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On the Isolation of Ground Plane Booster Antenna Technology in Wireless MIMO Devices

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ACTA DE L'EXAMEN

DEL TREBALL FI DE CARRERA

Reunit el Tribunal qualificador en el dia de la data, l'alumne

D. LUIS GRAU GRANADA

Va exposar el seu Treball de Fi de Carrera, el qual va tractar sobre el tema següent: "On the isolation of Small Antennas in Wireless MIMO Devices"

Acabada l'exposició i contestades per part de l'alumne les objeccions formulades pels Srs. membres del tribunal, aquest valorà l'esmentat Treball amb la qualificació de

Barcelona,

VOCAL DEL TRIBUNAL

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ABSTRACT

The research conducted during this project has been supervised by PhD. Jaume Anguera and PhD. Aurora Andújar.

This project is based on the challenge to develop antennas capable of providing several operating bands within physical limitations and consists in a radiating system using Ground Plane Boosters as compact antenna technology.

The goal of the project is to mitigate the isolation between small antennas on wireless devices through the modification of the ground plane and the design of a suitable matching network in MIMO systems.

Several prototypes are built in order to demonstrate the hypothesis proposed and its correlation and multiplexed efficiency are measured.

RESUMEN

La investigación llevada a cabo durante este proyecto ha sido supervisada por el Dr. Jaume Anguera y la Dra. Aurora Andújar.

Este proyecto se basa en el reto de desarrollar antenas capaces de conseguir abarcar diferentes bandas dentro de una serie de limitaciones y consiste de un sistema radiante usando Ground Plane Boosters como tecnología de antena compacta.

El objetivo del proyecto es mitigar el aislamiento entre antenas pequeñas en dispositivos wireless mediante la modificación del plano de masa y el diseño de una red de adaptación en sistemas MIMO.

Se han implementado diferentes prototipos para demostrar la hipótesis y se ha medido su correlación y la eficiencia multiplexada.

RESUM

La investigació duta a terme durant aquest projecte ha estat supervisada pel Dr. Jaume Anguera i la Dra. Aurora Andújar.

Aquest projecte es basa en el repte de desenvolupar antenes capaces d'aconseguir abastar diferents bandes dins d'una sèrie de limitacions i consisteix d'un sistema radiant utilitzant Ground Plane Boosters com a tecnologia d'antena compacta.

L'objectiu del projecte és mitigar l'aïllament entre antenes petites en dispositius mòbils mitjançant la modificació del pla de massa i el disseny d'una xarxa d'adaptació a sistemes MIMO.

S'han implementat diferents prototips per demostrar la hipòtesi i s'ha mesurat la seva correlació i l'eficiència multiplexada.

KEYWORDS

ENGLISH

Antennas, MIMO, Ground Plane Booster, LTE, Bandwidth, Isolation, Multiplexed efficiency, Impedance, Correlation, matching network, Printed Circuit Board, stub.

SPANISH

Antenas, MIMO, Ground Plane Booster, LTE, Ancho de banda, Aislamiento, Eficiencia multiplexada, Impedancia, Correlación, Red de adaptación, Circuito impreso, Stub.

CATALAN

Antenes, MIMO, Ground Plane Booster, LTE, Ample de banda, Aïllament, Eficiència multiplexada, Impedància, Correlació, Xarxa d'adaptació, Circuit imprès, Stub.

ACKNOWLEDGEMENT

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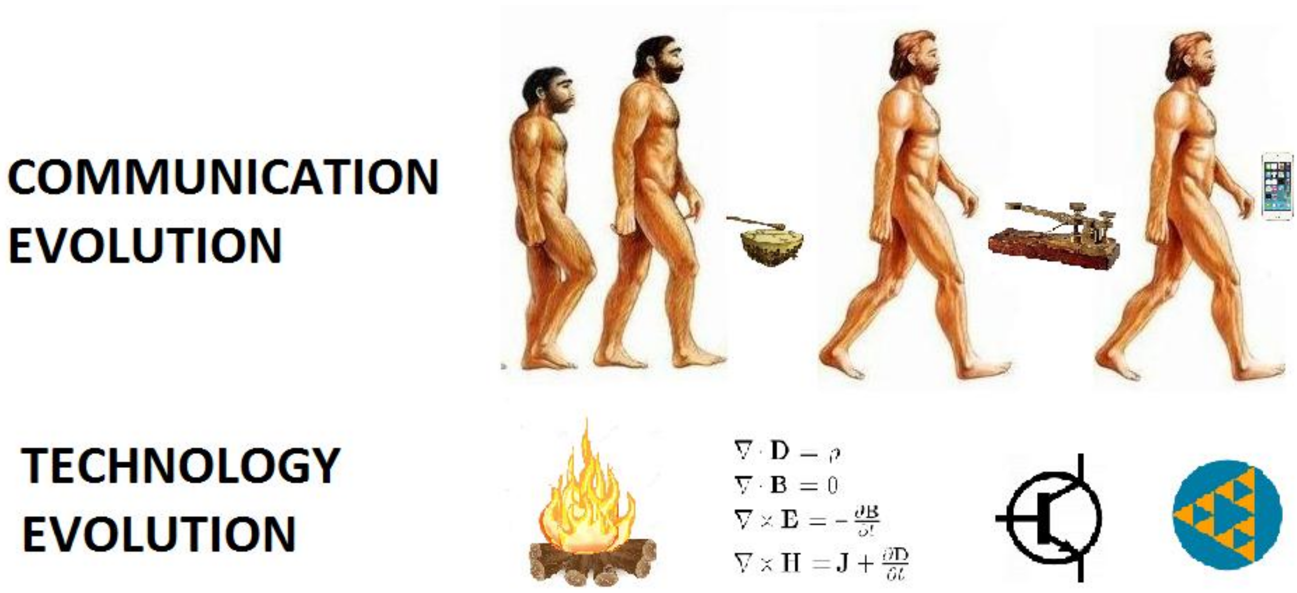
1. INTRODUCTION



1.1. A CONNECTED SOCIETY'S IDIOSYNCRASY

In order to understand how we as a society got to the point where needing not only to develop devices with elements such as antennas but also to optimize them, the evolution and working structure of it must be minimally explained.

1.1.1. THE ORIGIN

Telecommunication birth can be considered to have been taking place back in Africa, America and some Asia parts with the smoke signals and drums use as a way of warning for a hypothetical danger or to inform how many animals were out there to be hunted [1]. The fact of getting together as a society in order to survive in a more comfortable and safe way leads to a warning need to ensure those individuals safety from any possible danger and then the (maybe) most important need: the need to establish a common link between those individuals as to get differentiated from another group or society (that fact would later during the arise of the German romanticism become Nationalism) and in order to cohere the group so that it could perform better as a whole. The need of establishing a common link between us lead us to communicate with each other [1], to share experiences that would, in fact, become culture and to establish connections between us in order to ensure our survival over the rest of societies or social groups.

It is because of that need (communication), among others, that telecom was born. After thousands of years of evolution, the human being has deployed a great network that allow us to communicate in less than a second with each other between great distances regardless whether there are deep oceans or high mountains.

1.1.2. THE INFORMATION SOCIETY

The information society's engine is telecom, the information society exists since global-wide communication networks and powerful systems ready to process information are available [3]. While we know that those telecom networks world widely connected exist long ago. It has not been until the possibility of transmitting complex information in real time thank to a sufficient network bandwidth that the information society hasn't developed itself to the point we all know now.

1.1.3. TECHNOLOGY IN INFORMATION SOCIETY

The base from where all has been built is the transistor invention. Even for small antennas; the fact that technology has been able to evolve from valves to transistors, the possibility of making complex and integrated circuits has expanded the market and all the immediate applications. That invention has lead the technology evolution and information society evolution to the point where, as happens nowadays, a message can be sent worldwide in terms of milliseconds. As for antennas, the possibility of having a component such as the transistor who gave low consumption and small dimensions, the industry has been led into a revolution and made possible all of the technology that is now surrounding us.

Given the transistor invention in the Bell laboratories back in 1947, then a race for getting the smallest and most compact devices launched. The fact of creating several elements in the same piece of material took place to chips or integrated circuits. Complexity added to those circuits gave birth to the microprocessor. Thanks to its tiny volume and low price, those elements that are in fact, computers itself, have been place in all kinds of devices, such as handset devices.

Telecom is considered to be the sector where the advances in electronics and informatics have been best used to evolve.

Thanks to the microprocessor invention back in 1968, a series of elements were then given such as multiplexors, controlling elements, and those that took place to the actual networking system.

If we try to analyze internet and its nature that will give us a glimpse of our actual situation: a series of supported services over several networks with the aim of integration between them, increasing their capacity every day in order to get better performance. That is, trying to look for convergence: a vital concept in today's information society.

It is then assumable that future will, indeed, keep finding the way to synthesize technology as history demonstrates information society has done so far.

1.1.4. GLOBALIZATION

Maybe one of the most important agents taking part in telecommunications is globalization. Society's evolution as we know it, has taken us to live in a globalized world.

Globalization can be defined and understood depending on the view taken. xxx highlights three different definitions on globalization[4]. He noted that "at some level (globalization) consists on the process that leads to a global independence and to a fast growth on sharing through great distances". He also noted three different differentiations:

a) From the information point of view, globalization is based in "forces that are changing the way of exchanging of information around the world and the creation of the bases of what we know now as the information highway".
b) From the economic point of view, globalization is the transformation of the "global market, creating new economic independences through great distances".
c) And finally, he stated that "all forces changing and transforming the world into a global city, the distance compression, homogenizing cultures and accelerating mobility through the reduction of politics leader's power".

All the above agents have converged into a global wireless device network using small antennas so that they can get and exchange information. The constant fight and effort towards getting better performance, efficiency and getting that into handset devices that are everyday thinner and smaller, gets us a deep focus of what we will try to study during this pages: state of art and try to understand the great role that small antennas play in the global network and globalization.

1.2. SCOPE

The market demands in terms of design and performance in the new Smartphone generation require a deep research in terms of technology and the integration of that technology in a market demanded design. It is now assumed that a common device will have at least ten hours of usage per day and that the usage means feeding a large and high resolution screen and very powerful processors connected to sensors and peripheral devices which means having a large battery that also needs to fit in the device structure.

Thus the need of optimizing the dimensions of all the parts that form the device is a priority. This leads to the need of using such antenna technologies that can be implemented in a small volume and the need to optimize the power that require in order to radiate. The fact of having to find small antennas is the reason for using the Ground Plane Booster Antenna Technology [27] - [53]. This technology not only has small dimensions but, as we will later on see, can be tuned in order to work in several bands. More precisely, for this project, two Ground Plane Boosters have been taken in order to analyze its behavior and see if the fact of using simple techniques can be considered in order to improve their isolation.

Improving the isolation between adjacent MIMO antennas is a challenging task especially for technologies that operate at low frequency bands (< 1 GHz). Since the internal handset antennas are allowed to occupy a very limited volume, the compactness of diversity antenna is critical design requirement while the conditions of a low signal correlation and minimized mutual coupling between closely spaced antenna elements must be also satisfied.

1.3. OBJECTIVES

The objectives for this projects will be divided into two clear branches that will join into the final and most important objective among all: to be able to achieve the maturity expected from the sector to be able to undertake a new adventure as a new graduate.

The first branch takes into account what law and the degree expects from all students.

Having studied a degree where several competences and abilities should have been developed and where through several subjects, concepts and methodologies have been studied and practiced; the aim of a final project shall be to integrate all those concepts, methodologies, abilities and competences in order to develop a project within the degree framework that will help the student address the gaps and consolidate those aspects.

Thus the student will achieve the maturity expected from the sector.

However, in order to be able to structure such a project, a series of bases and knowledge shall be clear. That implies being able to deeply explain why this research is being conducted.

More precisely, and this brings us to the second brand, the objective underneath such brand is to understand what has brought the attention to the field of study; the need to understand why the trend is to follow the market needs and how our evolution has shaped the needs in terms of investigation.

The objectives set for this project are:

a) From an Anthropological point of view:
   - Understand why evolution has led to investigate towards small, compact and high capable antenna systems and solutions.
   - Understand how the action-reaction and database experience lets us determinate the best solutions.
   - Understand the market and manufacturers needs within an area of knowledge; to know what drives companies in terms of risk and interests when having to make a decision.
b) From an Enterprise Point of view:
   - To understand the processes within a real R&D based enterprise and all the actors taking part on it.
   - To be able to undertake a great project within a real enterprise and under the supervision of an actual R&D manager from a leading company. Understand his role and learn the interaction between actors within the R&D industry.
   - To be able to plan, realize, present and defend a project within an area of personal interest and the restrictions of the interests and necessities of a real enterprise.

c) From an Academic and Investigation point of view:

- Learn to find information and process it in order to find relevant conclusions.
- Understand the limits and the approach of actual work and investigation.
- Deep into an interesting area of knowledge.
- To learn new investigation methodologies.
- Ability to find solution to a specific problem with the technological resources available and be able to adapt actual resources to problems that may arise while working towards a solution.

All of which merge into more ordered list of objectives that will be progressively treated during this project and will be discussed at the end of it. This objectives are not ethereal; they are the synthesis and the consolidation of the previous objectives explained:

1- Understand why it is important to find a new and more optimal way of improving an antenna system.
2- Investigate and find what investigators, inventors and companies are working on in order to optimize an antenna system.
3- Understand the most important parameters and requisites when having to design an antenna system.
4- To be able to conclude which of the previous proposed methods could be a starting point for this project. To be able to understand if an eventual solution could be interesting within the market expectations.
5- Understand the behavior and the cases where an optimization is actually worth it.
6- To be able to design a solution that using software simulation could optimize an antenna system and decide whether is a viable solution.
7- To be able to produce such solution and measure if it could match the expectations.
8- To be able to conclude whether if the solution implemented could be extrapolated into other cases and if it could be a viable solution.

1.4. WORKING STRUCTURE

As previously explained, this project aims to accomplish several goals and objectives. In order to do so, the project has been structured following several chapters aiming to complete the goals proposed.

The first chapter explains the need of investigating towards a new and more optimal way of designing new antenna systems, and why society and its evolution has a very strong relationship with that need. During the first chapter, basic concepts will be also reviewed.

During the second chapter, the state of the art is reviewed in order to see what is being done and what could be expected from the project. After reviewing several papers, a conclusion will be achieved choosing a path to follow. A research within the existing information sources is done and documents and papers are studied in order to know the state of the art.

In the third chapter, the Ground Plane Booster Antenna Technology is introduced as well as the magnitude order of this technology within several platforms. During the third chapter, several simulations will be discussed in order to find out the best position, frequencies and platform to conduct the isolation mitigation techniques.

Along the fourth chapter, the platform, frequencies and disposition of antennas will be taken in order to study several possible candidates to isolate better the antenna system. This will be thon through a deep study of the matching networks and the simulations obtained. A candidate from them will be chosen and then proposed to be implemented.

At the fifth chapter, the candidate will be implemented and simulated in real life. The prototype will be simulated and its behavior will be compared to the previous simulations and previous assumptions in order to know if it could be an acceptable candidate. This chapter includes all the work done at the Fractus laboratory in order to conduct a series of experiments and implement a prototype.

Finally, the sixth chapter takes all the information from the project to conclude whether if the objectives have been achieved and if the solution could be viable in terms of isolation mitigation.

1.5. METHODOLOGY

In order to implement the project, several processes will be followed. First we proceeded to conduct a study of the state of the art, which has gained the knowledge and information needed to understand the basic parameters of a MIMO antenna system and what the problems posed by such systems.

Once an investigation into the main theme of the project was carried out electromagnetic simulation where it was possible to extract the first data of the proposed models, the response device S parameters and Smith chart. Electromagnetic simulation was performed with the program IE3D and Microwave Office.

The IE3D and the Microwave Office are simulation programs and both can be found in Fractus enterprise. The IE3D is the first SCALABLE EM design and verification platform that delivers the modeling accuracy for the combined needs of high-frequency circuit design and signal integrity engineers across multiple design domains.

Once the first designs have been implemented with the IE3D software, they are exported to the Microwave office in order to see their behavior. Depending of its behavior in terms of impedance and S-parameters, a matching network has been designed and added to the system.

Finally, when the most optimal solution for the design has been found along with the matching network working for that design and frequencies, the simulated designs have been implemented. The process followed for implementing the design will be described in the fifth chapter. The implementation process includes a final fine tuning done in the laboratory that could eventually imply iterating the design process.

1.6. BASIC CONCEPTS

During this chapter, the basic concepts that will need to be understood are introduced. All of them can be found in the book of the theory of antenna [5] where are deeply explained and described. The parts mentioned during this chapter are a summary of those concepts in order to clarify and give an easy definition of them. This will help understand the figures and ideas explained through this project.

1.6.1. ANTENNA IMPEDANCE

The antenna impedance is the relationship between the voltage and the input port current. This impedance has a real and an imaginary part. Both of them depend in frequency.

On the one hand, an antenna can be resonant at several frequencies but will only resonate when its impedance imaginary part is 0.

On the other hand, the real part from the antenna impedance can be separated into the radiation impedance and the loss impedance which represents the energy or power that the antenna will radiate and the loss that the antenna will have.

The main goal when designing an antenna system is to have the antenna adapted in order to be more efficient and by so the radiation will be greater.

$$R_r + R_\Omega = R_g \tag{1}$$

$$X_a = -X_g \tag{2}$$

1.6.2. BANDWIDTH AND S- PARAMETERS

The antenna bandwidth is the frequency margin where the antenna is considered to radiate efficiently. This is when the reflection coefficient is lower than -6dB. The bandwidth is calculated by the relationship of the margin of frequencies that meet the requirements and the central frequency.

$$BW(\%) = \frac{f_{max} - f_{min}}{f_0} \cdot 100 \qquad (3)$$

The S-parameters can be defined as a relationship of power waves between the incident and the reflected. Those waves are related to the characteristic impedance of the system.

Depending of the number of ports, a matrix defining the relationship mentioned can be analyzed. The S_{11} parameter gives information of the relationship of the reflected signal and the S_{21} parameter gives information about the coupling between them.

$$a_n = \frac{V_n^+}{\sqrt{Z_0}}, \quad b_n = \frac{V_n^-}{\sqrt{Z_0}} \qquad (4)$$

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \qquad (5)$$

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \qquad (6)$$

1.6.3. RADIATION EFFICIENCY

The radiation efficiency can be defined as the relationship between the power radiated and the power given to the antenna system.

$$\eta_r = \frac{P_r}{P_r + P_\Omega} = \frac{I^2 \cdot R_r}{I^2(R_r + R_\Omega)} = \frac{R_r}{R_r + R_\Omega} \qquad (7)$$

1.6.4. ANTENNA EFFICIENCY

While the radiated efficiency (η_r) only takes into account the efficiency over the Ohmic losses, the antenna efficiency (η_a) takes into account the impedance matching of the antenna (S_{11}), the radiated efficiency and the coupling between antenna(for a MIMO 2x2 antenna system).

$$\eta_a = \eta_r \cdot (1 - |S_{11}|^2) \qquad (8)$$

$$\eta_a = \eta_r \cdot (1 - |S_{11}|^2 - |S_{22}|^2) \qquad (8)$$

1.6.5. QUALITY FACTOR (Q)

The Q factor of a component gives information about how close is the component to its ideal behavior without losses. A high Q factor means that the component has few losses. This is a very important issue in terms of design of a matching network in order to match an antenna with low losses.

$$Q = 2\pi \cdot \frac{W_a}{W_e} \qquad (9)$$

1.6.6. CORRELATION

This parameter measures how similar two signals are when received in two antennas in the same system and platform. If the correlation value is 1 then the signal in both antennas is the same; if the correlation value is 0, then the signal in both antennas is different. It is very important to have a close-to 0 correlation as this would increase the capacity of the data processing which is vital in LTE systems. In fact, one of the MIMO reasons to exist is to enhance data rates in mobile devices and one way to do it is by getting in several antennas different signals to process them in parallel.

$$\rho_e = \frac{\left| \int\int_{4\pi} \overrightarrow{E_1}(\theta,\phi) \cdot \vec{E}_2^*(\theta,\phi) d\Omega \right|^2}{\int\int_{4\pi} \left|\overrightarrow{E_1}(\theta,\phi)\right|^2 d\Omega \int\int_{4\pi} \left|\overrightarrow{E_2}(\theta,\phi)\right|^2 d\Omega} \qquad (10)$$

1.6.7. MULTIPLEXED EFFICIENCY

The multiplexed efficiency is important in MIMO systems because considers all the important factors taking place in MIMO systems such as efficiency of both antennas and the correlation.

The multiplexed efficiency is defined as the ratio between the ideal MIMO SNR to get a certain data rate and the real SNR needed in order to get that data rate. In real scenarios it is required to provide more power in order to get the same data rate from the ideal scenarios.

During this project, an increment of this efficiency will be seek. An increment of a 50% will be considered as an acceptable solution.

$$\eta_{MUX} = \sqrt{\eta_1 \eta_2 \cdot (1 - \rho_c)} \qquad (11)$$

Where η_1, η_2 are the antenna efficiency for antenna #1 and antenna #2, respectively.

1.6.8. SMITH CHART

The smith chart is a polar diagram that represents a graphic relation between the input impedance normalized and the reflection voltage at the same point. Thanks to this chart all the difficult calculus in order to know the input impedance or the reflection coefficient can be avoided.

Within this project, a system is adapted when the reflection coefficient at the port (S_{11} and S_{22}) show a response of under -6 dB which translated into the Smith Chart would mean having the impedance inside the SWR=3 circle.

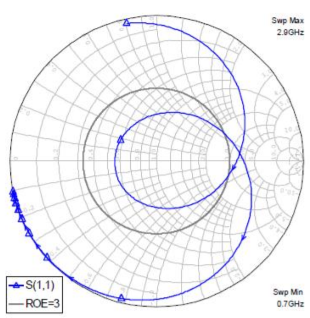


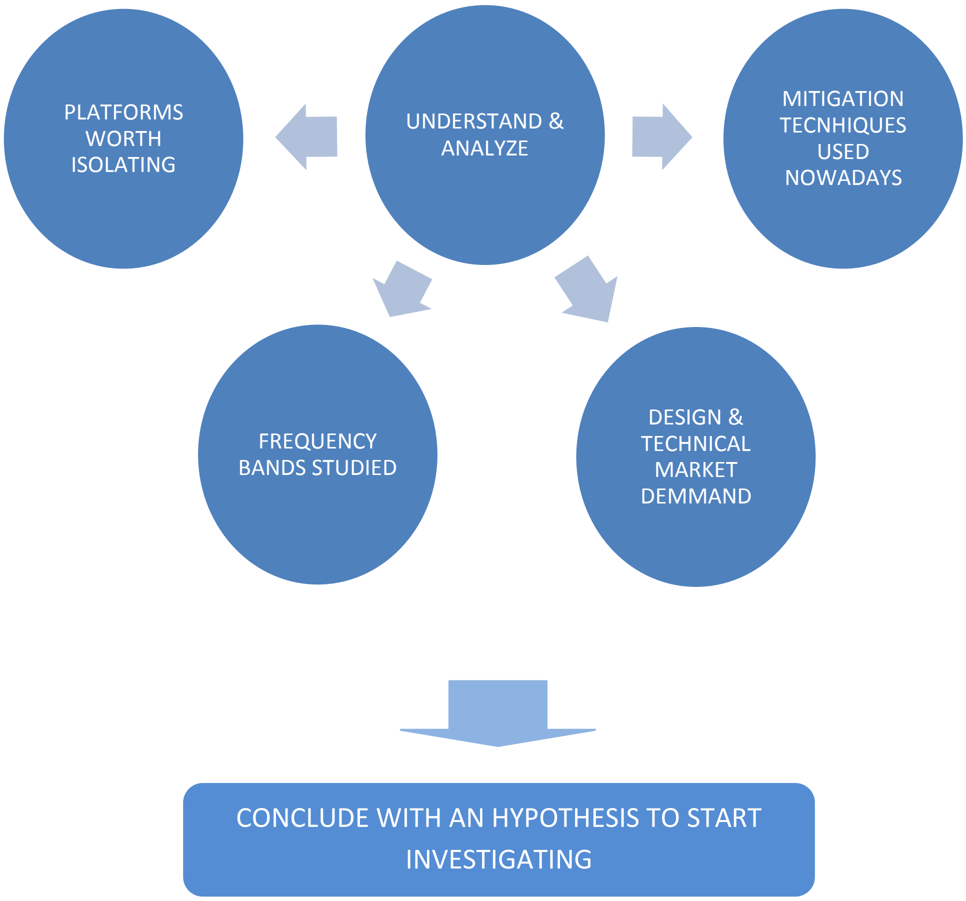
Fig. 1 Smith chart; Impedance curve with section within the SWR=3 limit

2. STATE OF THE ART

2.1. INTRODUCTION

Along this section, a series of scientific papers are revised and discussed in order to analyze the state of the art in the field of MIMO antennas for wireless devices. From this analysis, the possibility of knowing what is the industry going through will lead us into a global vision of the antenna world; its situation and the future.

The problems that are faced in this particular section and part of the antenna world are the correlation and isolation of MIMO wireless devices. A series of problems appear when antennas can't be placed where they should and have to deal with several platforms and frequencies. The final effect of this problem can be observed in the capacity and performance of portable devices. Such problems affect power supply and throughput capacity.



2.2. REVIEW OF PRIOR ART

During this chapter, a series of papers selected in order to understand how the market is working and what is being done in order to perform better in terms of isolation are reviewed. The isolation mitigation technique explained along the papers will be analyzed.

2.2.1. COMPACT ANTENNA ARRAY WITH PORT DECOUPLING FOR LTE STANDARDIZED MOBILE PHONES

Along the article [6], the possibility of mitigating the isolation problem is faced via an LC branchline hybrid coupler (Fig.2). Given a handset platform with two monopole antennas printed at a $\lambda/45$ distance (Fig.3), finding the 25 dB edge isolation is the main goal. The hybrid coupler proposed connects both antennas and their transmission lines for feeding and grounding. Those connections are the ones that compose the LC branchline. A high improvement in S-parameters show that the branchline actually works (less than -25 dB).

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
710 MHz	Handset	22 mm x 29 mm	Two Monopole	10MHz @ 0.71 GHz	25dB @ 0.71 GHz	-43dB @ 0,71 GHz	LC branchline hybrid coupler.

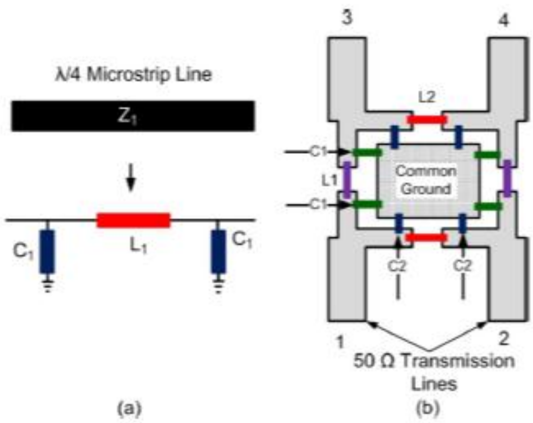


Fig.2: LC-based branchline coupler configuration; equivalent and coupler

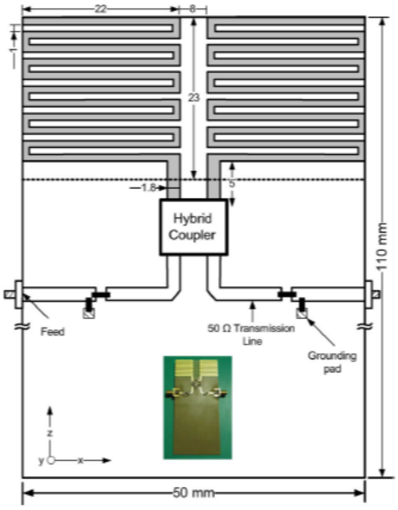


Fig.3: Layout of the meander-line monopole antenna array

2.2.2. A COMPACT DUAL PORT DIVERSITY ANTENNA FOR LONG TERM EVOLUTION HANDHELD DEVICES

In this article [7], the bands of LTE/WIFI at 2.6 GHz are studied. The results are analyzed with ECC and MEG. The proposed solution is a dual port PIFA compact antenna situated at one of the corners of a PCB (Printed Circuit Board) (Fig.4). The diversity is found with the switch diversity method which means monitoring one antenna branch at a time. Results are taken into account in both free space and within a handheld device in close proximity to a model of a human head and simulating currents and isolation. Results show that the edge is passed so the solution works. These results take into account the scattering parameters and the ECC (Envelope Cross Correlation) .

