A Thesis for the

Master in Telecommunication Engineering

Dual-Band Antenna Booster for Tracking Devices

by
Loubna El Madi Azuz

Supervisor: Dr. Aurora Andújar and Dr. Jaume Anguera

Escola Tècnica Superior d'Enginyeria (ETSE)
Universitat Autònoma de Barcelona (UAB)

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El tribunal d’avaluació d’aquest Treball Fi de Màster, reunit el dia ____________________, ha acordat concedir la següent qualificació:

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Els sotasignants, **Josep Parrón Granados**, Professor de l'Escola d'Enginyeria de la Universitat Autònoma de Barcelona (UAB), **Aurora Andújar Linares** i **Jaume Anguera Pros**, tutors de l'alumne a l'empresa **Fractus Antennas** i directors del projecte.

CERTIFIQUEN:

Que el projecte presentat en aquesta memòria de Treball Fi de Màster ha estat realitzat sota la seva supervisió per l'alumne **Loubna El Madi Azuz**

I, perquè consti a tots els efectes, signen el present certificat.

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Aurora Andújar Linares Jaume Anguera Pros Josep Parrón Granados

Resumen:

Análisis de una antena compacta de doble puerto y banda dual para operar en bandas GNSS y Bluetooth. Investigaremos el impacto del tamaño del plano de tierra del dispositivo inalámbrico en los parámetros S (coeficiente de reflexión y aislamiento), así como en la eficiencia.

Las bandas operativas se ajustarán mediante el diseño de circuitos y filtros coincidentes para minimizar el acoplamiento entre puertos. Una vez que se obtengan los mejores esquemas, se fabricarán prototipos para validar físicamente los resultados numéricos.

Resum:

Anàlisi d'una antena compacta de doble port de dual banda per funcionar en bandes GNSS i Bluetooth. Investigarem l'impacte de la mida del pla de massa del dispositiu sense fils mitjançant els paràmetres S (coeficient de reflexió i aïllament), així com en l'eficiència.

Les bandes de funcionament s'ajustaran dissenyant circuits adaptats i filtres per minimitzar l'acoblament entre els ports. Un cop obtinguts els millors esquemes, es fabricaran prototips per validar físicament els resultats numèrics.

Summary:

Analysis of a dual-band dual-port compact antenna for operating at GNSS and Bluetooth bands. We will research the impact of the ground plane size of the wireless device on the S-parameters (reflection coefficient and isolation) as well as efficiency.

Operating bands will be adjusted by designing matching circuits and filters to minimize coupling between ports. Once the best schemes are obtained, prototypes will be fabricated to physically validate the numerical results.

ACKNOWLEDGEMENT

Thanks to all and each of the people who have supported me and encouraged me to work on this project, even going through the difficult moments that 2020 has left us. I would like to dedicate this project specially to my grandmother, who unfortunately is gone, and I know that she would be very proud to see how her little grandchild is finishing the last stages as a student.

Thanks to Fractus Antennas S.A. for giving me the opportunity to develop this project with them in their installations. Thank you for your trust in me and confidence.

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A picture is worth a thousand words.

1. Introduction

Since some decades ago, there is a growing interest in the wireless communications coming from the continuous increase of connected devices and, consequently, the need of reducing the number of existing wires.

This reduction of the number of wires, apart from being aesthetically more pleasant, allows everything to be connected to make everything easier and more comfortable for people to control devices remotely. For instance, be able to check your mobile phone notifications through your smartwatch or to turn on the air conditioner without looking for its remote controller is faster than taking your phone out of your pocket or than finding the remote controller. To be wireless, these "smart" devices must integrate antennas, which substitute the functionality of communications of the wires.

Continuing with the comfort topic, it would not be comfortable at all to have, for instance, a large and heavy smartwatch tied on the wrist, so the size trend of those devices is to make them small. This means that the batteries that feed those devices will be small too, so low consumption is a main target when designing them.

In this thesis we will focus on Bluetooth and GNSS applications. The range of possibilities that these applications allow is very wide, in this last decade different functionalities have been developed that involve Bluetooth and GNSS from connecting the wireless headphones to the phone to locating the positioning in real time in a smartwatch of reduced dimensions.

What is developed along this thesis is an analysis of a dual band tracking device with an antenna booster for Bluetooth and GNSS applications.

1.1. Objectives

The main objective is to investigate a small form factor of 90 mm x 50 mm which is representative of a low-cost tracker.

We will use *DUO mXTEND™* antenna booster, initially, at the center of the long edge, as a slot, also other position will be tested as monopole for both ports.

1.2. Methodology

I. State of the art.

Dual-band/dual-port compact antennas for GNSS and Bluetooth bands. Read IEEE, IEE papers and similar literature to analyze existing techniques.

II. Analysis of a Dual-Port antenna solution for GNSS and Bluetooth bands.

Analysis using EM software (CST Studio Suite) of a dual-band dual-port compact, antenna for operating at GNSS and Bluetooth bands. We will research the impact of the ground plane size of the wireless device on the S-parameters (reflection coefficient and isolation) as well as efficiency.

Operating bands will be adjusted by designing matching circuits and filters to minimize coupling between ports. The design of such matching and filter circuits will be addressed from two ways. A first one, using engineering-based method. A second one, will use a circuit synthesizer tool to obtain both the matching and filter circuits. Both approached will be compared in terms of electromagnetic performance (reflection coefficient, isolation, efficiency, gain) but also in terms of design time and complexity.

Once the best schemes are obtained, prototypes will be fabricated to physically validate the numerical results. Therefore, the simulation schemes should be designed to consider the real PCB (Printed Circuit Board) layout and layout for allocating the matching and filter circuits.

III. Physical Validation

According to the best solutions obtained in step 2, a prototype/s will be fabricated and tested in the lab.

Both the matching and filter circuits will be built using SMD components. S-parameters will be tested using a VNA. If there is any shift or discrepancy between simulated and measures results, adjustment should be done. Once the prototypes/s are adjusted in terms of $S_{11}/S_{22}/S_{21}$, total efficiency and radiation patterns will be tested in an anechoic chamber (Satimo Stargate-32).

1.3. Relevant parameters

Some antenna concepts appear through the project, so for a better understanding and the clarification of all these concepts, it has been explained what it has been considered the basics as far as the antenna parameters.

- *Antenna impedance:* The input impedance of an antenna is defined as the relation between the voltage and the current of the antenna in question. The antenna impedance has a real/resistive part (Ra) which is dependent to the frequency and an imaginary part (Xa) which also depends to the frequency.

$$Z_a = \frac{V_{in}}{I_{in}} \qquad \Longrightarrow \qquad Z_a = R_a + jX_a \qquad (1)$$

Regarding the resistive part, is the result of sum between the radiation resistance (R_r) which is caused by the radiation of electromagnetic waves from the antenna, and the loss resistance which is caused by electrical resistance and is converted into heat.

$$R_a = R_r + R_\Omega \qquad (2)$$

S parameters

The S parameters are defined as the relation between an input voltage wave and the voltage wave, which is returning from an impedance changing point of the system. This returning voltage wave is caused by the impedance untuning between where the input voltage wave is coming (in our case the impedance of the antenna Z_L) and the mentioned specific point (in our case the impedance of the signal generator Z0).

$$S_{11} = \frac{V_{in}^-}{V_{in}^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad S_{11}|_{dB} = 20\log|S_{11}| \qquad (3)$$

When the antenna impedance and the generator impedance are equal, then the antenna is tuned and therefore, the S_{11} is zero (there is no returning signal).

The S parameters are referred to two sub-indexes (S_{nm}), where “n” is the output port and “m” is the input port, where the measure has been done. Consequently, S_{21} is considered the coefficient transmission or the coupling between port 2 (output signal) and the port 1 (input signal).

- *Reflection coefficient*: Ratio of reflected voltage wave respect to the input voltage wave. Along this project, it will be used the reflection coefficient and the return loss (or S_{11}) indistinctly.

$$Reflection\ coefficient = \frac{Reflected\ voltage\ wave}{Input\ voltage\ wave} \quad (4)$$

$$S_{11}\ (dB) = 20\log\left(\frac{Reflected\ voltage\ wave}{Input\ voltage\ wave}\right) \quad (5)$$

  Example:
  If $S_{11}\ (dB) = -6\ dB$, then 25% of the wave is reflected, 75% of the wave is delivered to the antenna.

- *Radiation efficiency* (η_r): Ratio of the radiated power respect to the accepted power by the antenna considering the losses that the matching network components introduce.

- *Antenna/Total efficiency* (η_a): Ratio of the radiated power respect to the available power by the antenna considering the mismatch losses and other losses that the system introduces.

$$\eta_a = \eta_r\ (1 - |S_{11}|^2) \quad (6)$$

The objective is to maximize the antenna efficiency (η_a). This is achieved maximizing the matching (ideally $S_{11} = 0$) and choosing the best components in terms of the Q-factor (maximizing the radiation efficiency, η_r).

Smith chart

The Smith Chart is a polar diagram which shows how the complex impedance of a transmission line or a matching circuit, changes along the frequency spectrum.

The Smith Chart can be normalized for the impedance, admittance or both at the same time. The most common normalization impedance is 50Ω which is located at the center of the diagram.

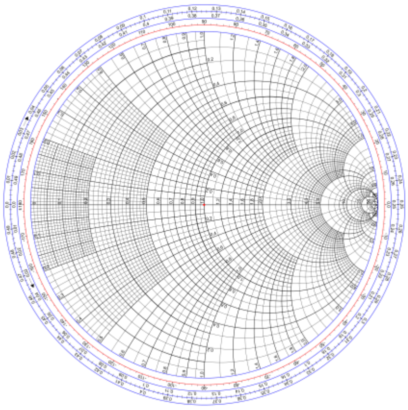


Figure 1: Smith Chart normalized for the impedance.

In the next section we will present the concept of virtual antenna, so we must explain in advance how to work with this type of antenna in terms of the smith chart. From the antenna booster response, it can be tuned the matching network in order to cover only the desired frequencies. To do that, is necessary to observe the moves in the Smith Chart done from the system measured in every component introduced in the matching network.

It is important to note there are four possible moves it can be done in a matching network: a serial inductor, a serial capacitor, a parallel inductor and a parallel inductor (figure 2). But not all the moves are equal for every frequency, when a serial capacitor or a parallel inductor is placed in the matching network the moves for the lower frequencies are quicker than the moves for the high frequency, due to the characteristic impedance of the component is bigger when the frequency is low and thus the impact of the component is bigger to.

On the other hand, for the serial inductors and parallel capacitors the effect is the opposite. As bigger is the frequency observed, bigger it is the effect of those components.

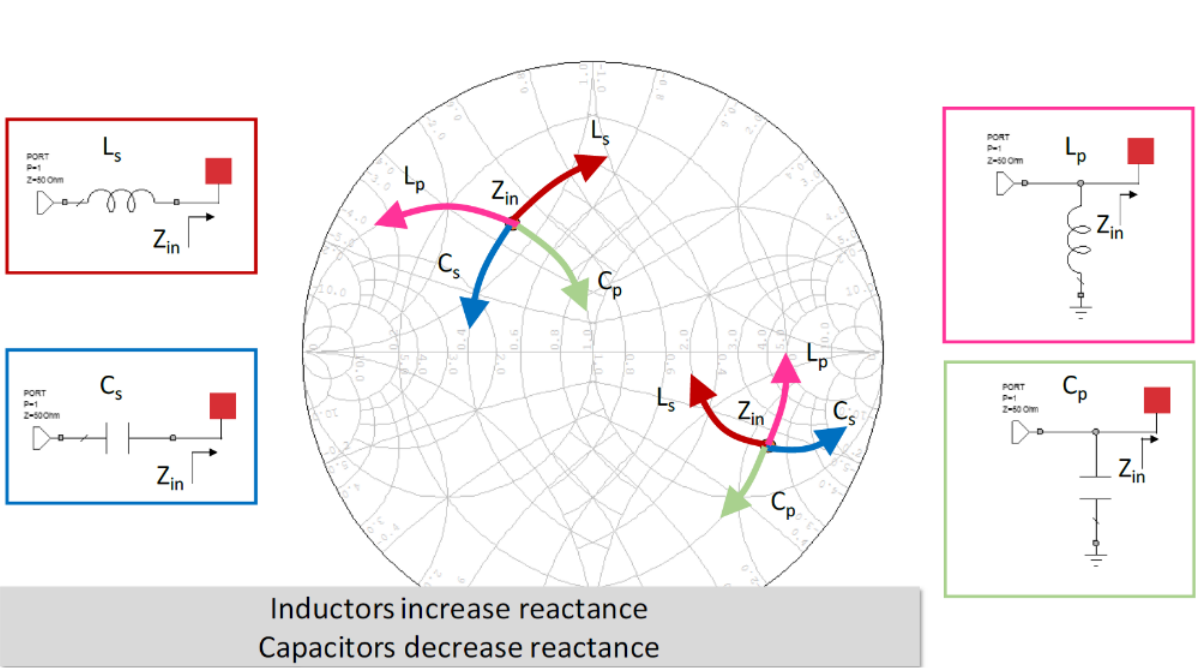


Figure 2: Moves on the Smith Chart done by the components of the Matching network [1]

1.3.1. Virtual Antenna

The virtual antenna concept is also known as antenna booster. In order to understand how it works, we must imagine it as a black box where the geometry of the antenna does not vary, but to be able to adjust the antenna to certain frequencies, what you must do is adjust the matching network. The impedance box used with this method is based on a non-resonant antenna element electrically short in terms of the operating wavelength (approximately $\lambda/30$). Its correct operation will also depend on its position on a ground plane of a wireless device to enable the excitation of efficient radiating modes on the ground plane. [2]

As we have mentioned, an antenna booster is not a resonant element, so it does not depend on its geometry to resonate at the desired frequencies. Thus, using this type of antennas should not be adapted to each device to which it is integrated, such as the printed antennas, but we adapt only the matching network.**¡Error! No se encuentra el origen de la referencia.**

However, virtual antennas are very small electrically speaking, and for this reason its impedance is predominantly reactive, and, thus, it is poorly matched at most of the bands of operation in the frequency range. Almost all communication systems used today are located in the compressed range between 0.7GHz to 3GHz range such as applications as LTE, GSM, Universal Mobile Telecommunications System, Global Navigation Satellite System (GNSS), and Bluetooth (BLE/BT) as well as the industry, science, and medicine (ISM) bands. This mismatch issue is overcome with the addition of a multiband matching network, resulting in a multiband antenna system with a small antenna element and competitive efficiency values.

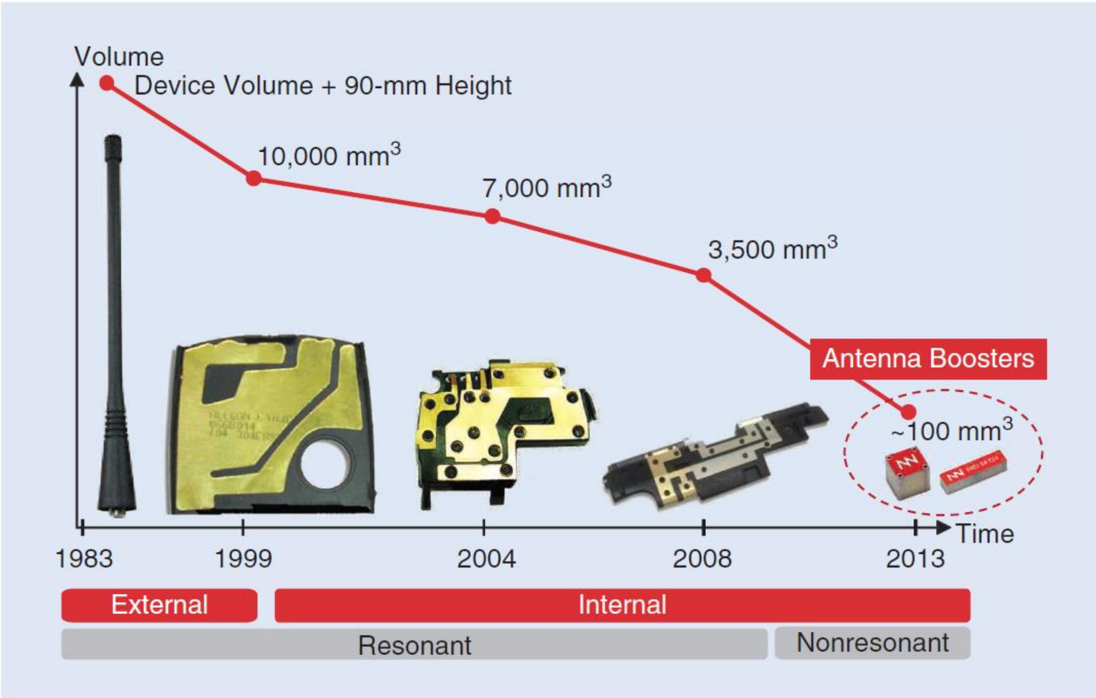


Figure 3: Evolution of antennas for wireless devices ***¡Error! No se encuentra el origen de la referencia.***

2. Benchmarking

2.1. Introduction

In this chapter it is going to be presented the benchmarking that has been carried out in order to analyze some of the typical specifications of the most common devices that include in its application GNSS and Bluetooth.

2.2. GNSS and BLE solutions

The two significant specifications that are considered in the analysis are the dimensions of the device and the antenna characteristics to cover GNSS and Bluetooth.

Device	Application	Company	Frequency band	Dimensions (mm)
BT 500	Fleet management	ViTech	BT/GNSS	70 x 47
Piccolo STX	Fleet management	ORBCOMM	BT/GNSS	140 x 105
XB3-C-A2-UT-001	Module	Digi international	BT	25 x 33
NRF52832	Module	Nordic Semicoductor	BT	20 x 20 (module dimensions)
MiniELM327	OBD	Moonar	BT	48 x 35
V06H4K-1	OBD	KiMood	BT	43 x 25
K880	OBD	kkmoon	BT	47 x 31
NOBD2BT	OBD	iLC	BT	33 x 46
GPS2000C	OBD	ViTech	BT	70 x 47
BlueLinkELD	OBD	Wireless Links	BT	69 x 38
Amazfit Bip	IoT	Xiaomi	BT/GNSS	20 x 20
DM182022	IoT	Microchip Technology	BT	59 x 39
UG309	IoT	Silicon Labs	BT	45 x 30
ATAVRBLE-IOT	IoT	Microchip Technology	BT	23 x 29
1270553	IoT	ILT	BT	59 x 55

Table 1: GNSS and Bluetooth devices

2.3. DUO mXTEND™ antenna booster[1]

As has been reflected in the search above, about antennas in current market for Bluetooth and GNSS, very few antennas can cover both application at the same time. And when an antenna is dual port, the dimensions increases considerable. In Fractus Antennas has developed the DUO mXTEND™ antenna booster, a tiny antenna for simultaneous GNSS and Bluetooth operation with no clearance beyond the antenna footprint. [4]

The DUO mXTEND™ tiny can get an optimum performance, while no ground clearance beyond the antenna footprint is needed, making this component the ideal solution for small IoT wireless devices. This antenna has been specifically designed for providing worldwide Global Navigation Satellite Systems (GNSS) and Bluetooth (BT) performance in wireless devices with small space requirements.

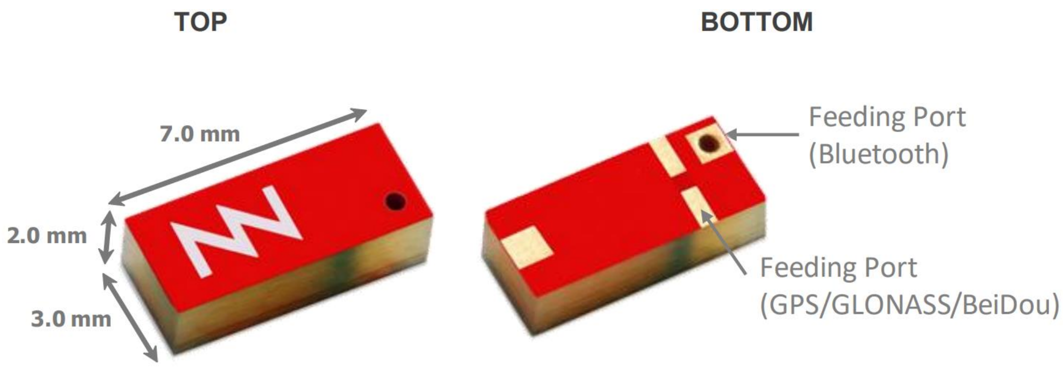


Figure 4: DUO mXTEND (TM) antenna booster

The DUO mXTEND™ antenna booster belongs to a new generation of antenna solutions based on Virtual Antenna technology. This technology enables to relplace conventional and custom antenna solutions by a new class of so-called antenna boosters, delivered in the form of a new range of miniature and off-the-shelf chip antenna components. These new chip antennas are by nature multiband and multipurpose, so they fit in a variety of wireless platforms to provide a wireless link at many different communication services.

[1] https://fractusantennas.com/duo-mxtend-mobile-iot-antenna/

a) Specification

Technical features	BeiDou	GPS & GALILEO	GLONASS	Bluetooth
	1561MHz	1575MHz	1598 – 1606MHz	2400 – 2500MHz
Average Efficiency	> 40%	> 45%	> 50%	> 50%
Peak Gain	-1.1 dBi	-1.0 dBi	-1.0 dBi	-0.9 dBi
VSWR	< 3:1			
Radiation Pattern	Omnidirectional			
Polarization	Linear			
Weight (approx.)	0.11 g.			
Temperature	-40 to +125 ºC			
Impedance	50 Ω			
Dimensions (L x W x H)	7.0 mm x 3.0 mm x 2.0 mm			

Table 2: Technical features

b) Evaluation Board

This Evaluation Board integrates one DUO mXTEND™ antenna booster to provide operation in four frequency regions as shown in the following table.

Frequency range	*Application*
1561MHz	BeiDou E1 band
1575 MHz	GPS L1 band and GALILEO E1
1598 MHz - 1606 MHz	GLONASS L1 band
2400 MHz - 2500MHz	Bluetooth

Table 3: DUO mXTEND™ application

The board also includes a couple of UFL cables connect this dual input/output port solution to the SMA connectors for testing purposes.

