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Mini Chip Antenna Integration

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Bachelor of Engineering

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The purpose of this thesis work was to implement two mini chip antennas instead of tilt whip dipole antenna to Pexraytech company's X-ray scanning panels. Panels are used by military and police bomb squads alongside construction works for inspection of water pipes and therefore expected to have robust design.

Because of radiation restrictions scanning panels must have distances between user and the equipment while in use. Therefore, good communication is needed between panel generator and the computer. X-ray panels receive and transfer the data through Wi-Fi network and panels use spectrum of 2.4GHz Wi-Fi frequency.

Antenna PCBs were designed using KiCad program. All the tests were carried out with network analyser. Most of the simulations and calculations for the matching circuits were done with web based programs.

Mini chip antennas were soldered to a flame retardant glass-reinforced epoxy laminate(FR4) printed circuit board (PCB) with balancing components. Primary antenna PCB is placed panel's handle which is 3D printed from reinforced plastic and the secondary antenna is attached to the panel's left side closure which is manufactured from aluminium as well as the panel's main frame.

The result of the implementation is mostly successful but still there is room for improvements. Panel can receive and transfer data through Wi-Fi network effortlessly. For the next panel version these antenna designs can be used with a third chip antenna which is still under development. Newly developed x-ray generator might use one of this antenna implementation in the future.

Keywords	X-Ray, Wi-Fi, Chip Antenna

Contents

List of Abbreviations

RF	Radio Frequency.
PCB	Printed Circuit Board.
FR4	Flame Retardant Glass-Reinforced Epoxy Laminate.
IC	Integrated Circuit.
Z_S	Source Impedance.
Z_L	Load Impedance.
Z_O	Characteristic Impedance.
VSWR	Voltage Standing Wave Ratio.
Γ	Reflection Coefficient.
LAN	Local Area Network.
kV	Kilovolt

Glossary

X-Ray	Electromagnetic Radiation or Roentgen Radiation.
Wi-Fi	Wireless Fidelity or Wireless Local Area Network.
IP55	Product protection rate against dust ingress that could be harmful for the normal operation of the product but is not fully dust tight. It is protected against solid objects and water jets projected by a nozzle (6.3mm) from any directions.
Dipole antenna	Two conductors of equal length oriented end-to-end with the feedline connected antenna.
MIMO	Multiple input multiple output. A method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation.

1 Introduction

Pexraytech scanning panel is a portable x-ray equipment ,as seen in figure 1, which has communication with x-ray generators and computer through Wi-Fi or ethernet cable.

Figure 1: Pexraytech scanning panel

The purpose of this thesis work was to implement two mini chip antennas instead of tilt whip dipole antenna and prove the benefits of having two chip antennas instead of one whip tilt antenna. Working principal of the panel is that x-ray generator shoots high energy electromagnetic waves through the object which is in front of the scanning panel and panel scans the image and transfers it to the computer digitally. Originally panel used a whip tilt dipole antenna connected to the right side of the panel. Dipole antenna establishes the communication effortlessly but due to design of the antenna it is prone to be broken with the medium light impacts which customers complained about and not considered as the best option. Therefore, chip antennas (dielectric resonator antenna) were considered as a better replacement for this project.

Chip antennas or in other word dielectric resonator antennas are mostly used at microwave frequencies and higher. Chip antennas are made of ceramic material and mounted on the copper layer of the PCB or on ground plane. Transmitter circuit's resonator material carries radio waves inside to the circuit and standing waves formed by bouncing waves back and forth between the resonator walls which are partially transparent to radio waves, allowing the power to radio into space. Chip antennas do not have any metal parts, which become lossy at high frequencies, dissipating energy. Therefore, chip antennas can have lower losses and be more efficient than metal antennas at high microwave millimetre wave frequencies [1].

Implementing a mini chip antenna into the handle, as seen in figure 2, provides good protection for the antenna and sleeker design for the panel.