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
2,4-2,7 GHz	Handset Blackberry 8300 curve	1,8 cm x 3,5 cm	Two PIFAs	200MHz @ 2.55 GHz	17dB @ 2.5 - 2.6 GHz	ECC: 0.1@2.55GHz	PIFAs

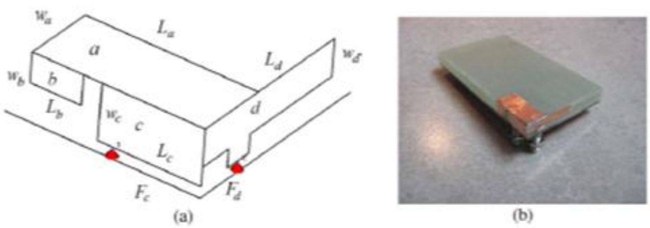


Fig.4: Proposed compact dual-port antenna (a) radiation element (b) prototype

2.2.3. DESIGN OF A NOVEL ANTENNA ARRAY FOR MIMO APPLICATIONS

Along this article [8], the capacity of a MIMO system is studied at the 5.2GHz band. A 4 antenna device is taken and then its capacity is measured via a series of studies such as measuring its S-parameters and radiation parameters in different positions between emitter and receiver. In order to avoid mutual coupling and high isolation a decorrelation network with a hybrid circuit (Fig.5) that introduces 180ºphase between the signals from two antenna branches is the proposed solution. In fact, the decorrelation network is made from a hybrid ring. It is also taken into account the capacity and compared between rotation of the antennas with and without the hybrid circuit and the scattering parameters.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
5.2 GHz	Handset	Doesn't apply	2 Patch antennas	850MHz	8dB @ 4.85 - 5.37 GHz	-35dB	Hybrid decorrelation circuit. (hybrid ring)

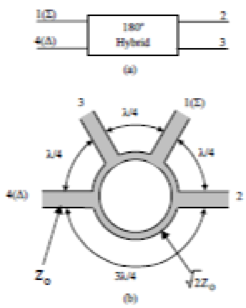


Fig.5: (a) Schematic hybrid circuit. (b) how can be implemented with PCB stripline technology

2.2.4. ENVELOPE CORRELATION IN (N,N) MIMO ANTENNA ARRAY FROM SCATTERING PARAMETERS

The article [9] discusses and explains the envelope correlation using scattering parameters. Although the calculation can be approached in different ways such as the far-field pattern and the one based on Clarke's formula, this article proposal is to calculate the envelope correlation with the Scattering parameters and a simple formula (Fig.6). To prove the theory proposed, a MIMO antenna is taken and then their

Scattering parameters calculated in several frequencies and antenna configurations. The approach taken to calculate the envelope correlation is less laborious and relatively cheaper as the S parameters are nowadays an easy and cheap to measure.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1,2 - 2,4 GHz	Handset (40 mm x 100 mm ground plane)	40 mm x 1,5 mm x 5 mm	3 PIFAs	Doesn't apply	Doesn't apply	ECC: 0.05 @ 1.8 GHz	PIFA + ground plane combination

$$\rho_e(i,j,N) = \frac{\left|\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}\right|^2}{\prod_{k=i,j}\left[1-\sum_{n=1}^{N} S_{k,n}^{*} S_{n,k}\right]}.$$

Fig.6: Equation for envelope correlation between i and j antennas in NxN MIMO antenna system

2.2.5. ENHANCED DIVERSITY ANTENNAS FOR UMTS HANDSETS

Along the article [10], several systems will be approached during this article. All of them measured in the UMTS band. Firstly, two antennas are located at the top of a ground plane and measured its scattering parameters. Then, a solution composed of a Neutralization line is proposed (Fig. 7) to finally measure the S parameters results and conclude that both the isolation between the two antenna and the efficiency increased significantly. Once the proposed solution is proved, then a four antenna system is tried. The radiators from the other top are decoupled by inserting a neutralization line as it was done before. Finally, the results prove that the solution also works for the four antenna proposal as the insertion loss between the diagonal elements are very good as well as the S_{ij} parameters of the four antenna structure are nearly -15dB. It is also demonstrated that the 0.5 envelope correlation coefficient value is in any case reached.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1,92-2,17 GHz	Handset mobile phone	26,5 mm x 8 mm	2 PIFAs	300MHz @ 1.95 GHz	45 dB @ 1.95 GHz	ECC< 0,1 @ BW interested	Neutralization line + swapping the position of the shorting and feeding strips

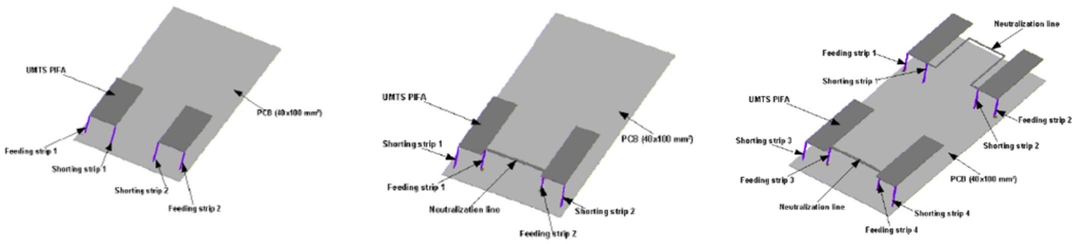


Fig. 7 different dispositions for radiators in UMTS antenna; neutralization line between radiators showed as a proposed solution

2.2.6. HIGHLY EFFICIENT MULTIPLE ANTENNA SYSTEMS FOR SMALL MIMO DEVICES

In this article [11] all the solutions considered before by previous researchers are revised. The basic idea is to optimize the total efficiency of the antennas. Then the proposal is presented: a two PIFA operation in the UMTS band over a PCB with a Transmission Line neutralizing structure (Fig.8-Fig.9). All of which is to focus on maximizing the isolation and the total efficiency of the antennas. After succeeding in isolating the feeding ports of the two antennas (PIFA TYPE) without link between them, the solution is tried. The solution proves to work thanks to a result of S_{21}>65dB at the desired frequencies.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1,2,2.4 GHz	Handset	Doesn't apply	2 PIFAs	300MHz @ 1.95 GHz	68dB @ 1.95 GHz	Doesn't apply	Neutralization line between feeding ports and connecting both PIFA by thin TL

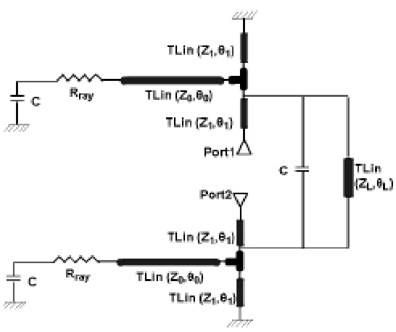


Fig.8: Transmission Line model of the neutralized structure (2 PIFAs operation at UMTS)

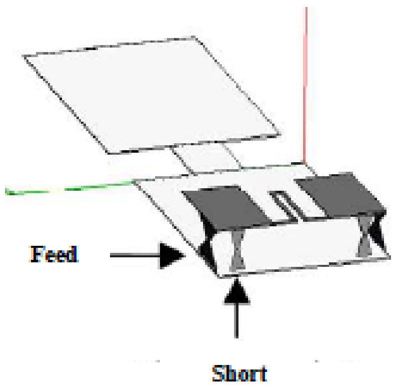


Fig.9: Neutralization technique applied to a clamshell phone

2.2.7. LOW CORRELATION ANTENNA DESIGN FOR DIVERSITY HANDSET APPLICATIONS

In this article [12], after introducing the problem that will need to be faced and the possible solutions, the proposed antenna is presented: a pair of printed tuned monopoles and optimized T-stub ground plane (Fig.10). The parameters used to prove its effectiveness go from the calculation of envelope correlation coefficient by different methods confirming the very low correlation between antenna elements to the calculation of antenna efficiencies and gain radiation pattern under 2-port excitation in order to confirm the applicability of proposed design for handset antenna platforms. In order to maximize the benefits of the solution, dependence of the mutual coupling level on the dimensions of the T-stub has also been studied. Once found the best solution for the antenna performance, the proposed design has a very low correlation coefficient(less than 0.1 (widely accepted less than 0.5)) within all its band (1.83 to 2.4GHz) and also very good isolation parameters .

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1.9 - 2 GHz	Handset	3 mm x 20 mm	2 Monopoles	200 MHz @ 1.95 GHz	20dB @ 1,9GHz	ECC< 0.1 @ BW interested	2 mm wide strips T stub + capacitor between ground plane and antenna

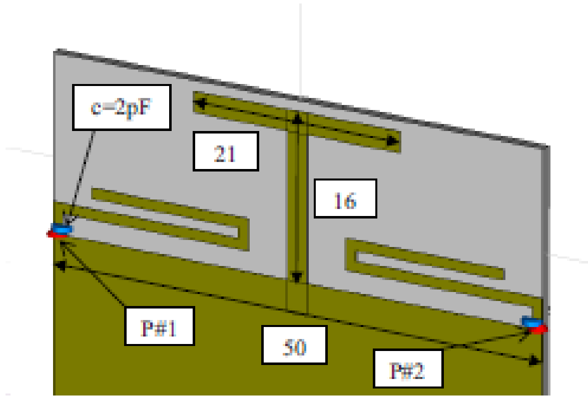


Fig.10: Layout of the proposed diversity antennas

2.2.8. MULTIPLE PRINTED ANTENNAS FOR INTEGRATION INTO SMALL MULTIBAND HANDSETS

In this article [13], an antenna system with seven different printed elements (Fig.11) (two PIFAs and five IFAs) is tried in order to provide enhanced capacity for a MIMO system. In order to validate the concept, the bands of GSM 1800, UMTS, IEEE 802.11b and Bluetooth are tested. The antennas are disposed as follows: Five IFAs integrated along the edges of the air gap, printed on substrate strips and placed perpendicularly to the ground and two PIFAs have been integrated into the top back side of the handset. To prove the solution, S-parameters, Envelope Correlation and radiation pattern have been simulated. Finding all satisfactory results by measuring less than 0.04 for the IFAs and less than 0.4 for the PIFAs through all its bands for ECC and less than -12 dB at all S_{ii} parameters. One of the best benefits of the antenna system is its volume, meaning only about 23% of the volume of a typical handset device.

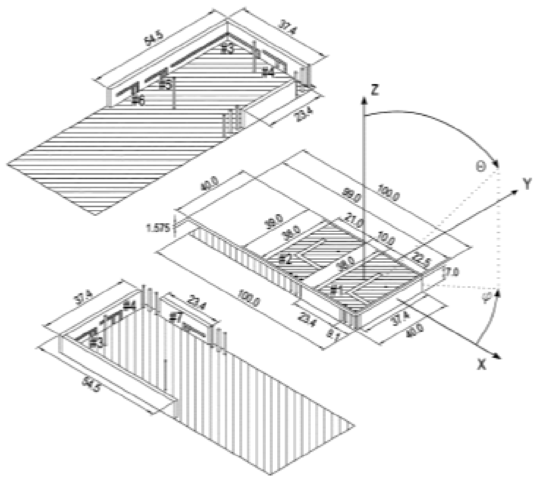


Fig.11: Geometry and overall dimensions of the multi-antenna system

2.2.9. RECENT DEVELOPMENT OF MIMO ANTENNAS AND THEIR EVALUATION FOR SMALL MOBILE TERMINALS

During this article [14], antenna configurations in small mobile terminals for MIMO are discussed. Challenges that will need to be faced are exposed and explained. The options researchers are dealing with are reducing the volume of each antenna element and the total number of elements. The essential part of this paper is to evaluate the performance of the several antenna configurations to estimate the benefit from the location and dimension. In order to minimize its volume, well-known circuit techniques to match the antenna at desired frequency ranges (Fig.12) is taken into account and implemented instead of a small self-resonant antenna. Before analyzing the results, the paper goes through the way the results must be considered and how the measures need to be taken by discussing the MEBAT tool. Bandwidth is analyzed in order to see best operating bands and the ECC is calculated in order to prove its reliability as a choice and its result satisfies the 0.5 limit for all frequencies unless the 1GHz. Getting the best results at 2, 3 and 4.5 GHz. Finally several antenna configurations are tested (Fig.13) and its capacity is measured to conclude that depends on its configuration.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1; 2,5 ; 3,7 and 5,3 GHz	Handset	4,5mm x 40 mm x 8,2 mm	2 non resonant coupling elements	27%; 22%; 15%; 10%;	Doesn't apply	ECC: 0.92 @ 1GHz ; 0,2 @ 2GHz; 0,45 @ 2,5GHz; and <0.3 above 2,7 GHz	Non-resonant antenna elements in different locations

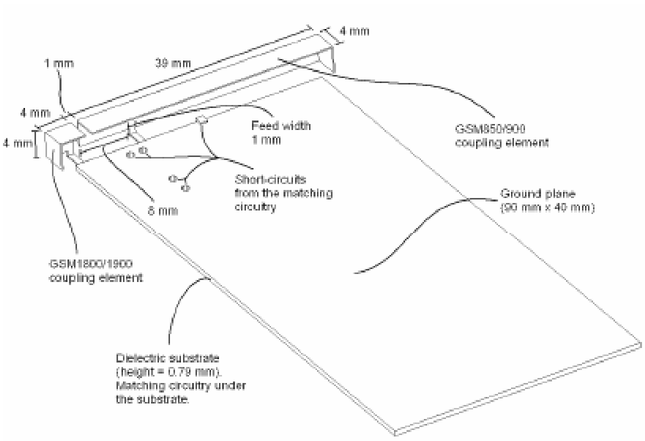


Fig.12: An example of multi-system antenna based on the non-ressonant coupling element technique

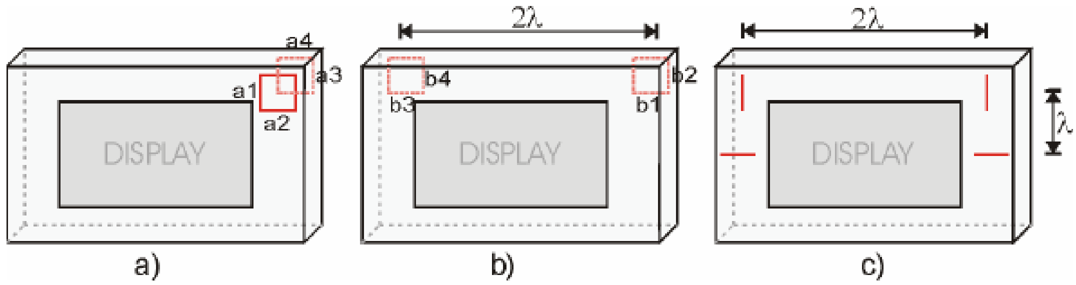


Fig.13: Location of antennas in configurations. Antennas drawn with dashed line are located at the back side of the terminal

2.2.10. SIGNAL CORRELATION INCLUDING ANTENNA COUPLING

This paper [15] explains the effects between antenna elements on signal correlation. In handheld devices there is a very limited volume available for antennas. The influence of different parameters on the correlation is discussed. A two antenna (Fig.14) scenario is studied with one antenna element active and another terminated into load. Then the correlation magnitude is calculated through different antenna separations and through several loads. The paper concludes that the correlation depends very strongly on the termination of the passive antenna and the propagation environment.

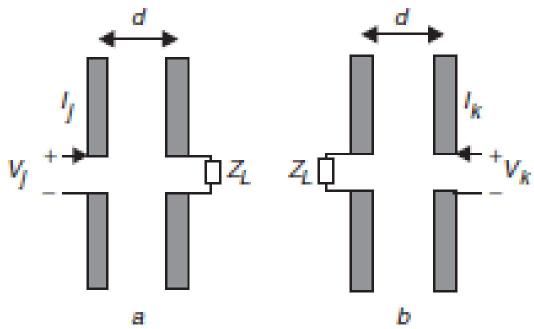


Fig.14: Two diversity antenna configurations with one antenna element active and other terminated into load

2.2.11. THE INFLUENCE OF MIMO TERMINAL USER'S HAND ON CHANNEL CAPACITY

Along the article [16], as the title prefaced, the hypothetical user's hand effect and influence on channel capacity is studied. A 4x4MIMO system is considered in a PDA terminal (Fig.15). In order to conclude whether if the hand will affect the results, the radiation patterns of the antenna elements are simulated in the presence of a user's hand. The antenna configuration used for this particular experiment is a PIFA for dual band mobile terminal application, more precisely are folded PIFA patches designed for operating at 1800 and 2450 MHz frequency bands. The simulation results show that there is a small influence of the hand presence in antenna scattering parameters. The difference is very small. In order to get more conclusions the channel capacity for hand and PDA is tested. The average difference in channel capacity for SNR10dB is 1.6 bits/sec/Hz.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1800 and 2400 MHz	Handset PDA	10 mm x 22,05 mm	4 Patch elements PIFAs	100 MHz @ 1.7 GHz ; 90MHz @ 2.45 GHz	25dB @ 1.7 GHz; 17 @ 2.45 GHz	Doesn't apply	Location and materials

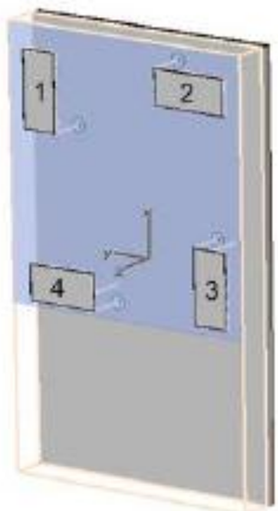


Fig.15: A PDA model with four antennas

2.2.12. TWO ELEMENT PIFA ANTENNA SYSTEM WITH INHERENT PERFORMANCE OF LOW MUTUAL COUPLING

The main goal of this paper [17] is to demonstrate a new technique for reducing mutual coupling between closely packed antenna elements. This method doesn't need any additional baffler between elements nor depends on the element orientation arrangement and form. The paper firstly discusses the common use of PIFA antennas due to its cost. It discusses though the problems that it needs to consider when using this kind of antenna. The system is designed to work at the 2.46 range using two PIFAs bended (Fig.17) at the edge of the platform (Fig.16). Its materials, form, shorting points and feed configuration makes it suitable for the problems that usually need to be faced. After measuring scattering parameters for reflection and mutual coupling, the target is to reach an S_{21}< -25 dB for all kind of configurations at the desired frequencies. Then a baffle plate is taken into consideration in order to see if it would make such a difference by blocking electromagnetic wave propagation, resulting in a notable disappeared stop band of the mutual coupling and moving toward high frequency in the last case. It is concluded that when parameters are selected properly, the EM waves emitted by one element pass through the two routes and are about of phase at the other antenna at the operation frequency. Therefore, results validate the development faced. Low mutual coupling performance does not depend on the element arrangement but on the coupling routes of the electromagnetic energy.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
2.6GHz	Handset	7,6 x 14x 10 mm	2 PIFAs	200 MHz @ 2.5GHz	55 dB sim 30 dB meas (from 32 to 42 dB depending on placement)	Mutual coupling: from -40 dB to -20 dB	Location and separation. studies the influence of a baffle plate

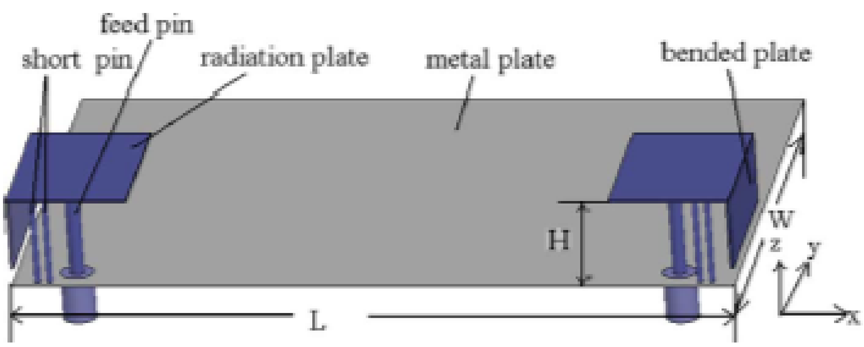


Fig.16: 3-D view of the two-element antenna system with opposite element arrangement

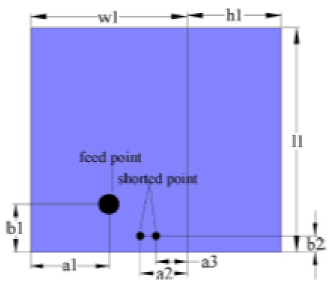


Fig.17: Top view of the expanded metal radiator of the PIFA element

2.2.13. A COMPACT MIMO DRA ANTENNA

During this paper [18], a different antenna structure is proposed to work at the 2.6 GHz band. The antenna is called DRA (Fig.18) and its design is based on Finite Integration Method. It consists of a monopole antenna and two patch antennas in DRA. Given a set of parameters of DRA (Dielectric Resonator Antenna), the antennas are optimized to cover the UMTS band 7. In order to prove its effectiveness, Scattering parameters are studied and reach a S21< -25 dB at the desired frequencies. After combining several possibilities between ports, monopole and Patch, the apparent Diversity Gain is always better than 9.9 dB.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
2,6 GHz	Handset	Monopole: 2 x 10,5 mm Patch: 4 x 7 mm	2patch antenna and 1 monopole	200 MHz @ 2.65 GHz	27dB simulated vs 25 measured	Cumulative probability vs relative received power Actual Diversity gain goes from 9.3 to 9.9	Use of PWB and combination of different types of antenna

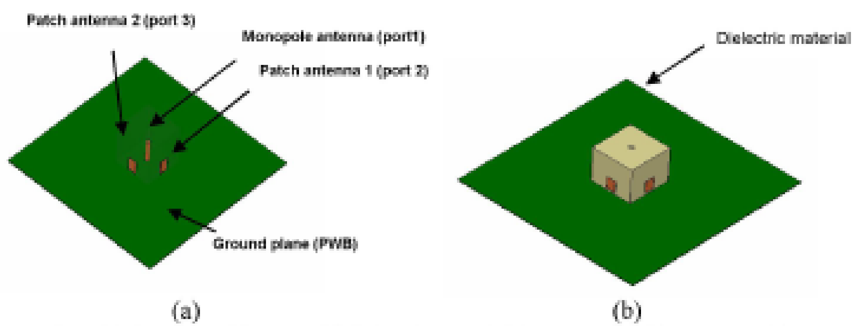


Fig.18: Antenna with PWB

2.2.14. WIDEBAND DUAL-ELEMENT ANTENNA ARRAY FOR MIMO MOBILE PHONE APPLICATIONS

Along this article [19], a dual element antenna for mobile phone applications is presented. Both elements are symmetrically placed. Each of them consisting of a novel driven strip and a shorting strip and a loop (Fig.19). The proposed antenna system covers seven operating bands: GSM 850/900/1800/1900/UMTS2100/LTE2300/2500. Results show that isolation is more than 10dB. As for the ECC, all bands get a less than 0.37 result, where all bands above 960MHz get less than 0.5 for ECC. Radiation patterns and efficiency are measured in order to conclude that the proposed antenna array has good radiation characteristics and diversity performance over the whole operative bands.

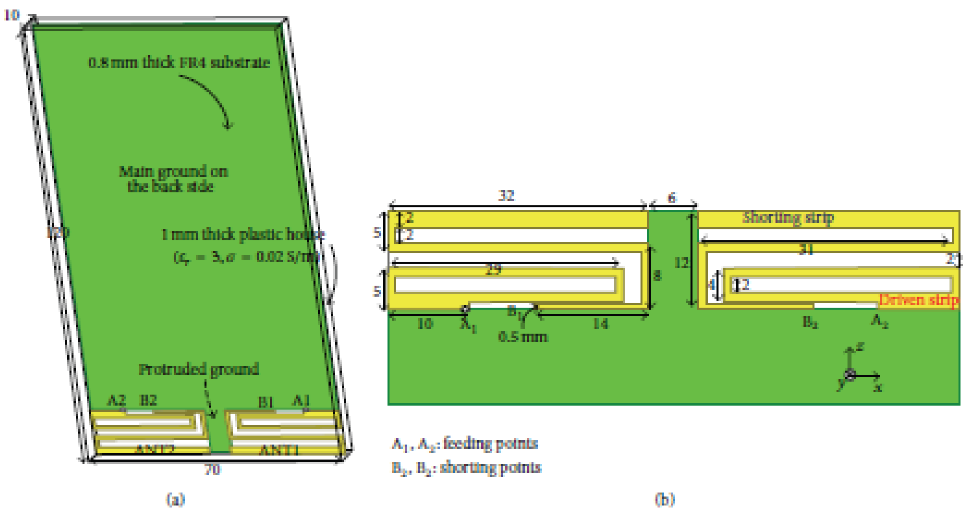


Fig.19: Proposed antenna array configuration. (a) Geometry of the proposed antenna array for mobile phone applications (b) Detailed dimensions of the proposed antenna array in millimeters

2.2.15. ADVANCES IN ANTENNA TECHNOLOGY FOR WIRELESS HANDHELD DEVICES

This paper [20] goes through the history and evolution that wireless handheld technology has experienced in the last years. Firstly, the paper describes how society and the market has gotten to the point that we are now living, where, design and performance are both very important parameters for the mobile industry. The paper precisely goes through the integration of those two parameters, and how the antenna industry must take those requirements into the next level. Once the design criteria are exposed, then the evaluation of the mentioned performance is explained. Finding models in order to see how the particular handset device will perform near a human head or hand has also been very important in order to get to the standards needed. Then, the paper goes through the whole evolution of antenna technology to finally discuss how powerful is, as results show, adding intelligence into the device's ground plane. That has given the opportunity to investigate and invent the Ground Plane Boosters (Fig.20), where the paper concludes saying that that solution becomes an alternative to current antenna technology and appears as a promising standard solution in the emerging multifunctional wireless devices.

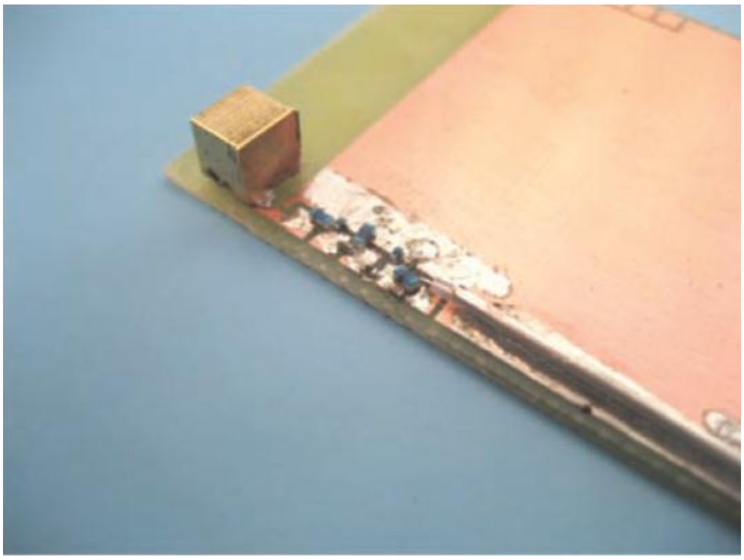


Fig.20: Single-band prototype including the reactance cancellation inductor and the broadband matching network

2.2.16. ISOLATION IMPROVEMENT IN A DUAL-BAND DUAL-ELEMENT MIMO ANTENNA SYSTEM USING CAPACITIVELY LOADED LOOPS

In this particular paper [21], a new way of finding isolation is studied. The improvement from a 2x1MIMO antenna system is proposed by modifying it by adding capacitive loaded loops on the top side and etched out from the GND plane at the bottom side (Fig.21:). The antenna system is studied to resonate around 800MHz and to cover the 2.5GHz as well. The composition and disposition of the antenna elements is discussed to then conclude with the results of the simulations, obtaining a 18.9dB isolation (+9dB improvement from original system) for the low band and 9.8 dB isolation (+2dB improvement from the original system) for the upper band. In terms of bandwidth, the system gets -6dB bandwidth of 28MHz for the low band and more than 125MHz for the high band. In terms of the correlation coefficient, a 0.05 level is reached for the lower band and less than 0.2 for the upper band. It is then concluded that the system fulfills the requirements of isolation improvement.

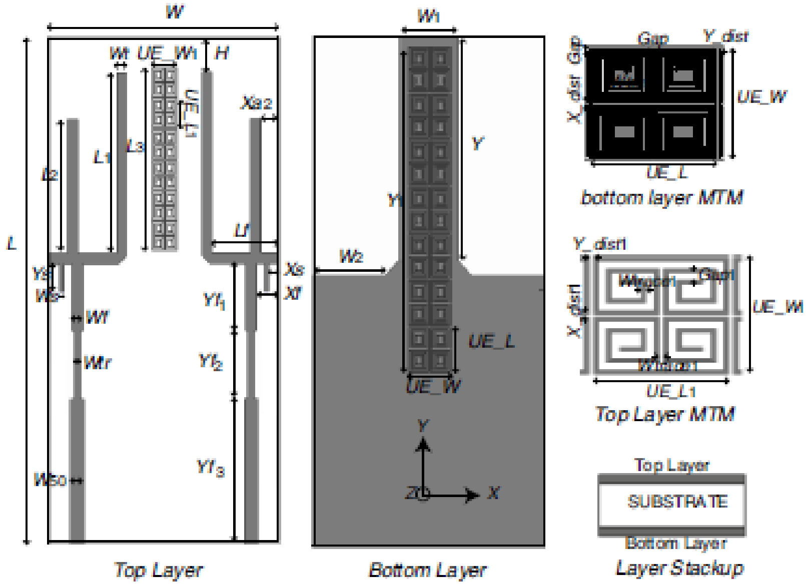


Fig.21: Geometry of the 2x1 4-Shaped MIMO antenna system

2.2.17. DUAL SLOT DIVERSITY ANTENNA WITH ISOLATION ENHANCEMENT USING PARASITIC ELEMENTS FOR MOBILE HANDSETS

The main goal of this paper [19] is the design of an antenna system to fight against Isolation problems. A dual-slot diversity antenna with isolation enhancement using parasitic elements (Fig.22) for mobile handsets is presented consisting of two symmetric slot elements. In order two fight against isolation, two parasitic monopole elements are added. To find if the proposed solution actually works, at the band of interest (UMTS) S21 reaches levels below -18.5dB and an ECC below 0.05. It is then proven that the system is isolated.

BAND	PLATFORM	VOLUME	TYPE	BW	ISOLATION	CORRELATION	TECHNIQUE
1920 - 2170 MHz	Handset	25,3 mm- 60 x 75 mm	Dual slot diversity antenna	200 MHz @ 2.1 GHz	>18,5 dB (27 dB measured @ 2,1GHz)	VSWR<3 (correlation coefficient from 00,0258 to 0,041 @ 2,1 GHz)	Use of 2 parasitic monopole elements.

