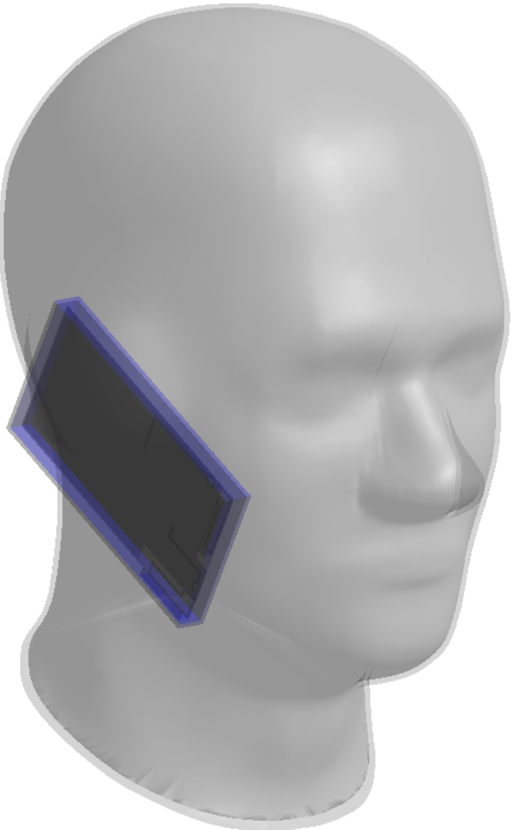
CHALMERS



Tunable WWAN/LTE Handset Antenna and Its LTE MIMO Application

Master's Thesis in Wireless and Photonics Engineering

LINUS HALLBERG

Engineering Physics
Department of Signals and Systems
Division of Antennas
Chalmers University of Technology
Gothenburg, Sweden 2012
Master's Thesis 2012 : nr X

Thesis Supervisor:

Kin-Lu Wong - *wongkl@mail.nsysu.edu.tw*
Professor, National Sun Yat-Sen University, Kaohsiung, Taiwan

Thesis Examiner:

Per-Simon Kildal - *per-simon.kildal@chalmers.se*
Professor, Chalmers University of Technology, Gothenburg, Sweden

Conducted at National Sun Yat-Sen University, Kaohsiung, Taiwan, 2012

Preface

This report is the Master's thesis report that concluded my five year Swedish university degree (Civilingenjör) in Engineering Physics. The Master's studies of the five year program was done within the Master's program Wireless and Photonics Engineering at Chalmers University of Technology.

The first year of courses within the master were taken as an exchange student in Hsinchu Taiwan at National Chiao Tung University during 2010/2011. Afterwards, half a year of studies within the program was done at Chalmers in Sweden. Finally, on February 1, 2012 I started working on this thesis by joining Prof. Kin-Lu Wongs antenna lab at National Sun Yat-Sen University in Kaohsiung Taiwan. I got in contact with professor Wong by a recommendation from Malcolm Ng Mou Kehn, who was my teacher in computational electromagnetics at National Chiao Tung University.

My examiner of the thesis was professor Per-Simon Kildal, who is the leader of the antenna research group of Chalmers. He assisted me with the project through email and helped me in making the thesis conform with writing practice, not only in Taiwan, but also in Sweden.

The writing of the thesis was concluded in June and a final presentation was held in Taiwan at the 22 June 2012. This presentation was held in Chinese, since it was the main language used in the lab. The presentation at Chalmers was held at the 23 August 2012.

Abstract

The goal with this project was to produce an eight-band WWAN/LTE handset antenna supporting MIMO, by using a tunable matching circuit to switch between WWAN and LTE operation. The switching design with eight bands was investigated with simulations and a 7-band MIMO antenna was produced and measured successfully.

Sammanfattning

Målet med detta projekt var att producera en åtta-bands WWAN/LTE mobiltelefonantenn med stöd för MIMO. Antennen ändrar från WWAN till LTE med hjäp av ett ställbart matchningsnät. En konfigurationen med åtta band samt ställbart matchningsnätet undersöktes med simuleringar och en 7-bands MIMO antenn tillverkades och testades med bra resultat.

Acknowledgements

Thanks to Per-Simon Kildal, my examiner at Chalmers University of Technology, Kin-Lu Wong my advisor at National Sun Yat-Sen University, Malcolm Ng Mou Kehn at National Chiao Tung University and all my classmates in the antenna lab at National Sun Yat-Sen University.

A special thanks to my experienced classmates Tsung-Ju Wu and Po-Wei Lin for giving me a lot of help and support in the everyday research. Thanks to Malcolm for recommending me to go to National Sun Yat-Sen University for my Master's Thesis, thanks to Kin-Lu Wong for receiving me as master thesis writing student and thanks to Per-Simon Kildal for making it possible for me to go abroad making my thesis work.

Contents

List of Figures

List of Tables

List of Abbreviations

AUT	Antenna Under Test
FEM	Finite Element Method
HFSS	Ansoft High Frequency Structure Simulator
FCC	Federal Communications Commission
FDTD	Finite-Difference Time-Domain
GSM	Global System for Mobile Communications
HAC	Hearing Aid Compatibility
LTE	Long Term Evolution
PCB	Printed Circuit Board
PML	Perfectly matched layer
RX	Receive
SAR	Specific Absorption Rate
TX	Transmit
UMTS	Universal Mobile Telecommunications System
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WWAN	Wireless Wide Area Network

1

Introduction

BACK in the 1990's, having a protruded mobile phone antenna was the standard for mobile phones. Nowadays, one hardly ever sees any antennas on mobile phones and laymen occasionally falsely state that today's mobile phones don't have antennas. Nevertheless, today's mobile phones all have antennas, usually more than one. Antenna size is mainly decided by which frequency the antenna is supposed to radiate at, higher frequency gives shorter antennas. Since, mobile networks tend to use higher and higher carrier frequencies, antennas can be made smaller and smaller. Today's mobile phones usually use microstrip antennas, a thin metal strip on a dielectric sheet, which make it possible to efficiently hide the antenna inside the phone.

The most common network technologies in use today are GSM, UMTS (3G) and LTE (4G). These technologies all use different frequency bands, so an antenna supporting all three would need to be able to transmit and receive signals at three different frequencies. However, different countries have different spectrum laws and policies, so the actual amount of different frequencies the antenna needs to support in order to support these three technologies in all countries are eight. (In fact LTE have many more different bands, but this report will try to support three of the most common LTE bands) Since LTE still is a new technology, these kind of antennas are very uncommon and open up research opportunities. In addition, in order to increase the data rate of the connection, LTE has opened up for the possibility to send with multiple antennas. This technique is known as Multiple Input Multiple Output, MIMO.

The goal with this thesis is to design a small size mobile phone microstrip antenna supporting eight frequency bands and LTE MIMO.

1.1 The Importance of Good Handset Antenna Design

The antenna is one of the major hardware parts of a mobile phone. It does not constitute a big cost in production, but it has a major impact on the performance and design of the mobile phone. For example, the cell phones reception is completely depending on the performance of the antenna. That is, a badly designed antenna won't be able to receive a clear signal from a base station and hence cripple the usage of the cell phone. Furthermore, since mobile phones usually turn off the screen during voice conversations, the part draining most energy from the battery is the mobile phone transmitter. Thereby, energy consumption will be heavily dependent of the mobile phone antenna's efficiency.

The mobile phones visual design was in the 1990s clearly very dependent on the antenna, since it usually was mounted externally. Nowadays, with internal antennas, the visual design's dependence of antenna design is less obvious, but still a major factor. For example, recently many mobile phones, computers and tablets have been designed with a metal casing. However, the case usually have a couple of plastic areas for the antenna, which enables the antenna to receive and transmit. Hence, a smaller antenna will put a smaller constrain on the visual design of the mobile phone. This design constraint is becoming more and more important due to mobile phones going towards thinner designs with bigger screens.

Finally, there is yet another important area where antenna design plays a major role, that is radiation safety. Mobile phones radiate microwaves in frequencies similar to those of microwave ovens and will likewise have a heating effect in the head while using the phone. Design of the mobile phone antenna is the most important factor to consider when trying to keep inside of the allowed radiation limits put up by organizations such as IEEE and FCC. GSM and 3G frequencies used in different countries have been rather uniform and making antennas supporting all bands have been achievable. In contrary, LTE has at the moment been separated in more than 20 different bands ranging from 698MHz to 3800MHz.[1] Making small antennas that can support all these frequency bands might require tuning, one of the techniques that is used in this project.

1.2 Objective

The objective is to design a handset antenna that can cover WWAN/LTE operation with a size as small as that of a penta-band WWAN antenna. That is, a WWAN antenna which by using a Reconfigurable Matching Circuit (RMT) can tune the operating bands to reach LTE frequencies. The RMT mainly comprises of two matching circuits which are connected so that when the antenna is connected to the first matching circuit, it can cover the penta-band WWAN operation (824-960/1710-2170 MHz). Later, when the LTE operation is required, the antenna will be switched to connect to the second matching circuit, with the first matching circuit disconnected, so that the antenna can cover the LTE700/2300/2500 (704-787/2300-2400/2500-2690 MHz). In this case, the WWAN handset antenna can be switched to perform as an LTE antenna without the need of increasing the antenna size. Such a design can lead to a small-size eight-band WWAN/LTE handset antenna with an occupied volume of $1cm^3$ or even less. The obtained WWAN/LTE antenna can be a main antenna for future handsets. Finally, by disposing another LTE antenna as an Aux antenna in the handset, performances of the LTE MIMO operation will be studied.

1.2.1 Goals

The two main goals with the thesis are:

1. Design a tunable WWAN/LTE handset antenna.
2. Design, produce and measure performance of the antenna described in 1. together with an aux antenna performing in LTE MIMO operation.

The design is supposed to reach four criterias. Having a size smaller than $1cm^3$, an efficiency over 50%(in non-MIMO setup), reaching a HAC of at least M3 and reaching a SAR of less than $1.6W/kg$ at 1g spatial average.

1.3 Limitations

The antenna will not be mounted inside a mobile phone. However, a plastic casing will be used both in simulation and measurement to simulate the case of a mobile phone. Furthermore, components such as screen and battery also affect the behavior and performance of the antenna, nevertheless, they are still disregarded in this project. However, the techniques that will be used still apply inside a real mobile phone, there would only be need for some tuning and possibly a loss in performance.

LTE coverage will be limited to LTE700, LTE2300 and LTE2500.

1.4 Related Research

A very small size loop antenna covering GSM900/1800/1900/UMTS operation has been proposed by Prof. Kin-Lu Wong [2]. By using a band-stop matching circuit, the 900-MHz band of the antenna can become a dual-resonance band covering both GSM850 and GSM900 [3]. It is expected that by applying this matching circuit technique, the very small size loop antenna can become a penta-band WWAN antenna [4]. Then, the challenge is to devise a second set of matching circuit, so that the antenna can be tuned to cover LTE700 (704-787 MHz) or LTE700/2300/2500 bands.

Antenna measurements for MIMO need to be done in a multi-path reference environment. This reference environment should be isotropic, rich and with low Line Of Sight (LOS) coupling compared to the coupling from the environment, where rich means it should give hundreds of incoming waves to the Antenna Under Test, AUT. A multi-mode reverberation chamber from Bluetest [5][6] supplies such an environment and is ideal for small antenna measurements.

1.5 Method

This part of the report describes the process of this project. That is, all steps of the project are described. The project was conducted in the Antenna Lab of National Sun Yat-Sen University in Taiwan.

The main theoretical background to the project were found in previous works by Prof. Kin-Lu Wong at National Sun Yat-Sen University. Articles are available at IEEE Xplore Digital Library [7] and at Wiley Online Library [8]. All used references are reffered to and listed in the bibliography of this report.

1.5.1 Process

Below is a small description of all the steps in the process.

1. **Theoretical Studies**
   Get familiar with NSYSU Antenna Lab and all formalities. Read the most important theoretic material, check papers about earlier solutions and familiarize with the software Ansys HFSS [9] and SEMCAD [10] that will be needed for design and simulation.

2. **Produce an Antenna**
   Take a finished design and go through the whole simulation, production and measurement process.

3. **Design**
   Try out different approaches and complete an, according to simulations, successful antenna design for fabrication. A step by step approach will be used successively adding more and more of the features to the antenna. Furthermore, an iterative approach will be used between simulation and design, trying to maximize performance of the final design.

   An antenna efficiency over 50% will be pursued with HFSS and compliance with Specific Absorption Rate (SAR) [11] and Hearing Aid Compatibility (HAC) [12] regulations will be checked with SEMCAD using a head phantom provided by SEMCAD. The design goal for SAR is to be below 1.6 W/kg at 1g tissue. A HAC rated as M3 or higher will be pursued.

4. **Final Measurements and Analysis**
   Do measurements in an echo free chamber and a Bluetest chamber. Compare the results with simulations.

5. **Write the Final Report**
   Produce a report addressing every part of the project. Briefly talk about the relevant antenna knowledge, describe the design process and primarily present and discuss the results.

6. **Presentation**
   The project is presented in Chinese at National Sun Yat-Sen University and in English at Chalmers University of Technology.

2

Antenna Design

2.1 Definitions and Concepts

2.1.1 Radiation

Electromagnetic radiation is produced by accelerating charge particles. In an antenna, the radiation is produced by an alternating current, which is composed of accelerating electrons.

A non accelerating electron has a static electric field around it. The static field is retarded and derived directly from Maxwell's equations. This retardation means that a change of the electron position, won't be noticed at a distance r from the electron until r/c seconds later. That is, if the electron is moved (accelerated), it will start to produce a static field from a new position and therefore create a crease in the electric field. This crease is a phi directed electric field that propagates in r direction and is what we call an electromagnetic wave.