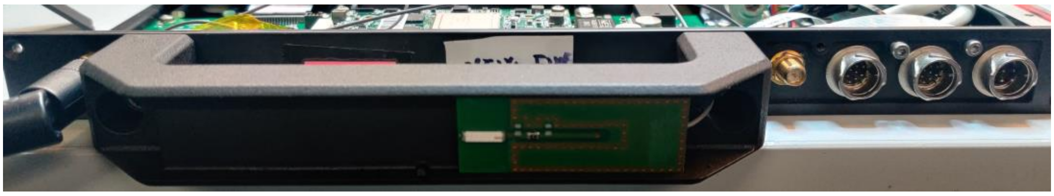

Figure 2:Panels handle and antenna

In addition, implementing second antenna to the left side of the panel, as seen in figure 3, might improve communication. For the first antenna's signal wave propagation handle must be made of insulated material and for the second antenna's signal wave propagation left side panel closure, which is made of conductive material, needs to be milled and some material needs to be cut off.

Figure 3: Left side panel closure and antenna

2. Theory and Calculations

Wi-fi signal frequency protocol is regulated all around the world between 2401MHz to 2483MHz as seen on the table 1 therefore when designing antenna this regulation must be taken into account.

Table 1: Wi-fi frequency range [2]

Channel	F_0 (MHz)	Frequency range (MHz)	North America	Japan	India	Most of world
1	2412	2401–2423	Yes	Yes	Yes	Yes
2	2417	2406–2428	Yes	Yes	Yes	Yes
3	2422	2411–2433	Yes	Yes	Yes	Yes
4	2427	2416–2438	Yes	Yes	Yes	Yes
5	2432	2421–2443	Yes	Yes	Yes	Yes
6	2437	2426–2448	Yes	Yes	Yes	Yes
7	2442	2431–2453	Yes	Yes	Yes	Yes
8	2447	2436–2458	Yes	Yes	Yes	Yes
9	2452	2441–2463	Yes	Yes	Yes	Yes
10	2457	2446–2468	Yes	Yes	Yes	Yes
11	2462	2451–2473	Yes	Yes	Yes	Yes
12	2467	2456–2478	No except CAN	Yes	Yes	Yes
13	2472	2461–2483	No	Yes	Yes	Yes
14	2484	2473–2495	No	11 only	No	No

In electronics when designing a PCB for high speed and high-frequency devices, it is necessary to match the impedance of source and load. Impedance matching is the process of removing mismatch loss [3]. In order to reduce power reflection from the antenna or load reflection coefficient needs to be minimized. That is one of the main tasks for designing well propagating antenna. Antenna or load impedance has to match to the transmission line in order to get perfect matching. That is, ZL=Z0 (or Zin=Z0). Smith chart is the tool which helps to make calculation for matching the circuit. Smith chart is a graphical mapping of the reflection coefficient magnitude and phase to specific combinations of resistance and reactance or conductance and susceptance and can be seen in figure 4 [4].