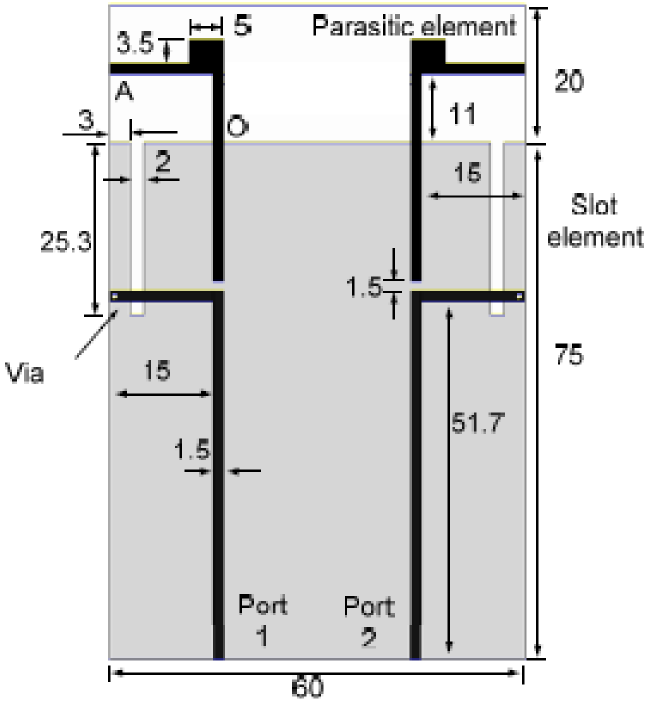


Fig.22: Geometry of the proposed antenna with dimensions in mm

2.3. CONCLUSIONS

Along the previous section, one can observe what the industry and the R&D departments are working on in order to find a solution to a very important problem: how to improve the isolation within a mobile platform with a solution that provides matching to several platforms in a simple way.

By doing so, the proposal will give solution to one of the biggest issues of today's manufacturing problems in technology: to adapt components in several different platforms and to give a solution without needing to occupy a large volume and with no power loss as well as a good capacity towards a high data throughput.

The review of prior art has lead to a set of conclusions that will help this work proceed in such a way that will improve and give another point of view to what has been done. It is then very important to note the facts that have in common all the reviewed papers and articles. By finding what worries to the majority of R&D departments, manufacturers and inventors, the setting of all bases of this project will be much more realistic and useful.

More precisely, the aspects that need to be considered are:

- Small dimensions and easy to integrate: the market and consumers are directing the design in mobile platforms in such a way that make manufacturers worry about design and dimensions. Finding a solution that will help address the necessity that the market shows will help the brand sell more mobile phones. Being able to integrate the same solution in several models and platforms and the lack of need to personalize each solution to a platform or model will help manufacturers spend less money in industrial processes and will help them optimize the manufacturing process.

  In terms of dimensions and integration, it is more attractive a solution that occupies small volume and that is able to be integrated in several platforms and models.

- Bandwidth: The evolution of society noted in the last chapter has led an increment of data consumption. This demand has given place to several sets of protocols and technologies that use different parts of the spectrum in order to enhance some parameters such as the speed and throughput. A modern design must meet this requirements in terms of data capacity in order to have a certain commercial value. This has led manufacturers to find solutions in order to be able to tune their devices into several frequencies so that they could work for the different protocols and radio technologies.

  In terms of bandwidth, it is very important that the solution covers several bands.

- Frequency Bands: the frequencies that are more important to cover, are the ones that will need to be used to have a high speed rate and throughput like for example LTE 4G. More precisely the most important are:
  - LFR (0.7 GHz - 0.96 GHz)
  - HFR (1.71 GHz - 2.69 GHz)

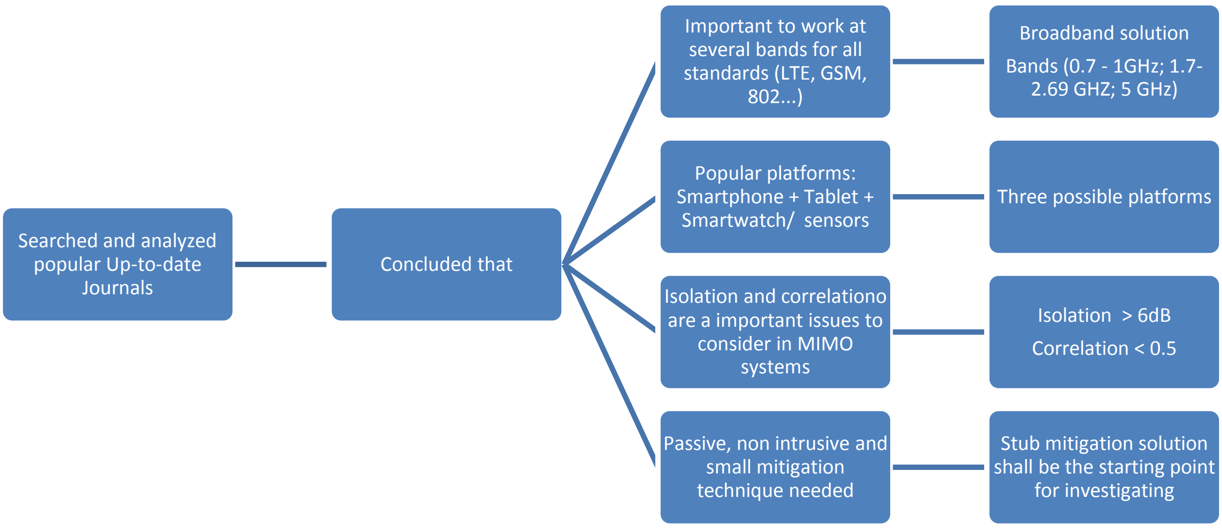
  Thus notes the necessity of a solution that can be tune into different frequency bands within the same platform.

- Isolation & Correlation: Given a certain point, increasing the platform capacity meant having more than one antenna. The MIMO systems perform better if are well designed. Designing those systems in order to meet the requirements that will let them perform better mean isolating them and having a low correlation. Right now the pursue of an optimization of those parameters is making manufacturers find solutions.

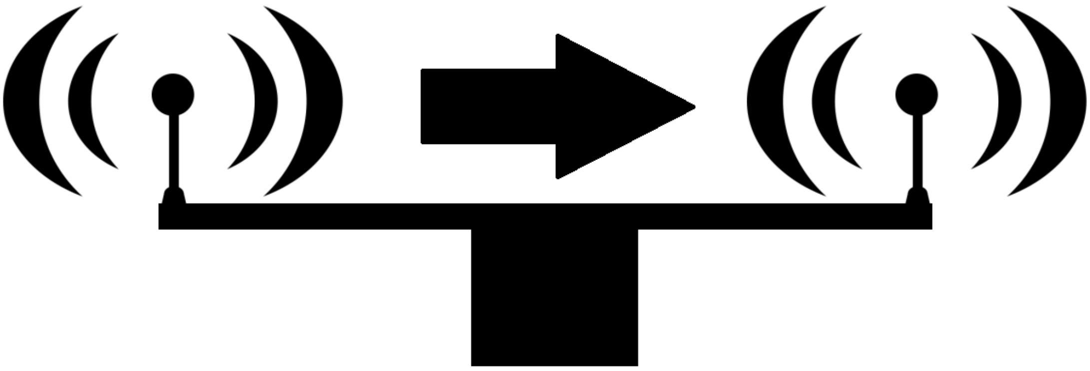
Thus, the paper that will help us base our studies and will help us start working on the solution that will be proposed is the LOW CORRELATION ANTENNA DESIGN FOR DIVERSITY HANDSET APPLICATIONS article [7]. This article shows a solution that seems easy to integrate within a mobile platform and is easy to design without needing to be tuned in terms of frequency nor dimensions.

Our study will then be based upon the following bases:

- Wireless platform
- Great Bandwidth
- Easy to operate within several bands
- Great isolation and low correlation
- High Multiplexed efficiency



3. ISOLATION WIRELESS DEVICES

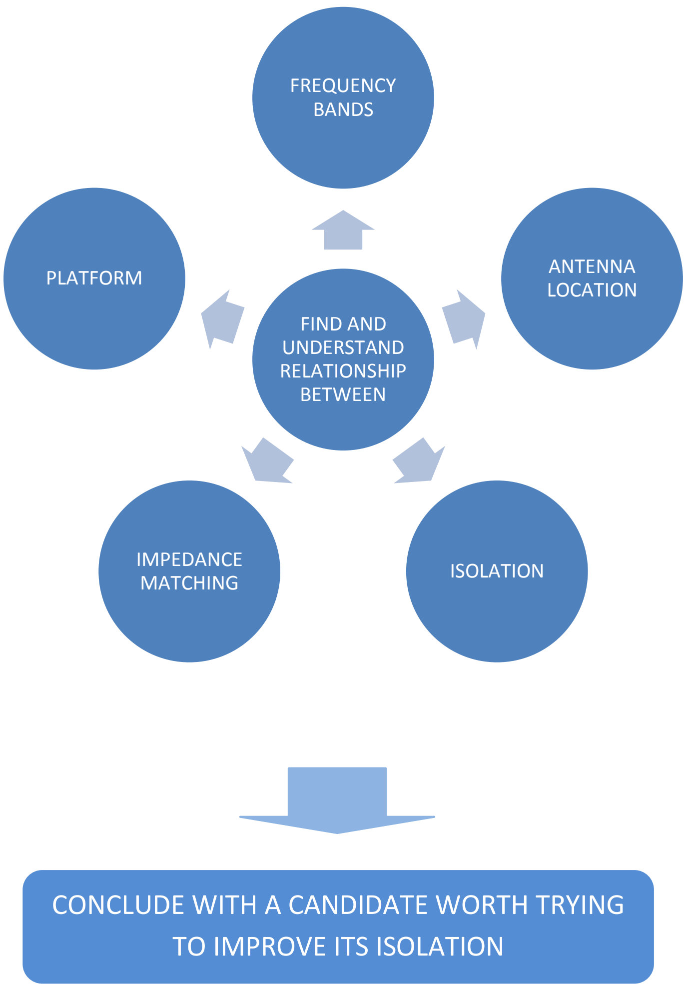


3.1. INTRODUCTION

Along this section, in order to know and understand the behavior of the antennas to be used in several placements, for several frequencies and different platforms, several tests will be taken.

First, an analysis of monopole antennas will be done for several bands and platforms in order to have a high level approach to what can be obtained in terms of frequency, location and platforms, and in order to get familiarized with the procedure to be followed. Based on the results obtained, another analysis will be done with the technology invented by Fractus: the Ground Plane Booster Antenna Technology [27] - [53].

The antenna to be used will be explained and simulated for several scenarios. The results of the scenarios will be shown and then discussed in order to know what is the best scenario to work on.



3.2. ISOLATION RELATIONSHIP

This chapter summarizes the series of simulations and proves that have been taken for the case of a two monopole on the PCB with two size variations. The main goal of which has been finding and analyzing its behavior at the 0.7-3 GHz range.

Pursuing a relationship between the distance of both monopoles and its isolation, the monopoles have been placed in several locations around the PCB in order to observe differences and appreciate such relation. Both monopoles are "L" shaped and are fed from the PCB with a port. The monopole is composed of a PCB strip line 2 mm width and 6 mm x 23 mm dimensions.

Both PCB sizes are such as the ones for a mobile phone and a tablet. For the first one a 120 mm x 60 mm dimension PCB has been taken into consideration and for the second one, a 240 mm x 170 mm dimension PCB has been taken as to have a similar size to a mobile phone and tablet.

3.2.1. MEASURING PROCEDURE

First, the PCB has been designed with the IE3D electromagnetic simulation tool. A combination of two layers has been drawn. Once the PCB has been designed, monopoles were located in several places for both sizes:

- Both GPB (ground plane boosters) at the right side of the PCB (*Fig.* 23).

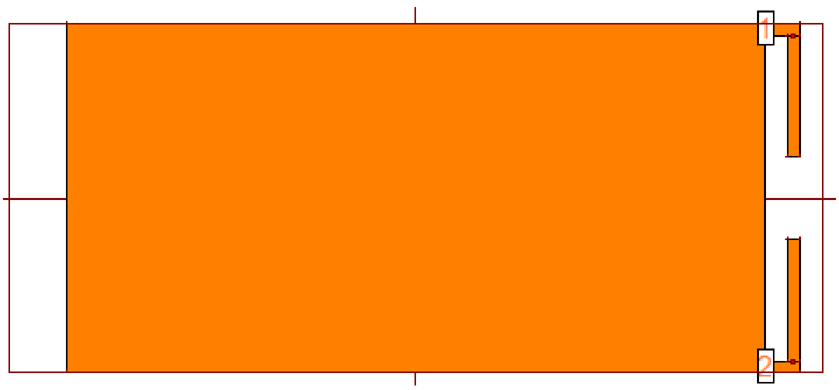


Fig. 23 : Two monopoles L-shaped (6x23 mm) located at the same right side of a 120 x 60 mm PCB. Both antennas and the ground plane are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013. Monopole is composed of a strip line 2mm width and 6 x 23 mm dimensions

- Both monopoles at the upper opposite side of the PCB (*Fig.* 24).

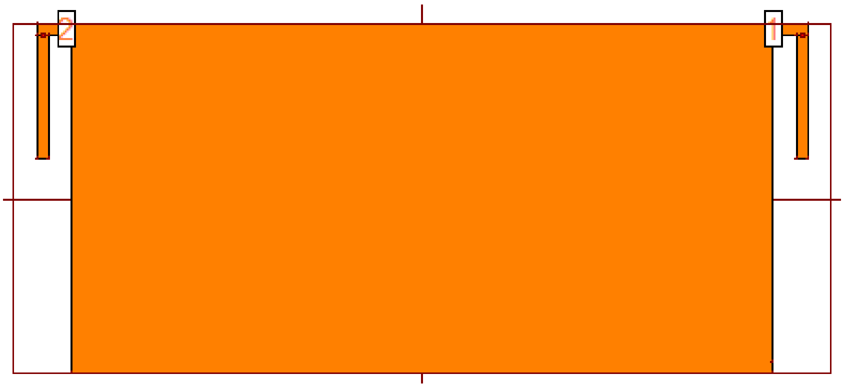


Fig. 24 :Two monopoles L-shaped (6x23 mm) located at opposite upper side of a 120 x 60 mm PCB. Both antennas and the ground plane are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013). Monopole is composed of a strip line 2mm width and 6 x 23 mm dimensions

- Both monopoles located at opposite diagonal corners of the PCB *Fig.* 25.

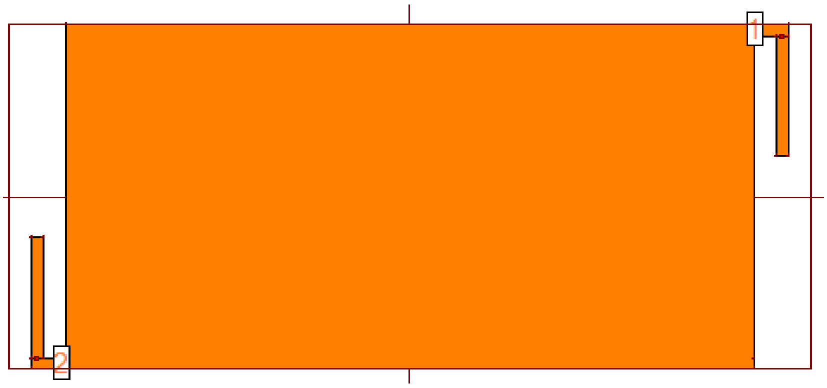


Fig. 25: Two monopoles L-shaped (6x23 mm) located at opposite diagonals of a 120 x 60 mm PCB. Both antennas and the ground plane are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013. Monopole is composed of a strip line 2mm width and 6 x 23 mm dimensions

Second, the design has been simulated for the range of 0.7 to 3 GHz using 116 points. That means considering through the frequency range mentioned points every 0.02 GHz. This range will cover the frequencies desired which are:

- 0.829 GHz
- 1.9 GHz
- 2.45 GHz

Third, using the AWR software and the project mentioned above, a simulation has been carried out in order to see its isolation. In order to achieve that, the project has been invoked and its ports has been configured as such. Then, the parameter S21 was measured (Table 1 - Table 3).

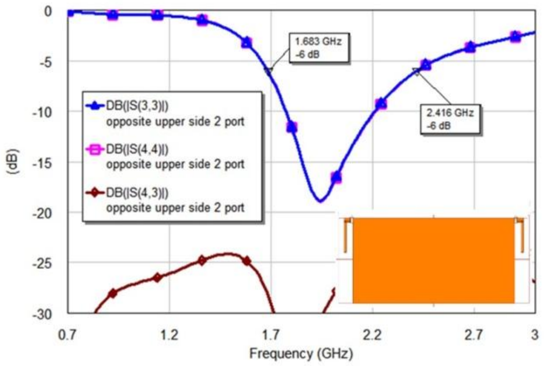
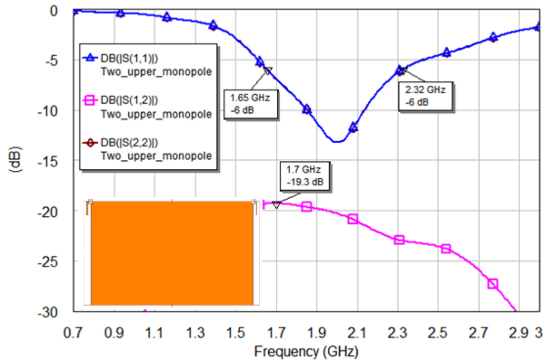
Once those parameters were simulated, the natural resonance and working frequency of the system was found and turned out to be the 1.9 GHz frequency. In order to find other bands to operate such as the 900MHz band and the 2.4GHz band, a matching network has been studied and taken into account for the S-parameters simulations. A combination of inductor and capacitor located in both ports in serial and parallel disposition has been tried. Depending on the location of the monopoles and the size of the platform, those parameters varied and its matching has been more difficult to approach. In order to conduct such matching, the values of those capacitors and inductors have been changed in order to find the best S_{ii} matching and the best S_{ij} isolation.

The procedure carried out in order to tune the system so that it could operate in the desired bands consisted of two very important steps, the main goal of which was to adapt the S_{11} parameter to a 50 Ohm real value.

- Firstly, using the AWR, the parameter S_{11} was simulated and displayed in a Smith Chart.
- Secondly, depending on the situation of the particular desired frequency, as mentioned before, the value of such inductors or capacitors were tuned in order to place that frequency in the center of the Smith Chart.
- Once the S_{11} was tuned to the 50 Ohm value, the S_{21}, S_{11} and S_{22} parameters were displayed in a rectangular chart and if both S_{ii} parameters weren't equal, a final tune was carried out.

3.2.2. SIMULATIONS

During this section, a table showing different results of simulating the antenna systems can be observed. The aim of the table is to compare the behavior of the different platforms having the same antenna disposition and working at the same frequencies.

<table>
<tr><th>Smartphone Simulations</th><th>Tablet Simulations</th></tr>
<tr><td colspan="2">1.9 GHz</td></tr>
<tr><td>
</td><td>
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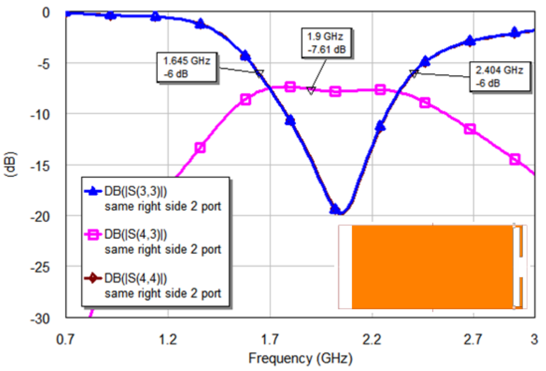
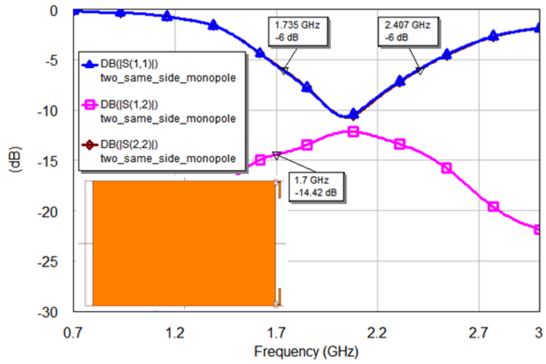
<tr><td>
</td><td>
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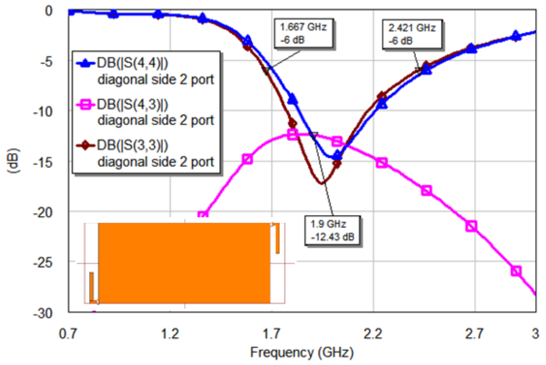
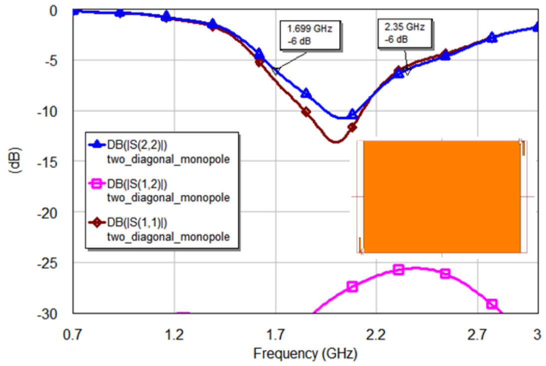
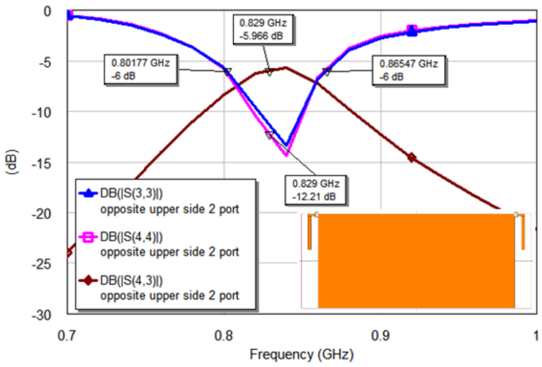
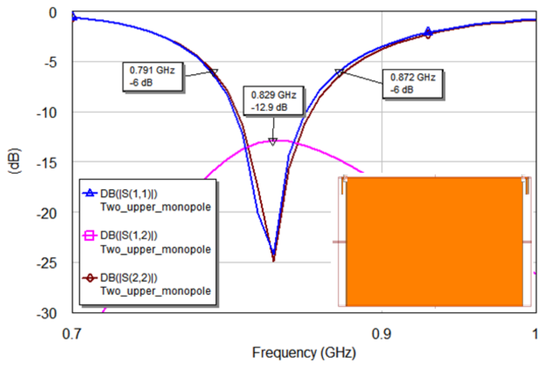
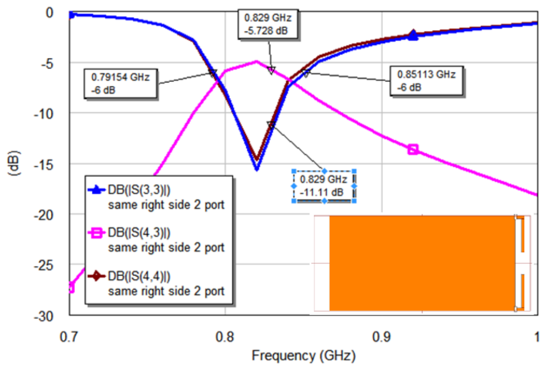
<tr><td>
</td><td>
</td></tr>
</table>

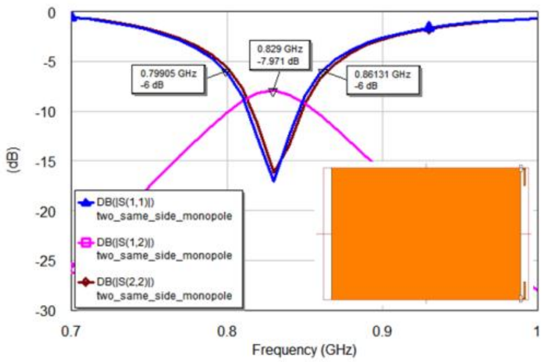
Table 1 Difference between Smartphone simulation over tablet simulation in terms of similar antenna disposition and for same frequency simulated for the 1.9 GHz frequency

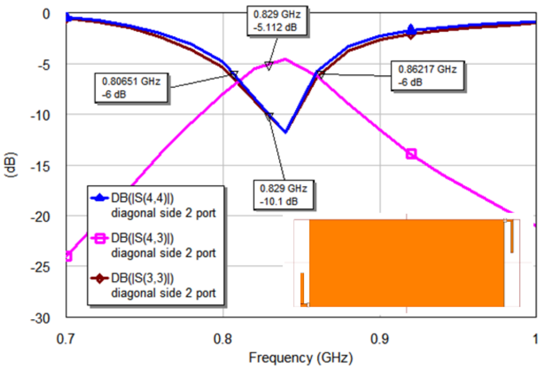
Smartphone Simulations	Tablet simulations
0.829 GHZ	











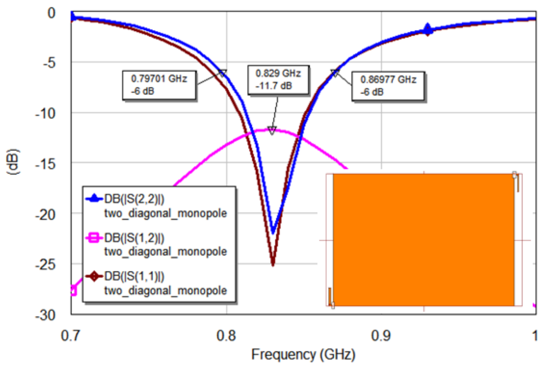
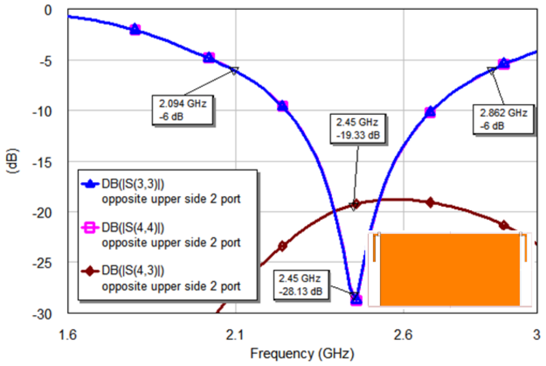
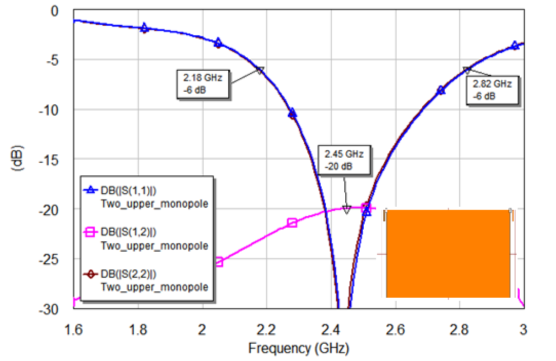
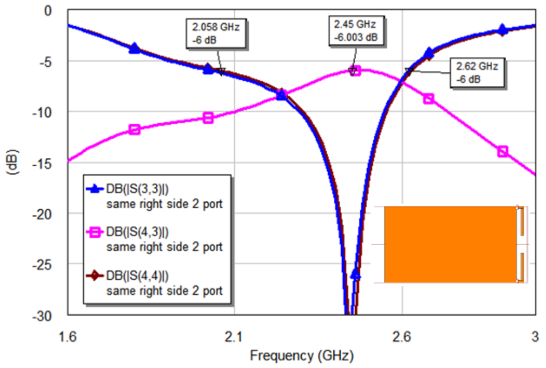


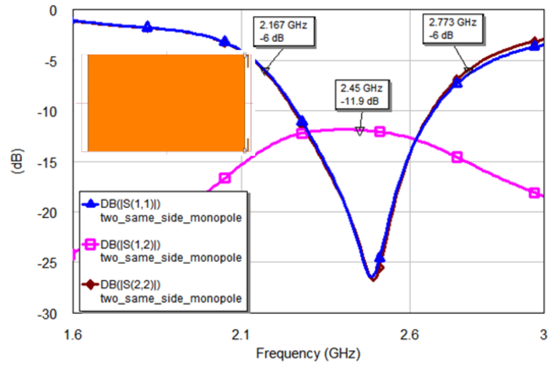
Table 2 Difference between Smartphone simulation over tablet simulation in terms of similar antenna disposition and for same frequency simulated for the 0.829 GHz frequency

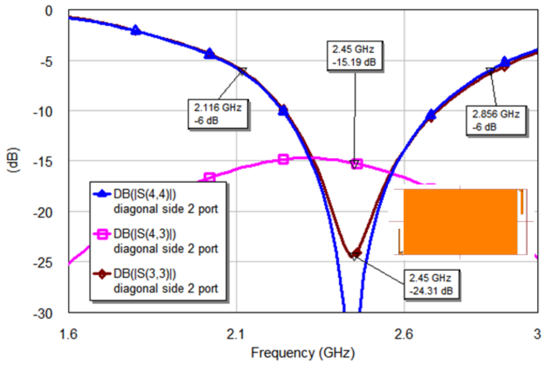
Smartphone Simulations	Tablet Simulations
2.45 GHz	











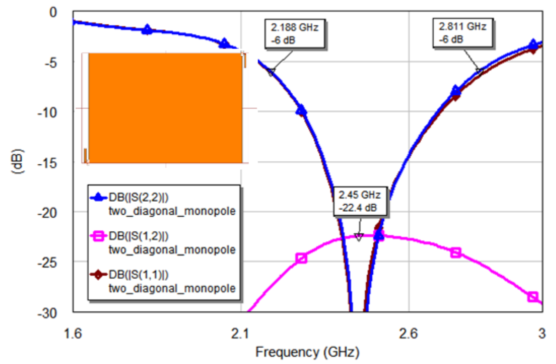


Table 3 Difference between Smartphone simulation over tablet simulation in terms of similar antenna disposition and for same frequency simulated for the 2.45 GHz frequency

Once the simulations have been compared, it can be seen that, for the tablet platform there is always a better isolation result. Intuitively, it can be seen that, distance is not always the key factor for achieving better isolation, further analysis of this comparison will be done in order to obtain more conclusions.

