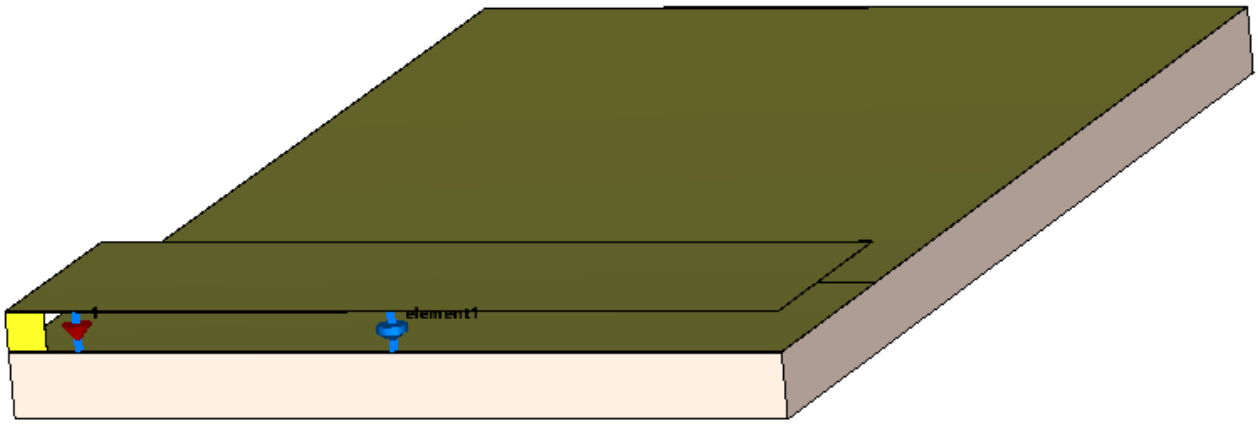

Reconfigurable PIFA with a capacitive lumped element - Simulation and measurements

Oskar Feldstedt

712 - 7th semester

Bachelor's thesis

STUDENT REPORT

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Abstract:

The project is based on a case where an antenna for an IoT device is needed. The device must have dimensions 100x60x10mm with a clearance of 20mm. The project must be able to be used in North America and Europe. The device must use LTE in the spectrum of 698-960 MHz. Therefore the project explores IoT devices in short and LTE devices. From this, it is seen that AT&T has a requirement of TRP requirement of 18 dBm. Meaning the antenna efficiency must be at least -5 dB.

The antenna ended up being a PIFA. Different configurations simulated with CST. The antenna was built to the same specifications as the simulated model. When testing it is seen the different antenna configurations do not cover all the bands. Therefore some further development is needed to cover all the bands. But it is seen that the antenna is reconfigurable by adding a capacitor to the antenna design.

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Preface

The quantities and units in calculations are represented in the International System of Quantities under ISO / IEC 80000. Other standards and abbreviations will appear introduced in parentheses the first time they are used in a context.

Source references are indicated as a number enclosed in square brackets: "[X]". Each square number will correspond to an index in the bibliography, which can be found in the last part of the report (before the appendixes). The number acts in the digital version of the report as a hyperlink giving the possibility to go to the position in the bibliography. Sources are indicated with title, publication/url and possible time of access in the case of online sources. However, sources from books are referenced by page numbers "[X, pp. XX-XX]". Material made by the student can be found in the appendix.

Contents

Chapter 1

Introduction

1.1 Case

The case is based on a fictive company that needs an antenna for an IoT device. This device will use an LTE module for communication. The device will therefore need an antenna to operate in the LTE spectrum of 698 – 960 MHz and 1710 - 2170 MHz. The product must comply with EU and US legislation, as it is intended to be sold in both locations. The device is a non-medical device that is unspecified, there for the device needs to be small and still be able to send the necessary data. The company has also specified a size for the circuit board. The total size of the board is 100x60x10 mm and the clearance given for the antenna is 20 mm as seen in figure 1.1. In figure 1.1a. is a front view and the side view is seen in figure 1.1b. The figures are only sketched to illustrate the idea of the case.

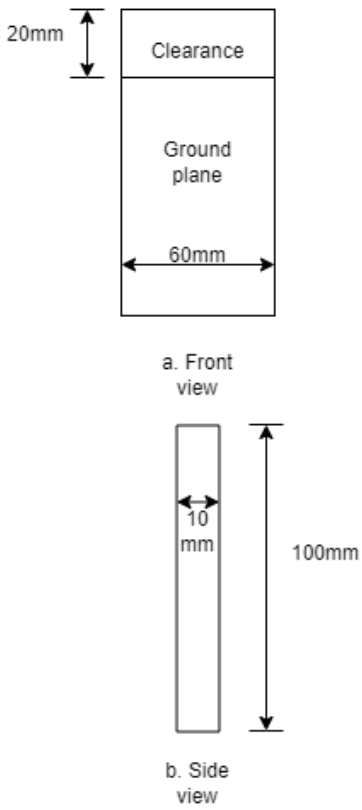

Figure 1.1: Graphical representation of the size of the board, made with information from the case.

1.2 Requirements

The requirements are derived from the case and are seen in table 1.1.

Requirements	
R1	The antenna must fit on a board that is 100x60x10 mm, with a 20mm clearance
R2	The device must comply with requirements about IoT using LTE, both in Europe and North America.
R3	The device must be able to handle the environment of both Europe and North America.
R4	The device must communicate with lower band frequencies of 698 - 960 MHz.
R5	The device must communicate with upper band frequencies of 1710 - 2170 MHz.

Table 1.1: Requirements made with the information from the case.

From these preliminary requirements, the preliminary analysis will continue to elaborate on wireless communication focused on LTE and IoT devices.

Chapter 2

Preliminary analysis

2.1 IoT

In the case in section 1.1, it is stated the device is an IoT device. In this section, the topic of IoT will shortly be explained. Internet of Things(IoT) is when you connect devices for monitoring or other devices that can do an action and connect them on in the internet. This is often done with home automation sensors or devices e.g., Smart light bulbs. Devices can be connected to a cloud server and monitor activity in the home. An example of this could be motion detection sensors, which can detect a possible intrusion and alert the owner. So, the application could be many, connecting all sorts of sensors, not only in home automation applications but health care, military, and industrial applications. E.g. trash disposal, a device could notify the operator when to come empty the container or bin. This way operators can monitor levels of bins in their system, and collect only when need [1].

2.1.1 LTE

To communicate between the cloud and the device, the device needs a way to connect to the internet. There are numerous ways of doing that, one used in home automation could be WiFi. But if the device is not close to a WiFi network, something else must be done. Therefore this case gave an LTE module for communication, as described in section 1.1. This makes the device able to communicate with the cloud or the monitoring system of an operator. In the two spectra that were given, 698 – 960 MHz and 1710 - 2170 MHz. 3GPP gives the requirements for using LTE in release 14 there are 3 power classes determined, of transmission power 14, 20, and 23 dBm, where the LTE-M power classes have a maximum transmission power of 20 and 23 dBm. The power classes are power class 3 with a maximum power of 23 dBm, power class 5 with a maximum dBm of 20 dBm and power class 6 with a maximum transmit power of 14 dBm. This requirement is essential to be connected

to a base station [2, 3]. In the US the cellular network provider determines the total radiated power(TRP) requirement. The provider AT&T requires a test of TRP must comply with the "CTIA Test Plan for Wireless Device Over-The-Air Performance", for IoT devices. Using the north American frequency band 2,4,12 as these bands fall into the two spectra given in the case [4]. AT&T requires a power class 3 LTE module with a maximum transmit power of 23 dBm a minimum TRP of 20 dBm in bands 2 and 4, and a TRP of 18 dBm in band 12 [5]. This requirement affects the requirements of the antenna as the LTE module transmits with a maximum power of 23 dBm, the requires the antenna to radiate at least 18 dBm or 20 dBm depending on which band is used. As TRP relates to the power radiated by the device and the transmit power relates to the output from the LTE module, thus must the antenna assure limited loss from 23 dBm to be able to deliver a minimum 20 dBm, seen in figure 2.1

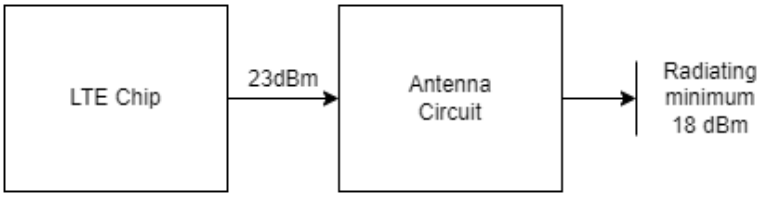

Figure 2.1: Block diagram of the power from LTE chip to the radiated power.

The TRP is determined by the effienciency as seen in equation 2.1[6].

$$TRP_{min} = P_{transmitter} + \eta antenna \tag{2.1}$$

It is then possible to calculate the minimum effieciency for the minimum requirement for TRP which is 18 or 20 dBm depending on the band used.

η	Effieciency	[dB]
TRP	Total radiated power	[dBm]
$P_{transmitter}$	Power from the transmitter(The chip)	[dBm]

$$18 = 23 + \eta antenna => \eta antenna = 18 - 23 = -5[dB] \tag{2.2}$$

$$18 = 23 + \eta antenna => \eta antenna = 20 - 23 = -3[dB] \tag{2.3}$$

It is seen in equation 2.2 and 2.3, that the efficiency should be -5 and -3 dB.

When looking at the different bands operating in this spectra in Europe and USA for NB-IoT. There are several bands seen in the list below:

- Band 8 EU
- Band 12 US
- Band 20 EU
- Band 26 US

These bands are optimized for low-power usage, as IoT devices. There fore these bands are ideal for this type of device[7]. The frequency spectra of each band can be seen in table 2.1.

NB-IoT LTE bands		
Band	Uplink(MHz)	Downlink(MHz)
8	880-915	925-960
12	699-716	729-746
20	832-862	791-821
26	814-849	854-894

Table 2.1: Table of bands with respective uplink and downlink channels [8].

2.1.2 IP-classification

As the case only states where this device will be sold and not what materials are used for an enclosure. So this means an IP rating with sufficient ratings to survive in the environments of North America and Europe. First IP classification is used to rate a device's resistance against dust and/or water, as dust and water tend to cause problems inside electronic devices. IP-classification is a way to divide devices into classes of resistance against water and dust. This is used in many industries and follows the IEC 60529 standard. The classification is seen in table 2.2, with the two classifications.

IP-rating		
	Solid foreign objects(1st numeral)	Water(2nd numeral)
0	No protection	No protection
1	Protected against solid foreign objects of 50mm Ø and greater	Protected against vertically falling water drops
2	Protected against solid foreign objects of 12,5mm Ø and greater	Protected against vertically falling water drops when enclosure tilted up to 15°
3	Protected against solid foreign objects of 2,5mm Ø and greater	Protected against spraying water
4	Protected against solid foreign objects of 1mm Ø and greater	Protected against splashing water
5	Dust-protected	Protected against water jets
6	Dust-tight	Protected against powerful water jets
7	–	Protected against the effects of temporary immersion in water
8	–	Protected against the effects of continuous immersion in water
9	–	Protected against high pressure and temperature water jets

Table 2.2: IP-rating[9].

As the device is not specified to be in an environment that is extreme. As the device is an IoT device it would be likely that the device will have some shelter. Taking the example from section 2.1, where the IoT is a trash container, it will be likely the device will have some shelter from harsh environments. IP-rating of 55 would likely be sufficient. This is highly dependent on what the device is being used for and where the device will be used. But IP 55 means it is dust protected and protected against water jets. This could protect the device against situations where water is directed at the device[9].

2.2 Antenna Parameters

This section will look at the antenna parameters that are essential to understand for small device antennas. Therefore, some basics will need to be explained.

2.2.1 Directivity

First to understand the topic of directivity the topic of radiation patterns will need to be introduced. Because of the fact that the directivity relates closely to the radiation pattern. Looking at the radiation patterns of two types of antenna, mainly the isotropic antenna and the directional antenna.

The isotropic antenna is an antenna that in theory radiates equally in all directions.

The directional antenna is an antenna that radiates in such a way were the highest power is at a specific angle. The smaller the beamwidth of such an antenna is, the more directional it is. To understand this half power bandwidth (HPBW) needs to be introduced. It should be noted that beamwidth indicates either the first null bandwidth (FNBW) or HPBW. FNBW is just the point in the main beam where the first null is found and is written as the angle between the nulls. HPBW is the angle between the points where the power is -3dB of the maximum power of the antenna, this tells something about where the antenna is effective. This can be seen in figure 2.2.

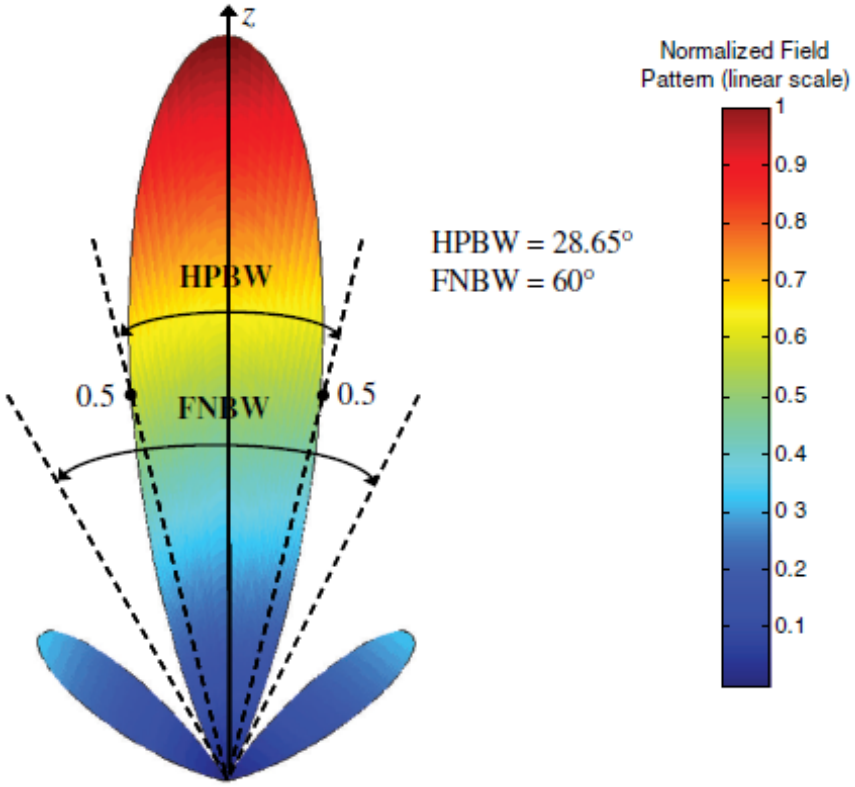

Figure 2.2: Illustration of HPBW and FNBW[10, p.39].

It is clearly seen that the beam is most intense in the HPBW.

The radiation intensity is given in equation 2.4.

$$U = r^2 W_{rad} \tag{2.4}$$

U	Radiation intensity	[W/unit solid angle]
r	Distance to source	[m]

From here the total power can be calculated, as it is possible to integrate both in the θ and ϕ axis. The radiation intensity is related in this way to total power radiation. As seen in equation 2.5. There fore total power radiation is not dependent on a specific angle but is a term used to describe as indicated in the name the total power radiation across all angles.

$$P_{rad} = \oiint_{\Omega} U d\Omega = \int_0^{2\pi} \int_0^{\pi} U sin\theta d\theta d\phi \tag{2.5}$$

P_{rad}	Total power radiated	[W]
U	Radiation intensity	[W/unit solid angle]
θ	Elevation angle	[$\circ$]
ϕ	Azimuth angle	[$\circ$]

With these definitions of total power radiated and radiation intensity, directivity can be explored. Directivity is given as in equation 2.5.

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \tag{2.6}$$

D	Directivity	
U	Radiation intensity	[W/unit solid angle]
P_{rad}	Total power radiated	[W]

Equation 2.6 is true for an isotropic antenna. If the directivity is not specified, then the maximum directivity can be expressed as in equation 2.7

$$D_{max} = D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}} \tag{2.7}$$

D	Directivity	
U_{max}	Maximum radiation intensity	[W/unit solid angle]
P_{rad}	Total power radiated	[W]

For an isotropic antenna, it is seen that U, U_0 and U_{max} are the same, because of the fact that the radiation is the same in all directions. But for an antenna that is not isotropic, the directivity is changed thru angles. Therefore U must take the different angles into account, both in θ and ϕ directions. This means U and P_{rad} needs to be dependent on where in the sphere the point is. This gives equation 2.8.

$$D_{\theta,\phi} = 4\pi \frac{F(\theta,\phi)}{\int_0^{2\pi}\int_0^{\pi} F(\theta,\phi) sin\theta d\theta d\phi} \tag{2.8}$$

With this expression, a general expression for maximum directivity can also be created. Equation 2.9 is just a general term of equation 2.7, which is the term for maximum directivity of an isotropic antenna [10].

$$D_0 = 4\pi \frac{F(\theta,\phi)|_{max}}{\int_0^{2\pi}\int_0^{\pi} F(\theta,\phi) sin\theta d\theta d\phi} \tag{2.9}$$

2.2.2 Gain

When talking about antennas, the gain is a useful term to describe the performance of the said antenna. As gain both take efficiency and directivity into account. Constantine A. Balanis describes gain as:

> "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π."[10, p.61]

Gain is defined as:

$$G(\theta,\phi) = e_{cd}[4\pi\frac{U(\theta,\phi)}{P_{rad}}] = e_{cd}D(\theta,\phi) \tag{2.10}$$

G	Gain	
e_{cd}	Antenna efficiency	
P_{rad}	Total power radiated	[W]

It is seen in equation 2.10, that gain is dependent on directivity. Eg. An isotropic antenna radiates equally in all directions, then the directivity will be the same in all directions, therefore the gain will be the same in all directions. So for a directional antenna the gain will be higher where the directivity is higher. There fore the maximum gain can be defined as:

$$G_0 = G(\theta,\phi)|_{max} = e_{cd}D(\theta,\phi)|_{max} = e_{cd}D_0 \tag{2.11}$$

As the gain is dependent on directivity, the maximum gain can be defined in the same manor as maximum directivity, in equation 2.7 and 2.9.