2.1.2 dB, dBi, dBm

The unit decibel is commonly used when working with electromagnetic fields. Decibel is abbreviated as dB and is defined by ten times the logarithm of a dimensionless fraction. See the definition in equation 2.1. Hence, negative decibels is a number between 1 and 0, not negative. For example, 1 is equal to 0 dB, 100 is equal 20dB and 25% is approximately equal to -6.02 dB.

$$A_{dB} = 10log_{10}(\frac{A_1}{A_0}) \tag{2.1}$$

dBm is a logarithmic unit used to express power [W]. The definition is given in 2.2. Therefore, dBm is simply adding the unit [mW] to decibel, that is, 0 dBm is 1mW, 20dBm is 100mW and -6dBm is approximately 0.25mW.

$$P_{dB} = 10log_{10}(\frac{P}{1mW}) \tag{2.2}$$

dBi works in the same way as dBm, but instead of comparing size with 1mW the reference is the Gain of an isotropically radiating antenna. That is, 30dBi means a gain 1000 times stronger than if the same amount of radiated power was uniformly radiated in space.

2.1.3 Antenna Impedance

Basically, small antenna design is all about matching the antenna so that it can resonate. Antenna impedance is therefore a very important parameter, which generally is a complex number. However, it is when the imaginary part is zero or close to zero, that the antenna is resonating and radiating at an exited mode. Doing modifications and changes to the antenna design is usually done by modifying the complex part of the impedance. For example, by matching the antennas ends with capacitors or inductors. The real part and imaginary part of the impedance plotted as a function of frequency give much information of the antennas behavior. What usually is need to get good performance is moving or flattening the curve of the imaginary part of the impedance, where flattening means increased bandwidth.

2.1.4 Return Loss

Return loss is traditionally expressed as the ratio between incident and reflected power expressed in dB, see equation 2.3. However, this report will in accordance with common practice within antenna engineering report return loss with a negative sign, that is the fraction of reflected power divided by incident power in dB.

$$R_L = 10log_{10}(\frac{P_r}{P_i}) \tag{2.3}$$

Return loss evaluated at different frequencies of an antenna usually give a good representation of its radiating properties. For example, if the return loss is close to 0 dB, it means that the antenna isn't radiating at that frequency and if the return loss is around -20dB or lower, it means that at least 99% of power either is radiated or absorbed and converted into heat inside the antenna. Microstrip antennas usually have rather poor efficiency, of those 99% typically 70-80% would be radiated power. The reason small antennas have low efficiency is due to the fact that they are working in resonance, allowing the wave to travel through the antenna many times and thereby lose more power.[13]

For systems with more than one antenna low return loss and low losses inside the antenna won't necessarily mean the energy is radiated to the far field, it might also get absorbed by other antennas. Hence, it is important to also consider the energy absorbed

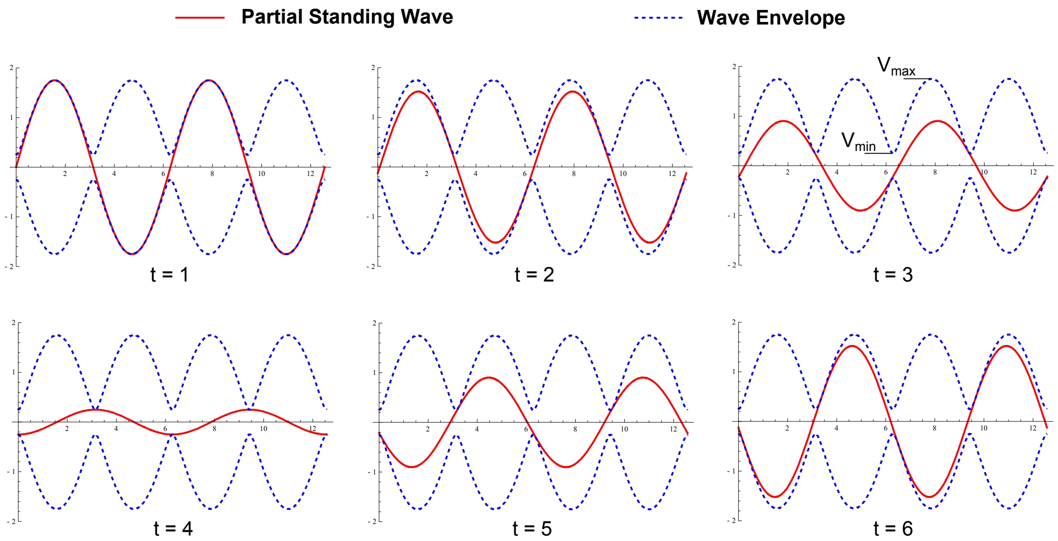


Figure 2.1: *A partial standing wave with its envelope. The VSWR is decided from the minima and maxima of the envelope. The six graphs are representing different times.*

by the diversity antenna when simulating and measuring MIMO configurations. Simulation software can give direct information about radiation efficiency, but since return loss is much faster to calculate, it is the most common parameter to use as guidance during the design. This is true since calculating radiation efficiency requires knowledge about the radiated far-field, while calculating return loss only requires knowledge of the lumped element circuits and the antenna.

2.1.5 Voltage Standing Wave Ratio

Voltage standing wave ratio is usually noted VSWR. It gives information about how much of a wave that is reflected. The properties of an electromagnetic wave needed to calculate the VSWR can't be read directly from a time independent plot of the wave. Both time and space need to be considered to get the properties of the wave needed to do the calculation, see figure 2.1 The definition of VSWR is seen in equation 2.4.

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.4}$$

As it can be seen from the definition, the VSWR will be equal to infinity for total reflection and to 1 for zero reflection. A partial standing wave is partially travelling and thereby making a net transport of power. A VSWR of 3:1 will be used as a design guide line and is approximately equal to a return loss of -6dB.

2.1.6 Scattering Parameters

Scattering parameters, usually referred to as S-parameters, of a electrical system is describing the behavior of the system. The S-parameters is a very useful quantity since it is very easily measured and can be used to calculate for example return loss, VSWR and isolation between MIMO antennas. See equations 2.5, 2.6 and 2.7 for calculation of antenna design parameters from S-parameters.

$$ReturnLoss = 10log_{10}(|S_{11}|) \tag{2.5}$$

$$Isolation = 10log_{10}(|S_{12}|) \tag{2.6}$$

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|} \tag{2.7}$$

2.1.7 Radiation Efficiency

Radiation efficiency is by IEEE defined as ”The ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter.” [14]. Radiation efficiency does not consider losses in the mismatch between the antenna and the transmitter and is therefore rarely used in this report.

2.1.8 Total Embedded Efficiency

Total embedded efficiency is the ratio of total power radiated to the far-field by the antenna to the net power supplied to the port of the antenna. That is, it includes both mismatch in the port and radiation absorbed by other antennas in MIMO configuration. While return loss is most frequently used during the design, what really matters in the end is the antenna’s efficiency. Total embedded efficiency is what will be used throughout this report and will be used interchangeably with antenna efficiency.

2.2 Radiation Limitations

2.2.1 SAR

SAR is an abbreviation for Specific Absorption Rate, which is a measure used when defining limits for the amount of radiation an antenna can radiate into the human body. Specific Absorption is defined as the amount of incremental energy absorbed divided by an incremental mass and SAR is simply the time derivative of the specific absorption. The SI unit of SAR is watts per kilogram (W/kg).

SAR measurements of human tissue will give a 3D field result. However, the limits of SAR are always defined as an average, which is stating that the average SAR within any piece of the tissue can’t exceed a certain limit, where the pieces of tissue should be cubic squares of a certain weight, usually 1g or 10g. [11] The design goal for SAR in this project is to pass both the American and European standards. However, since the American standards put up by FCC is more strict than the European, only the American limit of 1.6 W/kg at 1g tissue will be used. When investigating SAR, SEMCAD is used. SEMCAD finds the 1g cube with highest average SAR by running a search algorithm in the areas with high SAR.

SAR is well defined and rather easily investigated for transmitters with one antenna. But, MIMO configurations is more complicated, though. When more than one antenna is included, each antenna must first be measured separately. The distance between the antennas as well as the distance between the maximum SAR locations will both have an impact on if the mobile phone passes the limit or not. For example, as long as the sum of the two antennas SAR does not pass 1.6W/kg, there is no need to do any more measurements or calculations.[15] If the antennas get a SAR above 1.6W/kg, the Antenna Pair SAR to Peak Location Separation Ratio have to be decided. This ratio should be below 0.3 in order to pass the SAR requirements without running any simultaneous transmission tests. Simultaneous test are more difficult since they need to take in to consideration the way the protocol works.

2.2.2 HAC

HAC stands for Hearing Aid Compatibility and is a rating for mobile phones that says how well it will work together with hearing aids. All mobile phones do not need to pass HAC limits, but there is a percentage of all phones sold by a manufacturer that must pass it. There are two different types of ratings, one for hearing aids operating in acoustic mode and one for hearing aids containing a telecoil. The ratings are called M1-M4 and T1-T4 respectively. [12] This report will investigate antennas HAC rating for hearing aids operating in acoustic mode with a goal to reach M3 or M4.

2.3 About Antenna Design

2.3.1 Broadband Analysis

Theory and mathematical models for electromagnetic waves and antennas are almost always expressed for single frequencies, with limited ability to make predictions and theoretical designs for complete frequency bands. However, cell phone antenna design is heavily dependent on good radiation performance over multiple frequency bands. Therefore, antenna design is strongly dependent on numeric simulations. That is, calculating antenna element lengths from theoretic models has a very limited usage for cell phone antennas. It's possible to approximate the size of the antenna directly from theory, and theoretic arguments are used for motivating trials of new design elements. But, most of design choices will have to be done from previous successful design methods and numerical analysis methods. Due to the complex nature of the equations, it's practically impossible to calculate the optimal lengths for the elements in a design, they have to be found by numerical optimization. The project have relied on results from related research papers and numerical parametric analysis. Optimization methods were tried but replaced by parametric sweep approaches due to the discreet nature of the sizes of the available inductors and conductors needed in the design.

2.3.2 Small Antennas, Microstrip Antenna

Dividing antennas in two groups, large and small when compared to its wave length, would place a handset antenna in the group of small antennas. The design in this project is approximately one fourth of the longest wavelength it will radiate. The main difference of small and large antennas is the possibility to achieve high gain, large antennas can have gains of 40dBi or more, while small antennas usually have a gain close to 0dBi. Actually, another common grouping of antennas is directional and omnidirectional. This separation would put small antennas in the omnidirectional group. However, since cell phone antennas are used in multi-path environments without being directed in any special direction, it would actually compose more of a challenge to get good and stable performance if the gain is high. For example, consider a cell phone user lying on the beach using a high gain antenna. He would be forced to hold his cell phone in the right direction to be able to make and receive phone calls.

2.3.3 MIMO Antennas

Mobile phone antennas are mainly used indoors in urban environments and will therefore usually exhibit strong fading due to multipath propagation. Buildings, walls, cars etc. in the environment reflects the signal, so that the received signal will arrive from many directions, with different polarizations and at different times. The effect of this fading is strongest when there is no Line Of Sight (LOS) between the sender and receiver, which is the most common case for mobile phones and mobile base stations. The dips, from destructive interference, in the signal strength will decrease data traffic speed and might even break phone calls. A method to handle this problem is to use antenna diversity. Antenna diversity in LTE mobile phones is realized by a MIMO system where the mobile phone has at least two antennas. These two antennas connect to one or more antennas at the base station in order to create more than one communication channel between the phone and the station. The antennas in the mobile phone need to give rise to diversity, so they are required to differ in the way they send the signal to the base station. This diversity could be reached by for example letting one antenna send with a polarization orthogonal to the other one, or simply by having the antennas separated in space, and thereby letting the different paths through the environment give rise to the diversity.

Diversity performance can be affected by many factors, such as the antenna radiation pattern and the antenna positioning. The radiation pattern seem to have small effect though, Per-Simon Kildal concluded that it does not improve diversity performance to combine element ports with wide beams to obtain the same number of beam ports with narrower directive beams.[16] Furthermore, Frank M. Claimi and Mark Monegomery concluded that it's mainly the phase difference not the gain of radiation pattern that decide how correlated two antennas will be. [17]

3

Modeling and Simulations

3.1 Ansys HFSS

When a model is designed, HFSS has an electromagnetic wave solver to solve for example return loss on the antenna ports and radiation efficiency. The methods used are 3D full-wave FEM with a PML-box boundary condition.

When one has values for all the field points at two time adjacent time slots, discrete versions of Maxwell equations is established for all the points and solved to give the fields in the upcoming time slot. The software is told to continue refine the simulation until every iteration will not change the value of the S-parameters by more than a limit delta S supplied by the user.[18] A picture of a calculated mesh in HFSS can be seen in figure 3.1.

3.1.1 PML

When solving electromagnetic problems by FEM one needs to limit the solution to an volume, this is simply due to the fact that it's impossible to do a mesh of infinite space. Simple electromagnetic problems could be solved without encapsulation by utilizing for example periodicity. But, the most general electromagnetic problems need a box encapsulating the area, allowing the calculations to be done only within that area. An earlier solution to this was to use absorbing boundary conditions (ABC), that perfectly absorb in one dimension. These absorbs the outgoing wave so that there is no need to calculate anything outside the box. However, a more modern solutions used in the simulations during this project is perfectly matched layer (PML). Perfectly matched layers are absorbing layers which have a theoretical reflection coefficient of zero. [19]

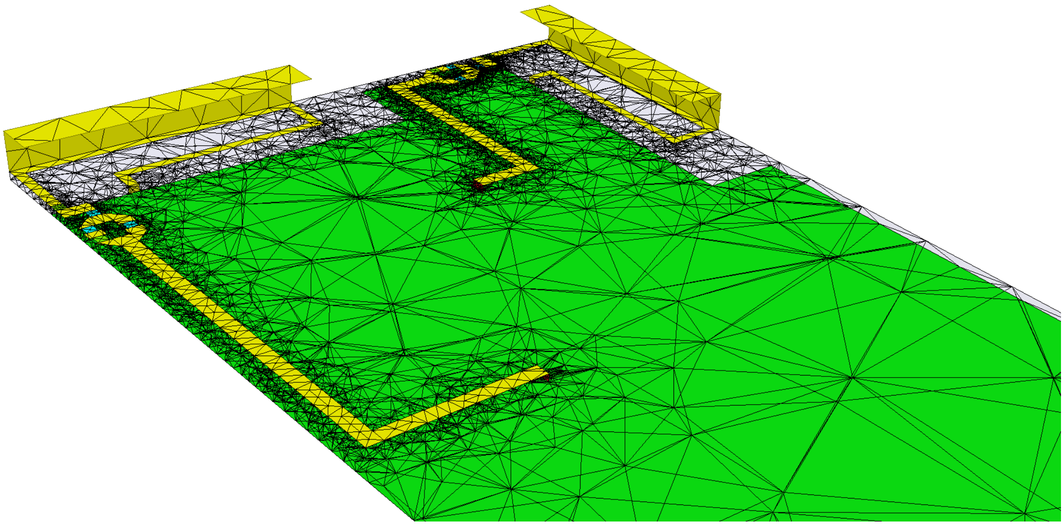


Figure 3.1: *A mesh for FEM calculations with HFSS. Notice how the mesh structure is denser in the areas with finer detail.*

3.2 SEMCAD

The design in HFSS can be exported to an ASCIS SAT model, that can be imported into SEMCAD. However, the ASCIS SAT model only contains the geometry of the antenna, not material parameters, lumped element settings or port settings. Therefore, some work needs to be redone inside of SEMCAD.

