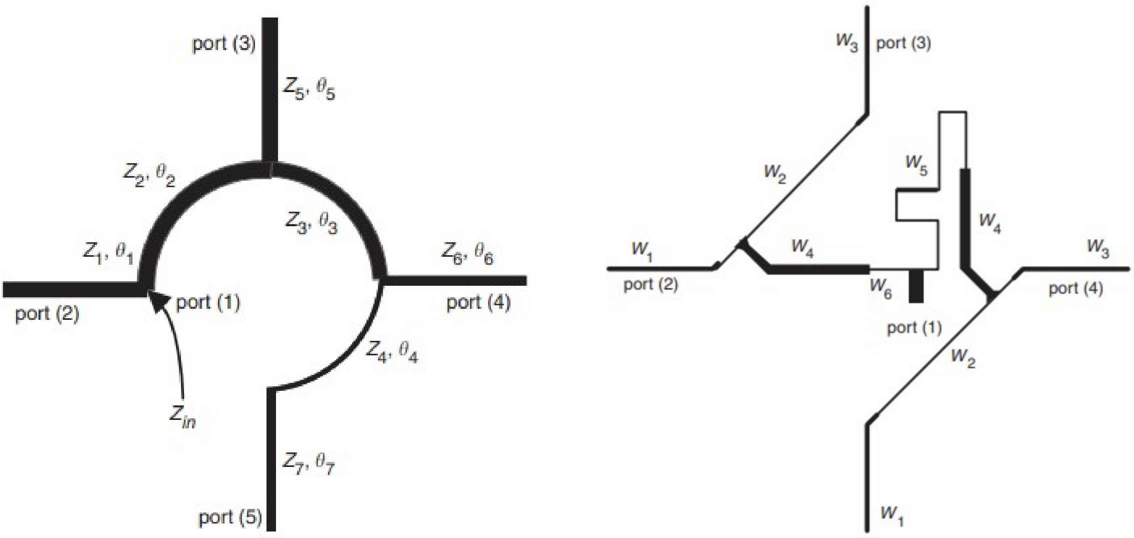
    1. Coupling effects.
    2. Spurious.

- To reduce the spurious radiation and coupling effects, the width of the microstrip-lines have to be as narrow as possible.

- A $\lambda/4$ transformer is used to achieve a 90° phase shift to compensate for the physical rotation of the element (achieve better polarization).

4.4.1 Feeding system options

After doing some research and looking at multiple options I came up with the following possible options (see images in figure 24)

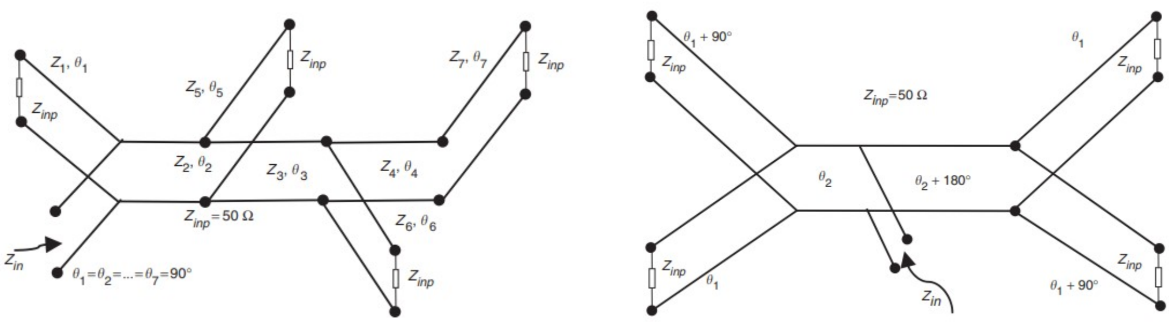


(a) Serial feed network.

(b) Sequentially rotated corporate feed network.

Figure 23: Feeding options

The correspondent line models are the following;



(a) Serial feed network.

(b) Sequentially rotated corporate feed network.

Figure 24: Line model of the Feeding options

Even though these two options are both robust and stable, one of them has better specifications regarding protection over reflected waves and many other problems, but the main and only disadvantage, is its implementation complexity, but once I achieved it, I did not have any other problem regarding the design of it.