	Dimensions (mm)
A	80
B	40

Table 4: Evaluation board dimensions

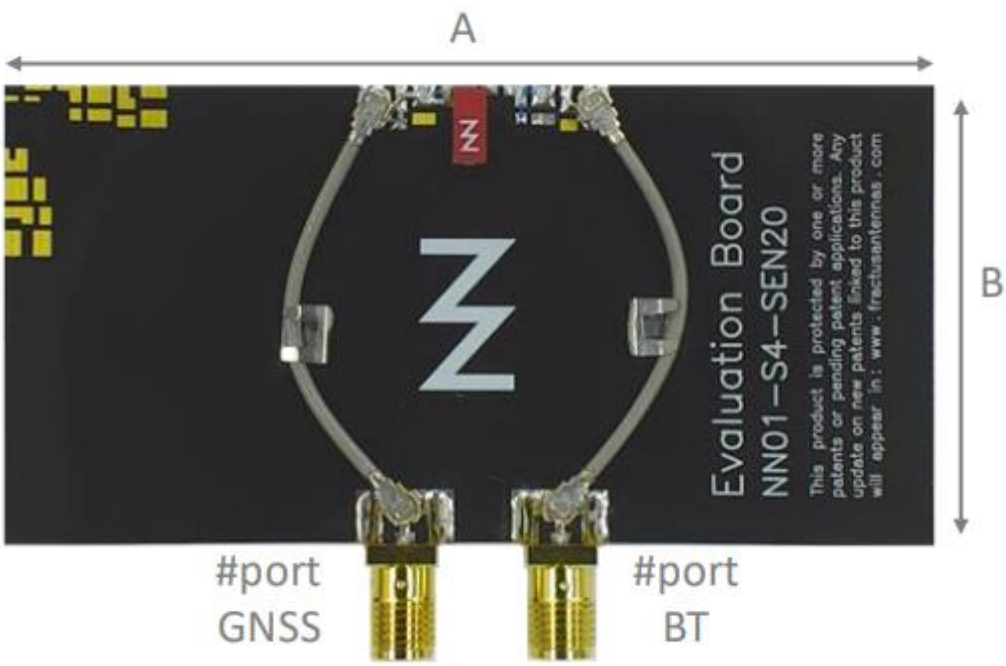


Figure 5: Evaluation Board

c) Matching Network (MN)

DUO mXTEND™ needs two matching networks, one for each application (GNSS and BT), a first for the Bluetooth port, a second for the GNSS one (Figure 2). This section describes in table 5 a suitable matching network for DUO mXTEND™. A virtual antenna is subjected to the evaluation board specification, nearby components, among others. So, the matching network should be readjusted for each case.

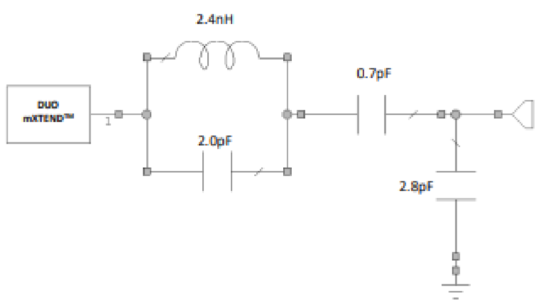
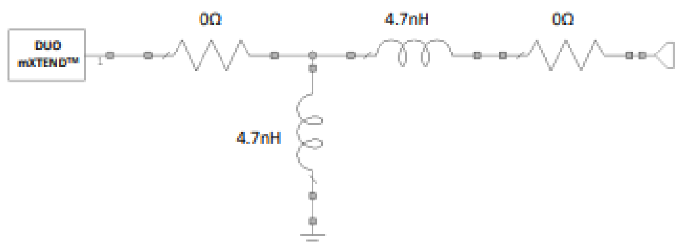
GNSS MN	Bluetooth MN
	

Table 5: Matchings network

d) VSRW and Efficiency

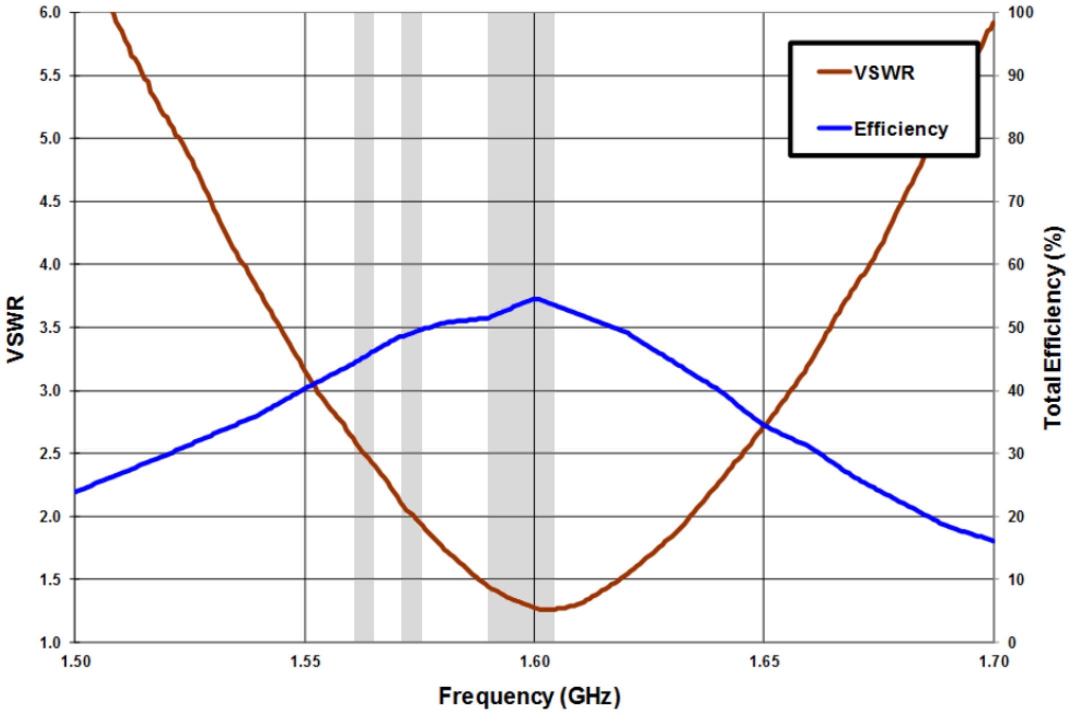


Figure 6: VSWR and Total Efficiency for GNSS

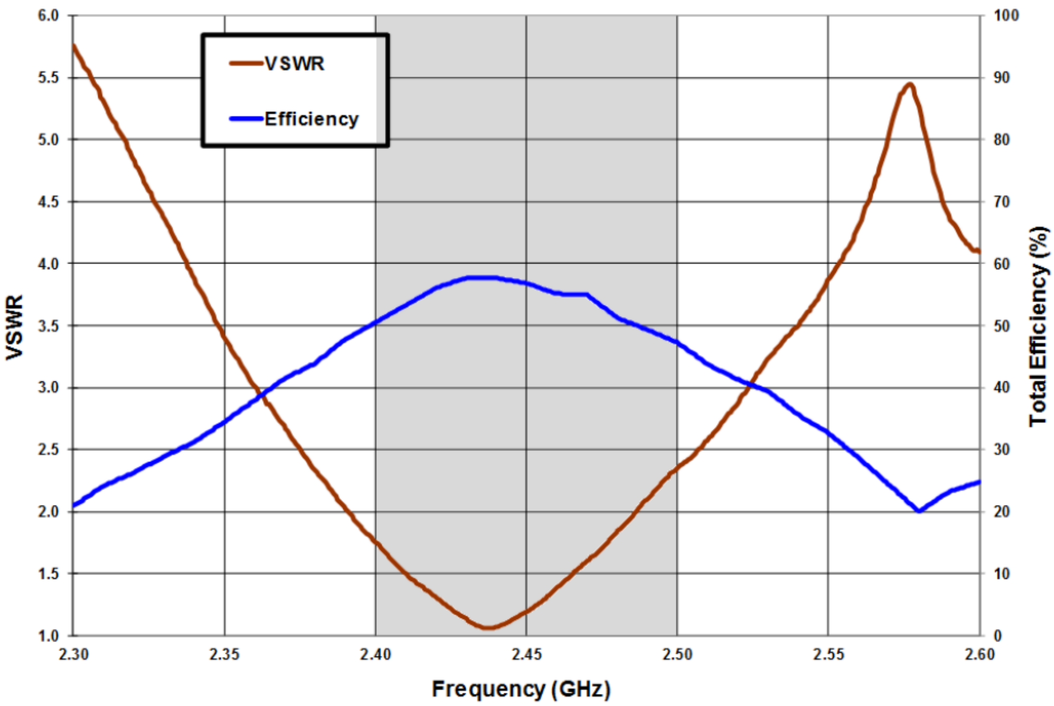
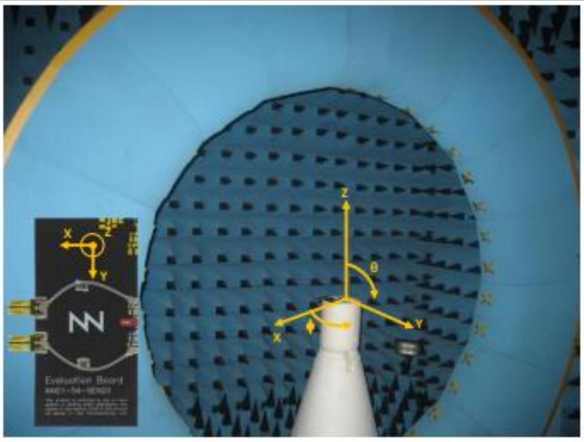
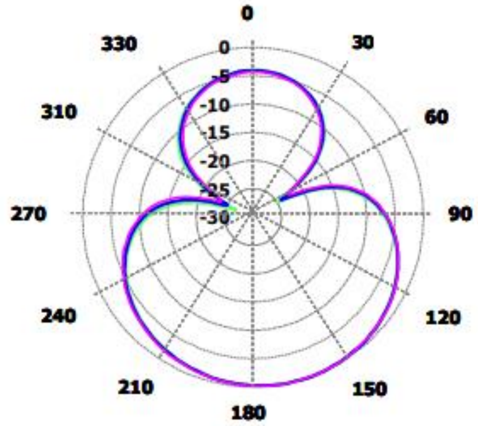


Figure 7: VSWR and Total Efficiency for Bluetooth

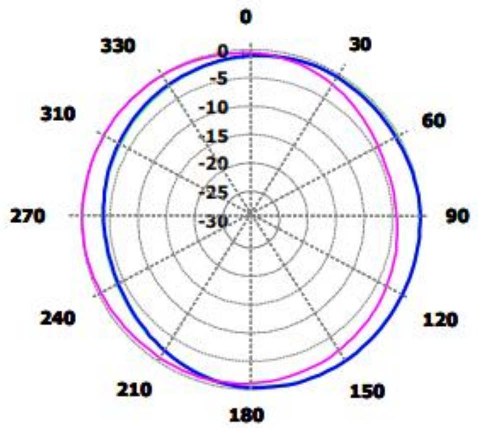
e) Radiation patterns, Gain and Efficiency



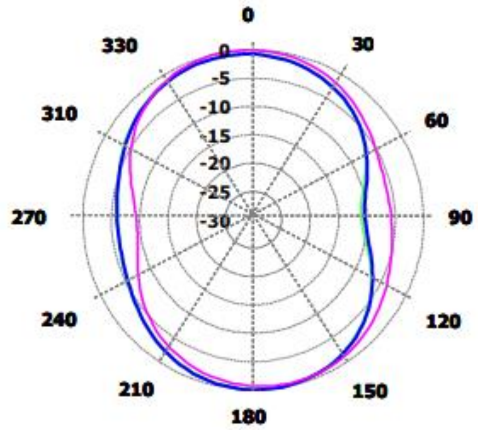
Measurement System Set-Up
Evaluation Board in Plane XY



θ = 90º Plane XY at 1.561 GHz, 1.575 GHz and 1.602 GHz



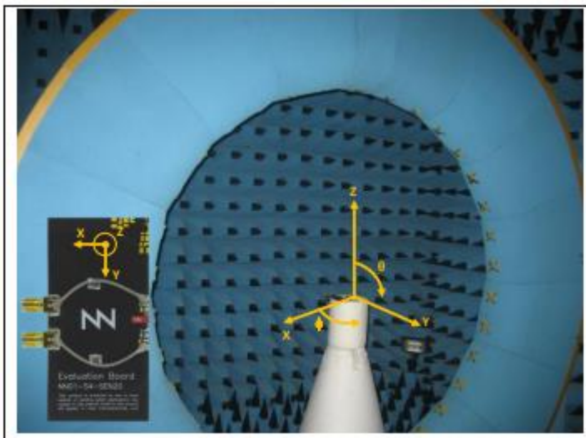
ϕ = 0º Plane XZ at 1.561 GHz, 1.575 GHz and 1.602 GHz



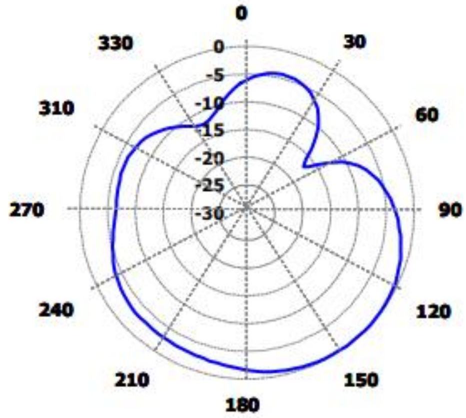
ϕ = 90º Plane YZ at 1.561 GHz, 1.575 GHz and 1.602 GHz

BeiDou	Gain		-1.1 dBi
	Efficiency		44.6 %
GPS	Gain		-1.0 dBi
	Efficiency		49.7 %
GLONASS	Gain	Peak Gain	-1.0 dBi
		Average Gain across the band	-1.0 dBi
		Gain Range across the band (min, max)	-1.0 <–> -1.0 dBi
	Efficiency	Peak Efficiency	54.6 %
		Average Efficiency across the band	53.9 %
		Efficiency Range across the band (min, max)	53.0 – 54.6 %

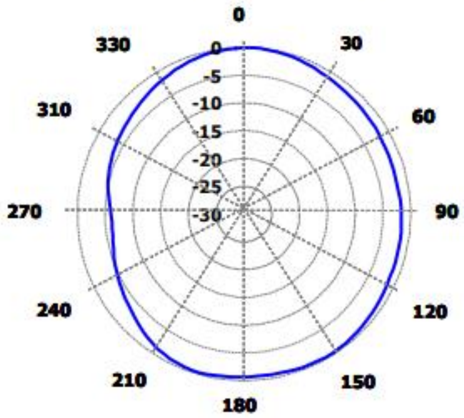
Table 6: – Antenna Gain and Total Efficiency from the Evaluation Board (Figure 2) for BeiDou E1 (1561 MHz), GPS L1 (1575 MHz) and GLONASS L1 (1598 MHz – 1606 MHz) bands. Measures made in the Satimo STARGATE 32 anechoic chamber.



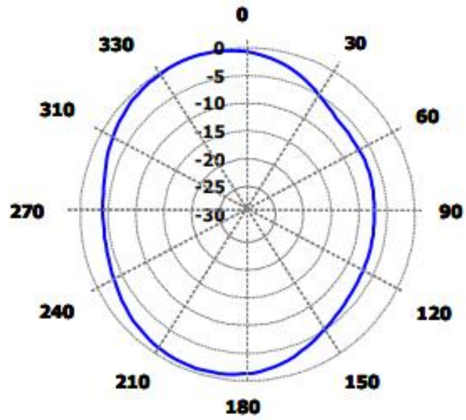
Measurement System Set-Up
Evaluation Board in Plane XY



θ = 90º Plane XY at 2450MHz



ϕ = 0º Plane XZ at 2450MHz



ϕ = 90º Plane YZ at 2450MHz

Gain	Peak Gain	-0.9 dBi
	Average Gain across the band	-0.9 dBi
	Gain Range across the band (min, max)	-1.0 dBi <–> -0.9 dBi
Efficiency	Peak Efficiency	57.7 %
	Average Efficiency across the band	54.1 %
	Efficiency Range across the band (min, max)	47.2 – 57.7 %

Table 7: – Antenna Gain and Total Efficiency for the Evaluation Board (Figure 1) for Bluetooth (2400 MHz - 2500 MHz). Measures made in the Satimo STARGATE 32 anechoic chamber.

2.4. Conclusions

It can be concluded that most of the devices cover the GNSS and Bluetooth frequency ranges, alongside other frequency bands such as Wi-Fi. Also, there are very few antennas capable of covering both frequency bands.

The size of the antennas is crucial in current devices since they must adapt to reduced PCB sizes, due to the current technological trend of manufacturing everything tiny and minimalist.

Considering the frequency bands to cover and the average PCB size of the analyzed devices, the DUO mXTEND™ is the most suitable Fractus Antennas (NN) product to use due to its dimensions and the frequency bands that can cover efficiently.

3. Design with electromagnetic simulation

3.1. Introduction

In this chapter it is presented a study that has been done for the DUO mXTEND™ (NN03-320) regarding how the efficiency changes depending on the clearance area dimensions. [5]

As mentioned in the first chapter, an antenna booster performance would depend on the PCB size, the matching network and, on the clearance area beyond the antenna. Then, when the antenna booster is correctly placed on the printed circuit board (PCB) of a wireless device, it excites efficient radiating modes in the ground plane. Usually, the corners of the ground plane are the preferred locations at which excite these modes to obtain a good bandwidth.

The followed steps to carry out this study consists of an analysis at an experimental level by using different software, such as *CST studio*[2], *Optenni*[3] and *Microwave*[4], to see how the DUO behaves as a slot in the middle of a 90mm x 50mm PCB. Likewise, the behavior of the antenna in the corner will be studied using it in GNSS and Bluetooth ports as a monopole.

In the latter case, the main objective will be to maximize efficiency while minimizing the clearance area. For this, various designs will be carried out, keeping the PCB of 90mm x 50mm and varying the clearance area starting from the dimensions of the antenna, which are 7mm x 3mm x 2mm. For this, some steps will be followed to ensure that all the processes that are carried out following the same procedure to be able to correctly validate the simulations and the results obtained.

a. To start adapting the DUO in the corner, the GNSS port will be prioritized, since being lower frequencies than Bluetooth, it will be more complicated to adapt. The GNSS port will be connected on the *via* and various measurements will be made, varying the clearance area starting with a minimum, which will be the dimensions of the antenna.

[2] https://www.3ds.com/es/productos-y-servicios/simulia/productos/cst-studio-suite/
[3] https://www.optenni.com/
[4] https://www.awr.com/awr-software/products/microwave-office

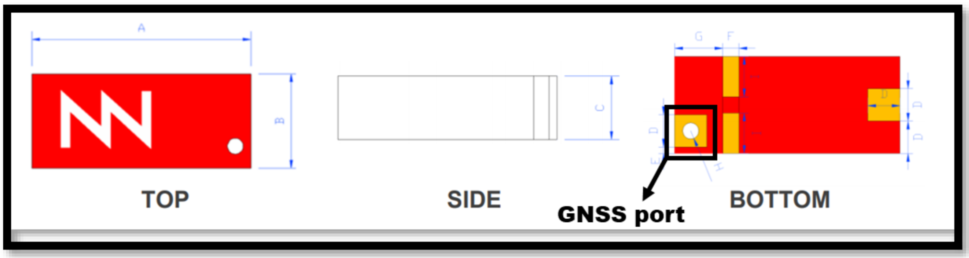


Figure 8: GNSS port location

b. After having performed the analysis only with the GNSS port connected, the clearance area dimensions that maximize efficiency will be chosen, and this will be the starting point to adapt the Bluetooth port.

   At this point, it will also be analyzed with the clearance area chosen as the optimal one, the DUO mXTEND™ in the corner but connecting the Bluetooth port shorted with the ground plane.

c. The steps mentioned in sections *a)* and *b)* are also carried out for a PCB with dimensions 80mm x 40mm, in order to make a comparison at the level of adaptation and efficiency.
d. For each design it will be necessary to provide a matching network [6], computed through the smith chart and Optenni software readjusting it with the Smith chart movements.