The solver in SEMCAD is a FDTD solver, where the grid is square boxes defined by the user. A head phantom is provided by the software providers to do measurements of the amount of absorbed radiation. SEMCAD is used to assure the mobile phone will radiate within safe radiation limits (SAR) and will be able to use together with hearing aids (HAC).

The SEMCAD calculations are done on a computer equipped with a Nvidia TESLA C2075 GPU Computing Processor. This brings the calculation times down from approximately one month to a few days.

4

Production Process

4.1 CAD Layout

In order to make a Printed Circuit Board (PCB) with the microstrip antenna on, a mask first need to be made. In order to get an accurate mask, the circuit is first redrawn in AutoCAD. Two patterns need to be drawn, one for each side of the PCB. Furthermore, in order to be able to align the two masks, some markers are added to the design. These markers will later be removed in an intermediate state of the etching production phase. Finally, the two layouts are printed out onto a semi translucent paper.

4.2 Etching Process

The antenna is produced on a double sided PCB. See figure 4.1, for an overview of the PCB production process. The dielectric chosen was a 0.8mm FR-4 (Woven glass and epoxy). The pattern of the antenna and the ground plane were first printed on translucent paper, where black areas represent areas that are supposed to be metal. Then, these two patterns are placed around the PCB and put inside a UV vacuum exposure unit, where a vacuum is used to ensure the patterns and PCB are in close contact. Then, the UV light will shine through the unpainted parts of the translucent paper and expose the photo sensitive layer of the PCB. Afterwards, the exposed parts are then washed away with a NaOH solution, allowing for some last adjustments to be done before the metal is etched away. For example, at this stage, some holes in the ground plane resist was repaired with scotch tape and a the lines solely there for making it easier to align the antenna and ground plane were also removed. Finally, the board is put inside the etching machine, which removes all uncovered metal areas and results in the final product.

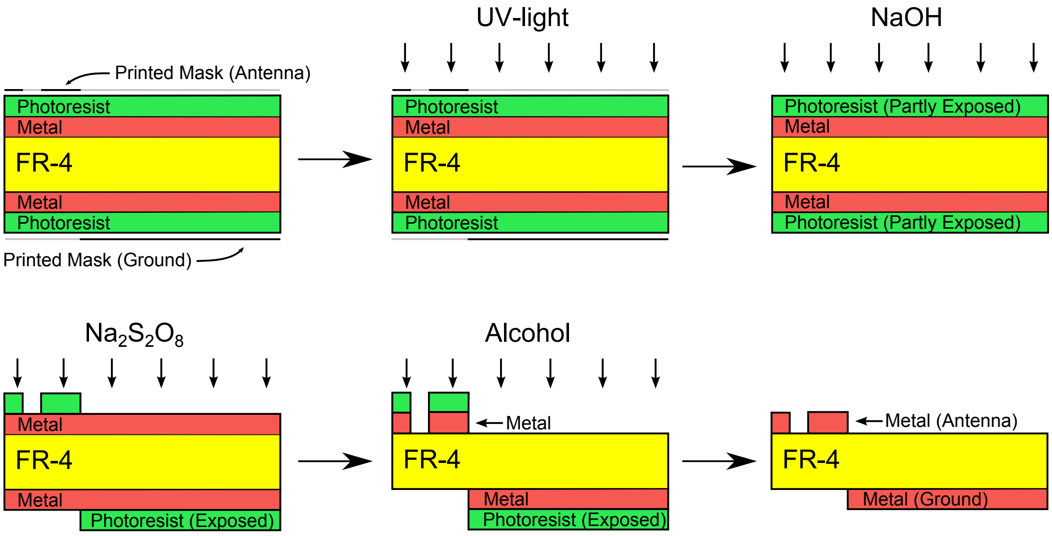


Figure 4.1: *The step by step process of developing the microstrip antenna on the PCB.*

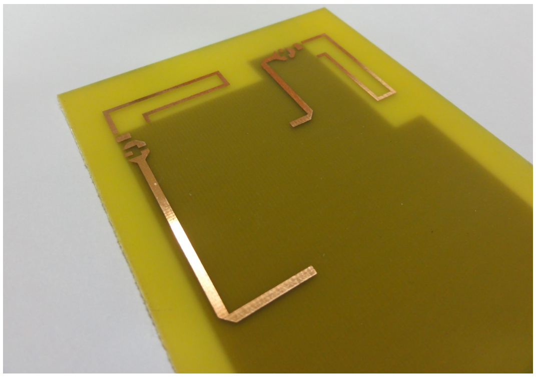


Figure 4.2: *A finished PCB. The next step is to cut the board.*

4.3 Soldering and Packaging

With a finished PCB, it's time to mount all lumped elements and any 3D structures of the antenna. The lumped elements used during this project are from Walsin Technology Corporation and come in a certain set of configurations, setting a constraint on the design. The capacitors come in 0.5pF, 1pF and then incremental sizes adding 20% each step. Likewise, the inductors come in 1nH and then in incremental steps of 20% per step. The elements are 1mm long and less than $0.5mm^3$ in volume. Since the design and simulations are all done for 2D elements and strips, it's important to keep the use of solder to a minimum. The case is made in translucent plastic and the antenna is rigged in the right place with the help of light weight plastic.

5

Characterization

5.1 Return Loss

The return loss is measured with a Network Analyzer. The one used in this project is the PNA-L Network Analyzer N5230C from Agilent Technologies. For the measurement, one port, or both ports for MIMO, is connected to the Network Analyzer which performs a S-parameter analysis. From this analysis, not only the return loss of the antennas is given by S_{11} and S_{22}, but also the isolation is achieved from S_{12}.

5.2 Anechoic Chamber

The antennas radiation pattern is measured in an anechoic. The one used for this project was a couple of meters wide and long. The chamber is isolated on the inside so that it absorbs most of the radiation from the antenna. That is, just like the case for numerical simulations. However, the main point in doing measurements in a chamber is to isolate the measurement from the surrounding. This is achieved by the chambers outer walls, which are metal.

In one end of the chamber, there is a horn antenna that receive the radiation from the antenna. The antenna on the other hand is mounted in the other end of the chamber on a structure that can turn the antenna around all axis. The measurement is done by letting the antenna radiate over a frequency sweep with a uniform selection of all possible angles to the horn. By comparing the result to a calibration run, the radiation pattern of the antenna is received. Finally, together with knowledge of the input power to the antenna, it is possible to calculate the efficiency of the antenna.

5.3 Reverberation Chamber

Anechoic chambers are the most common reference environment when characterizing antennas, however, it is very far from the urban environment that mobile phones are usually used in. Measuring performance of a MIMO antenna requires a multi-path environment and is therefore preferably done with a multi-mode reverberation chamber. A reverbation chamber can measure both radiation efficiency, diversity gain, correlation and channel capacity.[20]

Experiments could be done in a natural multi-path environment, but in order to make reproducible experiments, a multi-path reference environment is needed. This reference environment should be isotropic, rich (where rich means it should give hundreds of incoming waves to the Antenna Under Test, AUT) and with low LOS coupling compared to the coupling from the environment. A multi-mode reverberation chamber supplies such an environment.[21] The reverberation chamber is large enough to support many modes giving rise to many incoming waves to the antenna and the amount of different modes is then increased by mode stirring. Example of different ways to alter the ways the antenna receives signal from the chamber is rotating the antenna under test and moving plates along the walls, ceiling or floor inside of the chamber in order to excite different set of modes. In order to get a polarization balance one can use three orthogonal polarized chamber antennas, making sure all polarizations are present in the experiment. One method to decrease the LOS coupling is to make sure that the AUT is in a minimum of the chamber antennas radiation pattern. This kind of chamber has a good isotropic angle of arrival distribution and polarization balance. [22]

6

Results

6.1 Design Modifications

The original antenna design by Kin-Lu Wong manage to resonate at the 0.25λ mode, 0.5λ mode and 1λ mode by the use of an LC matching circuit.[2] The antenna was modified in two steps to reach the wanted frequency bands, see the illustration in figure 6.1. The band-stop filter[3] adds a sharp resonance at 1GHz broadening the low frequency band and the bending increases high frequency bandwidth. The bandwidth increase is due to the occurrence of a current peak in that area. A broader channel at a position will give a smother impedance behavior at that mode.[23]

A full view of the first design without MIMO can be seen in figure 6.2. The case is 1mm thick and there is a gap of 1mm between the case and the antenna.

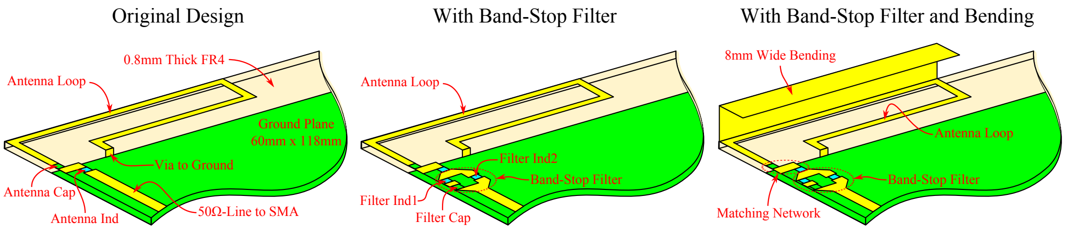


Figure 6.1: *The two changes made to the original design in order to reach the wanted frequency bands.*

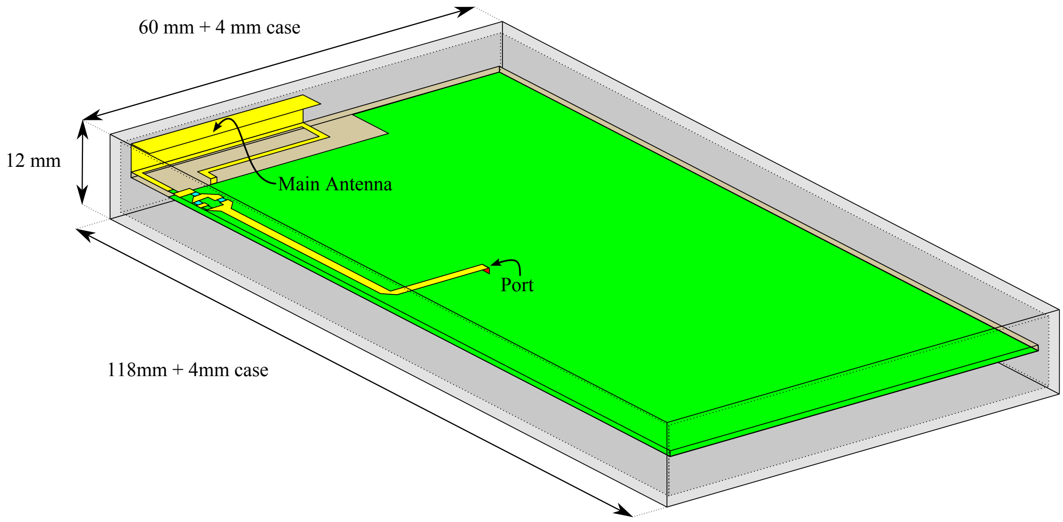


Figure 6.2: *The final antenna design in single antenna configuration.*

6.2 Parametric Analysis

The antennas behavior is changing depending on many parameters. The antennas behavior while varying different lumped elements can be seen in figure 6.3. The Antenna Cap affects the first resonance at $\sim 830MHz$ and the resonance at $\sim 1800MHz$. The Antenna Ind affects almost only high frequency. Primarily the resonance at $\sim 2500MHz$ is affected, but the other high frequency resonance is also noticeably affected. Changing the Filter Cap only affects the resonance created by the filter.

The antennas behavior under varying different structures can be seen in figure 6.4. Changing the length affects the whole curve, except from the mode created by the filter. Changing the Y-Gap affects primarily the $\sim 2500MHz$ resonance. Changes to the Z-Gap affects primarily the $\sim 2500MHz$ resonance and also slightly at the $\sim 830MHz$ resonance. Varying the Bending Width changes the high frequency bandwidth and the matching in the $\sim 830MHz$ and $\sim 1800MHz$ resonances.

In order to get as good return loss as possible, a parametric sweep, varying all parameters, was run. The antenna component values and the antenna structure were first modeled with variables. Then, HFSS was set to run simulations for many different combinations of values on the variables. However, trying out for example four different values each for seven different variables results in $4^7 = 16384$ simulations. The computer used during the project needed approximately 4 minutes to do one simulation. That means, running four values for each one of the seven different variables would take 45 days. Therefore, most parametric runs was done with approximately three values for six variables, resulting in a run time of $3^6 * 4minutes = 2days$ $(729simulations)$. Mathematical expressions were established in HFSS to sort out the simulations with the lowest possible Return Loss within the wanted frequency bands.