Considering the options pictured before in figure 24; ***Serial Feed Network*** and ***Sequentially Rotated Corporate Feed Network***, the first one is the best in terms of specifications, since:

1. It improves the 10 dB return loss, (i.e better ***S11*** parameters) and the 3 dB AR bandwidth, with respect to the other option.
2. Has lower losses. But why?

(a) Because the phase difference in this type of feeding system makes possible the cancellation of reflected waves inside.

3. Produces a less complex spurious radiation, therefore it will be easier to filter the non desired frequencies.

4. A better radiation pattern can be achieved with this design, since by increasing its size can lead to an improvement of it.

***Note that the corporate feed has more resistive losses.**
Since each arch that forms the T divisor must have different widths because we want to introduce a phase shift of $\Delta\phi = 90°$, knowing this electrical length one can compute the physical width of the line, since the length of every line in the T power divisor has to be $\lambda/4$, since we just one to see the right impedance at the input of each patch, nothing else has to be modified. The following table shows the obtained widths of each line for **electrical_lengths** $\in \{90°, 180°, 270°\}$

W_1 $[mm]$	W_2 $[mm]$	W_3 $[mm]$	W_4 $[mm]$	W_5 $[mm]$	W_6 $[mm]$	W_7 $[mm]$
1,37	3,59	3,19	1,37	1,37	3,19	3,19

Table 4: Widths

4.4.2 Simulations of the feeding system

The following figure shows the designed T divisor in HFSS:

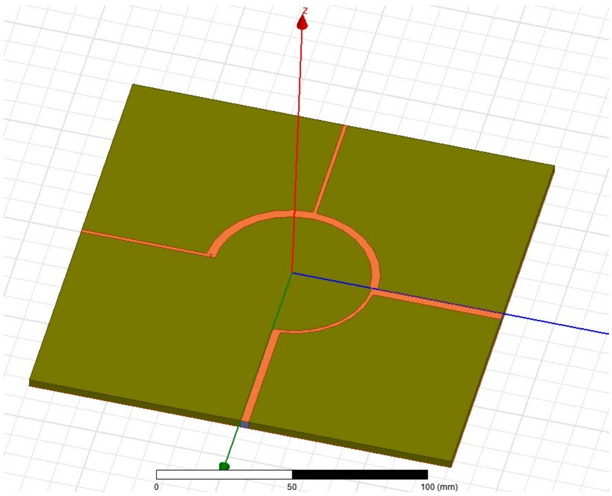


Figure 25: Serial Feed Network

Here are the results of the simulations of the feeding system, the following image illustrates the magnitude:

As we can see, this result is robust and correct, since one should see $\frac{P_{in}}{4}$ in each exit of the T divisor, and that's what it is shown, all of the entries are almost in the $-6\,\text{dB}$ level meaning that they are receiving a $\frac{1}{4}$ of the power since $-3\,\text{dB} \equiv \frac{1}{2} \therefore -6\,\text{dB} \equiv \frac{1}{4}$. Proving that the magnitude is correct, one should also check that the $\Delta\phi$ is also being respected (see image 27)

As we can see from image 27 the $90°$ phase shift of each line with respect to the others is being respected.