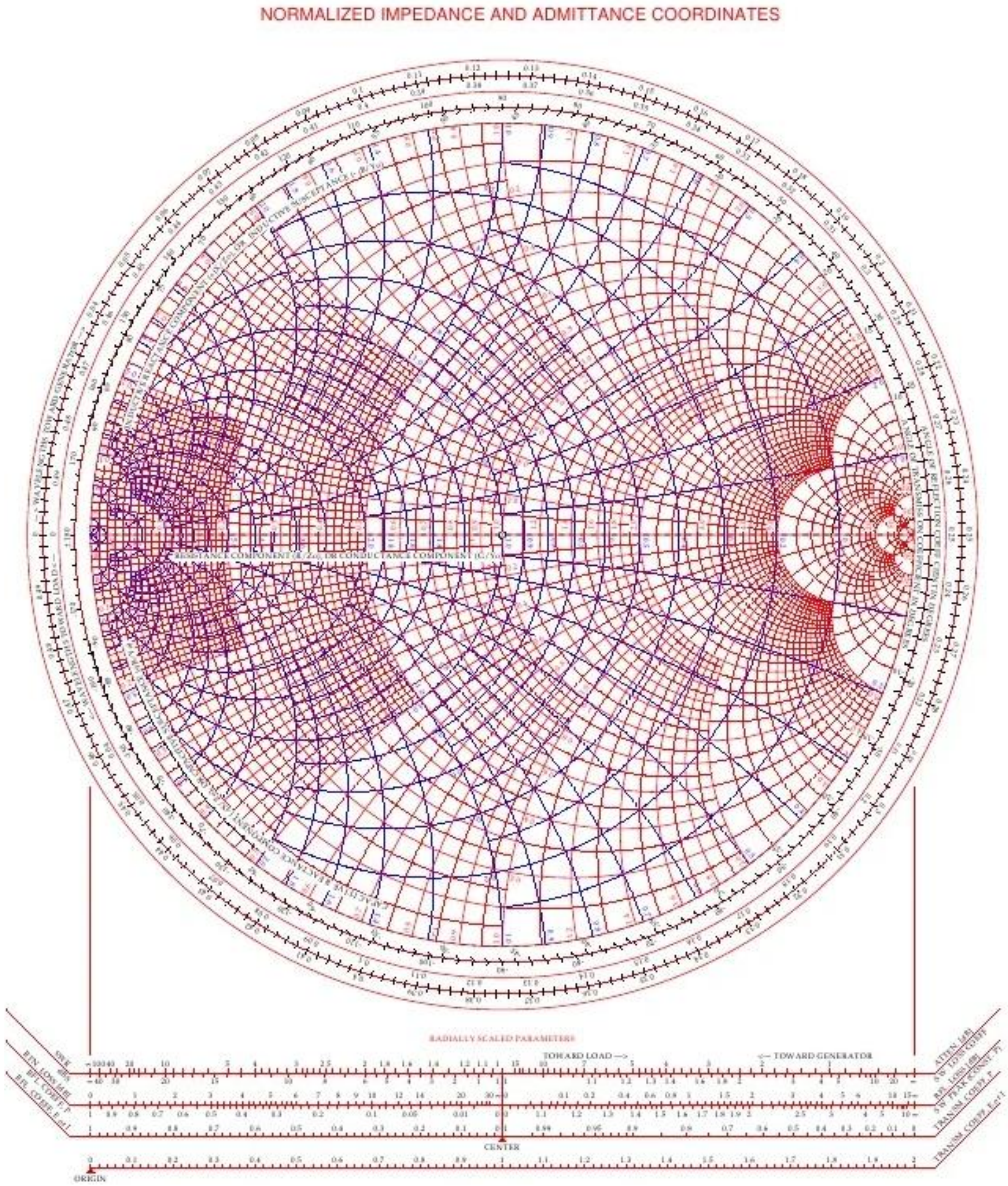

Figure 4: Smith chart [5]

By using the Smith chart complex reflection coefficient and complex impedance or admittance can be found. When real and imaginary part of impedance are solved in terms of the reflection coefficient constant values of resistance and reactance are traced out as circles and arcs on the Smith chart. When termination or load is not matched to the system impedance, unwanted reflection of power from the input of the termination occurs. These reflected waves are matched with the transmitted signals. And it may cause delays in data, phase distortion, and reduce the ratio of signal to noise or in other words if the impedance is not matched, the signal reaches the load and reflects back to the source. It will produce a standing wave. Once placed matching component ahead of the termination reflection can be eliminated and the termination becomes matched. Thus, transmission of power to the component is improved. In Smith Chart, impedance of the load ZL has to move towards the centre of the chart, where the reflection coefficient Γ is zero and that needs to be calculated for required frequencies for the project. Impedances on the Smith chart are placed on the horizontal axes and short circuit is placed on the left side of the chart and open circuit or infinite impedance is placed on the right side of the chart. Inductive terminations are in the upper half of the chart and capacitive terminations are in the lower half of the chart. When adding series components to the circuit it moves termination point along the red or impedance curve and shunt components moves termination point along the blue or admittance curve.