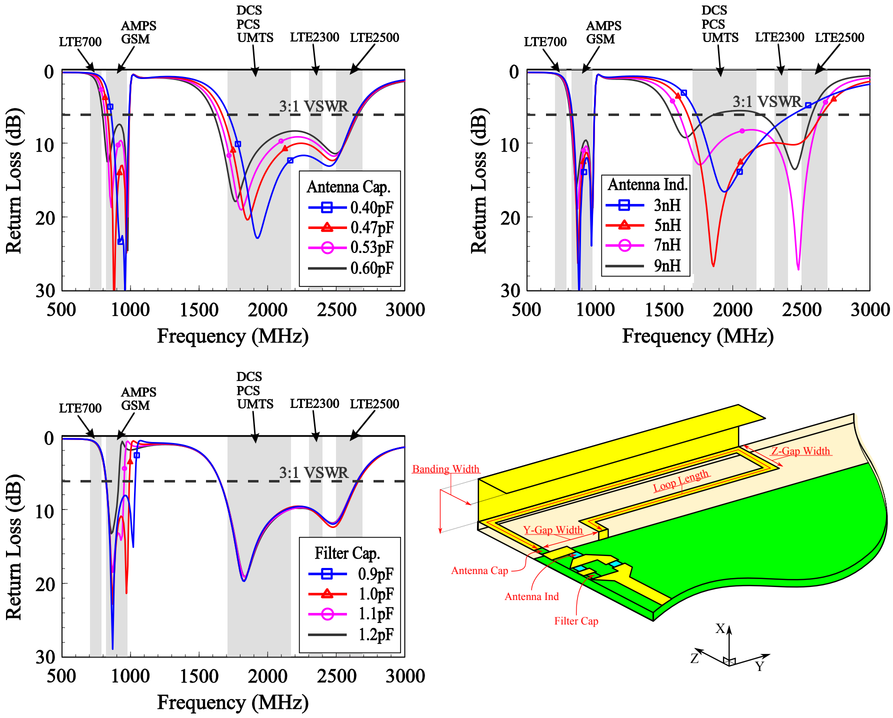


Figure 6.3: *Changes to different element values have different impact on the antenna.*

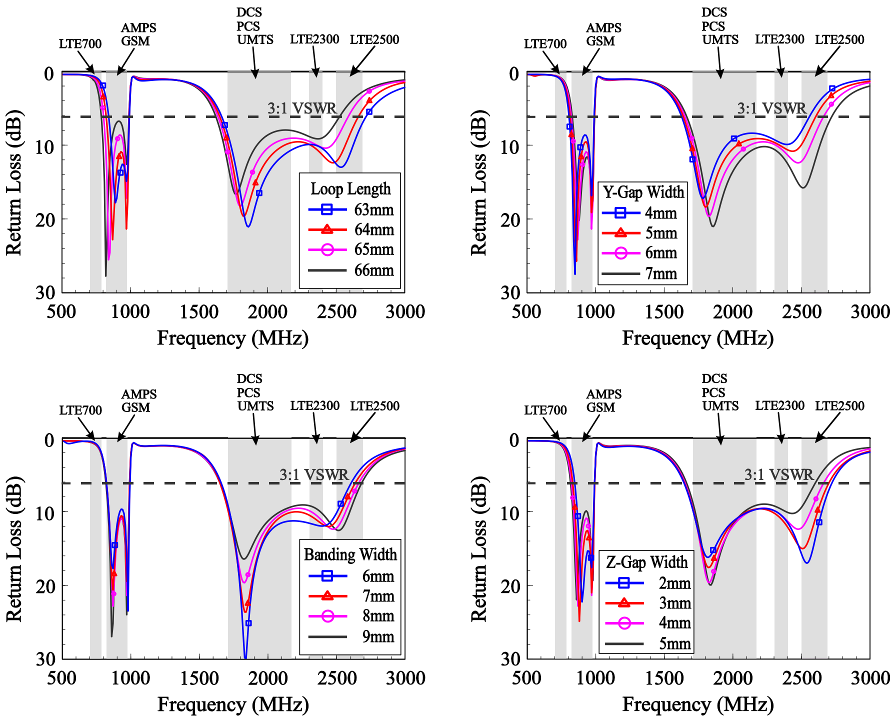


Figure 6.4: *Changes to different structures have different impact on the antenna.*

6.3 Statistical Analysis

A statistical analysis with varied lumped elements was done in order to know the stability of the design. The lumped elements used for the production have a tolerance of $\pm 0.1pF$ for capacitors under $10pF$ and $\pm 0.3nH$ for inductors under $6.8nH$. Larger capacitors and inductors both guarantee a tolerance of $\pm 5\%$. The distributions of parameter values was assumed to be a truncated Gaussian distribution where the tolerance values were set to two standard deviations away from mean. The result of the selected lumped element values can be seen in figure 6.5. A total of 1174 totally unique runs was simulated, requiring 64 hours of simulation with a Intel Core 2 Duo E8400 @ 3.0GHz. S_{11} was evaluated at 0.82GHz, 0.96GHz, 1.71GHz and 2.69GHz, which are the borders of the two frequency bands of the antenna. They should ideally be -6dB or lower. The result of the statistical analysis can be seen in figure 6.6. From the graphs, it's worth noticing the rather high probability that 8.2GHz will be over -6dB and how big variation there is at 0.96GHz. Moreover, 1.71GHz gets below -6dB for all variations and 2.69GHz has a Gaussian variation with very small standard deviation. In conclusion, errors due to the lumped elements are probable to arise at 0.82GHz, but will probably not have any big effect of the other borders. The number of trials that got above -6dB at 0.82GHz is $225 + 210 + 140 = 575$ which corresponds to 49% of the variations.

All the resulting return loss curves plotted at the same time can be seen in figure 6.7. It does not give as deep insight in the analysis as the histogram, but it gives a better overview of how the performance will vary.

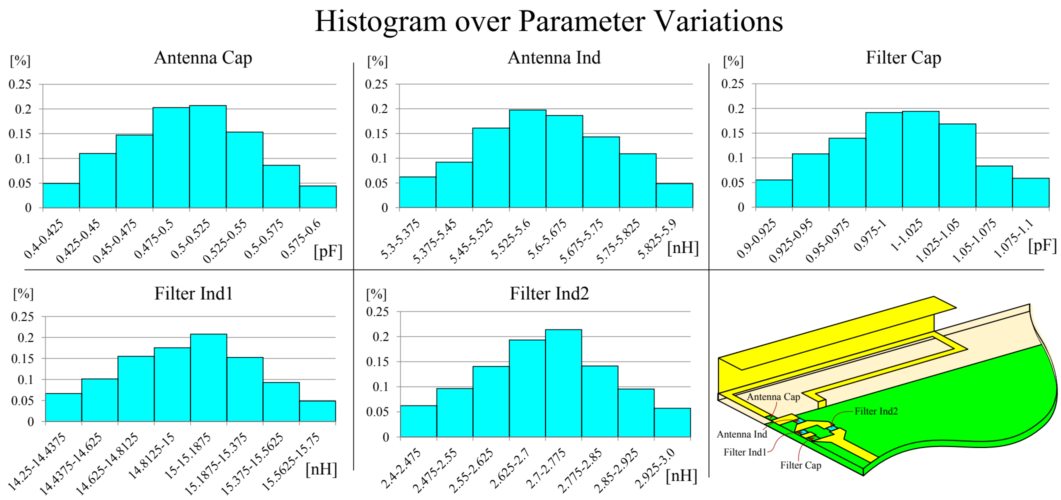


Figure 6.5: *The result of the randomized selection of truncated Gaussian distributed values of the lumped elements. Total number of different values of each element is 1174.*

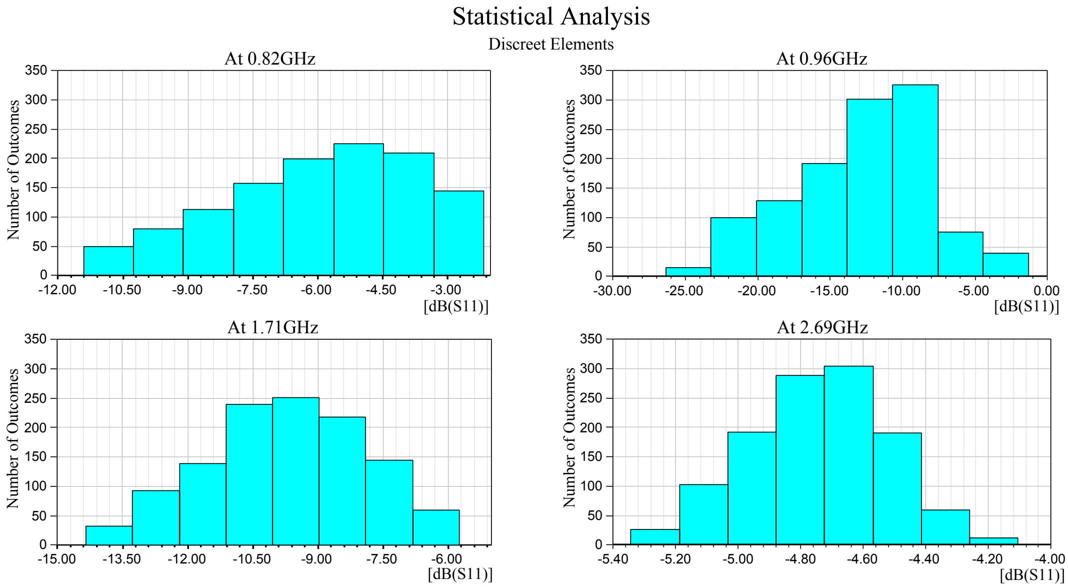


Figure 6.6: *A statistical analysis of S11 at the frequencies at the corners of the two emitting and transmitting frequency bands.*

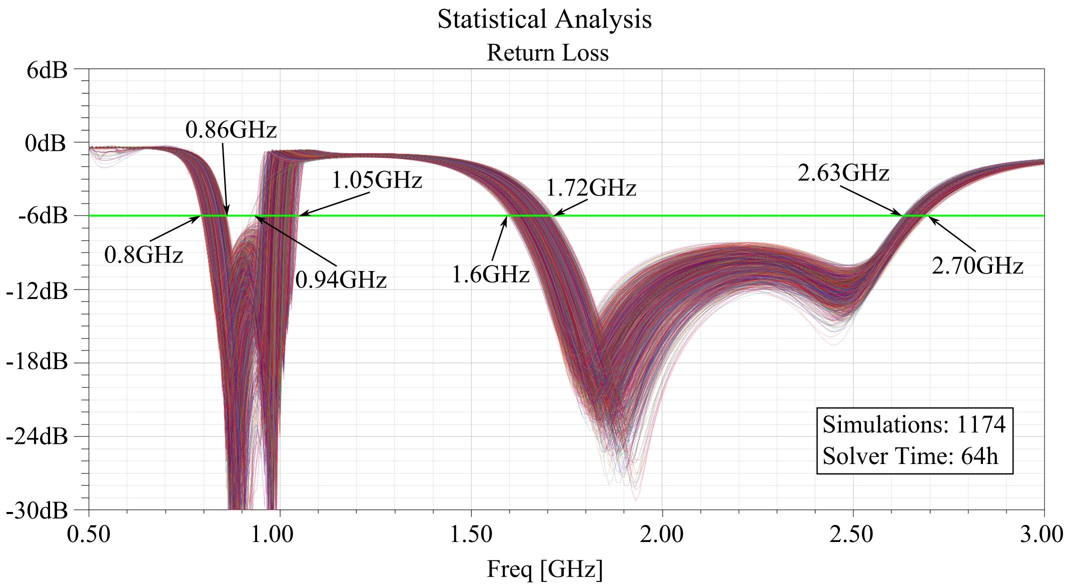


Figure 6.7: *A simulation of the return loss that can arise from the error in the values of the lumped elements. The component value variations are all within the tolerances given for the lumped elements used for construction.*

6.4 MIMO Design

When deciding how to put the aux antenna, three aspects were considered. First, the isolation between the aux and the main antenna. Second, the possibility to pass SAR and HAC limits. Third, the expected diversity achieved by the configuration. Four different positions for the aux antenna can be seen in figure 6.8. The isolation for configuration (b) and (d) is too weak and the possibilities to pass SAR and HAC for (c) is low[4], so the final configuration used is (a), where the limits for SAR and HAC should be possible to pass since both antennas can be placed far from the ear and the isolation is also acceptable. Furthermore, the diversity is also expected to be better than the more symmetric configurations (b) and (d).

The strange shape of the return loss curve of configuration (d) is probably due to coupling between the antennas. An analysis of the current densities in the antennas when only the main antenna was operating showed that the aux antenna had the highest currents, even though the aux port was terminated.

In order to further increase the isolation at low frequencies, different kind of cuts in the ground plane was tried without any success. Adding metal structures in-between the antennas did not have any effect either.