2.2.3 Antenna efficiency

The efficiency of an antenna describes how efficient the antenna is at radiating, their fore efficiency takes reflection, conduction, and dielectric losses into account. The total efficiency is used to take the losses at the input terminals into account. Losses can be due to reflection mismatch between the transmission line and antenna, or due to the conduction and dielectric loss. So total efficiency can be expressed as:

$$e_0 = e_r e_c e_d \tag{2.12}$$

e_0	Total efficiency
e_r	reflection efficiency = $(1 - \|\Gamma\|^2)$
e_c	Conduction efficiency
e_d	Dieelectric efficiency

2.2.3.1 Conduction and dielectric efficiency

Because of the nature of dielectric and conduction losses of an antenna is very hard to compute individually in most cases when measured. There fore they often are put together and represented by e_{cd}. The conduction-dielectric efficiency is defined as[10, p. 70-71]:

$$e_{cd} = \frac{R_r}{R_L + R_r} \tag{2.13}$$

So as seen in equation 2.13 the conduction-dielectric is dependent on the loss in the

e_{cd}	Conduction and dieelectric efficiency	
R_r	Radiation resistance	[Ω]
R_L	Radiation loss	[Ω]

antenna. In other words, the higher the loss the less efficient, the antenna is.

2.2.3.2 Measuring efficiency

There are different methods of measuring antenna efficiency. Two methods one could use is a method, where an antenna with known antenna efficiency is used to compare the rest of the measurements against. One could also use the wheeler cap method. In this project, the measurement with a reference antenna is explained.
When measuring efficiency one needs to know the fundamentals of efficiency. As antenna efficiency is a measure of losses in the antenna as described above. Antenna efficiency can be defined as:

$$\eta = \frac{G}{D} \tag{2.14}$$

When looking at the equation 2.14, it is seen that the efficiency is dependent on the

η	Efficiency
G	Gain
D	Directivity

gain and directivity [11].
Therefore the efficiency can be given as:

$$\eta_{AUT} = \eta_{ref} \frac{P_{AUT}}{P_ref} \frac{M_{ref}}{M_{AUT}} \tag{2.15}$$

η_{AUT}	Efficiency of antenna under test(AUT)
η_{ref}	Efficiency of reference antenna
P_{ref}	Power radiated by the reference antenna.
P_{AUT}	Power radiated by the AUT
$\frac{M_{ref}}{M_{AUT}}$	Mismatch correction.

When looking at equation 2.15, it is seen that the method requires the chamber to be calibrated with a reference antenna. Assuming the total power is measured [12].

2.2.4 Region of radiation fields

To understand the propagation of radiowaves, the regions of the radiowaves need to be explained. The field regions are known as reactive near-field, radiating near-field also known as Fresnel region and far-field region.

Reactive near-field is the region nearest the antenna, where $R < 0.62\sqrt{D^3/\lambda}$ for most antennas. In this region that immediately surrounds the antenna, the reactive field predominates. After the reactive near-field the Radiating near-field(Fresnel) region.

The Fresnel region is the region between far-field and reactive near-field. This region is where the radiating fields are predominant, and the angular distribution is also dependent on the distance from the antenna. It should be noted if the dimension of the antenna is not large enough compared to the wavelength this region may not exist.

Far-field is the region starting at $R > 2D^2/\lambda$, this region is the first region where the angular field distribution is essentially independent of the distance to the antenna[10]. The different fields of an antenna are seen in figure 2.3:

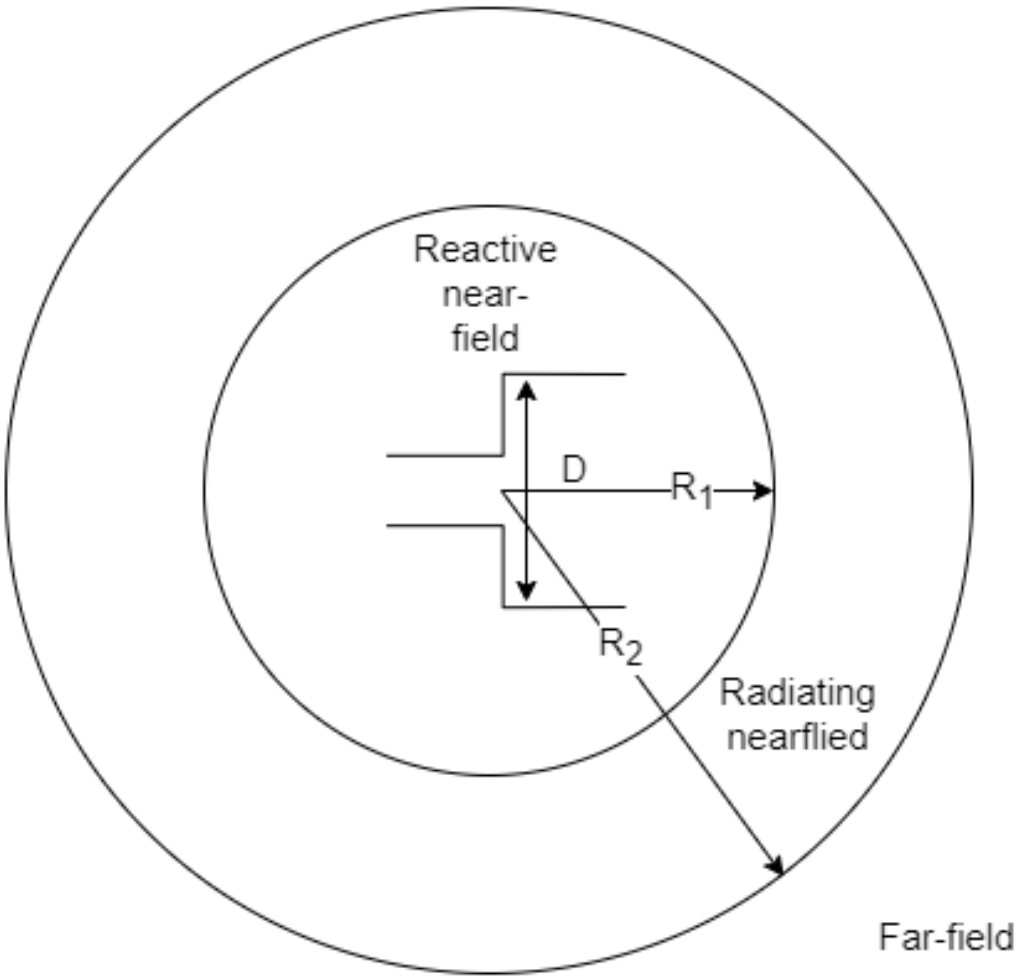

Figure 2.3: Antenna regions, $R_1 = 0.62\sqrt{D^3/\lambda}$ and $R_2 = 2D^2/\lambda$.

As explained it is seen that when measuring radio signals, it is very important to be aware their instruments are placed. For this project, the reactive near-field and far-field are the most important. This reasoning is that the reactive near-field batteries or

other disturbing components placed close to the antenna, can influence the antenna. Therefore the Fresnel region will not be discussed in this project.

2.2.5 Friis transmission equation

Friis transmission equation is based on the relation between the power that is received and the power that is transmitted, between two antennas. First look at equation 2.16

$$\frac{P_r}{P_t} = e_{cd,r} e_{cd,t} \frac{\lambda^2 D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r)}{(4\pi R)^2} \tag{2.16}$$

P_t	Power(Transmitted)	[W]
P_r	Power(Received)	[W]
D_t	Directivity of the transmitter antenna	
D_r	Directivity of the receiver antenna	
$(\frac{\lambda}{4\pi R})^2$	The freespace path loss(FSPL)	

If the assumption that the antenna is perfectly matched is not true, then the Friis equation can be written as in equation 2.17.

$$\frac{P_r}{P_t} = e_{cd,r} e_{cd,t} (1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2)(\frac{\lambda}{(4\pi R)^2})^2 D_t(\theta_t, \phi_t D_r(\theta_r, \phi_r)|\hat{\rho}_t \cdot \hat{\rho}_r|^2) \tag{2.17}$$

P_t	Power(Transmitted)	[W]
P_r	Power(Received)	[W]
D_t	Directivity of the transmitter antenna	
D_r	Directivity of the receiver antenna	
$(\frac{\lambda}{4\pi R})^2$	The freespace path loss(FSPL)	
Γ_t	Voltage reflection coefficient(Transmitter)	
Γ_r	Voltage reflection coefficient(Reciever)	
ρ_t	Polarization vector(Transmitter)	
ρ_r	Polarization vector(Reciever)	

It is seen that the difference in the 2 equations is the reflection coefficient and the polarization vector. Equation 2.17, considers these parameters. This makes it possible to calculate antennas that are not matched. Friis equation also dictates the antennas are placed apart with the distance $R > D^2/\lambda$, D is the dimension of the largest antenna[10].

Assuming that the two antennas are perfectly matched, and the align for maximal directional radiation, for the best possible scenario, the Friis equation can be expressed as in equation 2.18.

$$\frac{P_r}{P_t} = (\frac{\lambda}{(4\pi R)^2})^2 G_{0t} G_{0r} \tag{2.18}$$

G_{0t}	Maximum gain(Transmitted)
G_{0r}	Maximum gain(Reciever)

Further on in this project, the work will continue to assume that there is a perfect polarization match.

2.3 Antenna Matching

Antenna matching is when the circuits is matched, so to be as similar as possible. When matching circuits for antenna it is essential that lossy components as resistors are not used. Meaning that only capacitors and inductors, make it possible to radiate as much power as possible, which is the goal of antennas. The implementation of matching impedance can be done in many ways, depending on what the goal of the device is. If the device is a single band device a bigger circuit with dual band switching capabilities are maybe redundant, but if the device is a mobile phone, it is necessary that it can communicate in different bands [13]. As for this project, the case only uses two bands in the LTE range. There fore complicated dual band matching, used for smartphones will not be explored in this report.

2.3.1 Smith chart

To match antenna circuits it is necessary to understand the smith chart which is an essential tool, for the purpose. The aim of matching antenna circuits is to match the system's characteristic impedance as close as possible. In telecommunication, the target is normally 50Ω. But when matching antenna circuits it is critical to have a quantitative value, for measuring the effectivity of a matching circuit. This is done with voltage reflection(Γ), the definition seen in equation 2.19.

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = |\Gamma| \angle \theta_\Gamma \tag{2.19}$$

$V_{reflected}$ and $V_{incident}$ is a complex representation of amplitude and phase. As seen in equation 2.19, the voltage is a complex value. Where the amplitude is denoted as $|\Gamma|$ and the phase is denoted as $\angle\theta_\Gamma$. The goal is for the transmission line to have the same characteristics as the antenna, so it is only the incident wave that travels to the load, which is the antenna and achieves the minimum reflection coefficient of 0.

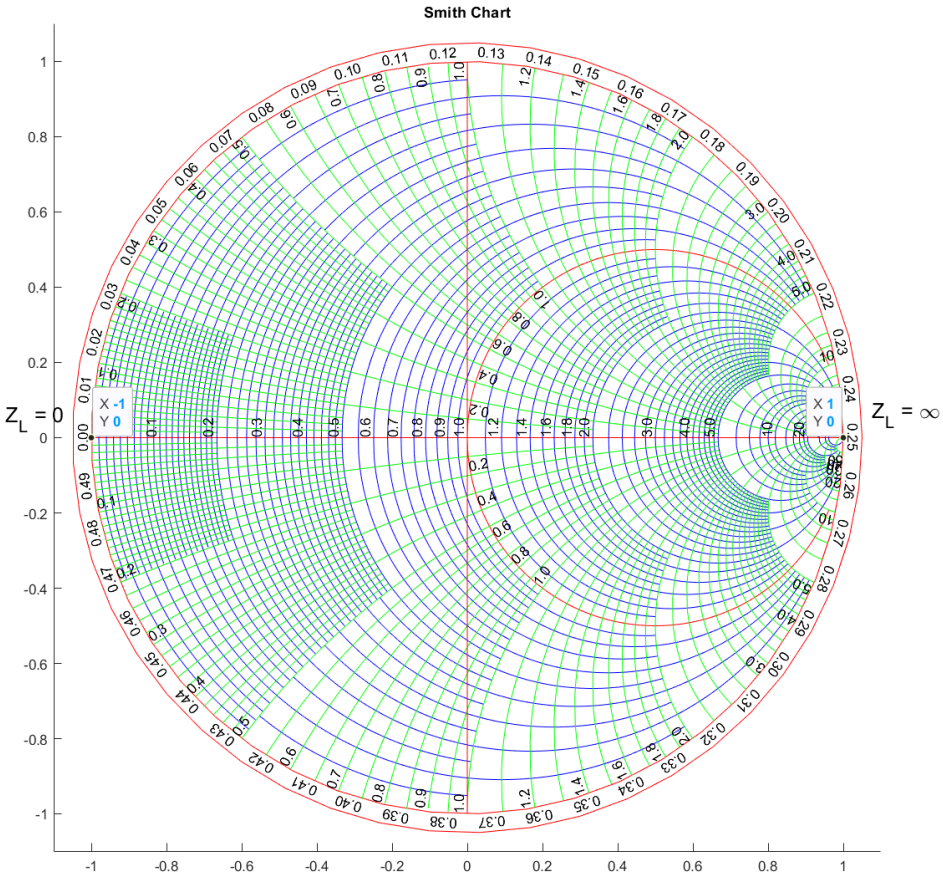

Figure 2.4: Smith chart from Matlab with markers -1,0 and 1,0, to show Short and Open circuit.

To explain what is seen on the smith chart a graphic representation of the chart is necessary, the smith chart is as seen in figure 2.4. At either end of the chart as marked on the figure, the left side Z_L is 0 there fore there is a short. At the rightmost side of the chart the Z_L is infinite, this is when there is an open circuit. The perfectly matched load lies at $|\Gamma| = 0$ and $Z_L = 1$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{Z_L - 1}{Z_L + 1} \tag{2.20}$$

With Z_L given as:

$$Z_L = r_L + jx_L \tag{2.21}$$

Z_L is a complex value that represents the load impedance. r_L is the normalized load resistance and x_L is the normal load reactance. Then it is seen that if one keeps either

the resistance or the reactance a constant. Then it is seen the circles represent the different resistance values and the curves are the different x_L values. Now the only parameter for the smith chart left is the admittance. The admittance is calculated by either fixing the real or imaginary part of the curves of the normalized load. As seen in equation 2.22:

$$y_L = \frac{1}{z_L} = g_L + jb_L \tag{2.22}$$

There is also another way to obtain admittance. One can calculate the impedance and rotate the smith chart 180°, and this also gives the admittance for a given load.

2.4 Electrically small antennas

When dealing with small antennas. Small antennas have their limitations, as the physical length is a limiting factor. An electrically small antenna is defined as, is an antenna where the maximum physical dimension is less than the radian length[14]. It can also be expressed as:

$$\frac{2 * \pi h}{\lambda} << 1 \tag{2.23}$$

With equation 2.23 the maximum dimension of the antenna in this project is 60 mm, then the maximum wavelength can be calculated as the lowest frequency is 698 MHz.

$$\lambda = \frac{c}{f} => \frac{c}{698 \cdot 10^6} \approx 0.42950[m] \tag{2.24}$$

$$\frac{2 * \pi 60 * 10^-3}{0.42950} = 0.8777 \tag{2.25}$$

It is seen with equation 2.24 and 2.25, that the antenna is electrically small.

2.4.1 Q-factor

The Q-factor is the factor that determines the rate of dampening. If the Q-factor is low, the slope will be flatter, than if the Q-factor was large. There fore unwanted signals outside the wanted spectrum will be dampened. But if the antenna is a wideband antenna the Q-factor wanted may very well be low, as a large Q-factor could dampen signals in the wanted spectrum. The Q-factor can be defined as[15]:

$$Q = \frac{1}{k^3a^3} + \frac{1}{ka} \tag{2.26}$$

The enclosing sphere can be seen in figure 2.5

$k = \frac{2\pi}{\lambda}$		
a	Radius of the enclosing sphere	[m]
λ	Free space wavelength	[m]

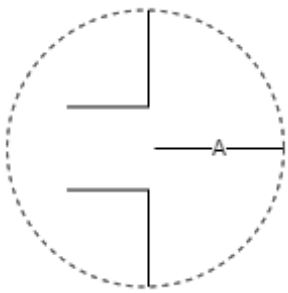

Figure 2.5: Illustration of the enclosing sphere, where a is the radius.

Eg. if the dipole antenna is $\lambda/2$, as this is the diameter of the sphere, then $a = \lambda/4$. If one wants a wide-band antenna, the resistance could be increased. But when doing antennas, the loss is unwanted, especially in small antenna circuits where power is limited. Therefore, resistance should be as low as possible.

Chapter 3

Design

3.1 Requirements

The requirements are derived from the preliminary analysis, and is seen in table 3.1.

Requirements	
R1	The antenna must fit on a board that is 100x60x10 mm, with a 20mm clearance
R2	The device must have an antenna efficiency of minimum -5 dB for AT&T requirement.
R3	The antenna must be matched to LTE band 8, 12, 20 and 26.
R4	The device must communicate with a lower band frequencies of 698 - 960 MHz.

Table 3.1: Requirements made with the information from the case.

These requirements will be the base of the design process. The testing of the antenna will be done to verify that the requirements is full filled. The requirements of the antenna will only take the lower band of the case into account, as the project is only based on proof of concept.

3.2 Design Analysis

3.2.1 IFA antenna

Inverted-F Antenna(IFA) is an antenna that looks like an inverted F, hence the name. The arm of the IFA is rough $\lambda/4$. The feed point in relation to the short controls the impedance of the antenna, the feed should be closer to the short than the open end to get 5Ω. The width of the short(W) should be much smaller compared to the wavelength.