Series inductor: An inductor has a normalized impedance given by**:**

$$Z_{ind} = \frac{j2\pi f L}{Zo} \qquad (1)$$

Series inductor will move the impedance zL along the constant resistance circles of the Smith Charts. Hence, if the reactance (*X*) of the load impedance ZL is negative, series inductor can be used to cancel out this reactance, making the input impedance purely real. In equation *f* is frequency, and *L* is the inductance in Henries.

$$Z_1 = Z_L + Z_{IND} = R + j\left(X + \frac{2\pi f L}{Zo}\right) \quad Z_{IND} = \frac{j2\pi f L}{Zo} \qquad (2)$$

Series capacitor: A capacitor has normalized impedance given by:

$$Z_c = \frac{1}{jZo2\pi f C} = \frac{-j}{Zo2\pi f C} \qquad (3)$$

$$Z_L = R + jX \implies Z_1 = Z_L + Z_c = R + j\left(X - \frac{1}{jZo2\pi f C}\right) \qquad (4)$$

Series capacitor will move the impedance zL along the constant resistance circles of the Smith Charts, but in the opposite direction that the inductor moves it. If the reactance (*X*) of the load impedance ZL is positive, series capacitor can be used to cancel out this reactance, making the input impedance purely real [6]. In equation *f* is frequency, and *C* is the capacitance in Farads.

Shunt Inductors: The normalized admittance of an inductor *y_ind* is given by:

$$y_{ind} = \frac{1}{Zind} = \frac{Zo}{j2\pi fL} = \frac{-jZo}{2\pi fL} \quad (5)$$

Admittance of an inductor is entirely imaginary and the result of adding an inductor in shunt is to change the susceptance of the antenna (load), that is, only altering the imaginary part of the antenna's admittance. The result of a shunt inductor is to move the antenna impedance/admittance in the counter-clockwise direction along the constant conductance circles.

Shunt Capacitors: The normalized admittance of a capacitor *y*_C is given by:

$$y_{C} = \frac{1}{Zc} = jZo2\pi fC \quad (6)$$

Shunt Capacitors move an admittance (the antenna) in the clockwise direction along the constant conductance circles [7].

Standing wave ratio (SWR) is a measure that defines how well the antenna impedance is matched to the connected Tx line impedance. A value less than 1.5 is desirable. A low flat SWR enables maximum power transfer from the transmission line. SWR can be expressed as the reflection coefficient Γ, which refers to the power reflected from the antenna. Γ is a function of load impedance, ZL , and characteristic impedance, ZO

$$SWR = \frac{1+\Gamma}{1-\Gamma} \quad (7)$$

First of all, reflected power needs to be calculated by using the reflection coefficient and equation,

$$\Gamma = \frac{ZL - Zo}{ZL + Zo} \qquad (8)$$

Vector Network Analyzer (VNA) is the, the most fundamental device for antenna testing. One port VNA, which is the simplest and able to measure the impedance of an antenna, which this thesis work mostly focused on due to lack of a test chamber.

Measuring of an antenna's radiation pattern, gain and efficiency is more difficult and requires more equipment and RF isolated testing chamber.

3 Specification and Features

Like most of the devices which have radio frequency communication Pexraytech panel's RF system consist of 4 main parts.

- Wi-Fi module
- Coaxial cable
- Antenna
- Matching circuit

3.1 Wi-Fi Module

Panel uses Texas Instruments manufactured WL18MODGI industrial wi-fi module, as seen on figure 5, to send and transfer data from antenna [8].

Figure 5: Orientation of wi-fi module on the panel PCB

This module has integrated RF, power amplifiers (PAs), clock, RF switches, filters, passives, and power management which can be seen on the figure 6 functional block diagram. Module has capacity to work with two antenna at the same time with multiple input multiple output (MIMO) mode and configured as first antenna to be the master and second antenna to be the slave. WL18MODGI module has a Linux firmware support that is needed to communicate panel's own operating software which is based on Linux as well.

