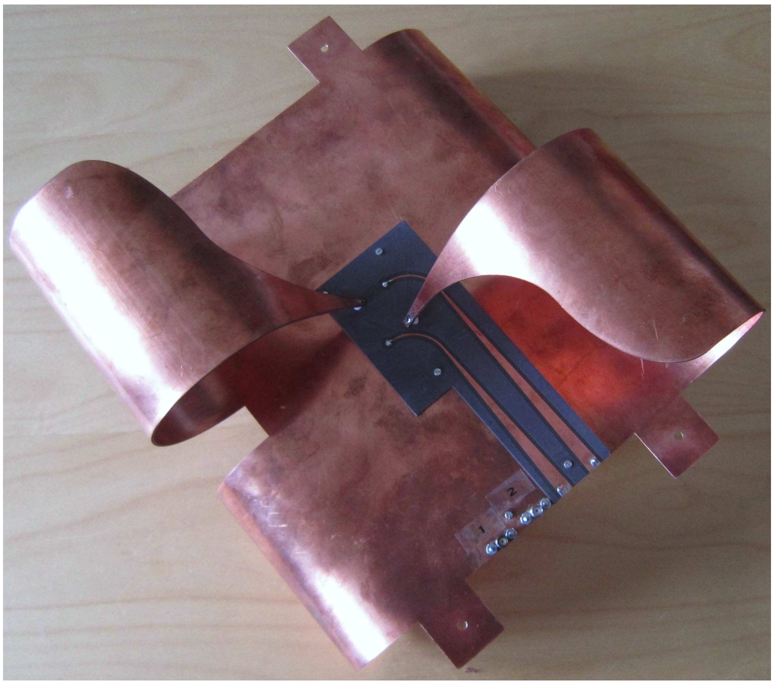

A New Compact Wideband MIMO Antenna for Reverberation Chambers

Master of Science Thesis

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Cover page: The manufactured four ports dual sided self grounded triangular antenna.
Antenna Group, Chalmers University of Technology.
Bluetest AB.

Preface

This is the technical report of the master degree project corresponding to the partial fulfillment of the master of science degree at Chalmers university of Technology. This project is the result of a one year research conducted at the department of Signals and Systems, Antenna Group, Chalmers University of Technology located in Sweden-Gothenburg. The project has been carried out by master student Ali Al-Rawi at Chalmers University of Technology. The project has been supervised by Dr.Jian Yang at Chalmers University of Technology as the first supervisor. The second supervisors are; Charlie Orlenius (CTO) and Magnus Franzén (Manufacturing Director) both at Bluetest AB Sweden-Gothenburg. Prof.Dr.Per-Simon Kildal is the project examiner. This project has been financed by Bluetest AB (www.bluetest.se), and has been performed at Chalmers University of Technology.

This report contain the design and analysis of a compact wideband MIMO antenna for BLUETEST AB Reverberation Chambers. The intellectual property rights of this project is patent protected.

Acknowledgements

Foremost,I would like to express my deep appreciation to my supervisor Dr.Jian Yang. without his extensive knowledge and experience this project will never see the light. I gained a valuable knowledge and skills from Dr.Jian Yang, I will always be grateful to him. I would like thank my supervisors at Bluetest AB; Charlie Orlenius and Magnus Franzen for trusting and supporting me.Their ideas and guides added crucial advantages to this work. Finally I would like to express my appreciation to my Professor Prof.Dr. Per-Simon Kildal for editing and reviewing the report.

Ali Al-Rawi, Gothenburg, Sweden 2012

Dedication

To my family;
my father Dr.Naseer, my mother Dr.Ekbal, my brothers Ahmed and Alhussain, my sister Aisha and her family...

"***Imagination is more important than Knowledge***" ... ***Albert Einstein***

Abstract

A new compact wide band antenna MIMO (multiple input multiple output) has been designed and manufactured to work as the fixed measurements antenna for the reverberation chamber. This chamber is a metal cavity which has a specific size in order to support several resonant modes. These chambers has been used for electromagnetic compatibility (EMC) testings and to characterize small antennas and active terminals used in multi-path environments. The current fixed measurements antenna that is used to excite the chamber environment is consisting of three triangular monopoles mounted above a square shape ground plane forming a cube.

The preliminary requirements were to develop a high performance antenna within the bandwidth range 0.65-6(GHz). The requirements for the new antenna has been set to be a reflection coefficients around -10(dB), mutual couplings below -10(dB) and high radiation efficiency. The self grounded-Bow-Tie concept has been implemented as the main brick for the new antenna. This concept which is based on truncating the radiating element (lower cutoff frequency) to the ground plane to form the self grounded shape. The self-grounded-Bow-Tie has been transformed to generate the multiple self grounded monopoles. The new antenna consist of four triangular monopoles self grounded to the ground plane. The new antenna has been modeled using CST (Computer Simulation Technology) MS (Microwave Studio). Optimization scheme has been employed by using MATLAB in order to reduce the reflection coefficients and the mutual couplings between ports.

The genetic algorithm optimization where seven genes represent the antenna parameters. The optimization scheme has produced an individual with optimized parameters and an impedance port of (confidential)(ohm) required at the antenna input port in order to achieve a reflection coefficients below -7(dB) and mutual couplings below -15(dB). However the mutual coupling had been dropped from the optimization scheme due to the excellent antenna performance regarding the mutual couplings. The (confidential)Ohm implies the necessity of using a matched network between the antenna input port and the coaxial port. Therefore a tapered micro-strip line transformer technology has been implemented to work as the matching network between the antenna and the coaxial port. This transformer has been designed through parametric study in order to estimate the the transmission line dimensions.

The transformer has been designed in a manner to be well integrated to the antenna geometry. By simulating while the transformer is feeding the antenna, it has been found the performance at frequencies below 1 (GHz) is poor regarding the reflection coefficients. Therefore scaling the antenna size to cover these frequencies has been performed. It has been observed that the performance is slightly enhanced but not sufficient with

increased reflections at higher frequencies than 1 (GHz). Due to these factors, reducing the radiating elements in the antenna geometry to form four ports dual sided self grounded antenna. The scaled size of this configuration has better response than the previous one. The reflection coefficients is below -7(dB) in the frequency range (0.5-16) (GHz).

The prototype is made from copper (PEC) and the transformer dielectric material is set to be Rogers RT(5880) with dielectric thickness of 3.175(mm). The prototype has a geometry dimensions of $250\times250\times170$(mm) corresponding to the length, width and the hight, respectively. The simulation predicted a reflection coefficients below -7(dB), a mutual couplings below -15(dB), embedded radiation efficiency higher than -0.2 (dB) and total embedded radiation efficiency higher than -1(dB) all within the bandwidth range 0.6-16(GHz). The simulation showed that the antenna has low ohmic losses and high decoupling efficiency (>-0.2dB). Due to the low mutual couplings between ports and low ohmic losses, it was possible to predict the correlation between ports through the envelop correlation coefficients formula. the envelop correlation coefficients is below 0.05, indicating uncorrelated antenna.

The measurements regarding the S-Parameters showing that a reflection coefficients below -7(dB) within the frequency range 0.5-9(GHz) and reflection coefficients below -4.5(dB) within the frequency range 9.1-16(GHz). This mismatch between the simulation and measurements at the later bandwidth has to do probably with difficulties to manufacture the antenna with a close match to the model that was used in the simulations. The measurements regarding the mutual couplings is below -15(dB) as well. The measurements regarding the embedded radiation efficiency has been conducted using the reverberation chamber. The embedded radiation efficiency measurements is higher than -0.5(dB) and the total embedded radiation efficiency higher than -1 (dB) both within the frequency range 0.6-8(GHz).

The antenna is a potential candidate to serve as the base station antenna for the reverberation chamber. A manufacturing of a second prototype is undergoing to overcome the previous one flaws. However, the new antenna is under further development before being introduced to the volume production.

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1

Introduction

A novel compact wide band MIMO (multiple input multiple output) Antenna is designed, manufactured, measured and proposed as the base station antenna for the reverberation chamber. The master thesis project is divided into two parts. The first part is a preliminary study of BOR1 efficiency for Bow-tie and Dipole antennas while the second part is the design of the new compact wide band MIMO antenna which represent the main core of this thesis.

Wide band antennas are a critical element in the signal flow of UWB (ultra wide band) system. It's possible to classify wide band antennas into short range application, low power indoor UWB radio systems and outdoor based station communications. The antenna in UWB systems has considerable considerations than narrow band systems because of the very large bandwidth owned by the UWB signal. Therefore the antenna is more carefully designed. UWB antennas might have directive or omnidirectional radiation pattern. Directive antenna like feed antennas for reflector antennas. These antennas serve in a line of sight scenario and in short distance. Omni-directional wide band antenna is desirable for mobile application where the antenna works in a multi-path environments [1].

The first part of the project represent a preliminary study of BOR1 efficiency for dipole antenna and Bow-tie antenna. The decade performance of BOR1 efficiency for the Bow-Tie and dipole antenna is examined. The purpose this investigation is to get understanding for the design of feed antenna for reflector antenna for radio telescope applications regarding BOR1 efficiency. Future radio telescopes will require a decade bandwidth performances. Such systems like the very large base line interferometry (VLBI 2010) and the square kilometer array (SKA) [2, 3]. These projects will contain several reflector antennas which require a feed antenna with a constant directive radiations characteristics over a decade bandwidth or more. Several antennas has been proposed to work as a feed antenna for the mentioned project (VLBI 2010,SKA) for example, the eleven antenna and the ETS-lindgren Quadridge [4, 5].

The main core of the project representing the second part is mainly to design a compact wide band MIMO (multiple input multiple output) antenna for Reverberation Chambers. Reverberation Chambers (RC) is a metal cavity large enough to support many resonant modes. It has been tested for EMC (electromagnetic compatibility) testing for decades. Recently, it has been also developed to characterize small antennas and active terminals used in multi-path environments. These chambers are able to emulate multi-path environment similar to that environment exist in cell phone network[6, 7]. In order to have a wide band measurement by the reverberation chamber, the transmitting antenna of the reverberation chamber must have a wide band performance. As an example, the Bluetest reverberation chamber [8] has three triangular monopoles mounted on a metal cube. Modern communication system use frequencies below 800(MHz). Also other wide band antennas measurements demand up to 13 GHz [9, 10]. Therefore an even wider band antenna with multi ports is required.

The purpose of this work is to develop a new wide band MIMO (multiple input multiple output) antenna covering 0.65-13 GHz with a size similar to that of the current Bluetest triangular monopole antenna. The basic concept of the new antenna comes from the self grounded Bow-Tie antenna [11, 12]. The design employs the genetical algorithm in order to reduce the return loss and mutual couplings. Electromagnetic computations is performed by using CST (computer simulation technology) MS (microwave studio). The simulation results has been predicted a good performance for the new designed antenna. The project objective is to develop a wide band MIMO antenna operating in the bandwidth range (0.65-6)GHz. This bandwidth has been set to be the preliminary bandwidth to be achieved while ambitious is to cover a wider bandwidth. The new system should provide multi ports antenna in order to support the MIMO performance and diversity measurements. The circuit requirements is to achieve a reflection coefficients around -10 (dB), Mutual couplings below -10(dB) along the assigned bandwidth. The new system should be compact and easy to manufacture.

1.1 Outlines of the Thesis.

The first chapter is the introduction which will introduce the reader to the main core of the project. This chapter will provide the reader an insight to the project objectives.

In chapter two will be the characterization of antennas by efficiencies. The chapter will explain the aperture efficiency and its sub-efficiencies and phase center. With more emphasis on BOR1 efficiency. he eleven antenna will be an example to demonstrate the efficiencies and phase center. The purpose of this chapter is to verify the previous calculated efficiencies for the eleven antenna. Also to acquire enough skills of programming and using commercial software for example, CST(computer simulation technology) MS(microwave studio). Chapter two will represent the preliminary study of BOR1 efficiency for dipole antenna and Bow-tie antenna. Chapter two will contain the modeling, simulation and results analysis regarding BOR1 efficiency. This will include BOR1 efficiency investigation for different geometry cases regarding the Bow-Tie and dipole antennas.

Chapter three will contain the modeling and investigation of different antenna cases. This chapter represent the modeling of the new compact wide band MIMO (multiple input multiple output) antenna as the fixed measurements antenna for the reverberation chamber. The chapter will explain modeling strategies that have been followed. These strategies representing the employment of the self grounded Bow-Tie antenna concept to generate the multiple self grounded monopoles. This idea builds on a geometry of four self grounded monopoles within a compact area. This chapter will contain the analysis of the currently in use antenna (cube antenna). Also this chapter will contain the analysis of two ports self grounded Bow-Tie antenna, the four ports self grounded Bow-Tie antenna and the four ports self grounded triangular tapered antenna. The analysis contain characterizations regarding the reflection coefficients, mutual couplings, embedded radiation efficiency and total embedded efficiency.

Chapter four will explain in details the optimization process that has been implemented. The genetic algorithm optimization has been employed in order to reduce the reflection coefficients and the mutual couplings between ports.

Chapter five will contain the designing of the tapered micro-strip line transformer technology. This transformer is essential for the new antenna in order to achieve the desired reflection coefficients. This chapter will introduce the four ports dual sided self grounded antenna.

Chapter six is the characterizations of the fabricated prototype. The characterizations are based on the simulation and measurements results. Measurements and simulations regarding the S-parameters will present the reflection coefficients and mutual couplings. The simulation results were obtained through the CST(computer simulation technology) MS(microwave studio) simulator. The S-parameters measurements on the prototype were carried out by using Vector Network Analyzer. Embedded radiation efficiency and total embedded radiation efficiently were explained in this chapter and demonstrated through simulation and measurements results. Embedded radiation efficiency and total embedded radiation efficiency measurements were conducted by the reverberation chamber at Chalmers University of Technology. The chapter will address the correlation coefficients and diversity measurements. Also, measurements regarding the radiation pattern were conducted by using chalmers' anechoic chamber.

Chapter seven will draw conclusions regarding the work of designing the new wide band MIMO antenna. These conclusions are based on the measurements and simulation results. This chapter will contain conclusions regarding reflection coefficients and mutual couplings measurements and simulations results. This chapter will draw conclusions regarding the total embedded radiation efficiency and what is the dominate efficiency. The chapter will also contain recommendations for the future work regarding the manufacturing of a second prototype.

2

Antennas by Efficiencies

Antenna can be defined as an adapter or an interface medium which converts electrons to photons and vice versa. the photons is the quantum unit of the electromagnetic energy. Many types of antennas exist with different shapes and geometry and goes even to more complex structures. The verity of antennas stand for the different applications antennas are involved in. With the verity of applications and antennas level of complexity, all share the same principle. This principle is the radiation phenomena which is caused be accelerated (decelerated) charge. Antenna parameters can be divided into three groups; Circuit Quantities, Physical Quantities and Space Quantities. where the circuit quantities includes Antenna impedance, radiation resistance and antenna temperature. The physical quantities include the size and shape considerations of the antenna. The space quantities includes the field patterns, polarization, power pattern, beam area, directivity and aperture efficiency [13].

Antenna apertures, if we assume a horn antenna place in a uniform plane wave. The area of its mouth or the physical aperture will affect the horn power extraction from the incident wave. Aperture efficiency is an important factor to characterize the directive feed antennas. This efficiency and be extended into sub-efficiencies. The sub-efficiencies are; BOR1 efficiency, illumination efficiency, spill over efficiency, polarization efficiency and phase efficiency [14]. Therefore the aperture efficiency is the multiplication of the sub-efficiencies;

$$e_{ap} = e_{BOR1} e_{SP} e_{ill} e_{pol} e_{\varphi}. \tag{2.1}$$

2.1 BOR1 Efficiency

BOR is an abbreviation for bodies of revolution. This term called for the kind of antennas that have rotationally symmetric mechanical structures. For example the circular horn antenna. Body of revolution antennas do not necessarily have rotationally symmetric far field functions [15]. Therefore it is possible to classify such antennas as types of BOR_0 and BOR_1 depending on whether the polar components of the radiation filed have zeroth of first order φ variations around the symmetry axis of the BOR [16]. BOR1 efficiency represent the power in the index n=1 term of the pattern relative to the total radiated power. This efficiency is an important characterization of a feed for reflector antenna. Fourier Expanding of the far field function, it is well known that the first order φ variation contribute to axial radiation filed, while the higher order φ terms represent a power loss to sidelobes [17]. The far field function of a feed as well as any antenna as:

$$G(\theta,\varphi) = G_\theta(\theta,\varphi)\hat{\theta} + G_\varphi(\theta,\varphi)\hat{\varphi}. \tag{2.2}$$

since φ is periodic with period 2π, therefore the φ variation of the far field can be expanded into a fourier series as:

$$G(\theta,\varphi) = \sum_{n=0}^{\infty}\{[A_n(\theta)sin(n\varphi) + B_n(\theta)cos(n\varphi)]\hat{\theta} + C_n(\theta)cos(n\varphi) + D_n(\theta)sin(n\varphi)]\hat{\varphi}]\} \tag{2.3}$$

then we should use the discrete fourier transform to calculate the φ components as:

$$A_n(\theta) = \frac{2}{N}\sum_{k=0}^{N-1} G_\theta(\theta,k\Delta\varphi)sin(kn\Delta\varphi) \tag{2.4}$$

$$B_n(\theta) = \frac{2}{N}\sum_{k=0}^{N-1} G_\theta(\theta,k\Delta\varphi)cos(kn\Delta\varphi) \tag{2.5}$$

$$C_n(\theta) = \frac{2}{N}\sum_{k=0}^{N-1} G_\varphi(\theta,k\Delta\varphi)cos(kn\Delta\varphi) \tag{2.6}$$

$$D_n(\theta) = \frac{2}{N}\sum_{k=0}^{N-1} G_\varphi(\theta,k\Delta\varphi)sin(kn\Delta\varphi) \tag{2.7}$$

where n = 0,1...,(N-1)/2. N is the number of φ-cut planes and $\Delta\varphi = 2\pi$/N. k = 0,1,2,...,N-1 [18]. then the BOR_1 efficiency can be calculated by:

$$e_{BOR_1} = \frac{\int_0^{2\pi}\int_0^{\pi}[|G_{\theta 1}|^2 + |G_{\varphi 1}|^2]sin\theta d\theta d\varphi}{\int_0^{2\pi}\int_0^{\pi}[|G(\theta,\varphi)|^2 + |G(\theta,\varphi|^2]sin\theta d\theta d\varphi} \tag{2.8}$$

where

$$G_{\theta 1} = A_1(\theta)sin\varphi + B_1(\theta)cos\varphi. \tag{2.9}$$

$$G_{\varphi 1} = C_1(\theta)cos\varphi + D_1(\theta)sin\varphi. \tag{2.10}$$

and

$$\int_0^{2\pi}\int_0^{\pi}[|G_{\theta 1}|^2 + |G_{\varphi 1}|^2]sin\theta d\theta d\varphi = \tag{2.11}$$

$$\pi \int_0^{\pi} [|A_1(\theta)|^2 + |B_1(\theta)|^2 + |C_1(\theta)|^2 + |D_1(\theta)|^2] sin\theta d\theta. \quad (2.12)$$

BOR1 efficiency represent the power in the $n = 1$ term of the pattern relative to the total radiated power.

2.2 Sup-Efficiencies

The rest of the sub-efficiencies requires prior estimation of the co-polar and cross polar of BOR1 in the 45 plane as well explained in [19]

$$BOR_{co45}(\theta) = \frac{1}{2}[A_1(\theta) + C_1(\theta)]. \quad (2.13)$$

$$BOR_{xp45}(\theta) = \frac{1}{2}[A_1(\theta) - C_1(\theta)]. \quad (2.14)$$

2.2.1 Spill over Efficiency

It is the power within the subtended angle θ_o relative to the total power. spill over efficiency is expressed as:

$$e_{SP} = \frac{\int_0^{\theta_o}[|BOR_{co45}(\theta)|^2 + |BOR_{xp45}(\theta)|^2] sin\theta d\theta}{\int_0^{\theta}[|BOR_{co45}(\theta)|^2 + |BOR_{xp45}(\theta)|^2] sin\theta d\theta}. \quad (2.15)$$

2.2.2 Polarization Efficiency

This efficiency is caused by polarization losses. The power of the co-polar within the subtended angle relative to the total power within the subtended angle as :

$$e_{pol} = \frac{\int_0^{\theta_o}[|BOR_{co45}(\theta)|^2] sin\theta d\theta}{\int_0^{\theta_o}[|BOR_{co45}(\theta)|^2 + |BOR_{xp45}(\theta)|^2] sin\theta d\theta}. \quad (2.16)$$

2.2.3 Illumination Efficiency

which is given as following formula:

$$e_{ill} = 2cot^2(\frac{\theta_o}{2}) \frac{[\int_0^{\theta_o} |BOR1_{co45}(\theta)| tan(\frac{\theta_o}{2}) d\theta]^2}{\int_0^{\theta_o}[|BOR1_{co45}(\theta)|^2] sin(\theta) d\theta}. \quad (2.17)$$

2.2.4 Phase Efficiency

The remaining Sub-efficiency is due to phase errors in the co-polar radiation field $BOR1_{co45}$ as:

$$e_{\varphi} = \frac{|\int_0^{\theta_o} BOR1_{co45}(\theta) tan(\frac{\theta}{2}) d\theta|^2}{[\int_0^{\theta_o} |BOR1_{co45}|(\theta) tan(\frac{\theta}{2}) d\theta^2]^2} \quad (2.18)$$

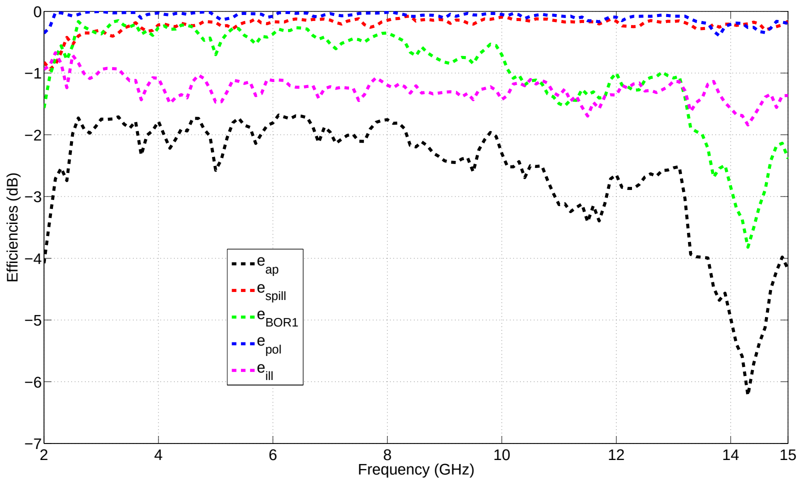


Figure 2.1: Eleven Feed Efficiencies: black doted line is aperture efficiency, green doted line is BOR1 efficiency

2.3 Eleven Feed

Eleven antenna or eleven feed is a log periodic dual-dipole array, developed at Chalmers University of Technology. The antenna has decade-bandwidth performance operating within 2-13 GHz. The Antenna has been proposed to work as a feed for the SKA and VLBA projects. The properties of the antenna support such a claim. The Antenna is constructed from two dipoles each dipole consist of two log periodically petals [20]. the aim of this section is to verify the antenna efficiencies performance; see Fig.2.1. Also to gain necessary skills for the next project. The simulations carried out using MATLAB where the efficiencies formulas programmed. The measurement of the antenna far-field conducted at Denmark Technical University through my advisor Jain Yain.

The calculations of the eleven feed phase center is an attempt to understand the location of the center of the curvature of the wave front of the radiation fields [21]. The phase center can be approximately calculated as:

$$\frac{Z_{pc}}{\lambda} = \frac{\phi_{co}(0,\varphi) - \phi_{co}(\theta_{max},\varphi_o)}{360degree(1 - cos\theta_{max}}. \tag{2.19}$$

where $\phi_{co}(0,\varphi_0)$ stand for the first angle of $BOR1_{co}$ and $\phi_{\theta_{max}}(0,\varphi_0)$ determined by θ_{max} which is half power beam width at each frequency by measuring the -10dB or -3dB beam width of the co-polar radiation pattern. The results are presented in figure 2; see Fig. 2.2 but the reliability of the results are not yet verified.