To calculate the length of the arm in the antenna the center wavelength is calculated. The center frequency is 829 Mhz.

$$center_frq => 960 - 698 => 960 - \frac{262}{2} = 829\lambda = \frac{c}{f} \approx \frac{3 \cdot 10^8}{829 \cdot 10^6} = 0.362[m] \quad (3.1)$$

$$center_frq => 960 - 698 => 960 - \frac{262}{2} = 829\lambda = \frac{c}{f} \approx \frac{3 \cdot 10^8}{829 \cdot 10^6} = 0.362[m] \quad (3.2)$$

$$L_{IFA}\frac{\lambda}{4} = \frac{0.362}{4} = 90.5[mm] \quad (3.3)$$

So the arm should be bigger than the enclosure. There the resonant frequency can be decreased by adding either an inductance or capacitance. This increases the length of the antenna electrically.

Simulation

For the simulation, the calculated length of the arm of the antenna is longer than the specifications of the device. Therefore, the arm of the antenna must be smaller. A way to increase the length of the antenna electrically is to add a capacitor. The capacitor is added, to match the center frequency with 829 Mhz. The model for the simulation is depicted in figure 3.1 and 3.2.

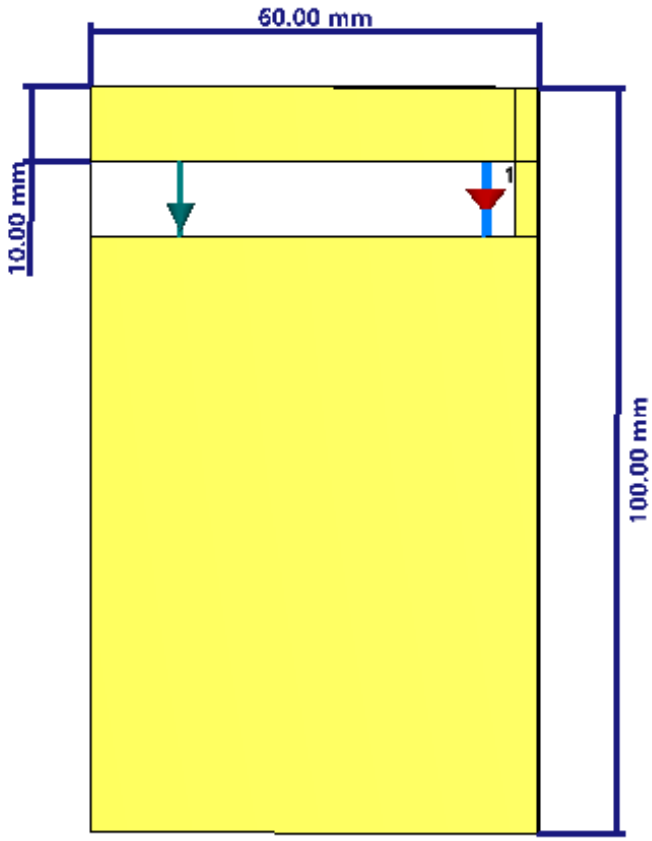

Figure 3.1: Front view of the IFA with dimensions.

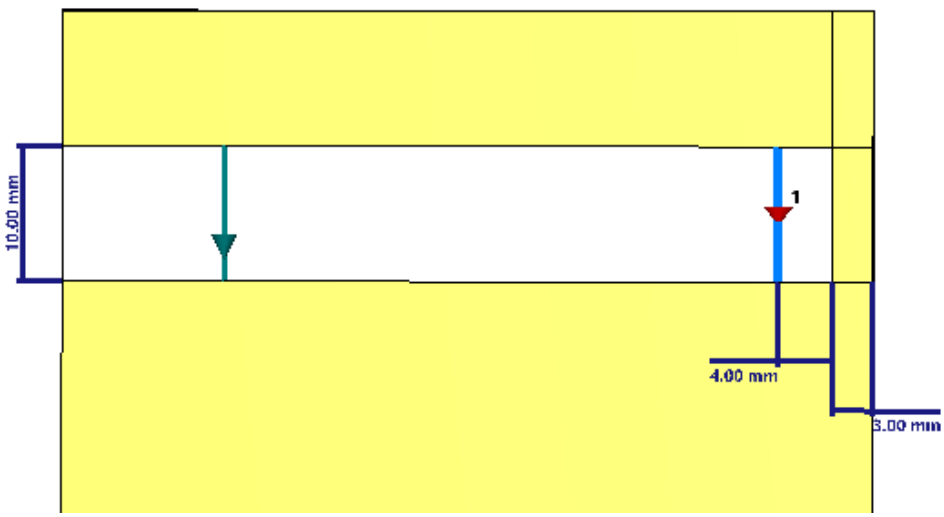

Figure 3.2: Front view of the IFA arm with dimensions.

When simulating the S11 parameter of the IFA antenna as depicted in figure 3.3.

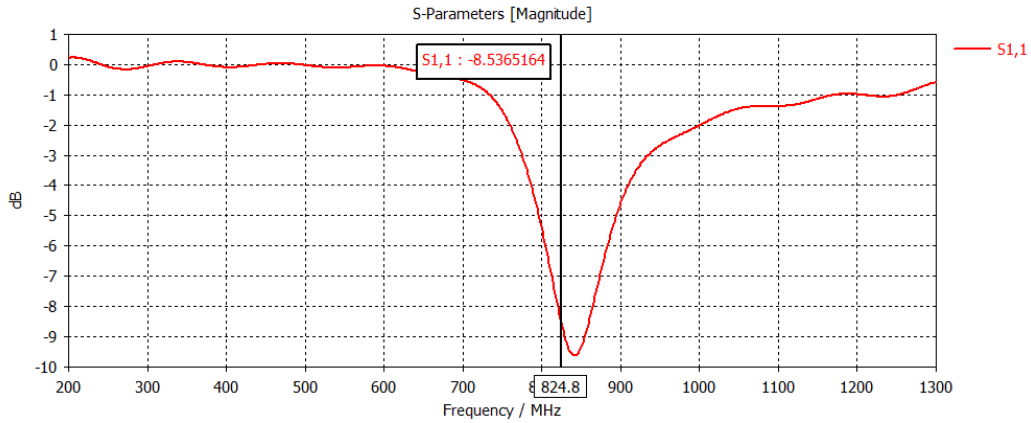

Figure 3.3: S11 with IFA without any lumped elements added.

When adding a capacitor at the end of the IFA it is seen the voltage is high. Depicted in figure 3.4.

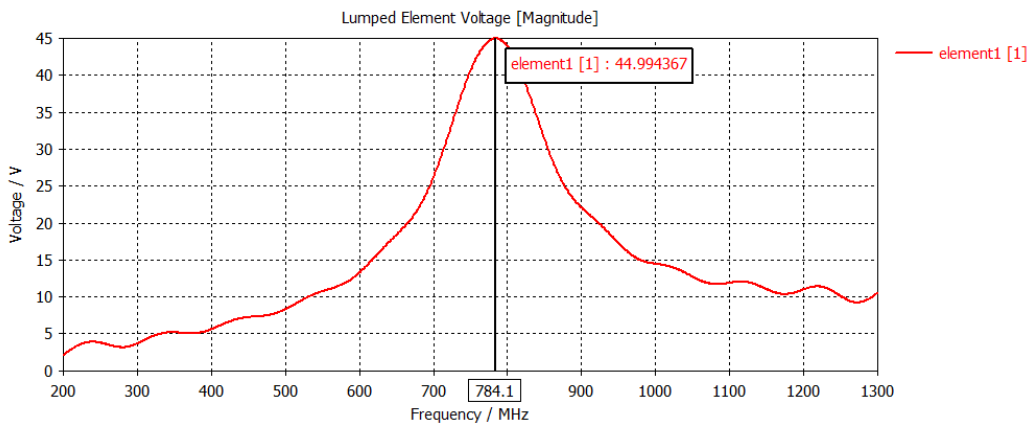

Figure 3.4: Voltage over lumped element, with a capacity of 0.124 pF.

This could pose a problem depending on the tolerances of the capacitor.

3.2.2 PIFA antenna

The PIFA antenna is nearly the same as the IFA design. The main difference is that the antenna is raised above the ground plane in PIFA, and typically the PIFA antenna resembles more a patch antenna. This type of antenna is typically used in mobile communications, as the design of the antenna has a degree of freedom that others do not. The resonant frequency of a PIFA is determined by the length(L), width(W), the height of the substrate(h), and the width of the shortening wire(w_s).

$$L + W - w_s = \frac{\lambda}{4} + h \tag{3.4}$$

It can be seen in equation 3.4 that. It is seen the biggest impact is from the length and the width if the width of the short is considered to be small compared to L and W. This means the width can be calculated if some of the parameters are set. If all of the space used L is equal to 60mm, and the w_s is set at 2 mm for the reason that practically it can be hard to make it smaller. And frequency spectrum is as stated in the requirements. Then firstly the wavelength of the center frequency can be determined:
Then the height can be chosen to something practical, such as 2mm. Then a new calculation can be done to find the necessary width.

$$60 \cdot 10^{-3} + W - 2 \cdot 10^{-3} = \frac{0.362}{4} + 2 \cdot 10^{-3} = 0.0345[m] = 34.5[mm] \tag{3.5}$$

From this a simulation model can be built to determine if the performance of the antenna will satisfy the requirements stated earlier in section 3.1.

Simulation

Firstly the simulation model can be built in CST, from the information determined above. As the board is 60x100mm with 20mm clearance, this model will be able to build easily. When designing the antenna, it can be seen in the simulation with an antenna without any lumped elements that the antenna that matches, the antenna that is built with the same specification. Also when designing the dimensions of the PIFA quick simulation experiment of varying the short width was conducted it can be found in appendix A. In figure 3.7 and 3.8 the S11 parameter of the simulation and the measurement look quite similar. Therefore, the simulation can be used in the design process as a guide for how the design should be. The discrepancies seen could be due to errors when building the physical model, as the antenna is very thin and is easily bent out of shape.

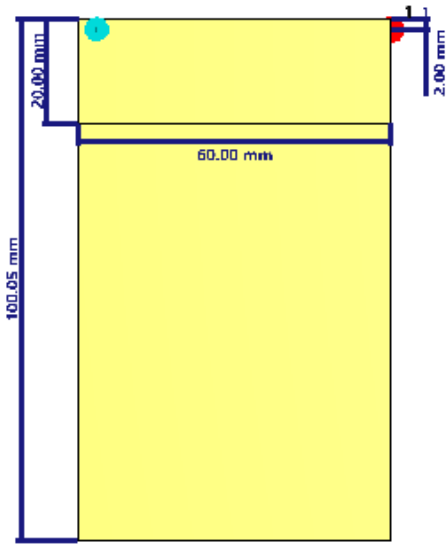

Figure 3.5: Front view of the antenna and ground plane.

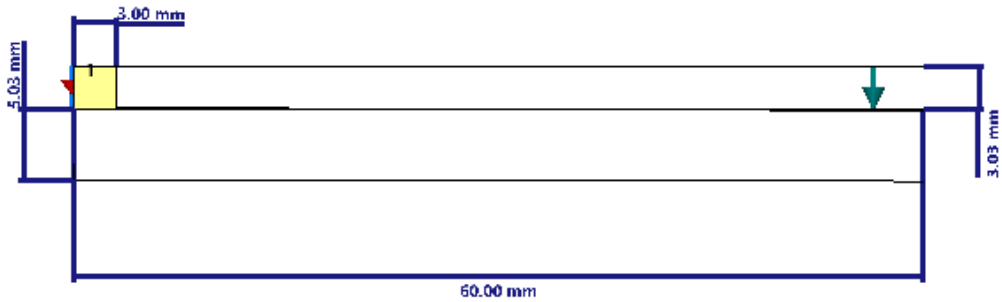

Figure 3.6: Front side of the antenna and ground plane.

It should be noted that figure 3.5 and 3.6 have a voltage monitor in the 3D drawing, not to be confused with a lumped element.

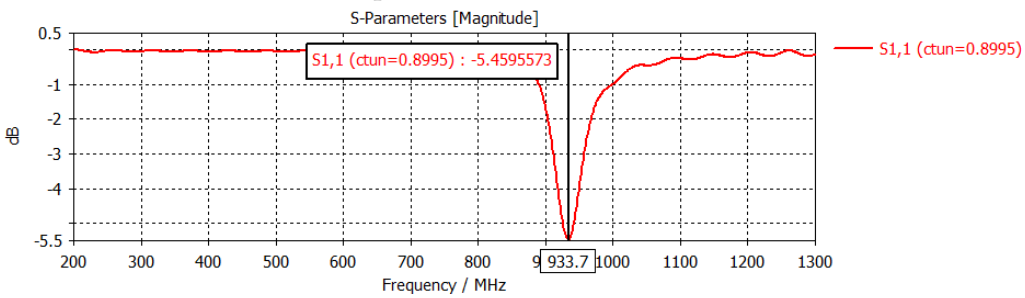

Figure 3.7: S11 parameter of the PIFA simulation without a capacitor.

As seen in figure 3.8 there is some variance in the measurement from the simulation.

This may be due to noise from the measurement environment.

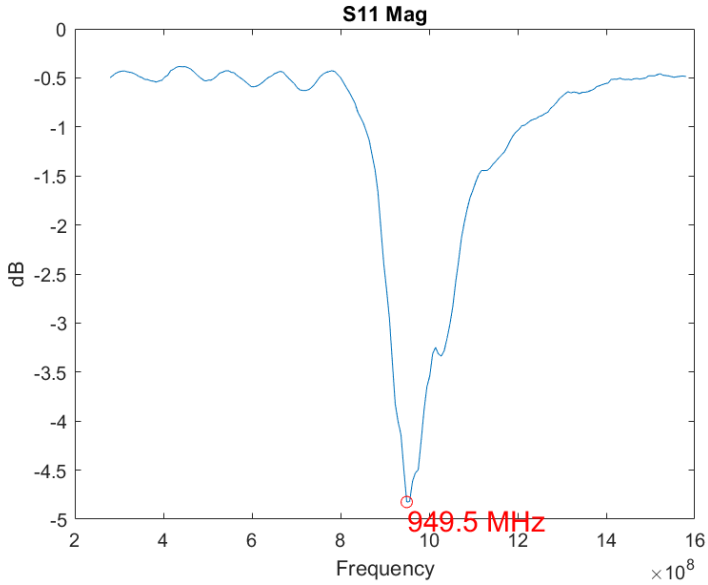

Figure 3.8: S11 parameter of the PIFA simulation without a capacitor.

To further test of design of the design process of the antenna. As the antenna cannot fulfill the requirements without lumped elements, due to the dimensions of the device. As the antenna is a $\lambda/4$ PIFA.

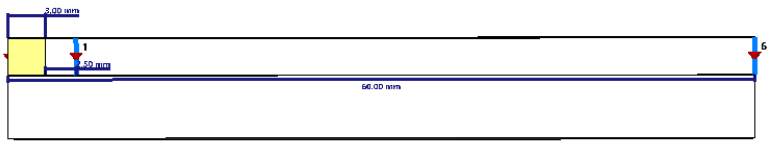

Figure 3.9: PIFA side view with capacitor seen from the side with feed.

But the PIFA design allows for the capacitor to be placed closer to the open end of the antenna, thus giving more design freedom. And the capacitor will also have a more noticeable effect closer to the open end.

3.2.3 Conclusion of design analysis

IFA has a high voltage close to the open end, this limits the places where the lumped element can be placed. As capacitors can be damaged by exceeding their voltage capabilities. PIFA does not have this problem to the same extent, therefore the PIFA design is the one chosen to continue working on this project.

3.3 Design

First, the model made in CST of the PIFA will now be modified until the antenna can meet the requirements of the specifications. The requirements could be met in several different ways, but first, the antenna will have a capacitor to increase the electrical length of the antenna. Thus, the placement of the capacitor is crucial as the placement can dictate how effective the tuning is. To show the effect of placement of the capacitor a small experiment is done, where the capacitor is moved in the length of the antenna.

3.3.1 Capacitor placement - Simulation experiment

This experiment is done to get estimates of the voltages over the capacitor, firstly a measurement is done by placing the open end of the antenna on the same side as the feed.

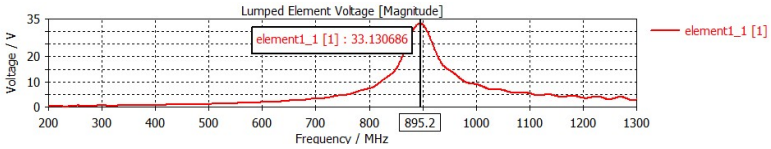

Figure 3.10: Voltages over the capacitor when the capacitor is at the open end on the same side as the short.

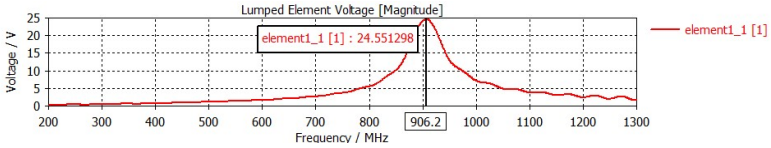

Figure 3.11: Voltages over the capacitor when the capacitor mid-way between the short and open end of the antenna.

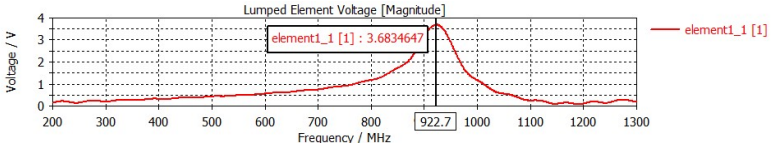

Figure 3.12: Voltages over the capacitor when the capacitor is placed next to the short.