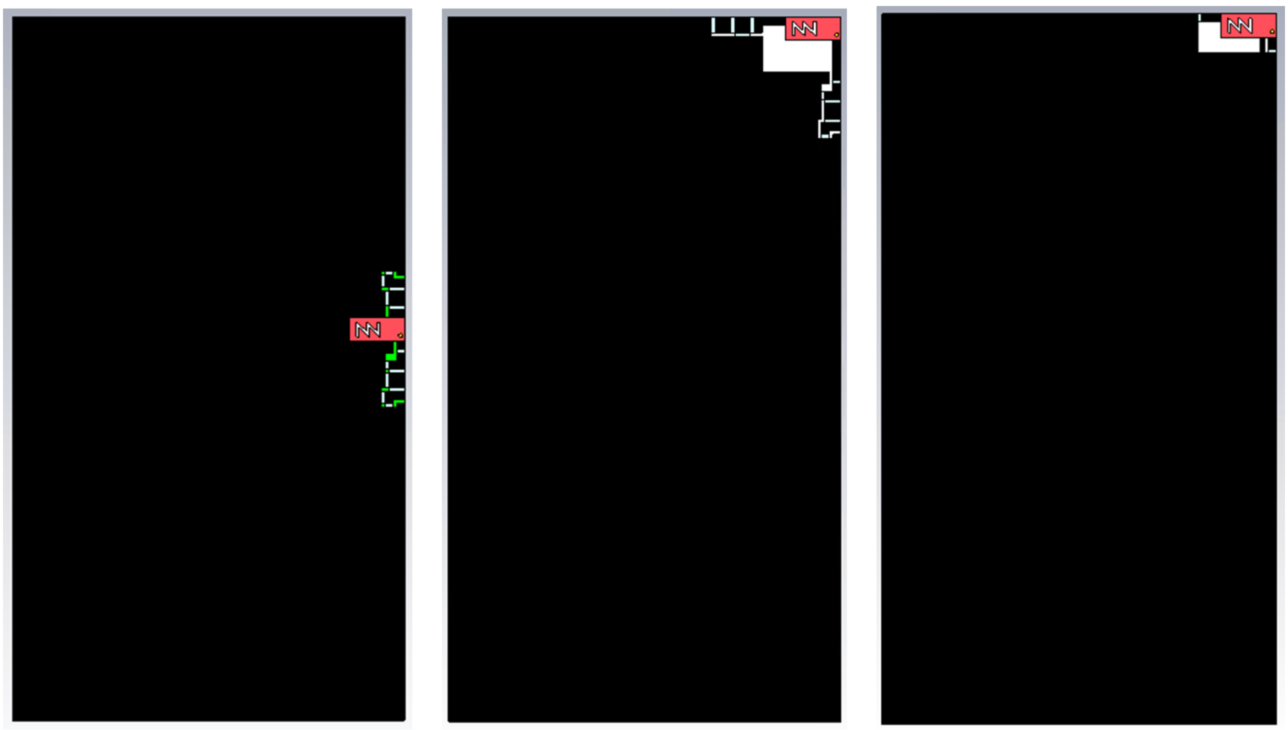


Figure 9: DUO mXTEND™ in a 90mm x 50mm PCB: 1) Dual port slot in the middle, 2) Dual port non-shorted in the corner and 3) Dual port shorted in the corner

3.2. Efficiency analysis

As previously commented for the analysis of the efficiency of the DUO mXTEND™ antenna booster dual port in the corner of a 90mm x 50mm PCB, we will start analyzing the GNSS (1561MHz – 1606MHz) port, varying the clearance area.

To understand all the steps followed it should be explained how the design is created and the methods to adapt the matching network for each case. Also, the tools and technics used to find the right components (inductors, capacitors and resistors) that will improve our matching network adaptations.

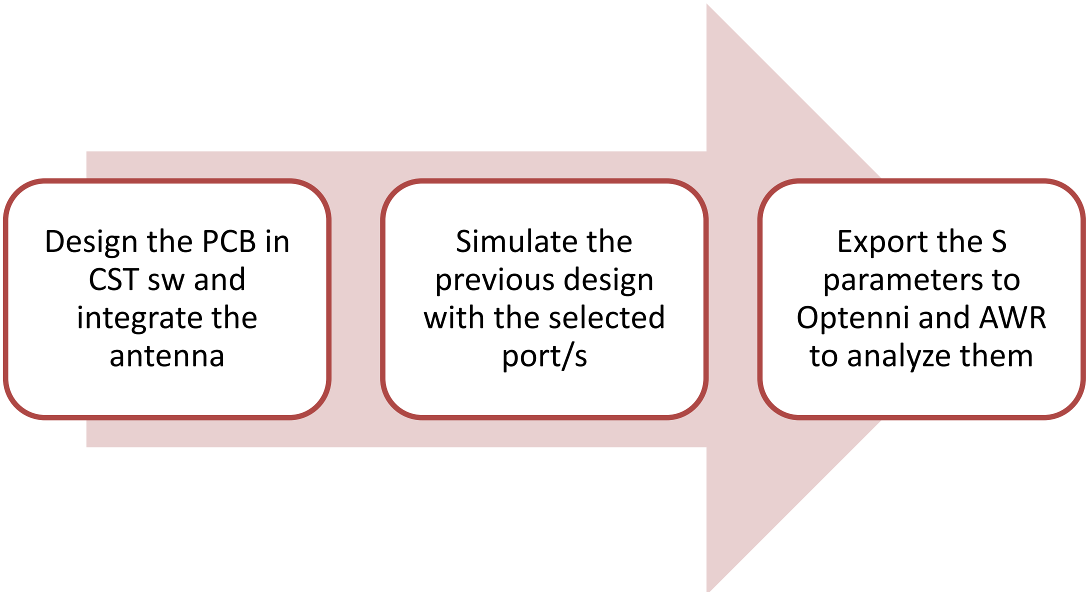


Figure 10: CST procedure

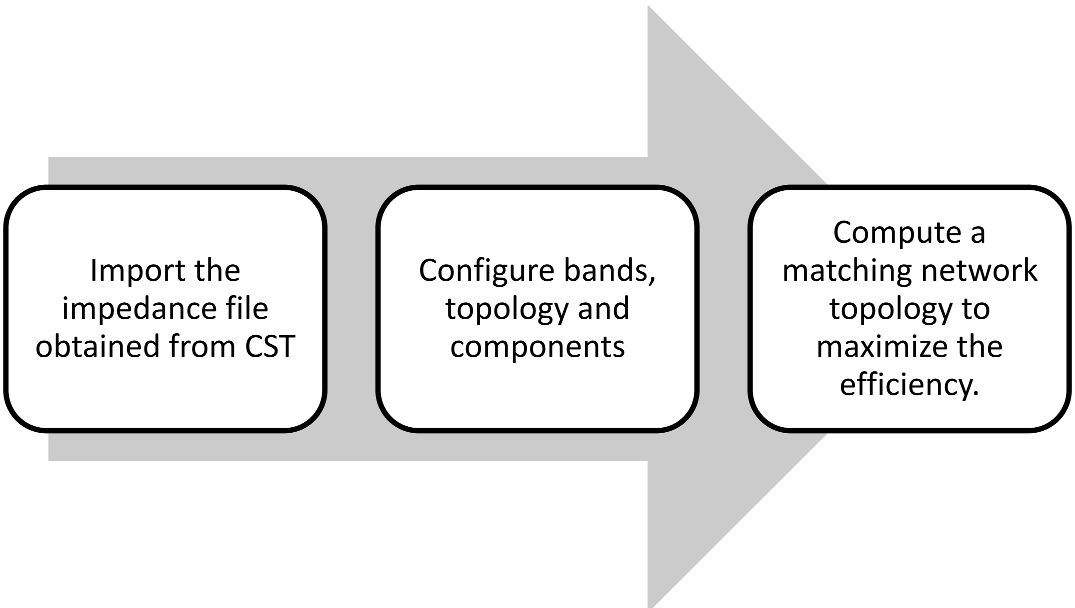


Figure 11: Optenni procedure

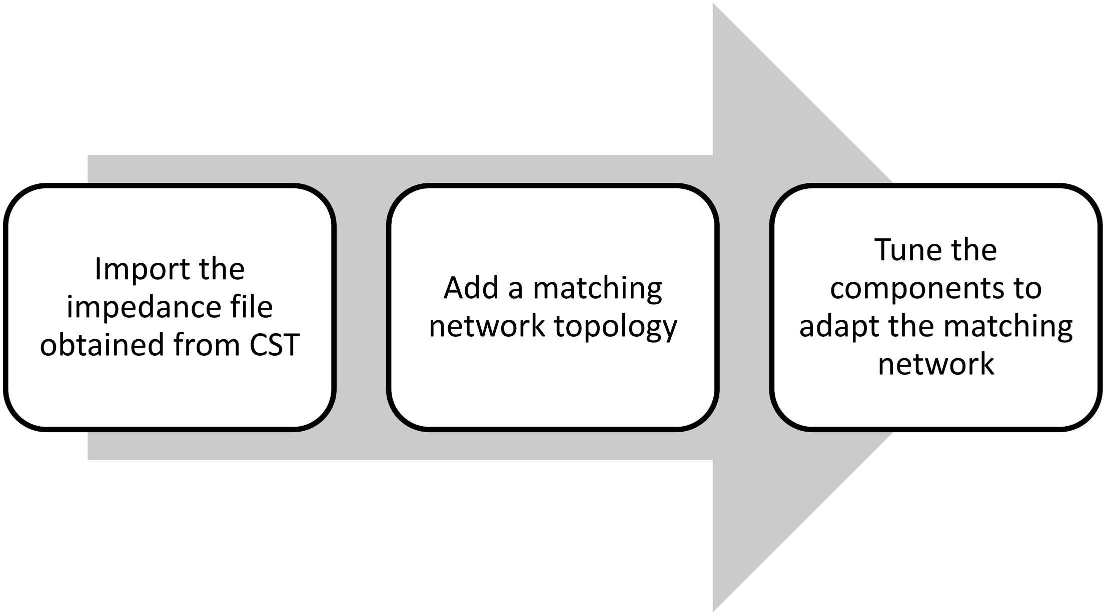


Figure 12: Microwave procedure

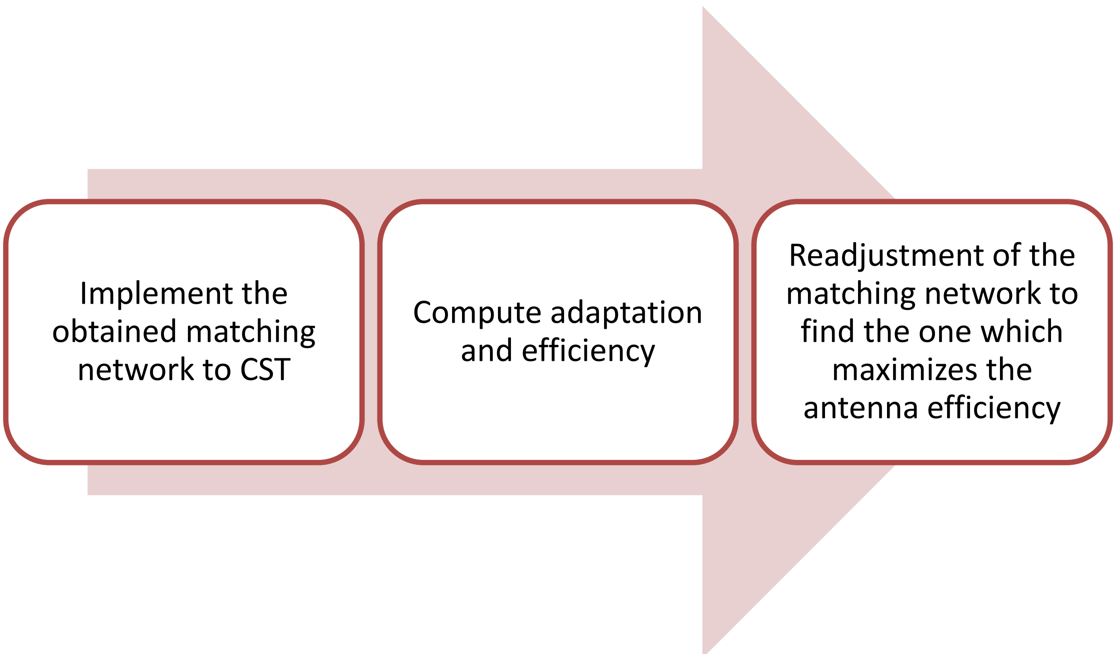


Figure 13: Matching network adaptation in CST

The Optenni and Microwave softwares are useful tools to be able to have some help when adapting the matching network and finish the process by means of small movements that we can see in the Smith Chart that CST shows us, as in figure 2. When we observe that the adaptation is correct, we proceed to the program to calculate the efficiency with all the parameters that we have adjusted.

PCB charactarisitics
In this section we want to expose the PCB characteristics that will be used throughout the CST simulations that are presented in this project.

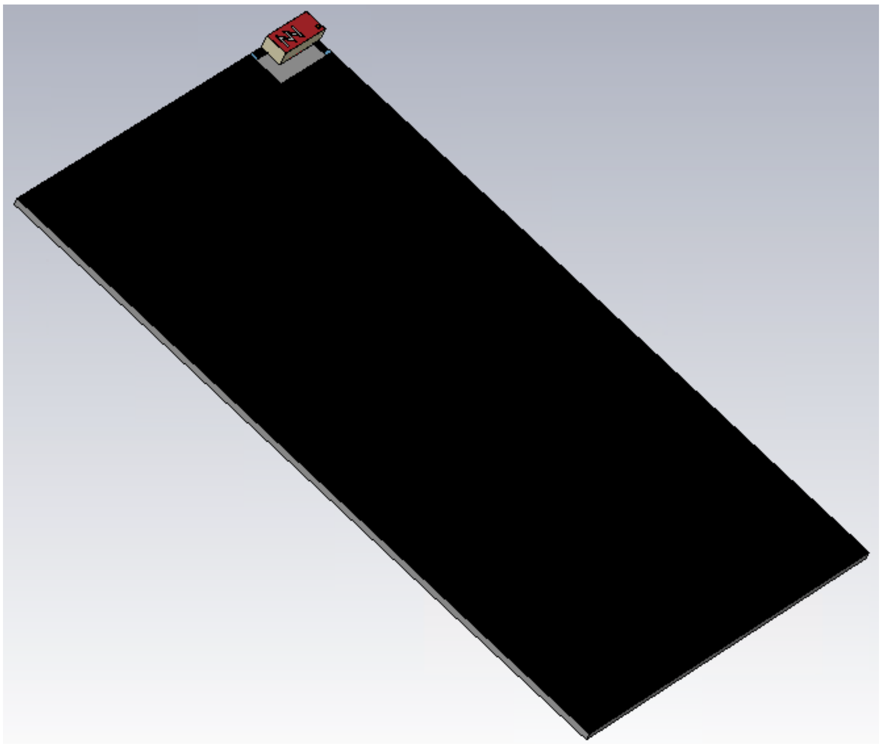


Figure 14: PCB model on CST

The PCB is basically made up of 3 main parts: substrate 1mm thickness, ground plane and port. Each of these parts has different physical and material. We will consider the antenna as a external component.

3.3. PCB dimensions vs Efficiency

3.3.1. GNSS port analysis

As we have commented previously, we will start by adapting the GNSS band, in order to know which clearance area dimensions are the ones that maximize efficiency, we will make different designs, varying the *length* (L) and *width* (W) of the clearance area.

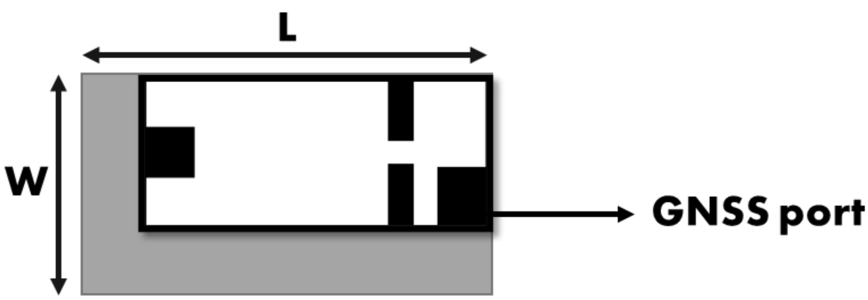


Figure 15: GNSS port schematic

As we can see in the designs that are proposed, the fact of varying the clearance dimensions is directly reflected in the design on how the PCB and the feeding that connects the antenna, port and ground plane varies.

Design	L (mm)	W(mm)
1	7	3.25
2	7	6
3	7	8
4	10	3
5	10	4
6	10	5
7	10	7
8	10	10

Table 8: Clearance area dimensions

Of the simulations carried out with the different designs, it will be analyzed in terms of efficiency which of them is the one with the best performance in order to also be able to add the Bluetooth port. The DUO mXTEND™ is an antenna that is used as a slot, as explained in the chapter 1 of this project. In this case, we are adapting it as a monopole in both ports so that efficiency can be directly negatively affected.

Simultaneously, once obtained the board design that best suits us, apart from adding the Bluetooth port as a monopole, we will do the test of connecting the Bluetooth port shorted to the ground plane to see the obtained antenna efficiency.