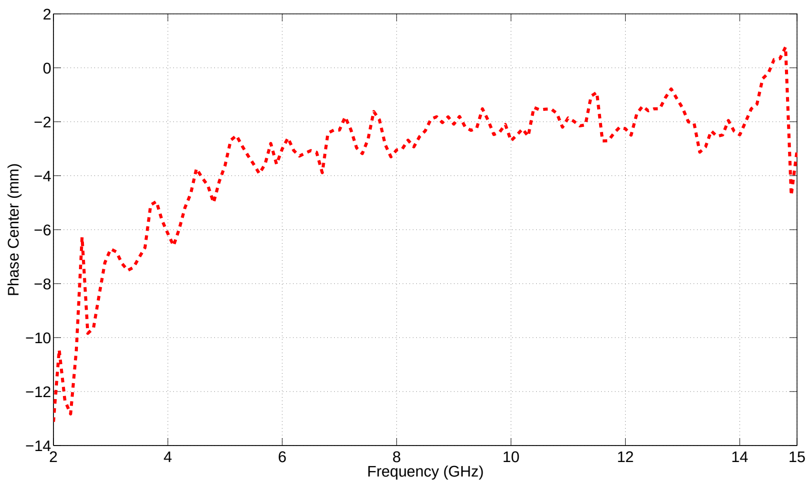


Figure 2.2: Eleven Feed Phase Center

2.4 Dipole Antenna

In this section we will conduct a preliminary study to investigate BOR_1 efficiency. This study will include investigation for Dipole Antenna and Bow-Tie Antenna. The purpose of this study is to provide an insight for the future design of feed antennas. BOR_1 efficiency is an important merit to determine the feed performance. The Dipole antenna is a classic antenna which is widely used in text-books to demonstrate antennas principles. We can look at the Dipole antenna as an antenna consist of two monopoles. For example a coaxial line, the inner conductor will be connected to one of the monopoles while the other monopole will be connected to the outer connector, which is grounded. The half wave length always used to design the Dipole length. In practise thats not true, it will be always require to tune the antenna length to reach the desired resonant frequency. However, the half wave length definition is enough for the far-field calculation. The Dipole Antenna will be modeled in CST Microwave Studio [22]. The procedure is quite simple. The requirements are two monopoles placed in the same direction (for example the Y-direction); see Fig.2.3. An enough space(a gap) between the monopoles to place an excitations source. A discrete port used to excite the antenna. The first case to simulate is the dipole in free space. Therefore the boundary conditions in CST MS is set to indicate the free space condition. Once the simulation done a macro will export the far field results. A MATLAB scripts will read the far-field readings and estimate BOR_1 efficiency; see Fig 2.4. The dipole has a length of $75mm$ which correspond to a frequency of $2GHZ$, the length tuned to $66mm$ for better $2GHz$ resonant. The tested bandwidth is up to $10GHZ$. The results shows that the Dipole has a high efficiency up to $5GHz$ when the efficiency starts to decay and oscillate at higher frequencies 2.4. One can argue that length might play a major rule to enhance the efficiency but that will depend on

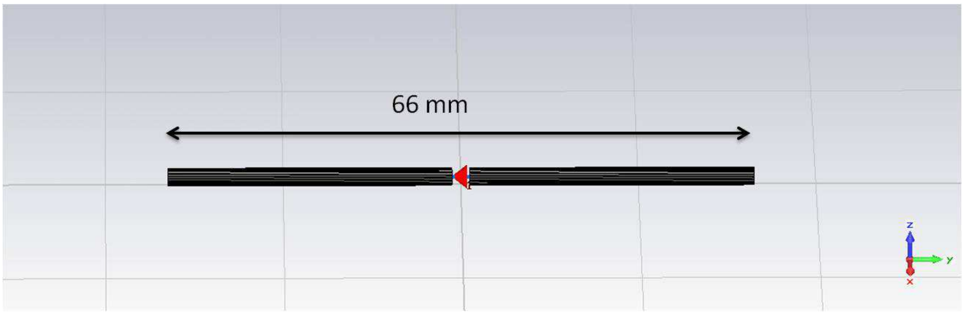


Figure 2.3: Dipole in free Space

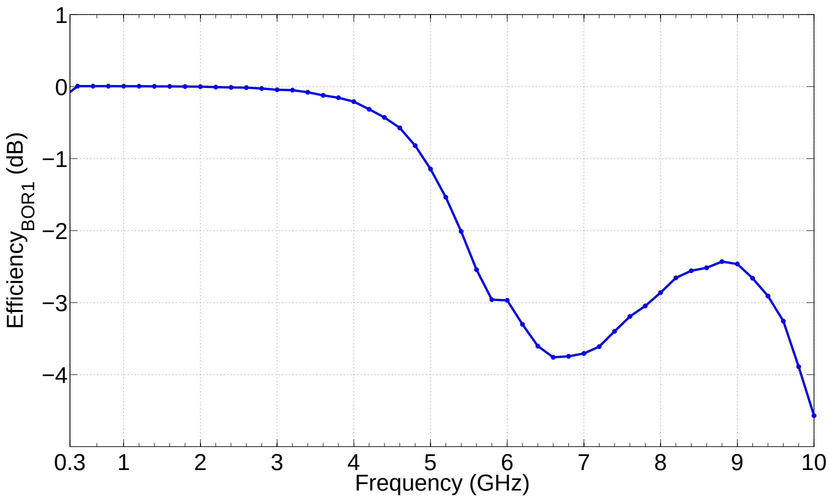


Figure 2.4: BOR_1 efficiency for a dipole in free Space

the application. in fact, changing the dipole length will only cause for frequency translation, In other words, that will change the matching impedance frequency. Therefore changing the length will not serve our purpose for the investigation of BOR_1 efficiency. But instead we will change the antenna geometry configuration. The configurations includes tilting the antenna'a arms with an angles with respect to the origin forming a (V) shaped dipole; see Fig 2.5. A similar procedure implied here as well, carrying out the results and estimating BOR_1 efficiency of a different cases with rotation angle with respect to Y-axis; see Fig2.6. When changing the angle, the Results showing unstable performance Fig.2.6. For example changing the angle to $20 degrees$ and the efficiency follows the original pattern for the un-rotated dipole. while increasing the frequency we noticed that the efficiency suddenly dropped in no sense way. Definitely the change in the geometry is supporting this sudden break down. Examining the radiation pattern we find out that at certain frequencies the radiation pattern split into more than one main

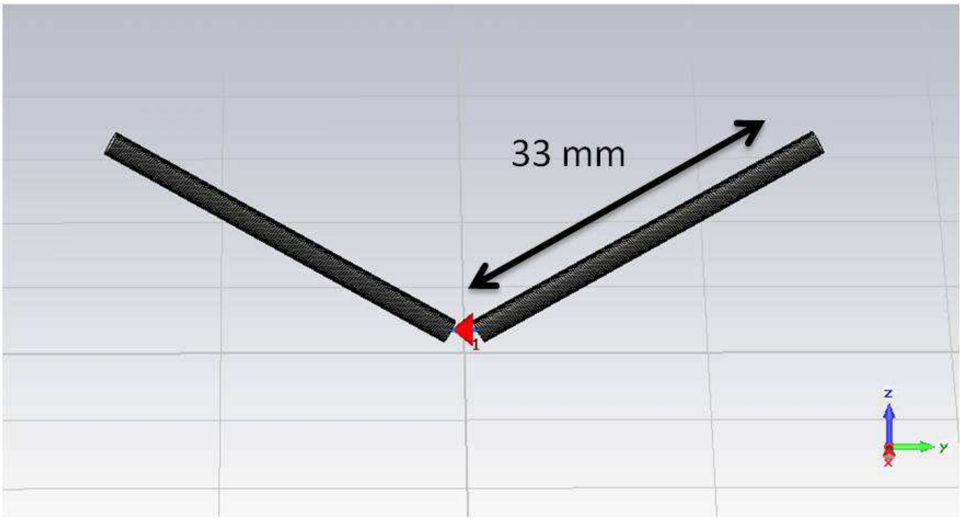


Figure 2.5: A V shaped dipole in free Space

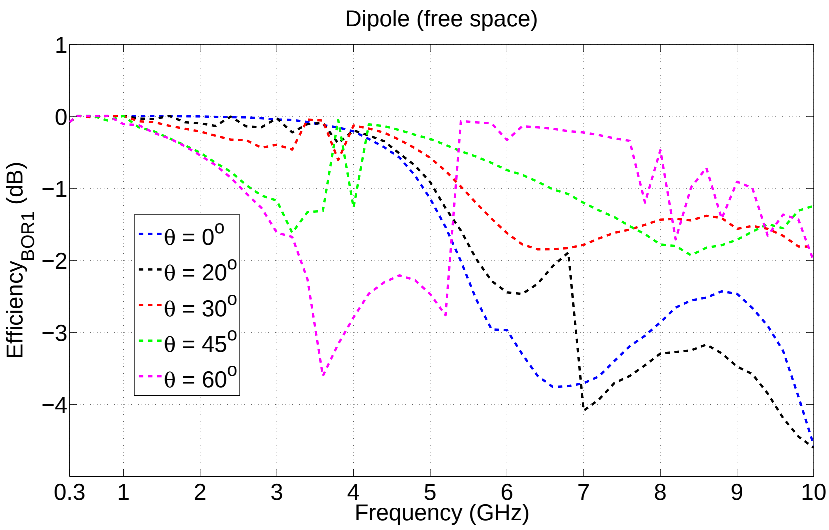
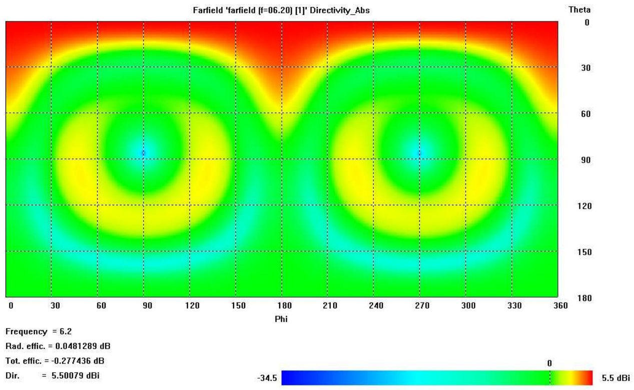


Figure 2.6: BOR_1 efficiency for The V-dipoles in free Space

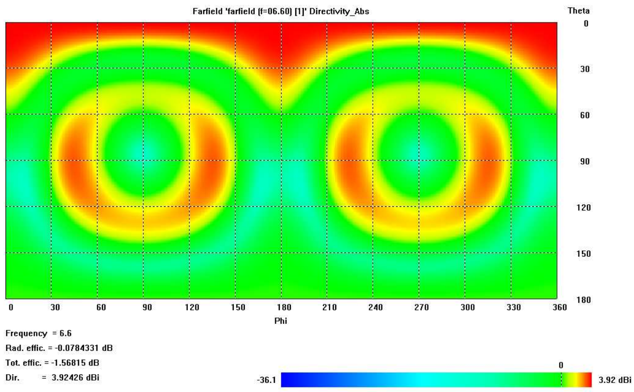
beam. This splitting losing the radiation pattern its rotationally symmetrical properties; see Fig.2.7. While changing the angle, in $30and40degrees$ the efficiency improved significantly over $-2dB$ Fig.2.6. This is give an indication that there is an optimal angle that might cause a high BOR_1 efficiency. Looking at the radiation patterns and the case of the dipole rotated $20degress$. BOR_1 efficiency decay when increasing the frequency. At certain range of frequencies the efficiency disturbed. These disturbances or the sudden break downs, mainly because the radiation pattern is losing the symmetrical properties

Fig.2.7.

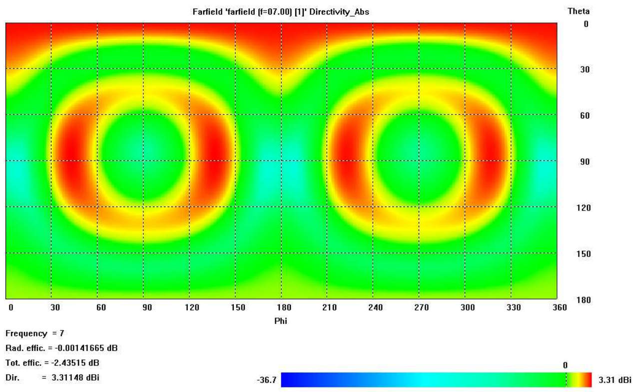
The next step we will examine BOR_1 efficiency when the dipole mounted above ground plane; see Fig.2.8. The dipole has the same length as before. A distance of $33mm$ between the dipole and the ground plane. The performance is severely effected compared to the free space cases. tilting the dipole forming the V-dipole cases as an attempt to improve the efficiency wasn't successful; see Fig.2.9



(a) Radiation Pattern at 6.2 GHz



(b) Radiation Pattern at 6.6 GHz



(c) Radiation Pattern at 7 GHz

Figure 2.7: Dipole Radiation Pattern (20^o V-dipole)

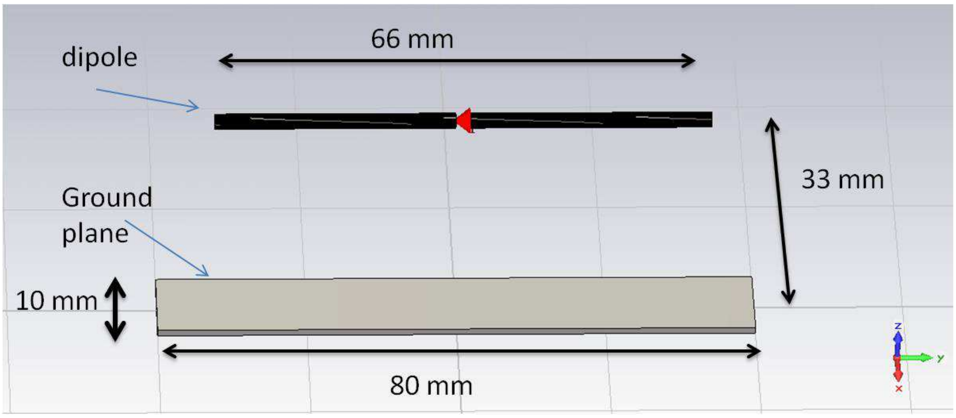


Figure 2.8: Dipole above Ground Plane

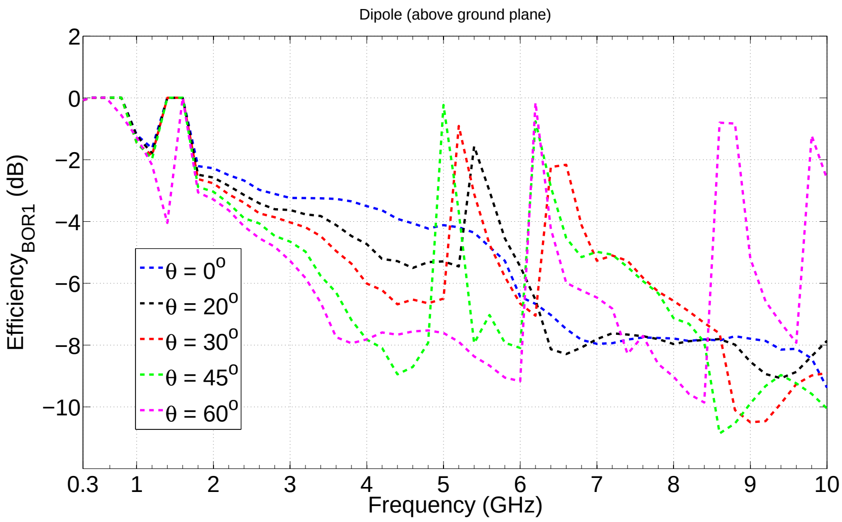


Figure 2.9: BOR_1 efficiency for a (V) dipole above Ground Plane

2.5 Bow-Tie Antenna

In This section we will look at another type of antennas which is the Bow-Tie antenna. This antenna has a bow-tie shape. The Antenna has the same length as the dipole but with a broader side to give the bow-tie shape; Fig.2.10. as we did for the dipole, the bow-tie experience the same procedures. simulating the bow-tie in free space. The BOR_1 efficiency for the Bow-Tie doesn't has a significant performance variation. In face the efficiency pattern for the Bow-Tie follows the the Dipole one; see Fig.2.11.Therefore the Bow-Tie antenna has a similar BOR_1 efficiency of the dipole. rotating the Bow-Tie antenna whether it is in free space or mounted above ground plane, resulting a

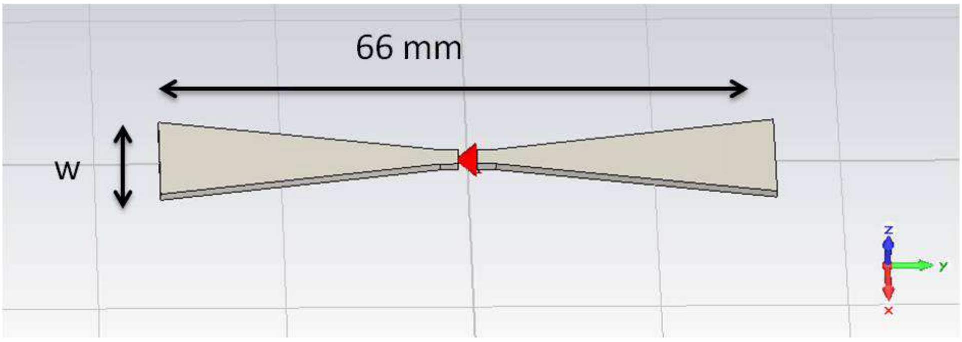


Figure 2.10: BOW-Tie Antenna Free Space

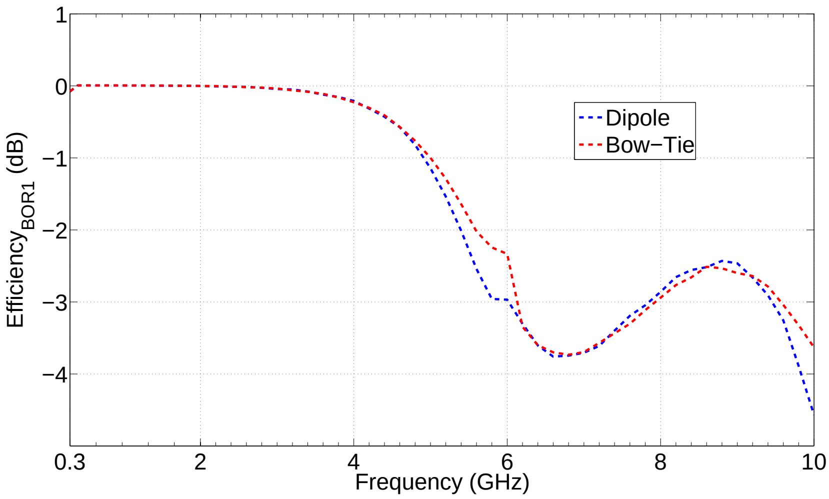


Figure 2.11: BOR_1 efficiency for The Bow-Tie and Dipole

very similar performances as for the dipole. Another investigation conducted which is changing the Bow-Tie broader side width to examine the affects on the efficiency. Simulation results showing that there isn't a significant effect to improve or decrease the efficiency. In fact the efficiency pattern constantly follows the dipole one; see Fig.2.12.

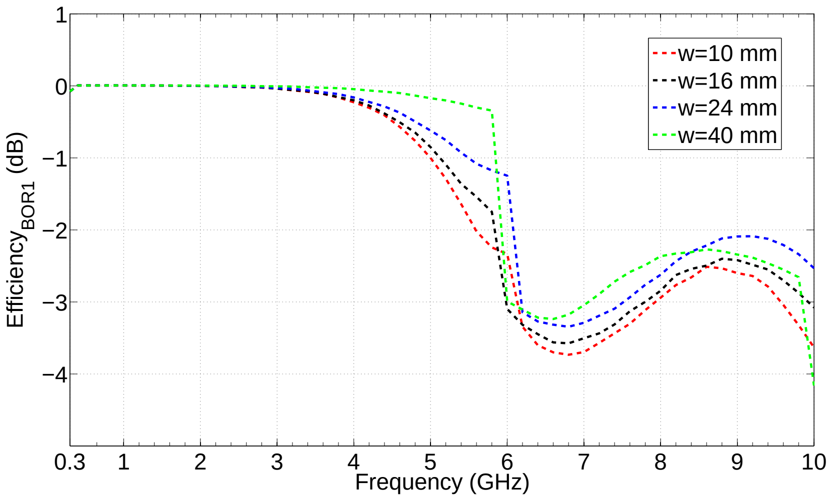


Figure 2.12: BOR_1 efficiency for the Bow-Tie with different widths (w)

2.6 Conclusion

A preliminary investigation of BOR_1 efficiency for Dipole Antenna and BOW-Tie Antenna have been conducted. Simulation results shows that the BOW-Tie and Dipole have similar BOR_1 efficiency. The Procedure conducted in different scenarios. Placing the Dipole in free space later rotating it. A ground plane placed to examine the performance changes for the dipole. The free space case showing that the efficiency is higher (better) than the ground plane case. The Procedure is also applied on the Bow-Tie antenna and the acquired results match the dipole one. We still have doubts concerning BOR_1 efficiency sudden improvement or decaying which it might be mathematically incorrect. The current explanation is concerning the radiation pattern. At some range of frequencies the radiation pattern spilt into more that one beam. This splitting losing the pattern rotationally symmetric properties. Beside this, The energy distribution among the beams might be even or different between them.

3

Modeling

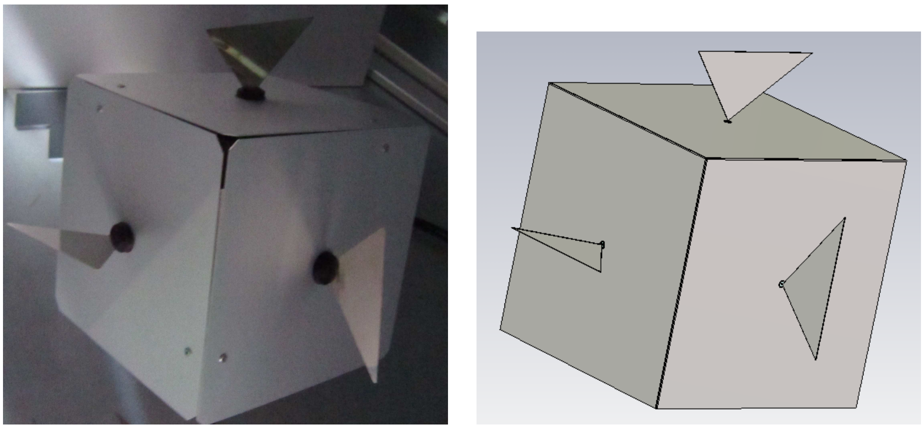
Reverberation Chambers (RC) is a metal cavity large enough to support many resonant modes. it has been tested for EMC (electromagnetic compatibility) testing for decades. Recently, it has been also developed to characterize small antennas or terminals used in multi-path environments, due to that a similar environment can be created inside the chamber [6, 7]. In order to have a wide band measurement by a reverberation chamber the transmitting antenna of the reverberation chamber must have a wide band performance. As an example, the Bluetest reverberation chamber [8] has three triangular monopole antennas as the transmitter, mounted on a metal cube. They cover a frequency band of 0.65-10 GHz. However, modern communication systems use frequencies down to 0.65 (GHz), and other wide-band antenna measurements demands up to 13 GHz [9, 10]. Therefore, an even wider band antennas are required.

3.1 The cube antenna

Bluetest Reverberation System is made of a metal cube. This metal cube consist of transmitting site and receiving site. A barrier or a metal wall placed in front of the transmitter to block the line of sight component. The receiver consist a turning table as an attempt to emulate the movements. Through these configuration and components a multi-path environment created inside the chambers to characterize mobile systems, for example cell phones; see Fig3.1. The current transmitting installation consist of a cube antenna as fixed measurements antenna. Three triangular monopoles mounted on the metal cube, serving as the transmitting antenna; see Fig3.2.

A CST (computer simulation technology) MS(microwave studio) model for the fixed measurements antenna has been created and simulated. Simulation results showing that the antenna has a performance (reflection coefficient) below -6(dB) in the frequency range (0.8-8)GHz. The antenna has reflection coefficients higher than -5(dB) in the frequency range (500-800) (MHz) as measurements and simulation indicating 3.3. These readings

Figure 3.1: Bluetest Reverberation Chamber at Chalmers University of Technology (Antenna Group)



(a) Fixed Transmitting Antenna **(b)** CST MS model

Figure 3.2: Bluetest fixed Measurements Antenna

is also a source motivation to develop an antenna with higher performance regarding the reflection coefficients.

The simulation regarding the mutual couplings between ports is very low, indicating a performance below -15(dB) between the three ports; see Fig.3.4. Simulation regarding radiation efficiencies indicating an embedded radiation efficiency higher than -0.2(dB) within the frequency range (0.5-10)(GHz) while the total radiation efficiency is below -1(dB) at frequencies below 1(GHz). This is mainly due to the reflection efficiency at these frequencies; see Fig.3.5.

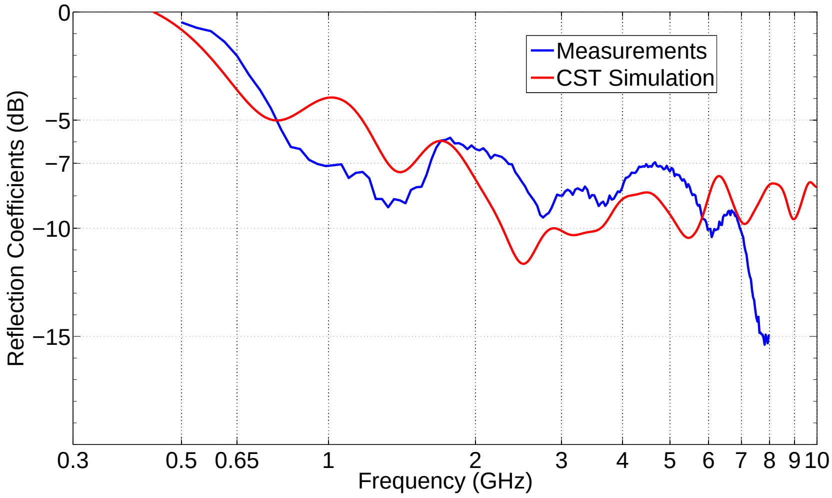


Figure 3.3: Reflection Coefficients for the current fixed measurements antenna

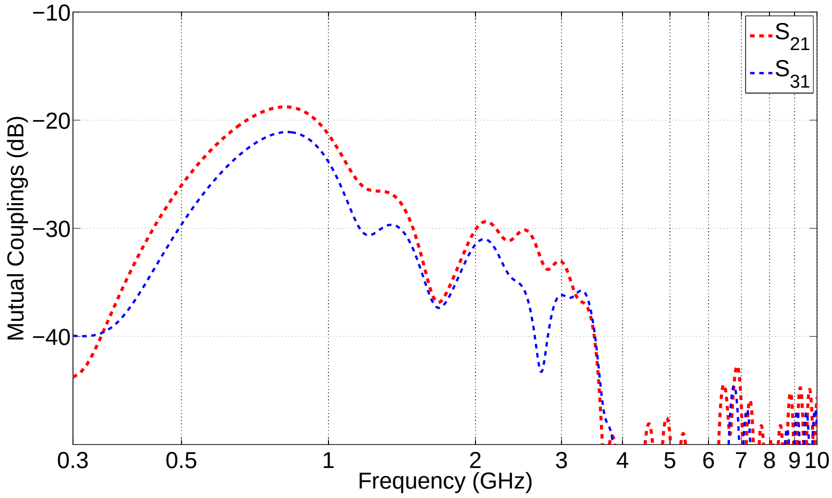


Figure 3.4: Cube Antenna Mutual Couplings (simulation)

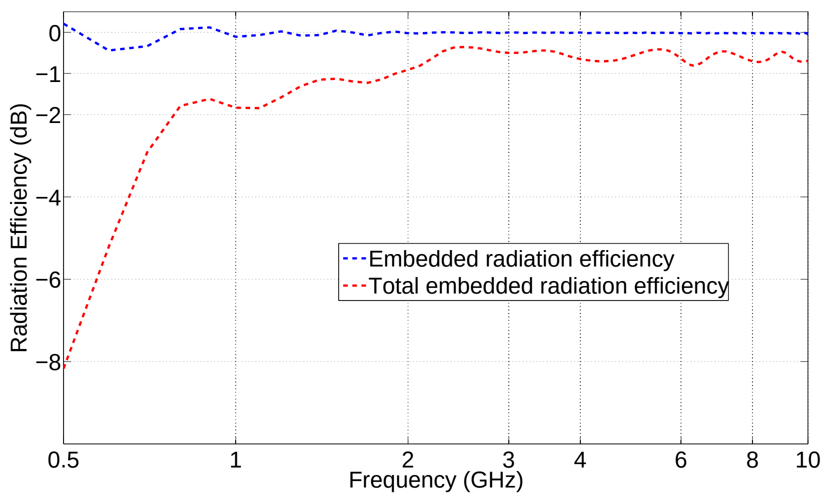
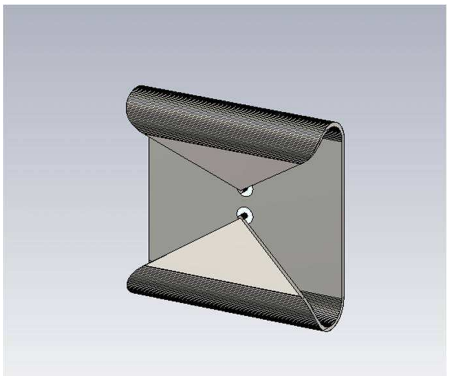


Figure 3.5: total embedded and embedded radiation efficiencies (Simulation)

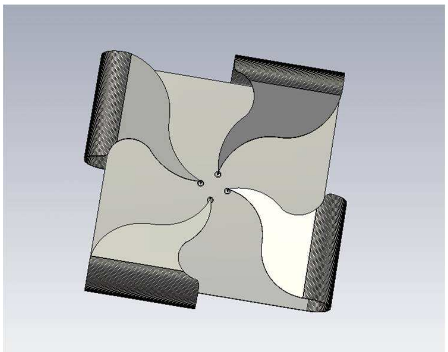
3.2 Concept Modeling

Through the necessity of having a wide band antenna capable to provide a satisfactorily performance down to $0.65GHz$ and up to $13GHz$. Therefore the research and Bluetest.Ab assigned several requirements to build a competitive multitasking Antenna. The term (UWB) ultra wide band is used to express the wide range performance. Even so the term is booked by the federal communications commission (FCC) to express the unlicensed use of (UWB) technology in frequency range from 3.1-10.6 GHz [23]. A multiple input - multiple output what so known abbreviated to (MIMO) is a required performance and an important option. Which the new system should have, therefore the antenna should have more than one antenna. The current system consist of three antennas or monopoles, in facts these antennas meant to keep the the polarization balance. in a manner to keep the MIMO performance of the new system, each system should have a considerable polarization balance. Another important factor for supporting the MIMO adjective are the mutual couplings between ports should be as low as possible. As a result the correlation between ports will be low. Therefore the Antenna has to have uncorrelated ports which is a merit entity important for multi-path environment measurements.