When looking at figures 3.10, 3.11 and 3.12. It is clearly seen that the voltages are dependent on the distance from the feed. When moving the lumped element closer to the open end the voltages will rise. So, the further away the higher the voltage. This can be used to determine where to place the capacitors.

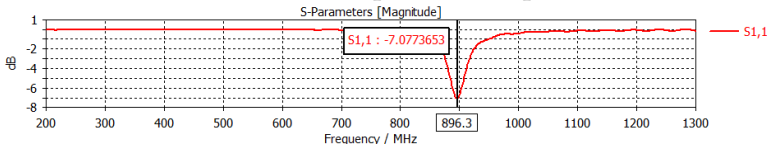

Figure 3.13: S11 parameters of the same placement as figure 3.10. The capacitor size is 0.25 pF

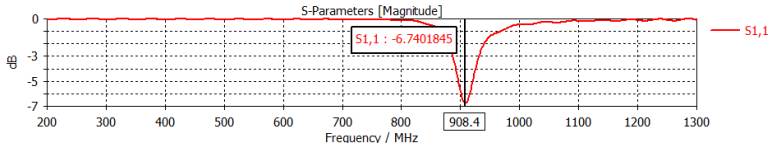

Figure 3.14: S11 parameters of the same placement as figure 3.11. The capacitor size is 0.25 pF

Lastly, it is seen in figure 3.13 and 3.14, that the distance influences the resonant frequency of the antenna. As the midway point has a slightly higher resonant frequency than when the capacitor is placed at the end.

3.3.2 Designing the antenna

The antenna is first designed in the CST software, to get an idea if the antenna is working as intended. After that, a prototype is made from the specifications from the model in CST, and then the

3.3.3 Design in CST

The same model as in section 3.2.2 will be considered the base for further development of the antenna. First, the placement of the capacitor is chosen. In this case, the position of the capacitor is midway between the short and the open end as seen in figure 3.15.

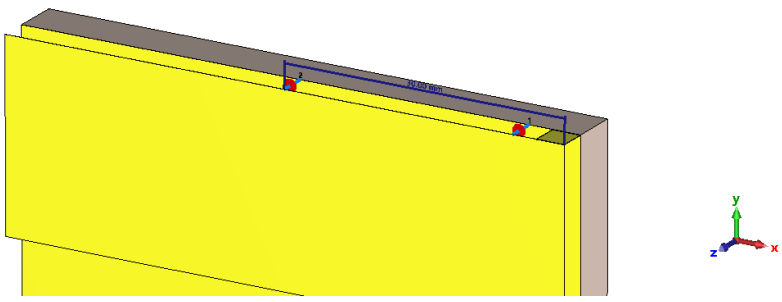

Figure 3.15: The capacitor is the port labeled as 2.

In the first part of the antenna design, the schematic in CST is used. Therefore the device is just a 2-port device, with port 1 being the signal and port 2 being the capacitor connected to ground. This is seen in figure 3.16.

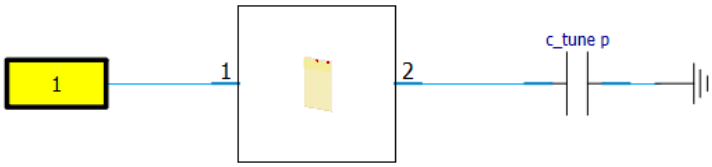

Figure 3.16: Schematic used to do the first part of the tuning of the antenna.

Using this method the simulation time can be cut significantly. The same values are from 0 to 2 pF. This is seen in figure 3.17.

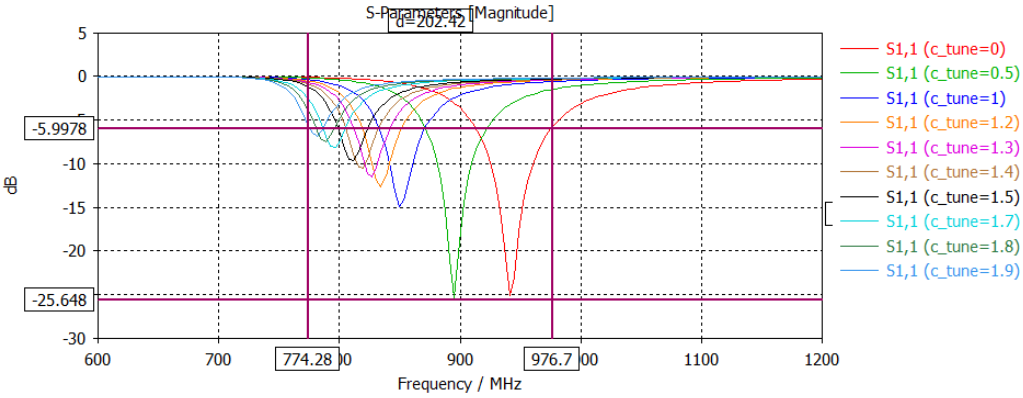

Figure 3.17: S11 parameters of the antenna with capacitor values from 0-2pF.

It is seen that one value cannot cover all of the band, but different states might. Some of the capacitors that are used can be used when doing the same simulation but as a 3D simulation in CST. First, the simulation before most of the capacitor values are selected, the rest is found by guessing and trying the value out in the simulation. As simulation only takes a couple of minutes this is the fastest way. The chosen values and the S11 parameters of the antenna tuned by the different capacitors are seen in figure 3.18.

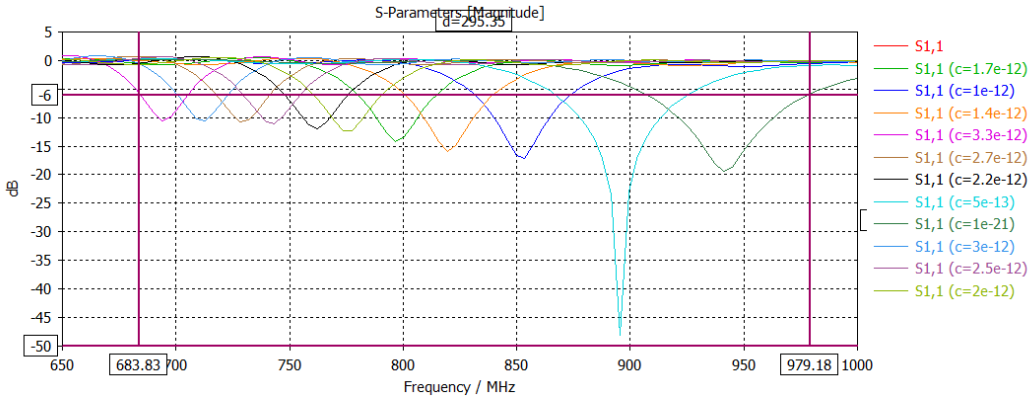

Figure 3.18: S11 parameters of the antenna with capacitor values from 0.5-3.3pF.

With this configuration, all the frequencies of the band are covered. More the efficiency total efficiency of the antenna is critical. As it needs to be at least -5 dB stated in section 2.1. In figure 3.19 the efficiency is depicted and there is some trouble with some of the configurations not having a high enough efficiency.

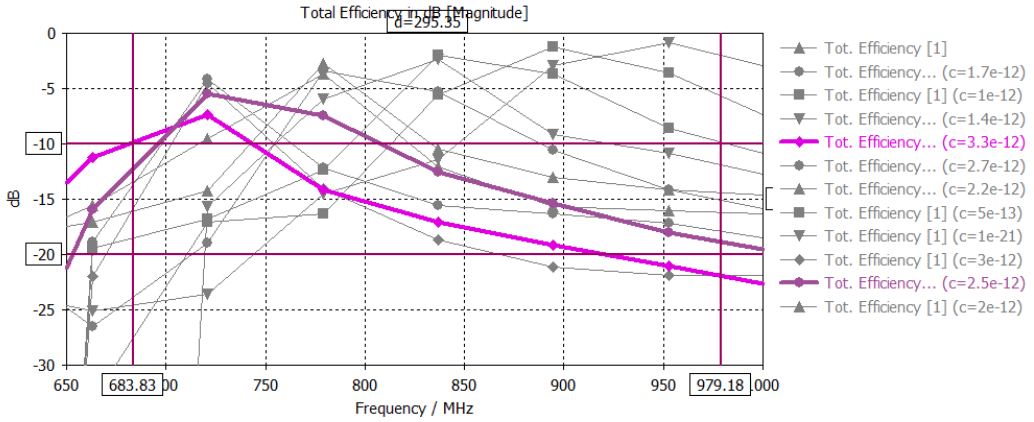

Figure 3.19: Total Efficiency with capacitors sizes 2.5 pF and 3.3 pF highlighted.

This can be due to poor tuning, this can be improved by moving the lumped element thus reducing the capacitor when moving the capacitor closer to the open end. When looking at the power lost in the lumped elements it is clear that some of the larger capacitors have much greater loss than, the smallest at 0.5 pF. This can be seen in figure 3.20

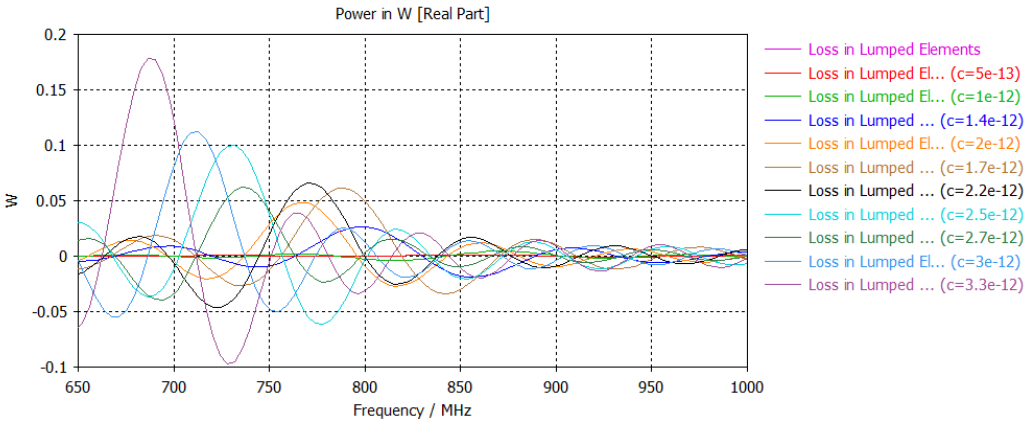

Figure 3.20: Loss in the lumped elements across all configurations.

3.3.4 Measurement setup for measuring S11 parameters of the antenna.

To measure the S11 parameters of the antenna a VNA is used. The setup is fairly simple as seen on the diagram in figure 3.21.

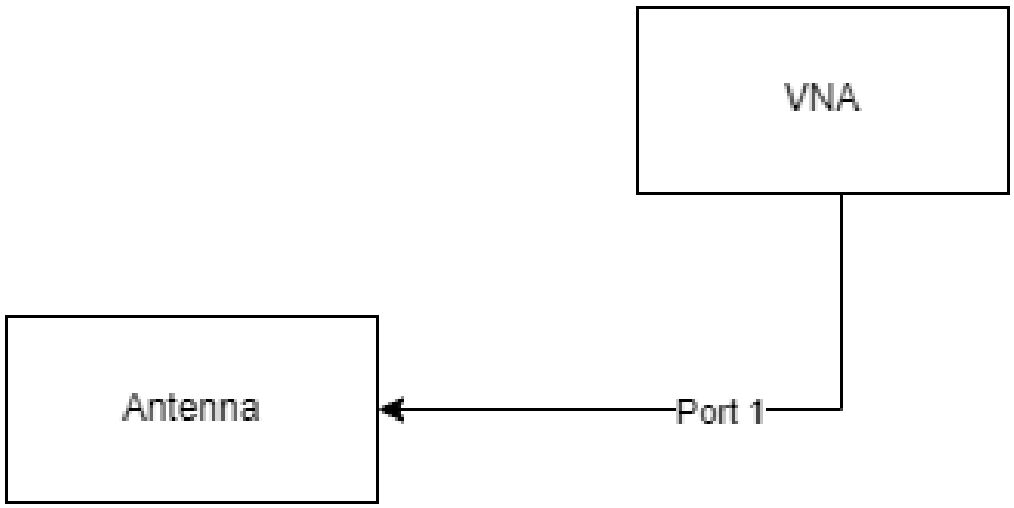

Figure 3.21: Diagram of the measurement setup.

The setup is also seen in figure 3.22.

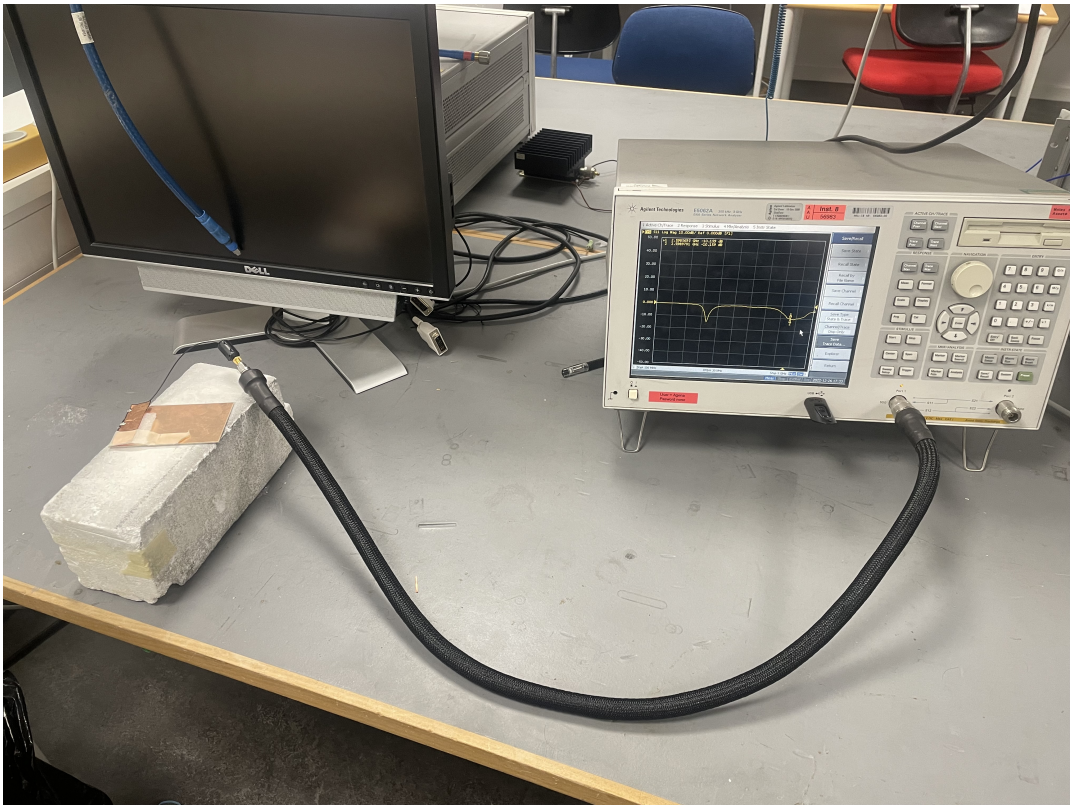

Figure 3.22: Photo of antenna and VNA during S11 parameter measurement.

When measuring the antennas, there was used one ferrite core on each antenna cable. As seen on the photo in figure 3.23. The ferrite core was placed nearest the connector on the cable to have some consistency when measuring the antennas. This way was most efficient when measuring multiple antennas.

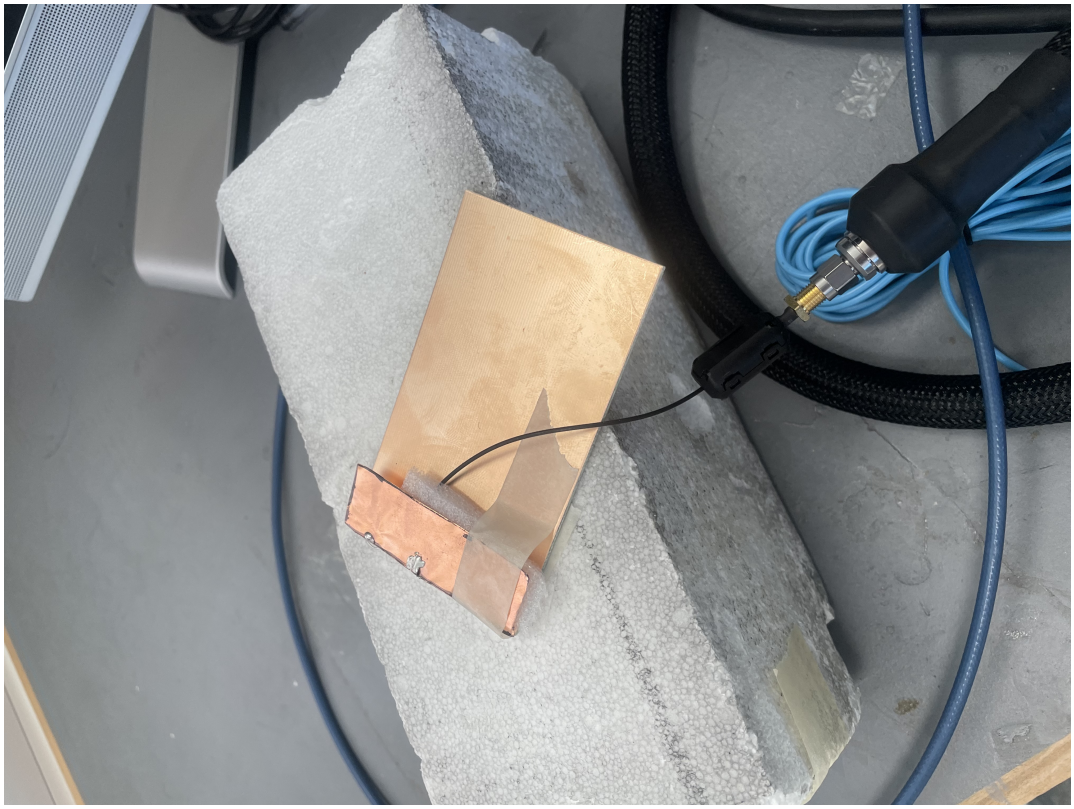

Figure 3.23: Photo of antenna during S11 parameter measurement.