1. Clearance area 7mm x 3.25mm

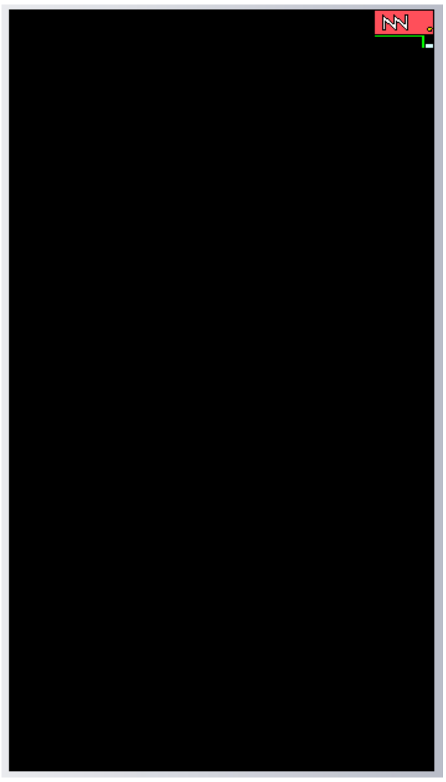


Figure 17: Design with a clearance area of 7mm x 3.25mm

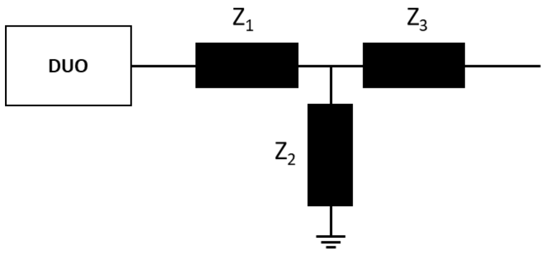


Figure 16: Matching network topology

Components	
Z1	14nH
Z2	2.5nH
Z3	0Ω

Table 9: Components for 7mm x 3.25 mm clearance area topology

2. Clearance area 7mm x 6mm

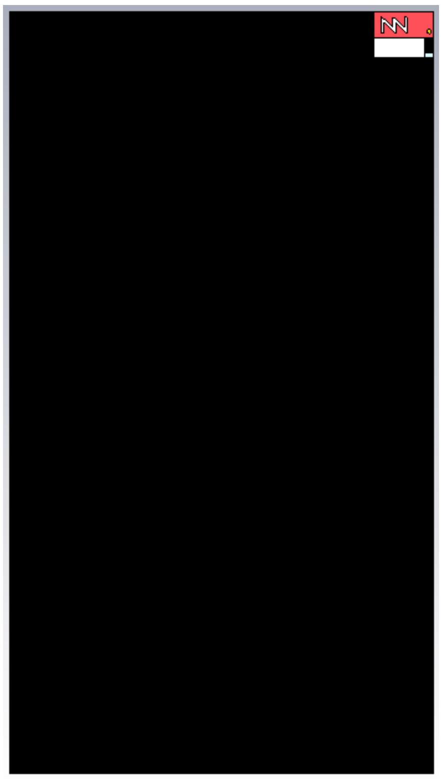


Figure 18: Design with a clearance area of 7mm x 6mm

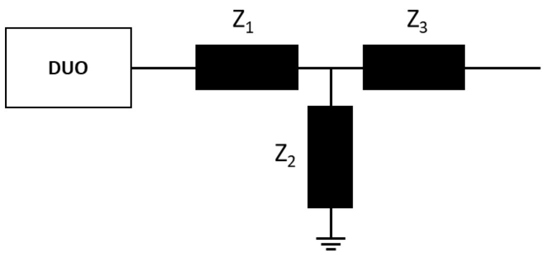


Figure 19: Matching network topology

Components	
Z1	15nH
Z2	3.5nH
Z3	0Ω

Table 10: Components for 7mm x 6mm clearance area topology

3. *Clearance area 7mm x 8mm*

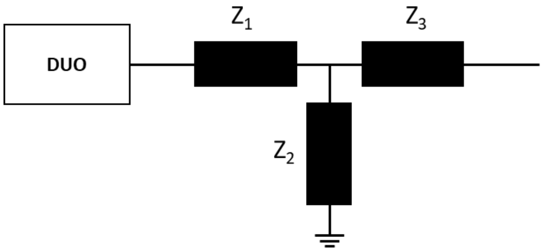


Figure 20: Matching network topology

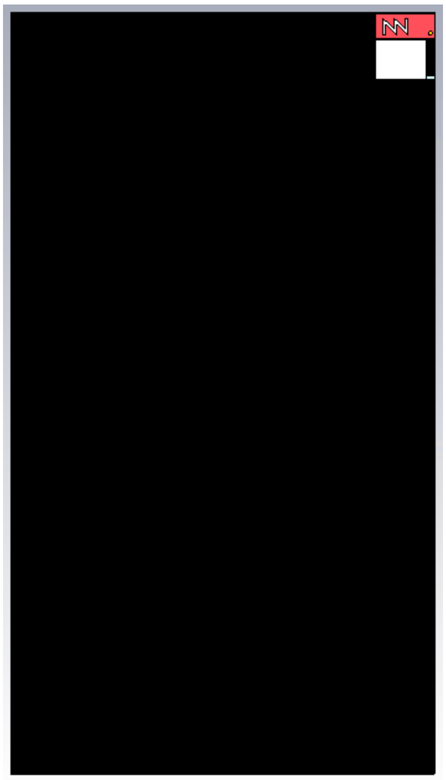


Figure 21: Design with a clearance area of 7mm x 8mm

Components	
Z1	*12nH*
Z2	*2.8nH*
Z3	*0Ω*

Table 11: Components for 7mm x 8mm clearance area topology

4. *Clearance area 10mm x 3mm*

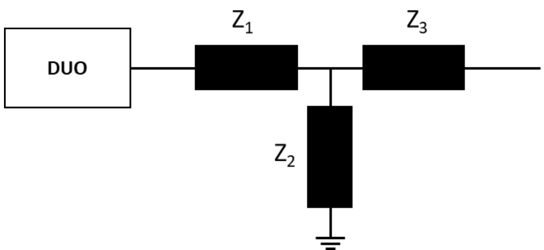


Figure 22: Matching network topology

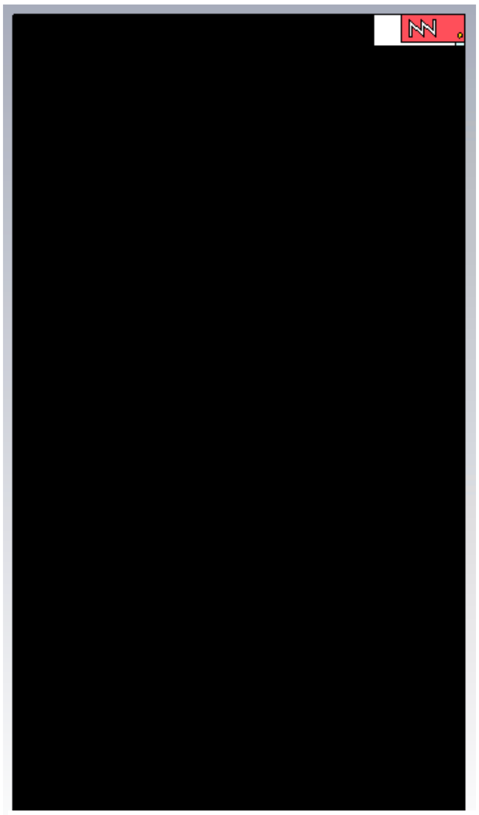


Figure 23: Design with a clearance area of 10mm x 3mm

Components	
Z1	*16nH*
Z2	*4.0nH*
Z3	*0Ω*

Table 12: Components for 10mm x 3mm clearance area topology

5. *Clearance area 10mm x 4mm*

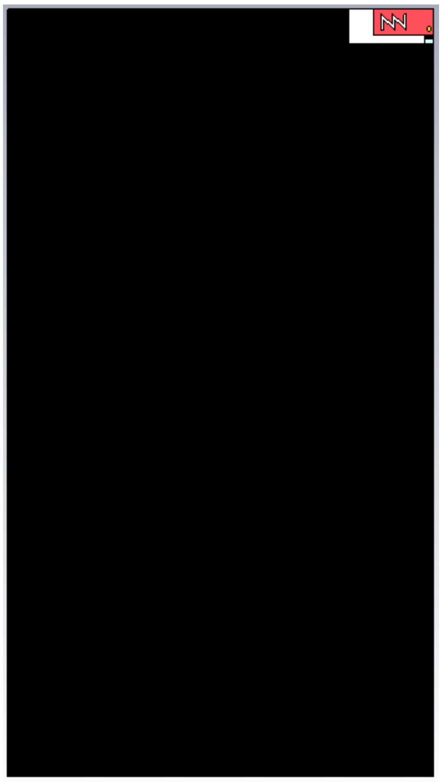


Figure 25: Design with a clearance area of 10mm x 4mm

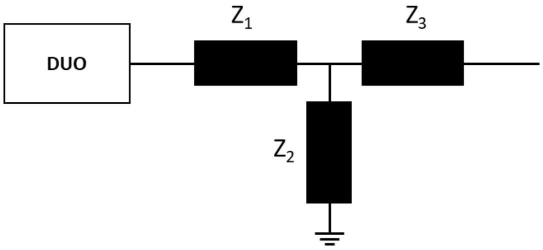


Figure 24: Matching network topology

Components	
Z1	*17nH*
Z2	*3.0nH*
Z3	*0Ω*

Table 13: Components for 10mm x 4mm clearance area topology

6. *Clearance area 10mm x 5mm*

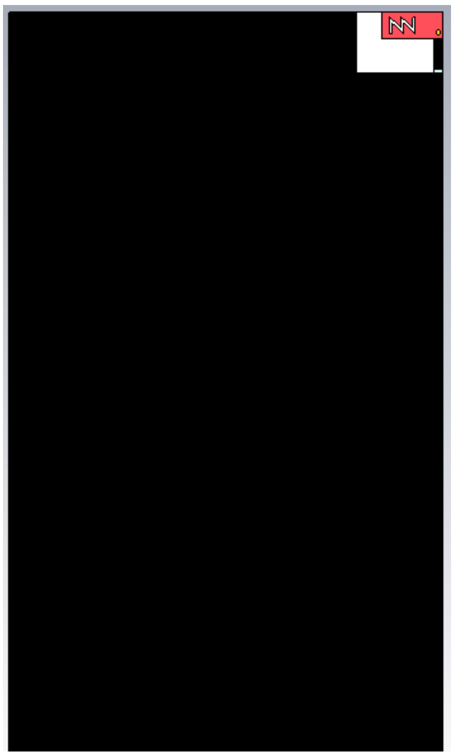


Figure 26: Design with a clearance area of 10mm x 5mm

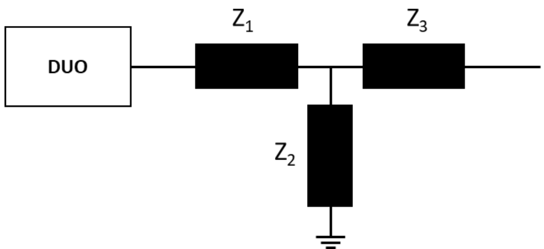


Figure 27: Matching network topology

Components	
Z1	*16nH*
Z2	*3.5nH*
Z3	*0Ω*

Table 14: Components for 10mm x 5mm clearance area topology

7. Clearance area 10mm x 7mm

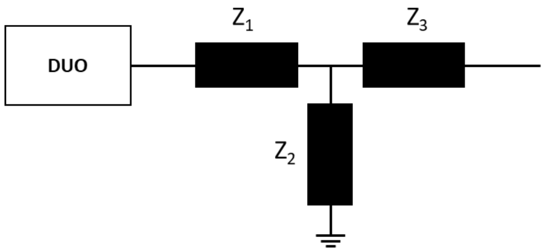


Figure 28: Matching network topology

Components	
Z1	12nH
Z2	4.0nH
Z3	0Ω

Table 15: Components for 10mm x 7mm clearance area topology

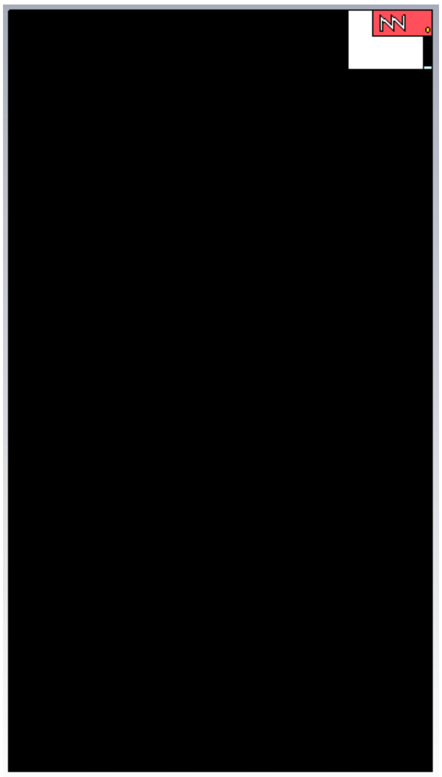


Figure 29: Design with a clearance area of 10mm x 7mm

8. Clearance area 10mm x 10mm

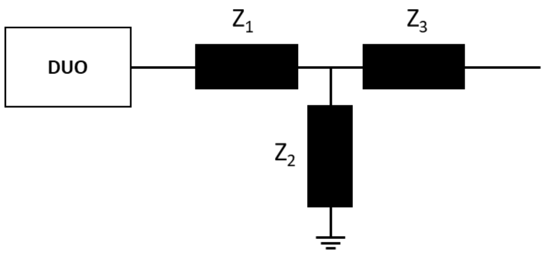


Figure 30: Matching network topology

Components	
Z1	12nH
Z2	3.3nH
Z3	0Ω

Table 16: Components for 10mm x 7mm clearance area topology

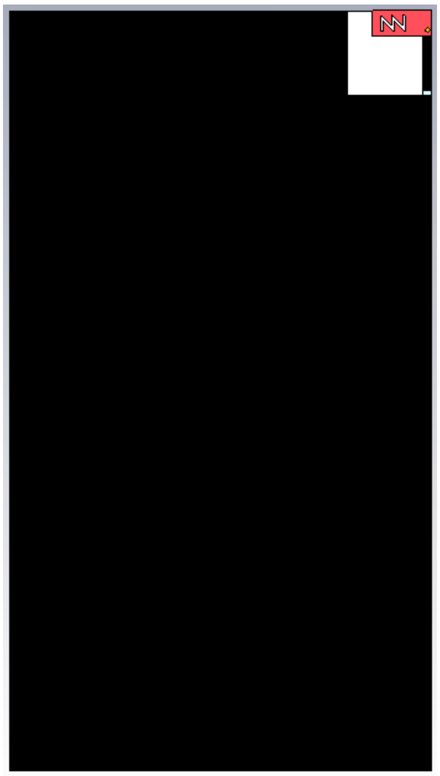


Figure 31: Design with a clearance area of 10mm x 7mm

3.3.2. *Clearance area impact*

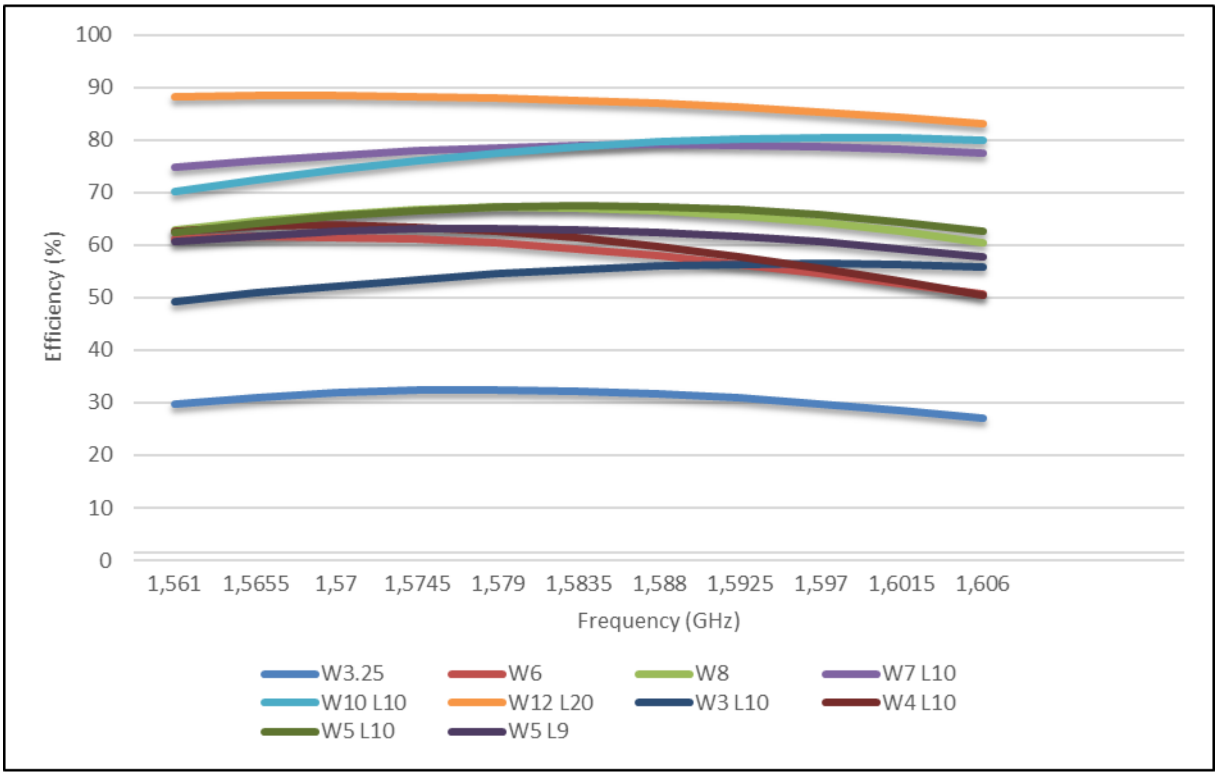


Figure 32: Total Efficiency vs Clearance area

In the figure 32 you can see the efficiency performance of the desings previously implemented. As we can see in the graph, as we increase the clearance area, the efficiency improves considerably. Thus, in order to work with a two-port model, we will consider those designs whose efficiencies are above 60% in the GNSS frequency range (1561 - 1606MHz).

From the results obtained, another design has been made with W=5 and L=9 to check how this minimal decrease in area clearance affects antenna efficiency. This dimensions still maintain the efficiency above 60%, so this design could be the one used to implement the Bluetooth port. One of the issues we will have to deal with when adding a second port is the coupling, so it will be necessary to design a filter that isolates the signals from the ports and avoid coupling between applications.

3.4. Antenna performance

3.4.1. Non-shorted vs Shorted

The challenge in this step will be to find a balance between PCB design/clearance area, matching network adaptation through filters and avoid coupling between ports. For the analysis of the antenna dual port, has been used the designs in the figure 33; a) *Bluetooth non-shorted – GNSS* and B) *Bluetooth shorted – GNSS.* The dimensions of both PCBs are L=10mm and W=5mm.

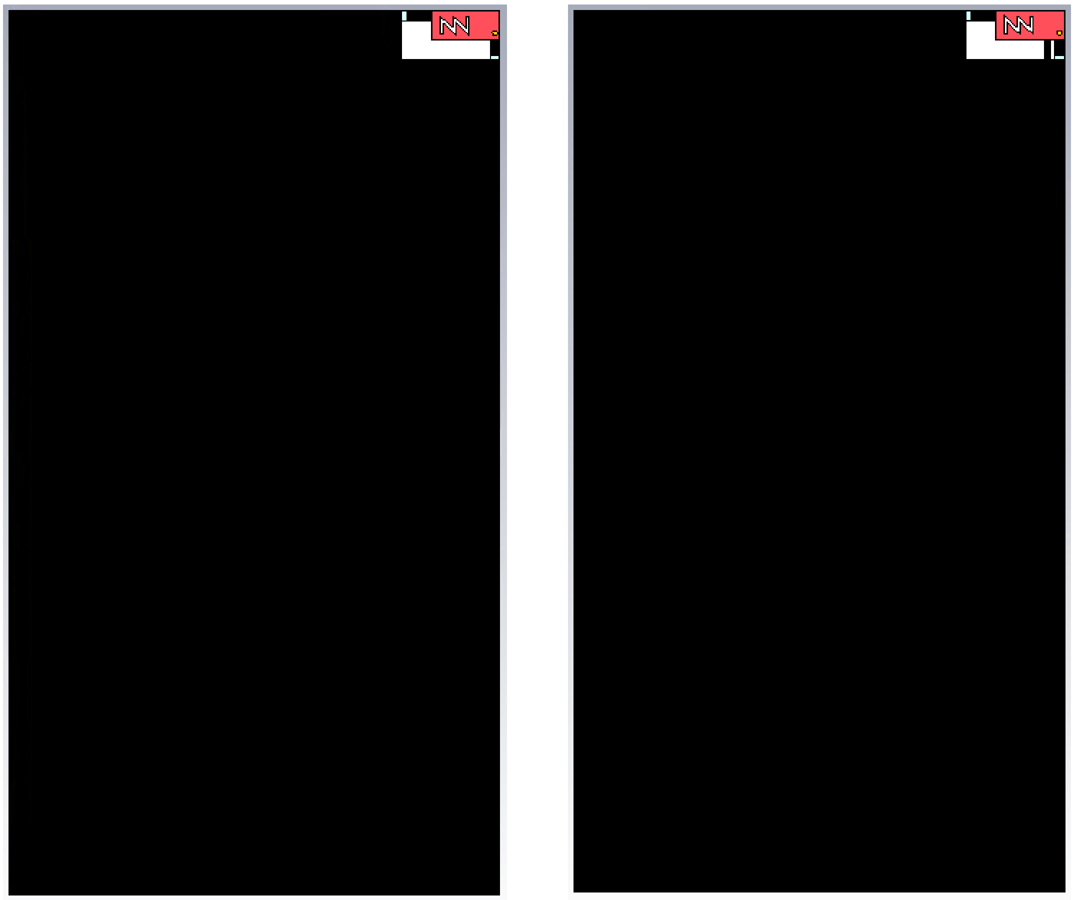


Figure 33: a) Bluetooth monopole – GNSS monopole *and b)* Bluetooth loop – GNSS monopole.

The designs shown in the figure 33 have been made to be able to choose which design provides us with the most efficient antenna. Through this comparison we will be able to know in terms of adaptation and consequently of efficiency which may be the definitive prototype, which will be implemented in the laboratory.

a. DUO mXTEND™ Bluetooth non-shorted - GNSS

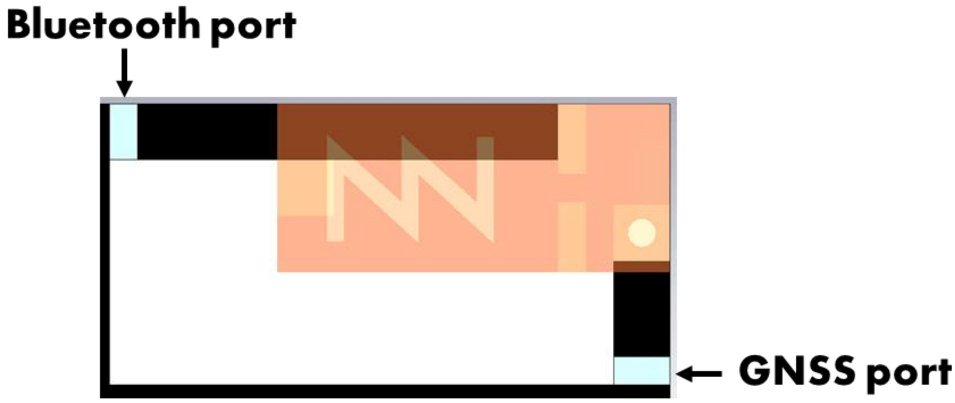


Figure 34: DUO mXTEND™ Bluetooth non-shorted - GNSS

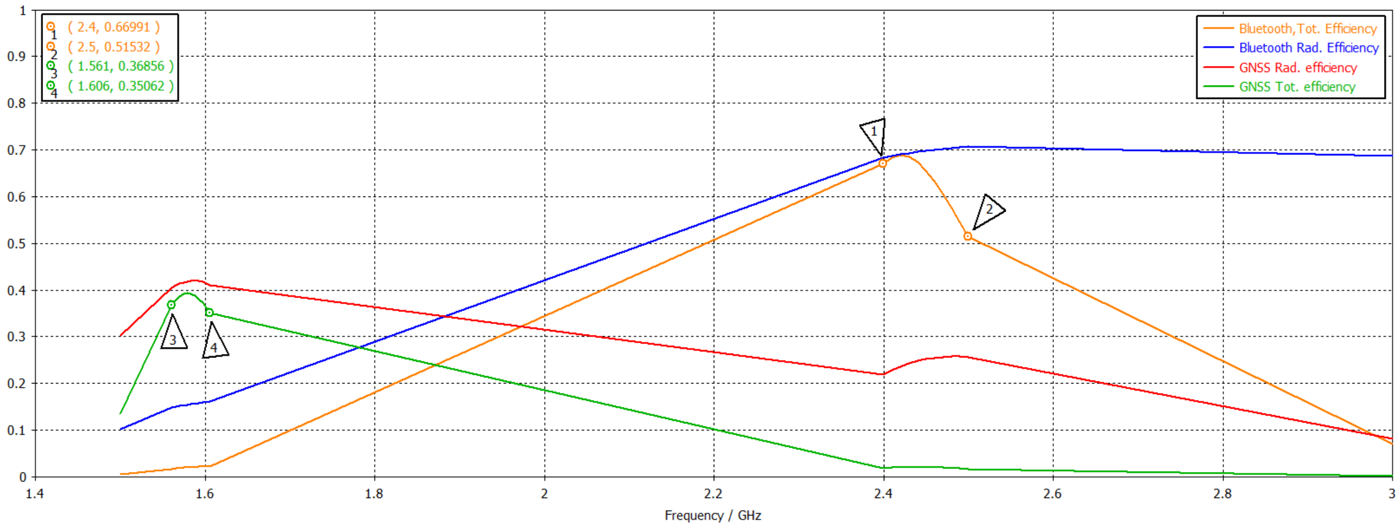


Figure 35: Efficiencies Bluetooth non-shorted – GNSS

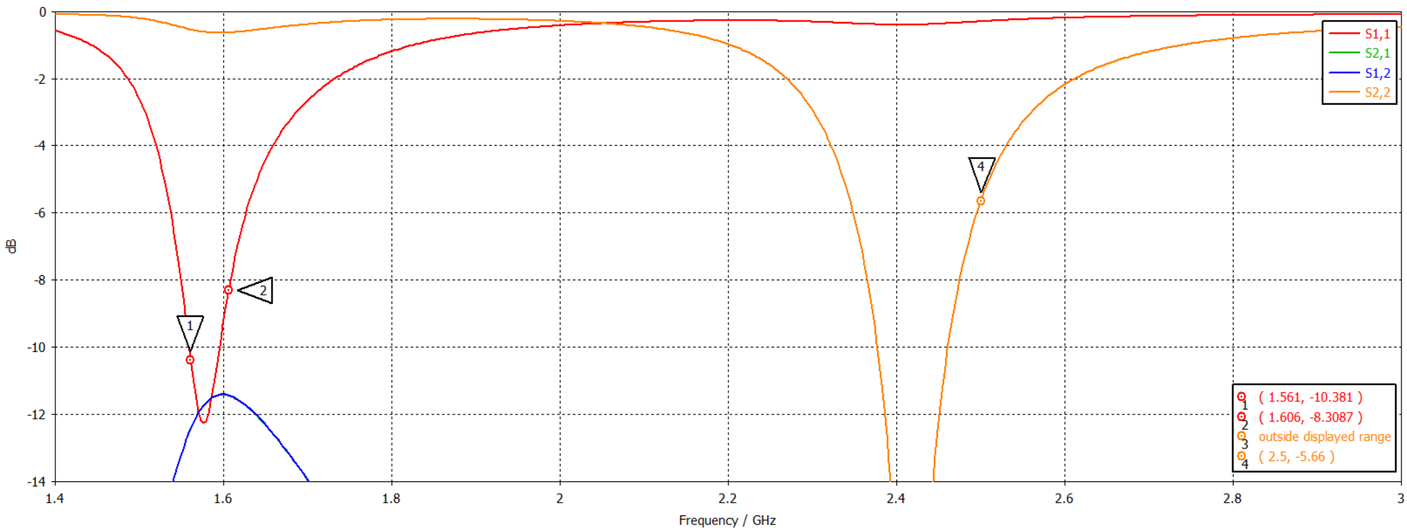


Figure 36: Sparameters Bluetooth non-shorted (S_{22}) – GNSS (S_{11})