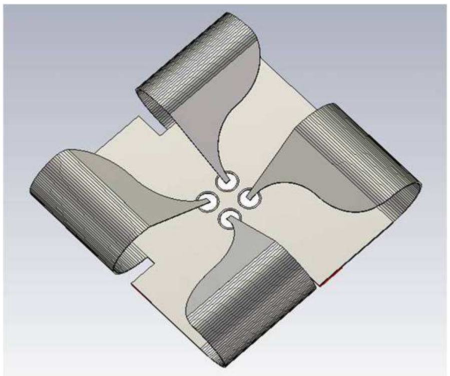
A major factor for the Antennas performance is the return loss. Since the new system will have more than one port, it is required to have a low reflectivity among the ports. We have to make sure the antenna is radiating which is determined by its radiation efficiency. A compact shape and size are main considerations in the design. A simple shape and compact size which can support the manufacturing on a large scale. Through these requirements we start to draw the first speculations. The work is a challenging task especially when you keep in mind the low profile and high performances. The first step is to think about the geometry of the antenna and how the geometry can provide the requirements. Dr.Jian Yang suggested that the self-grounded Bow-Antenna could be a good candidate. The self-grounded bow-tie antenna is a directive antenna invented by Dr.Jian Yang and Dr.Ahmed Kishk. This antenna is a new type UWB small antenna. the antenna beside its small size, has low reflection coefficient about $-10dB$ and stable radiation pattern over a wide bandwidth [12]. Since this antenna is directive and consist of one monopole, we knew from the beginning that the self-grounded Bow-tie antenna should experience a major modifications to fulfill our new design. What we will take for the new Antenna is the concept of the self grounding that provide the possible wide band performance within a compact size. The first step is to support self grounding bow-tie with two ports,therefore the antenna will support two monopoles. Since the requirements is to go in frequencies down to 0.65 GHz, the size of the antenna must be bigger. Also the antenna must provide the MIMO performance. Therefore increasing the the self grounding bow-tie antenna area enough to provide four monopoles. The shape of the monopole will differ than the one for the self-grounding bow tie. The concept is to lose the directive properties and replace it with an omnidirectional distributed field. The monopole will have an exponential shape on the sides, an attempt to provide the wide band performance. Therefore the monopole will look like a fan blade. But later we



(a) Two Ports Self Grounding Bow-Tie



(b) Four Monopoles self grounding antenna(fan blade shape)



(c) Four Monopoles self grounding antenna (one side with exponential shape)

Figure 3.6: Developments of the new concepts:The Multiple Self Grounding Monopoles Antenna

decide to give up this idea and keep only one side with exponential line and keeping the other side straight. these decision made after preliminary simulations which we find out that the later have a considerable performance than the others; see Fig.3.6

3.3 CST MS Modeling

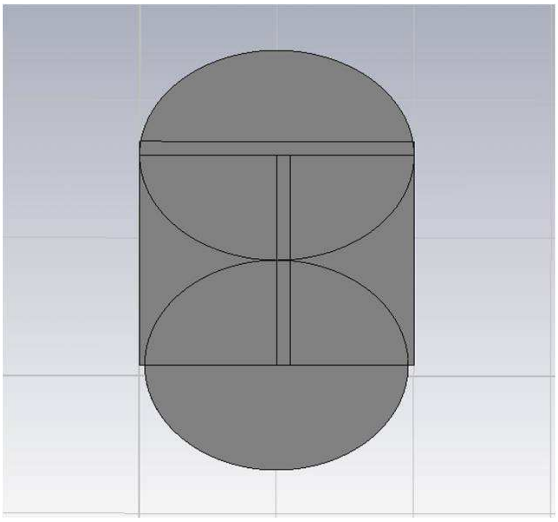
This section will explain in details the modeling procedure. The CST MS is used to model the antenna and simulate. The CST MS provide an excellent cad engine enable us to model the concept and modify it smoothly. A MATLAB scripts written to control the CST MS. In this way we are able to implement local modifications and globally. The MATLAB Scheme is also important for the later optimization scheme. The area of the new antenna will be large to support performances at lower frequencies. The area will be a variable parameter either during the optimization or scaling. The complex part of modeling is the monopole shape. The shape will have an exponential line on one side while the other side kept straight. This will provide the monopole with an increasing area happening in exponential way. Which is an attempt to provide the wide band performance.

3.3.1 Monopole Construction

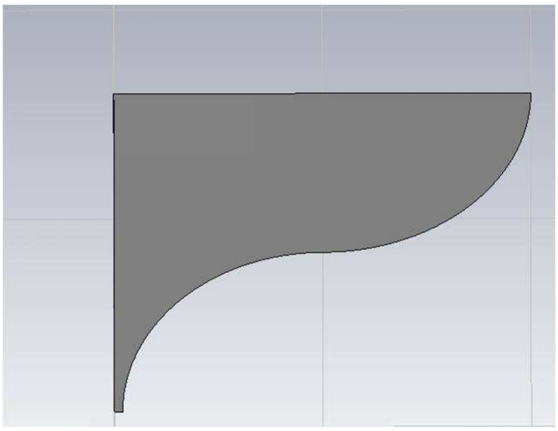
To obtain this configuration (exponential line) it is essential to transform the geometry into controlled functions. These functions are controlled through a scripts written in MATLAB. This step provide the flexibility to produce several antennas in one command line without using CST MS environment to change or tune the design. This scripts is essential for the optimization scheme where a large amount of antennas will be produced. The monopole shape is constructed through the junctions of several cylinders some has equal radius to form pure circle others with differen radius forming elliptical shape. By defining a brick in CST MS (*Createbrick*) which provide the basic foundations for the monopole. The Brick will have dimensions of 100×80 mm. Later two cylinders will be introduced to the same geometry location of the brick. The first circle will have the center points at the origin of the brick, for example if the brick has the origin points at (100,3.85) or (0,3.85) which 100 is the brick width, therefore the first circle will be placed having center points as (50,3.85). Then the second circle will be placed at the other end of the brick having center points of (50,80) which 80 is the total length of the brick. Later the circles will have an elliptical shape. Both circles will radiuses in the length direction to form a junction point. while the second circle diameter in width direction is equal to the brick diameter. The firs circle radius along the width direction will have a scaled width and that will form the feeding point for the antenna; see Fig.3.7a. The Boolean operation is implemented to get the final shape. Boolean operations is a typical tool in CST MS to produce complex shapes from the junctions of several planes. By using the inserting command *Insert* between the brick and the first circle. Also using the inserting command between the brick and the second cycle. later deleting the first cycle and the outer half of the second cycle. finally, adding the brick to the other half of the second cycle to have the final shape for the monopole. By that this shape is produced in a controlled manner which mean, its possible to tune the monopole dimensions on demand; see Fig.3.7b.

3.3.2 The Folding Shape

The folding shape will support the monopole being self grounded. This construction is done through introducing a circle along the X-direction. This circle will connect the ground plane to the monopole. Later the circle will be cut at the tangential point to be connected to the monopole plane as in Fig.3.8a. The following step is to scale up the monopole plane, in a manner to give a thickness enough to intersect with upper plane as in Fig.3.8b. Through the boolean intersection operation between the folded monopole and the scaled monopole plane the final shape will have an exponential folded shape as shown in Fig.3.8c. later through the mirroring command in CST MS, it is

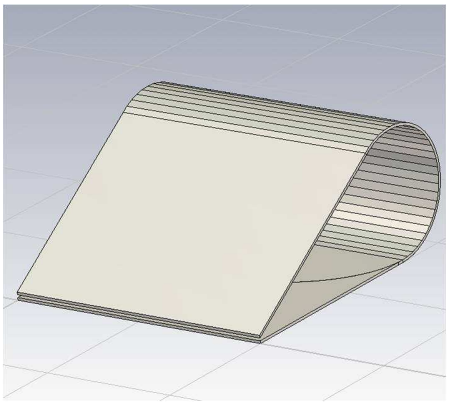


(a) The circles being used to produce the exponential shape

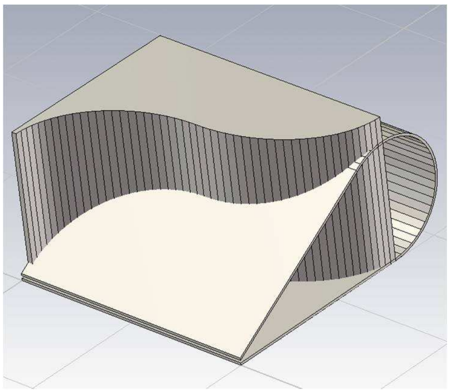


(b) The results after using Boolean Operations in CST MS

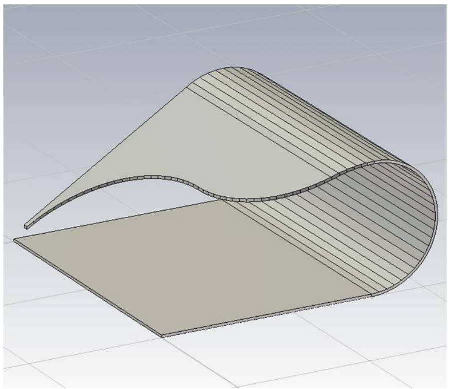
Figure 3.7: Monopole modeling steps



(a) The folding shape to support the self-grounding



(b) Scaling the monopole geometry



(c) The results after using Boolean Operations in CST MS

Figure 3.8: Process steps to produce the self grounding monopole

possible to generate multiple self grounded monopoles which represent the final system consisting of four monopoles; see Fig3.6c. The final geometry satisfy the requirement for having a MIMO performance represented in the four monopoles configuration. The self grounding concept provide the compact volume. Moreover, the modeling done in manner to be controlled, through a written scripts in MATLAB controlling the CST MS functions. This provide the possibility to tune the antenna dimensions or scaling the area of antenna.

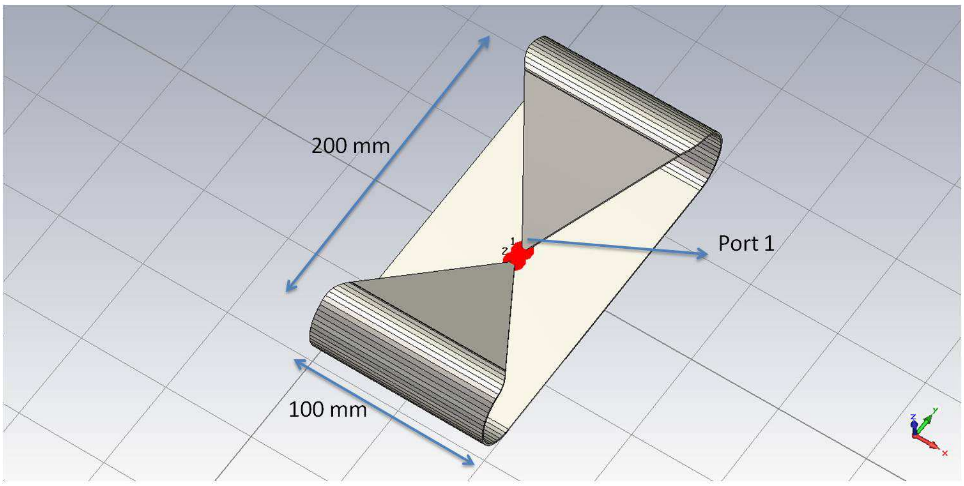


Figure 3.9: Two Ports Self Grounded Bow-Tie (CST MS Model)

3.4 Concepts Analysis

The investigation will be conducted on different antennas. These antennas will hold different geometries all of them sharing the self grounded concept. Which is first implemented on the self-grounded Bow-Tie antenna. The investigation will hold characterizations based on the reflection coefficients, mutual couplings, embedded radiation efficiency and total radiation efficiency. The first antenna to be model is the self ground Bow-Tie antenna with two ports; see Fig.3.9

Through the simulation results, it has been observed the wide band performances regarding the mutual couplings, reflection coefficients and radiation efficiencies; see Fig.3.10 and Fig.3.11

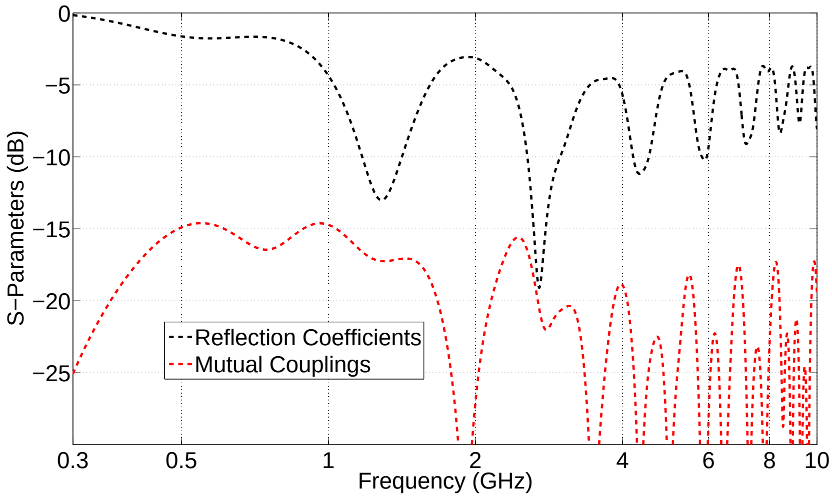


Figure 3.10: reflection coefficients and mutual couplings (CST MS simulation)

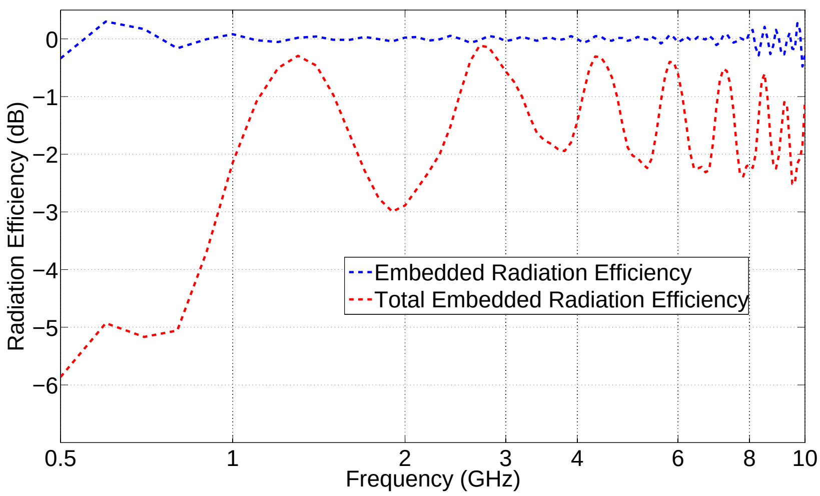


Figure 3.11: embedded and total embedded radiation efficiencies (CST MS simulation)

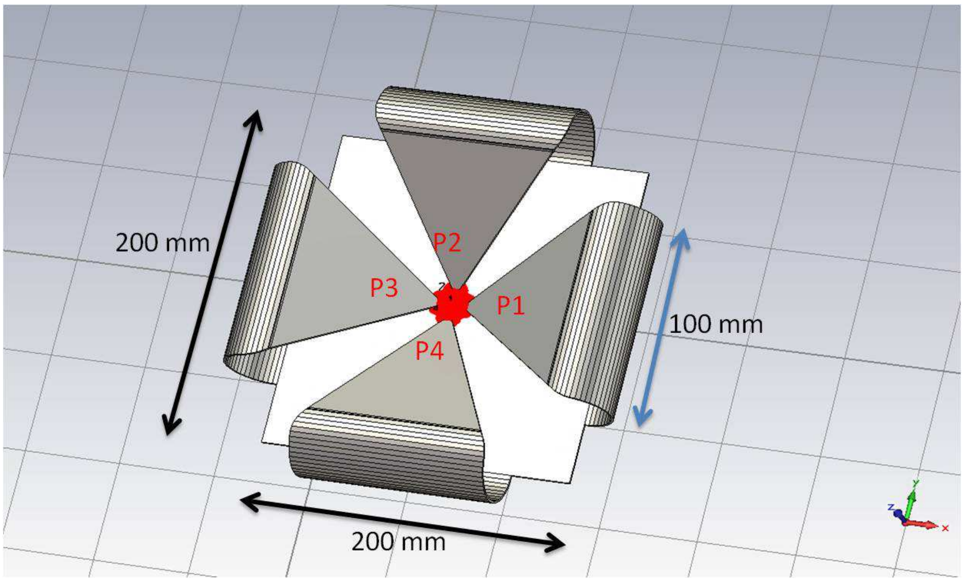


Figure 3.12: Four ports Bow-Tie antenna (CST MS model)

3.4.1 4-ports self grounded Bow Tie

Since the requirement is to have more than one port and the case of two ports Bow-Tie antenna is also not sufficient therefore the Bow-Tie will have four ports instead by increasing the number of monopoles in the antenna geometry; see Fig.3.12

similarly simulation results regarding reflection coefficients, mutual couplings and radiation efficiencies as in the following figures;

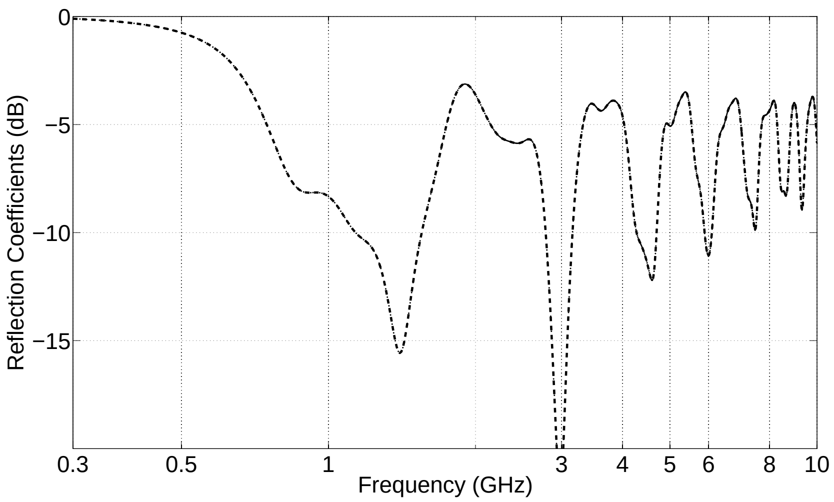


Figure 3.13: Reflection Coefficients for the four ports self grounded Bow-Tie (CST MS Simulations)

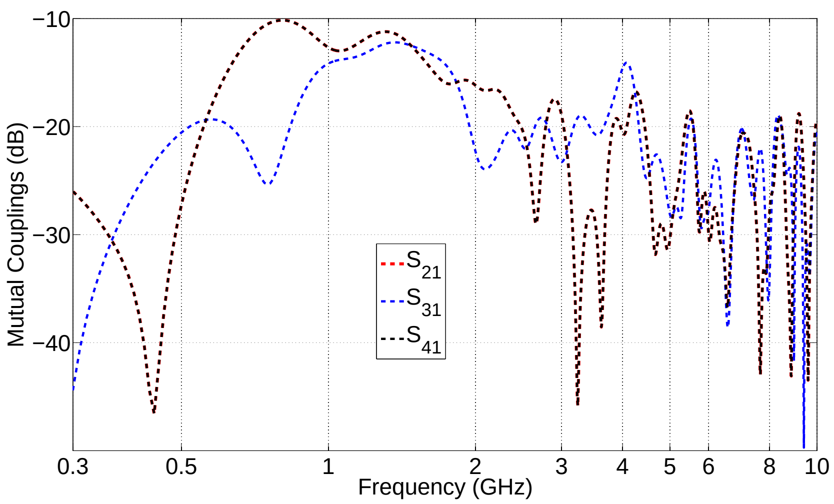


Figure 3.14: Mutual Couplings for the four ports self grounded Bow-Tie (CST MS Simulations)

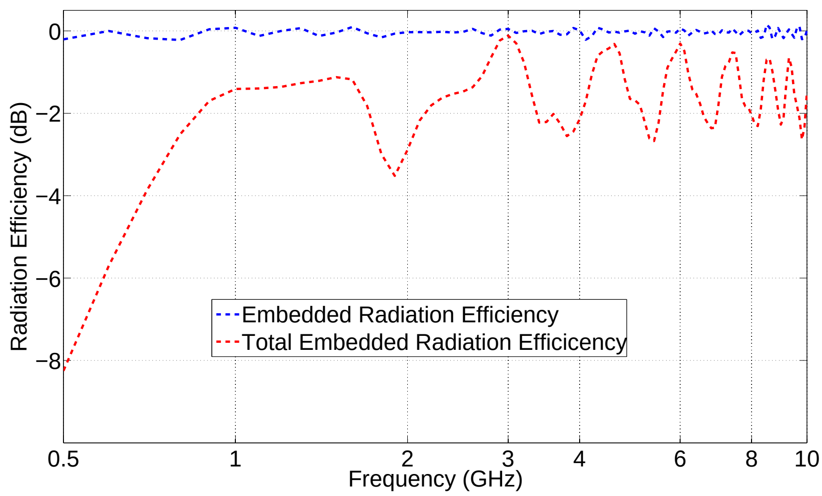


Figure 3.15: Radiation Efficiencies for the four ports self grounded Bow-Tie (CST MS Simulations)

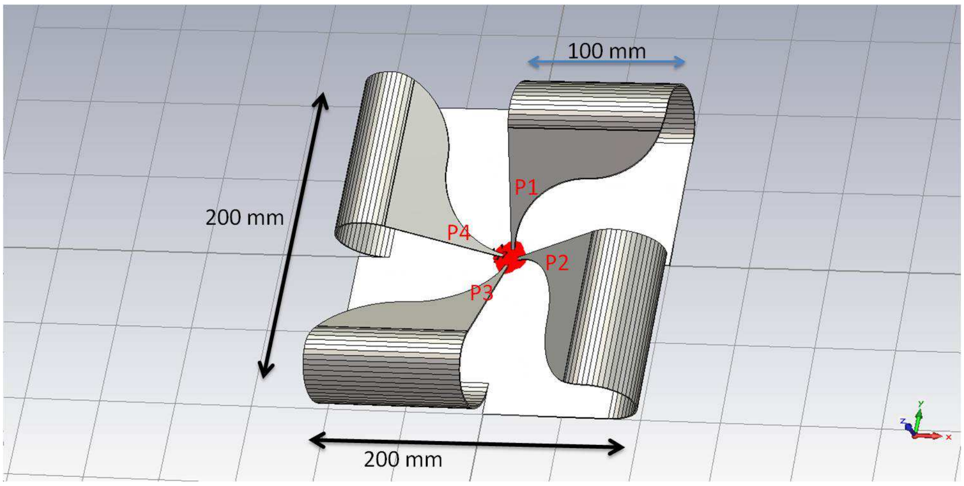


Figure 3.16: Four ports self grounded tapered triangular antenna (CST MS model)

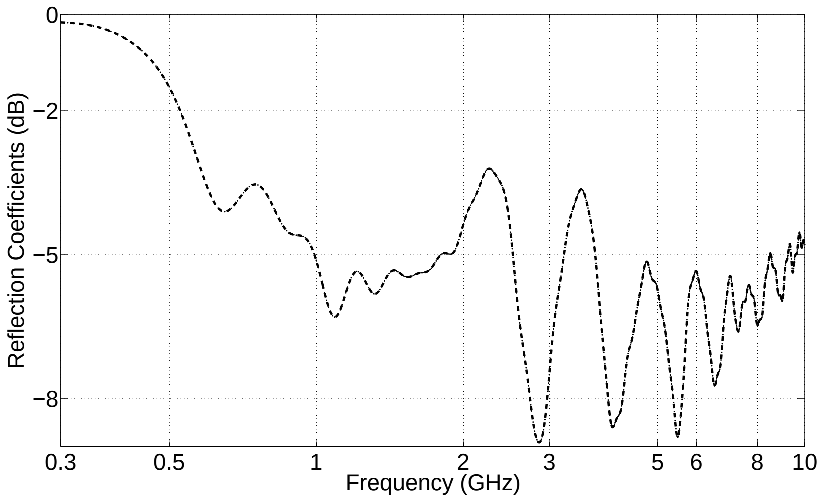


Figure 3.17: Reflection Coefficients (CST MS Simulations)

3.4.2 4-ports self grounded triangular

In this section we will analyze a type of antenna with tapered triangular monopoles. This is an attempt to develop a wide band performance through the tapered geometry; See Fig.3.16

similarly simulation results regarding reflection coefficients, mutual couplings and radiation efficiencies as in the following figures;

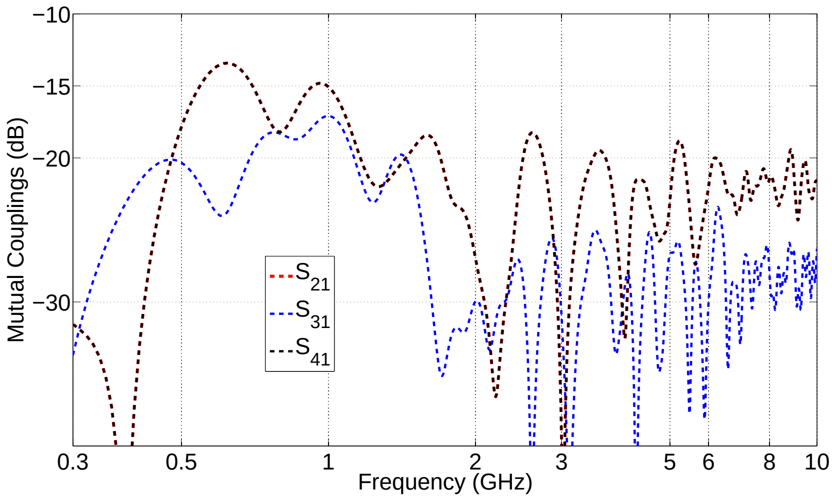


Figure 3.18: Mutual Couplings (CST MS Simulations)

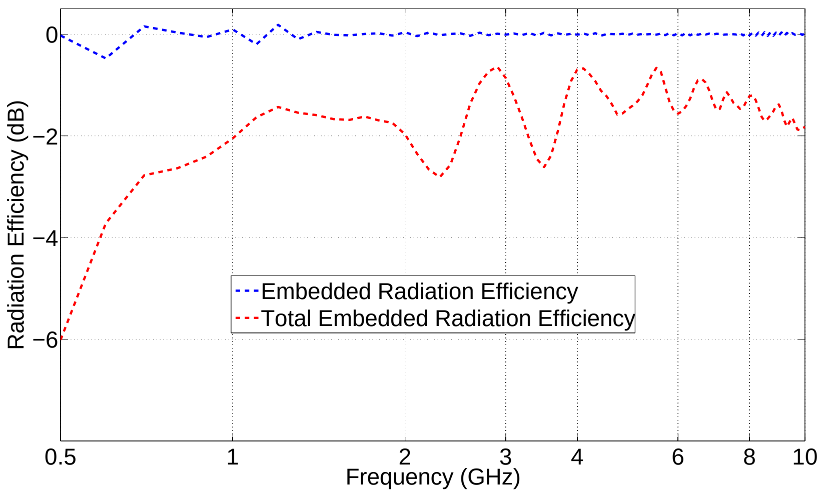


Figure 3.19: Radiation Efficiencies (CST Simulations)

3.5 Summary

This chapter is presenting the modeling and analysis of different self-grounded Bow-Tie geometries. The analysis is including the simulation results of reflection coefficients, mutual couplings and efficiencies of embedded and total embedded radiation efficiencies. The conventual self-grounded Bow-Tie single port concept has been employed in order to generate multi ports self grounded Bow-Tie antenna. These collection of self grounded

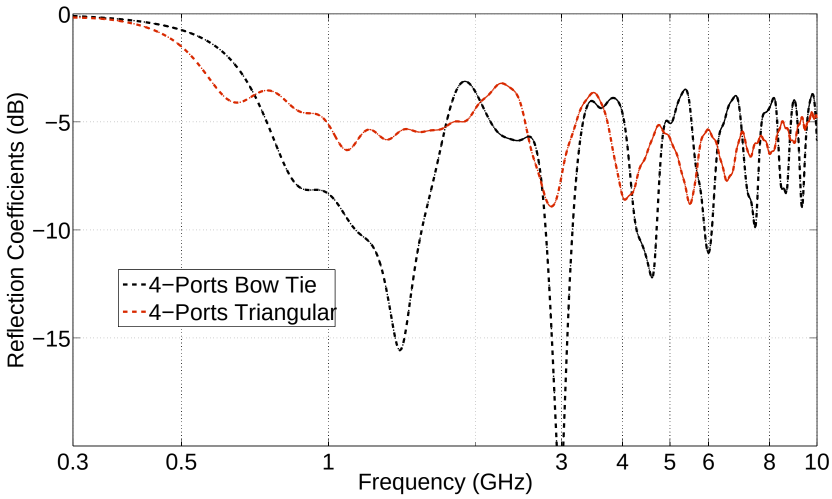


Figure 3.20: four ports self grounded Bow-Tie versus four ports self grounded Triangular antenna reflection coefficients (CST MS Simulations)

models include; Two ports self grounded Bow-Tie antenna, four ports self grounded Bow-Tie antenna and the last one which is four ports self grounded triangular antenna. The last model is also referred as the one sided multi-port self grounded antenna. The difference is the geometry of the single monopole. The last model has triangular shape with tapered side while the four ports self grounded Bow-Tie has a typical bow tie alike shape. These geometries share a general size which is 200×200 mm corresponding to the width and length, respectively. Through the analysis of the simulation results, the four ports self grounded Bow-Tie has a mutual couplings below -10(dB) in the frequency range 0.3-10 (GHz) while the self grounded triangular (one sided)four ports antenna has a mutual couplings below -15(dB). The performance of the self grounded tapered triangular and self grounded Bow-Tie antenna regarding the reflection coefficients is appeared that the last one (Bow-Tie) has has multi-band properties while the tapered triangular antenna has a wide band properties. This is observed between the maximum and minimum peaks of the reflection coefficients where the difference is high in the four ports self-grounded Bow-Tie antenna; See Fig.3.20.