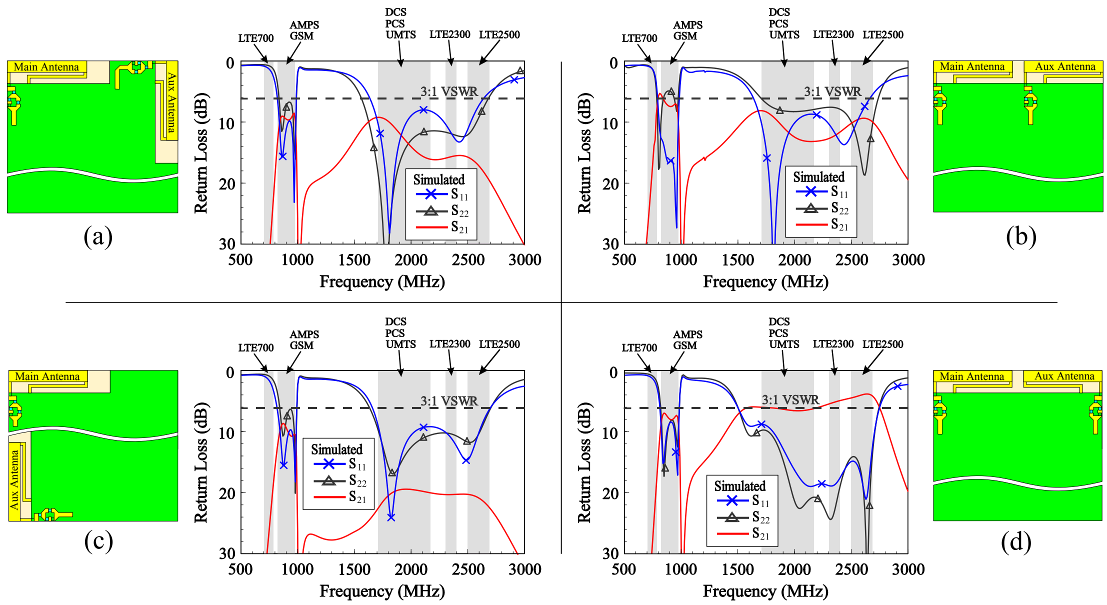


Figure 6.8: *The S-parameters for different positions of the AUX antenna. Configuration (a) was used for the final design, due to good isolation, good expected SAR and HAC, and good expected diversity performance in MIMO operation.*

6.5 Tuning Technique

Tuning was added to reach the LTE700 band. The solution required both antennas to be tuned in both ends, adding quite much complexity to the design. The changes consists of adding an inductor in series to the end of the loop, removing the Antenna Ind and changing the center frequency of the band-stop filter, see figure 6.9. The final values of the components found can be seen in table 6.1. The component positions are the same as in figure 6.5.

Measures of efficiency show that the main antenna in a MIMO configuration has lower efficiency than if the main antenna is used alone. This suggests that the aux antenna is absorbing energy, so some simulations of the main antenna efficiency during different matching of the aux antenna was tried. Making the port 2 open instead of terminated had very small effect, but detaching the whole antenna, that is, remove the via connection and the Antenna Cap did a great increase in efficiency. The efficiency increased with $\sim 15\%$, see figure 6.10.

Table 6.1: *The component values for the tuned antenna. Main antenna to the left and aux antenna to the right. Antenna Ind is removed and shorted.*

Component:	Value:	Component:	Value:
Antenna Cap	0.5pF	Antenna Cap	0.38pF
Antenna Ind	N/A	Antenna Ind	N/A
Filter Cap	1.2pF	Filter Cap	1.2pF
Filter Ind1	18nH	Filter Ind1	18nH
Filter Ind2	6.2nH	Filter Ind2	6.2nH
Antenna End Ind	7.5nH	Antenna End Ind	9.3nH

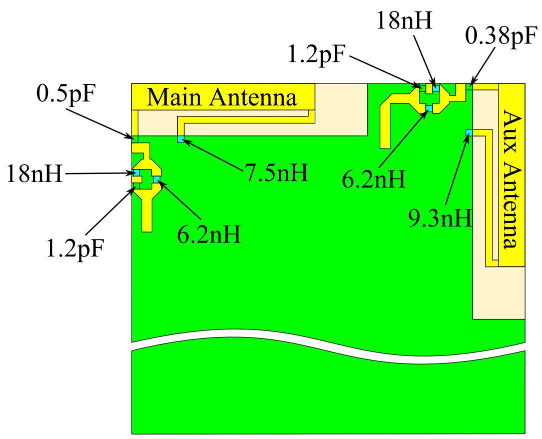


Figure 6.9: *The antenna design when tuned to reach LTE700.*

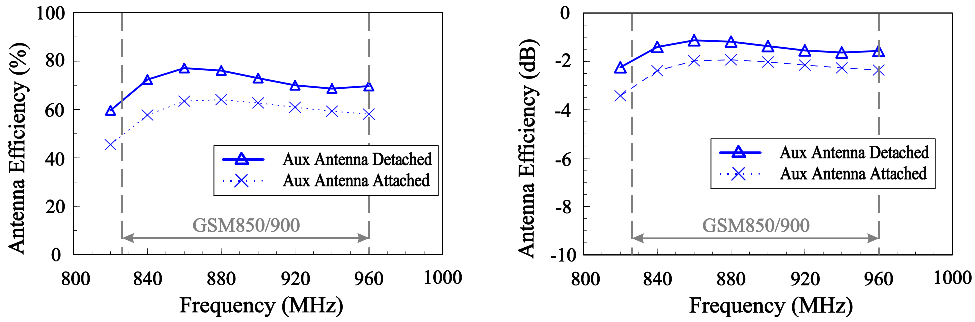


Figure 6.10: *The increase in antenna efficiency of the main antenna when detaching the aux antenna is approximately 15%. The efficiency expressed in % and dB are both shown.*

6.6 Design For Production

The final layout with MIMO can be seen in figure 6.11. That is the design for seven bands which is chosen to be produced. The details of the design of the MIMO enabled antenna can be seen in figure 6.12. The ports were separated so that two thick SMA connectors can be connected at the same time. The mitered bends in the 50Ω microstrip lines are calculated to have optimal performance with the equations supplied by R.J.P. Douville and D.S. James.[24] The final antenna design has the measures $8mm * 4mm * 28mm = 0{,}896cm^3$, well below the pursued size of $< 1cm^3$.

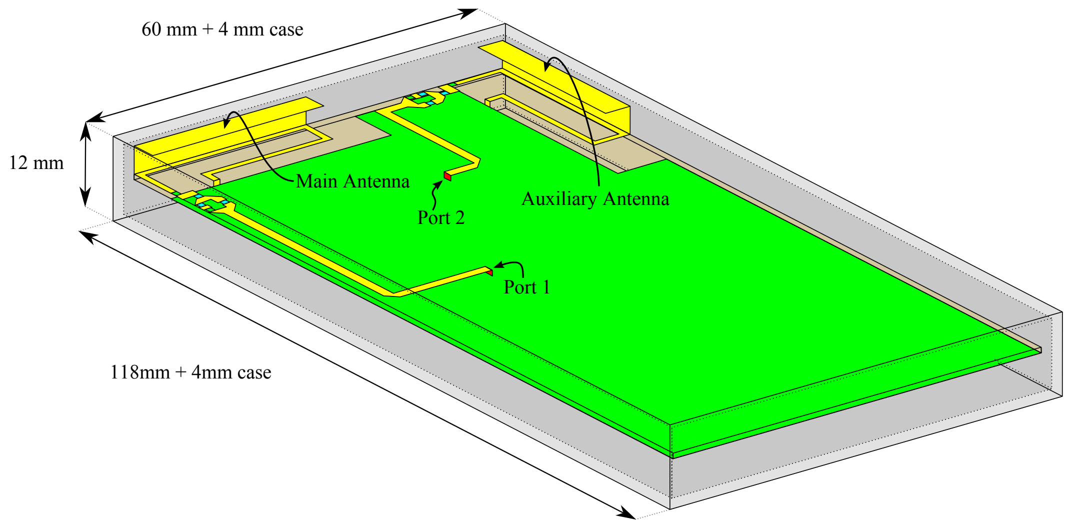


Figure 6.11: *The antenna design with MIMO.*

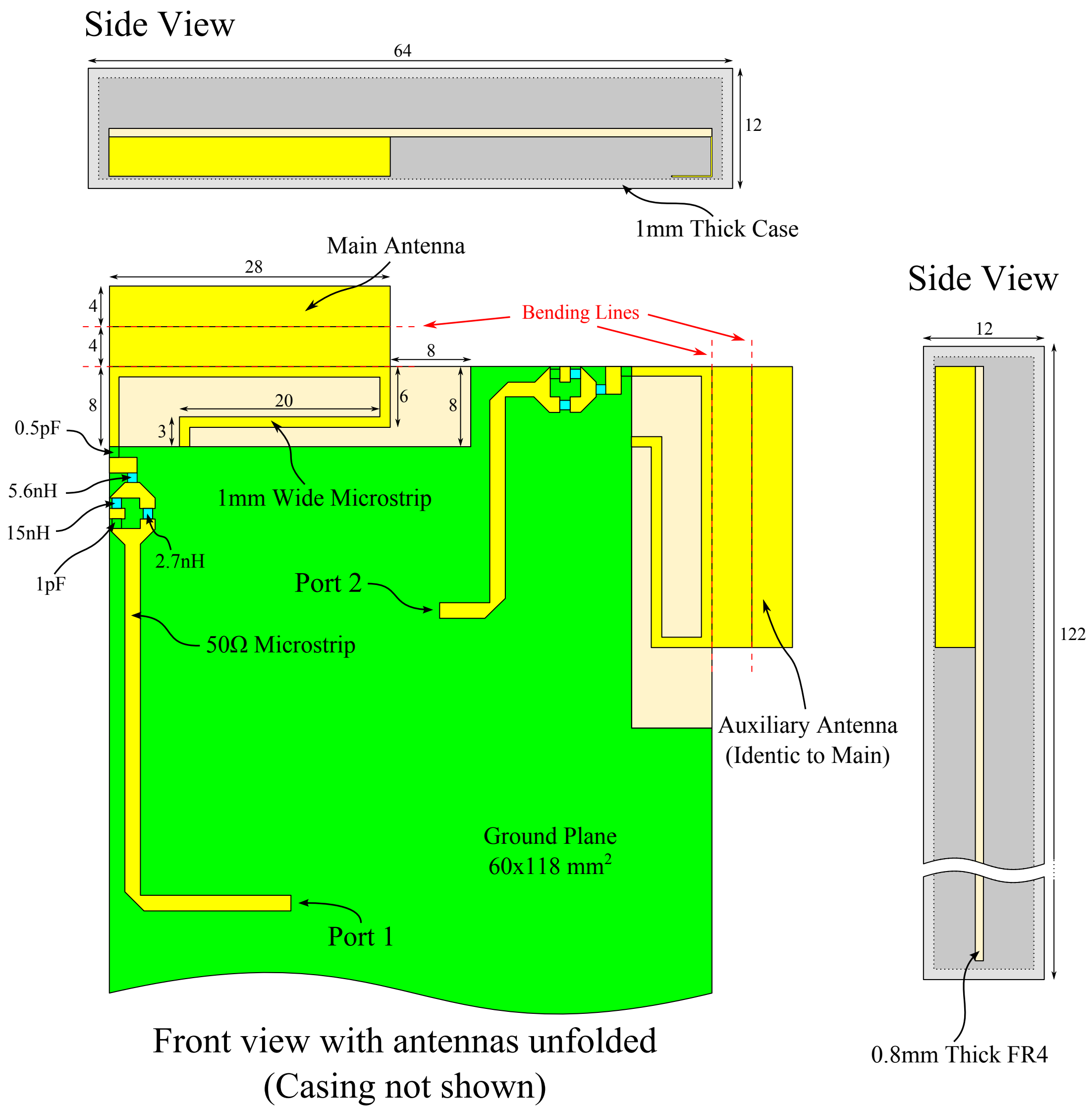


Figure 6.12: *Detailed sketch over the design of the MIMO enabled antenna.*

6.7 Simulations

6.7.1 Return Loss and Efficiency

The simulation of return loss in the 7-band antenna configuration can be seen to the left in figure 6.13. The performance of the aux antenna is only given in the frequency bands that it will be used in. The return loss is a little bit too high at the upper border of LTE2500 and the lower part of GSM850 just passes the design goal of -6dB. The efficiency can be seen in figures 6.14 and 6.15. From the graphs, it is clear that LTE2500 makes it over 50% antenna efficiency, and GSM 850 is just about 50%.

Applying the tuning, one can reach the 700MHz band. A simulation of the return loss of the tuned MIMO antenna at 700 MHz can be seen to the right in figure 6.13. The aux antenna is slightly high in the middle of the band. The efficiency can be seen in figure 6.16. Even though the performance is a bit under 50%, it is still considered an acceptable result since it is a MIMO configuration.