b. DUO mXTEND™ Bluetooth shorted - GNSS

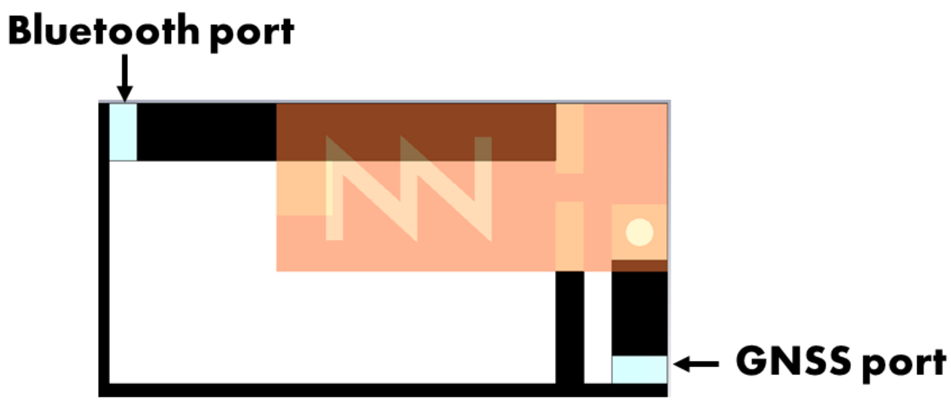


Figure 37: DUO mXTEND™ Bluetooth shorted - GNSS

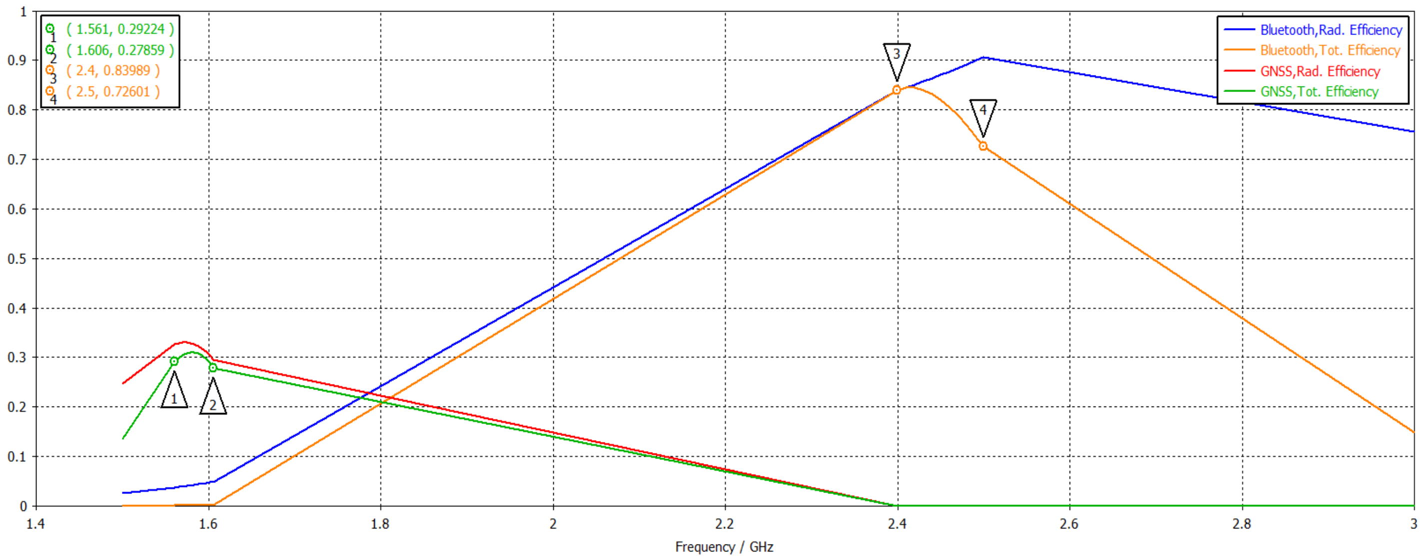


Figure 39: Efficiencies Bluetooth shorted – GNSS

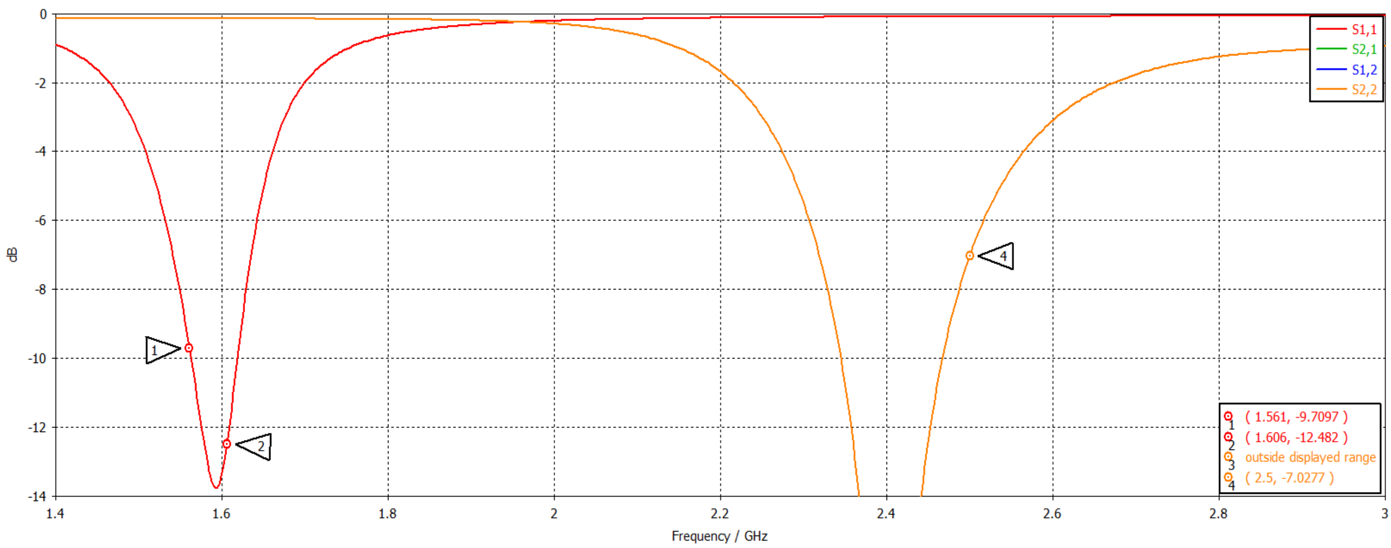


Figure 38: Sparameters Bluetooth shorted (S_{22}) – GNSS (S_{11})

ANTENNA EFFICIENCY (%)			
Design *a* *(Bluetooth non-shorted)*	1561MHz 2400MHz	1606MHz 2500MHz	Avg 1561-1606MHz/ Avg 2400-2500MHz
GNSS	36.9	35.1	**37.8**
Bluetooth	67.0	51.5	**63.1**
Design *b* *(Bluetooth shorted)*	1561MHz 2400MHz	1606MHz 2500MHz	Avg 1561-1606MHz/ Avg 2400-2500MHz
GNSS	29.2	27.9	**28.6**
Bluetooth	83.9	72.6	**80.5**

Table 17: Total Efficiency comparative

Table 18 shows the efficiency values for the two designs presented in the previous section. The design *a)* (bluetooth non-shorted and GNSS) we can see how the efficiency for GNSS band (1561-1606MHz) is higher than in design *b)* (bluetooth shorted and GNSS), instead it happens with the Bluetooth band (2.4 - 2.5GHz), the efficiency is higher in the *b* design. If we look at the reflection coefficient graphs (figure 38), we can see that both designs are well matched and almost all ranges of interest are below -6dB. Regarding coupling, we can see that the ports are well isolated since we have the S_{21} / S_{11} below -11dB.

To choose one of the designs, as a first requirement the GNSS band must be the highest since it is a more difficult frequency band to adapt than Bluetooth that works at higher frequencies. We see that design *a)* has higher antenna efficiency levels than design *b).*

1) Full Layout 90mm x 50mm

At this point, we will proceed to implement design *a)* in full layout mode. Carrying out a full layout model implies creating a design in which elements that exist in the physical model are considered. In this case, what we will add to the chosen design are pads, the space where the components of the matching network (MN) are soldered. In figures 40 and 41 it can be seen how the pads are implemented with the feeding lines.

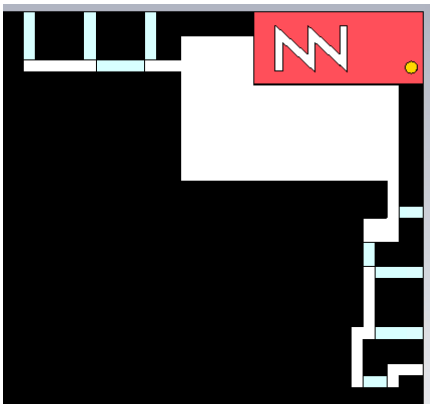


Figure 40: Pads components.

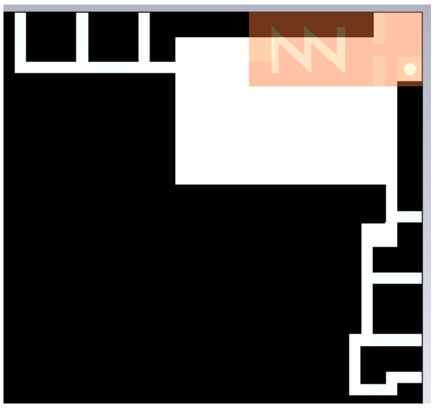


Figure 41: Pads + feeding

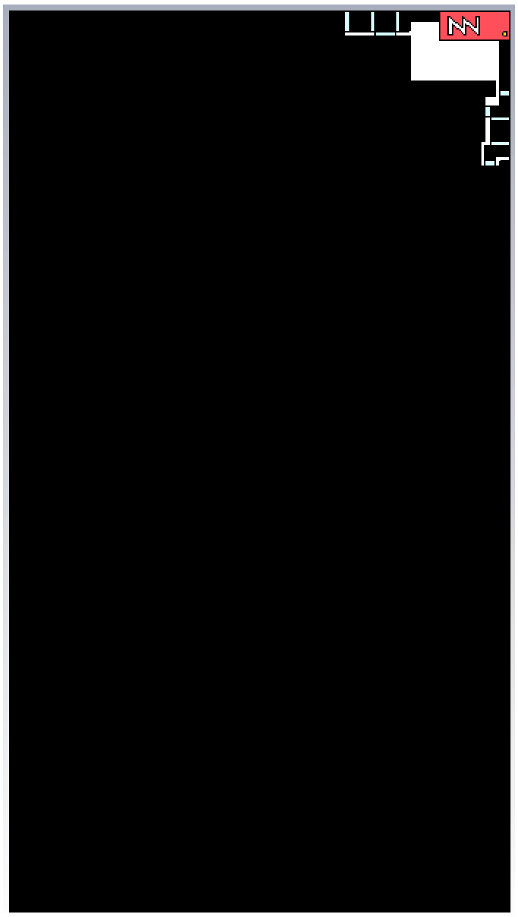


Figure 42: Full Layout design

MN for GNSS port	MN for Bluetooth port

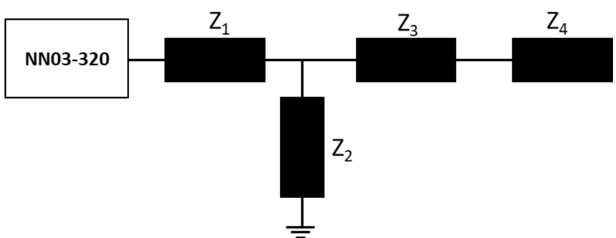


Figure 43: MN GNSS full layout

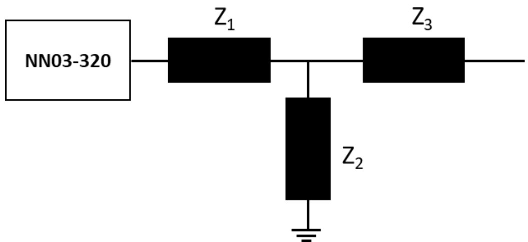


Figure 44: MN Bluetooth full layout

Components	
Z1	9.1nH
Z2	2.7nH
Z3	2.2nH
Z4	0Ω

Table 19: MN GNSS full layout values

Components	
Z1	0.20pF
Z2	8.7nH
Z3	0.10pF

Table 18: MN Bluetooth full layout values

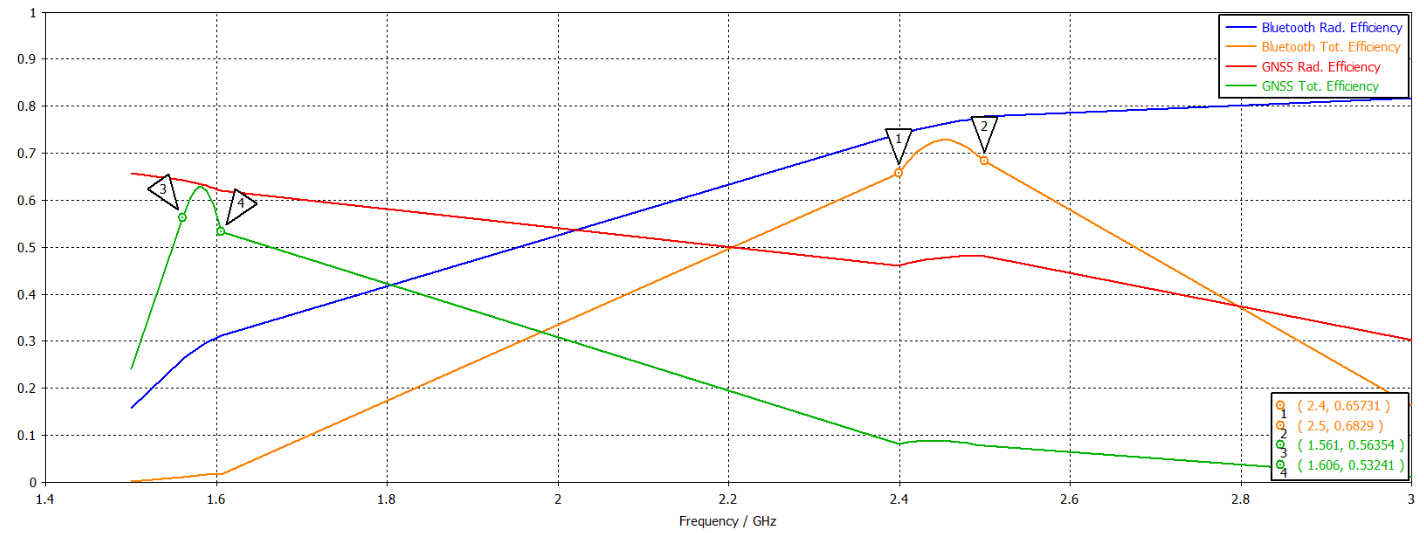


Figure 45: Full layout Efficiencies

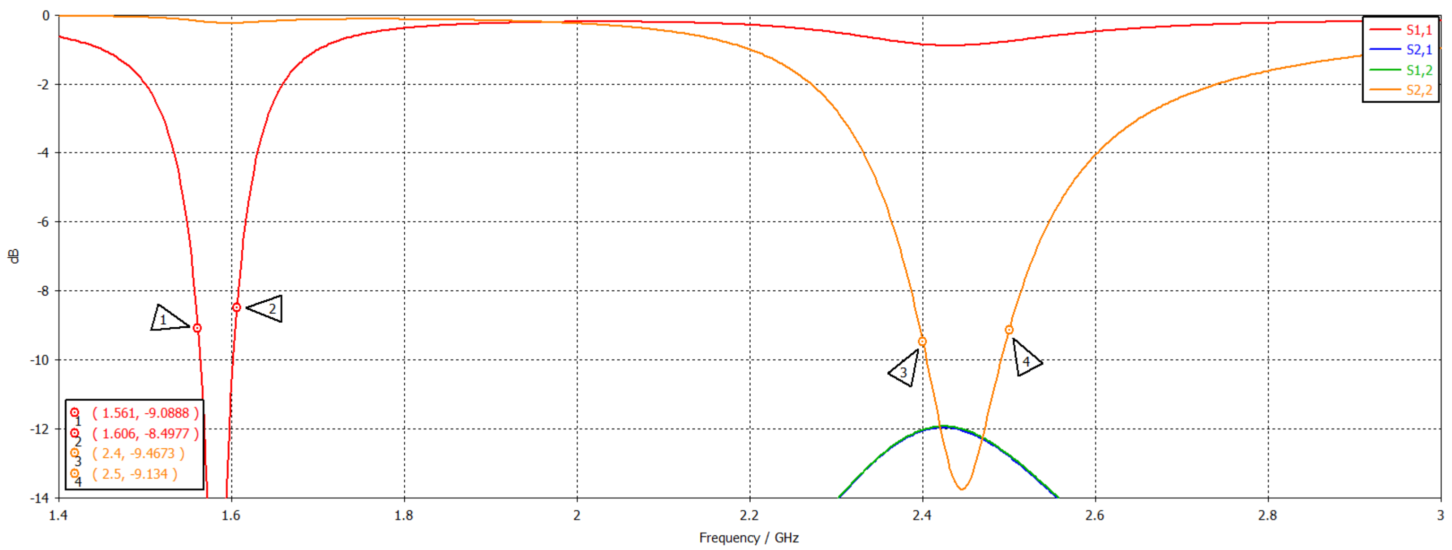


Figure 46: Full Layout Reflection Coefficient

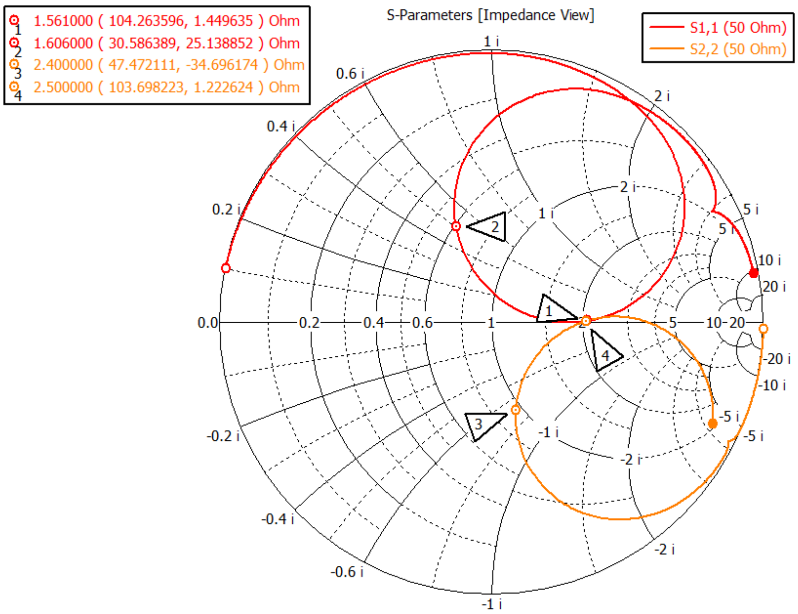


Figure 47: Smith chart full layout

ANTENNA EFFICIENCY (%)			
GNSS	1561MHz	1606MHz	Avg 1561-1606MHz
Efficiency	56.4	53.2	**59.5**
Bluetooth	2400MHz	2500MHz	Avg 2400-2500MHz
Efficiency	65.7	68.3	**70.5**

Table 20:Total Efficiencies Full Layout

After having passed the full layout design through a matching network optimization process, we can see that the total efficiencies for both GNSS and Bluetooth are in line with the expected values; the efficiency of Bluetooth is higher than that of GNSS as expected.

We also see in figure 46 how all the frequency ranges of the desired bands are below -8dB and the central frequencies below -12dB, results that reflect a proper adaptation, which we can corroborate with the smith chart (figure 47) where we see how the bands are adapted close to 1 (50Ω of characteristic impedance).

2) Full Layout 80mm x 40mm

In this section we will carry out the same steps as in section *1)* but using the PCB with the original measurements 80mm x 40mm. For this, we must readjust the adaptation of the matching network (MN) to the new measures and thus see that efficiency is obtained through the design.