4

Optimization

Genetic algorithm is a numerical optimization method. it is employ a global searching method for an optimum solution rather than the local schemes. Most of the creatures on earth including human adapted to the surrounding environments. An example, the trees grow a deep roots to stand the strong winds and to get moisture. Many animals developed defence mechanism such as changing color or releasing a chemicals to push away or to avoid potential predators. The philosophy of adaptation inspired and used by engineers to initiate such environments. This expressed in a computational algorithms by using modern computers. These algorithms has been used in various applications such as electrical and mechanical applications, and others. The genetical algorithms has a considerable interests in electromagnetic. This method has been used to optimize various antennas for low side lops, reducing the return loss, directive performances and other quantities [24]. The hat feed antenna is a type of reflector antenna where the feed is mounted on the focus or the center of the reflector. This configuration give the shape of the hat, in other words, the feed is self supported without struts being used [25]. This antenna is well known of its low side side lops and cross polarization. The initial prototype has been designed through parametric and local optimizations schemes. These schemes failed to produce a satisfactory low return loss. Later the global scheme, Genetic algorithms succeeded to produce an evolved antenna with a low return loss and maintaining the performance for the other merits as in [26]. The return loss is an important quantity especially in low noise application. In UWB antennas it is necessary to achieve the low return loss performance. A log periodic array antenna is a type of antennas with directive properties. The Eleven antenna employ that concept. The Genetic optimization is used to optimize the eleven feed Antenna. The scheme optimized a partial part of the array. This method compute the embedded S-parameters of the array and optimize the physical parameters for a group of dipoles. once an optimum performance reached, the dimension of optimized group would be scaled to the other dipoles in the array. By this method an evolved antenna has been produced with low return loss and the computation time has been reduced [27]. These previous projects motivated us to implement the Genetic Optimization to optimize the new Antenna for the reverberation chamber. The scheme consist of a sequence of events the overall sequences represent the genetic algorithms. The antenna parameters which are possible to tune are translated into genes. Where the single gene is responsible for a specific property in the geometry. Later a string of genes will represent a chromosome. A single chromosome hold the overall properties of single antenna. A group of chromosomes will represent a population, which is a group of antennas. The group members will experience evaluations according to the specified goal. The individuals with higher performances will be transferred to the mating pool. Where there the process of generating offsprings for the next generation will be done. A mutation could be followed to alter a specific gene which could lead into rapid searching for the optimum solution. This process represent a typical scheme for the Genetic algorithms. The processes repeat itself for a specified iterations or a convergence case occurred, where a satisfactory results obtained. However the process would be modified to suit the designs but will not differ from the main layout of the genetic algorithm main scheme.

4.1 Parameters Representation

The algorithms process has been coded by using MATLAB scripts. The codes are customized to fit the antenna CST MS model. Therefore it will be necessary to modify it for further applications. The first step is to represent the the model dimensions into genes. Therefore the different parameters of the model would be called genes to follow the algorithm terminology. A single gene is responsible for geometrical property, for example, *GeneA* will give the dimension for the length, width or height. By examining the model and carry out the possible optimized parameters. A total number of seven genes would form a chromosome. These genes represents the geometry dimensions of the monopole as;

$$chromosome = f(geneA, geneB, geneC, geneD, geneE, geneF, geneG) \tag{4.1}$$

where the chromosome is a function of the genes. *geneA* and *geneB* are responsible for the location of the monopole feeding point along the the X-direction and Y-direction, respectively. *geneC* is the gene responsible of the radius of the outer circle. The circle that connect the monopole with ground plane to form the self-grounded monopole. *geneD* will be responsible of the width of antenna feeding, this location represent the smallest area in the monopole, thus it is sensitive for high frequencies. *geneE* and *geneG* are the genes responsible for the ground plane dimensions in the x-direction and y-direction, respectively. *geneG* is the gene that will form the area under the exponential or tapered line. this gene will change the radius of the circles as in 3.7. By introducing unfolded model of the monopole, it will be clear enough to illustrate where are the genes lie on the geometry; see Fig.4.1.

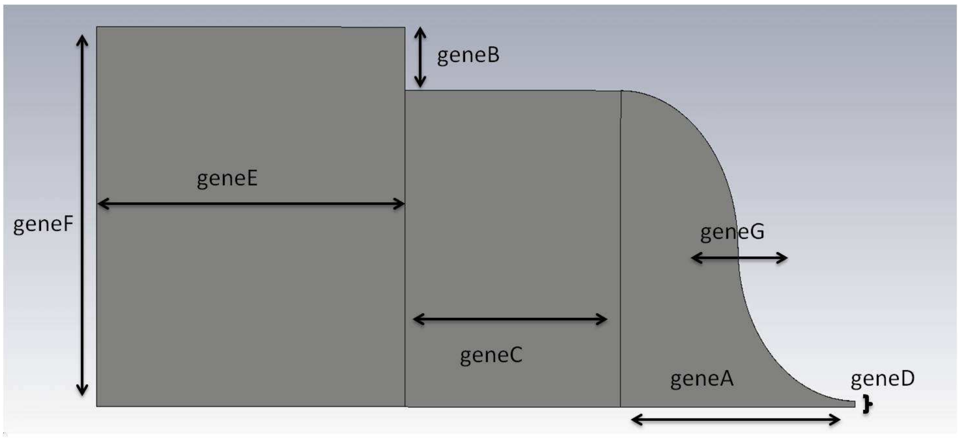


Figure 4.1: Genes distribution on an unfolded monopole

4.2 Initiating Population Pool

Usually the genes representation done through binary (zeros and ones) or continuous numbers. The later is used to represent the genes. It is easier to do it and these genes have physical or real dimensions on the model. Therefore it is an attempt to avoid dimensions are hard to realize for manufacturing. Every gene will hold a first guest value. This value is generated randomly through the MATLAB command *RAND*. The random values of the genes lie within a specified domain. Therefore the generated values will not exceed the maximum defined possible value neither lower than the minimum defined value [28].

$$Pop(\mathrm{M,N}) = gene_{low} + (gene_{hi} - gene_{lo}) \times Rand(N,1) \tag{4.2}$$

Where $gene_{low}$ is the lowest value and g $gene_{hi}$ is the highest value. It will require a pre-defining for these values taking into account that the gene's domain should project a realistic values possible to manufacture and keeping the original design layout. N represent the size of the population. M is the chromosome length or the total number of genes. The process start by initiating a community or a population. The population consist of the individuals. these individuals are the chromosomes holding the genes information. In other words the population individuals are the Antennas. as ;

$$Pop(N{,}M) = \begin{bmatrix} gene_{1,1} & gene_{1,2} & gene_{1,3} & gene_{1,4} & gene_{1,5} & gene_{1,6} & gene_{1,M} \\ gene_{2,1} & gene_{2,2} & gene_{2,3} & gene_{2,4} & gene_{2,5} & gene_{2,6} & gene_{2,M} \\ gene_{3,1} & gene_{3,2} & gene_{3,3} & gene_{3,4} & gene_{3,5} & gene_{3,6} & gene_{3,M} \\ gene_{4,1} & gene_{4,2} & gene_{4,3} & gene_{4,4} & gene_{4,5} & gene_{4,6} & gene_{1,M} \\ gene_{.,1} & gene_{.,2} & gene_{.,3} & gene_{.,4} & gene_{.,5} & gene_{.,6} & gene_{.,M} \\ gene_{.,1} & gene_{.,2} & gene_{.,3} & gene_{.,4} & gene_{.,5} & gene_{.,6} & gene_{.,M} \\ gene_{.,1} & gene_{.,2} & gene_{.,3} & gene_{.,4} & gene_{.,5} & gene_{.,6} & gene_{.,M} \\ gene_{.,1} & gene_{.,2} & gene_{.,3} & gene_{.,4} & gene_{.,5} & gene_{.,6} & gene_{.,M} \\ gene_{N,1} & gene_{N,2} & gene_{N,3} & gene_{N,4} & gene_{N,5} & gene_{N,6} & gene_{N,M} \end{bmatrix} \tag{4.3}$$

where N is the total number of the population. M is the total number of genes. The population can be rewrite as;

$$Pop(N) = \begin{bmatrix} Chromosome_1 \\ Chromosome_2 \\ Chromosome_3 \\ Chromosome_4 \\ Chromosome_5 \\ . \\ . \\ . \\ Chromosome_N \end{bmatrix} \tag{4.4}$$

where every chromosome represent an antenna, and every antenna hold different random generated gene values from the other members of the population;

$$Pop(N) = \begin{bmatrix} Antenna_1 \\ Antenna_2 \\ Antenna_3 \\ Antenna_4 \\ Antenna_5 \\ . \\ . \\ . \\ Antenna_N \end{bmatrix} \tag{4.5}$$

4.3 Cost function

The initial or the first population is consisting of the individuals. Those individuals in this project are the randomly created antennas. The antennas in the same time represents the chromosomes. The single chromosome contain the genetic information of a single antenna. This step is followed by evaluating the population cost function. The evaluation means that the population being optimized towards the assigned cost function. Therefore each chromosome will have a corresponding cost function. A one dimensional algorithm is said when the process is being optimized towards only one cost function. While A multidimensional algorithm is for optimization for more than one cost function. The representation of the cost function depends on the required performance to be optimized. In this project two parameters will define the cost function, The return loss and mutual couplings. Therefor the antenna parameters dimensions will be optimized to reduce the return loss and mutual couplings. The mutual coupling has been dropped from the cost function. This is due to the fact the antennas were keeping a high mutual couplings performance. Therefore the cost function has one goal to be optimized. Which is optimizing the antenna for a high return loss performance along the bandwidth. By computing the scattering parameters for each antenna, it would be possible to establish a cost function representing a wide band performance regarding the reflection coefficients. This done through a MATLAB scripts as;

$$\mathit{Cost(i,j)} = S_{11dB}(i,j) \tag{4.6}$$

where i represent the frequency and j represent the individual number. The j is the address which lead to the antenna or chromosome that has the gene information. By this function 4.6, it is establishing a matrix consisting the antennas' return loss values. where the row part of the matrix is the frequency and the columns are the different chromosomes as;

$$\mathit{Cost(freq,chromosome)} = \begin{bmatrix} S11_{(1GHz,chromosome1)} & \cdot\ \cdot & S11_{(1GHz,chromosomeN)} \\ S11_{(2GHz,chromosome1)} & \cdot\ \cdot & S11_{(2GHz,chromosomeN)} \\ S11_{(3GHz,chromosome1)} & \cdot\ \cdot & S11_{(3GHz,chromosomeN)} \\ \cdot & \cdot\ \cdot & \cdot \\ \cdot & \cdot\ \cdot & \cdot \\ S11_{(10GHz,chromosome1)} & \cdot\ \cdot & S11_{(10GHz,chromosomeN)} \\ \cdot & \cdot\ \cdot & \cdot \\ \cdot & \cdot\ \cdot & \cdot \\ S11_{(freqGHz,chromosome1)} & \cdot\ \cdot & S11_{(freqGHz,chromosomeN)} \end{bmatrix} \tag{4.7}$$

Where *freq* is the frequency range or the bandwidth. N stand for the population size. basically every chromosome will have one value corresponding to a frequency as in 4.9. The cost function should express the wide band performance. Many ways can be implemented to express the wide performance. Since the every chromosome has a one value along the frequency range. It is possible to take the maximum value of corresponding return loss. By taking the maximum value, the matrix will converge into a one column with a number of rows equal to the size of the population. This is an attempt to avoid getting stuck with antennas having narrow band performances, The new matrix will have elements as;

$$Cost_{Max} = \begin{bmatrix} chromosome1_{Max(S11)} \\ chromosome2_{Max(S11)} \\ chromosome3_{Max(S11)} \\ . \\ . \\ . \\ . \\ chromosomeN_{Max(S11)} \end{bmatrix} \tag{4.8}$$

Now every chromosome is represented by the maximum *return loss* in *(dB)*. The following Step is to rank the individuals according to their performances which means the chromosomes will be ordered according to their corresponding cost function. For example, the first individual will change its location in the matrix if it has a low performance. The ranking order of the upper side of the matrix reflect that those individual are having better performance than the lower individuals. Therefor the ranking of individuals suppose to reflect the wide band performance by locating individuals with wide band performances on the upper side of the matrix. As a result the bad performance or narrow band performances will be located at the bottom side of the matrix accordingly as;

$$Cost(Sorting) = \begin{bmatrix} Antenna_i widerbandperformance \\ Antenna_i lesswidebandperformance \\ . \\ . \\ . \\ Antenna_i narrowbandperformance \end{bmatrix} \tag{4.9}$$

where i= 1,2,3,4...,N, i is the antenna address and N is the population size. By this matrix we have the readings of the antennas performances. Considering the cost matrix for this project consist of 300 individuals. The cost matrix consist of one maximum value of the return loss corresponding to the bandwidth. Therefore the matrices will look before sorting as 4.10. In this matrix the individuals were sorted according to the history of creating, the first one produced will occupy the first location in the matrix and so one to the lest created individual. By ranking the antennas the occupation of the first location of the matrix will depend on the wider performance of each antenna as in 4.11. It is obvious in this matrix the order of the chromosomes is changed according to the corresponding performance. Chromosome with tag number *83* followed by chromosome with tag number of *96* are occupying the upper side of the matrix. It can be observed that chromosome holding the tag number *75* is occupying the lest position in the matrix. This is an indication that the ranking is working and changing the location of the individuals. It is important to indicate that the ranking is sorting the chromosomes according to the wider band performance. The indication is verified by examining the return loss S_{11} of the upper side matrix to the lower side of the matrix. The Algorithm will sort the individuals with wide band performance at the upper side while narrow band performances or high return loss will be sorted at the lower side of the matrix; see Fig.4.2.

$$Cost(maximum) = \begin{bmatrix} Antenna_1 maximumvalue \\ Antenna_2 maximumvalue \\ . \\ Antenna_i maximumvalue \\ . \\ Antenna_{300} maximumvalue \end{bmatrix} \tag{4.10}$$

$$Cost(maximum) = \begin{bmatrix} Antenna_{83} maximumvalue \\ Antenna_{96} maximumvalue \\ . \\ Antenna_5 maximumvalue \\ . \\ Antenna_{75} maximumvalue \end{bmatrix} \tag{4.11}$$

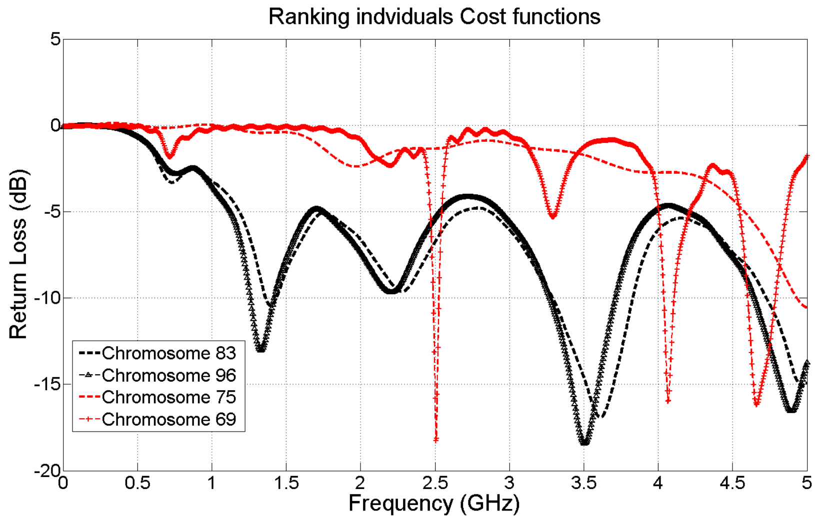


Figure 4.2: Chromosomes with black color at the upper side of the matrix, while red chromosomes will occupy the lower part of the matrix

4.4 Next Generation

Once the chromosomes were sorted according to the corresponding cost function. Where the upper matrix represent the chromosomes with wide performances and the lower side stand for high reflectivity or narrow band performances. Through the sorting process the individuals occupying the upper locations in the matrix are the candidates to produce the next generation. By selecting a certain number of chromosomes with wide band performances the mating pool will be ready. In the mating pool chromosomes will share its genetic information. The results of cross over the selected chromosomes will generate offsprings. Those offsprings forms the next generation. cross over techniques have different representations. The generated off springs has the following representation;

$$OffSprings(i,M) = (1 - beta) \times Parents_Genes(i,M) + beta \times Parents_genes(i,M) \tag{4.12}$$

where M is the chromosome length or the total number of genes. i is the location of a specific gene in the matrix. *beta* is a coefficient that determine the amount of genetic information that chromosomes will participate. For example if we assume *beta* is equal to 0.5, then 50 percent of *chromosome A* gene information will be mixed with 50 percent of *chromosome B* gene information.

4.5 Optimization Process

This section we will explain in detail the optimization process. The genetic algorithm was written in MATALB. The process start by defining the model genes. The genes represent the main block of the genetic algorithm. After carrying out the model genes, seven genes represent the model chromosome information as in Fig.4.1. Every gene will have random generated values within the specified domain. The model dimension were set to be in *mm*. Therefor The genes will have values in *mm*. Each gene should hold a symbol or a name to differentiate between the genes. *geneA* has responsibility of the location of the feeding point of the antenna in Y-direction and the monopole length also in the Y-direction. This gene will hold values between *10 mm* and *3.85 mm*. *geneB* has a similar duty as geneA, thus this gene will be responsible for the antenna feeding position in the X-direction. This gene will hold values between *10mm* and *3.85 mm*. *geneC* is the gene which is responsible of the outer circle radius that will connect the monopole with its ground plane to form the self grounded configuration. This gene will hold values between *35 mm*and *2 mm*. *geneD* is the gene responsible of the width of monopole feeding side. The gene tend to have small width for the high frequencies performances. This gene will hold values between *10 mm* and *2 mm*. *geneF* and *geneE* are the genes that responsible for the ground plane dimensions in the Y-directions and X-direction respectively. These genes will hold values between *100mm* and *80mm*. *geneG* is the gene responsible for the exponential line or the tapered curve. The variation in the line will be projected on the monopole's area. This area will have a considerable effects on wide band performances. *geneG* will hold values between *-0.9* and *0.9*. These values are unit-less unlike the the other genes values. In fact these values are scaling factor. These scaling factors are associated with the radiuses of the circles in the early forming stage of the monopole. The negative or positive values in this gene will indicate the exponential line increasing direction. By this increasing direction the area beneath will be influenced increasingly or decreasingly depending on the line direction. As observed these gene are bounded into an interval having a highes value and lowest value. The intervals are differen according to each gene function. These limitation is to keep a logical design and allowing possible manufactured values. The overall design will hold a Sizes between 175mm and 200mm both in the X and Y directions to keep the compact size of the antenna. But later we will find out we have to break some of these limitations to gain the required performances. The optimization will occur only on one monopole while the others are only a replica from the optimized one. By that we are reducing the time of optimization and transferring the optimized parameters to the other monopoles achieving fully optimized design. The following is a table showing each gene tag name with its duty and the interval of values; see Table.4.1

Now, every antenna in the population is represented by a chromosome. The populations consist of 300 individuals. This mean it will require to simulate all the population members to estimate the cost functions. The process is a combination of using MATLAB scripts and CST MS. The software provide the environment where simulations happened to carry out the S-Parameters. Also each models where modeled in MATLAB and then

Gene Name	Duty	Domain
Gena A	length of the monopole in the Y-direction	(3.85...random...10)mm
Gene B	length of the monopole in the X-direction	(3.85...random...10)mm
Gene C	The Radius of the outer circle	(2...random...35)mm
Gene D	The Width of the feeding side of the monopole	(2...random...10)mm
Gene E	The length of the ground plane in the Y-direction	(80...random...100)mm
Gene F	The length of the ground plane in the X-direction	(80...random...100)mm
Gene G	The exponential side area	(-0.9...random...0.9)

Table 4.1: Genes specification, names, duty and the interval of random values they are holding

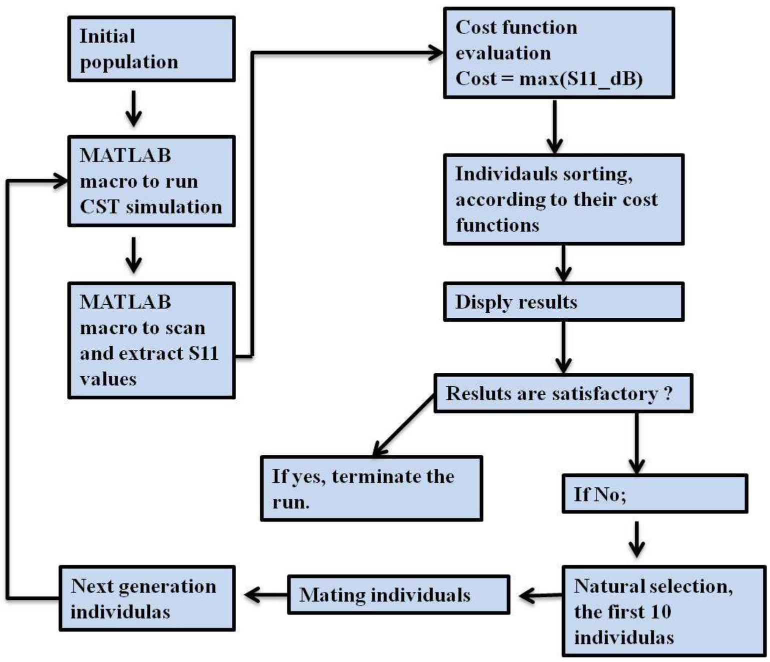


Figure 4.3: Genetic Optimization Flow chart

through a buffer the scripts will converts into a CAD model where CST MS can Read. The following is a flow chart of the optimization process; see Fig.4.3 According to the flow chart the first step is to initiate the population. This population consist of the Antennas or chromosomes. This population represent the first group to be simulated. In this project the population consist of 300 members. later a MATLAB scripts will transport these individuals to a the CST MS environment where the simulation is happening. In the CST MS environment, the antenna will consist of four monopoles, every