3.2.3. RESULTS

Along this section, the results of all the simulations have been put in a table *Fig.* 26 and are displayed in order to compare the bandwidth and the worse S_{21} result. By doing so, it will be easier to take the needed conclusions in order to keep on with the project analysis.

This comparison will lead to a forward understanding of behavior for the different platforms at the tuned frequencies. Further conclusions and decisions will be made based upon this.

PLATFORM (mm)	DISPOSITION	0.829 GHz				1.9 GHz			
	One monopole							BW	34,7%
	Two monopoles right side	S21	(-) 5,7 dB	BW	7,3%	S21	(-) 7,6 dB	BW	37,5%
	Two monopoles upper side	S21	(-) 5,9 dB	BW	7,6%	S21	< (-) 30,0 dB	BW	35,8%
120 x 60	Two monopoles diagonal side	S21	(-) 5,1 dB	BW	6,7%	S21	(-) 12,4 dB	BW	36,9%
	One monopole							BW	31,8%
	Two monopoles right side	S21	(-) 7,9 dB	BW	7,5%	S21	(-) 12,0 dB	BW	32,5%
	Two monopoles upper side	S21	(-) 12,9 dB	BW	9,7%	S21	(-) 20,0 dB	BW	33,8%
240 x 170	Two monopoles diagonal side	S21	(-) 11,7 dB	BW	8,7%	S21	(-) 27,0 dB	BW	32,2%

PLATFORM (mm)	DISPOSITION	2.45 GHz			
	One monopole				
	Two monopoles right side	S21	(-) 6,0 dB	BW	24,0%
	Two monopoles upper side	S21	(-) 19,3 dB	BW	31,0%
120 x 60	Two monopoles diagonal side	S21	(-) 15,2 dB	BW	29,8%
	One monopole				
	Two monopoles right side	S21	(-) 11,9 dB	BW	24,5%
	Two monopoles upper side	S21	(-) 20,0 dB	BW	25,6%
240 x 170	Two monopoles diagonal side	S21	(-) 22,4 dB	BW	24,9%

Fig. 26: Summary table relating the positions and frequencies of the platforms with the Bandwidth and S_{21} parameter

A graph showing the tendency (Fig. 27) of the isolation over the distance over wavelength has been done. Seeking a relationship between antenna disposition, platform dimensions and frequencies, the following graphs were implemented.

The general trend is the largest d/λ, the better isolation. However, there are interesting cases to outline. For instance, For the Smartphone case, the position with largest d/λ does not provide the best S_{21} result.

This means that distance is not only the key parameter, when a mode in the PCB is excited should also be taken into account.

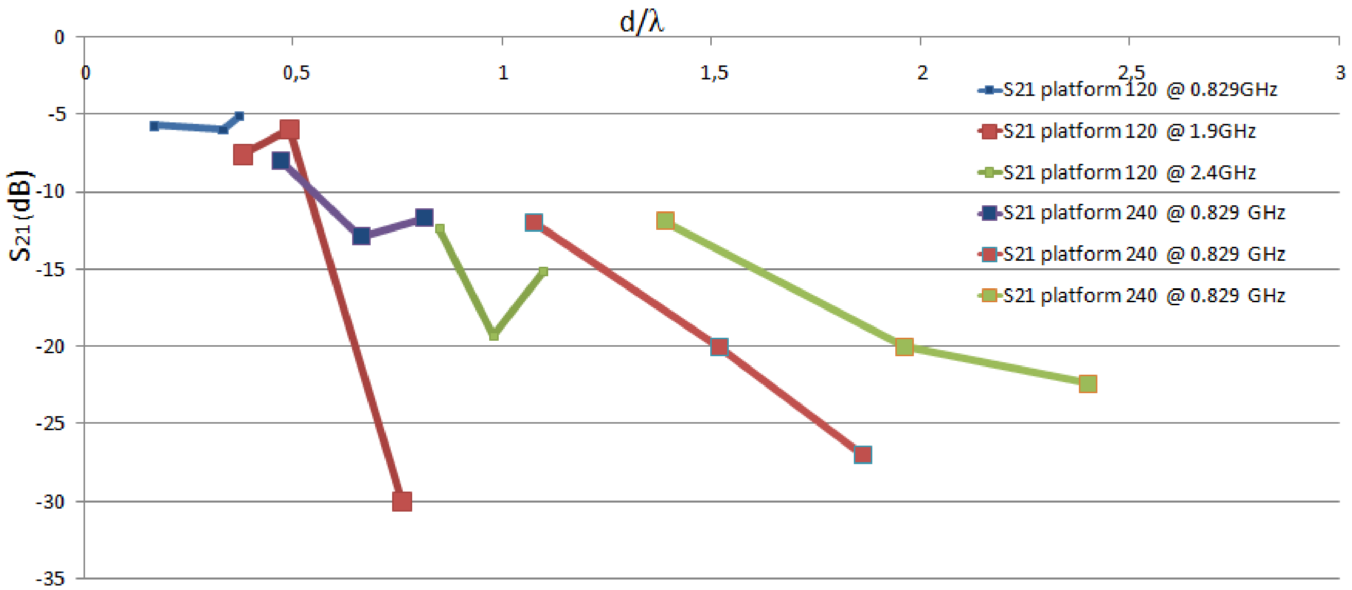


Fig. 27: Graph showing parameter S_{21} for several platforms in terms of distance over lambda

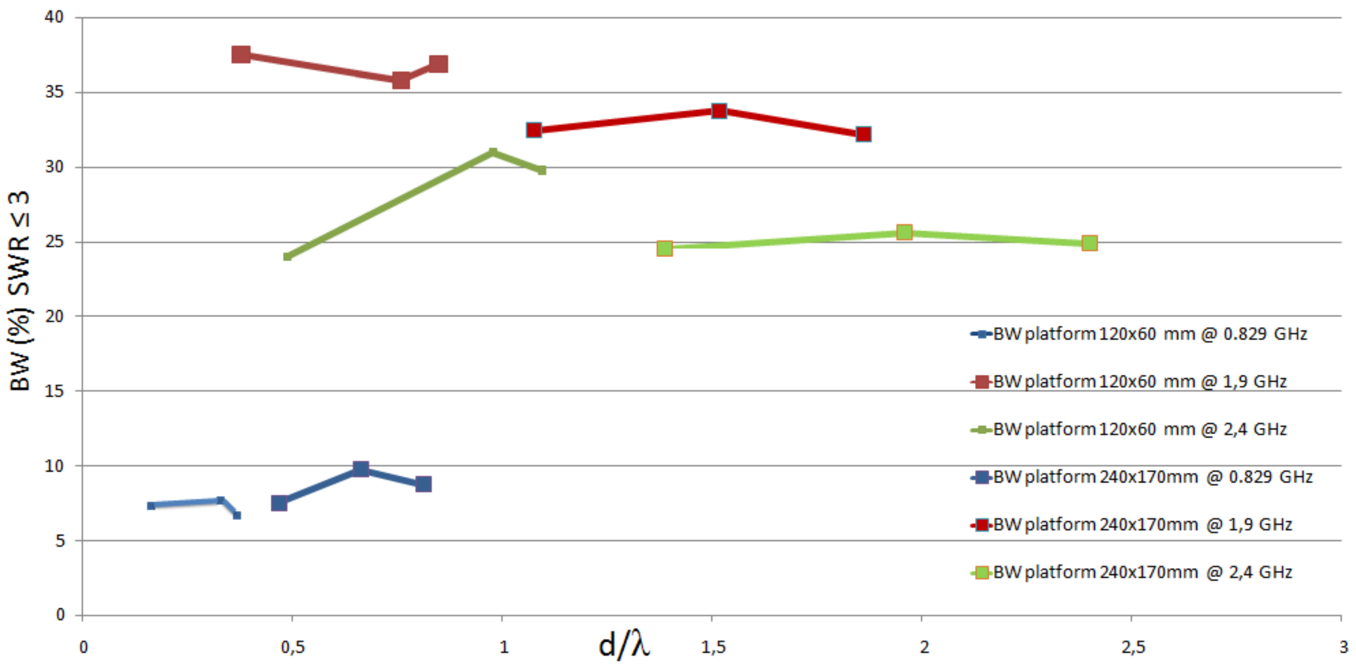


Fig. 28: Graph showing the bandwidth of the system in terms of distance over lambda

3.3. GROUND PLANE BOOSTER ANTENNA TECHNOLOGY

After seeing the effects and relationship between radiating antennas (monopoles) for several platforms and several frequencies (Fig. 26 - Fig. 28), some possibilities of future work have been seen in terms of placement, platform and frequencies. This section will try to understand a new kind of technology to be used that will likely improve such relationship between distances and frequencies in terms of isolation.

The technology implemented for this work is a different approach to the classic radiating elements used so far. This technology uses no radiating elements instead of radiating elements. The main goal of those elements is to get the ground plane excited so that it will become the radiating element of the device.

Thus with the adhoc matching network, the system will excite several modes at the ground plane and then radiate at a certain frequencies.

Among all the possible Ground Plane Booster Antennas (Fig. 29) [27] - [53], of 12mm x 5mm x 5mm is used.

For this case, two Ground Plane Booster Antennas have been taken in order to demonstrate the interaction between them working at the same platform and at the same frequency. This will lead to get a better understanding of the worse cases and possible scenarios in order to mitigate the eventual bad effects of using both GPB's.

3.3.1. TWO GROUND PLANE BOOSTER ANTENNA TECHNOLOGY BEHAVIOR WHEN EXCITING A GROUND PLANE

This part will explain the behavior that a platform has when using the Ground Plane Booster Antenna technology. This study is focused at the HFR (1,71 GHz to 3 GHz) band. Always trying to tune the radiating system so that this could operate within the desired bands.

The aim is to excite the needed modes at the ground plane using several lumped elements. The procedure to be followed can be observed at the 3.3 chapter from the project [55].

The final goal of all this procedure is to find such elements for the matching network that can make the impedance curved showed at the Smith Chart fit inside the SWR=3 circle.

3.4. ISOLATION WITHIN GROUND PLANE BOOSTERS

After seeing the behavior of radiating antennas in several platforms a second analysis has been taken using the Ground Plane Booster Antenna technology. This technology not only will let us undertake simulations using same size elements for different frequencies tuning a matching network, but also are very small in terms of size.

This section explains the simulations taken for the case of three different platforms at the bands of 0.829 GHz, 1.9 GHz and 2.45 GHz in order to analyze the behavior of Ground Plane Boosters as antennas.

A Ground Plane Booster Antenna Fig. 29 [27] - [53],, is an L- shaped monopole fed by 7 ports in order to provide a very versatile combination of elements for an hypothetic matching network. It has a strip line at a different height attached to it .

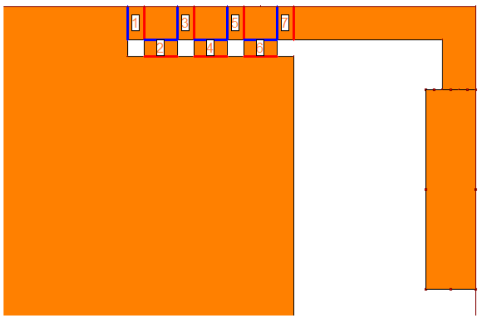


Fig. 29 Example of a Ground Plane Booster Antenna designed at the top vertex of a 120 mm x 60 mm platform ; The port is divided into 7 sections that will let design a suitable matching network. The Ground Plane Booster Antenna and the ground plane are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013. The Ground Plane Booster Antenna is 12mm x 5mm x 5mm

As with the monopole analysis, the Ground Plane Booster Antennas have been placed in several positions around the PCB (Table 4) in order to see the relationship between the distance between antennas, its isolation and bandwidth to then see if there is any notable conclusion to be taken and in order to have a magnitude approach to how this antennas behave for the cited frequencies and locations.

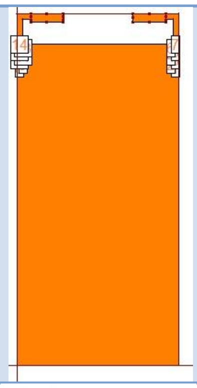
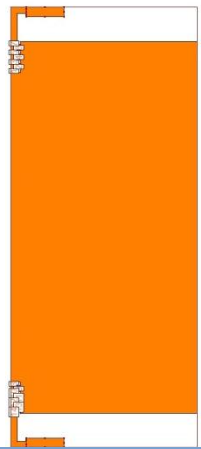
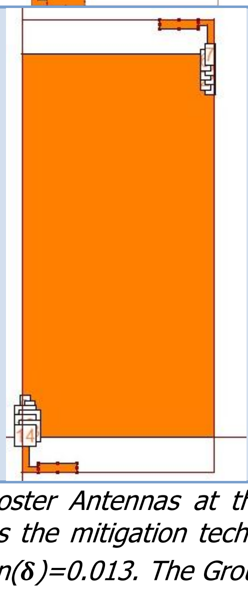
Ground Plane Boosters at the short same side	
Ground Plane Boosters aligned along the long side	
Ground Plane Boosters at the diagonal corners	

Table 4 Different disposition for the Ground Plane Booster Antennas at the platform. Both Ground Plane Boosters and the ground plane as well as the mitigation technique are printed over an FR4 substrate of 1mm width h (ε_r *= 4.15 and tan(δ)=0.013. The Ground Plane Booster is 12mm x 5mm x 5mm*

3.4.1. MEASURING PROCEDURE

The three different platforms taken are the ones that best could be fitted in a Smartphone, Tablet and a Smartwatch. The dimensions of which are, 120x60 mm, 240x170 mm and 30x20 mm respectively.

The reason for choosing such platforms is due to the market demand of such products and, as seen in the introduction, its search for an optimized size and shape. This leads to a need to understand the behavior and possibilities of such platforms.

First, the PCB has been designed with the IE3D electromagnetic software. A combination of two layers have been drawn. Once the PCB has been designed, the Ground Plane Booster Antennas were located in several places for the three cases (Table 4):

- Both Ground Plane Booster aligned at the shortest side of the PCB.
- Both Ground Plane Booster aligned at the longest side of the PCB.
- Both Ground Plane Booster located at opposite diagonal corners of the PCB.

Second, the simulation has been configured. A range from 0.65 GHz to 6 GHz has been taken in order to analyze the implications of the Ground Plane Boosters at such localizations for the bands of 0.829 GHz, 1.9 GHz, 2.45 GHz and 5 GHz. A step of 0.02 GHz has been taken between frequencies measured and the interpolation has been enabled in order to shorten the simulation time given the great amount of points to be simulated. Then, the simulations have been carried out.

Third, the AWR software has been used in order to see the impedance at both ports. Although at the IE3D, for the case of each Ground Plane Boosters, 7 ports have been disposed (Fig. 29), at the IE3D only one has been fed. The rest have been configured as such to have a total impedance matching at the desired frequencies. The fact of having 7 possible ports have given the opportunity to combine several lumped elements in order to find the best matching. The port 1 has been fed and the rest have been short circuited, left open circuit or provided by a lumped element. The priority in this part was to find the best matching in terms of each port without having any bandwidth restriction.

Fourth, as for the monopole review, the simulation for all localizations as well as all for all frequencies has been made. As the main goal was to adapt the ports, the procedure followed was:

a) In order to match at the desired frequencies, the smith chart has been used in order to see how the system naturally behaved feeding the antenna at the closest port to the Ground Plane Booster.

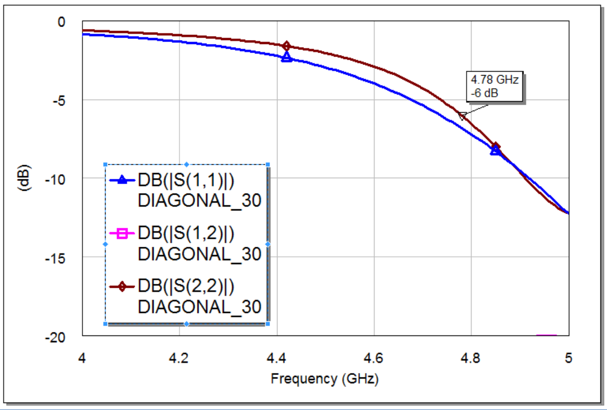
b) Firstly, in order to match the desired point from the impedance curve at the smith chart, the feeding port has been changed to the port 1 in order to start trying with new elements, a generic capacitor or coil tunable has been put in the closest ports to the Ground Plane Booster.

c) Secondly, the parameter S_{11} has been measured in a smith chart.

d) Thirdly, depending on the location of the desired frequency in the smith chart, the value of the components have been tuned in order to find the center of the smith chart and by so, adapting the port. By putting capacitors and inductors, the impedance curve varied in such a way that the desired impedance point at the desired frequency finally was located in the middle of the chart, meaning a perfect matching to the 50 Ohm from the port.

e) On the one hand, for the case of the second port, for both the Smartphone and the tablet, the matching network has been duplicated as the impedance behavior was the same. On the other hand, for the case of the Smartwatch, by tuning the matching network related to the port 1, the matching at port 2 also varied. A compromise between both ports had to be found.

f) Finally, the graph has been duplicated as rectangular in order to see the S_{21} and S_{22} parameters (Table 5 - Table 7).

<table>
<tr><th>DISPOSITION AND CASE</th><th>SIMULATED RESULTS</th></tr>
<tr><td>Smartwatch platform with the GPB aligned at the diagonal disposition at the 5 GHz band (Best case)</td><td>
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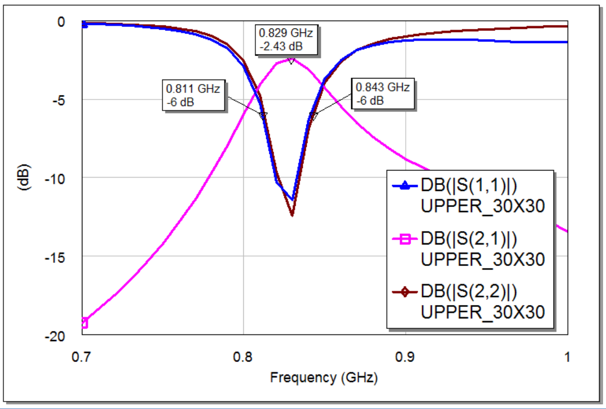
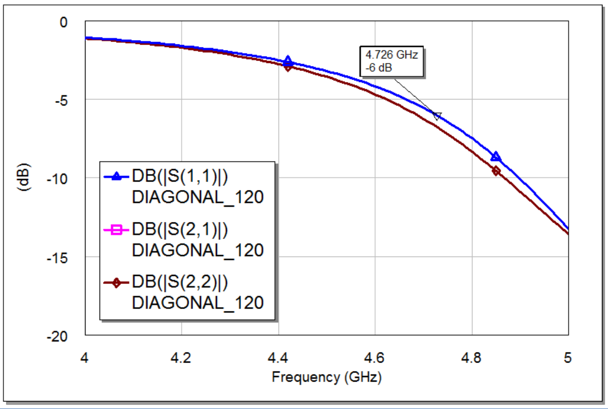
<tr><td>Smartwatch platform with GPB aligned at the longest side at the 0.829 GHz band (Worse case)</td><td>
</td></tr>
</table>

Table 5 Disposition and operating frequency for the best and worst case at the Smartwatch platform

<table>
<tr><th>DISPOSITION AND CASE</th><th>SIMULATED RESULTS</th></tr>
<tr><td>Smartphone platform diagonal disposition at the 5GHz band (Best case)</td><td>
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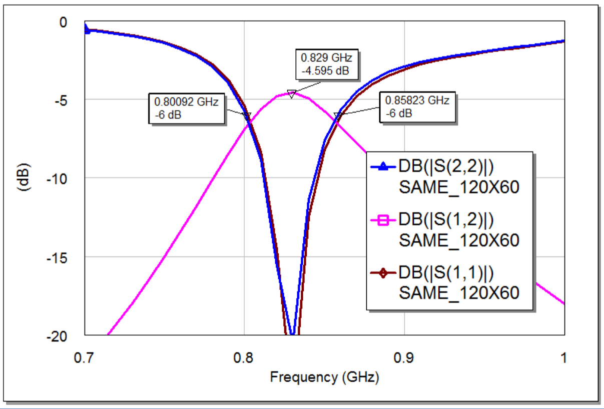
<tr><td>Smartphone platform with GPB aligned at the shortest side at the 0.829 GHz band (Worse Case)</td><td>
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Table 6 Disposition and operating frequency for the best and worst case at the Smartphone platform

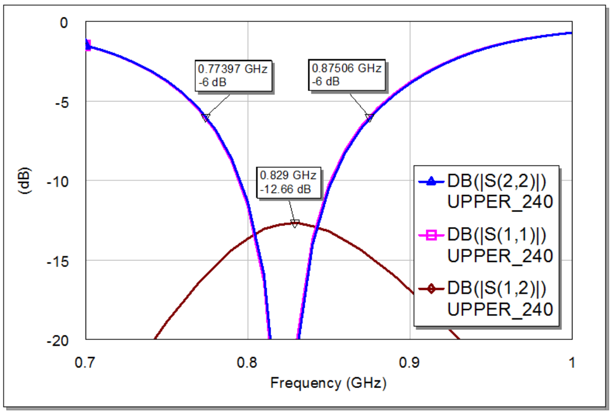
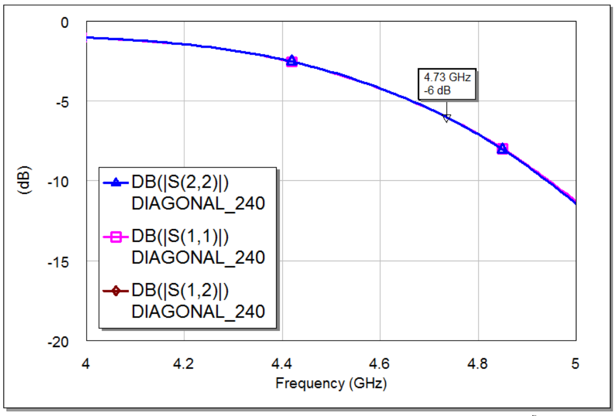
DISPOSITION AND CASE	SIMULATED RESULTS
Tablet platform with the GPB aligned at the shortest side at 0.829 GHz band (worse case)	
Tablet platform diagonal disposition at 5 GHz band (best case)	

Table 7 Disposition and operating frequency for the best and worst case at the tablet platform

PLATFORM (mm)	DISPOSITION	0.829 GHz S21 (dB)	BW (%)	1.9 GHz S21 (dB)		2.45 GHz S21 (dB)		5 GHz S21 (dB)	
	Two GPB shortest side	-12,7	7,3%	-12,4	45,0%	-15,3	24,0%	-10,1	24,0%
	Two GPB longest side	-13,0	9,4%	-19,3	52,4%	-21,6	25,9%	-15,1	28,8%
240x170	Two GPB diagonal side	-13,5	13,3%	-29,0	55,0%	-23,5	26,6%	-30,0	27,9%
					31,8%				
	Two GPB shortest side	4,6	5,5%	-6,8	39,9%	-5,4	24,5%	-21,3	29,2%
	Two GPB longest side	-4,7	4,3%	-24,7	35,8%	-17,9	34,0%	-13,7	28,1%
120x60	Two GPB diagonal side	4,7	9,6%	-12,8	36,5%	-16,0	32,3%	-21,7	29,2%
					31,8%				
	Two GPB shortest side	-2,4	3,0%	-3,8	38,1%	-4,6	48,9%	-5,1	27,6%
	Two GPB longest side	-2,5	3,5%	-5,0	29,5%	-7,0	25,2%	-7,5	29,6%
30x30	Two GPB diagonal side	-3,0	1,0%	-1,9	38,8%	-7,3	12,6%	-19,5	27,9%

Table 8 Summary table relating the positions and frequencies of the platforms with the Bandwidth and S_{21} parameter

3.5. CONCLUSIONS

Finally, a series of conclusions were observed from the simulations shown in *Fig.* 27 - Fig. 29.

3.5.1. MONOPOLE ANALYSIS

- One could imagine that, as distance between monopoles would increase in terms of the wavelength, its isolation would too. Results show that (*Fig.* 26, *Fig.* 27), maximum isolation is found for the second case, where the disposition of both monopoles does not give maximum separation.
- In terms of impedance matching, and measuring the S_{11} parameter, both first cases give the same values. The third case though, shows a greater Band Width at the same conditions.
- When matching the system to operate at the 900MHz band, before simulation one could think that, the greater the distance is, the best isolation between ports would be possible to achieve. By having a look into it is demonstrated that there are other factors taken into account for such improvement. It is very particular to see that for the diagonal case, which gives the greatest distance, the isolation is not the best of the three cases. This is due to the current Modes taking place in the PCB (Fig 27, Fig 28).
- It is also remarkable to say that, when trying to match the system for the 900MHz band, although trying to achieve a 50 ohm at the Smith Chart for parameters S_{ii}, when achieved, the isolation is not as good as if a compromise between isolation and matching is tried.
- For the case of the 2.4 GHz band, matching is much easier than for the 900MHz band. When matching the system to operate in such band, the compromise mentioned above to find the best relation between isolation and matching is not necessary. Just by matching S_{ii} ports to 50Ohms at the Smith Chart is enough to find a very good isolation and matching.
- The bandwidth at the 2.4GHz band is much greater than at the 900MHz band.

3.5.2. GROUND PLANE BOOSTER ANTENNA TECHNOLOGY

It can be observed that for the 5 GHz band, the results were so good in terms of isolation (for all cases > 15 dB) (Table 8) that it was unnecessary to keep working with it as the hypothetical mitigations techniques that one could proposed would not add a significant improvement to the results shown.

All the measures have been documented and situated in a table (Table 8). By so, one can see there is a certain relationship between frequencies, distance over lambda and dimension of the platform:

a) For the tablet platform, there is not such relation between component values at the matching network.

b) For the tablet platform, the isolation and Bandwidth is the biggest and this could be thanks to the distance between antennas.

c) When tuning the antenna system, there is a relationship between the S_{21} parameter and the S_{11} parameter. Commonly, the greater the S_{11}, the worse the S_{21} gets. In this document there is no compromise pursued as a perfect matching for the S_{11} and S_{22} was tried to be achieved.

d) For the Smartphone platform, the relationship between isolation, bandwidth and position of the antennas is not obvious; one could think that the more distance between antennas, the more isolation and bandwidth would be gotten but one can see that there are more implications as it can be seen that for the diagonal disposition, where there is more distance, the results are worse than for the second most distanced disposition.

e) For the Smartwatch platform, there is a very strong relation between component values at the matching network. As one port S_{11} is being tuned, the other port suffers changes in its S_{11} results. This could be caused by the same as the implication mentioned at the last point.

f) Finally it can be seen that for the case of this kind of antenna, the results are better than the ones obtained at the monopole review.

After carefully studying the table (Table 8), one can observe several results that can bring some light into the magnitude of this kind of antenna.

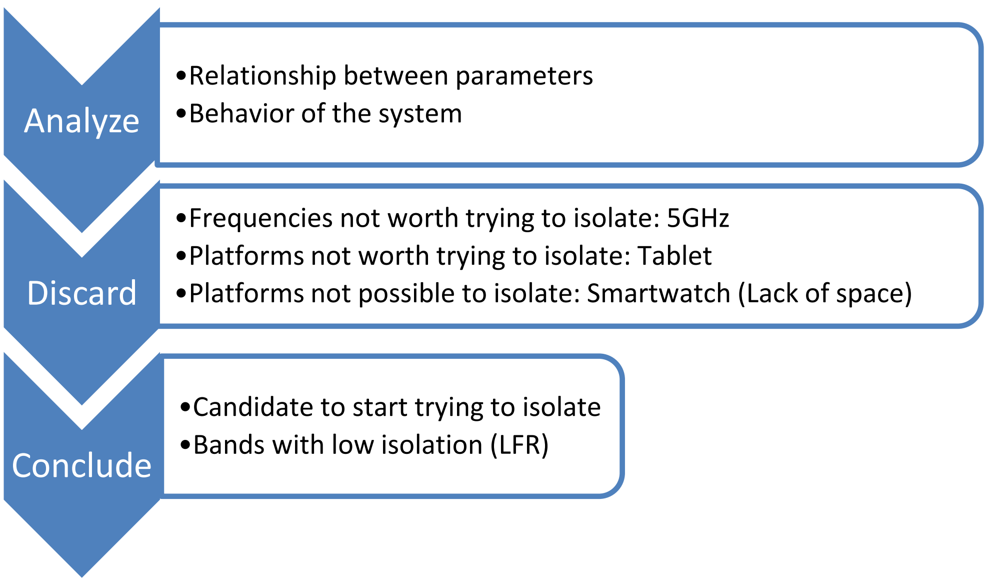
A fast look into the worse case of the tablet platform shows that considering mitigating the results is not needed as they show very good parameters even at its worst scenario.