MN for GNSS port	MN for Bluetooth port

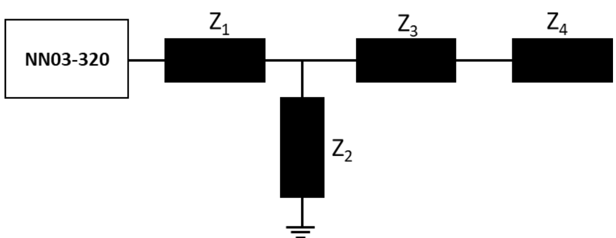


Figure 48: MN GNSS full layout

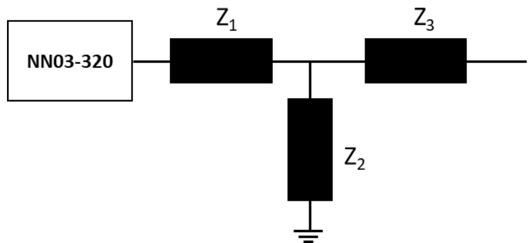


Figure 49: MN Bluetooth full layout

Components	
Z1	*13.0nH*
Z2	*2.5pF*
Z3	*4.1pF*
Z4	*0Ω*

Table 22: MN GNSS full layout values

Components	
Z1	*0.20pF*
Z2	*8.4nH*
Z3	*0.10pF*

Table 21: MN Bluetooth full layout values

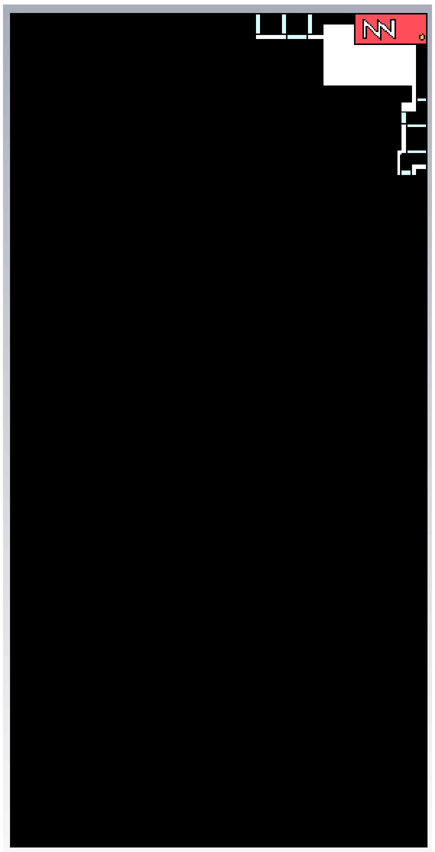


Figure 50: Full Layout design

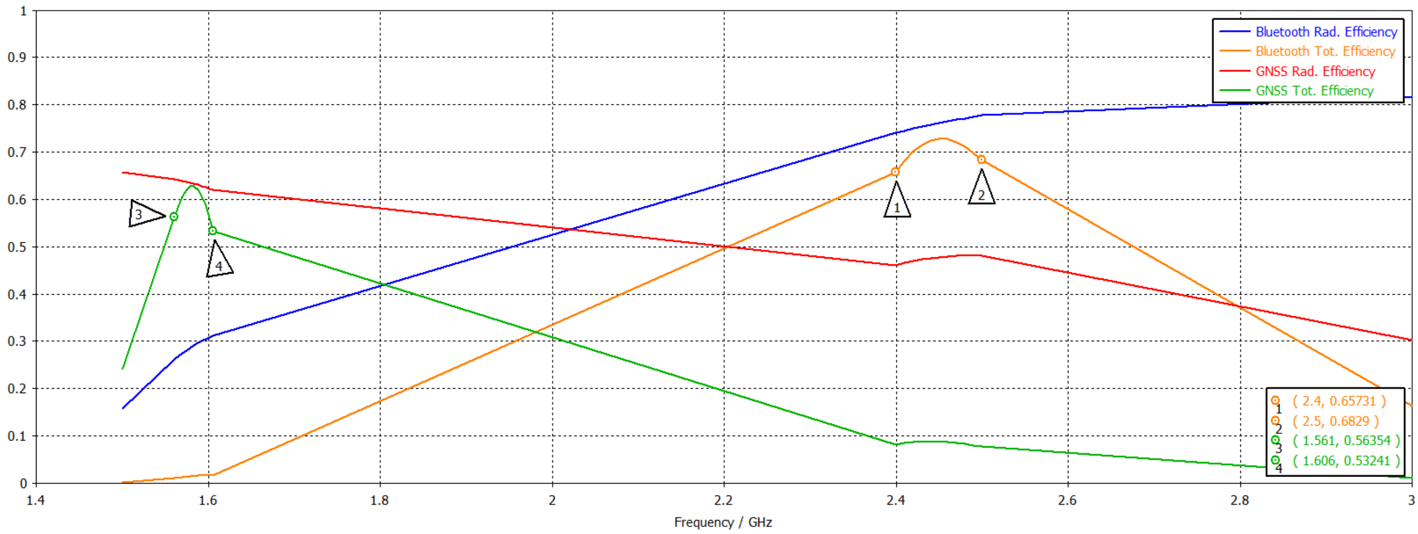


Figure 51: Full layout Efficiencies

ANTENNA EFFICIENCY (%)			
GNSS	1561MHz	1606MHz	Avg 1561-1606MHz
Efficiency	52.6	46.2	**52.6**
Bluetooth	2400MHz	2500MHz	Avg 2400-2500MHz
Efficiency	58.2	54.6	**62.6**

Table 23: Antenna total efficiencies Full Layout 90mm x 50mm

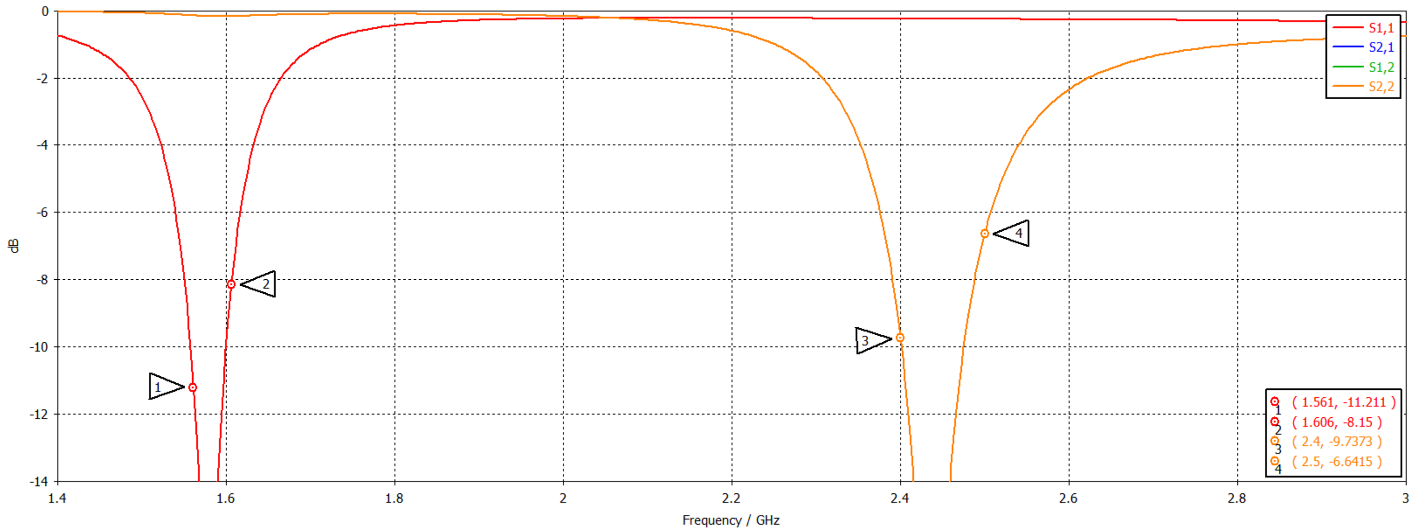


Figure 52: Full Layout Reflection coefficient

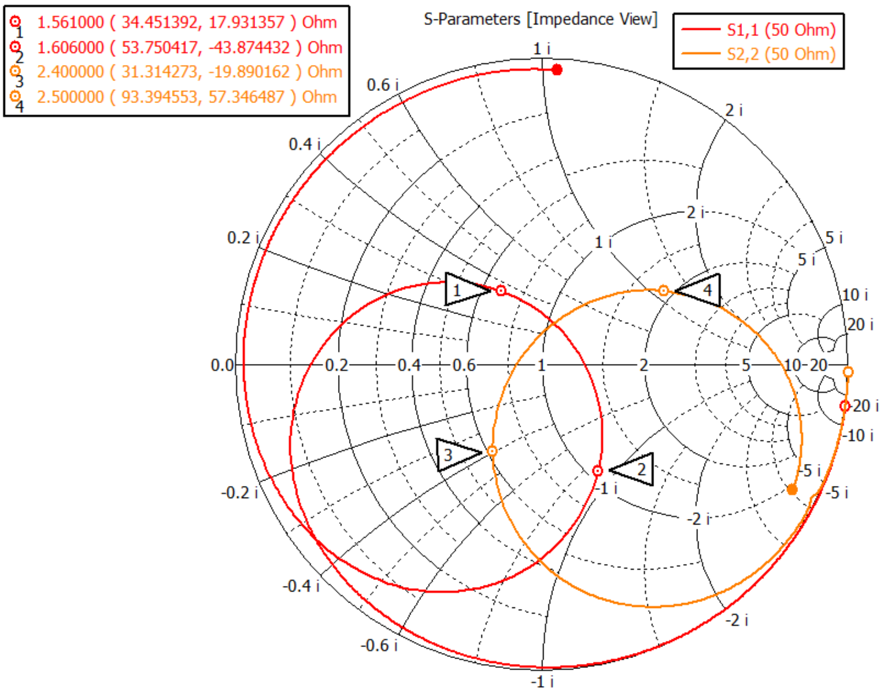


Figure 53: Full Layout Smith Chart

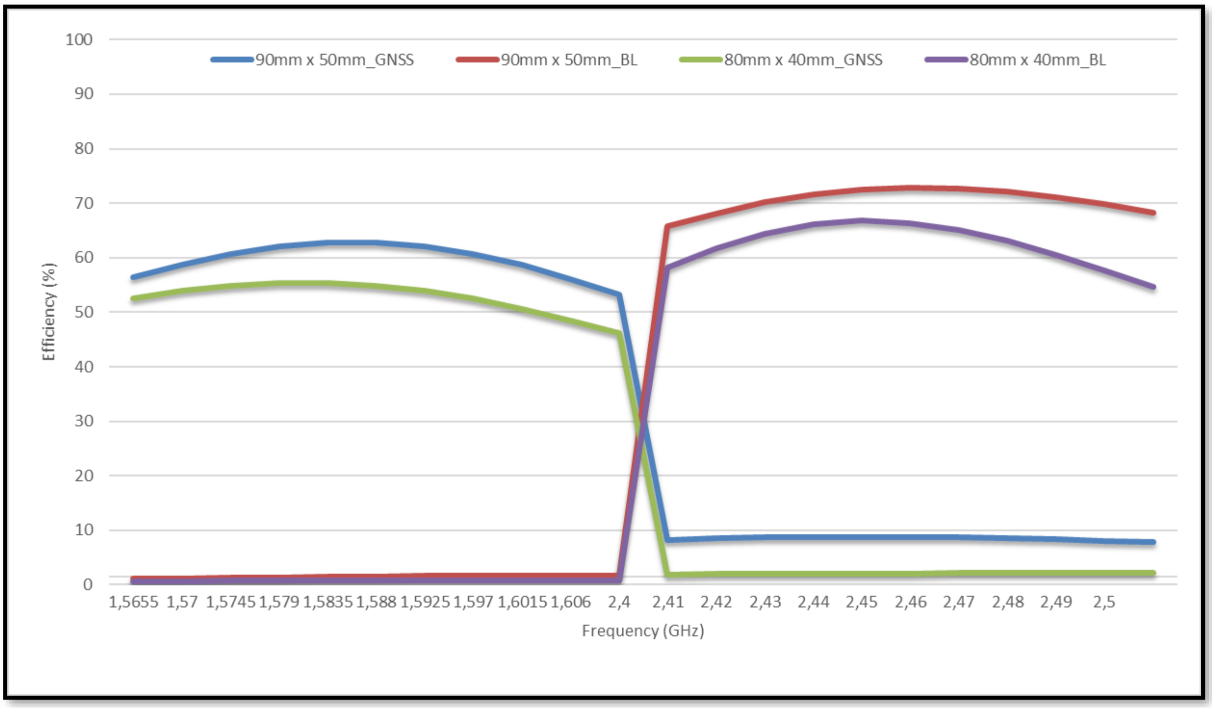


Figure 54: 90x50mm vs 80x40mm Full Layout total efficiencies antenna in the corner

As we can see in the figure 54 where the efficiencies for the two exposed models are reflected: *1) PCB 90mm x 50mm* and *2) 80mm x 40mm*. It can be affirmed that for the antenna in the corner we obtain a higher efficiency when the PCB has higher dimensions. This fact is contradicted when the antenna is used as a slot in the middle of the PCB, which is what we will see in the next section.

3) Slot antenna: 90mm x 50mm vs 80mm x 40mm

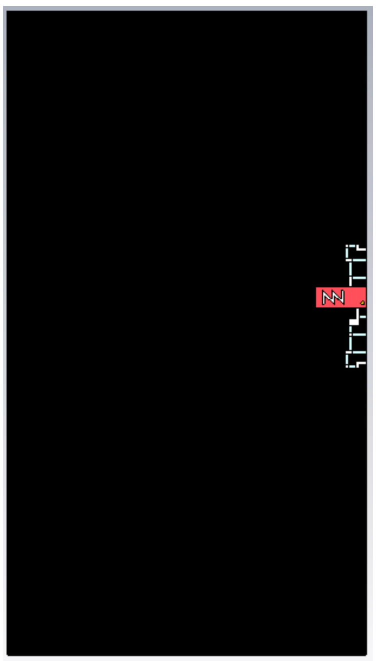


Figure 56: 90mm x 50mm

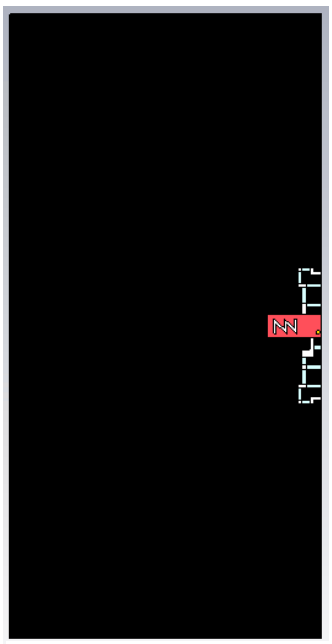


Figure 55: 80mm x 40mm

MN for GNSS port	MN for Bluetooth port

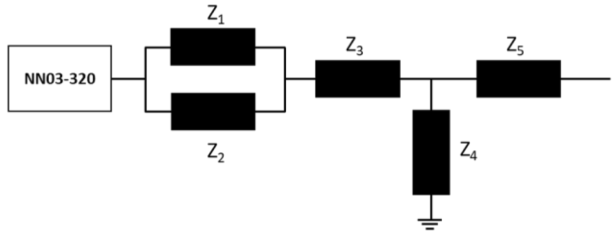


Figure 57: MN GNSS full layout

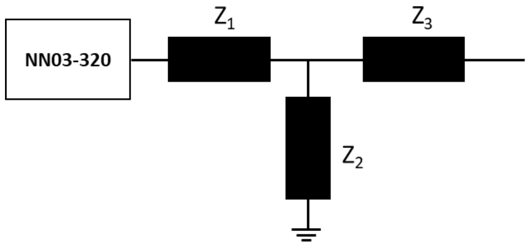


Figure 58: MN Bluetooth full layout

Table 24: MN for 90mm x 50mm antenna in the middle

Components	
Z1	*1.3nH*
Z2	*2.9pF*
Z3	*0.9pF*
Z4	*0.5pF*
Z5	*0Ω*

Table 26: MN component values 90mm x 50mm GNSS

Components	
Z1	*0Ω*
Z2	*4.5nH*
Z3	*6.5nH*

Table 25: MN component values 90mm x 50mm Bluetooth

MN for GNSS port	MN for Bluetooth port

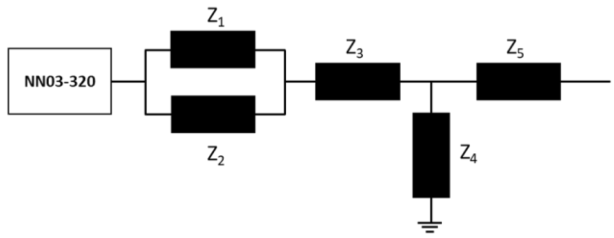


Figure 59: MN GNSS full layout

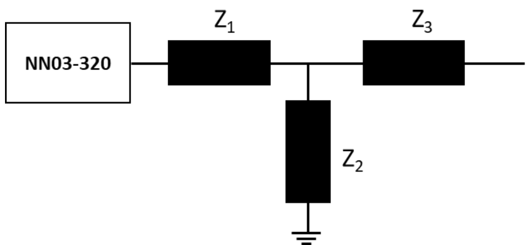


Figure 60: MN Bluetooth full layout

Table 27: MN for 80mm x 40mm antenna in the middle

Components	
Z1	*2.4nH*
Z2	*2.0pF*
Z3	*0.7pF*
Z4	*2.8pF*
Z5	*0Ω*

Table 29: MN component values 80mm x 40mm GNSS

Components	
Z1	*0Ω*
Z2	*4.7nH*
Z3	*4.7nH*

Table 28: MN component values 80mm x 40mm Bluetooth

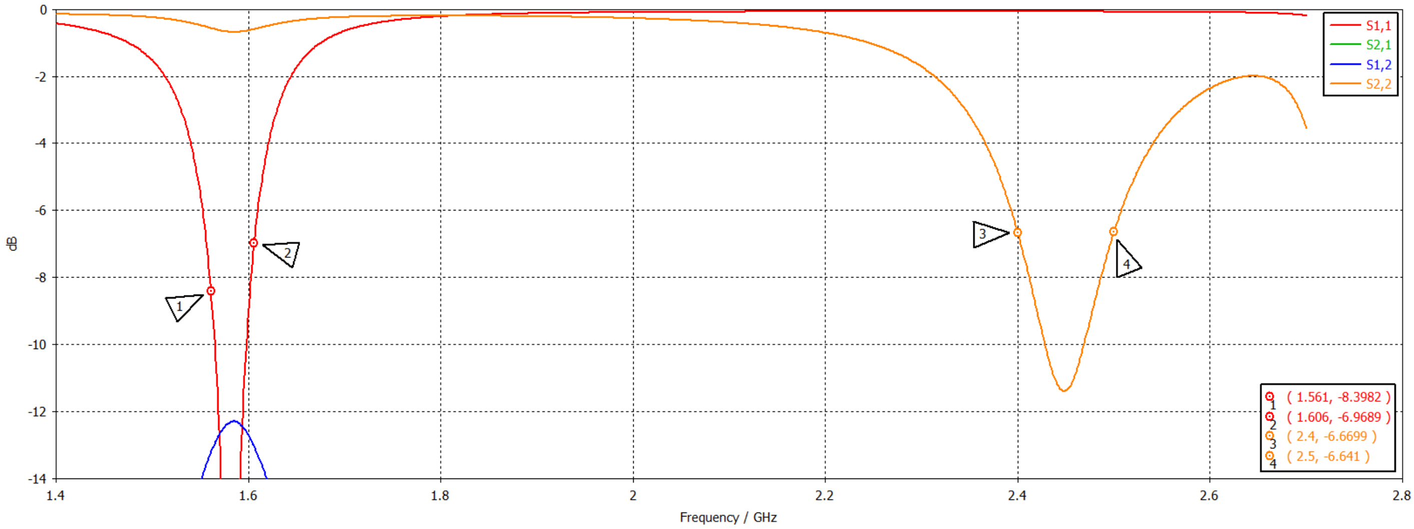


Figure 61: Reflection coefficient 90mm x 50mm

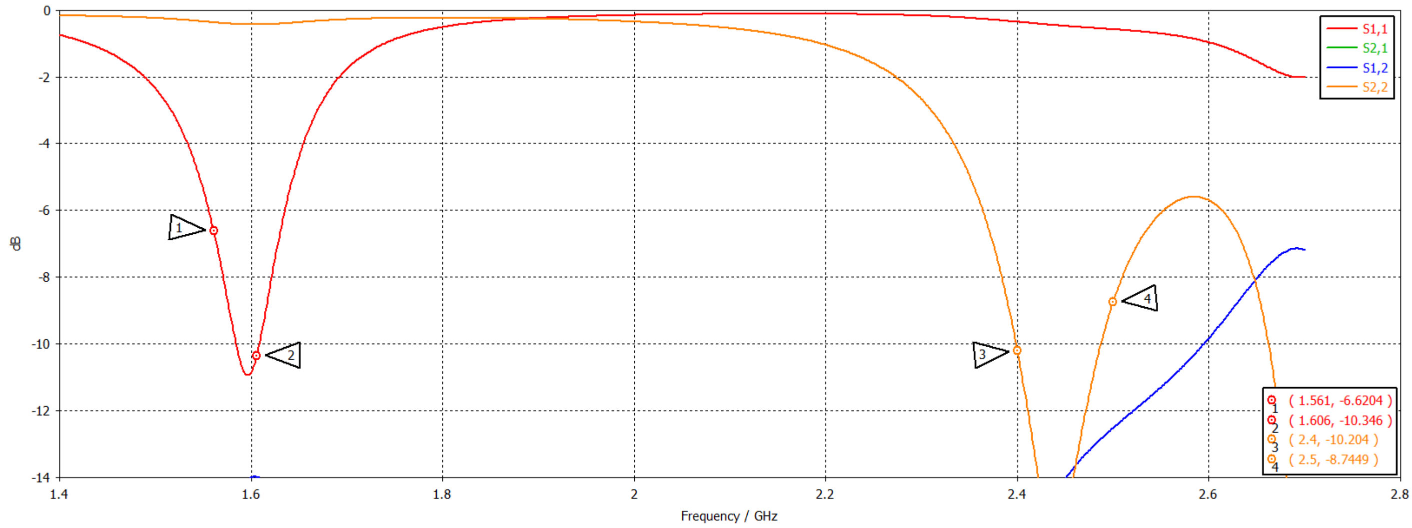


Figure 62: Reflection coefficient 80mm x 40mm

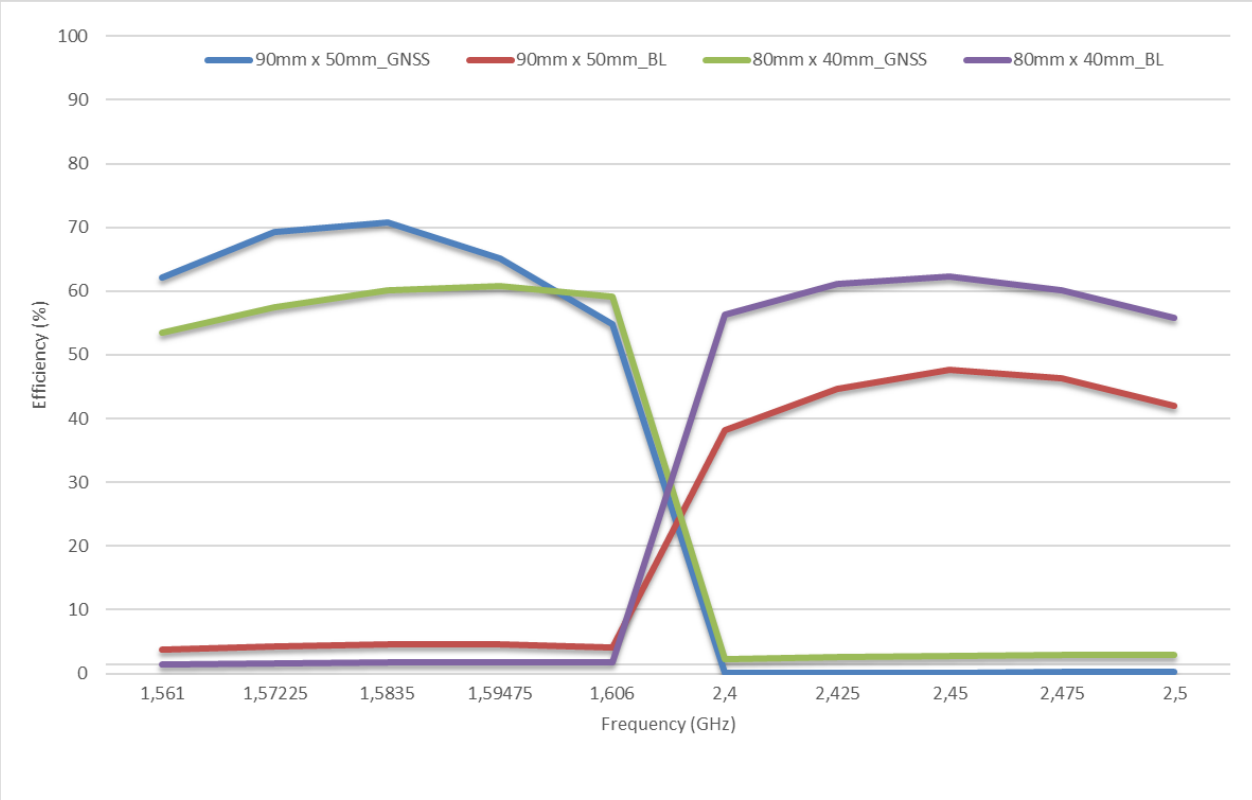


Figure 63: 90x50mm vs 80x40mm Full Layout efficiencies antenna in the middle

After the simulations made with the DUO mXTEND™ antenna we can see that in the case of the antenna as a slot and in the middle of the PCB, the behavior varies with respect to the antenna in the corner. When we integrate the antenna in the middle of the PCB, the fact that the board is more or less large does not influence as much as in the case of the antenna in the corner. We see that for the 90mm x 50mm dimensions the GNSS band is better than for the 80mm x 40mm PCB. On the other hand, for the Bluetooth band, the efficiency is higher for the board with smaller dimensions.
In general terms, when we use the antenna as a slot, we can affirm that the 80mm x 40mm PCB dimensions present better performance, balanced efficiency in both bands.