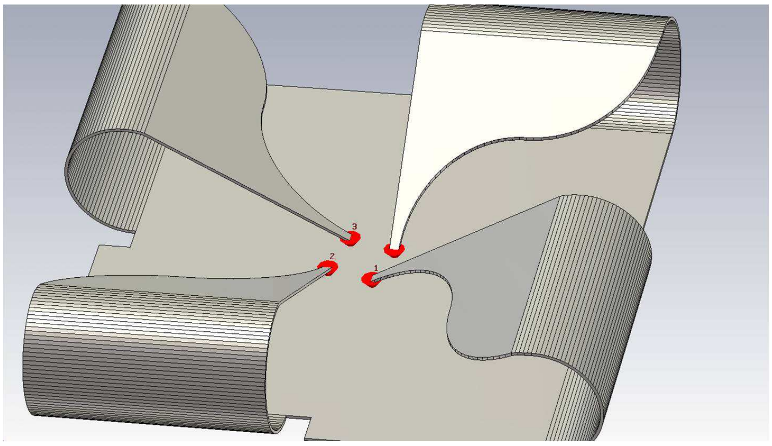


Figure 4.4: Discrete ports in red being used to excite the antenna

monopole will be excited through a port. The excitation port is a discrete type holding a default impedance of 50 ohm and this impedance is possible to change; see Fig.4.4. Every individuals will have the S-Parameters values. These values extracted from the CST MS and stored in a MATLAB extension file. once these S-Parameters are available especially the return loss, the cost function mechanism start to operate. A sub-routine MATLAB scripts will operate to extract the results simulation in CST. The simulation results are represented in the S-Parameters values. These values are transport to MATLAB platform to process the cost function for each individuals. During the optimization process another sub-routine will run to monitor the cost function and the sorting process;See Table4.2. Each value in the first column represent the maximum return loss. For example the first element in first column is standing for the maximum return loss for one antenna in the group. This will generate a matrix with a rows equal to the number of the population and one column consisting the cost function value for each antenna in the group. The second column in the table is the cost function values being sorted. This operation will sort the cost function decreasingly. The third column is the selection criteria where the individuals with better return loss will set to pass for the mating pool. The other individuals that got discards sing will be terminated from the process. This sorting technique is enabling the individuals holding the wide band performance to hold a prominent order in the matrix while antennas with narrow band and poor return loss will hold the bottom locations in the matrix. only 15 individuals will be let to be pass to the mating pool to generate the offsprings. The operation last for three generation or four generation when the whole operation decided to stop. The termination criteria based on the overall performances has no significant or a convergence status occurred through the developed generation. In our case this convergence status observed between the third generation and the fourth generation when the optimization process set to stop; see Fig4.5. Through this operation individuals with narrow band performances being suspended to survive. While individuals with wide performances will have the chance

Cost Max	Cost sort	Cost Select
-1.576	-3,575	pass
-1.416	-3,489	Pass
-0.4039	-3,275	Pass
-1.939	-3,2365	Pass
-3.103	-3,1678	Pass
-0.1711	-3,1029	Pass
-1.3362	-3,0274	Pass
-2.2052	-2,8883	Discard
-0.3263	-2,8162	Discard
-1,4195	-2,73011	Discard
-0,4038	-2,52645	Discard
-1,939	-2,4793	Discard
-3,102	-2,4574	Discard

Table 4.2: Cost function estimation, sorting and selecting

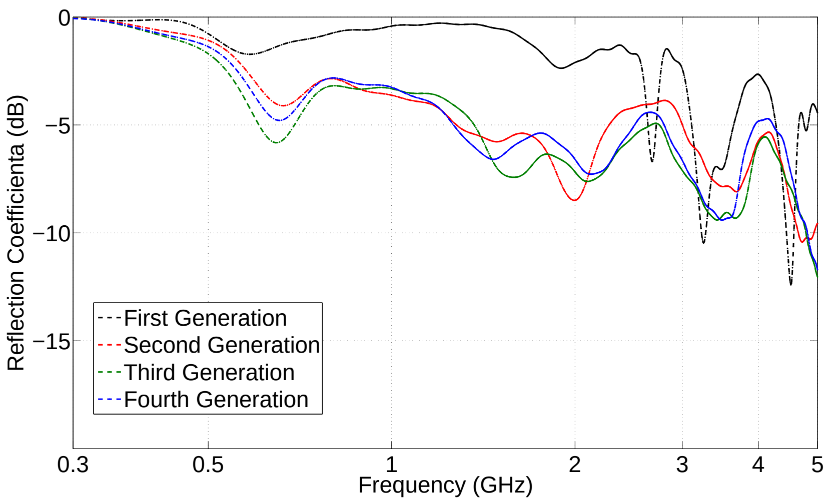


Figure 4.5: Improvement along generations, convergence status observed between the second, third and fourth generation

to be transferred to the mating pool. Therefore the objective of this genetic operation is to produce a wide band individuals even so they might experiencing poor return loss. Later we realized that the input impedance has to be changed for better performances regarding the reflection coefficients. Therefore we introduced a sub-routine scripts in MATLAB to search for the optimum impedance needed to be placed at the antenna input port. Since these antennas being excited by a discrete port in CST MS. This port is a digital form of the 50 ohm SMA port. Several best individuals from the second generation and third generation will be examined for possible best return loss performance. The sub-routine program will examine these antennas by changing the discrete port impedance value. The antennas with the best performances is being arranged in a Matrix. This matrix contain a 16 element forming a matrix with one column and 16 rows. A MATLAB scripts will be initiated extracting the S-Parameters of each antennas from the their CST model. The Return loss improvement will be examined by the theoretical impedance matching transformer. This transformer will take the return loss data and fine the antenna input impedance as ;

$$ZL = \frac{1 + S11}{1 - S11} \times Zc; \tag{4.13}$$

where ZL is the antenna input load, Zc is the discrete port characteristic impedance equal to 50 Ohm and $S11$ is the complex reflection coefficients at port one. Through that it is possible to implement a scheme that predict what impedance value could be placed between the 50 Ohm transmission line (the SMA impedance) and the antenna input impedance as;

$$S11_{new} = \frac{ZL - Zc_{new}}{ZL + Zc_{new}}; \tag{4.14}$$

where ZL is the antenna impedance estimated while a 50 ohm discrete port is connected, Zc_{new} is the medium impedance to be placed between the antenna input port and the SMA port. It is important to highlight that the antenna impedance is complex consisting of real part (resistance) and imaginary one (reactance). These mentioned equation represent the core of the algorithm for estimating the proper impedance for best return loss performance. The theoretical impedance process the best individuals along the generation through extracting their S-parameters. A MATLAB scripts will handle the extracting process from the CST MS and sort the data properly. Once these data are available the program will find the proper impedance that will result the best return loss. The program predicted that two antennas has best return loss among other competitors. one of the two belong to the second generation and the other belong to the third generation. This also an indication that extending the algorithm to the fourth of more is pointless since the design is experiencing a convergence status between the second and fourth generation. It was required an impedance between (confidential) and (confidential) Ohm to have a return loss performance below -8 dB. see Fig.4.6 The simulation was carried out up to 6 GHz. This antenna is satisfying the company needs at this moment, an antenna with low return loss operating from 0.65 to 6 GHz. An important reason that simulation carried out at this range is for time limitation. The process is very time expensive while implementing the optimization and CST MS simulation. The optimization process produced an individual with optimized dimensions and predicted

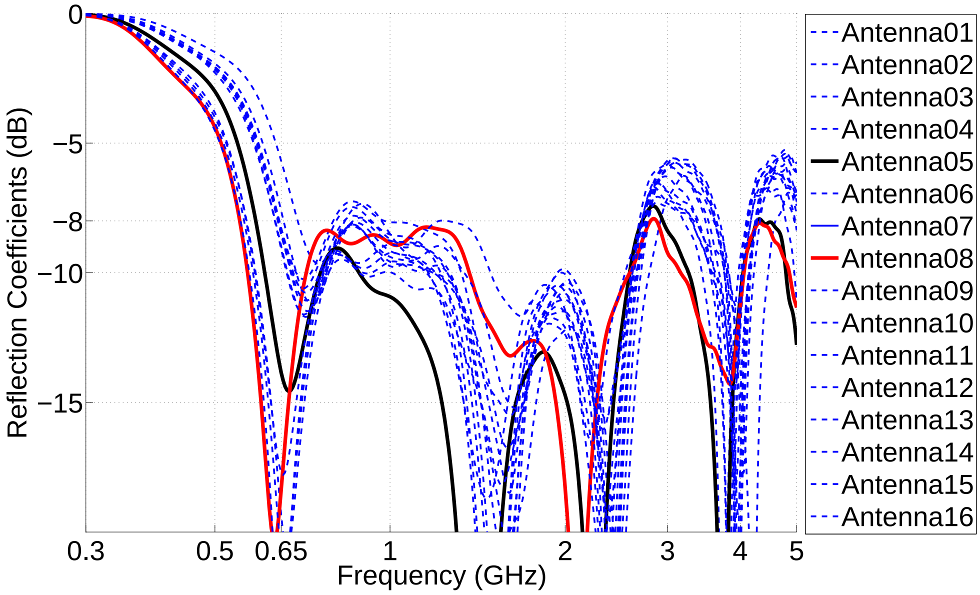


Figure 4.6: Antenna eight and five having the best reflection coefficients among other competitors

Parameters	Duty	Value
Impedance	medium impedance between the antenna port and SMA port	Confidential
Gena A	length of the monopole in the Y-direction	Confidential
Gene B	length of the monopole in the X-direction	Confidential
Gene C	The Radius of the outer circle	Confidential
Gene D	The Width of the feeding side of the monopole	Confidential
Gene E	The length of the ground plane in the Y-direction	Confidential
Gene F	The length of the ground plane in the X-direction	Confidential
Gene G	The area of the tapered curve	Confidential

Table 4.3: Optimized Parameters found by the Algorithm

required impedance at the antenna input port. These optimized values along side with impedance value are necessary for hiving a return loss below -8 dB see Table.4.3.

Thereafter, the new evolved antenna will be tested for a broader bandwidth regarding the reflection coefficients, mutual couplings and radiation efficiency. The simulation results regarding the reflection coefficients is a performance below -7(dB) in the bandwidth range 0.5-16(GHz); see Fig.4.7. The simulation regarding the mutual couplings is

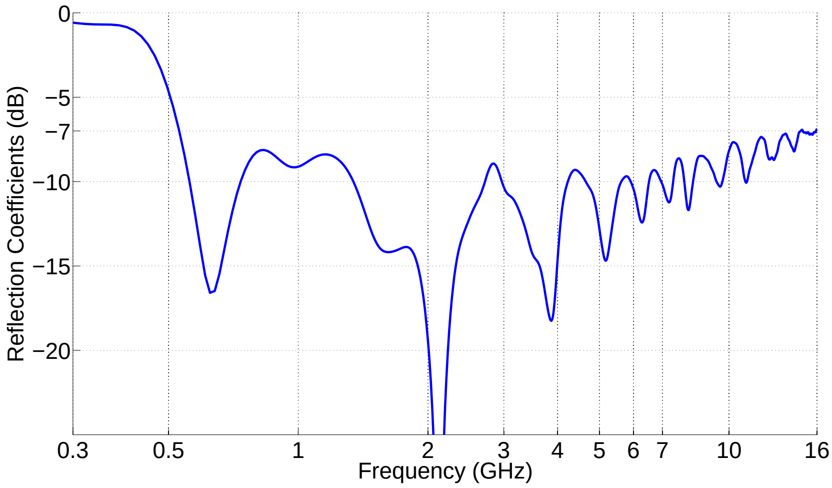


Figure 4.7: Optimized Antenna Reflection Coefficients (Simulation)

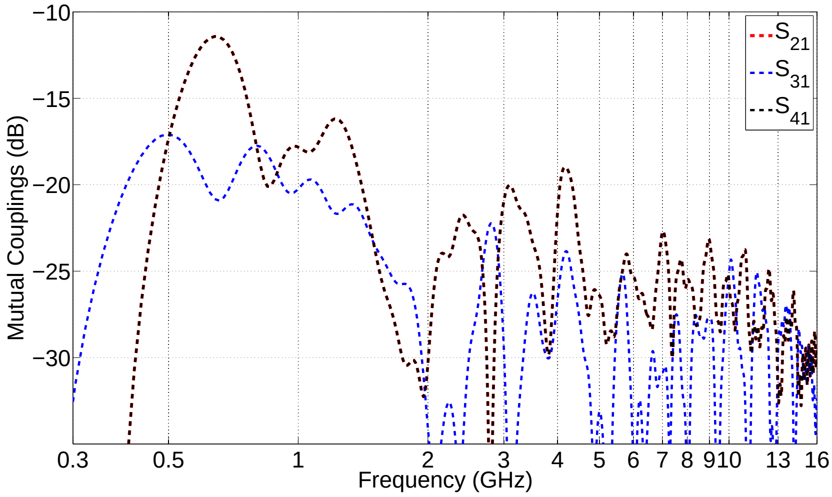


Figure 4.8: Mutual Couplings for the Optimized Antenna (Simulation)

below -15 (dB) in the frequency range 0.5-16(GHz); see Fig.4.8. The embedded radiation efficiency is very close to 0(dB). The total embedded radiation efficiency is higher than -1(dB) in the frequency range 0.6-16(GHz); see Fig.4.9.

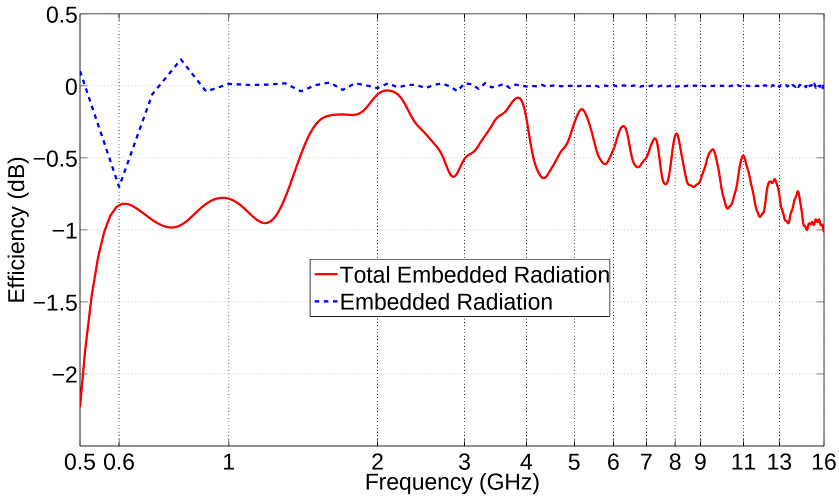


Figure 4.9: Total Embedded and Embedded Radiation efficiencies for the optimized antenna (Simulation)

4.6 Summary

In this chapter where the optimization scheme has been employed to optimize the self grounded tapered triangular (one sided) antenna in order to reduce the antenna reflection coefficients. The algorithm started by initiating of population consisting of 300 individuals. Seven genes represent the antenna dimensions . These genes for a chromosome, where a single chromosome represent an antenna. The cost function evaluation holding one target which is the reflection coefficients. There were no necessity to include the mutual couplings in the cost function evaluation since the starting geometry has a performance below -15(dB). However the algorithm was monitoring the mutual couplings performance. The optimization carried out while the antenna ports is excited through a discrete port, this is a virtual port that has a changeable impedance. The evolved antenna has the following parameters; a discrete port impedance between (confidential) (Ohm) and genes values that correspond to a general size of 175 $\times$ 175 (mm). These parameters has been found through the genetic algorithm. These Parameters correspond to a reflection coefficients performance below -7(dB) in the frequency range 0.6-16(GHz). The mutual couplings is below -12(dB) in the frequency range 0.6-16(GHz), in fact the performance is below -15(dB) in most of the bandwidth. The embedded radiation efficiency is higher than -0.5(dB) in the whole bandwidth (0.5-16)(GHz). This is expected since the geometry is set to be perfect electric conductor (PEC). The total embedded radiation efficiency is higher than -1(dB) in the frequency range (0.6-16 GHz). The is mainly due to the reflection efficiency since the ports has low mutual couplings and the antenna is treated as lossless.

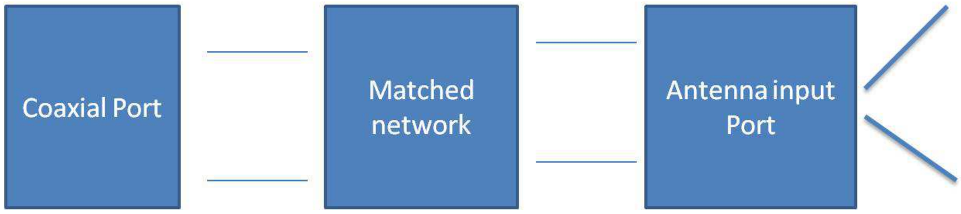


Figure 5.1: Block Diagrams of the antenna system components

5

Matched Network

In this section we will introduce a microstrip line transformer is being implemented. The duty for this transformer is to work as a matched network. Since the optimization scheme predicts a (confidential) ohm to (confidential) ohm in order to reduce the return loss. This transformer (Matched network) is to be placed between the antenna input impedance and coaxial port. A typical Block diagram is consisting of the radiating element, matched network and the input port; see Fig.5.1 By estimating the antenna impedances when the 50 ohm discrete port is exciting the antenna; see Fig.5.2. it is notable that the antenna has a higher impedance at low frequencies which is causing the poor return loss relatively to those at higher frequencies. It is important to point out that the antenna will have different impedance values for different frequencies. Therefore the (confidential) ohm value doesn't stand for the antenna input port. This value represent a single impedance to be placed at the antenna input port which will cause a return loss performance below -8 dB. In real life we have to use a matched network that produce such a performance. The matched network is a transmission line connect the antenna input port and the coaxial port. The transmission line is a microstrip line of a tapered type. In following section we will have only one model since the optimization scheme has been terminated. This will give the opportunity to test the model for a broader bandwidth since no time constrains will limit the frequency range.

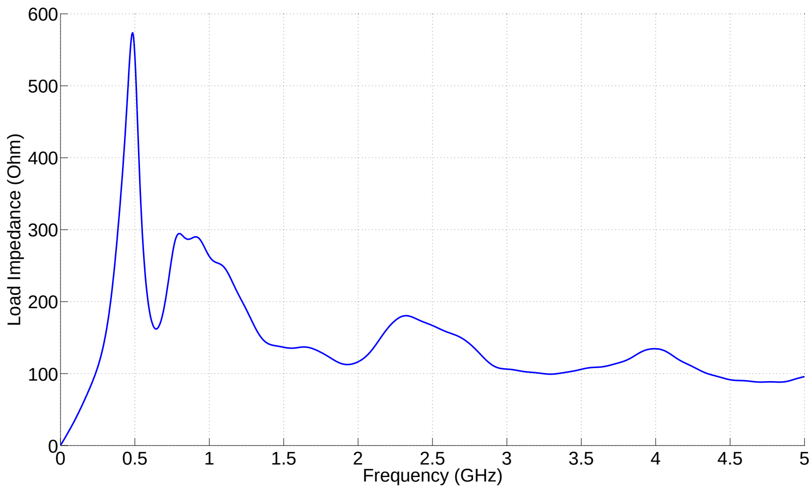


Figure 5.2: Antenna Impedances

5.1 Microstrip and tapered lines

Microstrip lines are transmission line that carry electromagnetic field from one point to another. The geometry of the microstrip line is consisting of a conducting plate mounted above ground plane and separated by a substrate material; see Fig.**??**. The dielectric material that separate the conducting plate from the ground plane is not filling the upper half of the conducting plate unlike the strip-line. this fact complicate the analysis of microstrip line. Unlike the strip line where all the fields contained within a homogenous dielectric region. Therefore part of the microstrip line field is contained with the dielectric material while fraction of the field will be in the air. This make the microstrip line quasi TEM (transverse electromagnetic) or hybrid TE-TM wave. This conclusion drawn from the phase velocities being different.At the free space where it equal to the speed of light and the dielectric material where the phase velocity is relative to the material permittivity. therefore it is impossible to have a phase match at the dielectric-air interface to attain a TEM-type wave[29]. This antenna will require a matched network. This matched network will be of a microstrip line type. This choice based on the fact that microstrip line have simple configuration and easy to be integrated or attached on the antenna surface. The tapered microstrip line has been intensively used since the day of their invention in microwave circuits. One of the important design criteria of the transformer is to calculate the widths of the microstrip line conductor plate. Therefore the transformer will have two different widths at the input and out ports. Usually the conductor with wider width is to be connected to the coaxial port while the narrower one is connected to the output port. The width at the out put port is the impedance to be placed at the antenna port. In this design the transformer output port width is represent the (confidential) ohm. To calculate the

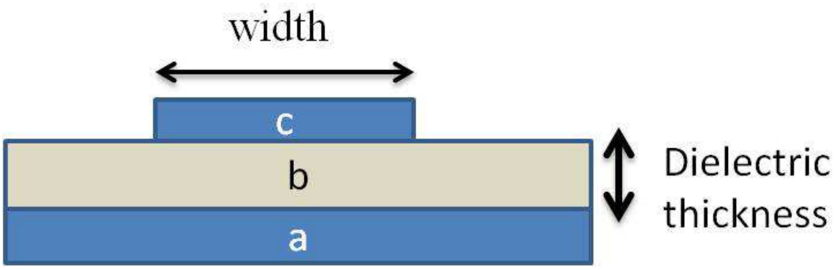


Figure 5.3: microstrip line components; a: ground plane, b: dielectric materia, c: conducting plate

width of the conductor plate, there are an approximate method or rigorous methods. An approximation method were implemented to estimate the microstrip line widths. Basically the widths will have slightly different values that the calculated ones. Therefore the objective of implementing the approximate method is to give a hint or a guess value to start with designing the width. Later these widths will be tuned according to the corresponding return loss performance. The implemented approximate method formula could be found in many classical microwave text book. The used formula are taken from Pozar microwave engineering text book. Since we have the knowledge about the substrate thickness, the characteristic impedances at both ports and the dielectric constant ϵ_r as;

$$\frac{w}{d} = \frac{8e^A}{e^{2A} - 2} \qquad \text{for} \qquad \frac{w}{d} < 2 \tag{5.1}$$

and

$$\frac{w}{d} = \frac{2}{\pi}[B - 1 - ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r}\{ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r}\}] \qquad \text{for} \qquad \frac{w}{d} > 2 \tag{5.2}$$

where

$$A = \frac{Z_o}{60}\sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}(0.23 + \frac{0.11}{\epsilon_r}) \tag{5.3}$$

and

$$B = \frac{377\pi}{2Z_o\sqrt{\epsilon_r}} \tag{5.4}$$

Where W is the width of conducting line, and d is the dielectric thickness. Therefore a transformer of a tapered type would be typical solution. This transformer will work as the matched network between the antenna input port and the coaxial port. The idea is based on the theory of small reflections[30]. if we assume that we have a transmission line with two ports,and this line consist of different impedances. The total reflection will be observed at the input port; see Fig.5.4. If we consider the discontinuity between the different impedances. The Total reflection will be dominated by the reflection from the input port and the followed impedance interface and the last impedance and the load

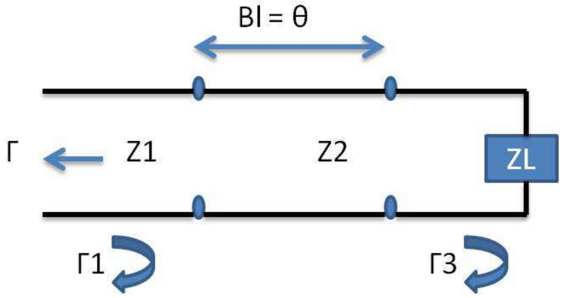


Figure 5.4: Transmission line small reflections

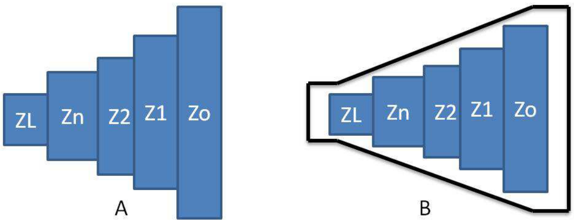


Figure 5.5: A: Multi-section transformer. B: A tapered transformer

interface. Therefore an approximate expression of the total reflection can be represented as;

$$\Gamma \approx \Gamma_1 + \Gamma_3^{-2j\theta} \tag{5.5}$$

Through the theory of small reflection a microstrip multi-section transformer can be implemented to work as a matched network. This transformer consist of multi impedances of discrete widths. These discrete widths between the coaxial port and the antenna can be formed as infinite number of sections. Therefore the multi-section transformer transformed into the tapered type transformer; see Fig.5.5. As principle both transformers share the same mechanism. This is based on the fact that effective permittivity will have different values along the transmission line. This is due to the differences occurring on the line width. The effective permittivities values along the line will influence the characteristic impedance of the line. Therefore at different lengths the line will have different impedances[31, 32]. The tapered configuration will mitigate the sudden changes in the line impedance. The effective dielectric constant of a microstrip line is given approximately by;

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12/dW}} \tag{5.6}$$

assuming the the transformer dimensions are known, the characteristic impedance can be calculated as;

$$Z_o = \frac{60}{\sqrt{\epsilon_e}} ln(\frac{8d}{W} + \frac{W}{4d}) \qquad \text{for} \qquad \frac{W}{d} \leq 1 \tag{5.7}$$

and

$$Z_o = \frac{120\pi}{\sqrt{\epsilon e}[W/d + 1.393 + 0.667ln(W/d + 1.444)]} \qquad \text{for} \qquad \frac{W}{d} \geq 1 \tag{5.8}$$

5.2 Transformer Modeling

In This section we will use computer modeling for the tapered transformer. The CST MS software implemented for our cause. The CST MS provided the CAD modeling and the electromagnetic simulation. The transformer designed has been designed through parametric calculations as explained in the previous sections. Therefore by implementing these formula in MATLAB it is possible to predict the transformer widths at the coaxial port and the antenna input port. Also it is possible to use the CST MS built in microstrip line calculator. The transformer physical parameter are fixed. therefore these physical parameter has to be integrated and fitted to the antenna geometry. The transformer length is determined roughly by connecting the antenna input port to coaxial port. A standard FR-4 lossy with 1.5 mm of substrate thickness used. A number of four transformers were connected to the monopoles to serve as the matched network in a configuration as shown in Fig.5.6,5.7. Since the optimization has been terminated producing one best individual. The focus now is not about the antenna dimension but about the transformer and how to integrate it or fitted in the antenna geometry. Also, since the work is only considering one antenna this give the opportunity to do further simulations regarding the bandwidth. Therefore we will present how far the antenna can go at higher frequencies. Also a similar test applied at lower frequencies. In other words, the antenna performance will be examined according to the bandwidth. Later this configuration has been avoided. The developer team was concern about the antenna feeding points since this configuration will require 4 different sides to be connected to the coaxial lines which will cause less compact antenna. Therefore the designing were towards a one feeding side where the SMA cables will be attached to the antenna. Through simulating the antenna in CST MS and especially we were concerning about the return loss at the ports. The purpose was to investigate the transformer performance as a matched network and what the degree of agreement with theoretical one. Through this investigation we were willing to draw some conclusions about the cut off frequencies and how to mitigate cutoff frequency if its happening close to the bandwidth requirements. Such as changing the antenna size by increasing the size corresponding to the lower frequencies or by reducing the size regarding the higher frequencies. Also by adjusting the transformer width that might enhance the bandwidth performance. Therefore the return loss at the ports has been investigated as in Fig5.8

The simulation has predict a satisfactory performance at frequencies higher than 1 GHz up to 16 GHz. However, the Antenna still experiencing poor performance at

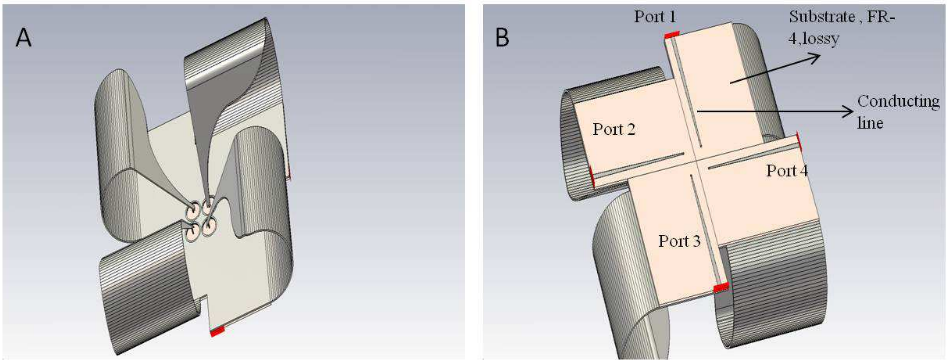


Figure 5.6: A: Antenna upper side. B: Antenna backside showing the transformer

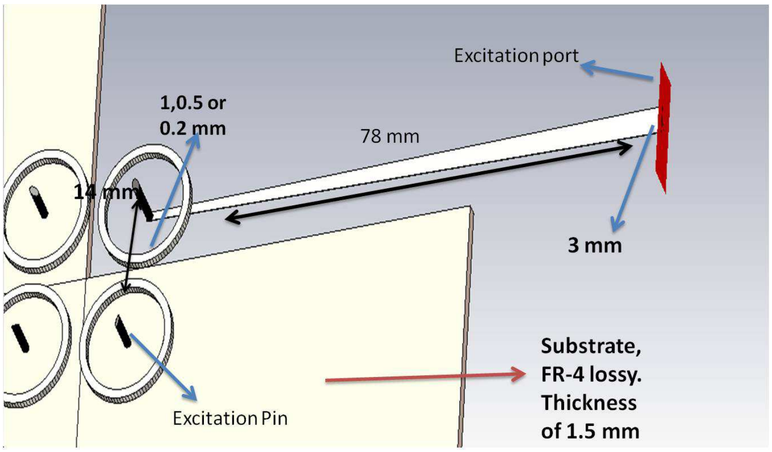


Figure 5.7: Tapered Transformer, CST modeling

frequencies below 1 GHz. therefore a conclusion can be drawn through the obtained results. one of the suggested method is to increase the antenna size or scale it and investigate the changes in the performance in particular those at frequencies below 1 GHz. keeping in mind that we have to avoid a large size that will loose the system its compact geometry. since the genetic algorithm generated an optimized dimensions. At this moment the antenna has a 175×175 mm geometry. therefore by scaling the optimized genes values into a larger size than antenna the optimized one. basically we were trying to avoid having a large size therefore we draw a road map of possible sizes, and still we consider the antenna is compact; see Fig.5.9.