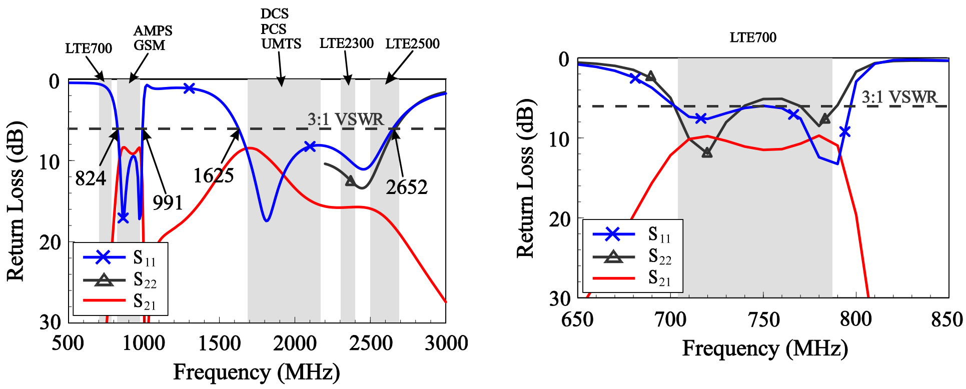


Figure 6.13: *The simulated return loss for the MIMO configured antenna. Results from the tuned design is to the right.*

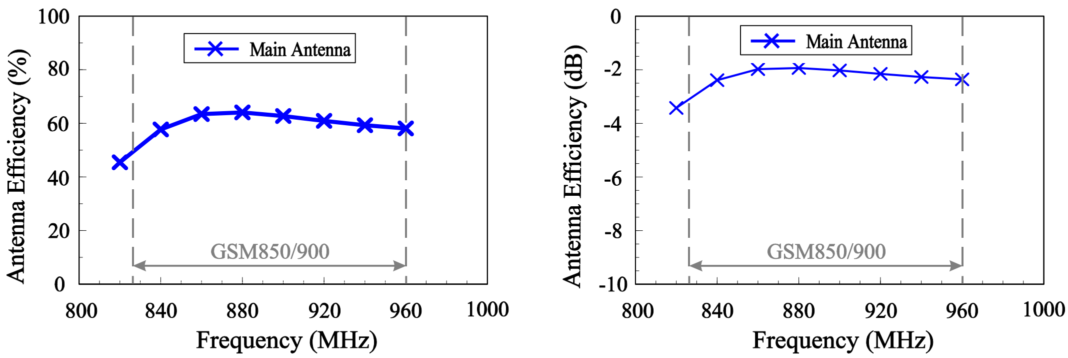


Figure 6.14: *The simulated efficiency for the MIMO configured antenna at GSM850 and GSM900. The efficiency expressed in % and dB are both shown.*

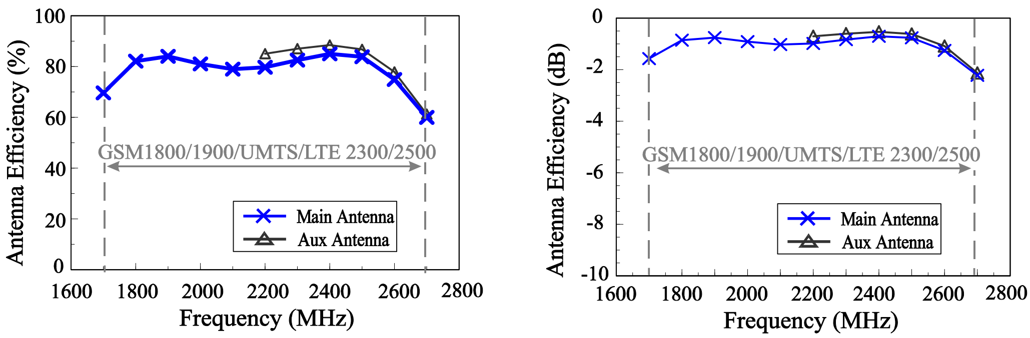


Figure 6.15: *The simulated efficiency for the MIMO configured antenna at the high frequency bands. The efficiency expressed in % and dB are both shown.*

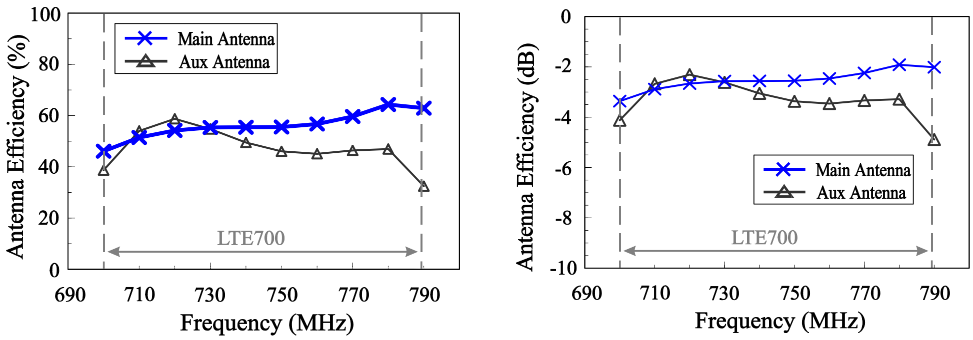


Figure 6.16: *The simulated efficiency for the tuned MIMO configured antenna at 700MHz. The efficiency expressed in % and dB are both shown.*

6.7.2 HAC

The HAC simulations were run with SEMCAD. The model was divided into 55x173x187=1 779 305 voxels, see figure 6.17. The picture does not show the case, ground plane or the FR4. The voxel density is considerably higher by the filters, since there is a slanted design in the microstrip there, which needs smaller voxels to be modeled properly. Accordingly, this also increases the voxel density in the other structures parallel with the filters, resulting in quite an increase in runtime for the simulations.

To confirm that the model gives appropriate results, a frequency sweep was simulated at GSM800/850 frequencies. In this way, it is possible to read the return loss and compare it with the simulation results from HFSS. S_{11} of the antenna calculated with SEMCAD can be seen in figure 6.18. The return loss at 0.9GHz is reported a little bit high, but the two modes of the frequency bands are clearly visible and considered to confirm the design is good enough for doing measurements.

The positioning of the plane where HAC is evaluated can be seen in figure 6.19. To decide the HAC rating, the plane is first divided into nine smaller squares. According to the specification of HAC measurements, the middle square has to be included in the calculation, but three connected squares on the border can be excluded. Then, the

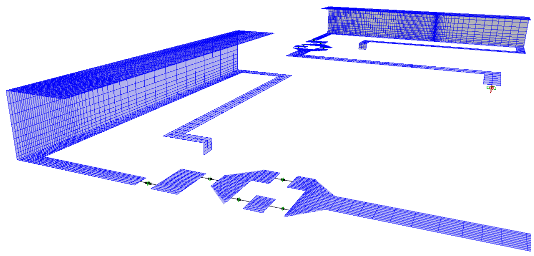


Figure 6.17: *A perspective view of the voxel model of the antenna in SEMCAD. Case, ground and FR4 is not shown.*

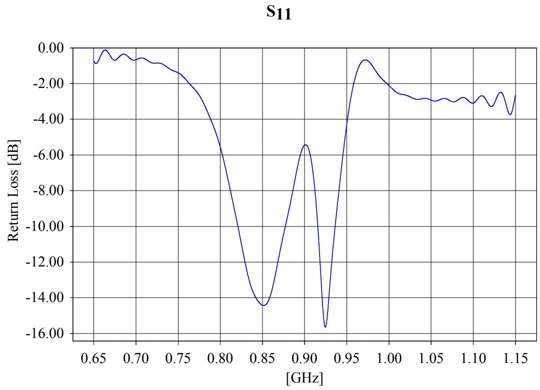


Figure 6.18: *A S-parameter simulation done in SEMCAD.*

HAC rating is determined by taking the maximum value from within the remaining six squares. The plane is at the position where the users' ear will be while talking in the phone. The antennas are placed as far away as possible from the ear. This will decrease HAC a little, but most importantly decrease SAR.[4] The electric field strengths in the plane for 890MHz are shown in figure 6.20. From the picture it is apparent that the HAC is actually caused by the border of the ground plane, not directly from the antennas. This is expected since the antennas are behind the ground plane. In conclusion, a more efficient HAC optimization method would be to alter the ground plane, not the antenna.

Simulations was run for one frequency of each frequency band, the result is shown in table 6.2. Most bands got a good rating of M4, but there was three bands that failed the test, that is GSM1900 for the aux antenna and both antennas. However, GSM1900 will only use the main antenna, so it will not stop the mobile phone from getting an approved HAC rating. 2045MHz is very close to 1900MHz, but the 2045MHz band uses UMTS which has lower output power, so it passed all HAC test without problem.

Loop antennas should in theory have lower HAC ratings since they do not have a sharp edge with strong electromagnetic fields. That seems to have been confirmed for this antenna, which produced very good HAC rating.

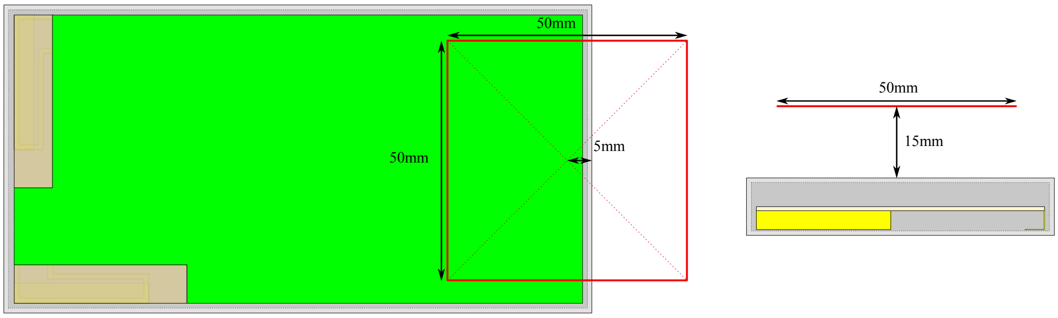


Figure 6.19: *The positioning of the plane where HAC is evaluated.*

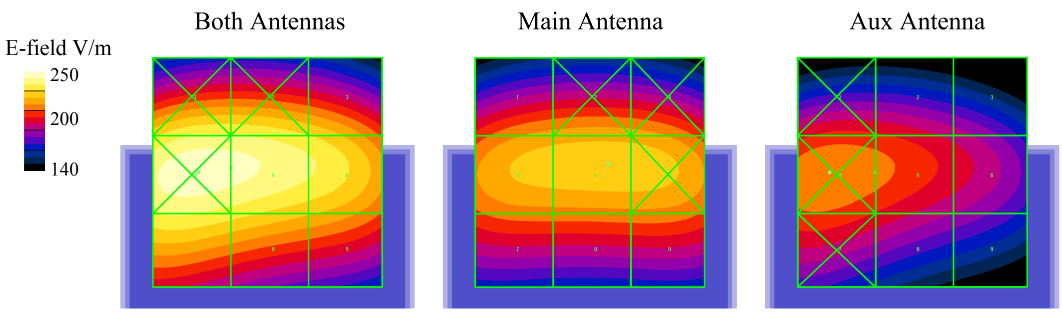


Figure 6.20: *The electric fields from the HAC measurement at 890MHz.*

	Both Antennas		Main Antenna		Aux Antenna	
f [MHz]	*E-field V/m (Category)*	*H-field A/m (Category)*	*E-field V/m (Category)*	*H-field A/m (Category)*	*E-field V/m (Category)*	*H-field A/m (Category)*
890	245 (M3)	0.396 (M4)	226 (M3)	0.282 (M4)	209 (M3)	0.37 (M4)
1900	109 (M2)	0.298 (M2)	72.7 (M3)	0.217 (M3)	124 (M2)	0.44 (M2)
2045	37.7 (M4)	0.129 (M4)	27.3 (M4)	0.095 (M4)	41.2 (M4)	0.131 (M4)
2350	32.1 (M4)	0.097 (M4)	24.4 (M4)	0.073 (M4)	30.4 (M4)	0.097 (M4)
2600	21.1 (M4)	0.067 (M4)	17.3 (M4)	0.055 (M4)	20.0 (M4)	0.069 (M4)

Table 6.2: *The measured HAC for different configurations and frequencies.*

Table 6.3: *The result of the SAR analysis.*

	Both Antennas	Main Antenna	Aux Antenna
f [MHz]	*SAR at 1g [W/kg]*	*SAR at 1g [W/kg]*	*SAR at 1g [W/kg]*
890	1.02	0.81	0.92
1900	0.47	0.22	0.67
2045	N/A	0.22	0.60
2350	0.41	0.25	0.51
2600	0.15	0.11	0.18

6.7.3 SAR

The SAR analysis is done for each antenna separately and for the two antennas transmitting together, see figure 6.3. The SAR values for the two antennas at 890MHz does add up to more than the accepted value. Furthermore, the peak locations of the two antennas SAR were separated by only $2.2cm$ at 890MHz. That gives a Antenna Pair SAR to Peak Location Separation Ratio of 0.79. Hence, more advanced methods is needed to decide whether the antenna can pass SAR requirements or not. However, GSM at 890MHz will not utilize more than the main antenna, so the fact that the measurement for the main antenna is lower than $1.6W/kg$ is enough to give it a pass.

6.8 Production

Soldering was kept to a minimum to get an antenna as close as possible to the computer design. The produced antenna without case can be seen in figure 6.21 and the antenna with case can be seen in figure 6.22. The final produced bending for the main antenna has the measures 28.05mm long, 4.3mm high and 3.85mm wide. The measures for the aux antennas bending are 28.15mm long, 3.8mm high and 3.7mm thick. Furthermore, the first end of the aux antenna bending structure was placed 0.5 mm in onto the microstrip antenna, while the other end was placed by the border of the microstrip antenna. However, it was mounted with very little solder and stood very straight, so no further trials of improvement was done.