3.5. Conclusions

In this section we have been able to analyze the behavior of the antenna in different positions on the PCBs of two different sizes: 90mmx 50mm and 80mm x40mm. We have been able to analyze the best contexts to maximize antenna efficiency by optimizing the matching network. We can conclude that by using the antenna in the corner, the efficiency increases as the ground plane increases, especially when the length increases (having previously set the clearance, since it is a parameter that, as we have seen, also influences). On the other hand, when the antenna is integrated in the middle of the PCB, the dimensions of the ground plane are not directly proportional to the antenna efficiency.

4. Prototyping and measurements

4.1. Introduction

This chapter proposes to implement the design obtained by optimizing the simulated solutions at the physical level. In the previous chapter we discussed which were the most efficient designs to manufacture and see their functionality in a real context. Thus, we will explain all the procedures that must be followed in order to implement the chosen model and thus be able to make measurements in real environments.

As a first experiment, it will carry out the implementation of the DUO mXTEND™ antenna in the corner with a clearance area of length 10 and width 7, on a 90mm x 50mm PCB, as shown in figure 64.

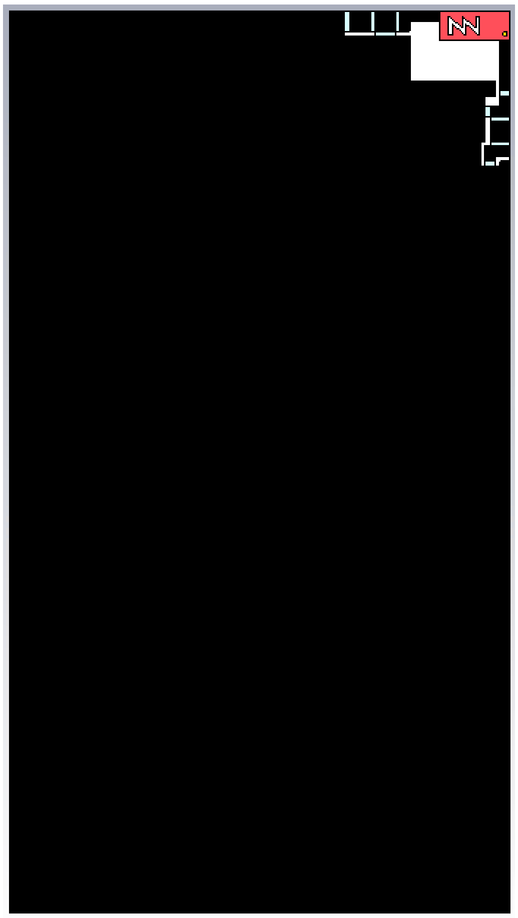


Figure 64: Full Layout 90mm x 50mm

4.2. Prototype implementation

A PCB in house is, as the name indicates, a PCB realized without any industrial manufacturing process. So, the PCB is made of a standard FR4 dielectric, the same used in the Electromagnetic Simulation and a copper top layer to make connectivity. The objective in the PCB in house realization is to remove some parts of the top copper layer, having the same antenna footprint as the simulated and the matching network footprint to put all the components in order to tune our antenna.

To achieve that purpose, it will be necessary to use an UV contact copier and mask to protect the copper that it must remain in the board. Then with a specific mix of acids, the non-desirable copper will be removed. So, see below the step by step guide followed for the PCB in house manufacturing:

1) Realization of the black mask with *AutoCAD*. It is important to note the black color printed it must be a pure black color. In a non-industrial printer, the quantity of ink used by the printer is not enough because in the UV contact copier process, the mask will not protect the desired copper zones

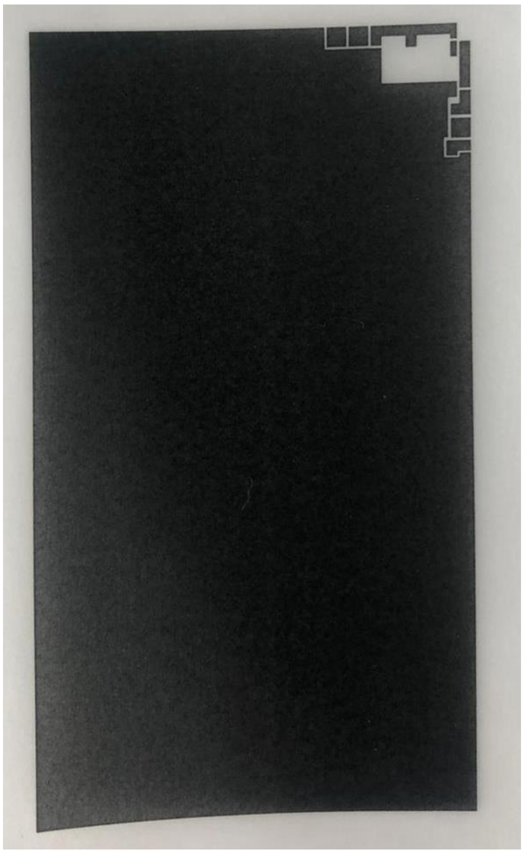


Figure 65: Mask used for the experiment of the DUO mXTENDTM in the corner in a 90mm x 50mm PCB

2) At the chemical lab must be the yellow light on. It is important to note the natural light accelerates the revelation process, so the yellow light helps to slow down the revealation.
3) Cut off a piece of substrate bigger than the mask we have printed. The substrate used for the experiment is the same as the supposed in Chapter 3: Electromagnetic Analysis, a 1.6mm width FR4 with a Loss tangent of 0.013 and a Permittivity of 4.15.
4) Put off the fiber protection showing the top layer copper.

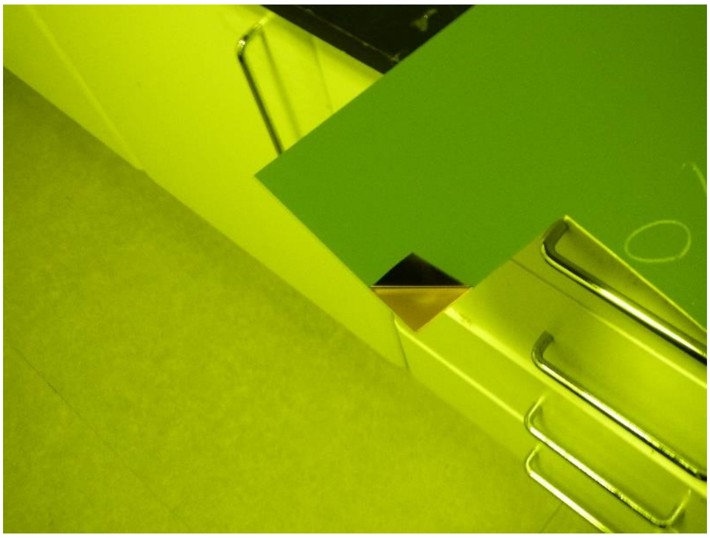


Figure 66: Piece of FR4 substrate used for the prototyping making off, without a piece of protective fiber, which shows the top layer copper.

5) Put the board on the UV contact printer with the footprint mask done right above the board. It is important to note the darker face of the mask must to be in contact with the copper layer of the board, so the footprint mask drawing must be the mirror of the footprint PCB wanted.

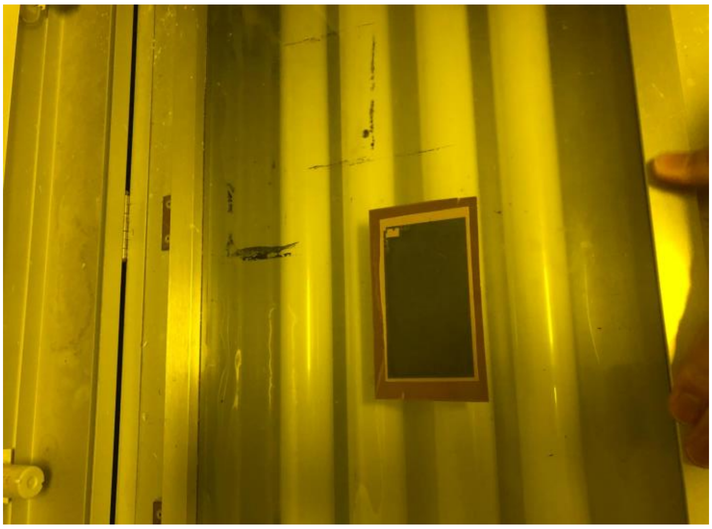


Figure 67: The UV contact printer with the footprint mask done right above the board

6) Making it empty with the board and the mask above. Therefore, push down the lid and apply the UV light the PCB during 3 minutes.
7) Once the time is over, take the PCB and apply the positive revelator to the board no more than 5-10 seconds, until the shadow of the footprint appears. The positive revelator has been done using caustic soda and water.

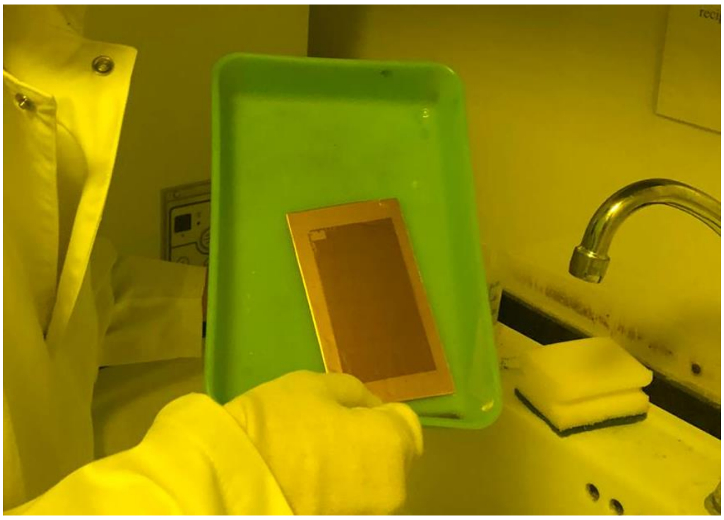


Figure 69: Positive revelator in action

Figure 68: Making positive revelator

8) Wash with water the board and then make the acid mix needed the remove the copper. That acid is compound by (in a total of 100ml):
    - 25% of Hydrochloric acid.
    - 25% of Hydrogen peroxide.
    - 50% water.
9) Tip out the created acid until the copper is totally removed from the board. Then it can be cleaned with Acetone.

Figure 70: From left to right, the components used to create the PCB in the chemical lab: Hydrochloric acid, Hydrogen peroxide, Acetone.

10) Cut off the substrate not necessary of the PCB. This last point is not mandatory due to the most important is the surface covered by copper, the substrate without copper have not any impact on the antenna performance.

Figure 71: Cuting off the remained substrate

So, once all the points have been followed step by step the result it will be the PCB desired, like the seen in the figure 72.

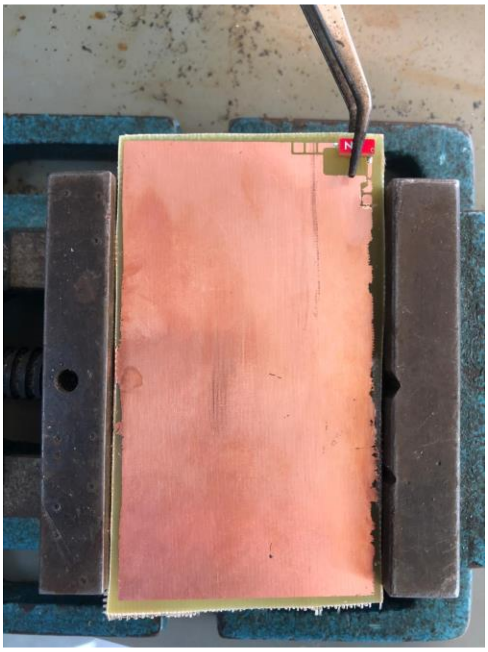


Figure 72: PCB board created with a 1.6mm width and 90mm x 50mm FR4 PCB

4.3. Electromagnetic analysis

After having manufactured the board, you have to solder the corresponding adaptation networks in the corresponding ports as is shown in figure 74. After that we proceed to solder the coaxial cable to be able to carry out the measurements (figure 73 and 74).

4.3.1. Set Up 1: *DUO mXTEND™ in the corner in a 90mm x 50mm PCB*

Figure 74: PCB with both matching network soldered

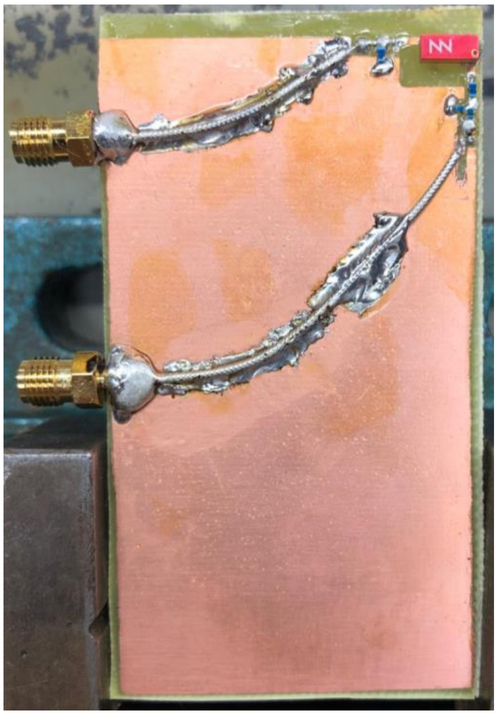


Figure 73: PCB with both matching network and coaxial connectors soldered

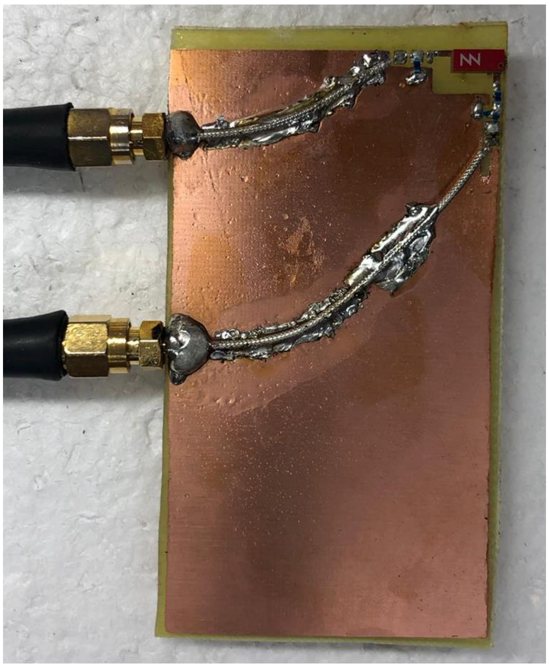


Figure 75: PCB connected to the VNA

MN for GNSS port		*Part number*
Z1	*9.1nH*	*LQW18AN9N1G80*
Z2	*2.7nH*	*LQW15AN2N7G80*
Z3	*2.2nH*	*LQW15AN2N2G80*
Z4	*0Ω*	*resistor*
MN for Bluetooth port		***Part number***
Z1	*0.20pF*	*GJM1555C1HR20WB01*
Z2	*8.7nH*	*LQW18AN8N7G80*
Z3	*0.10pF*	*GJM1555C1HR10WB01*

Table 30: Matching network components

1) VNA measurements

At this point, what we will do is measure the reflection coefficient and the coupling of both ports, GNSS and Bluetooth, using the VNA. In this way we can see through the Smith Chart how the matching networks are adapted.

Figure 76: Smith chart of GNSS and bluetooth ports

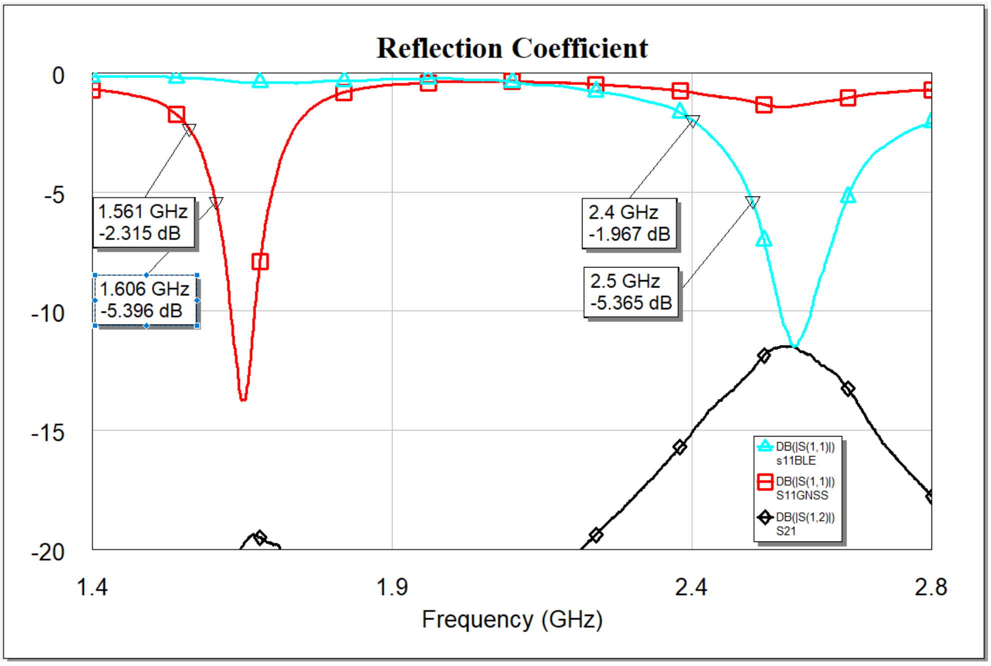


Figure 77: Reflection coefficient after matching network readjustment

We can see in figure 76 and 77 that the peak of S_{11} and S_{22} have been shifted to higher frequencies, so a readjustment of the matching networks will be necessary. The yellow trace of the graph in figure 76 with markers 1 and 2 correspond to the response from the GNSS port, and the blue trace, markers 3 and 4 correspond to the Bluetooth port.

2) Anechoic chamber measurements - SATIMO

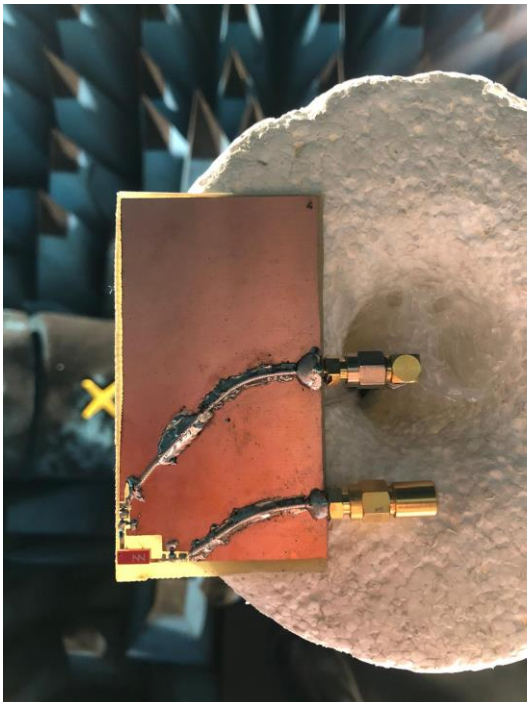


Figure 78: PCB connected to the anechoic chamber

In order to measure the total efficiencies in the anechoic chamber we must measure each port separately. For this, what we will do is connect a 50Ω load to the port that is not being measured. As we have seen in the reflection coefficient graph, the peak has shifted, so as the peak of efficiency, and that is what we expext from the efficiency measurement (figure 79).