By simulating these scaled individuals and carrying out the results represented by the return loss; see Fig.5.10. By examining the return loss performance at low frequencies we found out the performance have not change towards a better response. In fact, the increased size start to effect the performances at higher frequencies. Therefore we had to

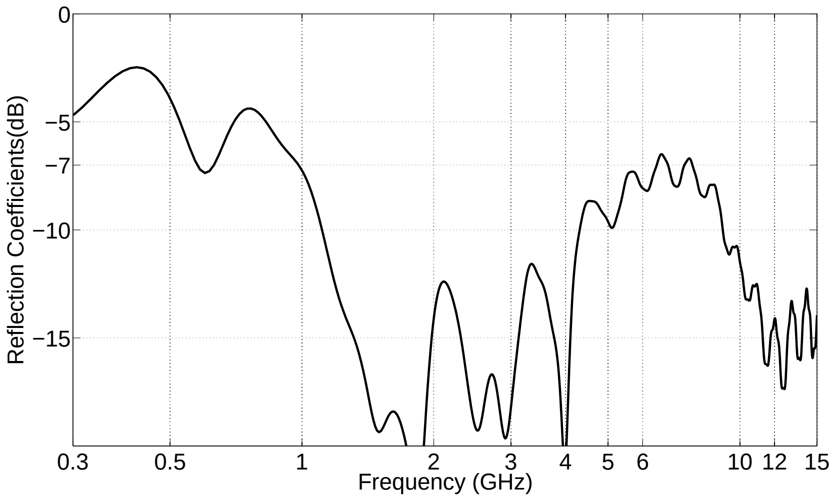


Figure 5.8: Reflection Coefficients by simulating one port

Scaling factor	Dimensions in mm
1.156	200 mm × 200 mm
1.445	250 mm × 250 mm
1.72	300 mm × 300 mm
2	350 mm × 350 mm

Figure 5.9: Scaling factors and the corresponding antenna size

establish a compromised performance at low and high frequencies. The solution require a homogenous performance at frequencies below 1GHz down to 0.5 GHz and up to 6GHz and further. Therefore we start to suspect that the performance for this geometry is reaching the cutoff region. The idea now is to change the configuration of the antenna but keeping the antenna optimized parameters. This change is happened on the antenna monopoles by keeping two radiating elements on one side of the ground plane while the other two will be pointing on the opposite side; see Fig5.11. The new geometry will

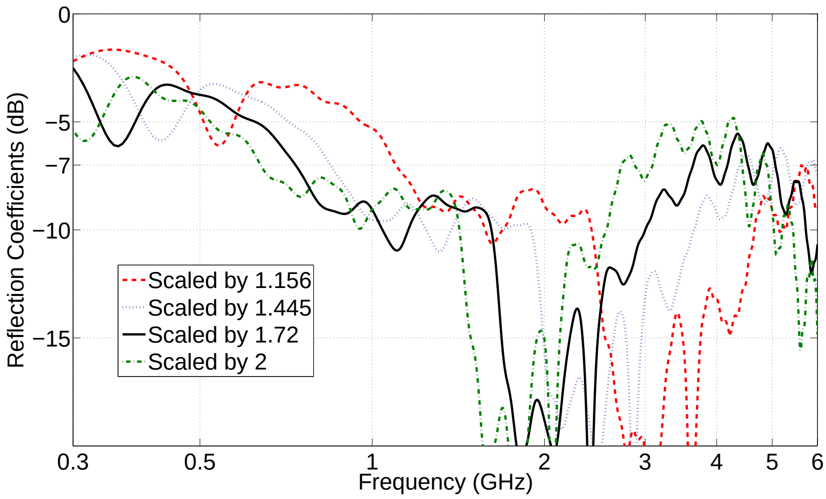


Figure 5.10: Reflection Coefficients performance for the scaled antenna

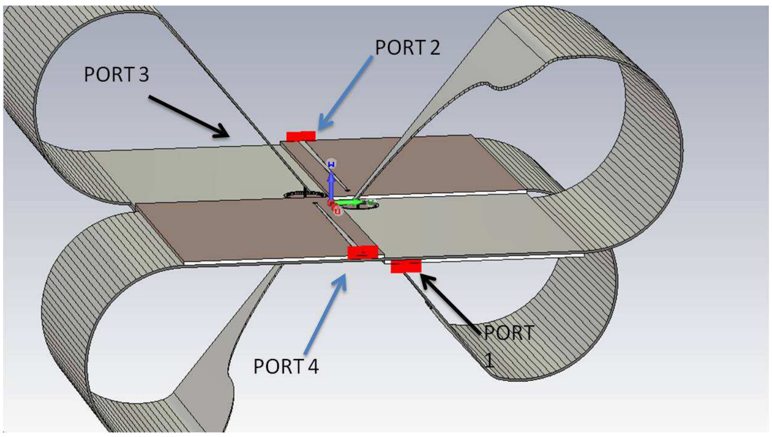


Figure 5.11: Changing the monopoles position

also experience a scaling process in case the geometry is reaching the cutoff frequency. Through simulating the new geometry along side with the scaled one we have found out the performance is enhanced at frequencies below 1 GHz and keeping a good performance at higher frequencies; see Fig5.12.

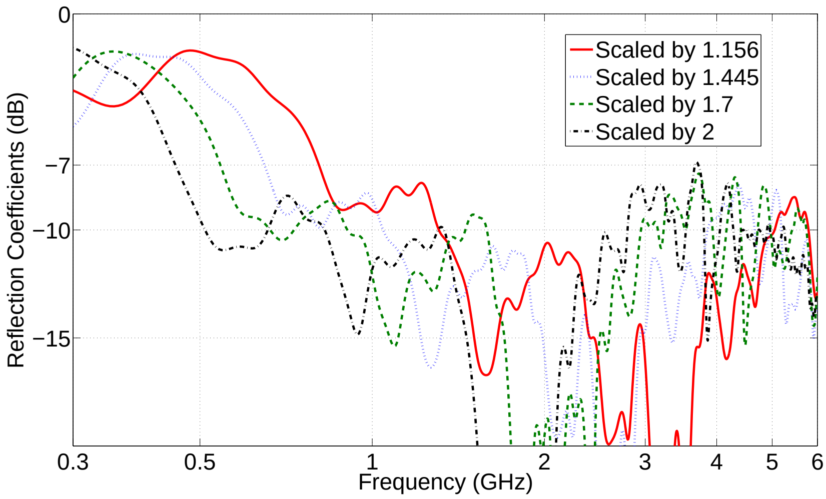


Figure 5.12: Reflection Coefficients performances for the new scaled antenna. the observed enhanced performance at frequencies below 1GHz

5.3 One side feeding

The new configuration (lower and upper monopoles configuration) proved better performance than the regular one. One of the mechanical problems is the feeding distribution. The current models is being fed by four transformers at every side of the monopoles. This configuration will require substrate material for each line which may result for a wasted expensive dielectric material. Another important reason is the connecting cables will surround the antenna which might halt immediate movements, also the requirement to be well integrated in the chamber. The need of a one feeding side is essential for being a compact antenna.In this design the feeding happening from four sides which mean the prototype will have to be fed from four cables at different positions which is a mess and not favored by the company. The next step is to make all monopoles being excited at one side. This is done by curving the transmission line at the far side. This curving is forming a quarter circle at a short distance before it becoming straight tapered line towards the coaxial line. Due to the new antenna configuration, the four transmission line will be distributed according to the antenna monopoles. This lead that two transmission lines are at one side feeding the monopoles while the other two are on beneath; see Fig.5.13 At this moment the project seems is fulfilling the main objective. By examining the antenna radiation efficiency performance, we noticed that that the antenna is not performing well.The antenna is suffering from a sever losses and the radiation efficiency is decaying dramatically along the bandwidth. Therefore we start to investigate the problem source whither the antenna material causing the sever losses or the other materials in the system. By investigating the simulation settings we have find out that the antenna structure is been assigned as a (PEC) perfect electric con-

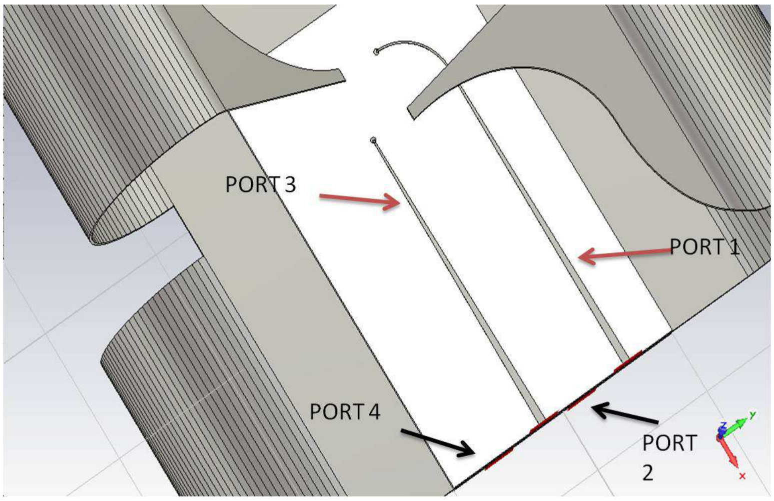


Figure 5.13: The antenna is being fed at one side

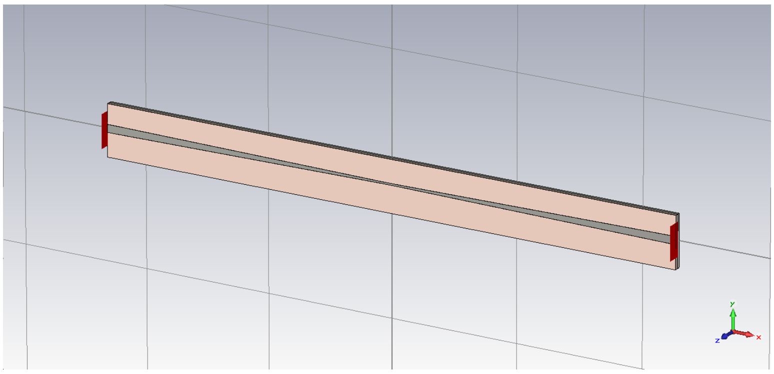


Figure 5.14: Modeled Transformer

ductor. Therefore we decided to drop the antenna material as a possible source for the the problem. Now all the doubts are oriented on the transformer being the source of the problem. The speculations are suspecting the substrate material itself causing the problem. Therefore we have to create a sperate investigation on the substrate material. This done by modeling a transformer with FR-4 material. Also we modeled another transformer with material known with its good performance at higher frequencies. The material known as Rogers RT5880. Therefore a transformer has been modeled in CST MS. The first transformer has FR-4 material while the other one with Rogers RT5880; see. Fig5.14. The simulation we carried out and by examining the efficiency factor that can be calculated as;

$$efficencyfactor = S_{11}^2 + S_{21}^2 \tag{5.9}$$

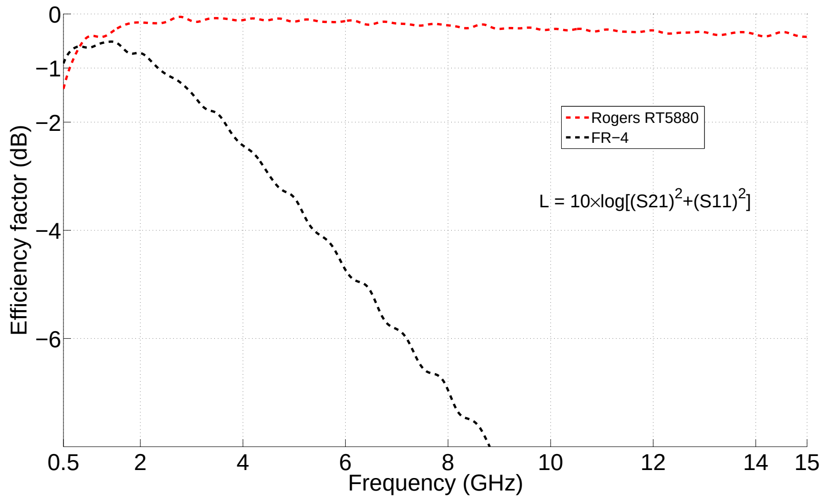


Figure 5.15: Loss due to the substrate material

Through the efficiency factor we concluded that the FR-4 substrate material is causing the sever decaying in the radiation efficiency at higher frequencies than 1GHz; see Fig.5.15. In the figure were the decibel representation has been taken. it is stating clearly that efficiencies at -1 dB indicating there is a 20 percent loss in the power. Both materials are showing poor efficiency at low frequencies especially around 500 MHz. But as a compromise the Rogers Rt5880 will be implemented in the design due to its excellent performance at high frequencies.

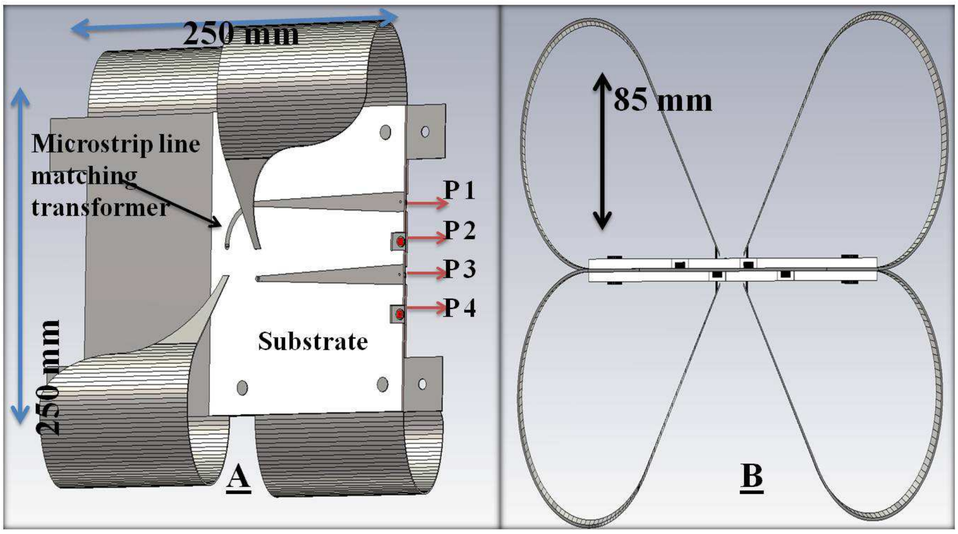


Figure 5.16: A CST MS model for the Prototype, A: Top view of the antenna. B: Side view of the antenna

5.4 The Prototype

The previous sections provided a valuable knowledge and information regarding the prototype. The scaling process provided us with information about the size of the antenna. Through that we were trying to keep the compact size of the antenna while keeping satisfactory performances. The final design has a an area of 250 $\times$ 250 mm of length and width. Which is a size still will be considered as compact; see Fig.5.16. The transformer has been tuned regarding the new material to enhance the return loss performance; see Fig.5.17 . Also the substrate material area has been reduced to increase the cost effective value of the antenna. This done through cutting the excessive dielectric material but keeping enough surrounding the transmission line; see Fig.5.18. Through the simulation regarding the antenna return loss and mutual coupling. the simulation predicted a return loss performance below -7 dB; see Fig.5.19 and a mutual coupling below -15 dB between the ports; see Fig.5.20.

According to these results the antenna become a candidate to work as the fixed measurements antenna for the reverberation chamber. This encouraged Bluetest AB to manufacture a prototype and conducting several measurements to indicated the antenna performance. Therefore it was essential to provide the manufacturer with enough information regarding the antenna dimensions. The modeling and simulation carried out while the folded shape is set. Therefore it was hard to manufacture this configuration at once. Therefore we have to provide a model of unfolded geometry; see Fig.5.21.later on the manufacturer will bend the antenna monopoles using a cylinder to produce the folded shape; see Fig.5.22. The transformer has to be manufactured and later will be attached to the antenna geometry; see Fig.5.23

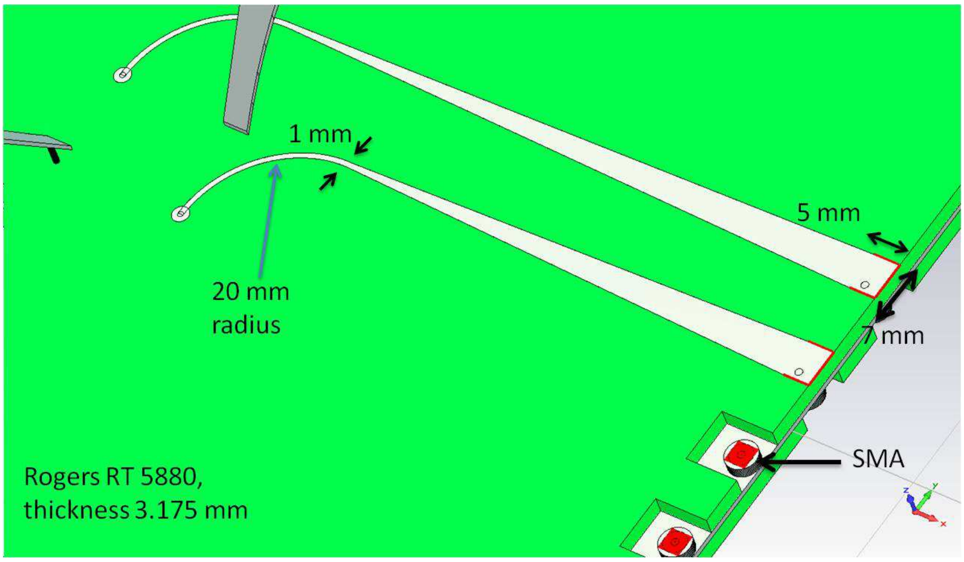


Figure 5.17: Tuned dimensions of the transformer

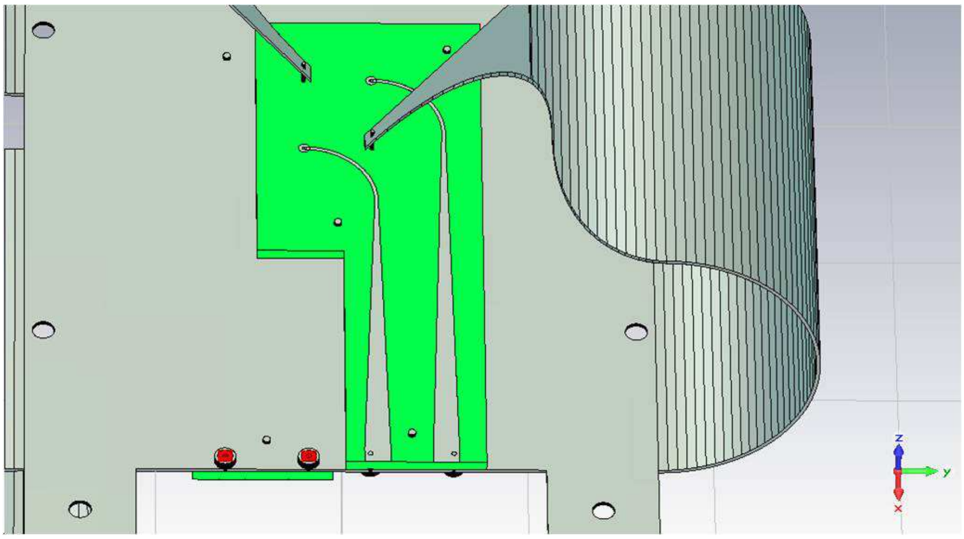


Figure 5.18: Reduced area of the transformer

5.5 Summary

This chapter is dealing with the design of the matched network. This network is necessary for the antenna feeding. By implementing the matched network of tapered microstrip line type and integrating it to the optimized single sided or the four ports self grounded tapered triangular antenna. The performance regarding the reflection coefficients is higher

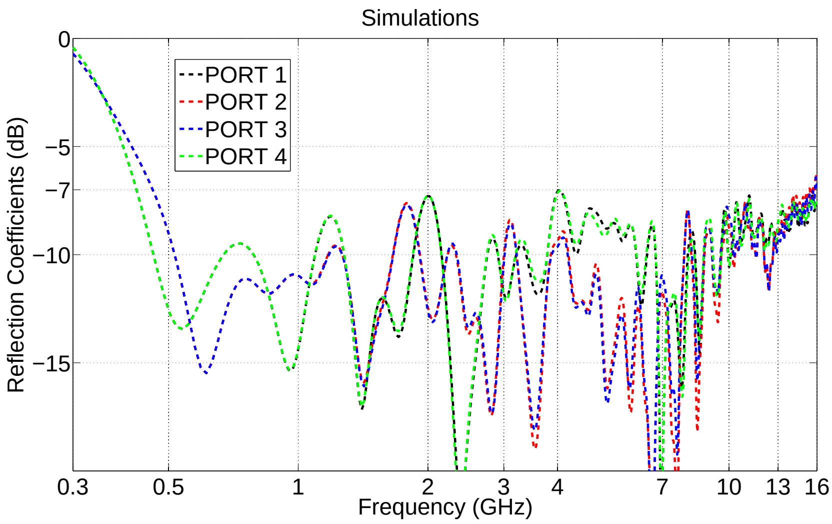


Figure 5.19: Antenna Reflection Coefficients

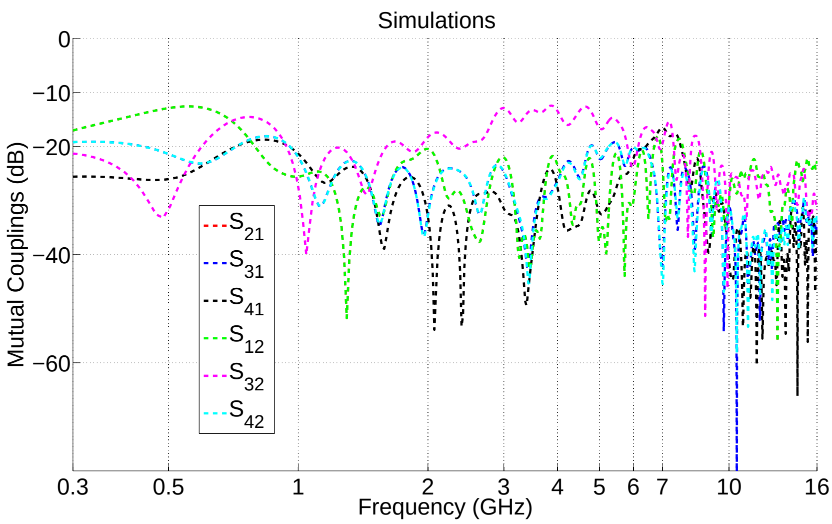


Figure 5.20: Mutual Couplings between ports

than -7 (dB) at the frequency range 0.5-1(GHz). Therefore a decision has been taken to scale the antenna size into a larger size in order to cover these frequencies. The scaling has a minor enhancement at these frequencies and affected the performance at higher frequencies. Another decision has been taken to reduce the number of monopoles to form the dual sided four ports self grounded triangular antenna. The performance of the scaled antenna succeeded to cover these frequencies and maintain a general performance

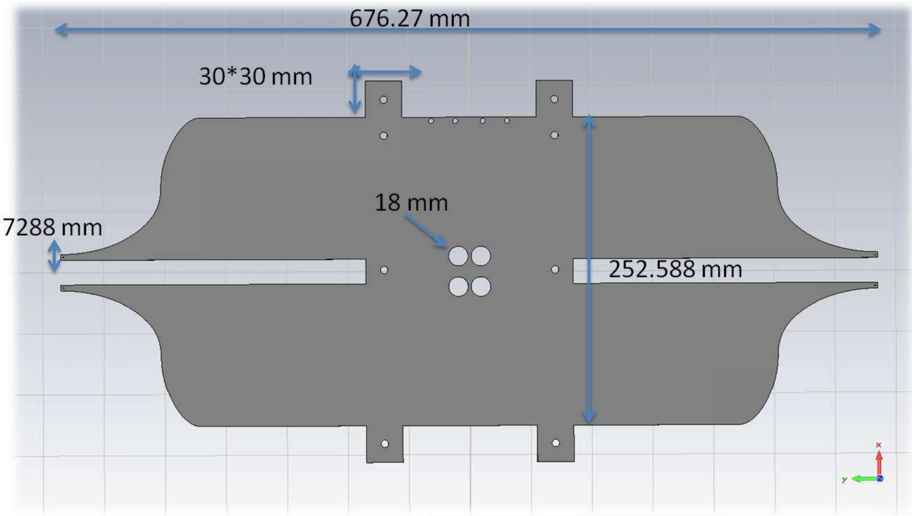


Figure 5.21: Unfolded geometry of the antenna

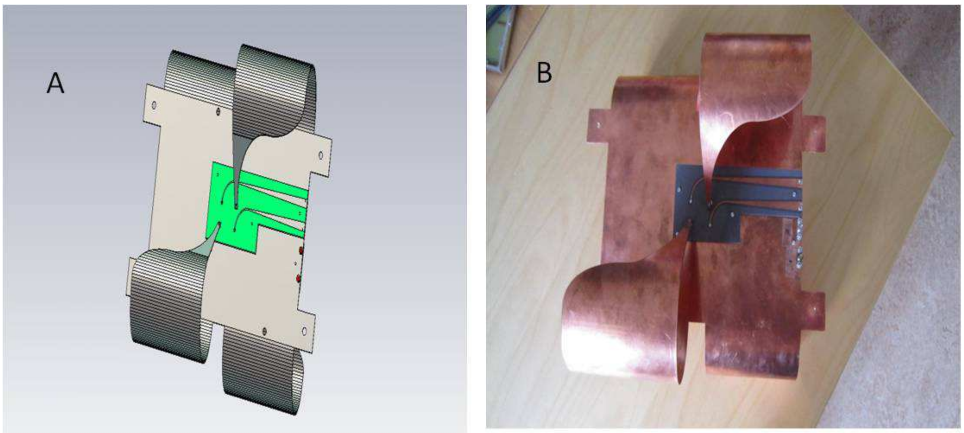


Figure 5.22: A: Antenna CST MS model. B:The Manufactured Antenna

below -7(dB) in the frequency range 0.5-16(GHz).