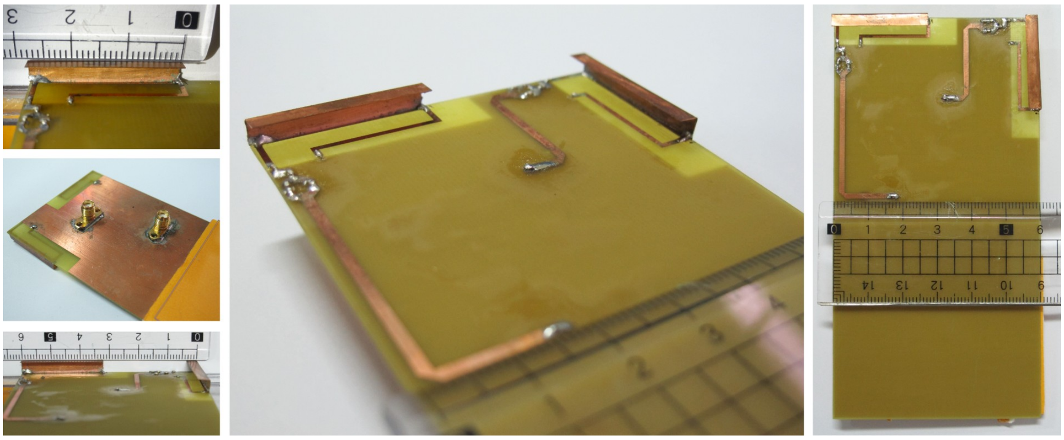


Figure 6.21: *Photos of the antenna without the case.*

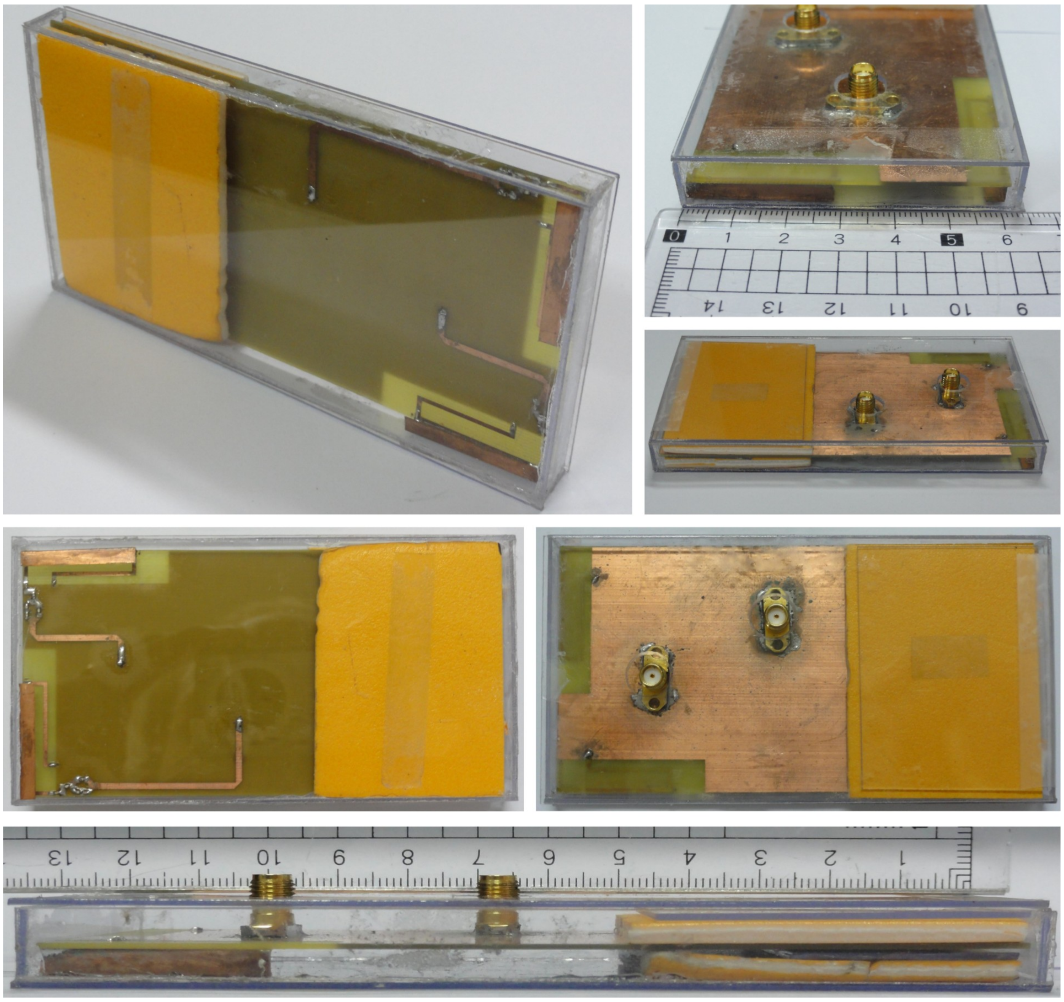


Figure 6.22: *Photos of the antenna with the case.*

6.9 Measurements

6.9.1 Return Loss

The results from the S-parameter analysis of the antenna can be seen in figure 6.23. The main antenna was connected to port 1 and the aux was connected to port 2. Two things worth noticing are that the high frequency got broadened quite much for the main antenna and became narrowed for the aux antenna.

6.9.2 Anechoic Chamber

The antenna was rigged in the anechoic chamber, see figure 6.24. The chamber only supports one antenna to be tested at a time, so the antenna that was not connected was terminated with a 50Ω termination.

The radiation pattern for the main antenna can be seen in figure 6.25 and the one for the aux antenna can be seen in figure 6.26. Low frequencies have a dipole like rotational symmetric pattern, while high frequency shows a more irregular pattern. This irregularity is probably due to the interference with the emission from the ground plane.[4] Not shown in these figures, but also extracted from the analysis is the fact that the antenna radiation only has a noticeable polarization preference at low frequency. The high frequency bands send elliptical or unpolarized radiation.

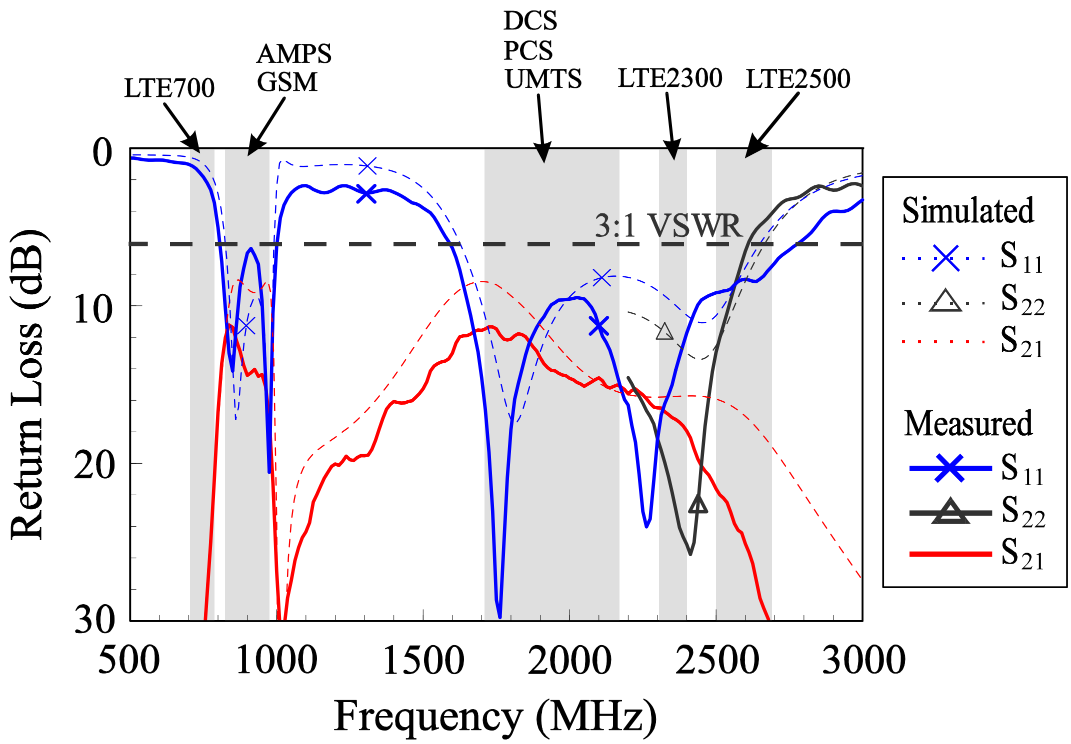


Figure 6.23: *The measured return loss compared to the simulated return loss.*

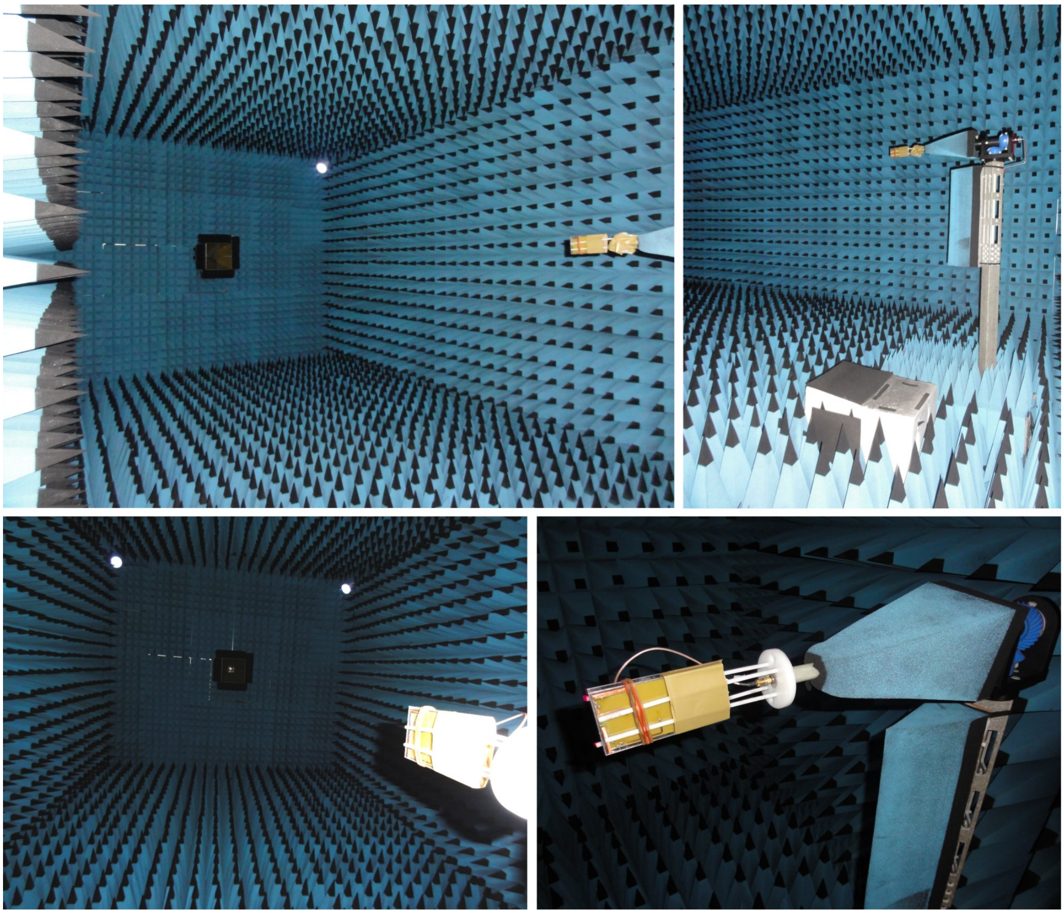


Figure 6.24: *The antenna mounted inside the anechoic chamber.*

The efficiency is calculated from the radiation patterns and the results can be seen in figure 6.27. The low frequency band begins very similar to the simulations and then breaks off. The high frequency band also shows slightly irregular behavior for low frequencies. At the upper frequencies it drops off, just like the return loss measurement. In conclusion, the efficiency is mostly above 40%, with exception of the bands upper boarders. Worth noticing is that the main antenna also has rather low efficiency at LTE2500, even though it has a good matching in the return loss measurements. This suggests that there might be a calibration error of the anechoic chamber at these frequencies. Maybe, the LTE2500 efficiency should be increased by 10% to 20% percent, matching the performance at seen UMTS frequencies.

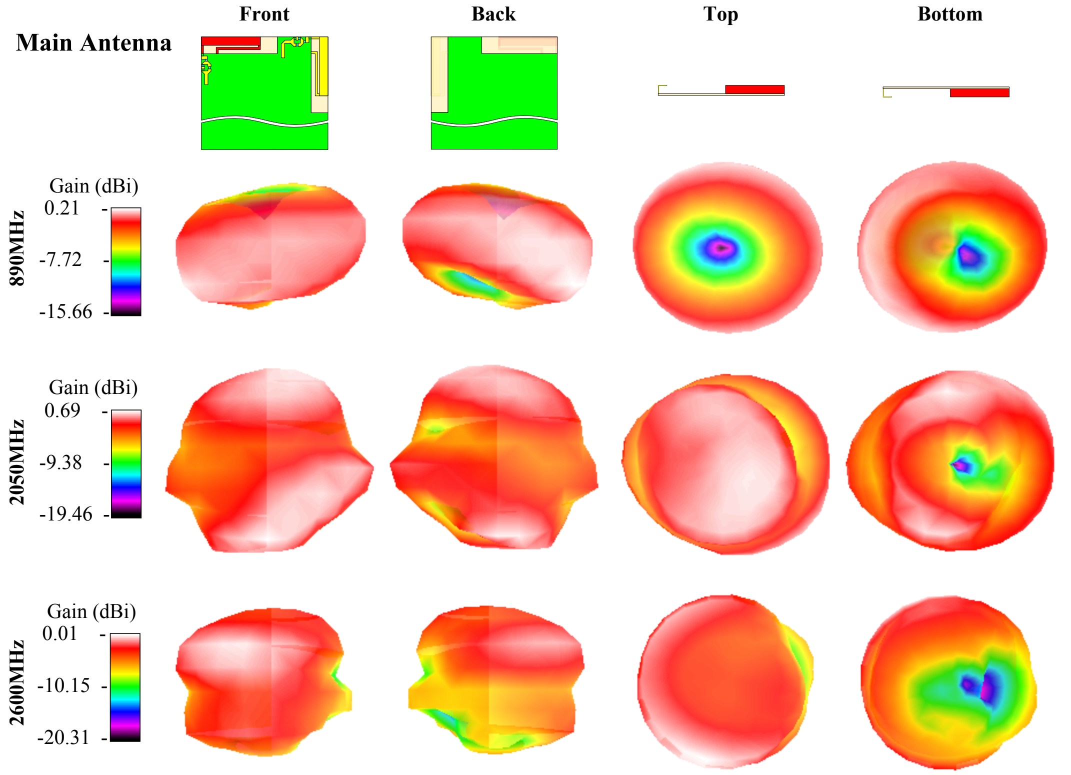


Figure 6.25: *The measured radiation pattern for the main antenna. The measurement was done in an anechoic chamber.*

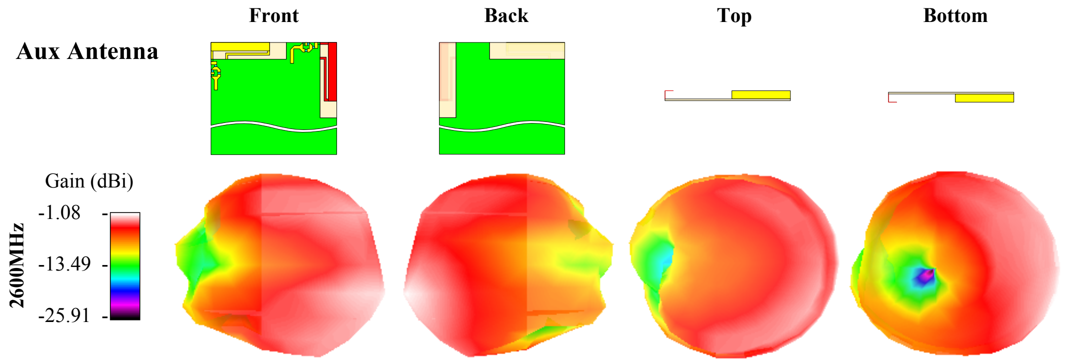


Figure 6.26: *The measured radiation pattern for the aux antenna. The measurement was done in an anechoic chamber.*