The results from the measurement are plotted in MATLAB, using the trace files transferred via USB. Before each measurement campaign, the VNA was calibrated according to the manufacturer, using a calibration kit. All measurement was done in a consecutive manner, meaning the VNA was not turned off in between measurements, also meaning the VNA was only calibrated once.

3.3.5 Results of the S11 parameter VNA measurements.

The results obtained from measuring with the setup described above, the trace files from the VNA is used to plot the results. The results of the S11 measurements are seen in figure 3.24.

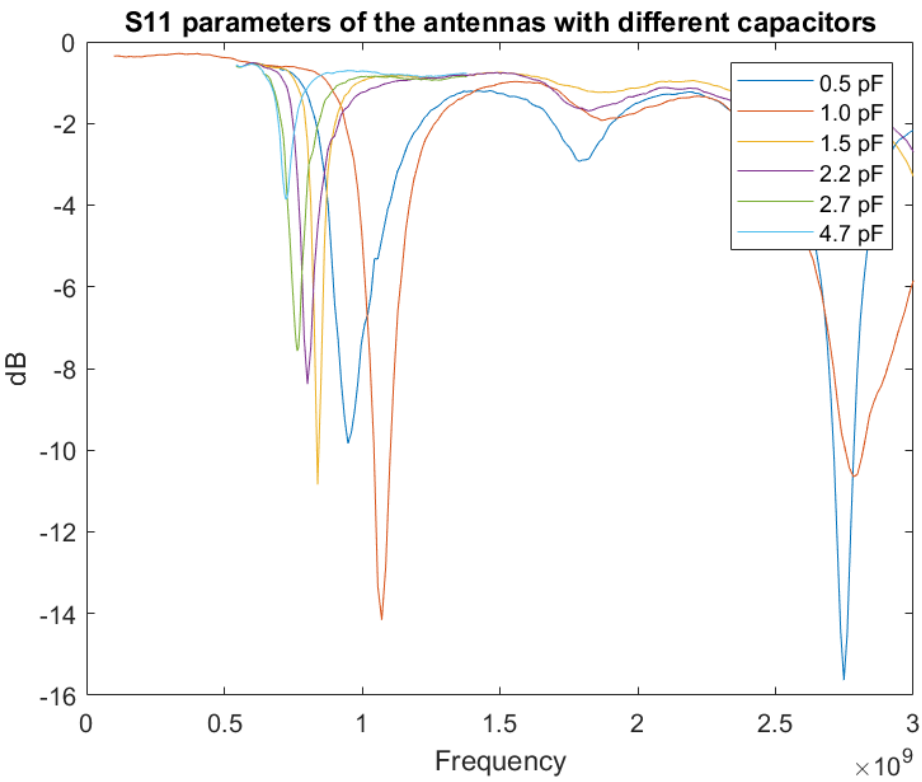

Figure 3.24: Plot of the S11 parameter of the antenna with different capacitor values.

The same plot with markers at the outer band of the different S11 plots shows that if all the antennas had enough gain the spectrum would be covered. But in reality, the spectrum is only covered from approximately 750-1100 Mhz, as seen in figure 3.25.

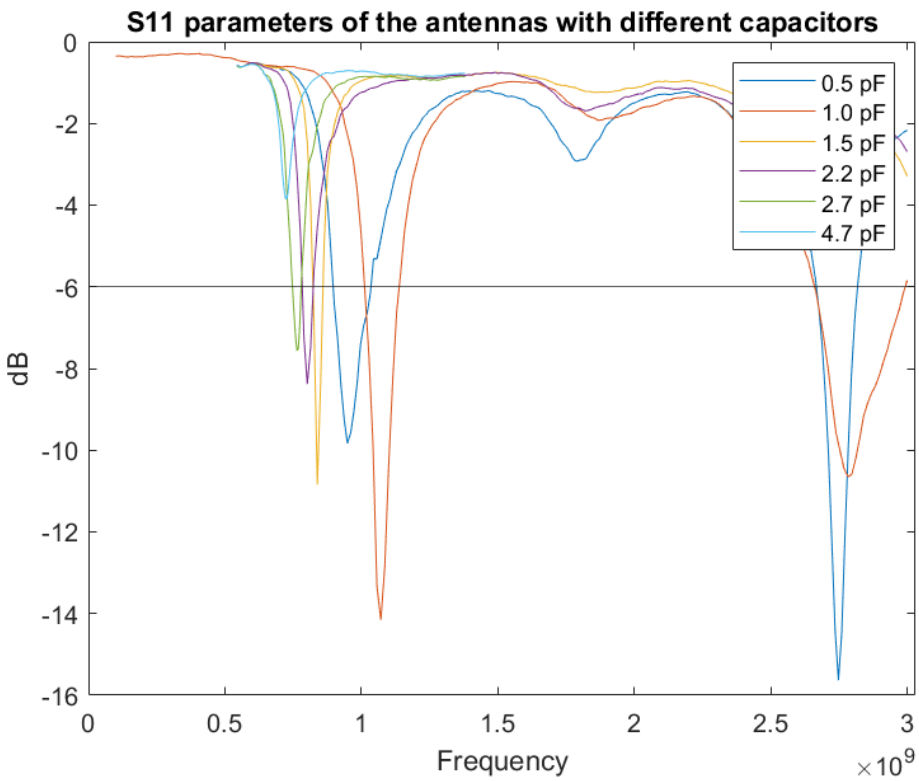

Figure 3.25: Plot of the S11 parameter of the antenna with different capacitor values with line at -6 dB.

Comparing the plot to figure 3.17, it is seen the measurements is using fewer capacitors, but the simulation is also using a higher power on the signal input than the VNA. The VNA used is limited to 10 dBm, which is lower than the required requirements, as the requirement at 23 dBm on the output from the LTE-module. There fore the S11 parameters can be affected by the limiting factors of the VNA. Considering this the results of the measurements could be affected by this and therefore efficiency must be the deciding factor. The spectrum is covered partially, but the coverage could be better with a capacity between 0.5 pF and 1.5 pF. It is also seen the capacity with 1 pF is spanning a higher frequency band than 0.5 pF. This is illogical as higher capacity should result in an electrically longer antenna, and the resonant frequency should be lower. This may be due to the error in the fabrication of the antenna. The physical length could be slightly shorter or the feed could be slightly misplaced.

When plotting the bands as a vertical line onto the plot of the S11 parameters then the coverage of the bands in the spectrum from table 2.1. It is seen in figure 3.26.

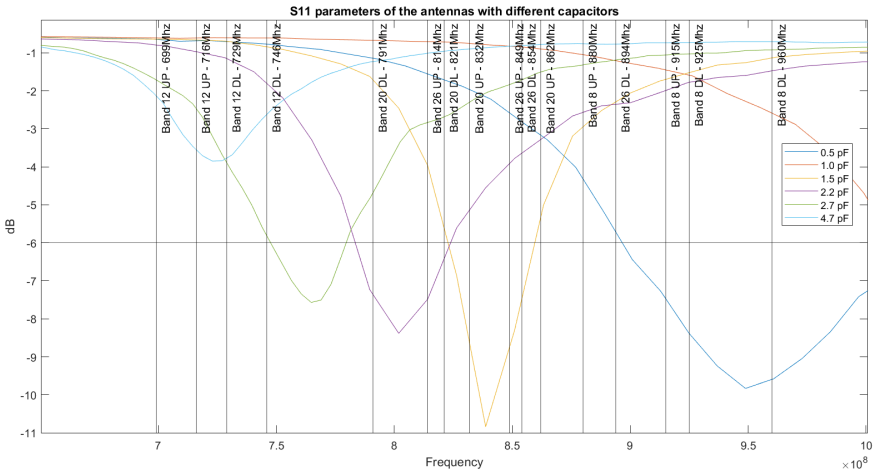

Figure 3.26: Plot of the S11 parameter of the antenna with different capacitor values and -6 dB plotted and all bands marked with uplink and downlink channels.

Looking at figure 3.26 it is seen that all bands are not covered. This is partially due to the reasons stated above. And also some of the resonant frequencies are slightly shifted away from the middle of the bands. It is also seen that there is channel spacing between the uplink and downlink of the different bands, in this space, there is no communication expected. Meaning that this space does not have to be covered by the antenna. Looking at the best-matched bands to the antenna. We can list those from best to worst:

1 Band 20 - Covered by 1.5 and 2.2 pF

2 Band 8 - Nearly covered by 0.5 pF

3 Band 26 - Covered somewhat by 0.5 and 1.5 pF

4 Band 12 - Covered by 4.7 pF but not sufficiently

When looking at the different bands, on top of the S11 parameters it is seen the gain on band 12 is too low. Therefore it is considered to be the worst match. Where band 26 is partially covered with gaps where the gain is lower than required. It should also be noted that the capacitor from the simulation at capacity 3.3 pF was swapped to 4.7 pF as the 3.3 pF capacitor did not have the wanted S11 parameter as expected, this can be due to the specs of the capacitor or the placement. The 4.7 pF capacitor has a similar S11 parameter as the simulated 3.3 pF.

Chapter 4

Test

In this chapter the test of the antennas made in section 3.3.2. The test of the antenna is done by measuring the efficiency. The reason behind it is that the requirement states that the antenna must have a antenna efficiency of minimum -5 dB, as stated in section 2.1. This is is derived from the TRP requirement from AT&T, as described earlier in section 2.1.

4.1 Measurement of antenna efficiency

First, the measurement with the MVG SG 24 chamber at AAU needs to be explained. Then the efficiency measurement of the antennas will be explained.

4.1.1 Calibaration of the MVG SG24 chamber

The way the chamber can measure the efficiency of the antenna is by using a reference antenna. In this measurement, the MVG SH400 is used. This antenna is an antenna with known characteristics. As described in section 2.2.3. When the measurement of the SH400 is done the software can make the calculation of the efficiency of the AUT.

4.1.2 Measuring in the chamber

Measurement was done in the order in the list below:

1 Measurement of SH400

2 Measurement of PIFA w. 0.5 capacitor

3 Measurement of PIFA w. 1.5 capacitor

4 Measurement of PIFA w. 2.2 capacitor

6 Measurement of PIFA w. 2.7 capacitor

7 Measurement of PIFA w. 4.7 capacitor

First, the MVG SH400 was measured as seen in figure 4.1.

Figure 4.1: MVG SG24 chamber seen with MVG SH400 used for calibration.

The antenna was used as a reference antenna. When the SH400 has measured the setup of the different configurations of the antennas. Then the setup with the PIFA is seen in figures 4.2,4.3 and 4.4, using the PIFA w. 0.5 pF capacitor as an example.

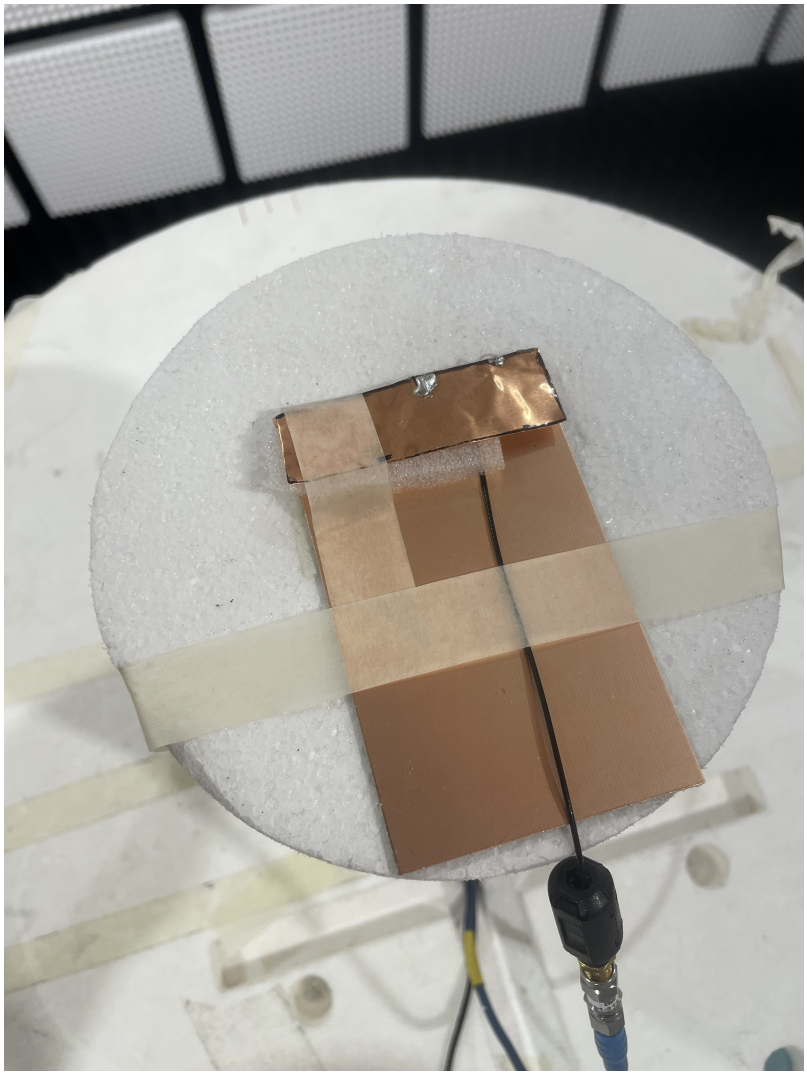

Figure 4.2: PIFA w. 0.5 pF placement

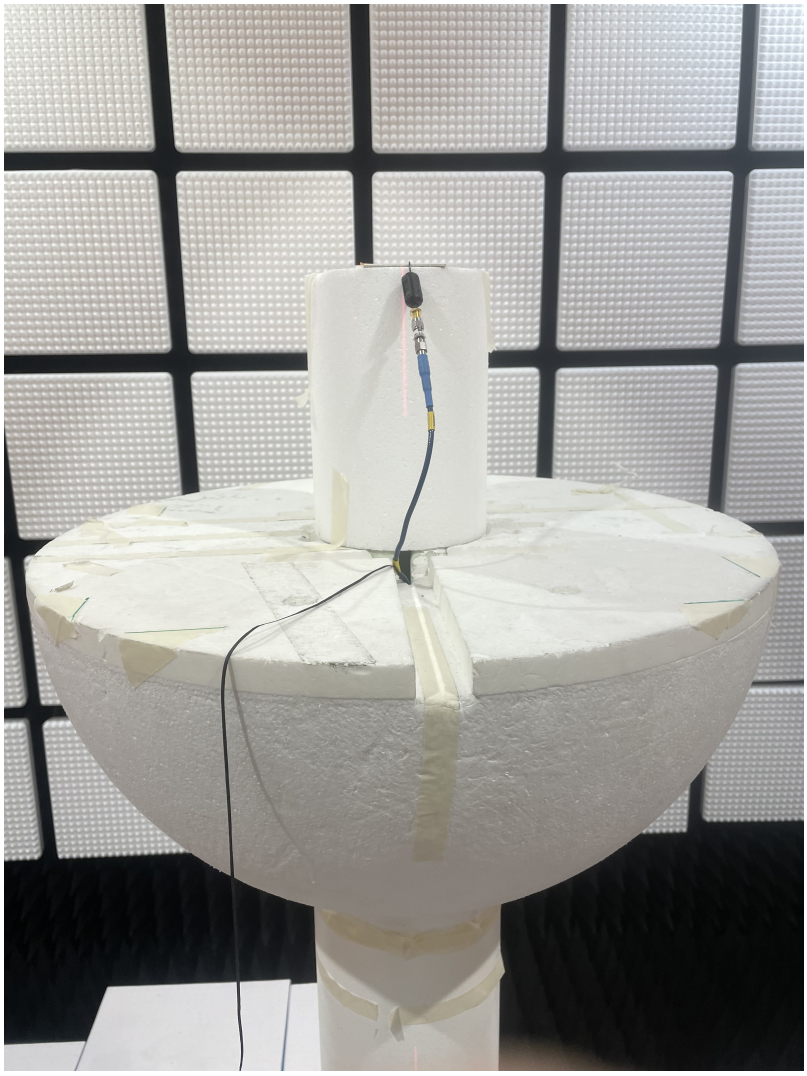

Figure 4.3: PIFA w. 0.5 pF

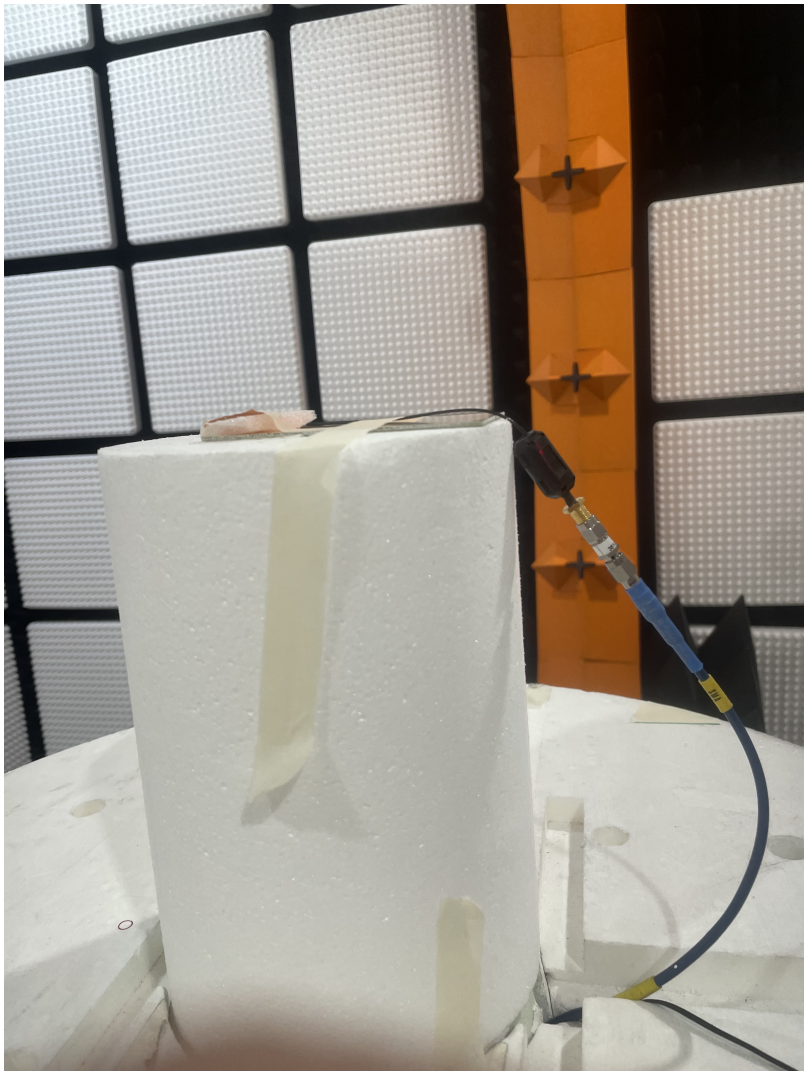

Figure 4.4: PIFA w. 0.5 pF

When looking at the figures it is seen that there is a ferrite core at the end of the cable and the feed is as seen in the schematic, with ground of the cable soldered directly under the feed, due to the durability of the cable.
The full measurement setup can be seen in appendix B.