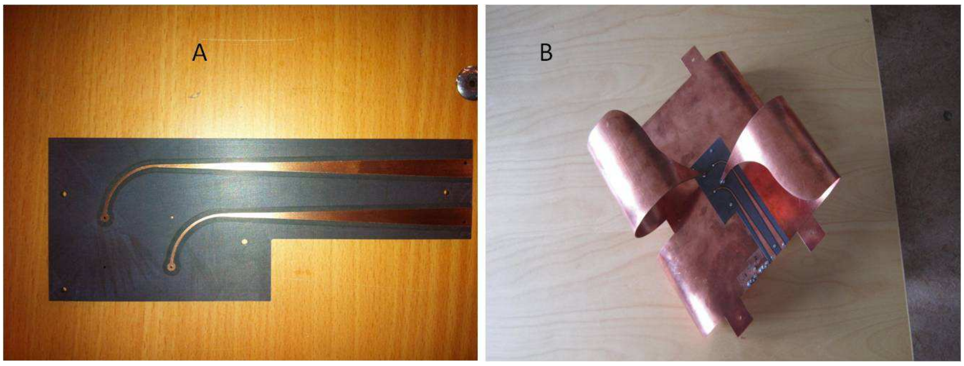


Figure 5.23: A:Manufactured Matched Network Transformer. B: The transformer being integrated with the antenna

6

Characterizations

In this chapter we will characterize the antenna through the obtained information. These information are based according to the simulation and measurements data. The characterization will mainly consist of two parts. The first parts will be about the circuit quantities which is mainly about the S-Parameters by using the vectorial network analyzer . The second part will characterize the space quantities. Including the the radiation pattern by using the anechoic chamber. Other important quantity, the radiation efficiency will be presented through simulation and measurements by using the reverberation chamber. While the other quantities such as the correlation coefficient and polarization balance will be estimated through analyzing the S-parameters and radiation pattern.

6.1 S-Parameters

The S-Parameters will characterize the antenna return loss at the ports. Another important quantity is the mutual couplings. According to the simulation the return loss performance is below -7 dB in the bandwidth range between 0.5 GHz and 16 GHz. The instrumentation start by setting the Vector Network Analyzer frequency range and calibrating the cables. Two ports measurements has been conducted by connecting two ports to the vector network analyzer and terminating the other ports with 50 ohm load; see.Fig6.1. The Prototype has a return loss Performance below -7dB with in a bandwidth range 0.5 GHz and 9 GHz. After 9 GHz; see Fig.6.2. the prototype performance start to deviate from the predicted performance. The speculation about why this deviation is happening is mostly oriented about some difficulties in the manufacturing. These difficulties are summarized about the monopole precisian to the feeding point. Where the excitation pins are being tilted. all these problems could result a poor return loss at higher frequencies; see Fig.6.3. In general the simulation and measurements are in agreement with the range of frequencies 0.5-9 GHz , later at higher the deviation start to happen; see Fig.6.4

Figure 6.1: S-Parameters Measurements using the Vector Network Analyzer

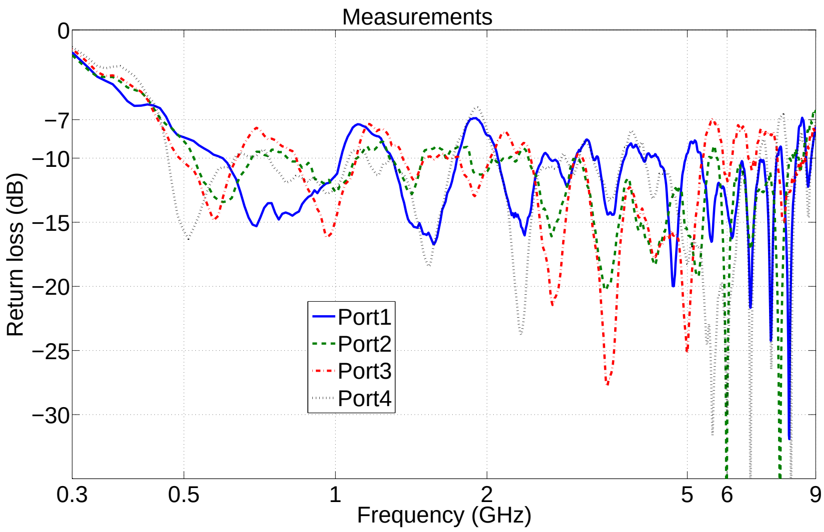


Figure 6.2: Reflection Coefficients performance below -7 dB in the bandwidth range 0.5-9 GHz

The mutual couplings between ports consistently shows an excellent performance with values between -15 dB in the bandwidth range 0.5-16 GHz; see Fig.6.5

Recalling the project main issue which is the return loss. Therefore it is very important to compare the new evolved antenna to the cube antenna, the one in service. The purpose is examine what kind of improvement we have been achieved. It has been found

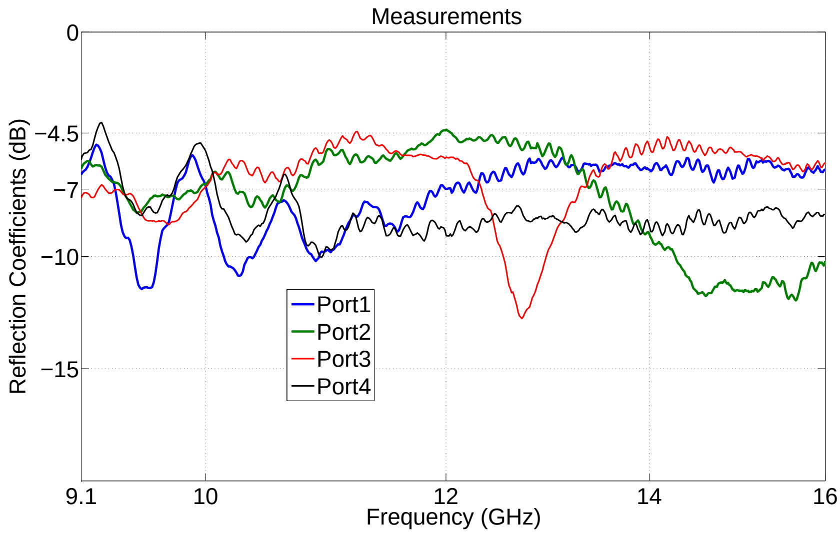


Figure 6.3: Reflection Coefficients performance below -4.5 dB in the bandwidth range 9.1-16 GHz

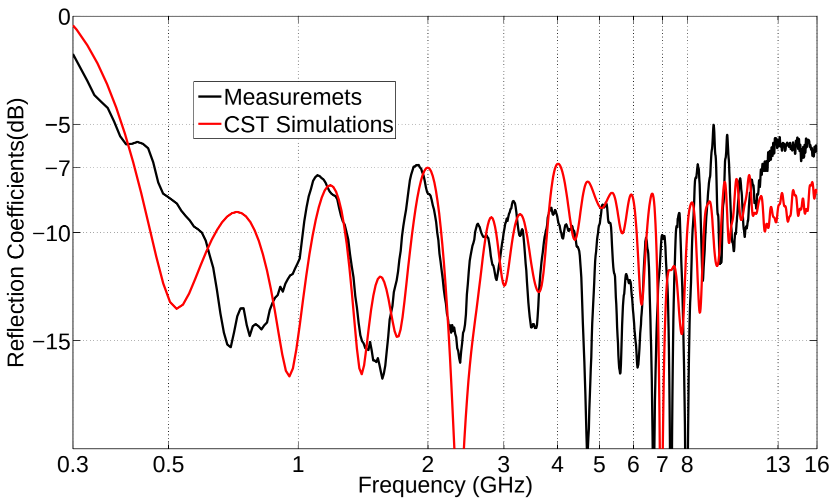


Figure 6.4: Reflection coefficients Simulations versus measurements

that the new antenna has a superior performance at frequencies below 1(GHz) down to 500(MHz) regarding the return loss. Also, the new antenna has a better performance within the frequency range (1-8) (GHz); See Fig.6.6

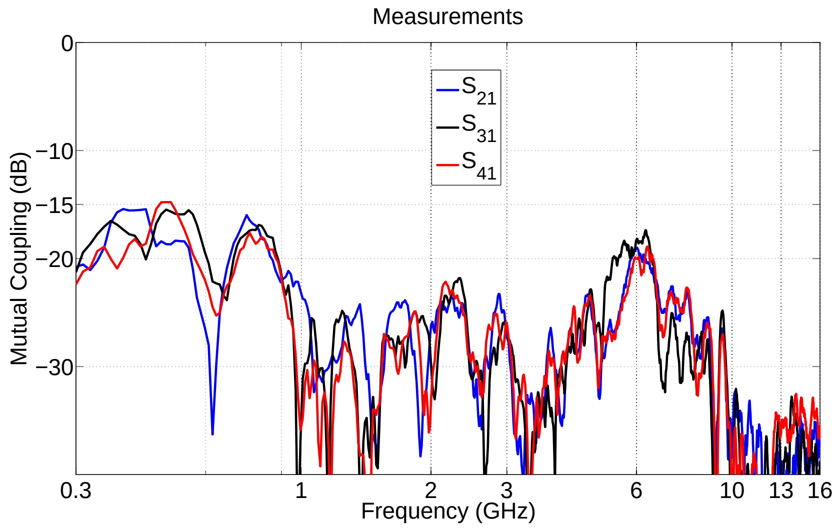


Figure 6.5: Mutual Couplings between ports

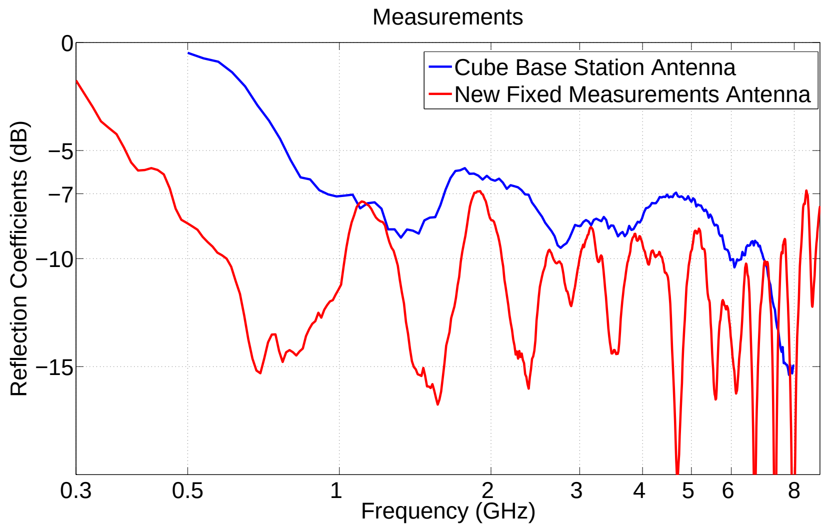


Figure 6.6: New antenna versus the cube antenna

6.2 Radiation Efficiency

The radiation efficiency measure the ohmic losses (i.e absorption) in the conductive and dielectric parts of the antenna structure. The IEEE standard for the radiation efficiency is expressed as:

$$e_{rad} = \frac{P_{rad}}{P_{acc}} \tag{6.1}$$

where P_{rad} and P_{acc} are the radiated power and the accepted power of the antenna, respectively.

This is representing a general expression for any type of antenna and assuming all the delivered power is accepted by the antenna without reflections. Usually antennas reflects back some power to the input power. The amount of reflections depend on the the level of matching between the antenna and the input port. Therefore the reflection coefficient will have a zero or -inf dB if the antenna is perfectly matched. In practice antennas reflects fraction of the delivered power to the input port. Therefore this will influence the radiation efficiency. To express the reflection efficiency as ;

$$e_{ref} = 1 - |r|^2 \tag{6.2}$$

where r is the reflection coefficient. Therefore the total radiation efficiency will be the contribution from the radiation efficiency and the reflection efficiency as ;

$$e_{total} = e_{rad} e_{ref} \tag{6.3}$$

This definitional is applicable for single port antenna where the radiation efficiency is the contribution of the return loss efficiency and the antenna ohmic losses. The case when the system is consisting of multi-port antenna, the radiation efficiency will have the contribution of the power being coupled or absorbed by the neighboring ports. Therefore the definition of the decoupling efficiency in the case of four ports as:

$$e_{decoupling} = \frac{1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2}{1 - |S_{11}|^2} \tag{6.4}$$

Therefore the total radiation efficiency will have the contribution from the decoupling efficiency, efficiency due loss and the reflection efficiency. This total radiation efficiency is known as the total embedded radiation efficiency due to the existence of neighboring radiating elements. The total embedded radiation efficiency is therefore given as;

$$e_{embedded} = e_{ref} e_{decoupling} e_{rad} \tag{6.5}$$

and

$$e_{embedded} = (1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2) e_{rad} \tag{6.6}$$

First we will present the simulation results regarding the radiation efficiency and the total embedded efficiency. The simulations were carried out by using CST MS as in Fig6.7, Fig6.8. The radiation efficiency indicating that most of the accepted power is being radiated but at some ranges in particular around 0.5 GHz the radiation efficiency

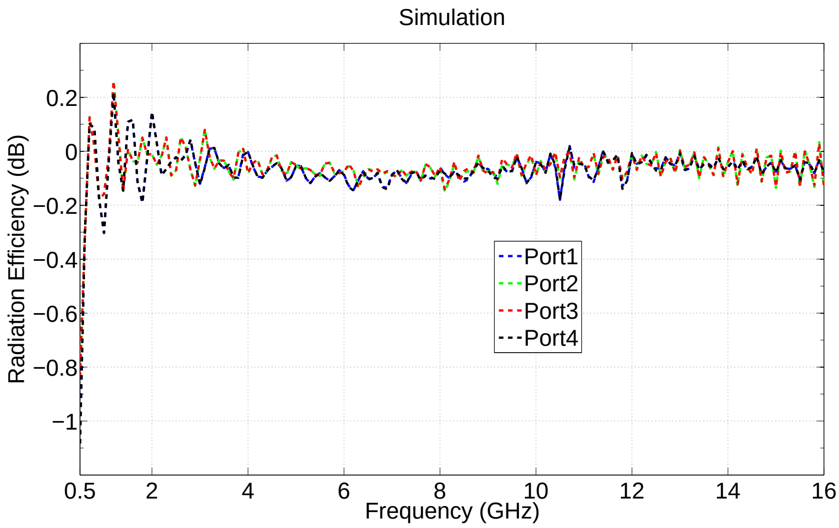


Figure 6.7: Embedded radiation efficiency due to loss

is around -1 dB. This decaying in the performance at lower frequencies than 0.6 GHz is came from the dielectric losses and its response at low frequencies. Where fractions of the energy is being absorbed by the substrate material. The total radiation efficiency is stating the contribution from both the return loss or reflection efficiency, the radiation efficiency due to loss and the decoupling efficiency. The total embedded radiation efficiency is indicating an efficiency performance of -1.5 dB at 0.5 GHz and this is mainly due to the material losses. In general at frequencies higher than 0.5 GHz, the performance is varying between -1 and zero dB along the entire bandwidth up to 16 GHz. It is possible to observe many fraction of the performance are actually above -0.5 dB. It is possible to say that performance is dependent of the frequency. In other words, the total radiation efficiency is indicating different performances along the bandwidth. The next step will include radiation efficiency measurements by using the reverberation chamber from Bluetest AB. the chamber is located at the antenna lab at Chalmers University of Technology. The instrumentation is including calibration of the vector network analyzer and measurements of reference antenna followed by the measurements of the new antenna; see Fig.6.9

The antenna radiation efficiency is measured in the frequency range 0.6-13 GHz. The reference antenna used for calibration,its recommended operating bandwidth is between 0.7-7.5 GHz. Therefore the bandwidths exceeding this range is not reliable. The measurements is conducted on port 1 which is enough for the current verifications. The radiation efficiency due to loss is in agreement with simulation up to 8 GHz ; see Fig.6.10 and Fig.6.11. The simulation of the total embedded radiation efficiency has a performance higher than -1 dB in the range 0.6-16 GHz while the measurements through the reverberation chamber is higher than -1 dB in the bandwidth range 0.6-8 GHz. Although the measurements has been conducted at frequencies higher than 8 GHz but these re-

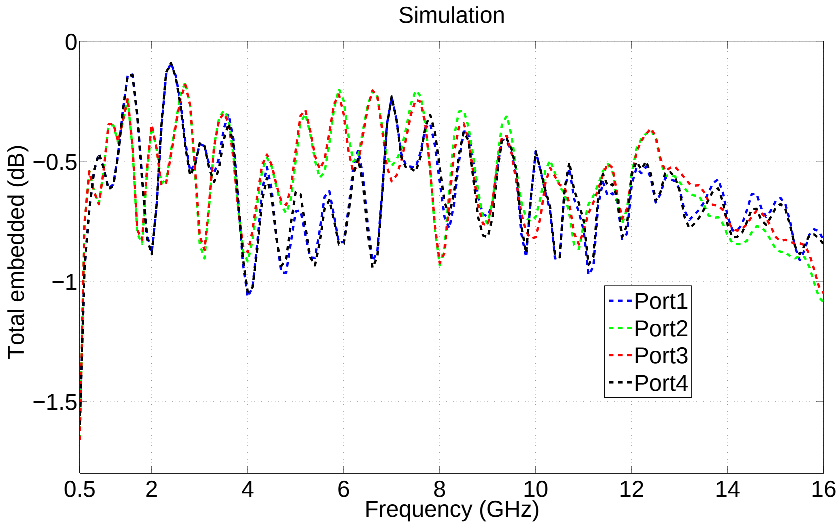


Figure 6.8: Total embedded radiation efficiency

sults are not valid or not reliable. This is because the reference antenna has a poor performance at frequencies higher than 8 (GHz) regarding the reflection coefficients; see Fig.6.12.

As mentioned in 6.6 the decoupling efficiency is a dominate efficiency in MIMO antennas. By the increased mutual couplings between ports the antenna will experience a poor radiation efficiency which will reduce its total embedded efficiency. Therefore MIMO antennas should be carefully designed in order to sustain a low mutual couplings between ports. The decoupling efficiency formula has been implemented, See Fig.6.13.

The simulation results are indicating a very low losses being involved in the total embedded radiation efficiency making the reflection coefficient is the major contributor to the total embedded radiation efficiency. in other words, the reflection coefficient efficiency is main responsible for the relatively poor total embedded radiation efficiency performance. Through these conclusions it is possible to estimate the envelope correlation coefficients between ports as;

$$\rho = \frac{S_{11}^{*}S_{12} + S_{21}^{*}S_{22}}{\sqrt{[1-(|S_{11}|^2+|S_{21}|^2)][1-(|S_{21}|^2+|S_{22}|^2)]}} \tag{6.7}$$

This coefficient is an indication on how the ports are correlated. Due to the mutual couplings between ports is low which resulted uncorrelated antenna; see. Fig6.14. It is important to understand that this formula is only valid for a lossless antenna[33]. This formula doesn't take into account the antenna losses. although, we have used this formula to have a preliminary results about the antenna correlation. This encouraged due to the low losses predicted by the simulation where the ohmic losses are bounded between -0.2-0 dB along the bandwidth range 0.6-16 GHz.

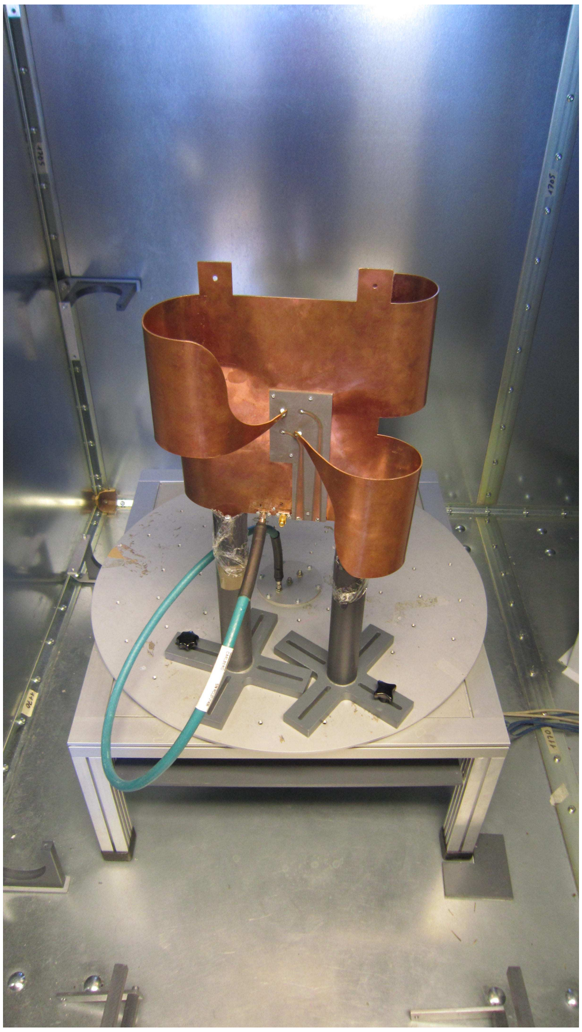


Figure 6.9: Measurements in the Reverberation Chamber

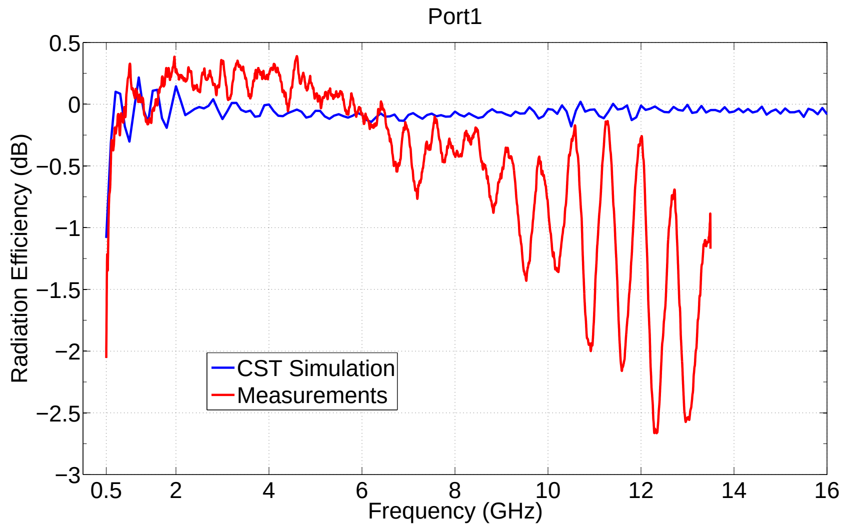


Figure 6.10: Embedded radiation efficiency(simulation and Measurements)

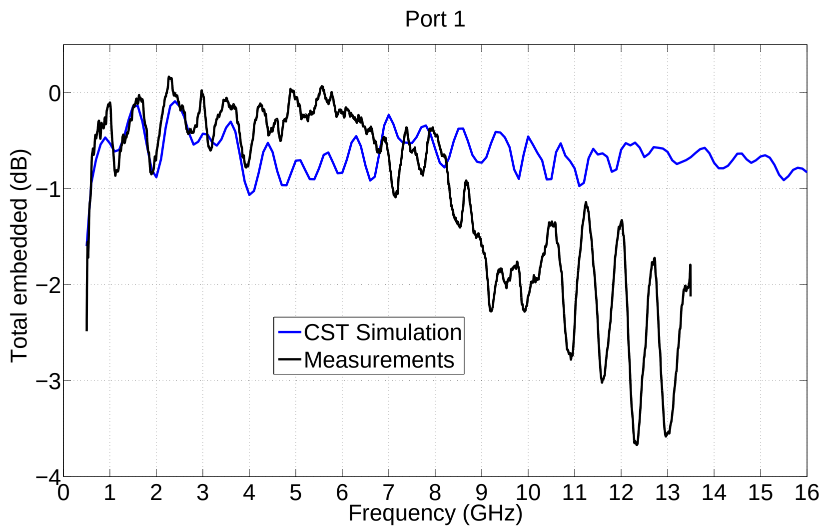


Figure 6.11: Total embedded radiation efficiency (Simulation and Measurements)

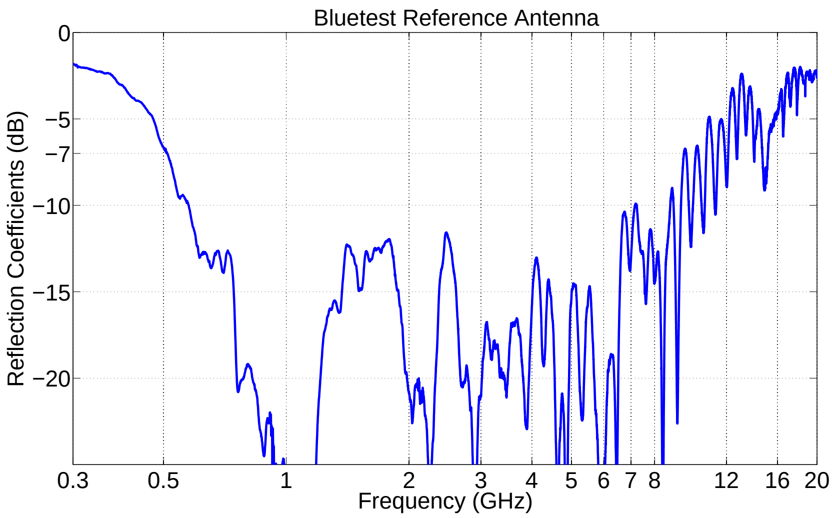


Figure 6.12: Reference antenna reflection coefficients (Measurements)

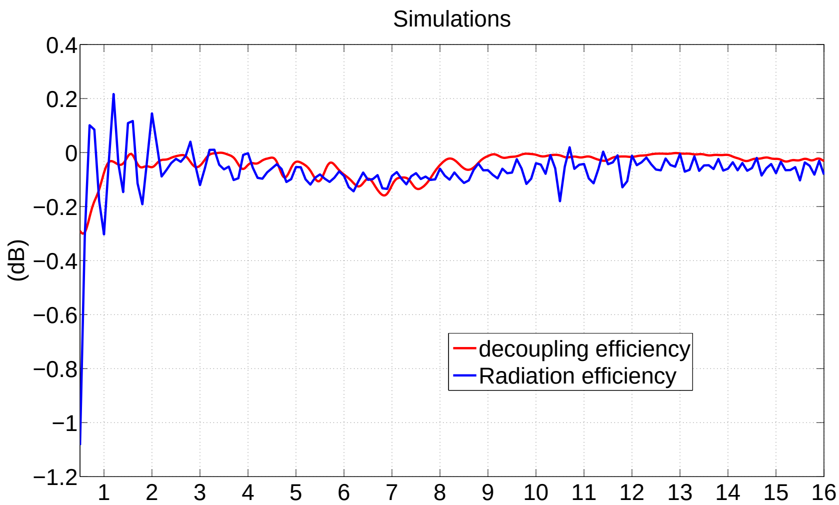


Figure 6.13: decoupling efficiency and embedded radiation efficiency (Simulation)