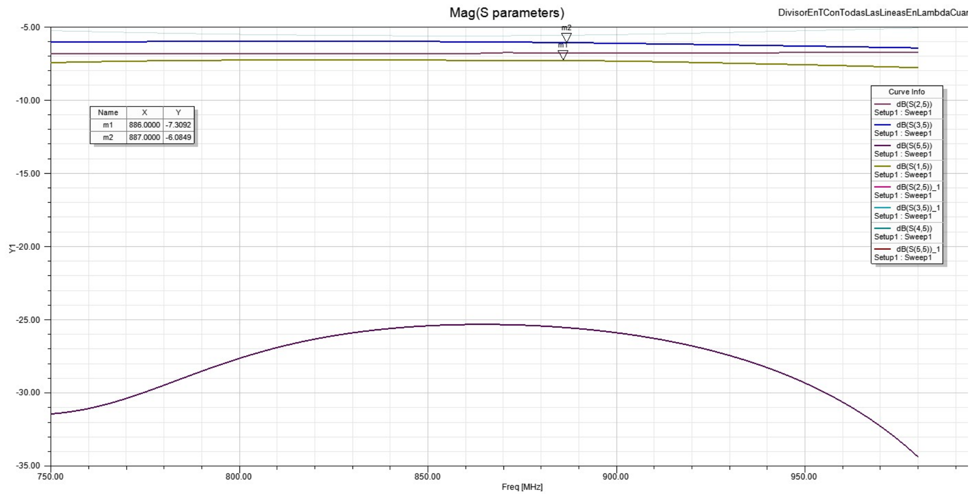


Figure 26: Magnitude of the S parameters dB at each entry of the feeding system

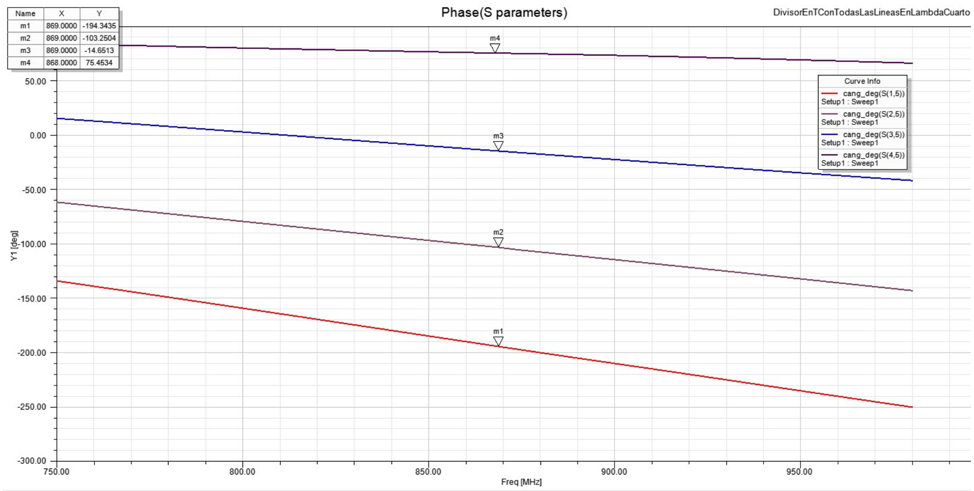


Figure 27: Phase of the S parameters $degrees(.°)$ of each entry in the feeding system with respect to the feeding point

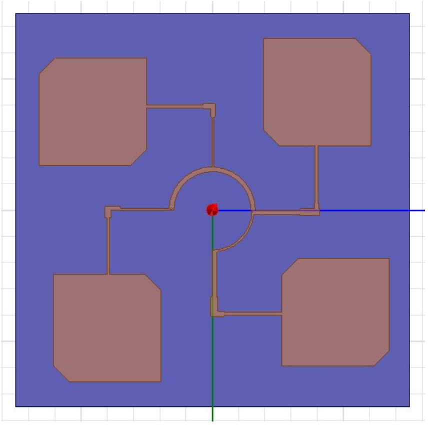
4.5 Integration of the feeding system in the 2×2 array

The aim of this section, is to integrate the designed feeding system in the 2×2 sub-array. Is worth mentioning that this process took a lot of time and is not completely finished, but this will be explained in the following paragraphs.

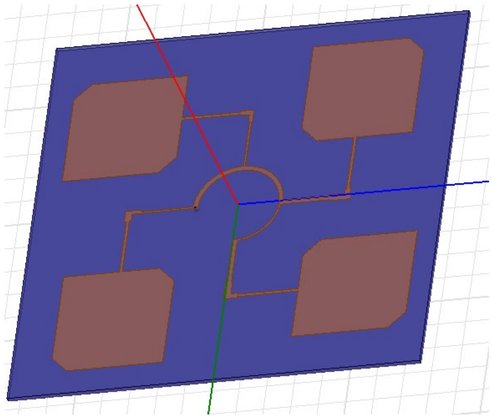
In order to achieve a correct feeding, the outgoing lines of the T divisor must have a length of $\lambda/4$, since a Z transformer of $\lambda/4$ has to be implemented in order to see the correct impedance in every single patch entry.