4.2 Results

When looking at the results of the efficiencies of the antennas, it should be compared to the figure 3.19. The efficiency is measured and processed with MVG Wavestudio. Therefore the data can be plotted directly. The efficiencies are depicted in figure 4.5.

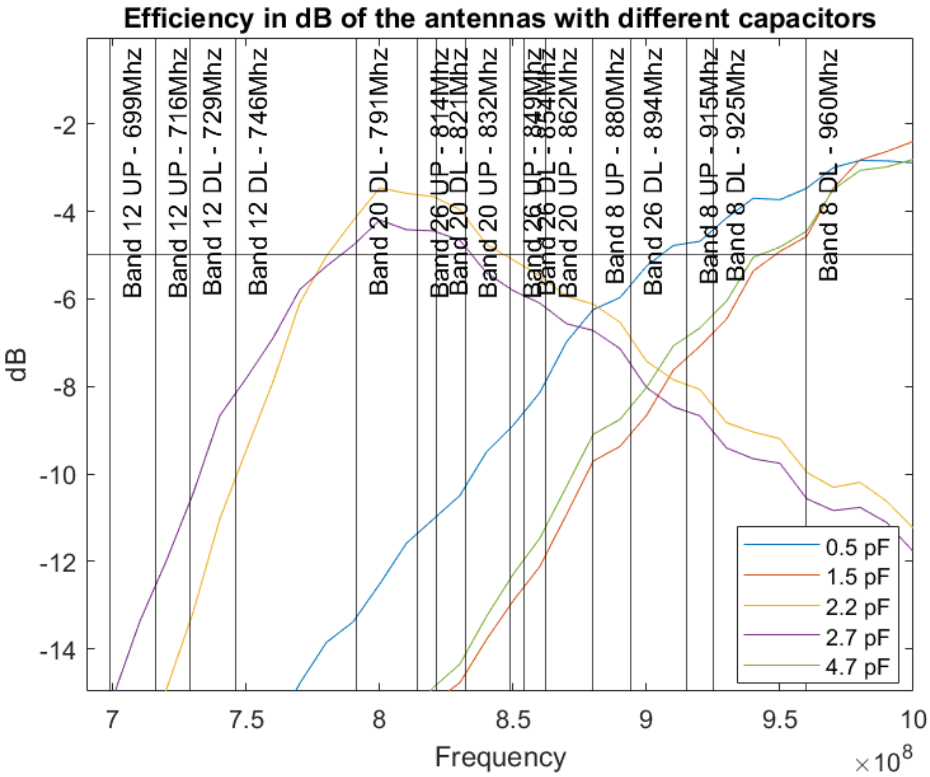

Figure 4.5: The efficiencies of all antenna configurations with all the bands plotted.

In figure 4.5 it is seen the efficiencies are in some cases mismatched for the bands, and band 12 is not covered at all. When the S11 parameters and the efficiencies are plotted against each other a mismatch between efficiency and S11 parameters is seen, this indicates the antennas cannot cover the bands. The only close match is the antennas with a 0.5 pF and 2.2 pF capacitor. It is also seen that the efficiencies of the antenna with 2.2 pF are a slight mismatch. This is seen in figure 4.6.

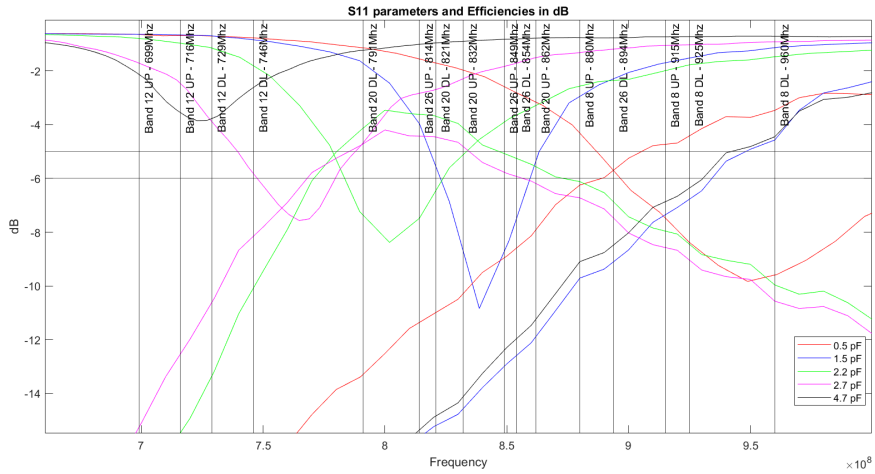

Figure 4.6: The Efficiency in dB and S11 parameter plotted against each other. The color is the same for the S11 measurement and efficiency measurement.

It seems that the S11 parameter does not match the efficiency center frequency, this seems like some of the antennas were damaged. Those that do not match resemble the efficiency of the antenna without any lumped element. Below is a list seen of the efficiency and S11 parameter match:

- PIFA w. 0.5 pF - Good match between S11 and Efficiency
- PIFA w. 1.5 pF - No match between S11 and Efficiency
- PIFA w. 2.2 pF - Good match between S11 and Efficiency
- PIFA w. 2.7 pF - Slight match between S11 and Efficiency
- PIFA w. 4.7 pF - No match between S11 and Efficiency

4.3 Review of the requirements

In this section, the requirements will be reviewed for the purpose of seeing if the prototype meets the requirements. The requirements review will be those seen in table 3.1. The review of the requirements is seen in table 4.1.

Is the requirements full filled yes/no	
R1	Yes
R2	No*
R3	No**
R4	No

Table 4.1: *In some instances the requirement is fulfilled. This requirement is derived from AT&T as for what they want. But in Europe, this requirement does not exist and it might be different from other Providers in the USA. **Some of the bands are covered by antennas.

4.4 Discussion

To mitigate some of the problems found when testing the antenna, certain methods can be used. First of the upper band which the project excluded from the work. These examples can also use combined with other techniques such as meandering and switches. This will not be explored further in this work but could make the design more efficient and more usable in a real-world scenario. The methods could all be a part of the next step in development as, they could improve the prototype, and would be explored in more detail if the time period of the project was not a constraint.

4.4.1 Upper band matching

When looking at figure 3.25, it is seen that the antenna is resonant in at more than one frequency range. This upper frequency resonance seen between 2.5 and 3 GHz for some of the antennas could be used to match the antenna to an upper frequency LTE band. Looking at the plot it is seen that different states with different capacities are needed to match the resonance to the upper band. It could be explored further if the antenna design needs modification to comply with the upper band spectra.

4.4.2 Bandwidth

To limit the states needed the expansion of bandwidth can be obtained in several ways. One could be dual resonance, where resonances are placed close enough together when looking at S11 that the bandwidth can be increased. This can be done by adding a second capacitor, but further exploration is needed to determine if the design is effective. This can be seen simulated in CST in figure 4.7

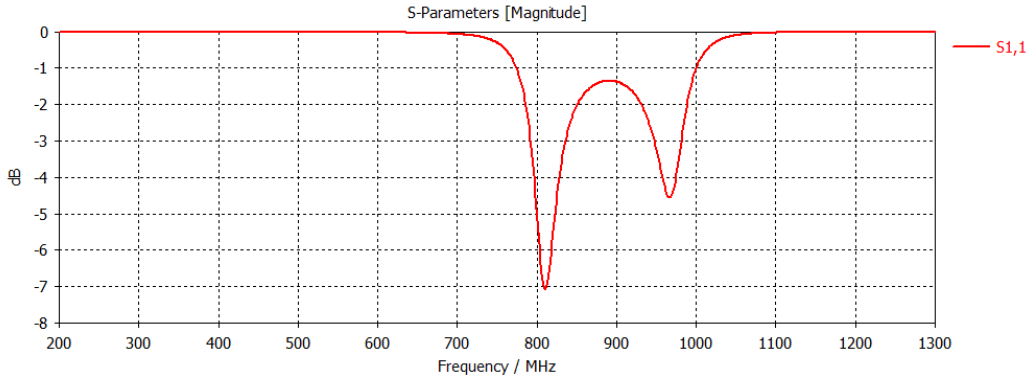

Figure 4.7: S11 Dual ressonance simulation.

This simulation is made with a model that look like this in CST. Depicted in figures 4.8,4.9 and 4.10.

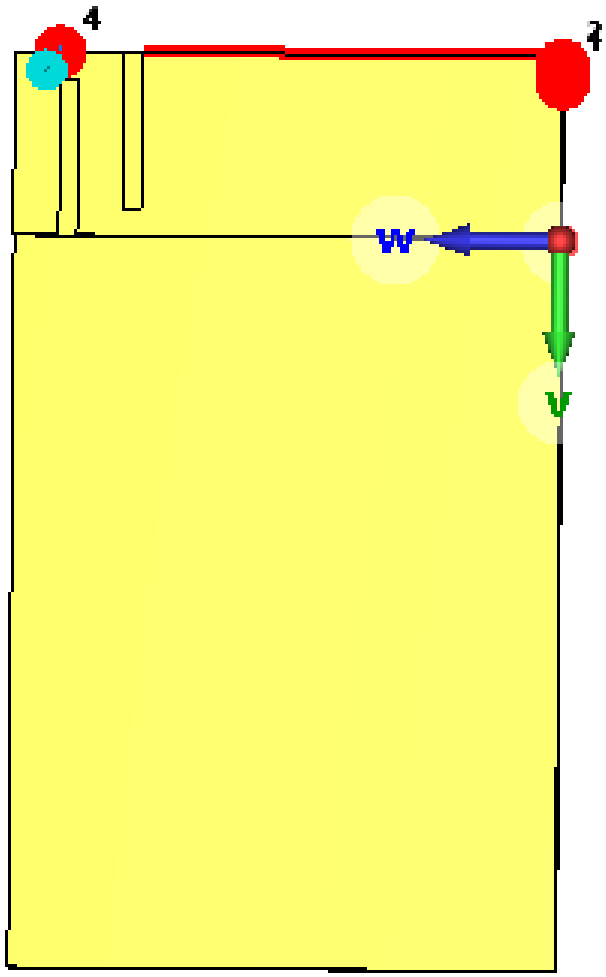

Figure 4.8: Front view of PIFA design with 3 capacitors.

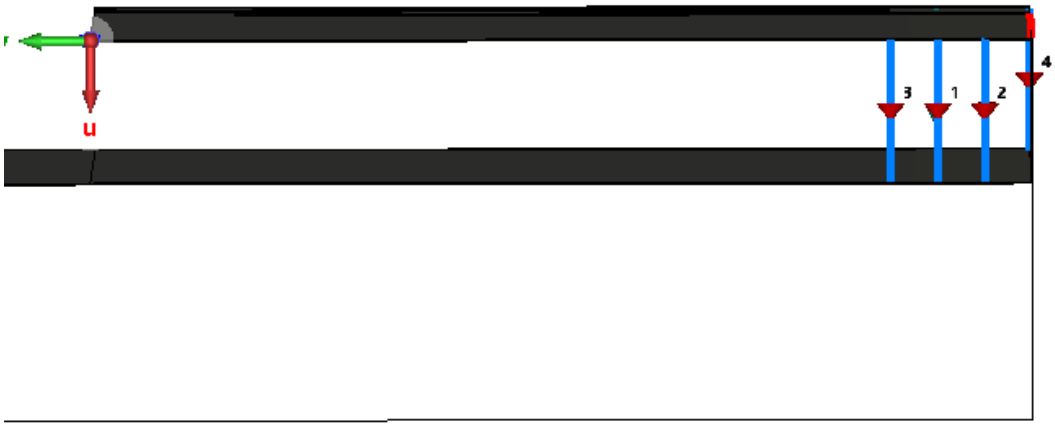

Figure 4.9: View from the feed side of PIFA design with 3 capacitors.

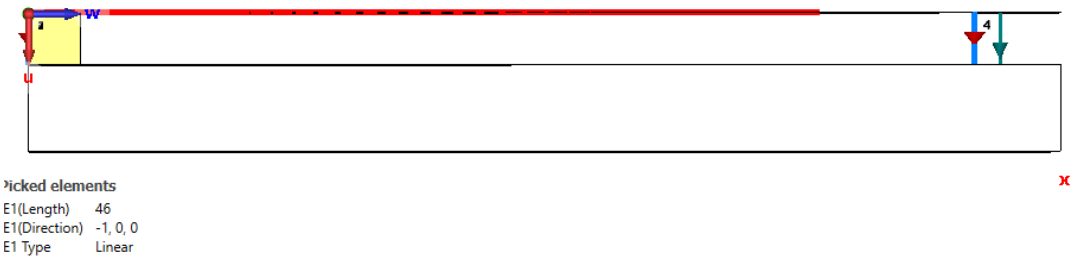

Figure 4.10: View from the short side of PIFA design with 3 capacitors.

The ports are listed below:

- Port 1 - Signal feed
- Port 2 - Capacitor 3 pF
- Port 3 - Capacitor 14 pF
- Port 4 - Capacitor 0.387 pF

The model still needs to be tuned better to be able to work. But this may be a possibility to increase the bandwidth.

As bandwidth is increased the need for different states decreases. So if the bandwidth is double half the states should be needed. But overlapping between states should be considered.

4.4.3 Consistency between measurements

As the antennas are made by hand with thin cobber plates cut by scissors the manufacturing of the different antennas can have impacted the different antennas. Slight discrepancies between antennas, which can affect the results. As it is hard to make the antennas perfectly similar. This could be somewhat avoided by manufacturing part by machine. This might make the tolerances lower as the machining process is probably more precise than doing it by hand. Also, this allows the antenna to be made more sturdy and not easily bend out of shape or break. If the project were to continue machining the antenna part would take some variables away when testing the antenna. Another solution to the problem could be to make a re-configurable antenna, that has the option to switch between capacities, this eliminates the need to produce an antenna pr. capacity. This method would probably be preferred when testing is over and the capacities are verified.

Chapter 5

Conclusion

When looking at the initial problem in the case given in the project, in section 1.1. The case requirements can be seen in table 1.1. These requirements were the basis of the preliminary analysis where different antenna topics are explored. LTE IoT devices were explored to gain knowledge before looking into the antenna theory. The topics are related to gain, directivity, and efficiency of the antenna as these are crucial to the requirements of LTE devices in the USA, because of the efficiency requirement. This is found in chapter 2.

After a short exploration of the theory, some designs were explored. The designs chosen were IFA and PIFA. As the two types of antennas are simple and have their advantages and disadvantages. The design chosen was PIFA because of the voltages being lower and closer to the open end of the antenna. As this can be a problem with capacitors if the voltage is very high. The antenna was first simulated and then built as multiple prototypes. This is done to ease testing, for testing different states. The S11 parameters indicated that there was a problem with coverage, and this was confirmed when testing the antenna efficiency. As the efficiencies did not cover all bands or match all S11 parameters. This is found in detail in the chapters 3 and 4.

When looking if the requirements were fulfilled or not, only one requirement was fulfilled fully, as seen in table 4.1. But it is seen that the concept has some merit as the capacitor did indeed change the antenna's center frequency, but not in all instances. Therefore as a proof of concept, it is shown that the antenna is tunable with a capacitor, but more is needed to improve the performance of the antenna. As the bands that were chosen were mostly uncovered. So one can conclude that it is possible to tune the antenna in this manner, but the effectiveness of tuning the antenna to the specific bands fails in this project.

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Appendix A

PIFA short width simulation

When testing different configurations of the PIFA the width of the short was also simulated in CST. To see what effect the short had on the S11 parameter. The plot of the PIFA S11 with different short widths(W) is depicted in figure A.1.

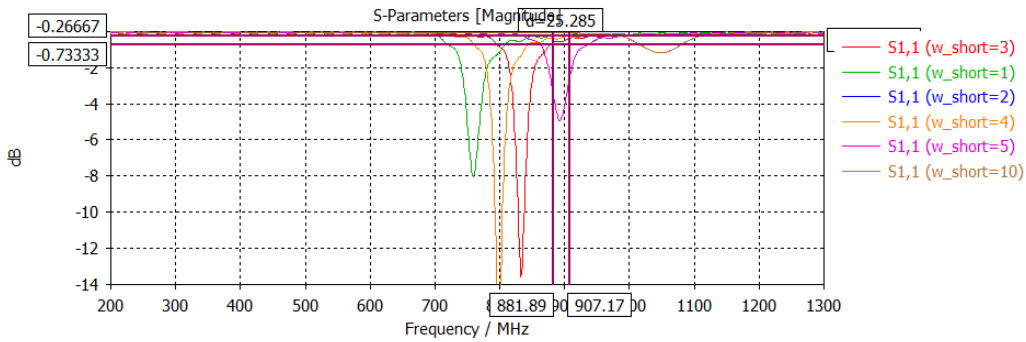

Figure A.1: PIFA varying short width. To see the effect on S11 parameter.