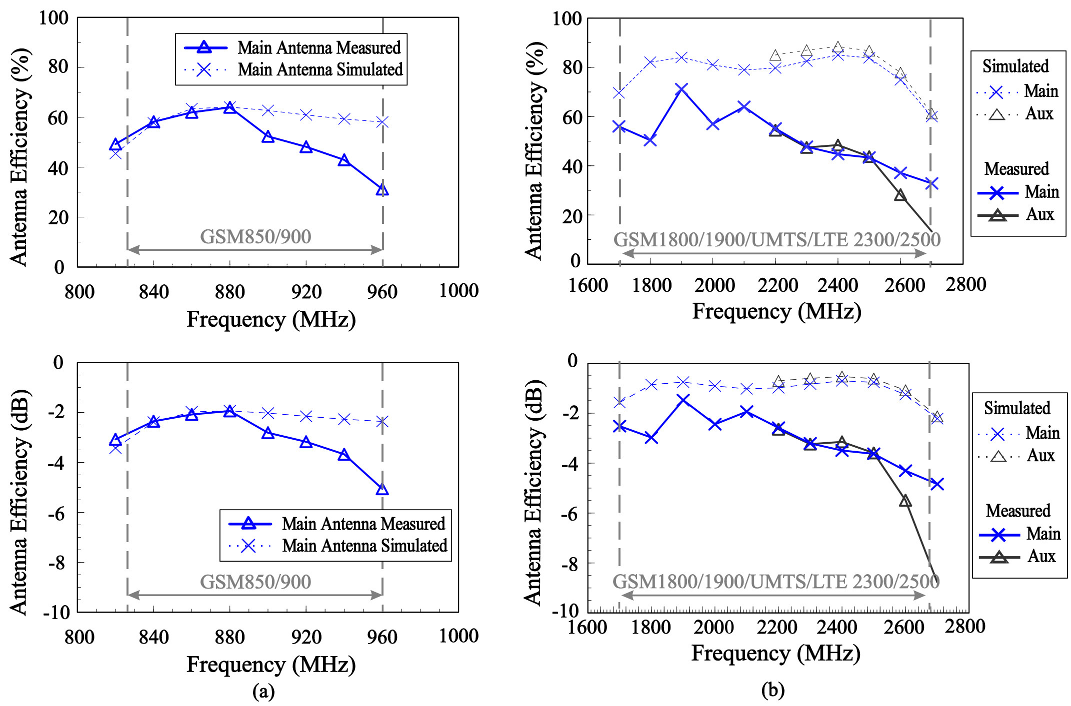


Figure 6.27: *The measured efficiency for the main and aux antenna for GSM850/900 (a) and GSM1800/GSM1900/UMTS/LTE2300/LTE2500 (b). The measurement was done in an anechoic chamber. The efficiency expressed in % and dB are both shown.*

6.9.3 Bluetest Reverberation Test System

The measurement of antenna efficiency at high frequencies was also done with a Bluetest reverberation chamber. The result can be seen in figure 6.28. The efficiencies at high frequencies are a little better according to the Bluetest chamber, around -7dB at 2700MHz compared to -8dB at 2700MHz from the echo-free chamber. A small antenna that radi-

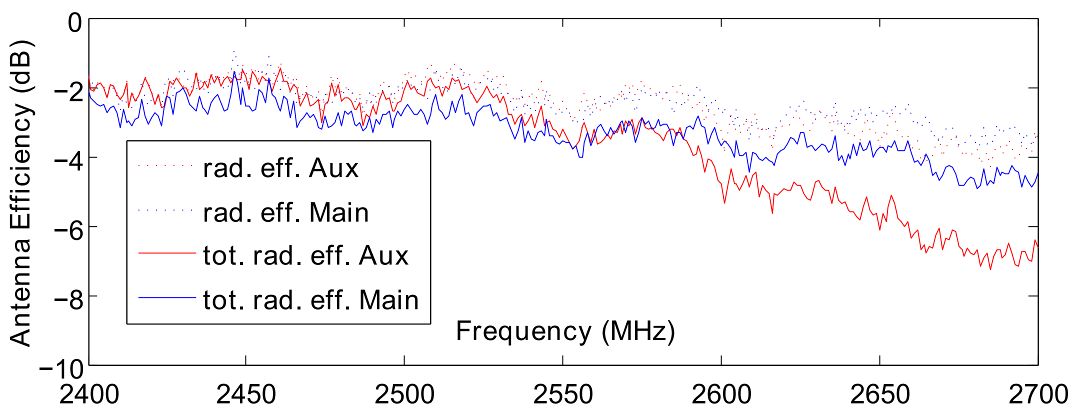


Figure 6.28: *The measurement results from the Bluetest reverberation chamber*

ates isotropically will get affected by the connector and stand in an echo-free chamber. But, in a reverberation chamber, which is already working with reflected waves, this problem does not have such a big impact and the measurement results should be closer to the real performance. However, -7dB is still a very low efficiency though.

7

Discussion

It seems probable to make a tunable antenna supporting 8-bands. The 7-band antenna produced have proven acceptable performance for everything except the upper part of LTE2500. Furthermore, simulations say very good performance should be reachable. The statistical analysis indicated very small variance at that frequency due to errors in lumped elements, so the error is probably not from the lumped elements. Furthermore, the upper part was achieved by adding the bending of the antenna, so the error in the bending positioning and size is probably what cause this error. Calculating the total bending from the measurements of the width of the bending it is obvious that the bending of the main antenna is wider. The main bending was 8.15mm while the aux only had 7.5mm of bending. A possible way to analyze this hypothesis is to do a model more similar to the produced antenna and run some simulations on that model. However, cutting metal plates with sub millimeter precision requires tools not available during this project. Moreover, the likelihood of the bad performance for the main antenna only being a calibration error is confirmed by other users of the same chamber.

The efficiency at GSM850 and GSM900 from the anechoic chamber test had quite unexpected behavior, which could be a sign of a measurement error. But, it also happens to coincide with the frequency that uses the band-stop matching filter. Maybe, the elements in the filter are absorbing a lot of the power. Looking at the parametric analysis in figure 6.3 it seems possible to increase the filters center frequency with up to 100MHz without affecting the antennas return loss more than a little. This might make the losses at GSM900 much smaller.

Reaching LTE700 was possible, but not easily done. There was a need to tune both antennas in both ends. This means that each antenna will need two switches, both causing losses. However, tuning could be used to do many improvements, for example detach the aux antenna in both ends when not used and always select the most suitable antenna even for GSM and UMTS. In fact, this is the development into smart antennas that is becoming more and more common. Antennas will start to relay on structures that is not dedicated to act antenna, consider for example the iPhone4 and iPhone4S which both use cell phone structure elements as antennas. Besides, the well known issue with iPhone4's reception when handheld is also something that could be partly handled with smart continuous tuning circuits. Where continuous tuning could be achieved with for example varactors acting as capacitors.

A small simulation was performed to see the gains in detaching the aux antenna when it was not used. In total, it resulted in efficiency gains of $\sim 15\%$ for the main antenna, without any change noticeable in the return loss. This is probably due to the fact that removing all matching networks from the antenna will leave a metal piece that resonates very badly at 1800MHz only. That is, the antenna is dependent on its LC matching network to resonate at its quarter and full wavelength mode.

The most important results from the MIMO investigations was that placing the antennas so that their current vectors will be vertical helped for the isolation and that isolating low frequency is more difficult than isolating high frequency. There is one method found in the literature that could help isolating low frequency, however, maybe only for a rather narrow frequency band. That is, connecting the two antennas ends with a line of a certain length and impedance such that the two antennas get increased isolation, higher efficiency and lower correlation. It is called negative group delay (NGD) technique and exploit the high attenuation that is associated with negative group velocity.[25]

7.1 Conclusions

The original thought was to create an 5-band antenna that could be tuned to use LTE700, LTE2300 and LTE2500. Reaching LTE700 with such a small antenna was quite a challenge, so MIMO operation at LTE700 and LTE2500 at the same time is not possible. However, it is probably not needed either.

Nevertheless, a tunable 8-band WWAN/LTE MIMO antenna has been proposed and it should be able to perform with efficiencies consistently over 40% if well fabricated. The size is kept under $0.9cm^3$ per antenna and it passes all required HAC and SAR limits. To further improve this design, a method to isolate the two antennas is needed. Besides, implementing clever tunable matching technologies that can detach the antenna completely should be investigated closer, since it seems to be able to increase the performance considerably.

Another interesting discovery that could be further researched is the difference in polarization from the antennas at different frequencies. Probably, good diversity performance can be achieved in different ways for different frequencies.

Bibliography

[1] Compact Power Amplifier for LTE Mobile Terminals Using Coupling Variation Reduction Technique , By Yang Li, Dmitri Prikhodko, Yevgeniy Tkachenko and Rick Zhu, Skyworks Solutions, Inc., April 2011, [Online] (2012-06-13).
URL http://www.skyworksinc.com/downloads/press_room/published_articles/MPD_042011.pdf

[2] Y.W. Chi and K.L. Wong, ”Very-small-size printed loop antenna for GSM/DCS/PCS/UMTS operation in the mobile phone,” Microwave Opt. Technol. Lett., vol. 51, pp. 184-192, Jan. 2009.

[3] Y.W. Chi and K.L. Wong, ”Very-small-size folded loop antenna with a band-stop matching circuit for WWAN operation in the mobile phone,” Microwave Opt. Technol. Lett., vol. 51, pp. 808-814, Mar. 2009.

[4] K.L. Wong, W.Y. Chen and T.W. Kang, ”On-board printed coupled-fed loop antenna in close proximity to the surrounding ground plane for penta-band WWAN mobile phone,” IEEE Trans. Antennas Propagat., vol. 59, pp. 751-757, Mar. 2011.

[5] Bluetest White Paper, (2012-03-28).
URL http://www.bluetest.se/download/BTW-002_System_test_in_RC_A.pdf

[6] P. S. Kildal and K. Rosengren, “Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: Simulations and measurements in a reverberation chamber,” IEEE Commun. Mag., vol. 42, pp. 104-112, 2004.

[7] IEEE Xplore Digital Library , (2012-03-28).
URL http://ieeexplore.ieee.org

[8] Wiley Online Library, (2012-03-28).
URL http://onlinelibrary.wiley.com

[9] ANSYS HFSS, Ansys Inc, (2012-03-28).
URL http://www.ansoft.com/products/hf/hfss/

[10] SEMCAD, Schmid & Partner Engineering AG (SPEAG) [Online], (2012-03-28). URL `http://www.semcad.com`

[11] American National Standards Institute (ANSI), Safety Levels With Respect to Human Exposure to Radio-Frequency Electromagnetic Field, 3KHz to 300GHz, Apr. 1999, ANSI/IEE standard C95.1.

[12] FCC Hearing Aid Compatibility (HAC), (2012-03-28). URL `http://www.fcc.gov/encyclopedia/hearing-aid-compatibility-hac`

[13] P.-S. Kildal, Fundamental directivity and efficiency limitations of single- and multi-port antennas, in: Antennas and Propagation, 2007. EuCAP 2007. The Second European Conference on, 2007, pp. 1 –6.

[14] IEEE Standard Definitions of Terms for Antennas, p24, IEEE Std 145 - 1983 (Revision of ANSI/IEEE Std 145 -1973) .

[15] SAR Evaluation Considerations for Handsets with Multiple Transmitters and Antennas, Sept 2008, Federal Communications Commission [Online] (2012-06-14). URL `https://apps.fcc.gov/kdb/GetAttachment.html?id=xGEEUdophoMP1YVJs%2Bb5zA%3D%3D`

[16] N. Jamaly, C. Gomez-Calero, P.-S. Kildal, J. Carlsson, A. Wolfgang, Study of excitation on beam ports versus element ports in performance evaluation of diversity and mimo arrays, in: Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on, 2009, pp. 1753 –1757.

[17] Frank M. Caimi and Mark Mongomery, "Dual Feed, Single Element Antenna for WiMAX MIMO Application," International Journal of Antennas and Propagation, vol. 2008, Article ID 219838, 5 pages, 2008. .

[18] User Manual to HFSS 14.0 64bit, 2011.

[19] Notes on Perfectly Matched Layers (PMLs), Steven G. Johnson, MIT, 2010, [Online] (2012-06-13).
URL `http://math.mit.edu/~stevenj/18.369/pml.pdf`

[20] K. Rosengren and P.-S. Kildal, Radiation efficiency, correlation, diversity gain, and capacity of a six monopole antenna array for a MIMO system: Theory, simulation and measurement in reverberation chamber, Proceedings IEE, Microwave Antennas Propa-gation, vol. 152, no. 1, pp.7-16, February 2005. See also Erratum published in August 2006.

[21] P.-S. Kildal, C. Orlenius, J. Carlsson, "OTA Testing in Multipath of Antennas and Wireless Devices with MIMO and OFDM", Proceedings of the IEEE, Vol. 100, No. 7, pp. 2145-2157, July 2012. .

[22] P. Kildal, Foundations of Antennas - A Unified Approach, Studentlitteratur, 2000.

[23] Y.-W. Chi, K.-L. Wong, Small-size multiband folded loop antenna for small-size mobile phone, in: Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE, 2008, pp. 1 –4.

[24] R.J.P. Douville and D.S. James, Experimental Characterization of Microstrip Bends and Their Frequency Dependent Behavior, 1973 IEEE Conference Digest, October 1973, pp. 24-25.

[25] J.-Y. Chung, T. Yang, J. Lee, J. Jeong, Low correlation mimo antenna for lte 700mhz band, in: Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on, 2011, pp. 2202 –2204.