First of all, in order to know the width of each line that connects the patch with the outgoing line of the power divisor, I designed a single patch separately with the same dimensions in order to find the correct value for the width of each line going into the patch. This was repeated for each patch, since the outgoing lines of the T power divisor have different widths. I started with a value of 0.35 mm. Due to the little time left I did not have time to finish this part, this is were I had to stop. Nevertheless some images in the next page will be shown in order to illustrate how the final design will look like.

The following figure illustrates the integrated serial feeding system in the patch array:



(a) Sub-array of 2×2 elements



(b) Sub-array of 2×2 elements (rotated)

Figure 28: Final design with the serial feed implementation

From the picture above, note that each patch is rotated 90° with respect to the others, and the final design (4×4 patch array) will host 4 sub-arrays of 2×2 sub-array with a phase shift of 90° between the others, in order to improve the value of the Axial Ratio, and hence the polarization.

I was not able to finish the integration of the serial feeding network in the 2×2 array, but the only thing that I have to do in order to achieve the final design is to find the correct widths for each line connecting the patch and the outgoing lines of the T power divisor, and simulate the schematic shown in figure 28.

The final design should look like the right image in figure 29;

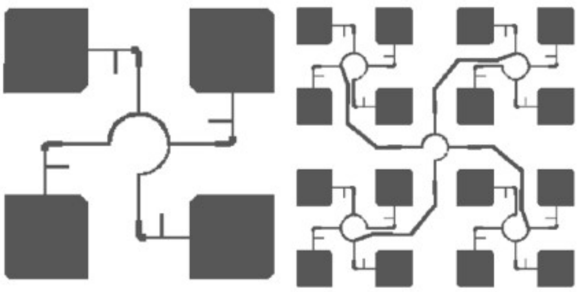


Figure 29: Series Feed line in 4×4 antenna Feed Network

Note that in the curves of the outgoing lines of the T power divisor, a cut has to be made in order to avoid an effect of capacitance.

5 Conclusion

This project deals with different approaches to the design of an array of antenna patches. During the design, I have modified multiple parameters and even the entire design, this has been of vital importance because it has allowed me to implement a simpler and more practical design, which has avoided major problems. Personally I think that the most difficult part of the project has been the first and the last part. The beginning of the project was a bit overwhelming, because there were too many possibilities, and filtering information is sometimes difficult and takes some time, the first part required me to remember a lot of knowledge and concepts about the theory of antennas and microwaves from the Microwave and Electromagnetic Compatibility courses I took last year, where we covered all the concepts that this project has invoked. As I said before, the last part has been also quite difficult, as it has required me to read more and remember a lot of concepts regarding micro-strip lines and its properties, and although it is not finished (the last part), the progress made, will help me a lot when finishing the design this summer (if possible).

I wanted to mention, how nice I found the path that this project has taken, because as I was researching, reading and trying to understand again some concepts I've already been taught, I have been remembering many of the things I studied in subjects such as, Electromagnetism I and Electromagnetism II, as well as those mentioned in the previous paragraph. During the design process I have being remembering some of the hard times I had to understand those quadrupole tensors that I studied in Electromagnetism I or the Smith Chart in Microwave Engineering, but I actually remember these moments with joy, since I enjoyed solving problems regarding these topics, and they remind me why I chose to study this beautiful degree. Even though it required me to a lot of time to understand them, this project has taught me that the world of Electromagnetism has infinite applications, and I consider the world of antennas to be one of the most important ones, especially nowadays.

I would like to thank the great help that Germán has given me during the project, without him, this project would not be possible as well as without the great advice of my supervisor Anja Skrivervik, who once reminded me the famous phrase of Colin Powell, who says; "There are no dumb questions, there are only stupid questions". It has been an honor to learn from very wise people. To have been able to work with such incredibly people in this field at such a prestigious university as EPFL is simply indescribable. It has been a very rewarding experience, and although the project is not completely finished, this path has taught me to believe a little more in myself and to give myself more credit.

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