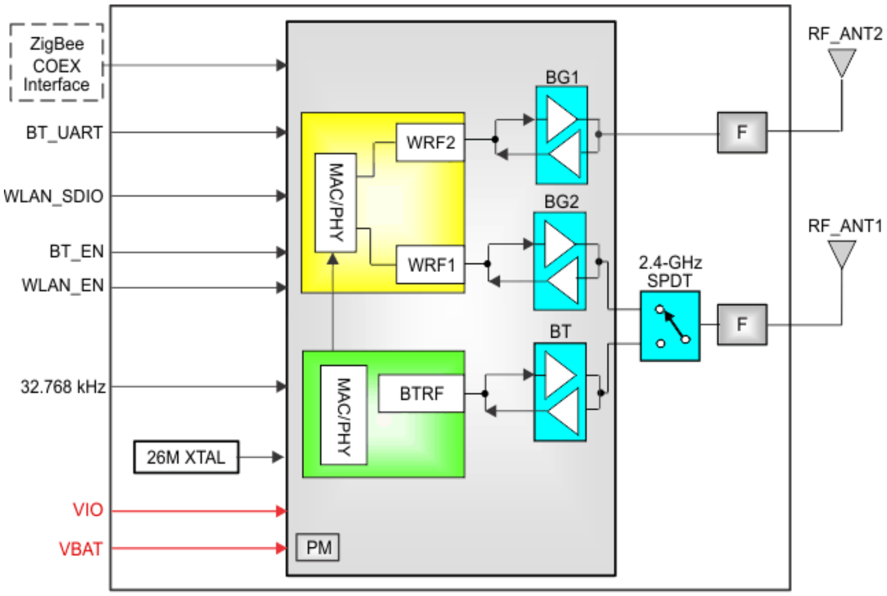

Figure 6: Functional block diagram [9]

3.2 Coaxial Cable

Panel provides connection between antenna PCBs and wi-fi module with two UFL to UFL female coaxial cable, as seen in the figure 7. First antenna which is located in the handle uses cable length of 40cm and for the second antenna which is attached to the side closure uses cable length of 80cm.

Figure 7: Coaxial UFL cable

3.3 Antenna

Scanning panel operates in 2.4GHz wi-fi frequency and chip antennas must be operating in this band and also must be small enough to fit in the panel’s closures. Therefore, as a primary antenna Johanson technologies 2450AT45A100 mini chip antenna and as a secondary antenna 2500AT44M0400 mini chip antennas were chosen. When designing a chip antenna PCB, grounded coplanar waveguide circuitry calculations need to be followed. On this project web calculator programs were used for calculating the grounded coplanar waveguide, as seen on the figure 8. To be able to use web calculator some information is needed to be entered which are, relative dielectric constant (ε_r) of the PCB track width (S) gap width (W) and dielectric thickness (h) of the PCB substrate. From these data only relative dielectric constant of the PCB can not be changed but changing any other information will have direct effect on the result of effective dielectric constant (ε_{ff}) and characteristic impedance (Zo). By adjusting the track and gap width needed result will be gotten.

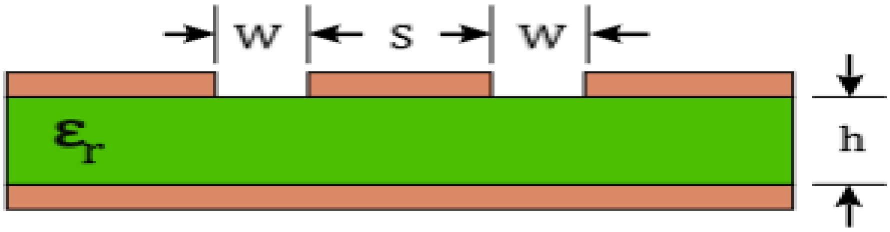

Figure 8: Coplanar waveguide measurements [10]