We can see that for the case of the Smartwatch, isolation and bandwidth is very poor. It is notable to mention that for the case of the diagonal disposition, a very poor S_{21} is achieved compared to the upper disposition of the antennas.

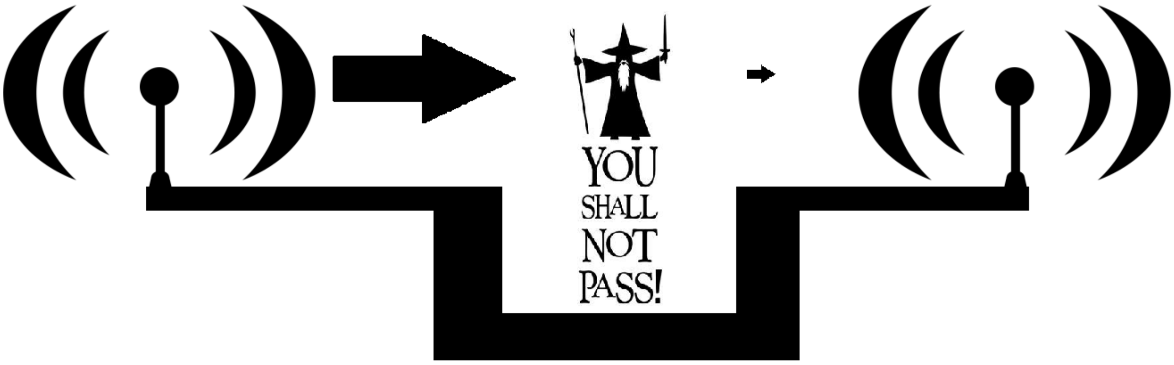
It is very hard to imagine that there is any mitigation technique using stub lines that could mitigate this effect having in mind that the longitude for this case of mitigation techniques is important and the S_{21} value to be mitigated is very bad (< 1.5 dB).

For the case of the Smartphone, it can be also observed that the difference between the diagonal and the upper disposition is very curious as distance is greater for the diagonal but results are better for the upper side.

A possible candidate for the mitigation techniques is then the same side (right side) disposition at the Smartphone platform as it gets the worse results but those results are not as bad as not to be considered.



4. ISOLATION MITIGATION



4.1. INTRODUCTION

It has been seen that for several placements, platforms and frequencies, parameters such as the isolation and the reflection ratio are different (Table 8, Fig. 26 - Fig. 28).

Following the aim of the project, and as it has been previously noted, taking the 120 mm x 60 mm and the "same side" disposition, which is the disposition with the shortest distance between Ground Plane Booster (Table 4), will exemplify and show if the possible isolation mitigation and its behavior in terms of isolation and impedance matching is possible to be improved.

For this chapter, the aim is to cover the 1,71 GHz to 3 GHz band and finding the best BW combined with a suitable isolation of always under -6dB. In order to do so, the combination of lumped elements in order to tune the system will differ from the ones treated the chapter before.

First, a suitable matching network will be seek in order to satisfy the operating band.

Second, a series of variations of the platform using a stub will be presented and simulated using a variation of the matching network in order to operate at the desired band.

Finally, a candidate will be chosen in order to follow with the investigation and see if it is practically operable.

4.1.1. THE DECISION MAKING PROCESS

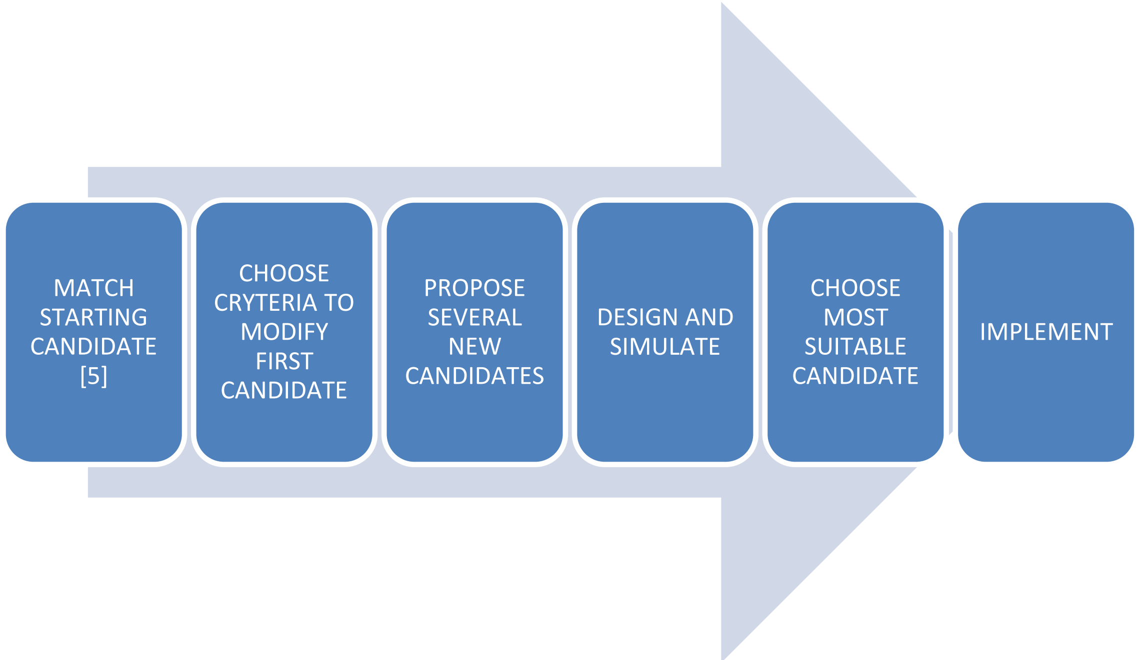
It is important to note the relevance of this chapter in terms of future work. As it will be seen, several candidates will try to isolate both GPB with a stub technique [6].

Understanding the behavior of this stub technique and predicting the results using mathematic and physical approaches would take a lot of time compared to the procedure that is taken in this chapter. As with other chapters in this project, the approach taken for this one is with a software simulator that not only processes the designed platform and shows its performance in terms of our desired parameters (isolation and reflection) but also helps simulating its behavior using lumped elements.

This analysis will lead to an understanding of the system at several frequencies for the selected platform although it can be inferred that for other platforms the behavior could be similar.

When making a decision, subjects try to find on their own "mental database" the information that led them make a previous decision. This information gives further knowledge and what it is also called experience to the subject making the decision. It is then thanks to previous decisions, mistakes and successes that the subject chooses what to do.

Through the results of the simulations and the prototype behavior, future designs will be able to have an easy understanding of how the stub solution works and behaves by observing how for this projects several solutions proposed performed and helped this project succeed.



4.2. BANDWIDTH INCREMENT WITH MATCHING NETWORK

In order to characterize the behavior of the platform with both GPB at the desired band, and as it has been noted before, the use of a matching network in order to tune the system is needed and designed.

The properties of the Ground Plane Booster Antenna Technology leads this design to operate at the band range desired by tuning the impedance curve within the Smith Chart thanks to the use of lumped elements.

4.2.1. UNDERSTANDING THE MATCHING NETWORK DISPOSITION

It is very important to note that when talking about matching networks, mapping components within ports of the design is important. Its order is not trivial.

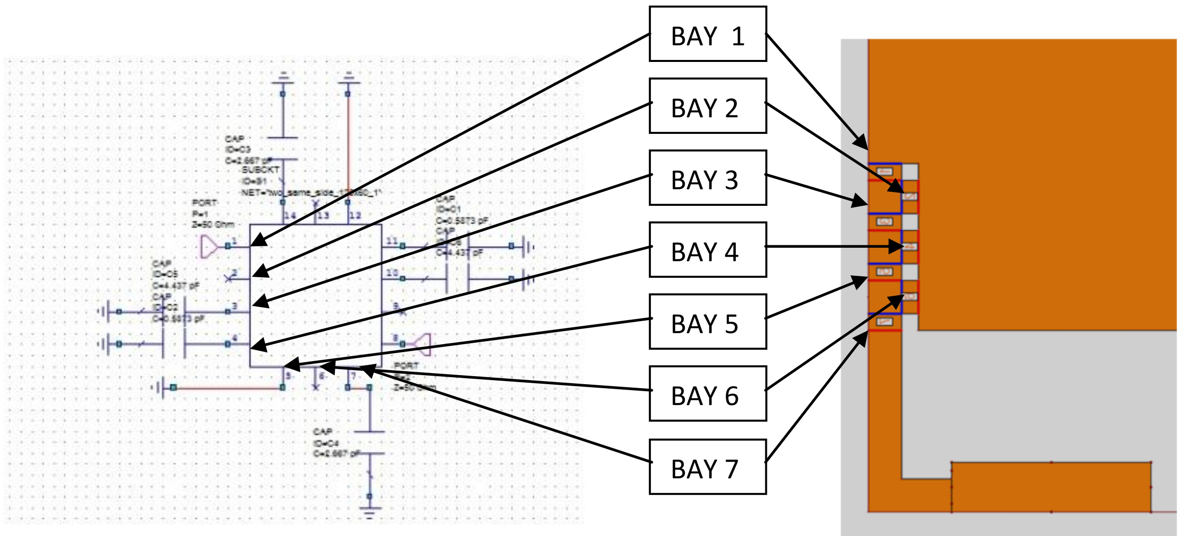


Fig. 30: Component mapping within the matching network

As it can be seen, there is a relationship between every connector in the AWR design software and every bay from the design in the IE3D electromagnetic simulator.

If there is no element nor ground means that the bay will remain open as an open circuit. If there is a ground located at the connector, that means that the bay will have a short circuit.

Bays 1, 3, 5, 7 will allocate serial components and bays 2, 4, 6 will allocate parallel components.

4.2.2. DESIGN OF A MIMO SYSTEM IN HFR

During this part, the basic design has been implemented and simulated for two GPB at the mobile phone platform (120 mm x 60 mm) for the HFR (1,71 GHz to 3 GHz) band without any mitigation technique.

This part will illustrate how by tuning the matching network in a proper way one can obtain the desired parameters in term of bandwidth and impedance matching.

Firstly, the natural behavior of the system (Fig. 31) is analyzed in order to know how what components shall be suitable.

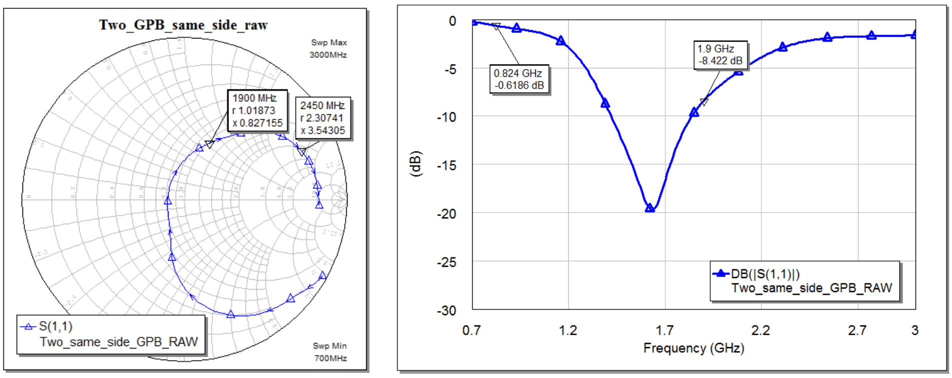


Fig. 31: Impedance natural response of a MIMO system composed by two GPB (left) and its S_{11} result (right)

As it can be seen (Fig. 31), the desired HFR frequency range is not following the SWR=3 limit and needs a matching network in order to operate within the range.

A capacitor is added in parallel (Fig. 32) in order to close a first loop. It needs to be noted that by having a loop centered, most of the frequencies within the loop will likely be inside the SWR=3 circle and then be adapted. This is how one can find a broadband situation.

After adding the capacitor (Fig. 32), as previously thought, the loop closes (Fig. 33) and the S_{11} parameter shows a broad matching.

As it can be seen (Fig. 33), the bandwidth of the system suffers an increment.

Pursuing a better impedance matching, another element shall be added to the matching network. The goal is to make all the points within the impedance curve in the smith chart related to the frequencies of the operating band be closer to the center (SWR = 1). The closest the curve is, the better matching the system will have.

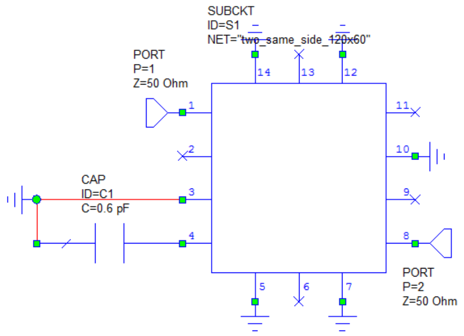


Fig. 32: First element for the matching network. A capacitor of 0.5pF is added in parallel

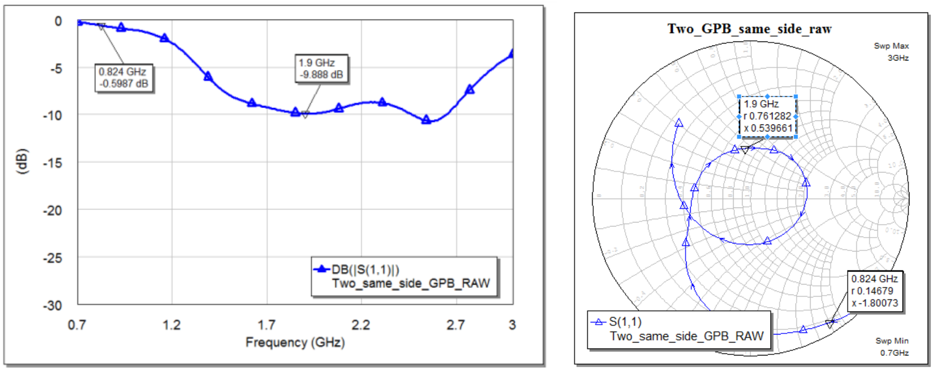


Fig. 33: Response for the system with the element added in the matching network

In order to do so, a serial capacitor is added to the system as can be seen in (Fig. 34).

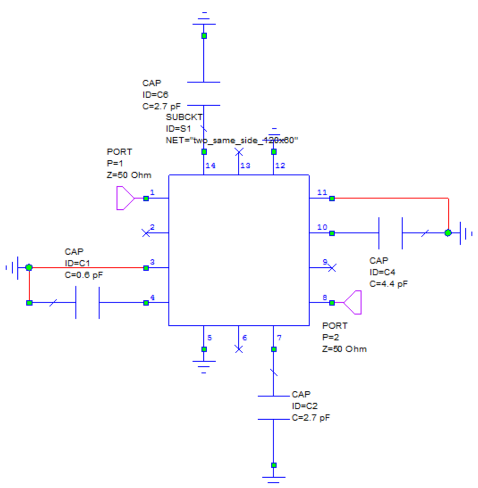


Fig. 34: Second element added to the matching network. A serial Capacitor of 2.7pF is added to the system

Thus it can be assumed that the system will now have a broad response and be adapted.

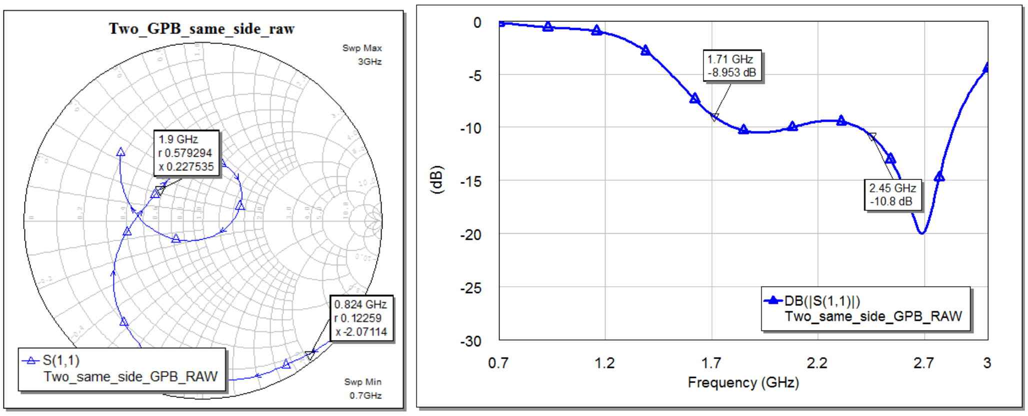


Fig. 35: System response with the new element added to the matching network. Impedance response (left) and S_{11} parameter (right) are displayed

As it was previously mentioned, the curve representing the frequency band is closer to SWR = 1 and by so the impedance matching is better (Fig. 35).

Although it may seem that all the range is adapted and meets the requisite (S_{11} < -6dB), the Smith Chart shows that the impedance can be better centered in order to find a constant good matching within the range.

In order to do so, another serial capacitor will be added (Fig. 36).

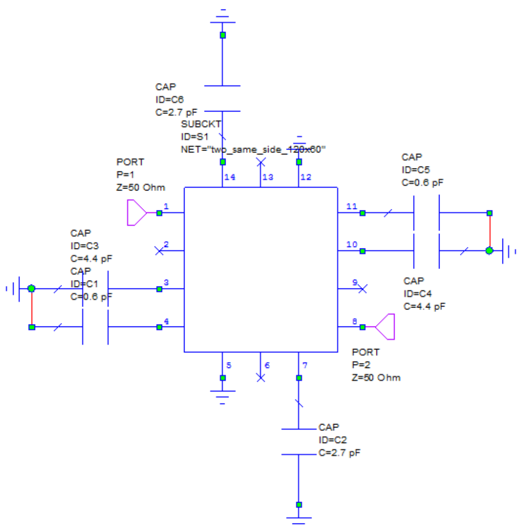


Fig. 36: System with the matching network and the third element added. A serial 4.4pF capacitor is added to the system

By doing so the system now will be well adapted and have a broad response because the impedance curve in the smith chart will be more centered and by so will be closer to SWR=1.

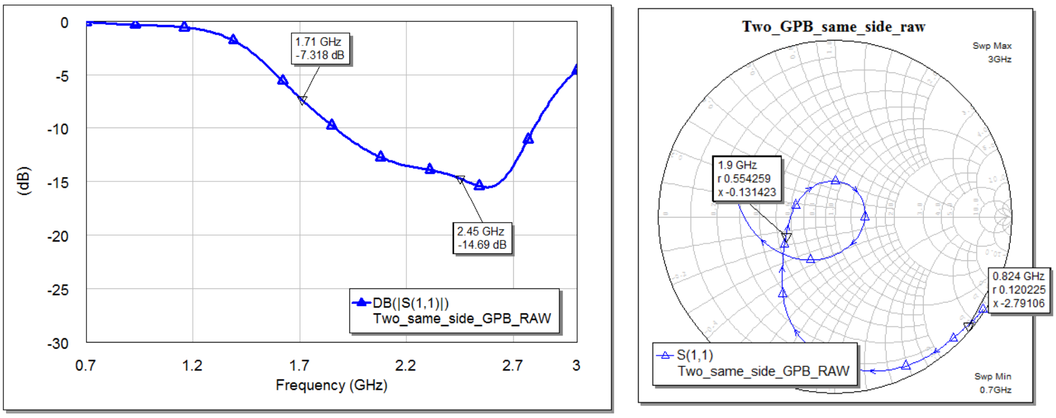


Fig. 37: Final result of the Broadbanding process. Impedance response (right) and S_{11} behaviour (left) are displayed

As it can be seen, by adding three capacitors at the matching network, the impedance curve has suffered a loop and this loop has been centered. This has helped to the better matching of the system by closing all the frequency points of the band to the SWR=1 (Center of the Smith chart) (Fig. 37).

4.3. ISOLATION BY STUB METHODOLOGY

The design methods in order to reduce the multi antenna mutual coupling, as it could be seen when reviewing the prior art and when analyzing the GPB MIMO behavior in terms of placement, platforms and frequencies, include the antenna placement optimization and modification of the device's ground plane and T-shaped ground plane stubs reducing the mutual coupling between orthogonal monopoles.

For this project, the design of a mobile phone platform using a pair of GPB exciting the platform ground plane and making it radiate with an optimized T-stub attached to the ground plane is the proposed solution.

This T-stub is taken from article [7] and then varied in order to understand its behavior and variations. Parametric study towards minimizing the mutual coupling will be done.

4.4. CANDIDATES

The study will be based on the solution proposed by the previous reviewed article [7] which T-stub is presented formed by 2 mm-wide strips in an extension of the ground plane (Fig. 38) and placed between the antenna elements as can be seen in Fig. 39.

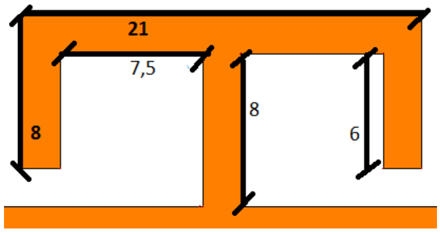


Fig. 38: Dimensions for the first candidate. Dimensions are in mm

It needs to be noted that the basic model from which the base is taken has been modified in order to operate at the desired frequencies by enlarging the T arms by the "y axis" due to the space occupied by the Ground Plane Boosters. The results will then be compared to several variations in terms of different parameters in order to see if a different approach can be found.

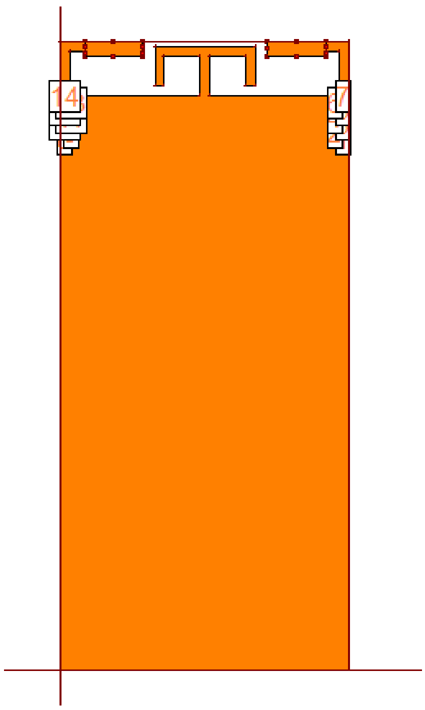


Fig. 39 First candidate to use as a mitigation technique. Both Ground Plane Booster Antennas and the ground plane as well as the mitigation technique are printed over an FR4 substrate of 1mm width (ε_r = 4.15 and tan(δ)=0.013). The Ground Plane Booster Antenna is 12mm x 5mm x 5mm

Firstly the basic candidate has been designed and simulated using the same matching network as the one used previously.

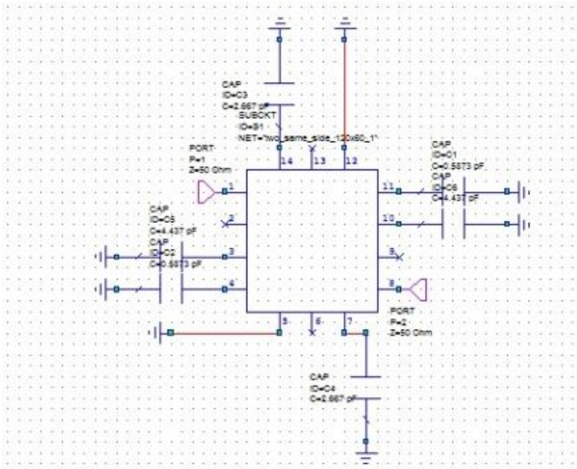


Fig. 40 Matching network for the first candidate

The results differ from the ones obtained before, therefore a slight modification of the matching network Fig. 40 in order to make the impedance curve match the SWR=3 requirement is needed.

This results leads us to understand that the isolation is better for the interested band.

As the approach from the T-stub solution is eventually good, having found an improvement from the last simulations, several modifications from it will be pursued. This modifications will try to understand if there is any relationship between the isolation and several modeling parameters for the T-stub such as:

a) Longitude of the Stub
b) Thickness of the Stub
c) Shape of the Stub
d) Area covered by the Stub
e) Location of the Stub
f) Symmetry of the Stub

Thus opens the door for several different candidates that can be seen in *Table 9*:

- A T-stub single-armed was tried in order to see if symmetry had a relation with port impedance matching.

- A T-stub with different arm lengths was tried in order to see if the symmetry could affect getting a better isolation or if different longitudes could isolate different bands.
- A long L-stub not centered was tried in order to see if the length of the strip *line could help isolate better.*

CRITERIA	PROPOSED SOLUTION
Initial T- stub	
T-stub single armed	
Different arm lengths T-stub	
Long L-stub	

Table 9 Table illustrating the different proposed solutions in order to use as mitigation technique. Both Ground Plane Booster Antennas and the ground plane as well as the mitigation technique are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013). The Ground Plane Booster Antenna is 12mm x 5mm x 5mm

4.5. SIMULATIONS

In order to find if the proposed candidates are suitable to be printed and used, several simulations will be carried out.

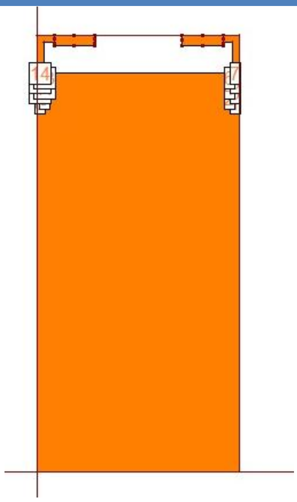
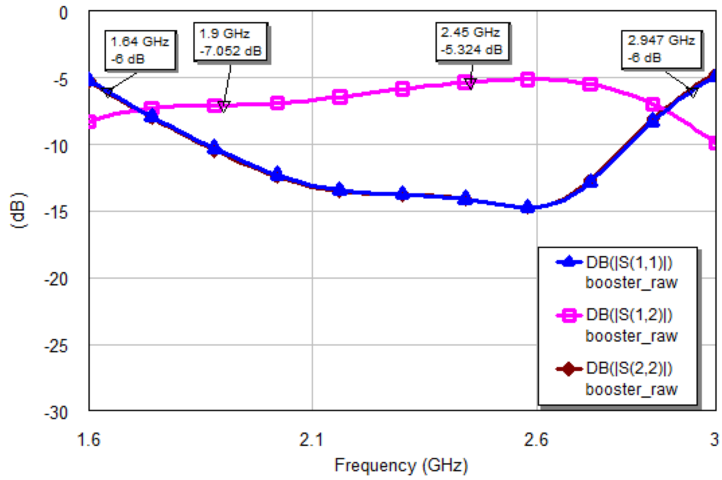
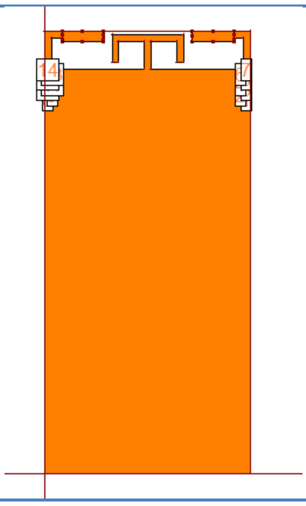
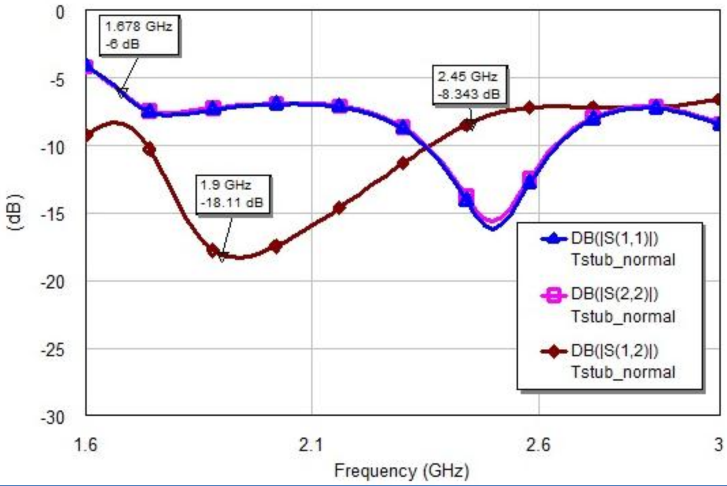
These simulations (Table 10) will try to find a better isolation that the one found in the previous part for the T-stub proposed by the article [7]. The procedure used for the simulation is the same as the one used for previous simulations:

a) Firstly, using the IE3D design software, the platforms have been designed following the same rules but changing the stub shape and dimensions in terms of the mentioned parameters.

b) Secondly, using the files obtained by simulating the design, a suitable matching network has been found.

c) Once obtained the suitable matching network, the S_{21} parameter in order to see if the isolation results are better is shown.