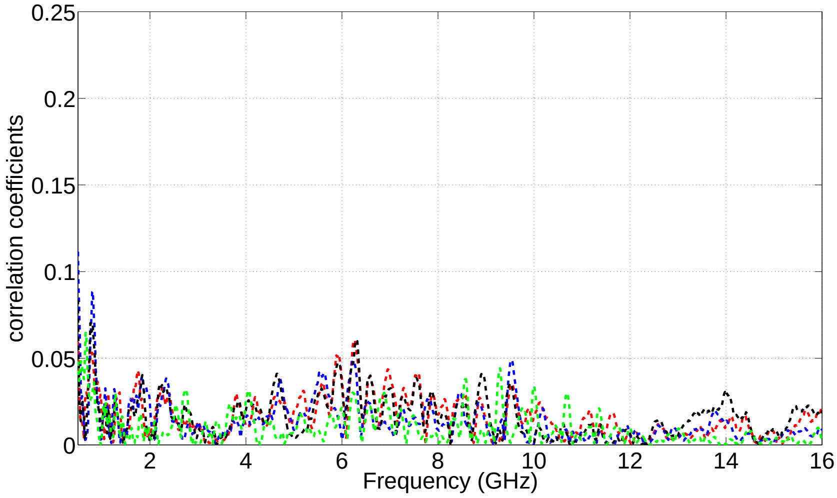


Figure 6.14: Envelop correlation coefficients

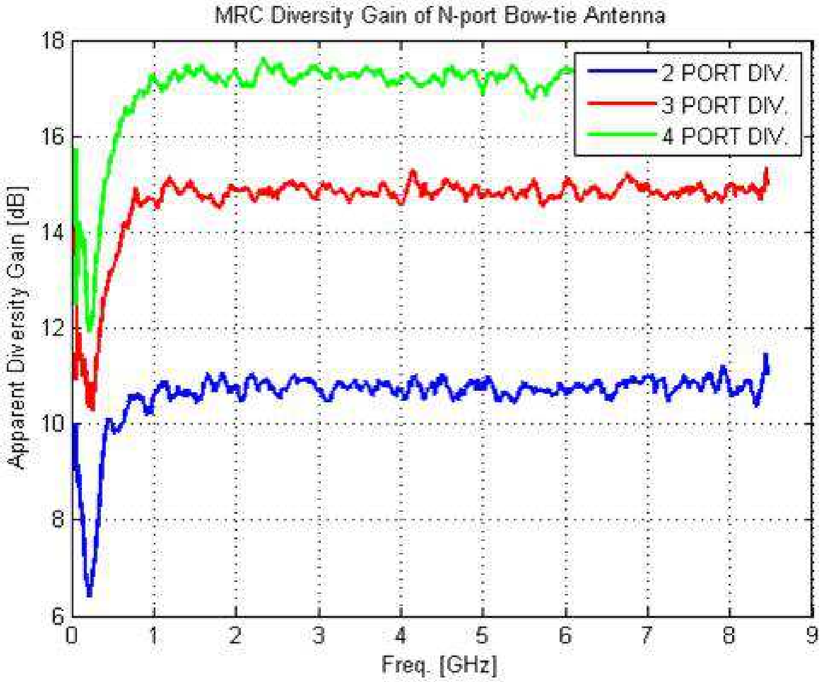


Figure 6.15: Diversity Measurements

6.3 Diversity Measurements

By increasing the directivity of the radiating elements in antenna array located in LOS environments. This increase in the gain and directivity of the radiating elements will influence and enhance the signal to noise ratio. In multi-path environments where a multi-port antenna (MIMO) is employed. Therefore the poor signal reception at one of the ports could have better signal reception at the other or the neighboring ports. Therefore a MIMO antenna has to be carefully designed regarding the couplings between ports to meet the MIMO performances of correlation and diversity gain. Therefore by increasing the number of ports the MIMO performance of diversity gain will be increased. The diversity measurements regarding the new antenna has been measured by using the reverberation chamber. The measurements are indicating a higher apparent diversity gain with four ports compared to three or two ports being used; see Fig.6.15.

6.4 Radiation Pattern

This section will study the radiation pattern through the anechoic chamber measurements. Due to the geometry and size of the antenna it was a tricky task to estimate the 3D pattern of the antenna. Therefore the result will only present patterns regarding the

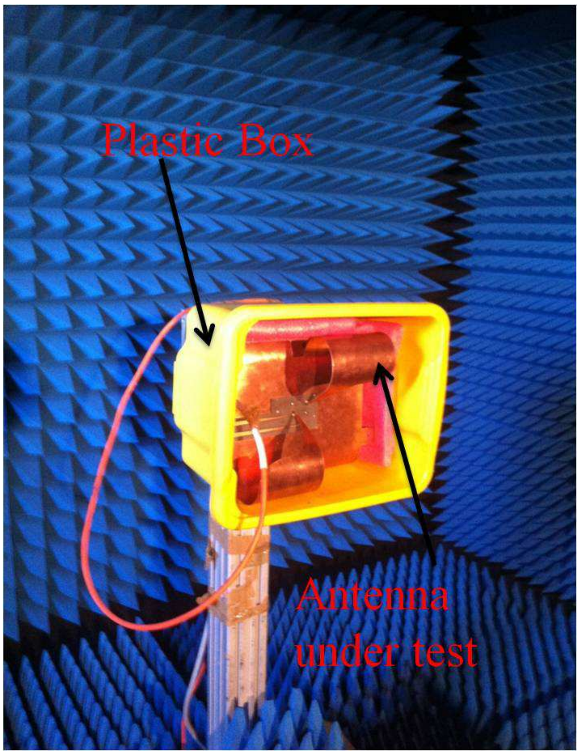


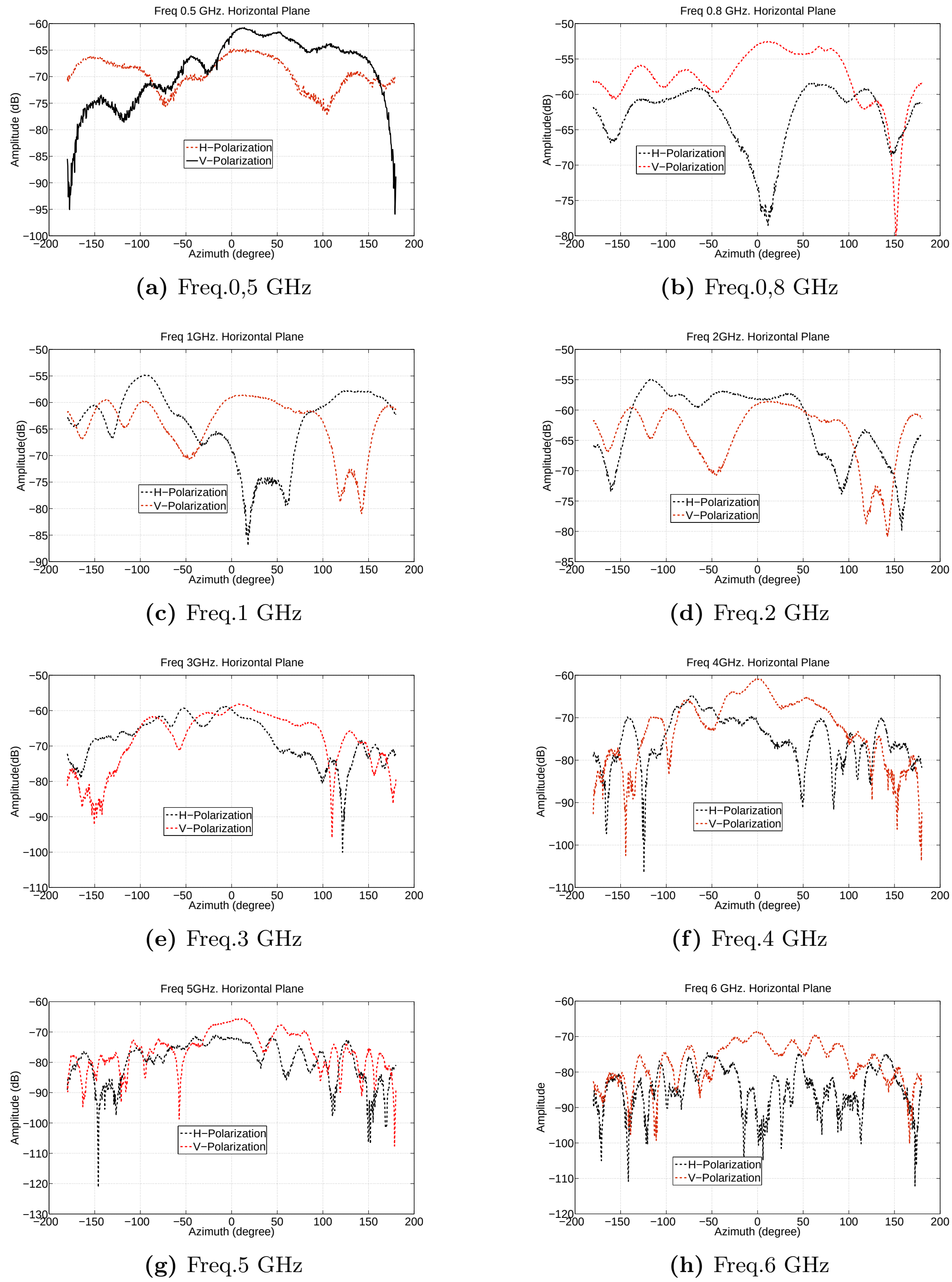
Figure 6.16: Antenna under test (Chalmers Anechoic Chamber) Horizontal Plane

H-Plane and E-Plane or the horizontal plane and the vertical plane and their corresponding vertical and horizontal polarizations. The measurements in anechoic chamber at the mast site where the antenna under test placed require a sort of a sitter to contain the antenna size. A plastic box were used for his task to hold the antenna. Although, there were some vibrations noticed during the test due to the mast movements; see Fig.6.16

It is important to point out that we don't have a desired polarization. In fact, we would like our antenna to have omni-directional properties. Therefore terminologies such as CO-Polar and Cross-Polar is not valid in this antenna but instead Horizontal and Vertical polarizations are being used to indicate that the both components are desired.

6.4.1 Horizontal Plane

The section will present the radiation pattern along the horizontal plane. The measurements will be conducted by setting the antenna under test at ($\theta = 0$) corresponding to the horizontal plane. The transmitter will be rotated along θ direction at (θ=0) and (θ=90) measuring the horizontal polarization and vertical polarization, respectively; see Fig.6.17



(a) Freq.0,5 GHz

(b) Freq.0,8 GHz

(c) Freq.1 GHz

(d) Freq.2 GHz

(e) Freq.3 GHz

(f) Freq.4 GHz

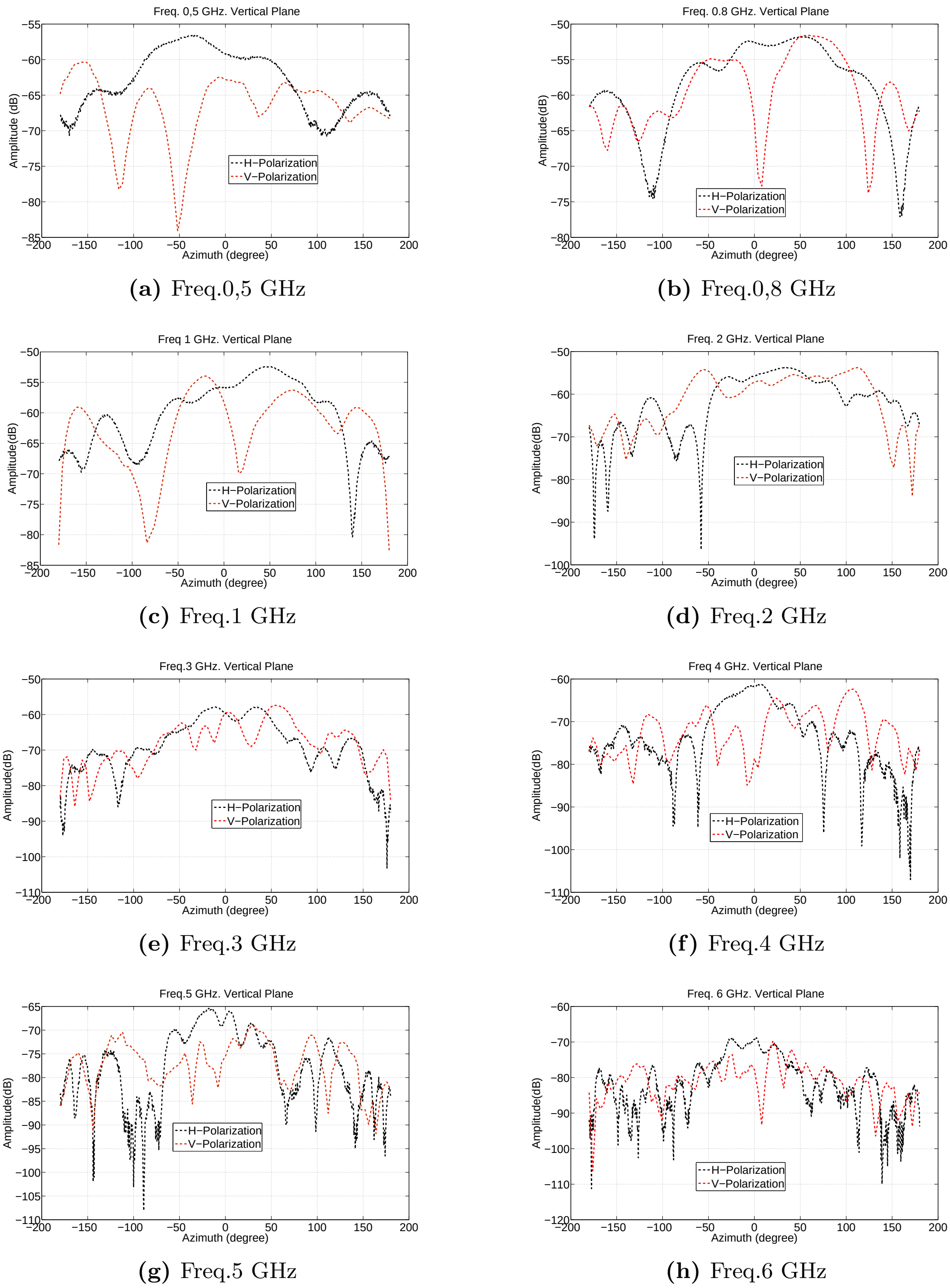
(g) Freq.5 GHz

(h) Freq.6 GHz

Figure 6.17: Antenna radiation Pattern (Horizontal Plane)

6.4.2 Vertical Plane

The section will present the radiation pattern along the vertical plane. The measurements will be conducted by setting the antenna under test at ($\theta = 90$) corresponding to the vertical plane. The transmitter will be rotated along θ direction at (θ=0) and (θ=90) measuring the horizontal polarization and vertical polarization, respectively; see Fig.6.18



(a) Freq.0,5 GHz **(b)** Freq.0,8 GHz

(c) Freq.1 GHz **(d)** Freq.2 GHz

(e) Freq.3 GHz **(f)** Freq.4 GHz

(g) Freq.5 GHz **(h)** Freq.6 GHz

Figure 6.18: Antenna radiation Pattern (Vertical Plane)

7

Conclusions and Future Work

This project present a fixed measurements antenna for Bluetest reverberation chamber. In this project we designed, developed and manufactured a prototype to serve as the fixed measurements antenna for the reverberation chamber. The previous system consist of three triangular monopoles antennas and provide a good performance at high frequencies but a poor reflection coefficients at low frequencies especially below 800 (MHz). A CST MS model has been simulated and compared to the prototype measurements. In fact, this not the only objective in this project. Since it is a research project, the requirements were to investigate other types of antennas and perform several simulations and measurements in order to characterize the overall performance. The requirements were to develop a wide band antenna with a range of 0.65 to 6 (GHz) as a primary target. The antenna should provide A MIMO capabilities represented by increasing the number of ports. A compact size and a geometry easy to manufacture for future volume production.

The circuit requirements were to have a reflection coefficients around -10 (dB) and low mutual couplings between pots below -15(dB). The concept of the self grounded antenna has been suggested to be employed. A previously designed and manufactured antenna so called the self grounded Bow-Tie antenna has been investigated. The purpose was to implement the self grounded concept in the design of the new antenna. The self grounded Bow-Tie is a directive antenna consist of two monopole fed by a balun (one port antenna). The new antenna is employing the same concept and forming four triangular self grounded monopoles each one fed by a separate transmission line, build on a compact geometry. The genetic algorithm scheme has been implemented in order to reduce the antenna return loss. The genetic optimization results shows that the antenna will require between (confidential) (Ohm) at its input beside the optimized parameters in order to achieve a return loss below -8 (dB). The antenna geometry at this level were 175 $\times$ 175 mm corresponding to the length and width, respectively. The antenna mutual couplings shows an excellent performance of -15 (dB) and even below at higher frequencies. However, after optimization prediction, its become essential that the antenna require a matched network to be placed between the antenna input port and the coaxial connectors.

Part of the work was focused on designing the impedance matching network which designed through parametric procedure. These parameters are based on the classical approximation micro-strip line formalism. The tapered line transformer has been designed in CST MS. An important issue has been aroused during the simulation which is the radiation efficiency. A sever degradation in the radiation efficiency at higher frequencies endangered the project. By Investigating the source of this problem, it appeared that the dielectric material is causing this degradation. Therefore we had to replace the FR-4 substrate with Rogers RT5880. The transformer has been designed in a way to be fit in the antenna geometry and to support the feeding at one side. Through simulation results it was found that the antenna geometry will require to be scaled larger in order to support resonant bandwidths at lower frequencies than 1 (GHz). Therefore the antenna has been scaled but with the consideration of keeping the compact size.

A geometry of 250×250 (mm) has been estimated in order the antenna is performing at frequencies near 0.5 (GHz). It has been noticed that the antenna with less monopoles in the area is achieving better performance at lower frequencies. Therefore the geometry experienced a modifications by keeping two antennas at one side while the other two are pointing at the opposite direction. By this act the dual sided four ports tapered triangular antenna has been introduced. The simulation predicted that a reflection coefficients are below -7 (dB), Mutual couplings are below -15 (dB) and total embedded radiation efficiency higher than -1 (dB) over a bandwidth of 0.5-16 (GHz). Other quantities such as the correlation coefficients has been estimated from the S-Parameters. A correlation coefficients below 0.1 which is indicating a very uncorrelated ports.

These results encouraged us to manufacture a prototype to assist the measurements. The return loss measurements showed a performance below -7 (dB) over the bandwidth of 0.5-9 (GHz) which is in agreement with simulations in this bandwidth. The disagreement start to be observed at frequencies higher that 9 (GHz) where the total performance is below -4.5 (dB). The Mutual couplings is consistently preserved the excellent performance even in the measurements with a performance below -15 (dB) over the bandwidth 0.5-20 (GHz).

The radiation efficiency quantity has been replaced by the the embedded radiation efficiency to include the losses at neighboring ports. In the same manner the total efficiency is realized through the total embedded radiation efficiency. This term is due to the reflection efficiency, decoupling efficiency and radiation efficiency due to the material losses. The CST MS simulations predicts that the embedded radiation efficiency is higher than -0.2(dB)in the frequency ranges (0.6-16)(GHz). The embedded radiation efficiency experience a high loses at 0.5 (GHz) and this is mainly due to the dielectric losses. The total embedded radiation efficiency is higher than -1 (dB) within the frequency range (0.6-16) (GHz). The measurements regarding the embedded radiation efficiency has been conducted by using the reverberation chamber. The total embedded radiation efficiency is higher than -1(dB) with in the frequency range (0.6-8) (GHz). By examining the total embedded efficiency contributors, it is possible to conclude that the reflection efficiency is the dominate contributor toward the poor radiation performance while decoupling and radiation due to ohmic loss efficiencies have very low impact on the total embedded radiation efficiency.

The future work will include many aspects, varying from the verifications to the development. We believe that the return loss can be enhanced more and can be extended to higher frequencies. Probably optimizing the antenna in a differen scheme than the implemented could produce higher performances. Problems related to the manufacturing difficulties such as soldering, the precision of the antenna feeding tap to the pin and the antenna thickness are all candidates to investigate. The measurements will require further verifications especially the radiation efficiency in the reverberation chamber to estimate the performance over the whole bandwidth. It will also require the measurements in the anechoic chamber to estimate the 3D radiation pattern. One important test is to use it as the transmitter antenna in the chamber and record the responses. The future work will also contain a research about the transformer materials based on the cost and performance. The future work will also contain reducing the thickness of the dielectric material of the transformer. This antenna has four ports therefore the future work will focus on increasing the number of ports (6 or 8) and maintaining or enhancing the achieved performances.

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A

Genetic Algorithm Codes

Genetic Algorithm Optimization

A.1 Initial Population

```
function pop = InitPopA(N)
% N- size of the population
pop = zeros(N,7); % population field
% scaling factor for (geneX)
geneX_hi = 10; % gene controller
geneX_lo = 3.85;
pop(:,1) = round(geneX_lo + (geneX_hi-geneX_lo)*rand(N,1));
% scaling factor for (geneY)
geneY_hi = 15 ;
geneY_lo = 3.85 ;
pop(:,2) = round(geneY_lo + (geneY_hi-geneY_lo)*rand(N,1));
% outer circle radius (geneR)
geneR_hi= 35;
geneR_lo= 2;
pop(:,3) = round(geneR_lo + (geneR_hi-geneR_lo)*rand(N,1));
% Y range (Yrange)
Yrange_hi= 100;
Yrange_lo= 80;
pop(:,4) = round(Yrange_lo + (Yrange_hi-Yrange_lo)*rand(N,1));
% X range (Xrange)
Xrange_hi= 100;
Xrange_lo= 80;
pop(:,5) = round(Xrange_lo + (Xrange_hi-Xrange_lo)*rand(N,1));
```

```
% scaling factor for (geneB)
geneB_hi= 10 ;
geneB_lo= 2 ;
pop(:,6) = round(geneB_lo + (geneB_hi-geneB_lo)*rand(N,1));
% scaling factor for (geneC)
geneC_hi= 0.9 ;
geneC_lo= -0.9 ;
pop(:,7) = geneC_lo + (geneC_hi-geneC_lo)*rand(N,1);
end
```

A.2 First Generation

```
clear all
close all
clc
addpath('C:\Users\ben\Desktop\Project_Work\Models_Scripts')
Population_Size = 300;
N = Population_Size ;
pop = InitPopA(N);
geneX = pop(:,1);
geneY = pop(:,2);
geneR = pop(:,3);
Yrange = pop(:,4);
Xrange = pop(:,5);
geneB = pop(:,6);
geneC = pop(:,7);
for i = 1:N
conceptA(geneX(i),geneY(i),geneR(i),Yrange(i),Xrange(i),geneB(i),geneC(i),i)
end
filename = 'Run_CST.m' ;
fid = fopen(filename,'wt+');
if (fid<1)
disp ('the file does not exist ')
end
for j = 1:N
fprintf(fid,'! "C:\\Program Files (x86)\\CST STUDIO SUITE 2011\\...
CST DESIGN ENVIRONMENT.exe" m C:\\%g\\Opt.bas\n',j)
fprintf(fid,'\n')
end
fclose(fid)
```

A.3 Next Generation

```
%% natural selection, sorting proccess
```

```
clear all
clc
% close all
% i = 0;
files = 122:1:300;
% sorting Process
for i = 1:length(files);
file = (['C:\First_Generation_results\Mat_files\S11_'...
    ,num2str(files(i)),'.mat']);
file = load(file);
fre = file.fre;
S11_dB(:,i) = file.S11_dB;
end
flag = find(fre==1);
i = 0;
while (i<=length(S11_dB)-flag)
%limiting the cost fuction between 1 and 5 GHz
cost(i+1,:) = S11_dB(flag+i,:);
i=i+1;
end
cost_max = max(cost);
[cost_sort ind] = sort(cost_max);
cases = files;
for j = 1: length(ind)
    cases_sort(j,:) = cases(ind(:,j));
end
% natural selection
nat_sel = 15; % determining the number of parents
cost_sel = (cost_sort(:,1:nat_sel))';
parents = cases_sort(1:nat_sel);
% restoring parents genes
for k = 1:nat_sel
filepath=['C:\First_Generation\',num2str(parents(k))...
    ,'\Chromosome_String.txt'];
fid = fopen(filepath,'rt+');
s = fscanf(fid,'%s\n',2);
geneX = fscanf(fid,'%f\n',1);
s = fscanf(fid,'%s\n',2);
geneY = fscanf(fid,'%f\n',1);
s = fscanf(fid,'%s\n',2);
geneR = fscanf(fid,'%f\n',1);
s = fscanf(fid,'%s\n',2);
Yrange = fscanf(fid,'%f\n',1);
```

```
s = fscanf(fid,'%s\n',2);
Xrange = fscanf(fid,'%f\n',1);
s = fscanf(fid,'%s\n',2);
geneB = fscanf(fid,'%f\n',1);
s = fscanf(fid,'%s\n',2);
geneC = fscanf(fid,'%f\n',1);
parents_genes(k,:) = [geneX geneY geneR...
    Yrange Xrange geneB geneC];
end
% Generating offsprings
beta = 0.5;
k = 1;
for i = 1:nat_sel-1
for j = i+1:nat_sel
off_Springs(k,:)=(1-beta).*parents_genes(i,:) + beta.*parents_genes(j,:);
k = k+1;
end
end
addpath('C:\Users\ben\Desktop\Project_Work\Models_Scripts')
geneX = off_Springs(:,1);
geneY = off_Springs(:,2);
geneR = off_Springs(:,3);
Yrange = off_Springs(:,4);
Xrange = off_Springs(:,5);
geneB = off_Springs(:,6);
geneC = off_Springs(:,7);
 for i = 1:length(off_Springs)
 conceptA(geneX(i),geneY(i),geneR(i)...
      ,Yrange(i),Xrange(i),geneB(i),geneC(i),i);
 end
filename = 'C:\Genetic_Algorithms\Run_CST.m' ;
fid = fopen(filename,'wt+');
if (fid<1)
disp ('the file does not exist ')
end
for j = 1:length(off_Springs)
fprintf(fid,'! "C:\\Program Files (x86)\\CST STUDIO SUITE 2011\\...
CST DESIGN ENVIRONMENT.exe" -m C:\\Second_GenerationB\\%g\\Opt.bas\n',j)
fprintf(fid,'\n')
end
fclose(fid);
```