From this simulation, the width was chosen to be 3 mm as the width of mm has good performance without being too small. It is all so easier when manufacturing the antenna as the short would be quadratic.

Appendix B

Efficiency measurement in MVG Star Gate 24 chamber at AAU - Setup

The measurement of the antenna efficiency was done in MVG Star Gate 24 chamber at AAU.

B.1 Equipment

Besides the chamber the equipment used for the measurement is listed below:

- Rohde & Schwartz ZNB VNA 9 kHz - 8.5 Ghz, AAU nr: 128541.
- Wavestudio v. 22.4.0 software.
- MVG SH400 - dual ridge horn antenna.

B.2 Setup

The antenna was placed on the middle platform for all measurements it is seen in the chamber with the MVG SH400 horn antenna in figure B.1

Figure B.1: MVG SG24 chamber seen with MVG SH400 used for calibration.

In the sections below it can be seen that there is used one ferrite core on each antenna below during the measurement.

B.2.0.1 PIFA w. 0.5 pF capacitor

The placement of the antenna seen in figures B.2,B.3 and B.4.

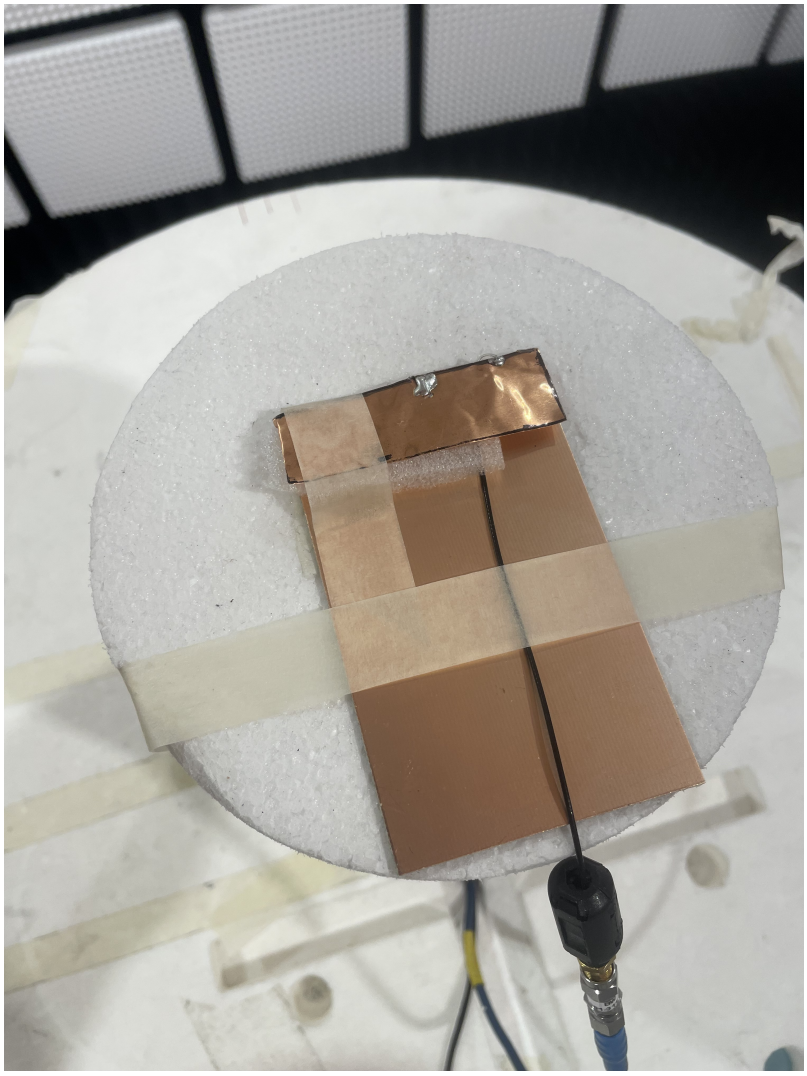

Figure B.2: PIFA w. 0.5 pF placement

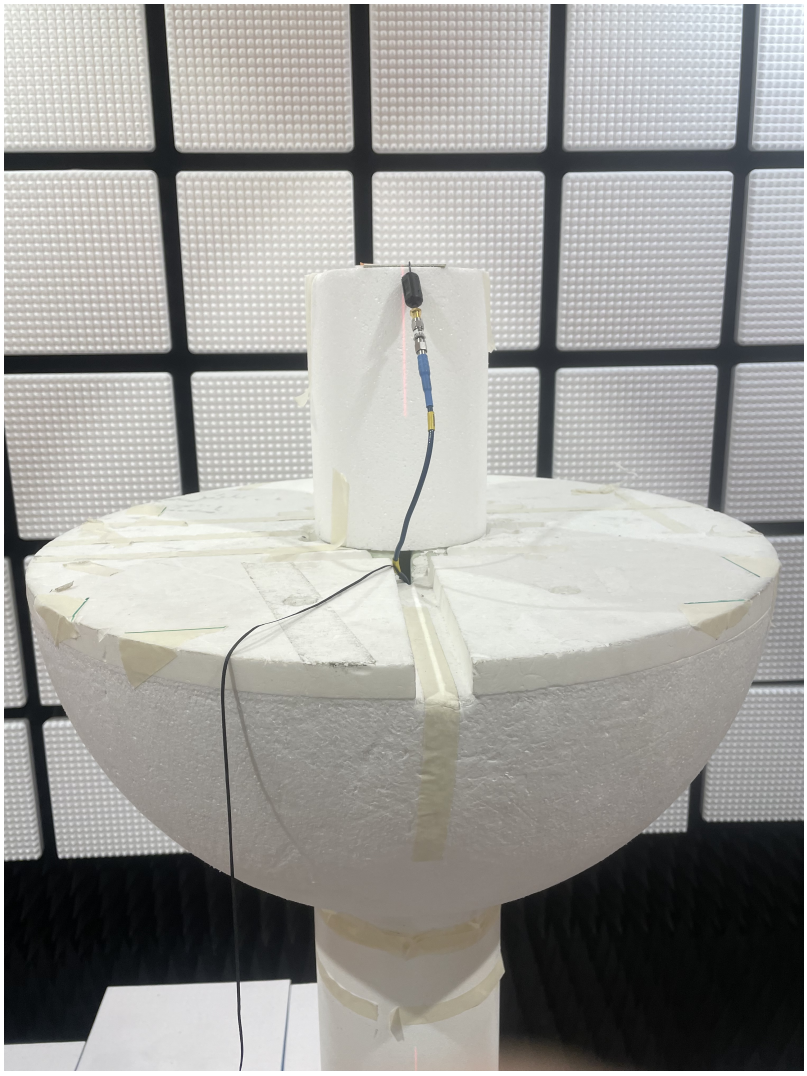

Figure B.3: PIFA w. 0.5 pF

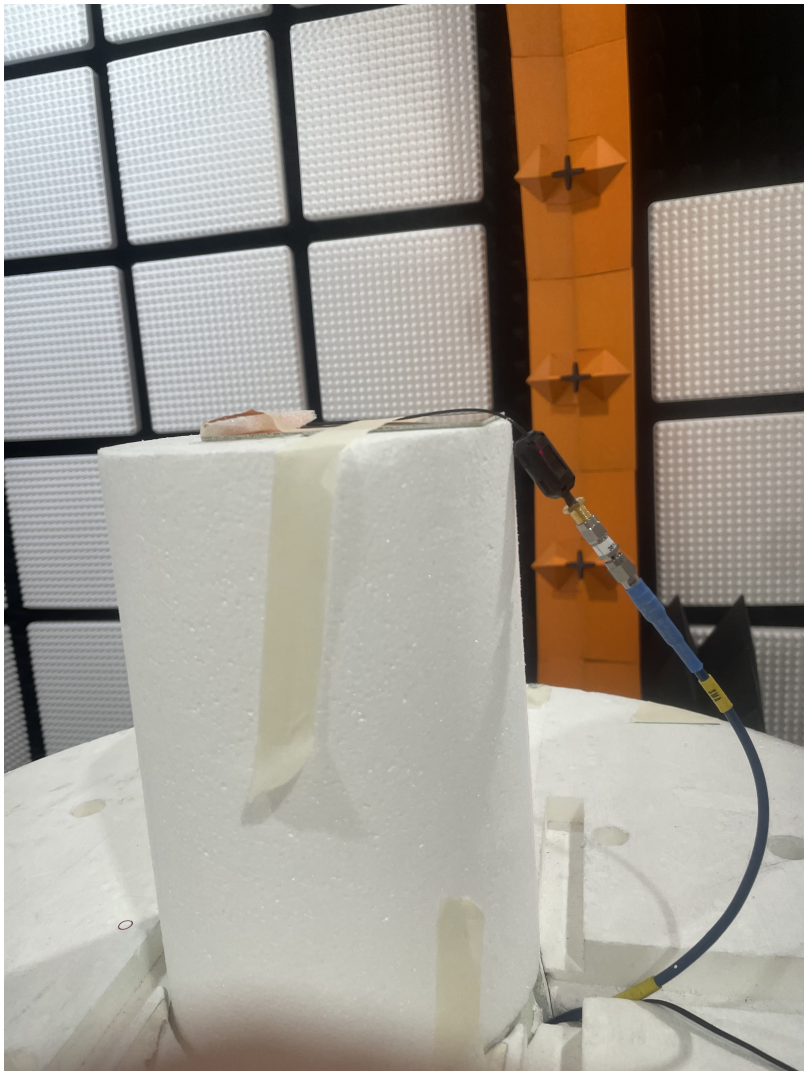

Figure B.4: PIFA w. 0.5 pF

B.2.0.2 PIFA w. 1.5 pF capacitor

The placement of the antenna seen in figures B.5,B.6 and B.7.

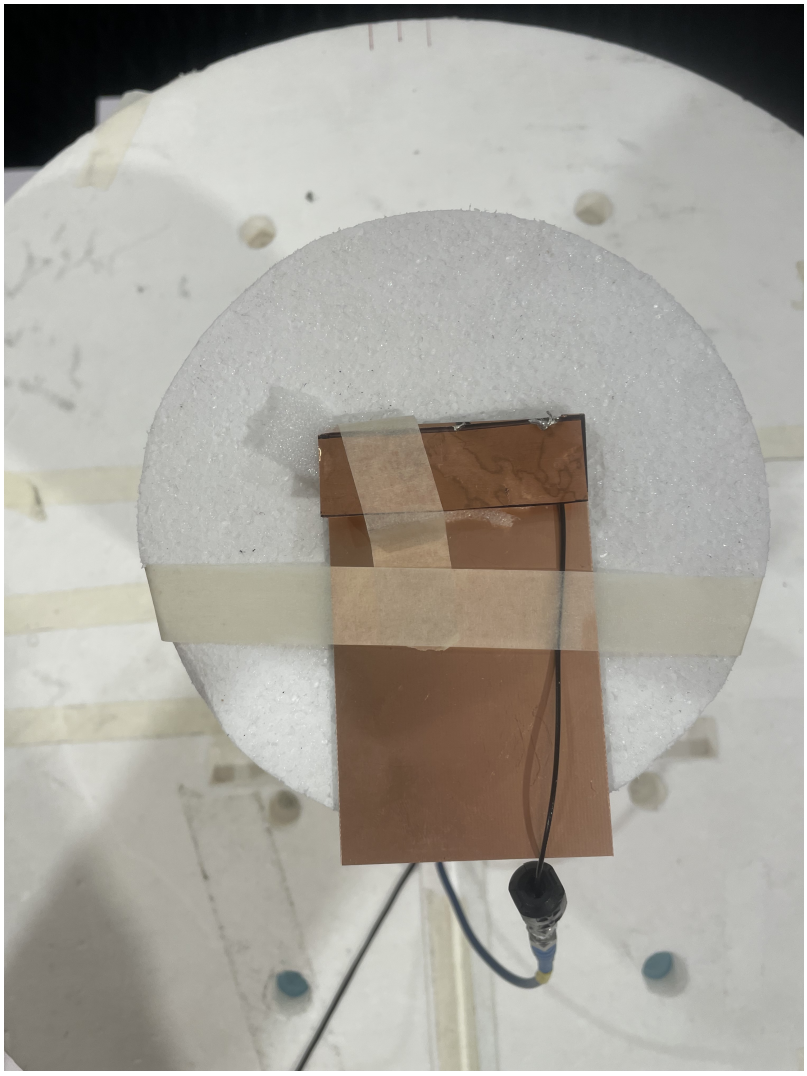

Figure B.5: PIFA w. 1.5 pF placement

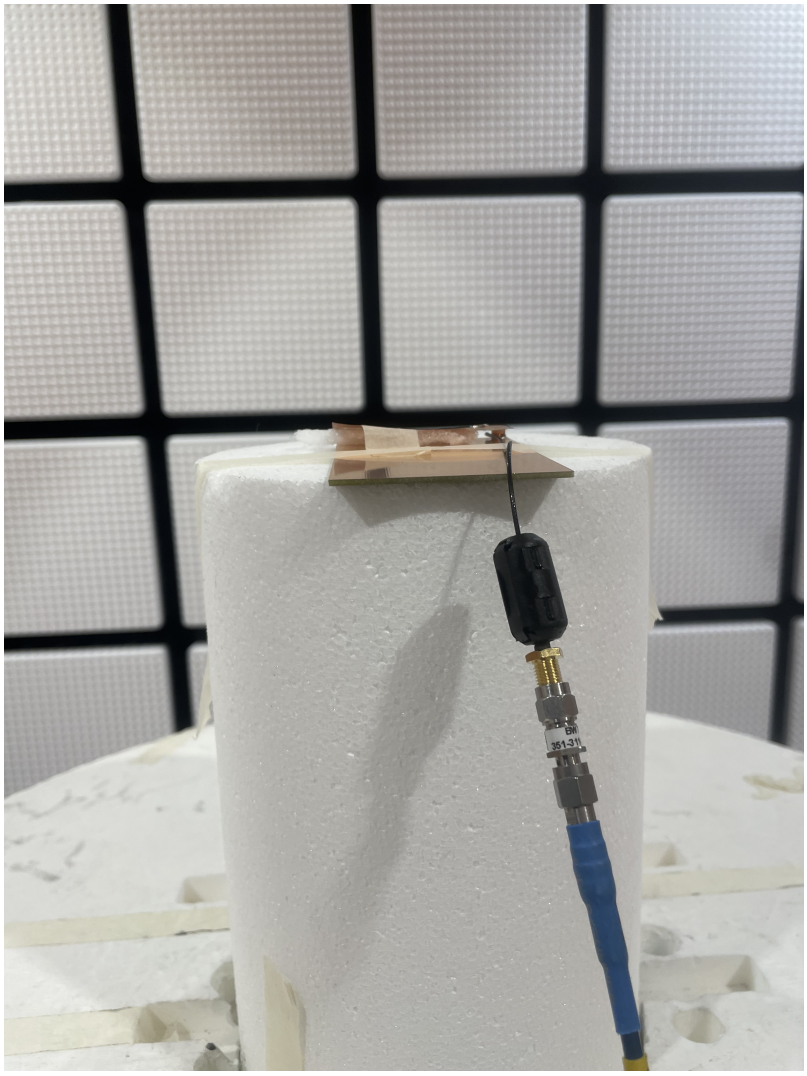

Figure B.6: PIFA w. 1.5 pF placement

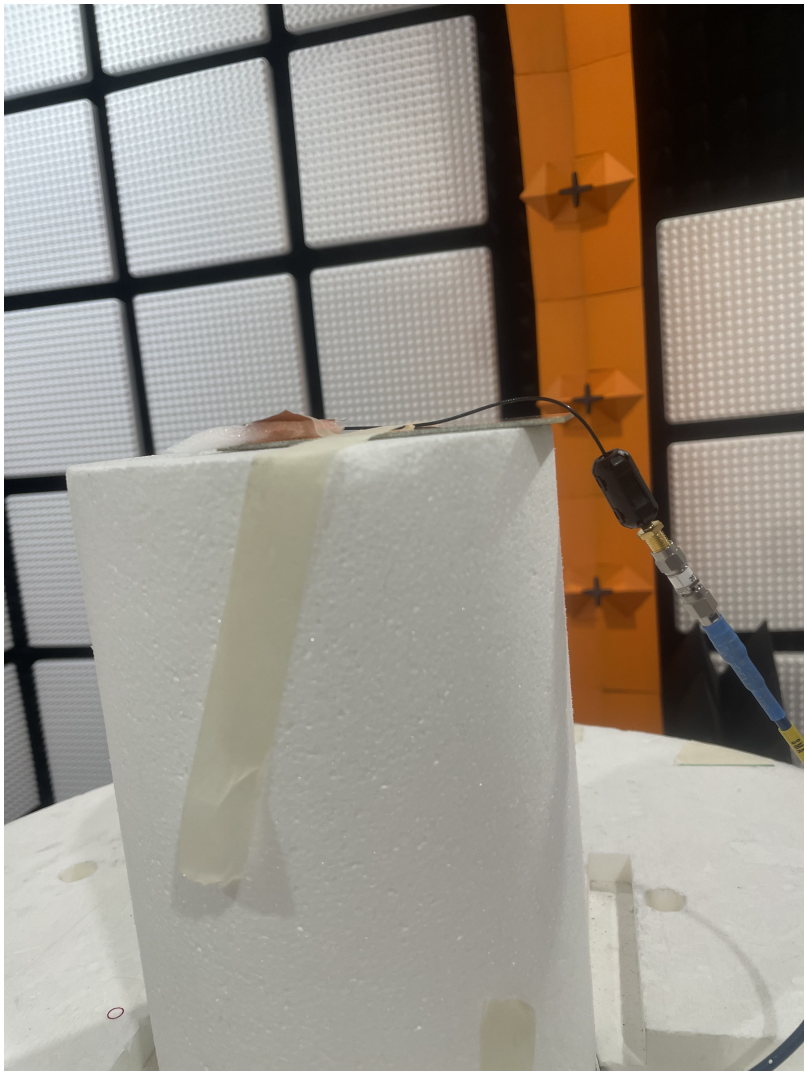

Figure B.7: PIFA w. 1.5 pF placement

B.2.0.3 PIFA w. 2.2 pF capacitor

The placement of the antenna seen in figures B.8 and B.9.