The following table (Table 10) shows the results obtained:

PROPOSED DESIGN	SIMULATION OF THE DESIGN
	
	

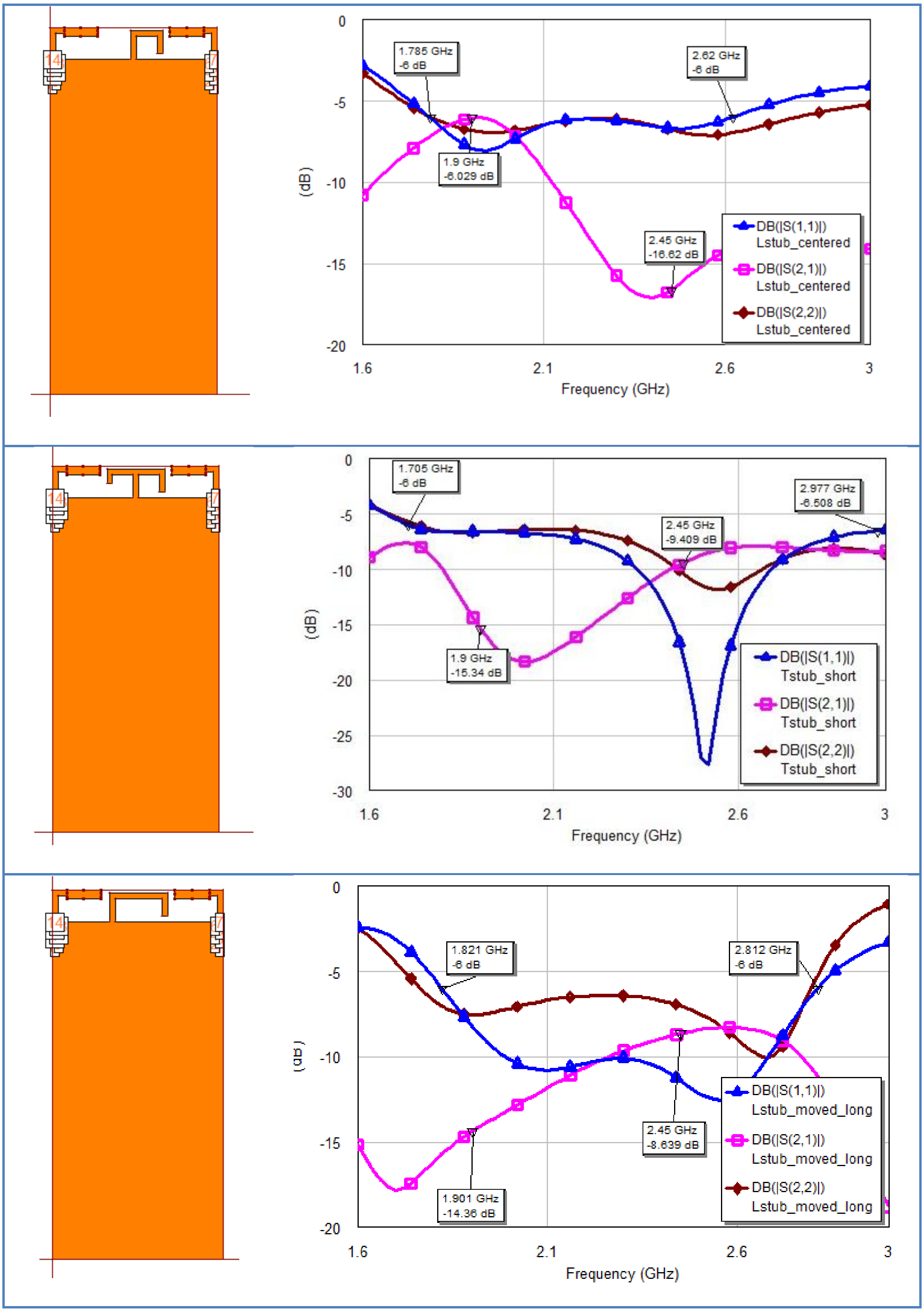


Table 10 Relationship between the mitigation technique and its result in terms of S_{21} , S_{11} and S_{22} parameters. Both Ground Plane Booster Antennas and the ground plane as well as the mitigation technique are printed over an FR4 substrate of 1mm width h (ε_r = 4.15 and tan(δ)=0.013). The Ground Plane Booster Antenna is 12mm x 5mm x 5mm

4.6. CONCLUSIONS

Once all the simulations have been carried out, several conclusions can be observed by looking at the table (Table 10).

One could think that there is are certain relationships between the parameters used to design the stub and the isolation but:

a) The distance of the stub and isolation has no relationship as it can be seen from the candidate "long L stub". The distance has been incremented but the isolation doesn't show an increment.

b) Trying to tune different frequencies by enlarging one arm just shows different impedance matchings at the S_{ii} for the same band.

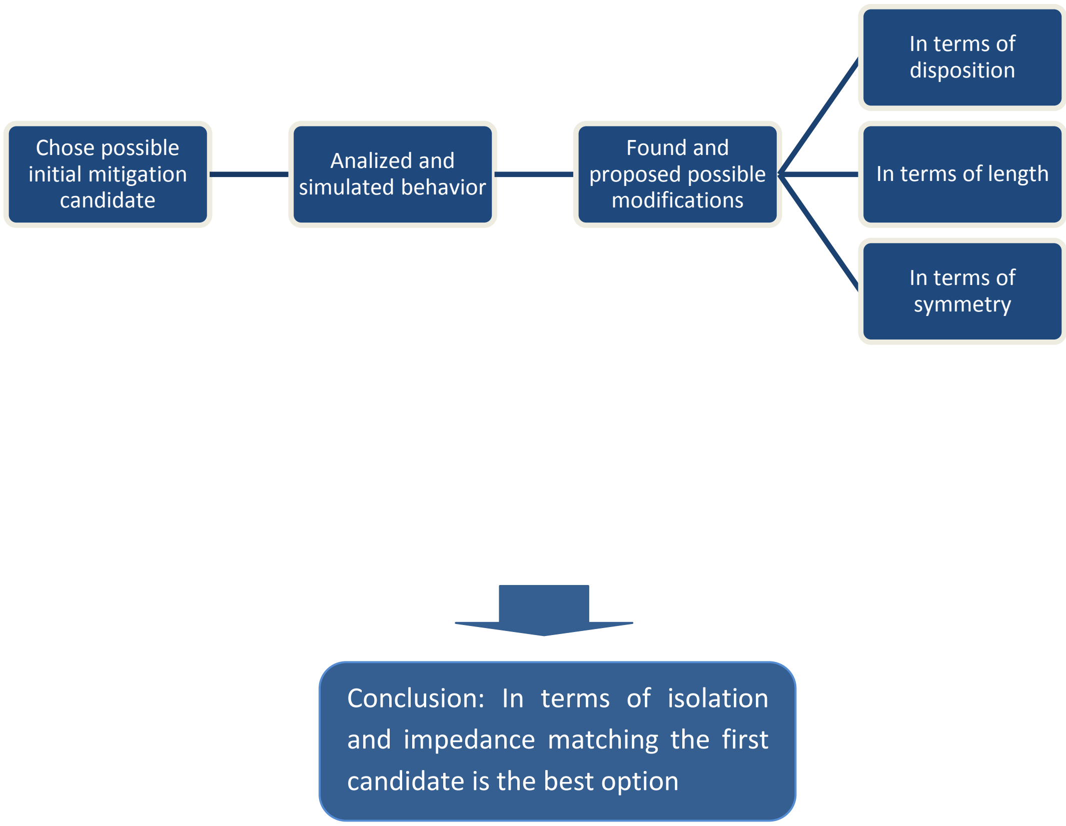
c) Using a single arm just shows a worse isolation at the low region of the band and a worse impedance matching for the higher bands.

d) The variations don't show a significant improvement from the original proposed solution

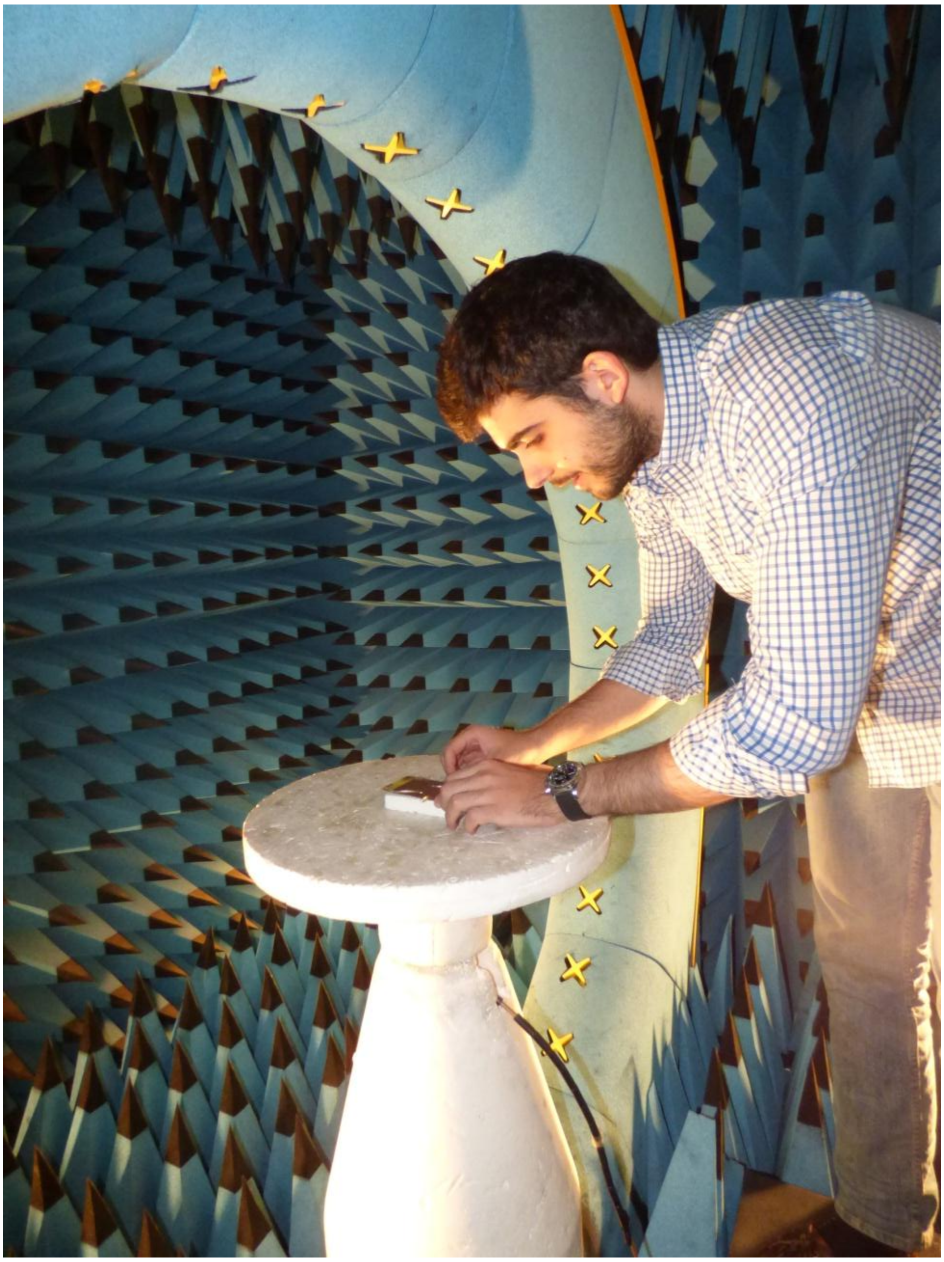
e) The initial proposed solution shows a better impedance matching for both ports along the band and gives a better bandwidth than the rest.

It is important to note that, as previously seen, the dimensions and volume of the solution are very important when having to find a mitigation solution. By seeing the differences in terms of isolation and bandwidth obtained by the proposed different designs, it can be noted that there is no such very relevant difference by using several shapes or different longitudes once a suitable solution has been found in terms of average isolation nor port impedance matching.

Thus, the prototype from where the analysis will be carried out will use the solution proposed by the article [7] with the modification of the enlarged arms in terms of the "y axis" proposed.


Chose possible initial mitigation candidate
Analized and simulated behavior
Found and proposed possible modifications
In terms of disposition
In terms of length
In terms of symmetry
Conclusion: In terms of isolation and impedance matching the first candidate is the best option

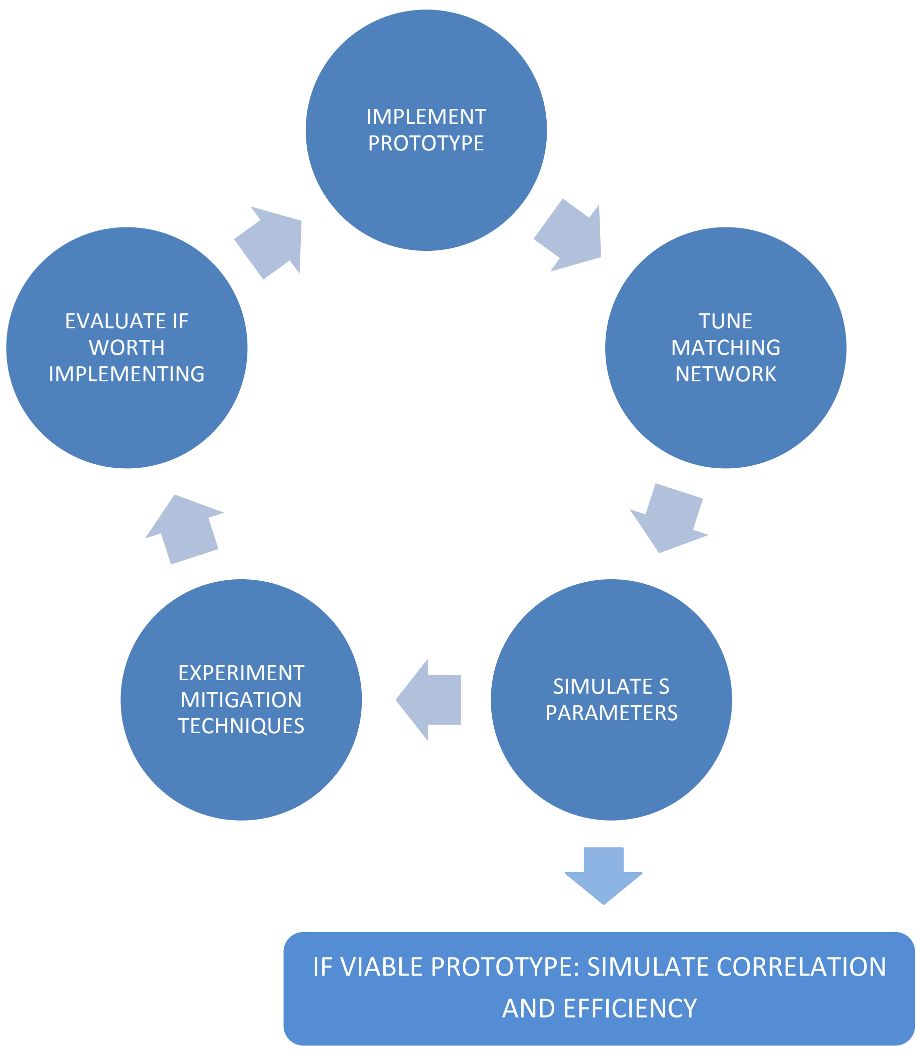
5. IMPLEMENTATION OF A MIMO SYSTEM USING GROUND PLANE BOOSTERS



5.1. INTRODUCTION

After designing, simulating and analyzing several candidates to use in order to address the market and manufacturers demand in terms of several factors reviewed previously such as dimensions, antenna efficiency and isolation, a candidate has been selected in order to build a prototype upon it and measure if the proposed solution simulated could, indeed, address such demands.

Aiming to validate the work of the simulation of MIMO systems based on Ground Plane Booster and using stubs for the isolation of them, this chapter will show the work done in the laboratory showing the selected candidates to be implemented and the results will be presented and commented.



5.2. PROTOTYPES

The prototypes selected are presented and their performance is shown to then be analyzed and conclude the viability of such prototypes.

The basic design from which all the analysis will be done is the same as the prototype proposed by the article [7] and modified as previously explained.

5.2.1. METHODOLOGY

In order to manufacture the proposed designs, a meticulous procedure has been followed so that the final measures could capture the real parameters of the systems.

First, the design of the platform with a CAD software of the solution is needed to be printed in greaseproof paper to be used as a mask when insolating a board of FR4.

The process of insolation consists in cutting a sheet of FR4 ($\boldsymbol{\varepsilon_r}$= 4.15 and tan($\boldsymbol{\delta}$)=0.013.) suitable for the design.

This material can be found at the chemical laboratory (Fig. 41) in Fractus.

Fig. 41 Chemical laboratory at Fractus

Second, at the chemical laboratory, the following steps must be followed in order to print the board in the perfect conditions:

a) Put the board into the insolator and keep it for 3 minutes and 30 seconds Fig. 42. It is very important to note that the board can't suffer any kind of light damage or any time isolation deviation as this could damage it and then the board wouldn't show its properties.

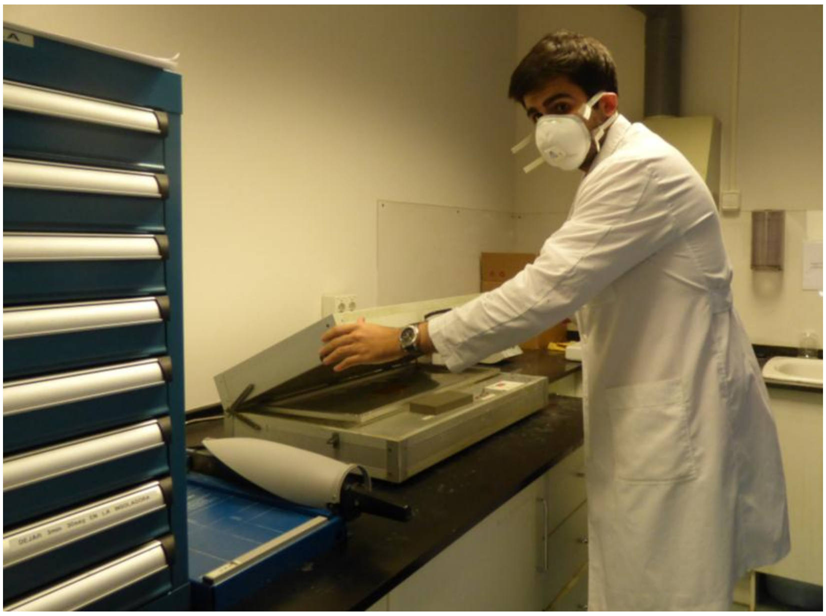


Fig. 42 Insolation process

b) Take out the board from the insolator and bath it in positive revelator liquid.
c) Once the design is drawn in the board, clean it with water.
d) A mixture of peroxide ¼, water ½ and hydrochloric acid ¼ is added to the board until the surplus copper is consumed.
e) Clean the board and put acetone in order to eliminate the rest of impurities.

Once this process has been achieved, the implementation of the matching network, ports and Ground Plane Booster Antennas within the board is done. Every step done must be analyzed with the network analyzer in order to know if the procedure followed gives the expected results from the simulation.

When the S-parameter response is the one expected from the simulations done in the previous chapter, the efficiency and E field measurements are done using an anechoic chamber SATIMO.

The SATIMO is an anechoic chamber where the prototypes are located and the results can be simulated.

Once obtained all the simulations, using a Fractus software, the correlation can be obtained with the efficiency results and the E field results.

5.2.2. PROCEDURE

The procedure followed in order to find the best candidate deals with several phases. These phases will assure a better understanding of the matter and will help find the real best solution.

a) Test parameters from the original design without mitigation technique.

In order to understand whether the solution was viable or not, a first prototype without any mitigation technique was built (Fig. 43). This prototype will be used in order to know if the proposed solution makes a difference in terms of isolation between ground plane boosters.

Fig. 43 First prototype: two Ground Plane Booster Antennas at a 120 mm x 0 mm platforms in order to have a basic solution and improve it

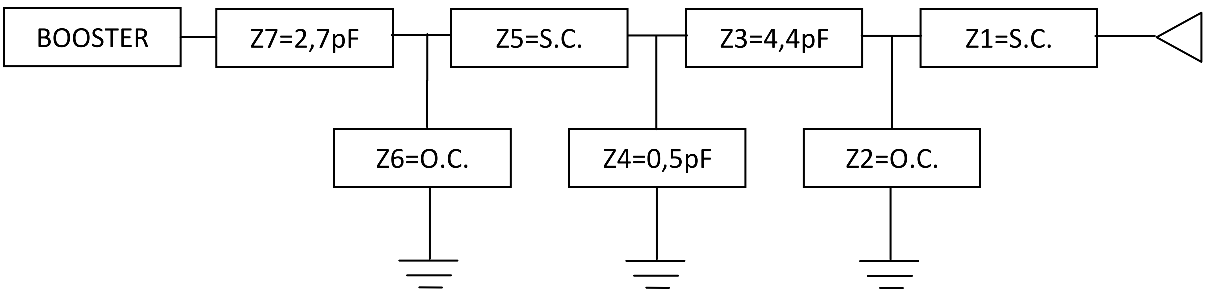


Fig. 44: Matching network for HFR prototype without mitigation technique. O.C= open circuit. // shunt. S.C. :short circuit. Same matching network for both ports

A set of measures will be done in order to know the magnitude of the isolation parameters between ground plane boosters.

b) Test parameters from the proposed first mitigation technique.

Then, the mitigation technique selected from the previous chapter is implemented in a new prototype (Fig. 45). By measuring its isolation and impedance matching one can see that the solution can, indeed, improve those parameters.

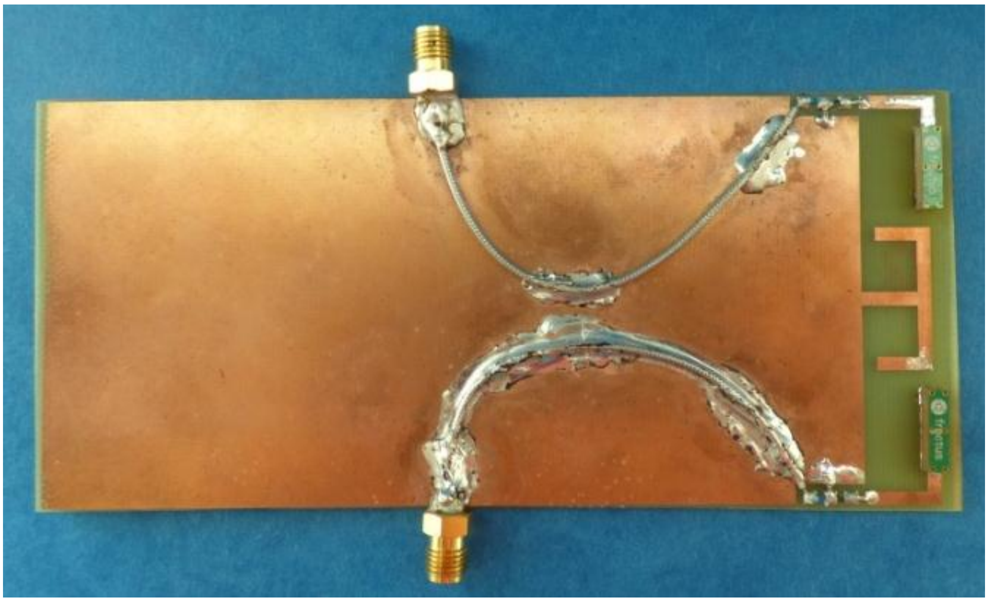


Fig. 45 First candidate to use as mitigation technique

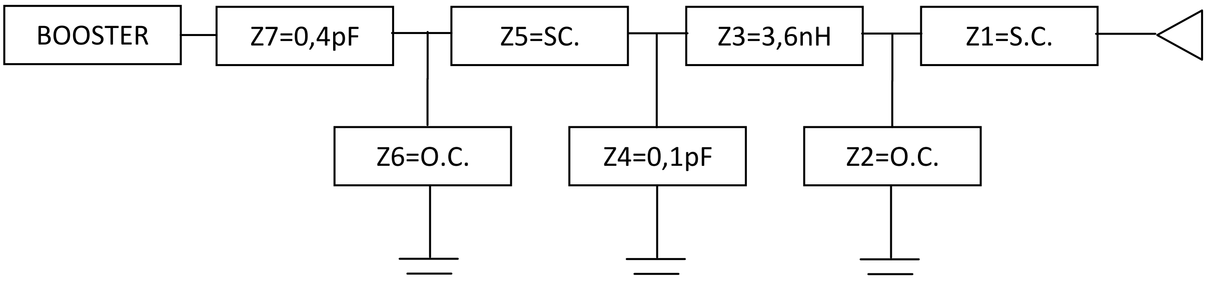


Fig. 46: matching network for the initial candidate to use as mitigation technique. O.C= open circuit. // shunt. S.C. :short circuit. Same matching network for both ports

A set of measures will be done in order to know the magnitude of the isolation parameters between ground plane boosters.

c) Experiment with new possible designs. And measure performance.

Seeking a way to find an even better solution, an experimental test will be carried out in order to see if there is any chance of getting better results by modifying the mitigation technique. By taking a copper tape and trying new figures one can presumably see if there could be an improvement (Fig. 47). The improvement that was pursued was measured using the network analyzer by measuring the S_{11}, S_{12} and S_{22} parameters as being related to isolation and impedance matching.

It is important to note that this eventual improvement shall not be taken seriously in mind as it must be simulated and tested.

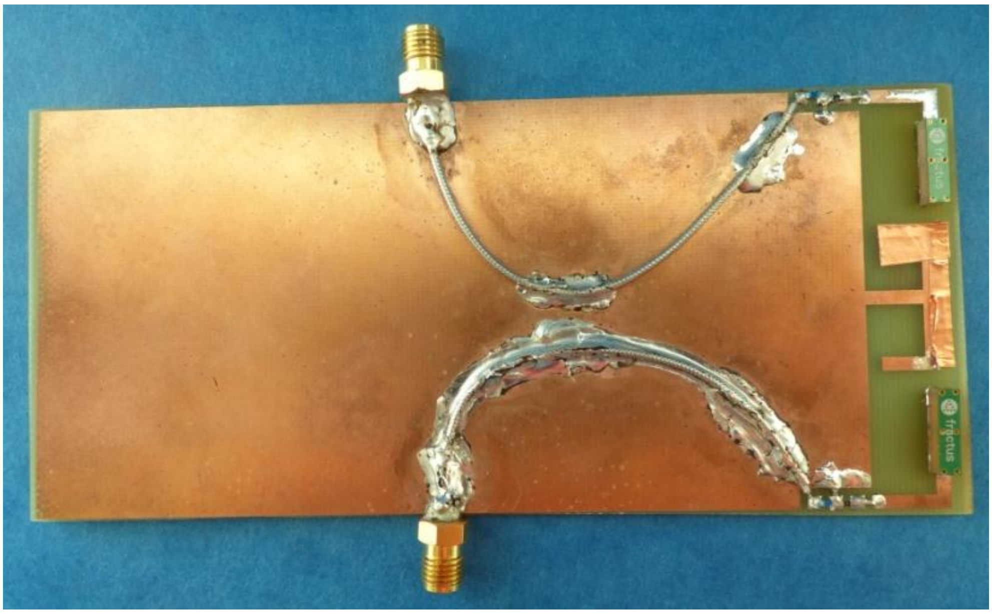


Fig. 47 Modifications made over the first candidate to find better solutions

d) Simulate such designs to find a proper matching network.

After several different proposals, a new candidate was found. Trying to extrapolate its dimensions (Fig. 48), a new simulation was carried out (Fig. 49) in order to see if the experimental procedure could have improved the first proposal.

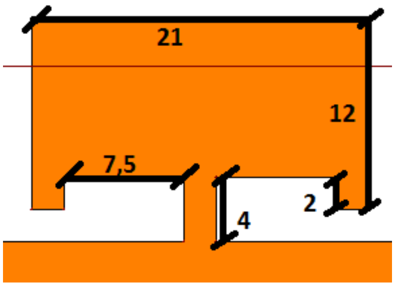


Fig. 48: Dimensions of the new solution found and designed. Dimensions are in mm

It was important to do that because the impedance matching could have change due to different dimensions and shapes from the original ground plane.

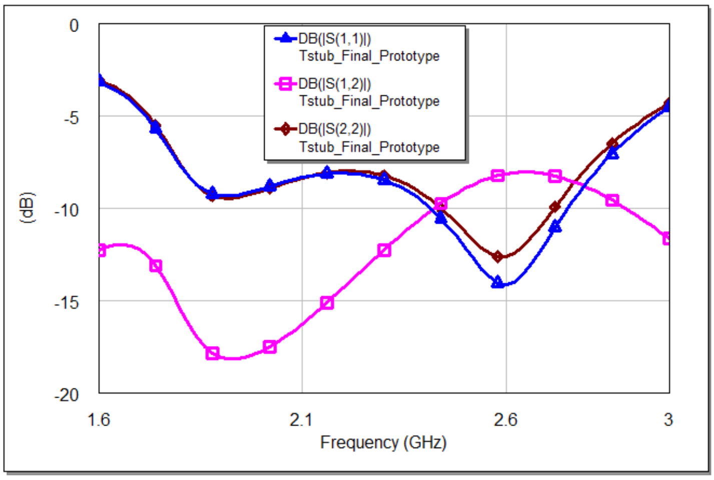


Fig. 49: S-parameter simulation for the new solution

e) Implement the new designs

Fig. 50: Design of the new mitigation technique

The new design was implemented (Fig. 51) in order to test if the solution would actually perform better.

f) Simulate the design in order to see if really can improve the first proposal.

Then the model was simulated in order to see if it could have changed its performance from the experimental test.

g) Back to experiment with new possible designs in order to refine the solution.

This process was kept iterating in order to refine the solution.