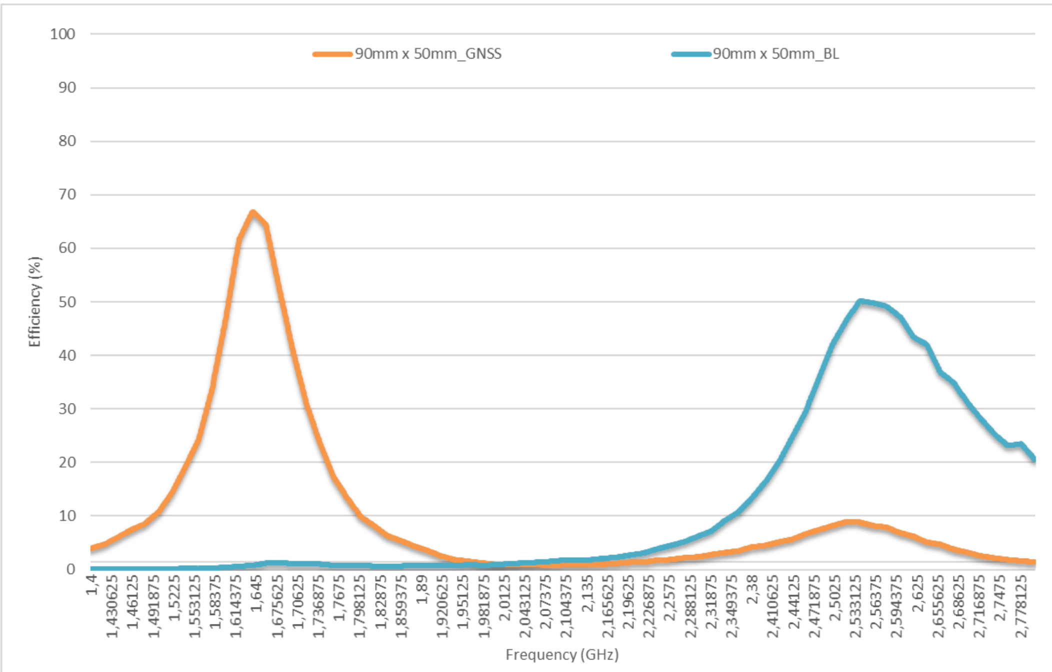
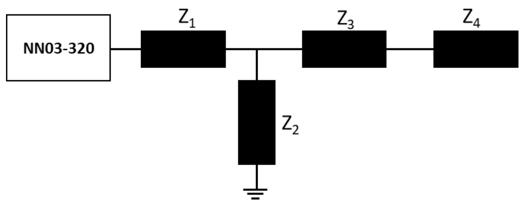
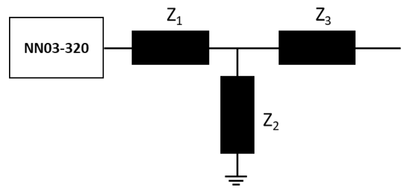


Figure 79: Measured efficiency before matching network readjustment

4.3.2. **Set Up 2:** *DUO mXTEND™ in the corner in a 90mm x 50mm PCB with matching network readjustment*

As mentioned in the previous section, in order to center the efficiency peak we must adjust the adaptation of the matching network. To do this, through the movements of the Smith Chart, to center the frequency ranges that we want to adapt, taking into account the influence of the coupling.

MN for GNSS port	MN for Bluetooth port
 *Figure 80: MN GNSS full layout*	 *Figure 81: MN Bluetooth full layout*

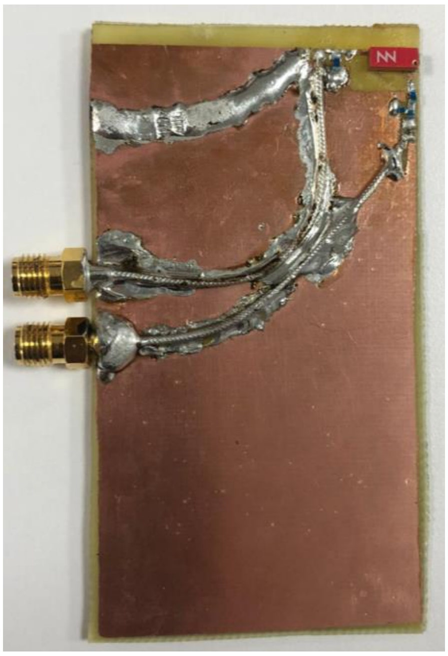


Figure 82: PCB with the matching network readjusted

MN for GNSS port		*Part number*
Z1	*9.9nH*	*LQW18AN9N9G80*
Z2	*2.7nH*	*LQW15AN2N7G80*
Z3	*2.2nH*	*LQW15AN2N2G80*
Z4	*0Ω*	
MN for Bluetooth port		
Z1	*0.20pF*	*GJM1555C1HR20WB01*
Z2	*8.2nH*	*LQW18AN8N2G80*
Z3	*0.20pF*	*GJM1555C1HR20WB01*

Table 31: MN readjusted values

1) *VNA measurements*

Starting from the base of set up 1, we see that for the GNSS curve we must increase the first serial inductor so that the frequencies get shifted to the left and thus center. On the other hand, for bluetooth, we must decrease the parallel inductor to raise the frequencies (see figure 76 for the starting point). After all the changes made, we obtain the results that can be seen reflected in the reflection coefficient graph of (figure 83).

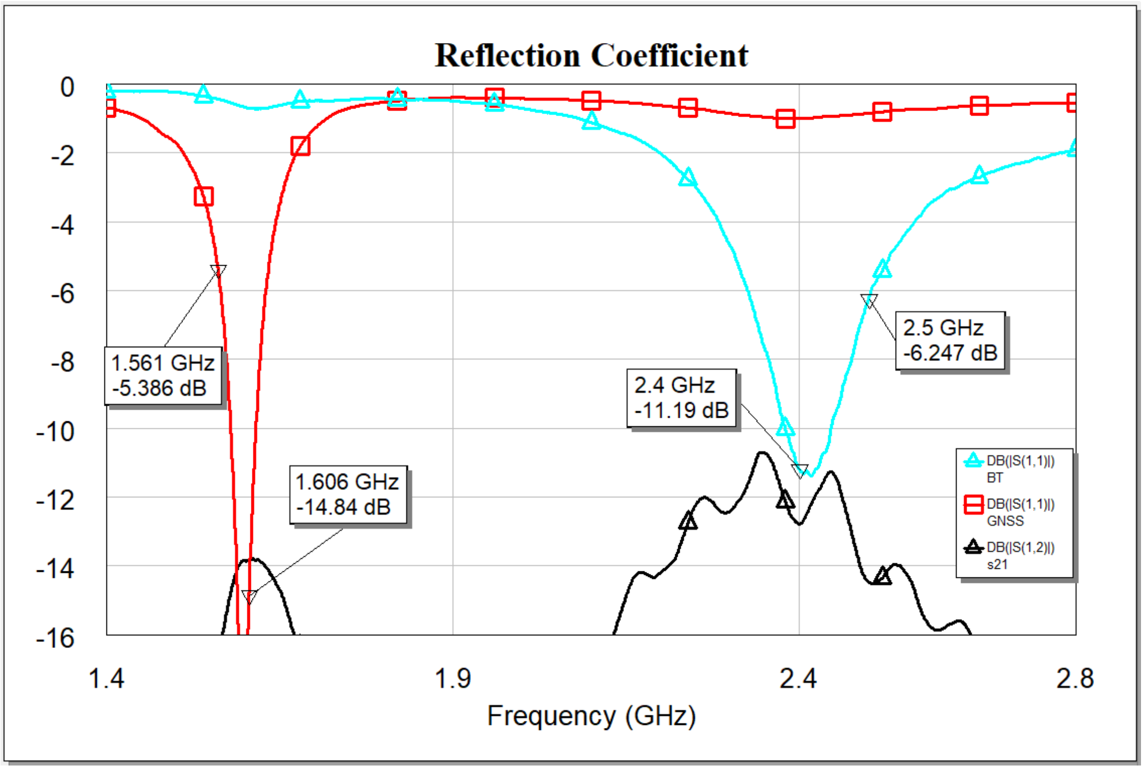


Figure 83: Measured efficiencies after matching network readjustment

In the figure 83, the changes made in the adaptation network are reflected, since the peaks are centered in the desired frequency range. On the other hand, we see that the coupling (S_{21}) is affecting the GNSS band, an effect due to the changes in the matching network, exactly in the capacitors of the BLE network, since in set up 1 we had in Bluetooth Z3 = 0.1pF, and in set up 2 , we have increased it to 0.2pF. Thus, the filter effect in somehow has decreased, but the S_{21} is also low.

1) *Anechoic chamber measurements*

When we extrapolate an experiment to a real environment, non-idealities arise that become direct effects on antenna efficiency. In this case we should take into account that all non-idealities in terms of losses are concerned. The use of components with a low Q factor, the home made PCB, the hand-soldered coaxial cables, may be reasons for us to see that variation between simulated and measured efficiency (figure 84).

Frequency Band	Efficiency Average (%)
GNSS (1561-1606MHz)	43.8
Bluetooth (2400-2500MHz)	50.1

Table 32: Measured Total Efficiency Average for Set Up 2

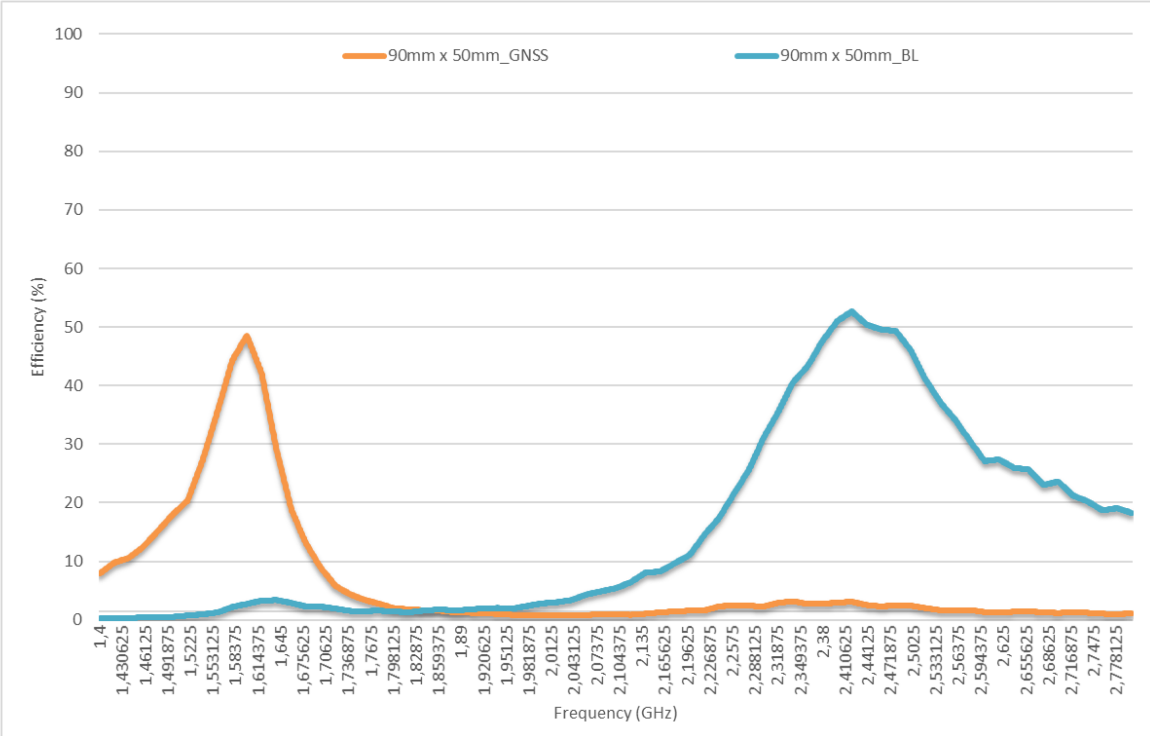


Figure 84: Measured total efficiency after matching network readjustment

4.4. Conclusions

Throughout chapter 4, we have been able to follow the steps and necessary processes to implement in the laboratory an experiment emerged from a simulation-level analysis. As a result to be highlighted, the comparison between the results obtained in set up 1 and 2, which shows us the nuance between the implementation of a design with the values obtained directly from a software and how said design should be modified in the real environment to be able to obtain useful results.

We have also been able to corroborate the effects that the non-idealities of the set up introduces in terms of losses in antenna efficiency of the device. These differences in efficiency values can be seen in the following table 34.

Set Up	Frequency Band	Efficiency Average (%)
1	GNSS (1561-1606MHz)	36.9
	Bluetooth (2400-2500MHz)	27.8
2	GNSS (1561-1606MHz)	43.9
	Bluetooth (2400-2500MHz)	50.1

Table 33: Total Efficiency Averages

5. Conclusion

The main goal of this project was to analize a small dual-band antenna booster for tracking purposes. The project has two main parts: the analytics at the software/theoretical level and the practice in the laboratory. In the first part (chapter 3) we have seen how to optimize a dual port antenna in the corner by varying the clearance area and the port connections. Through the simulations that have been carried out, we found out which clearance area dimensions maximize the efficiency of the GNSS and bluetooth antenna, in the corner of the 90mm x 50mm PCB. Thus, we arrived at that the proper measurements to adapt the DUO mXTEND™ was a clearance area of length 10mm and width 7mm.

Once the clearance area measurements were obtained, we had to deal with the adaptation of the matching network, which led us to more complex challenges such as the coupling effect and notch design to filter undesired signals. When all the parameters were controlled, they had to be configured in order to achieve that all together they could optimize the antenna efficiency.

The second part consisted of creating in the laboratory the final design obtained in the first part. This process has been challenging as many critical variants depended on a proper laboratory work. The creation of the PCB, the adaptation of the matching network adaptation, the coaxial connection and its placement, the physical characteristics of the PCB, the measurements in the anechoic chamber, among other processes, have been necessary to obtain a final prototype. The results of which are collected in Table 35. The measured results are not far from those obtained as shown in table 35, there is a discrepancy but it was already taken into account since we have made the measurements with environments that are not 100% ideal. The size of the pads where the components of the matching network are soldered are ideally 2mm x 2mm with a 0.5mm spacing between each one (GAP), this has not been possible since the UV contact printer used does not work with such accuracy, so we had to increase the spacing from 0.5mm between pads to 0.8mm. We still need to check if the thickness of the PCB has influenced the measured results, since a 1.6mm thick PCB has been used while in the simulations the PCB was 1mm.

To be able to compare properly the results obtained through measurements and simulations, we must redo the simulations in chapter 3*, 1)Full Layout 90mm x 50mm*, to modify the thickness of the substrate from 1mm to 1.6mm, since the measured PCB is of that thickness. As we see in figure 85, varying the PCB thickness is hardly reflected in overall efficiency. So we conclude that the thickness has not affected the measurements made with the 1.6mm PCB.

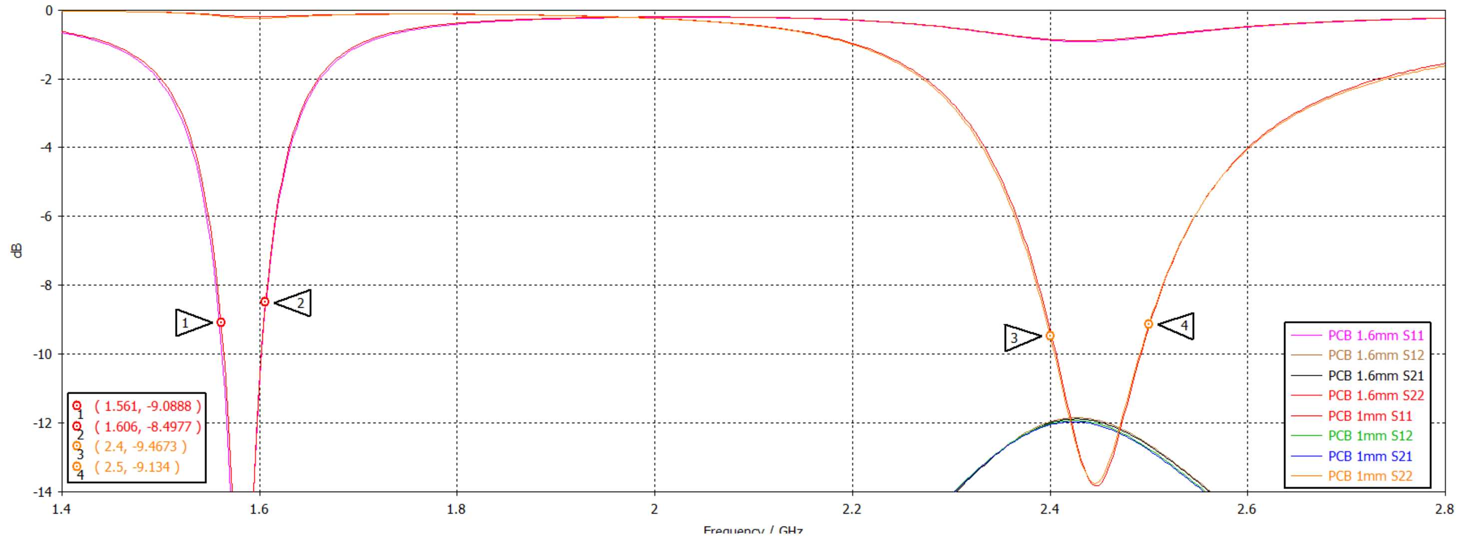


Figure 86: Reflection coefficient PCB 1mm thickness vs 1.6mm

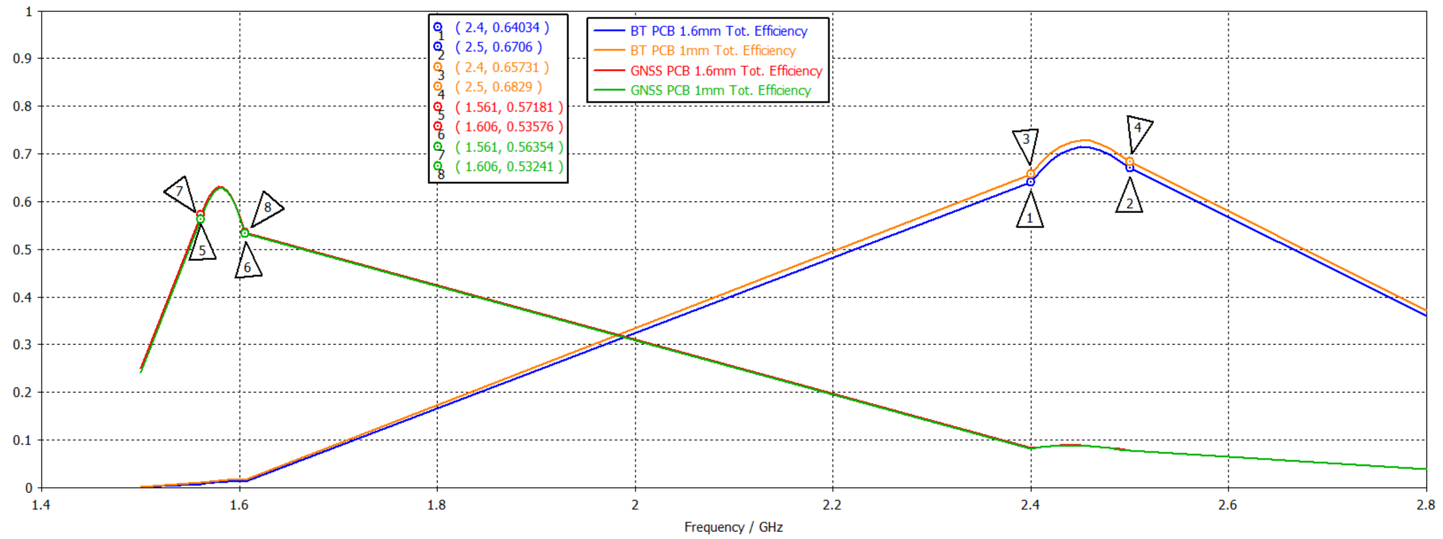


Figure 85: Total efficiency PCB 1mm thickness vs 1.6mm

	SIMULATIONS	MEASUREMENTS
GNSS	**Avg 1561-1606MHz**	
Efficiency (%)	**59.8**	**43.8**
Bluetooth	**Avg 2400-2500MHz**	
Efficiency(%)	**69.0**	**50.1**

Table 34: Simulated total efficiency vs Measured efficiency (PCB 1.6mm thikness, 90mm x 50mm PCB dimensions and 10mm x 7mm clearance area using the DUO mXTEND™)

On a personal level, this project has trained me in many fields of which I was not aware of how it works. Thanks to the analysis of simulations I have developed skills with programs like CST studio, Optenni Lab, Microwave Office and autoCAD which I had never used.
I have also put into practice theoretical knowledge studied at the university such as the use of the Smith Chart for matching network adaptation.

In the practical part, I have had to learn all the processes involved in creating a physical prototype from 0:

- Chemical processes to print a mask created with autoCAD on a copper surface.
- Solder 1mm components on 2mm x 2mm PADS without shorting the any part of the circuit.
- Connect the coaxial cable with the SMA and solder it on the board to analyze each port separately, and the use of 50Ω loads.
- Calculations in Satimo (anechoic chamber) and its post-processing in matlab to obtain antenna efficiencies.

The exposed points have been a few of many processes needed to move along the project, which in many cases have been tedious to be able to manipulate them but, very didactic, since, at the same time that I had to learn to carry out all the processes that entail the creation of a new prototype, I have also been able to enjoy the whole process of bringing a creation started in a program to a real prototype, "called magic".

5.1. Future Work

As further work that could be done in the future, it would be interesting to implement the obtained results in a professional PCB to see how the efficiency improves, and so it could be interesting to develop a solution to a 80mm x 40mm PCB instead of 90mm x 50mm. Also, implement a solution of the DUO mXTEND™ in the middle for a 90mm x 80mm.

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