Figure B.8: PIFA w. 2.2 pF placement

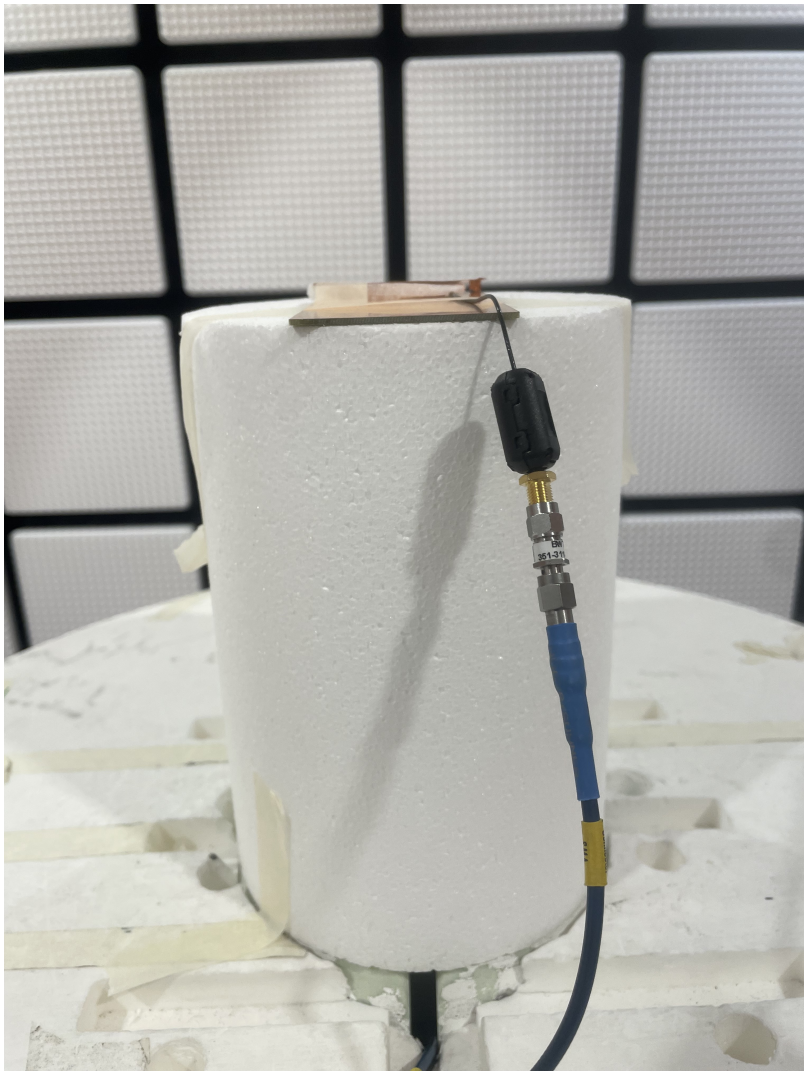

Figure B.9: PIFA w. 2.2 pF placement

B.2.0.4 PIFA w. 2.7 pF capacitor

The placement of the antenna seen in figures B.10 and B.11.

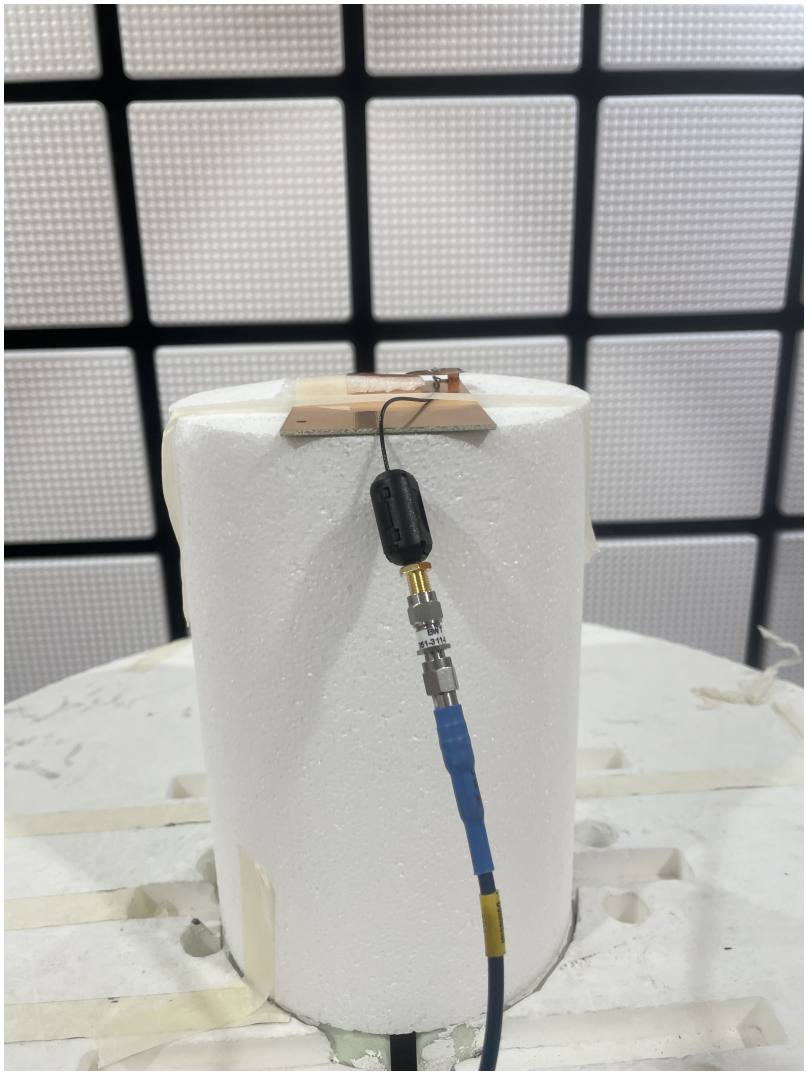

Figure B.10: PIFA w. 2.7 pF placement

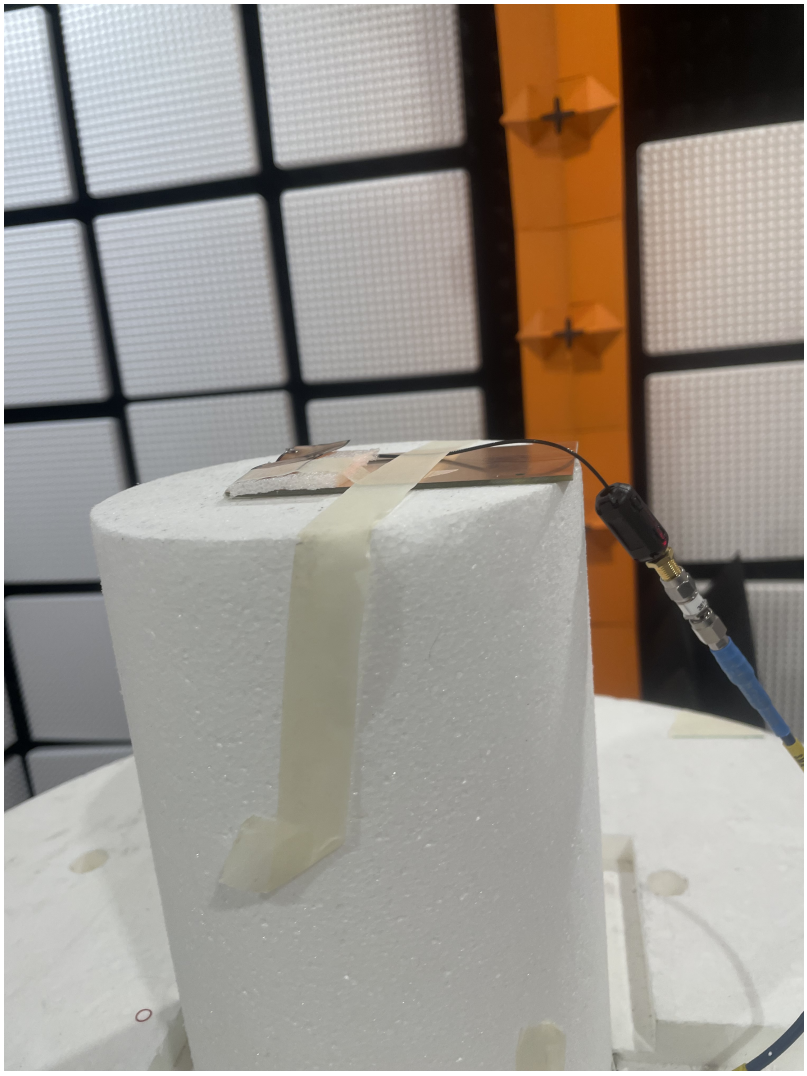

Figure B.11: PIFA w. 2.7 pF placement

B.2.0.5 PIFA w. 2.7 pF capacitor

The placement of the antenna seen in figures B.12,B.13 and B.14.

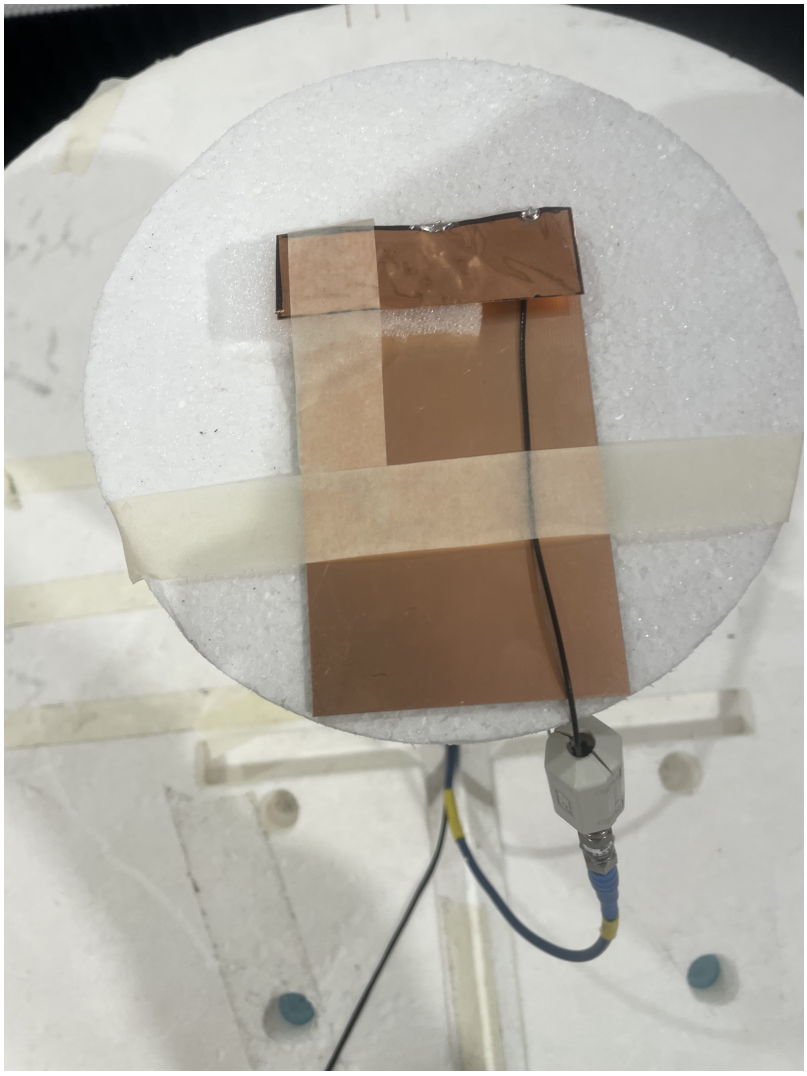

Figure B.12: PIFA w. 4.7 pF placement

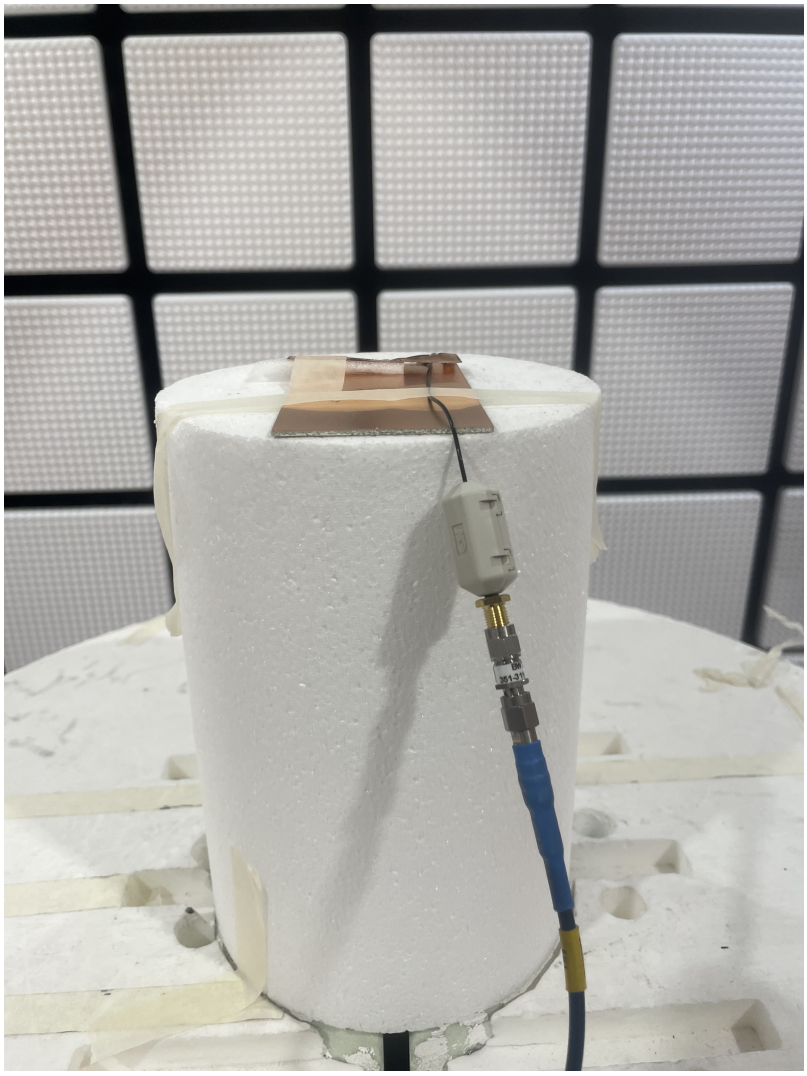

Figure B.13: PIFA w. 4.7 pF placement

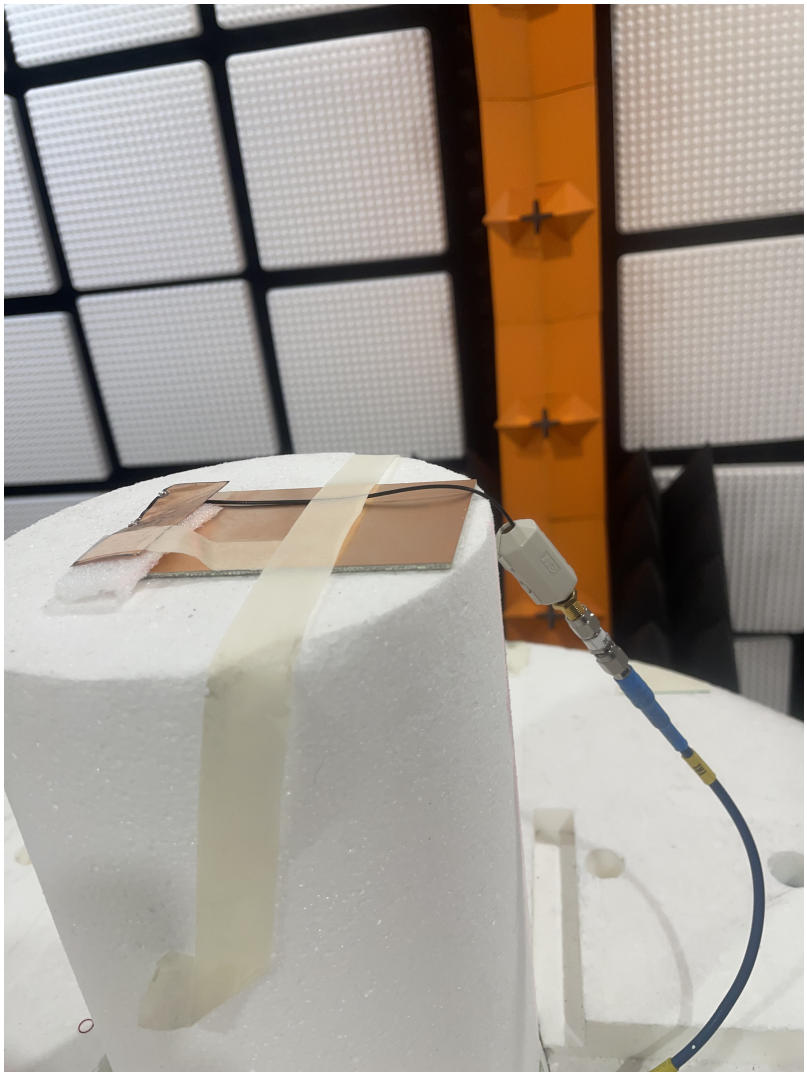

Figure B.14: PIFA w. 4.7 pF placement