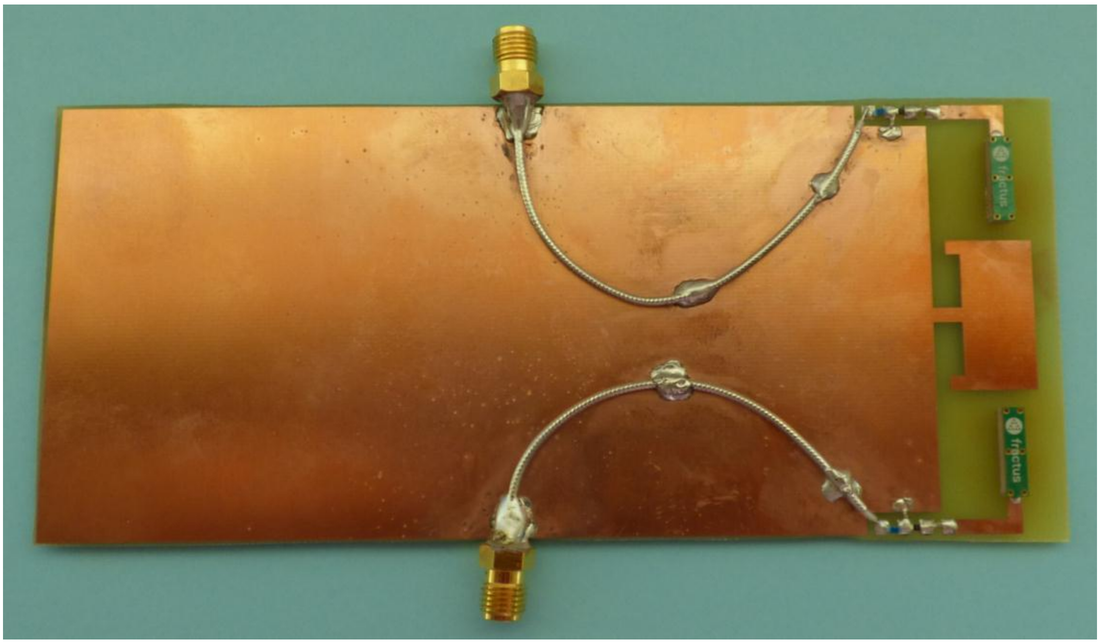


Fig. 51 Final mitigation technique proposal

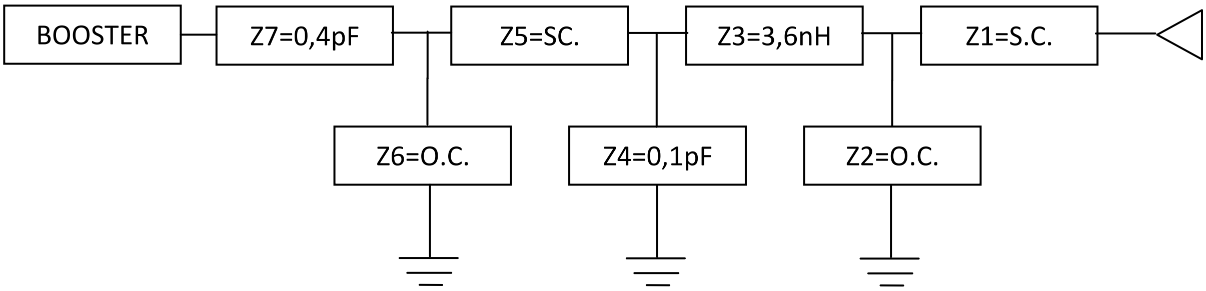


Fig. 52: Matching network for the prototype with the final mitigation technique. O.C= open circuit. // shunt. S.C. :short circuit. Both ports have the same matching network

5.3. RESULTS

After several iterations of the methodology exposed previously, three different prototypes where finally implemented.

As those prototypes where improved, the following table (Table 11) will show the original candidate, the first hypothesis and the final candidate. In order to see the difference between solutions, a final figure will be shown comparing the isolation for both prototypes (Fig. 53).

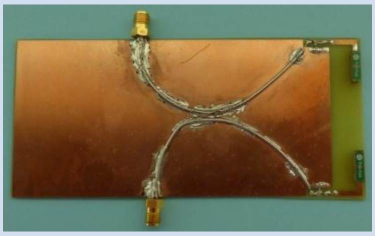
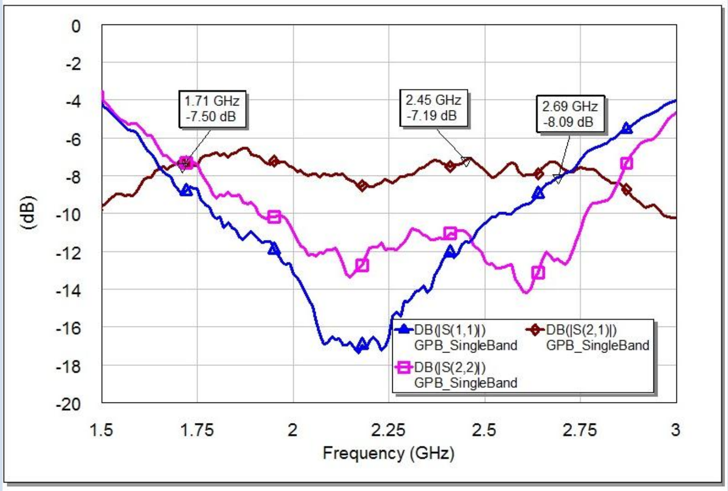
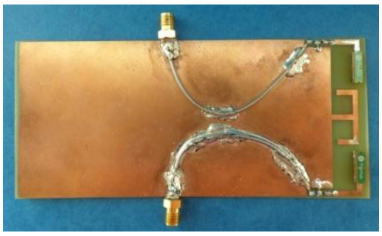
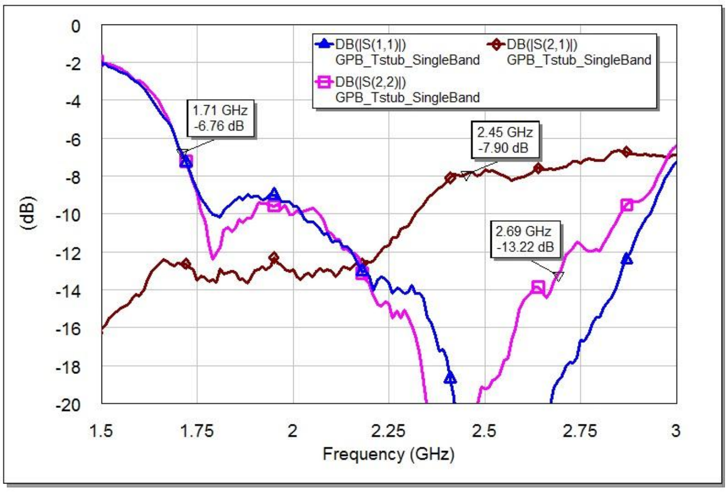
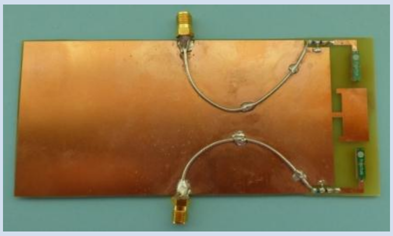
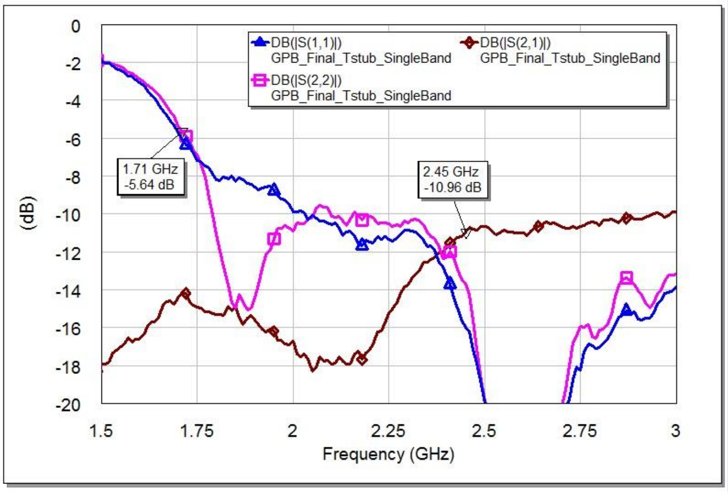
Original prototype with no mitigation technique. And matching network (Fig. 44) 	
First candidate. Original T-stub. And matching network (Fig. 46) 	
Final prototype with improved mitigation technique. And matching network (Fig. 52) 	

Table 11: Isolation and S_{11} for all Single Band (1.71GHz - 2.69 GHz) for the prototypes implemented

Once a firm candidate could be selected, a series of simulations were carried out. In order to see the viability of the proposal (Fig. 53), the correlation and efficiency of the system was simulated and compared to the original system.

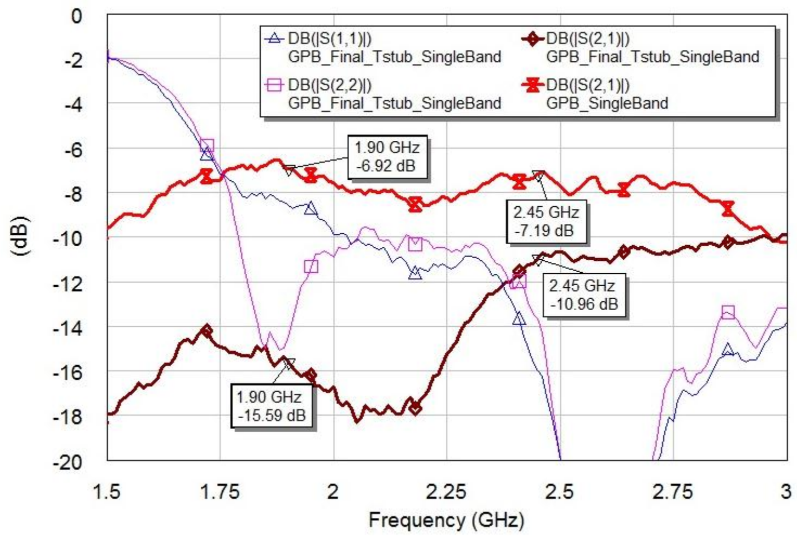


Fig. 53: Isolation difference between the first prototype without mitigation technique and the final prototype with the mitigation technique for the band 1.71GHz - 2.69 GHz

5.3.1. ANTENNA CORRELATION AND MUX PROCESSING

In order to obtain the results needed to understand and analyze the behavior of the antenna system, a strict procedure using a MATLAB code must be used.

More precisely, and before starting, several measurements at the SATIMO chamber must be done, and all the files must be exported into a .txt file:

a) E-fields for all the desired ports.

b) Efficiencies for all the desired ports.

All of which must be saved and well organized. The procedure to be followed in order to obtain the desired results, one must:

a) Put the desired files inside the same file where the .m MATLAB code named "codematlab_correlation_v20" is located Fig. 54.

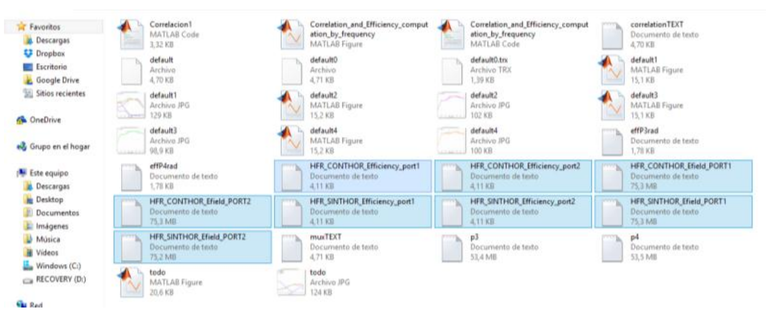


Fig. 54 Folder where the .m code is located

b) Delete all the headers from the .txt files and save the documents Fig. 55.

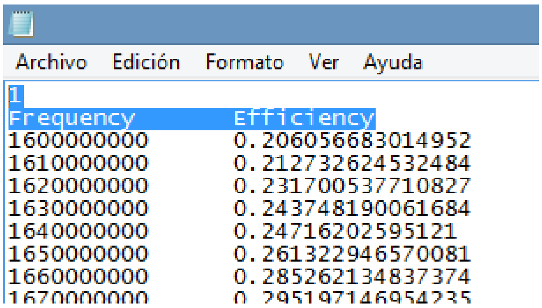


Fig. 55 .txt file with the header selected that needs to be deleted

c) Open the .m file named "Correlation_and_Efficiency_computation_by_frequency".

d) Run the code.

e) When the code is running and executed, a figure will open Fig. 56.

f) The documents saved and modified before along with other documents located at the folder must be uploaded within the several options Fig. 56, such files are:

I. Port 1 E filed simulation equivalent must be uploaded to "Load File Antenna 1" option.

II. Port 2 E field simulation equivalent must be uploaded to "Load File Antenna 2" option.

III. Port 1 Efficiency equivalent must be uploaded to "Load Antenna 1 Frequency efficiency chart" option.

IV. Port 2 Efficiency equivalent must be uploaded to "Load Antenna2 Frequency efficiency chart" option.

V. "Default1" file must be uploaded to "Capture Correlation Chart image file" option.

VI. "CorrelationTEXT.txt" file must be uploaded to "Export Correlation File Data configuration" option.

VII. "default2" file must be uploaded to "Capture Efficiency Chart image file config" option.

VIII. "muxTEXT.txt" file must be uploaded to "Export Efficiency File Data configuration" option.

IX. "default3" file must be uploaded to "Export Antenna1 efficiency Chart image file config" option.

X. "defaul4" file must be uploaded to "Export Antenna2 efficiency Chart image file config" option.

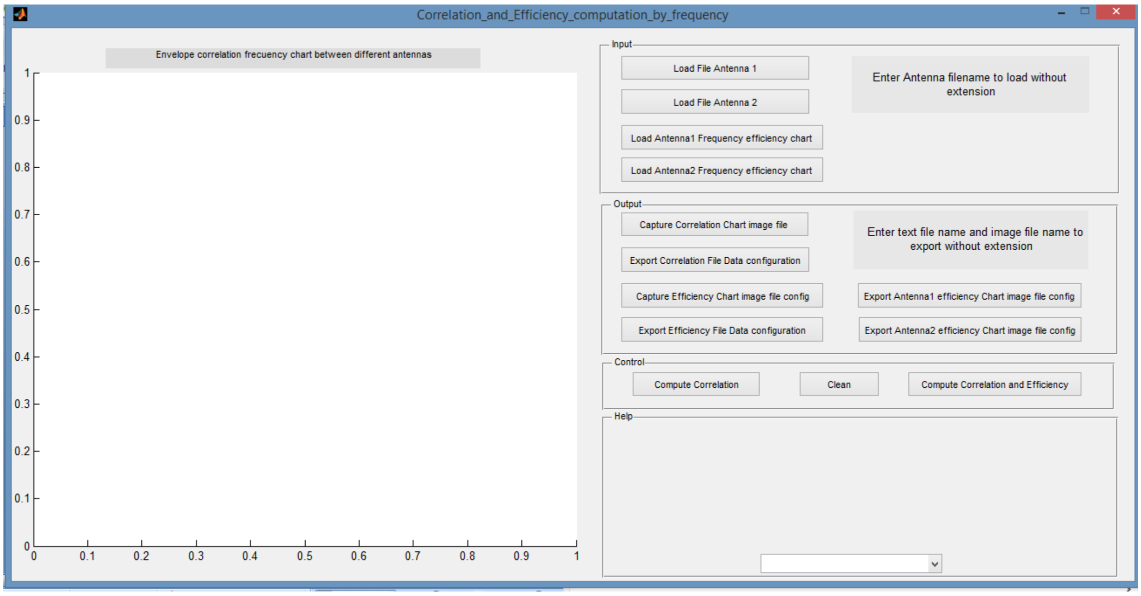


Fig. 56 Figure obtained after running the matlab code with all the described options

5.3.2. CORRELATION AND MULTIPLEXED EFFICIENCY ANALYSIS

After having simulated both the original and the final prototype, the treatment of the simulations has been done in order to find whether the solution improves the correlation and MUX efficiency results.

First, the prototype without the mitigation technique will be processed Fig. 57 in order to have a magnitude order and know what to expect from the platform, antenna disposition and frequency range. It is expected to find a fair result for both the correlation and the efficiency.

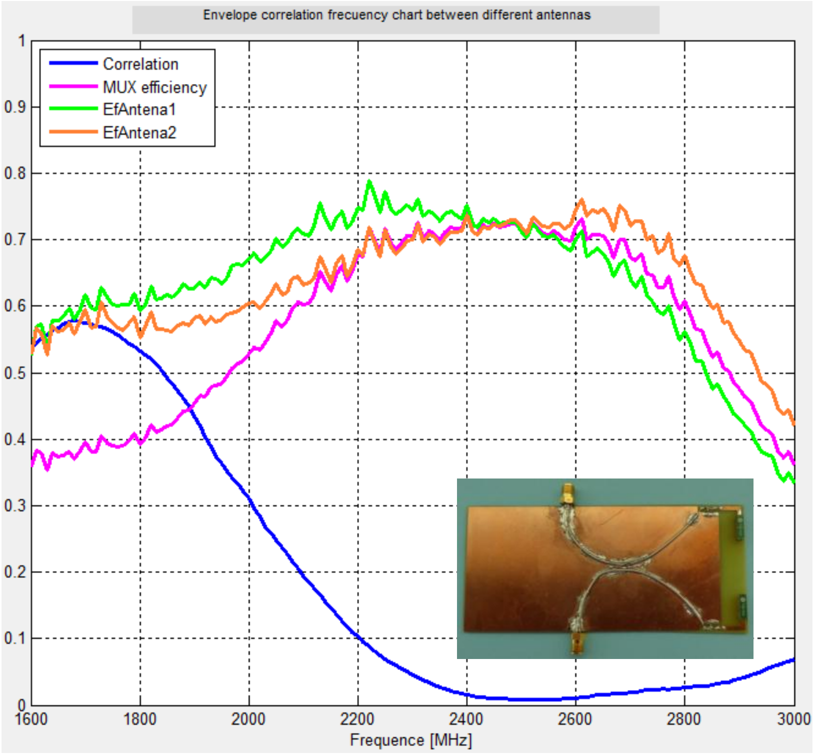


Fig. 57 Measured first Correlation and MUX result for the two GPB platform

As it can be inferred from the graph, the correlation for the high region of the HFR band is very good and would not even need to be improved. In terms of MUX efficiency, the results also show a fair result for the 2.45 GHz band.

The goal of the mitigation technique is to find an improvement of the MUX efficiency for all the band and to find a better correlation for the low region of the HFR band.

In order to do that, the second prototype implementing the final mitigation technique has been simulated and analyzed and reflected in Fig. 58.

After analyzing the simulations that can be observed in Fig. 57 and Fig. 58, a great improvement can appreciated in terms of correlation at the low region of the HFR band, lowering the correlation from 0.55 to 0.2 at the 1.8 GHz band. This improvement is very notorious and proves that the solution is very promising. In particular for this frequencies (1.8GHz), the solution without the T-stub used as a mitigation technique would need to increase radiated power by 2,5 dB in order to obtain the same capacity than the T-stub case. Thus, by implementing the mitigation technique the prototype requires almost half the power as initially needed.

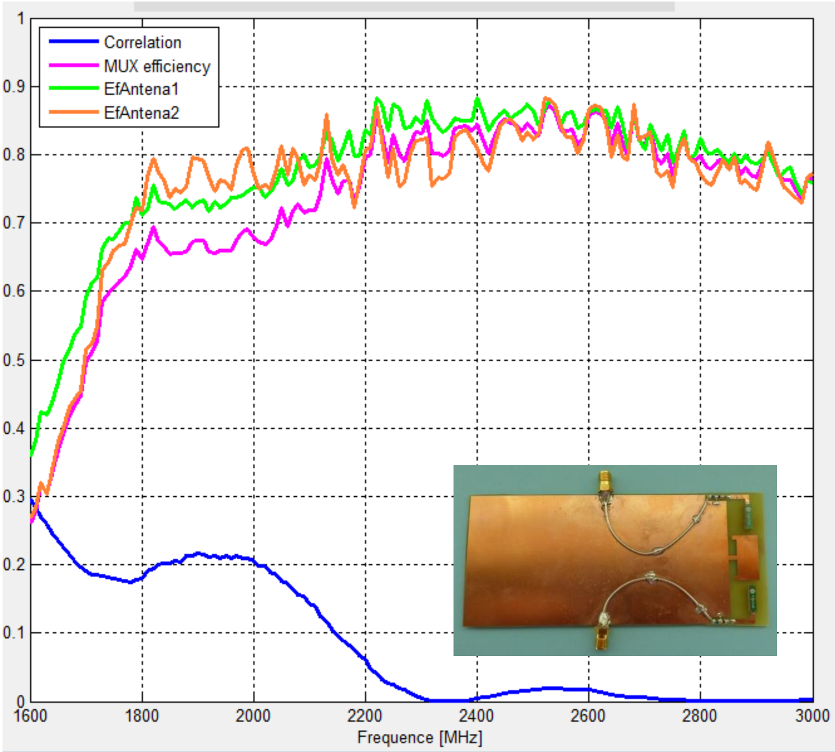


Fig. 58 Measured correlation and MUX result for the final mitigation technique candidate

In terms of MUX efficiency, the mitigation technique also improves the parameter by 0.2 points at the low region and by more than 0.15 at the high region of the HFR band.

	$\overline{MUX\ Efficiency}$ (1.71 GHz - 2.69 GHz)
Without mitigation technique	0.57
With mitigation technique	0.72

Table 12 Average multiplexed efficiency relationship for the 1.71 GHz - 2.69 GHz band with the mitigation technique and without it

5.3.3. CURRENT SIMULATION

In order to understand the effect of the currents running through the ground plane of the platform, a simulation has been of them has been done Table 13. The aim of this simulation is to understand what is the effect of the mitigation technique in terms of current distribution and to see if the fact of putting a stub in the middle of both Ground Plane Booster Antennas, the currents are dissipated and deviated from passing to the opposite port. The simulations are carried out at several frequencies, those frequencies are selected among the band in the worse possible cases, where the currents are stronger.

The goal shall be to find no current excitation at the Ground Plane Booster Antenna placement located at the opposite port from the fed port. The simulation has been carried out feeding port 1 and loading port 2 with a 50 Ohm load.

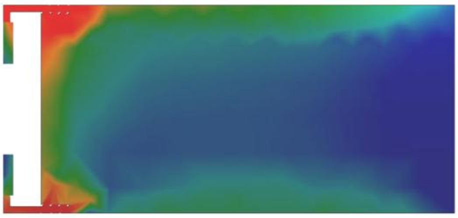
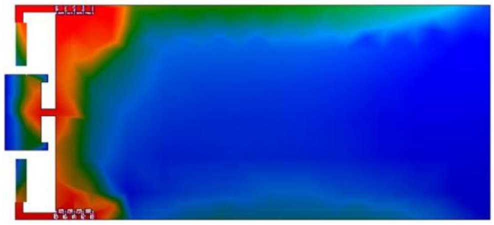
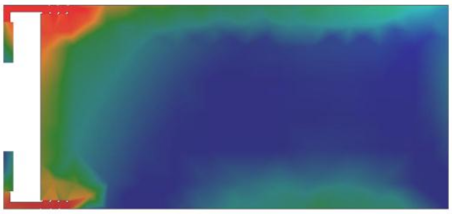
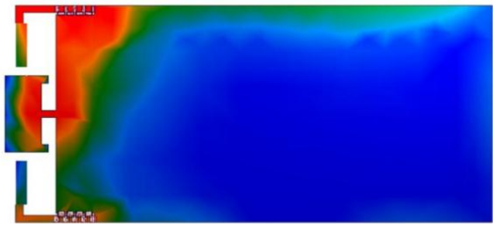
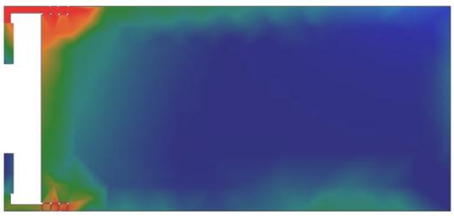
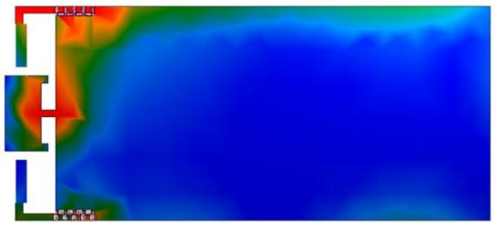
	Without mitigation technique	**With mitigation technique**
0.9 GHz		
1.7 GHz		
2.2 GHz		

Table 13 Relationship between the current distribution when feeding one port for both the platform without the mitigation technique and the platform with the mitigation technique at 0.9 GHz, 1.7 GHz, and 2,2 GHz frequencies. Matching networks have been included in both ports (Fig. 44,Fig. 52): one port is fed and the other is terminated with a 50 Ohm load at the end of the matching

5.4. MULTIBAND

As the results obtained were so encouraging, a new experiment was carried out.

First the multiband solution implemented by Fractus, where a GPB attached to an adhoc matching network can work both for HFR and LFR was taken.

A modification of the design adding a new GPB in order to convert it into a MIMO system was done. It was also designed using the new mitigation technique in order to simulate the differences.

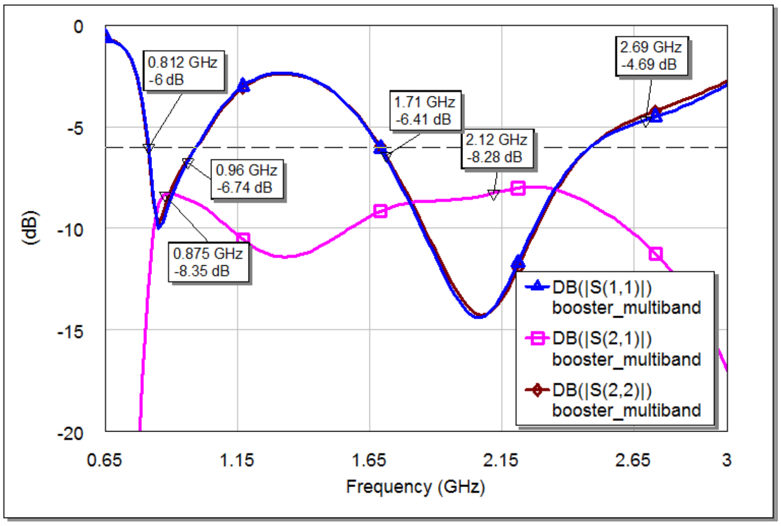


Fig. 59: Multiband design with matching network simulated without mitigation technique

Once it was designed, the simulations using the AWR software were done in order to see if there was such a difference.

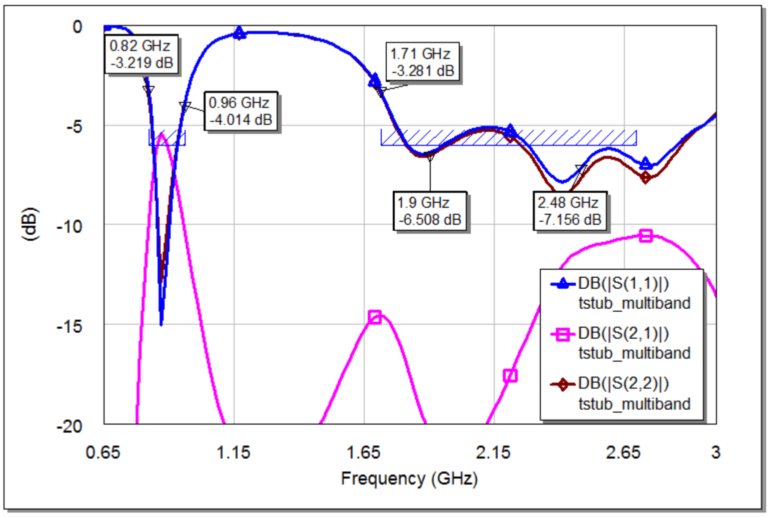


Fig. 60: Multiband design with matching network simulated with mitigation technique

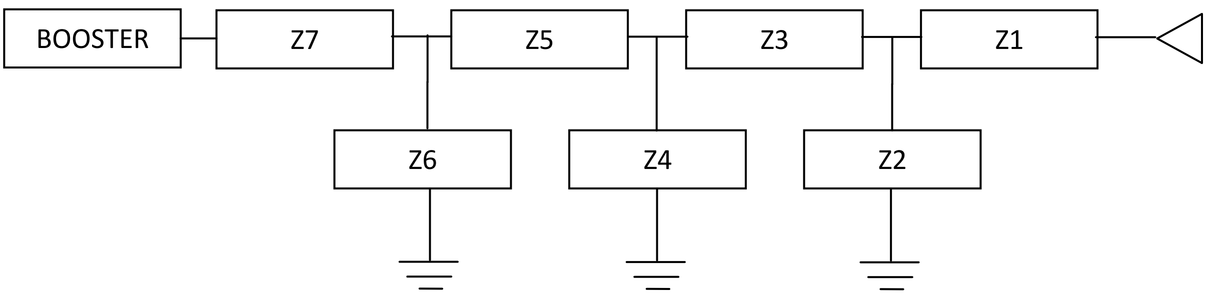


Fig. 61: Matching network scheme. Z_x refers to the bay and port where the component will be located. O.C= open circuit. // shunt. S.C. :short circuit. Both ports have same matching network

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
No mitigation technique	4.5 nH	O.C.	2 pF	1 pF // 13 nH	0.9 pF	18 nH	4.3 nH
Mitigation technique	4.9 nH	O.C	1.4 pF	0.8pF // 11 nH	0.5 pF	18 nH	6.2 nH

Table 14 Matching network for both multiband prototypes with mitigation technique and no mitigation technique. O.C= open circuit. // shunt

After simulating the designs, two more prototypes were built (Fig. 62): the first one would only implement the GPB and the matching network proposed by Fractus and the second one would also implement the isolation technique. They were both implemented because for the second simulation (Fig. 60), an improvement on the isolation was found and encouraging. As observed from the measured data (Fig. 60),more fine tuning would be needed to improve matching at the LFR as well as 1.71 GHz. However, the purpose is to analyze the isolation effect, this stage is reserved for future actions.

Once both prototypes had been implemented, simulations of the isolation and S_{11} parameters were carried out in order to see if there was an improvement (Table 14). Then a correlation and efficiency parameters simulation were carried out.

Before analyzing MUX efficiency and correlation, it is very important to note that one it needs to be seen if the S_{11}, S_{22} and S_{21} parameters simulated at both prototypes cover the desired bands.

It is very important to see if there is a difference in terms of isolation between prototypes before analyzing correlations and multiplexed efficiencies.

<table>
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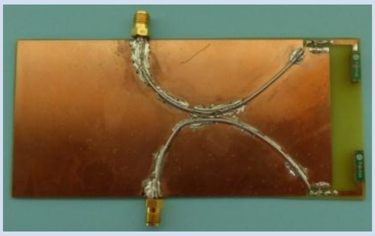
Original prototype with no mitigation technique. And matching network (Fig. 44)



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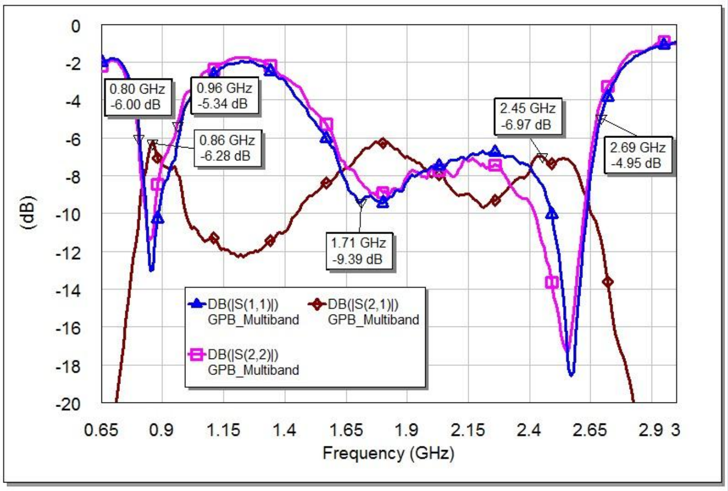

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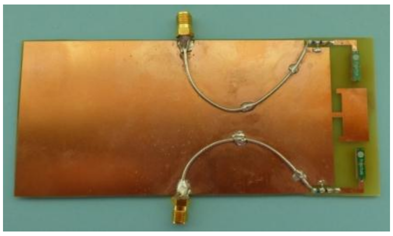
First candidate. Original T-stub. And matching network (Fig. 46)



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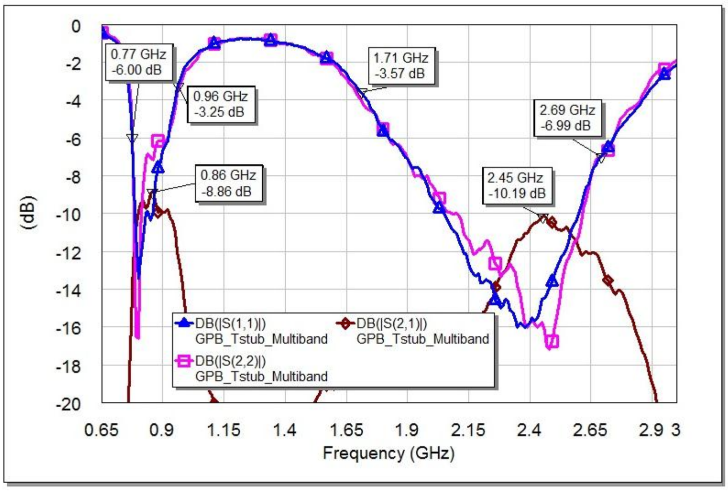

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Difference in terms of isolation for the first prototype and the prototype with the isolation technique

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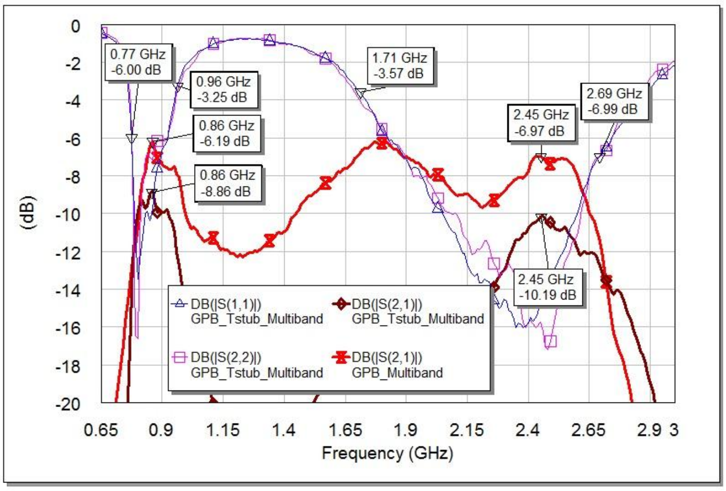

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Table 14: difference in terms of Isolation and S_{11} parameter for the initial prototype without mitigation technique and the final prototype with the mitigation technique implemented. Finally the difference is shown in terms of isolation for the bands 0.829 GHz - 0.96GHz and 1.71 GHz - 2.69 GHz

One could think that for this case, the efficiency for the LFR would decrease and by so, the MUX efficiency and the correlation would decrease their performance. In order to reject that hypothesis, an analysis of the LFR has been done in order to prove it.

First, the prototype without the mitigation technique was processed Fig. 63.

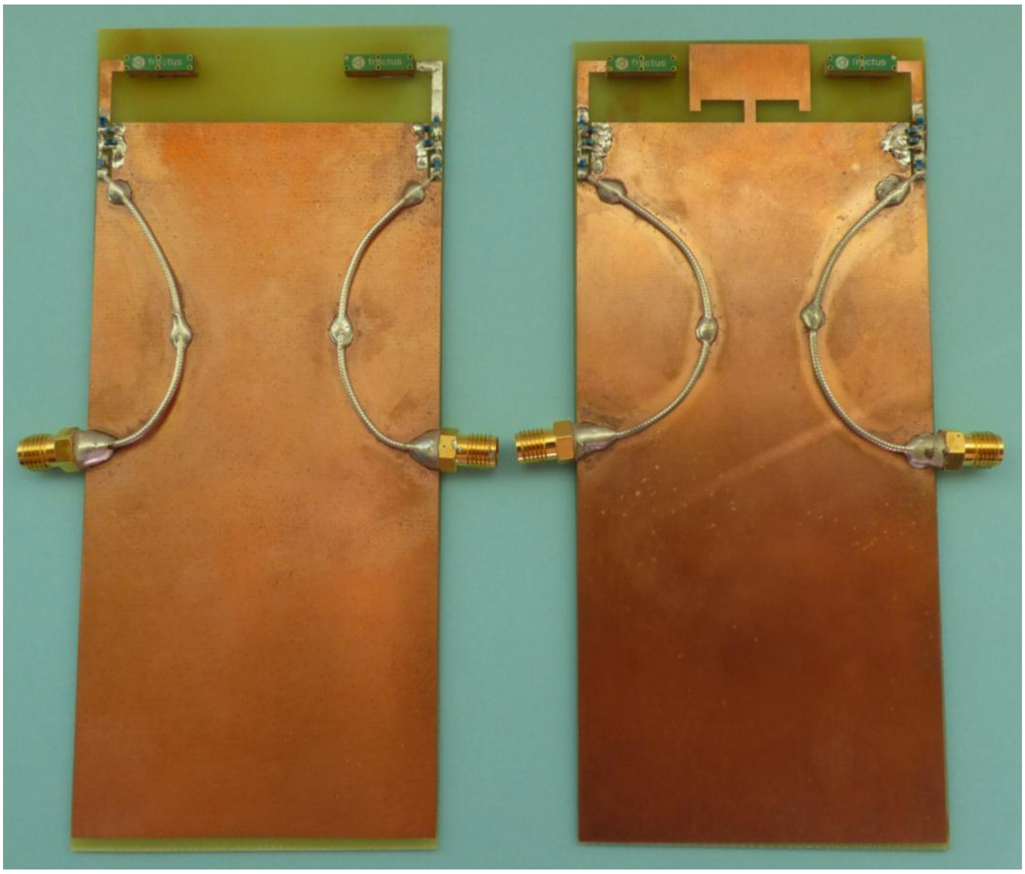


Fig. 62 Multiband prototypes; Left prototype without the mitigation technique proposed and Right prototype implementing the mitigation technique

As it can be seen (Fig. 63), the MUX efficiency is very around 35%. It can also be observed that the correlation is around 0.45. This is assumable in terms of the LFR band. Assuming such results for the low frequency region, it is very important not getting worse results due to a modification in the ground plane caused by the mitigation technique. In order to assure that the loss is not very significant, the simulation and processing of the MUX efficiency and correlation has been done for the prototype with the mitigation technique at the LFR band (Fig. 64).

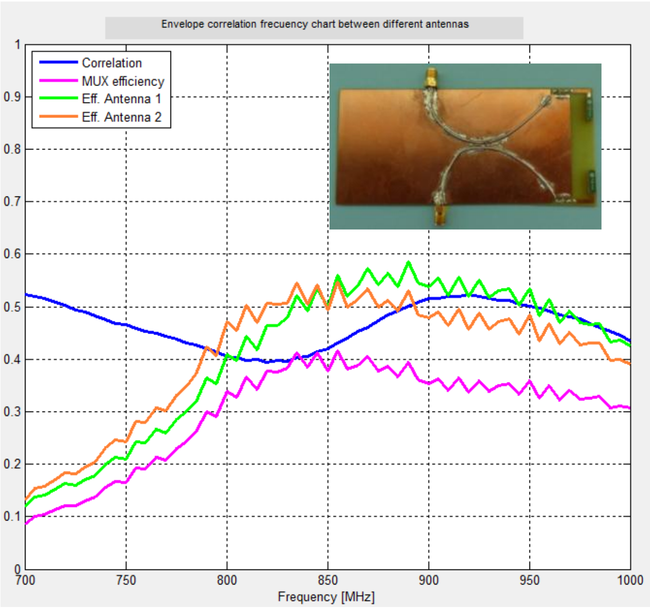


Fig. 63 Measured correlation and MUX result for LFR without mitigation technique

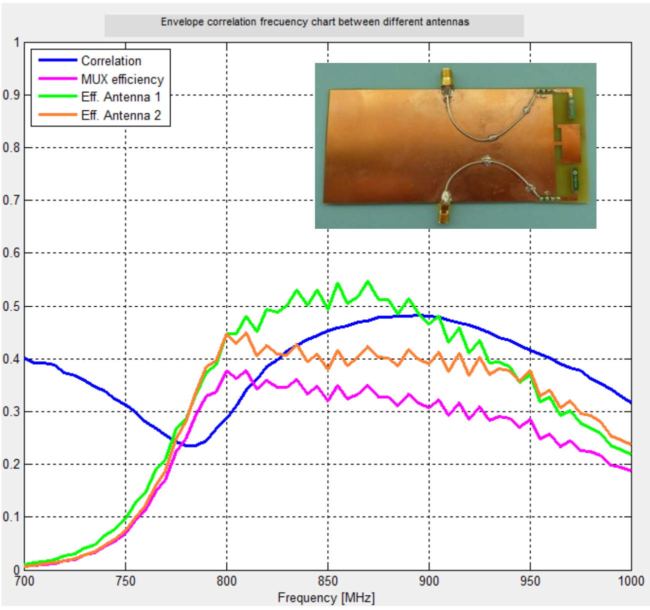


Fig. 64 Measured correlation and MUX result at the LFR with the mitigation technique

It can be observed that, far from getting worse correlation results, the mitigation technique improves the correlation at all the LFR, finding a significant improvement at the 750 MHz to 800 MHz region. It needs to be noted that there is a slight loss at 850 MHz.

It is then confirmed that for the LFR region the loss is not significant and then the mitigation technique doesn't affect.

In order to know whether if the mitigation technique works for the HFR and gets an improvement, a simulation and processing of the two same prototypes has been done at the mentioned region.

The first prototype to be measured was the original platform without the mitigation technique Fig. 65.

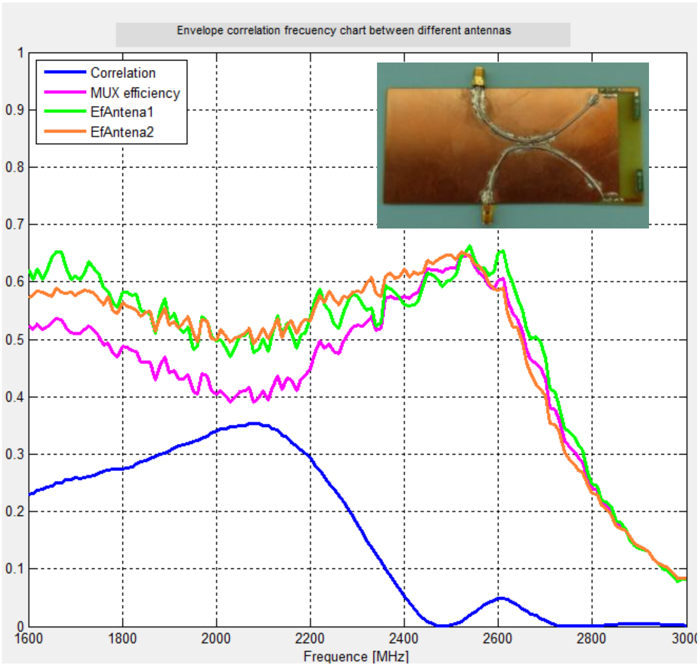


Fig. 65 Measured correlation and MUX result for HFR without mitigation technique

Then the second prototype was measured in order to observe differences.

As it can be seen (Fig. 65), for the first prototype, the correlation and MUX efficiency are improved. This was the original hypothesis; for the LFR not to find any improvement and get a similar result and for the HFR to find a great improvement. This way the mitigation technique could show its effectiveness.

As it can also be seen in Fig. 66, a correlation below 0.1 is found from the 2.2 GHz to the 2.7 GHz region. Not only the correlation is improved but also for more than 0.7 GHz is lower than 0.1. In terms of MUX efficiency, the mitigation technique also affects by improving it by 0.2 points at the desired band.

On the one hand, it is worth implementing the mitigation technique as correlation at the HFR has been improved. In terms of MUX, it also improves, in particular at the frequency range of 1.86 GHz to 2.69 GHz.

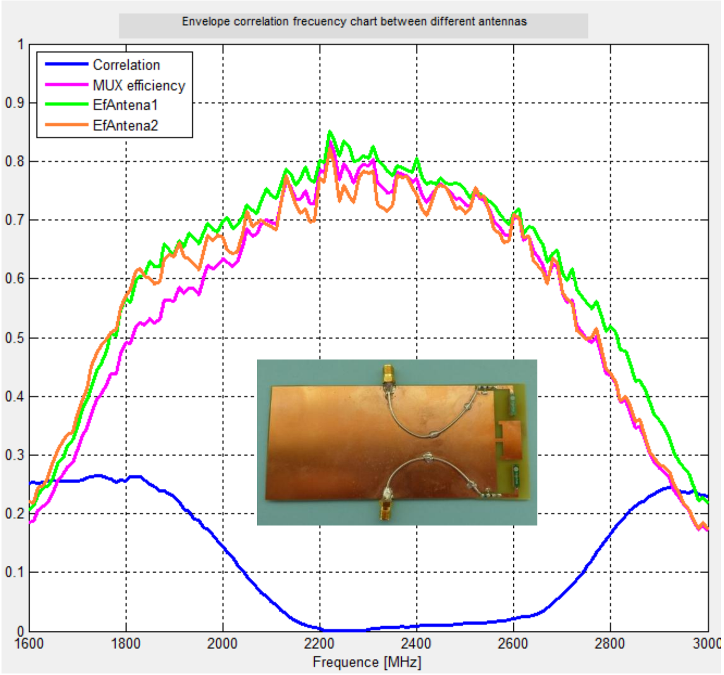


Fig. 66 Correlation and MUX result for HFR with mitigation technique

On the other hand, if we take particularly the 2.2GHz frequency, the multiplexed efficiency without the mitigation technique is 44%. When measuring with the mitigation technique, the multiplexed efficiency rises to a 75%. This shows the effectiveness at some interesting bands as, for the case of the 2.2 GHz frequency, for example, in order to get the same throughput, the system will have to provide 2.3dB less($2.3 = 10 \cdot \log(\frac{0.75}{0.45})$), which means almost half the power.

5.5. CONCLUSIONS

After having analyzed the possible candidates to be implemented, during this chapter several conclusions have been acknowledged.

In terms of implementation of a prototype:

- The implementation process must be meticulous. If for instance one insolates the board for too much time, the result will note behave as expected.
- The implementation of such solutions with small SMD components must follow a very tidy and organized procedure; the order of the components matter as well as the Q factor.

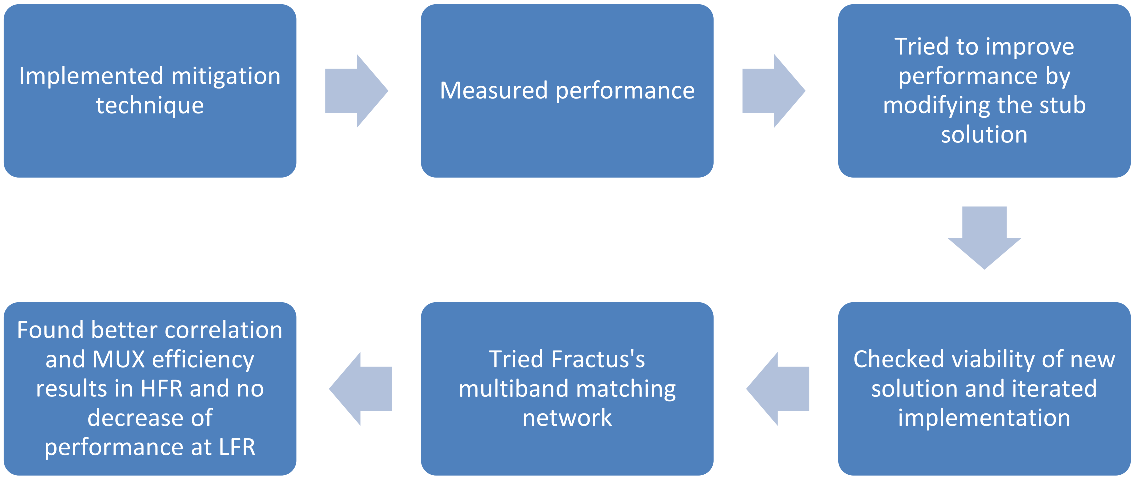
In terms of results:

- The solution initially designed and simulated not always behaves as it should; a fine tuning should always be considered in order to optimize the solution.
- The mitigation technique proposed, not only mitigates isolation between ports but also improves the correlation and the multiplexed efficiency for all the band.
- When analyzing the currents table, one can see that for the LFR, currents running on the GPB are greater than without the mitigation technique. That is the reason why the multiplexed efficiency is worse using the mitigation technique.
- When also analyzing the currents table, it can be seen that for the 1.7 GHz and 2.2 GHz frequencies, the mitigation technique dissipates the currents along the platform allowing opposite the ground plane booster to have less current distribution and by so having a better multiplexed efficiency.

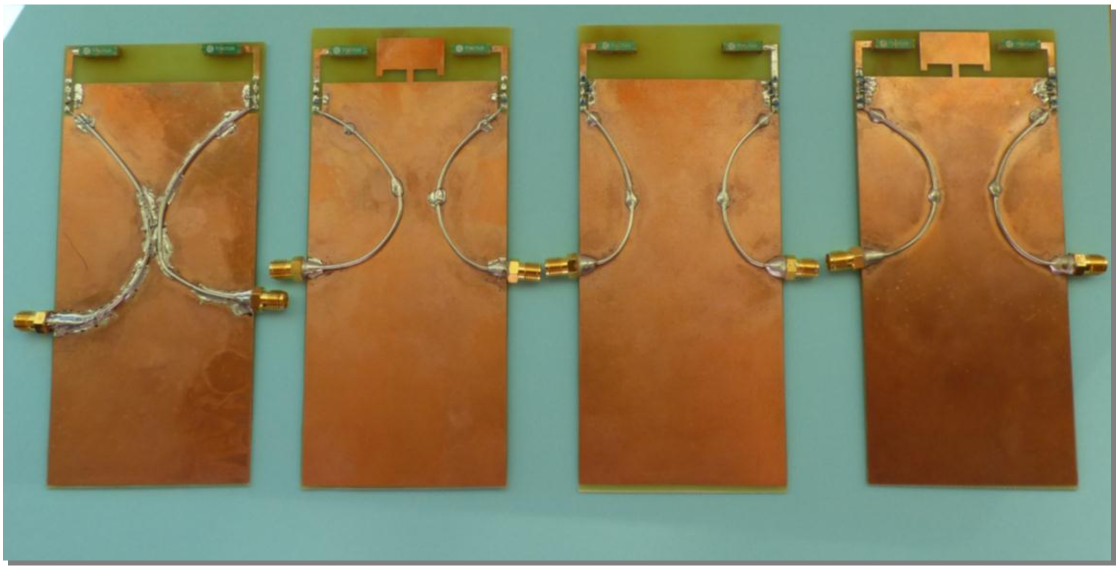
In fact, the results were so promising that an hypothesis was thrown: would the mitigation technique both affect the HFR and LFR? If so, would the mitigation technique, at the LFR affect at the matching and efficiency? In order to find out, it was concluded that a new experiment shall be conducted using a multiband solution. The conclusions from which are:

- The loss at the LFR is not significant in terms of MUX efficiency as it means increasing just a 5% of SNR to get the same throughput as with the basic platform.
- The correlation at the LFR also improves substantially at the 800 MHz region.
- Both the correlation and multiplexed efficiency are improved at the HFR region.

General conclusion: The mitigation technique proposed improves substantially both LFR and HFR bands in terms of correlation and the MUX efficiency at the HFR band; but what is more important is that the mitigation technique doesn't negatively affect the isolation and MUX efficiency between ports.



6. CONCLUSIONS



6.1 INTRODUCTION

A research within the antenna sector has been done. A review of the prior art and its analysis has been conducted. The relationship of several parameters with different platforms, frequencies and antenna dispositions has been studied. Several candidates have been proposed and studied in order to mitigate the isolation between ports. A candidate has been chosen and implemented. This candidate has been studied and modified in the laboratory to find a better solution. A better solution was found. Several measurements were conducted and analyzed. The proposed solution improved isolation, correlation and multiplexed efficiency.

When accomplishing such a project, our brains get structured in such a way that let the concepts acquired until now consolidate. The experience of developing and implementing such project also empowers the database of previous experiences and information in order to make a better future decision.

6.2 FINAL CONCLUSIONS

The main goal of this project was to consolidate and to address the concept gaps that during the degree were made.

In terms of personal development and enterprise objectives, developing the project in an R&D company has helped understand how a real ecosystem works and how the actors interact. The working structure and the organization within project management has also been understood.

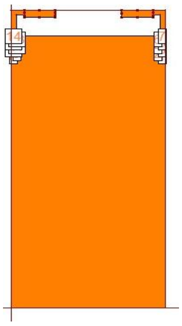
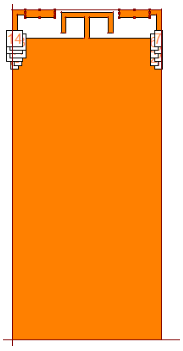
Not only achieving it but also taking very valuable conclusions this project has been finished.

In terms of technical achievement, the solution pursued has been a total success. Aiming to implement from a MIMO system consisting of two Ground Plane Booster being able to maximize the bands in order to work at the latest LTE standards over platforms of typical wireless devices (120 mm x 60 mm).

It is concluded that implementing an isolation technique between boosters located at the shortest distance edge of the platform affects and improves the isolation. It is also concluded that, the mitigation technique proposed doesn't negatively affect the LFR band and that in terms of correlation and multiplexed efficiency improves its parameters.

With all that, it is has been demonstrated that:

- It is possible to implement a mitigation technique within a Smartphone platform between the Ground Plane Booster Antennas.
- It is possible to match and work at different frequencies depending on the matching network used.
- A MIMO system is viable using GPB operating at LTE bands both low and high bands.
- Platforms as big as tablets have such isolations that would not show visible improvements.

		DESCRIPTION	RESULTS	CONCLUSIONS
CHAPTER 2: Review of prior art		Prior art is reviewed and analyzed	The market demands antenna systems with high throughput and small size. MIMO antenna systems : correlation and isolation is challenging.	MIMO systems present isolation problems; Several mitigation techniques can solve that problem. A candidate is chosen using Stub techniques to start the investigation
CHAPTER 3: Isolation wireless devices		Behavior of Ground Plane Boosters in different platforms (Smartphone & tablet), frequencies (2G, 3G, 4G) and locations is simulated and analyzed	Isolation in big platforms, great distances and high frequencies is acceptable; Isolation in small platforms is critical.	Increasing d/λ is not always the criteria to improve, currents also must be taken into account
CHAPTER 4: Isolation mitigation		Study of several possible mitigation techniques based on a modified reference are designed and simulated	Symmetrical T-shaped solutions with greatest length in arms have better isolation and impedance matching	A T-stub with long arms is selected to be implemented; Isolation at 1.71 GHz - 2.69 GHz in a platform (120mm x 60mm) is improved from -6.92dB to -15.59 dB at 1.9GHz and from -7.19 dB to -10.96 dB at 2.45 GHz.
CHAPTER 5: Implementation of MIMO system with GPB		A T-shaped stub is implemented in a 120mm x 60 mm platform with two Ground Plane Boosters operating each from 0.829GHz - 096 GHz and 1.71GHz - 2.69 GHz; it is simulated and its results are analyzed.	Results show a possible improvement for matching; experimental modifications are tried and a better prototype is achieved. A multiband prototype is also tried with the same solution and shows better isolation, correlation and MUX efficiency.	The use of a mitigation technique T-shaped stub doesn't affect the LFR in terms of matching impedance nor MUX efficiency and performs better in terms of correlation and isolation; For HFR the solution shows improvement in all parameters. The mitigation technique is viable. MUX at 0.829 GHz - 0.96 GHz is in average 0.31; at 1.71 GHz - 2.69 GHz is in average 0.65.

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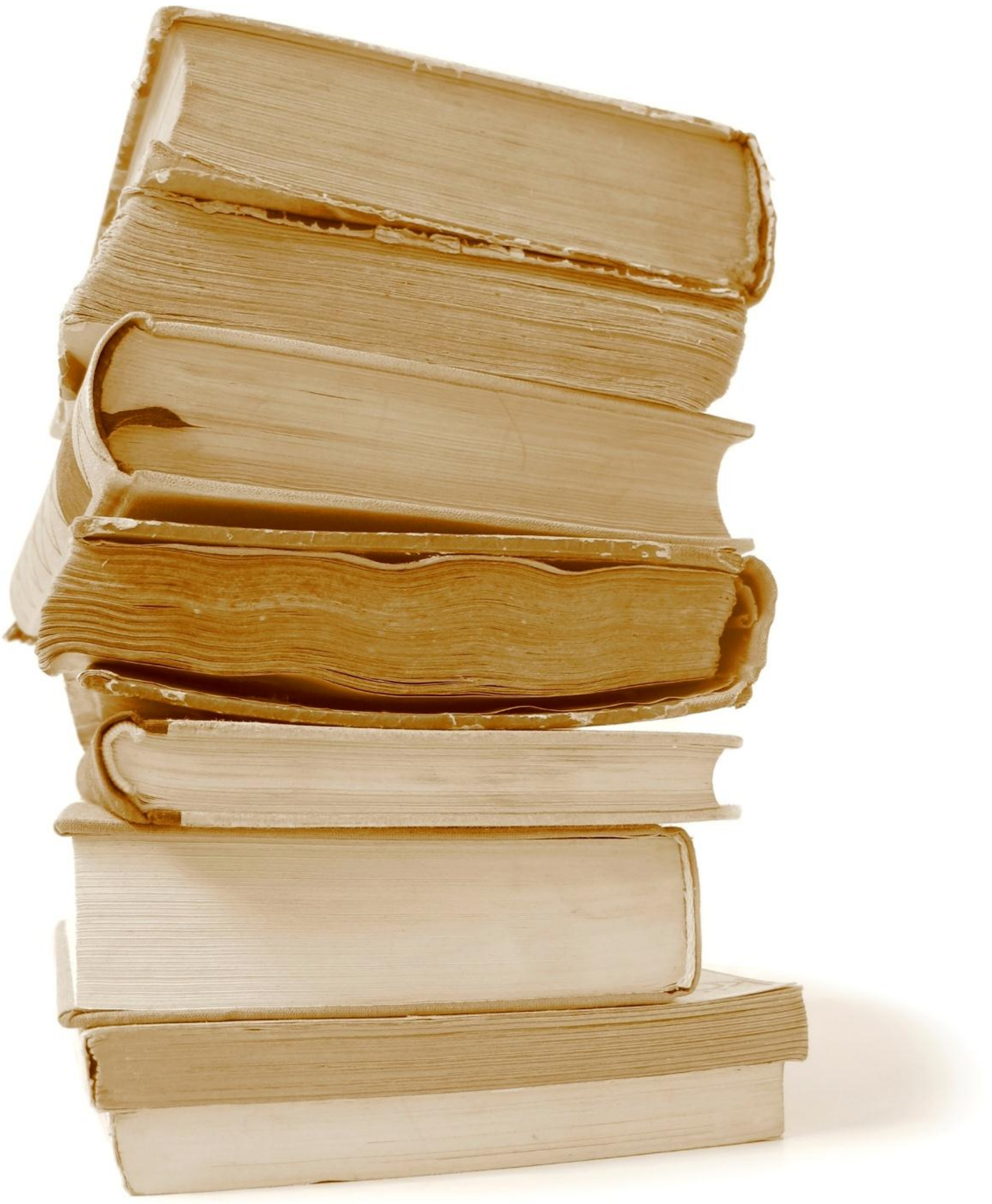

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