INPUT DATA	RESULT
Relative Dielectric Constant (ε_r): 4.6	Effective Dielectric Constant (ε_{ff}): 3.417
Track Width (S): 1.3 mm	Characteristic Impedance (Zo): 49.91 Ohms
Gap Width (W): 1.1mm	
Dielectric Thickness (h): 0.7mm	

Primary antenna chip is high gain SMD component, which can be seen in the figure 9, with 50 ohms impedance and frequency range is from 2400MHz up to 2500MHz. According to the data sheet of the antenna, when mounted vertically, as it is used in this project, it has 1.0 dBi average gain, 2.2 dBi peak gain and 9.5 dB min return loss.

Figure 9: 2450AT45A100 chip antennas. [11]

Secondary antenna is a wideband SMD component, which can be seen in the figure 10, with 50 ohms impedance and frequency range is from 2300MHz up to 2700MHz. When mounted vertically, as it is used in this project, bandwidth reduces to 190MHz, and antenna resonates between 2355MHz and 2545MHz. According to the data sheet of the antenna it has at 2380 MHZ and at 2600MHz 0.0 dBi average gain, 2.0 dBi peak gain and at 2450MHz 2.4 dBi, 2.5 dBi peak gain and 9.5 dBi min return loss

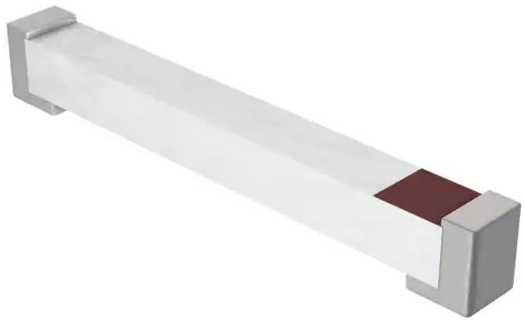

Figure 10: 2500AT44M0400 chip antennas. [12]

3.3.1 Design of Primary Antenna PCB

Johanson Technologies offers for this particular antenna three different antenna evaluation layout according to customers need and orientation.

Vertical orientation of the antenna layout, which be seen on figure 11, offers wide bandwidth (570 MHz) with -31.266dB return loss, as seen in figure 12. This type is considered as most useful for this project due to wide bandwidth.

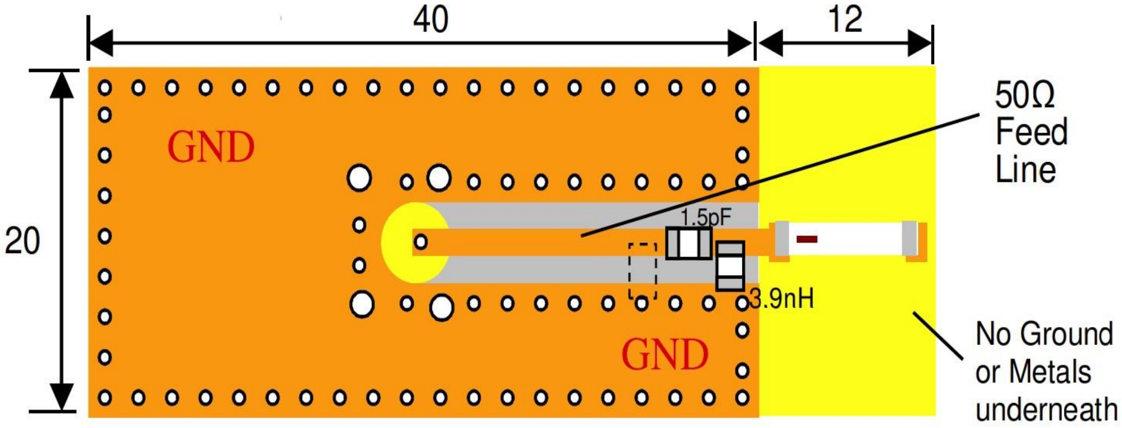

Figure 11: Vertical orientation [13]

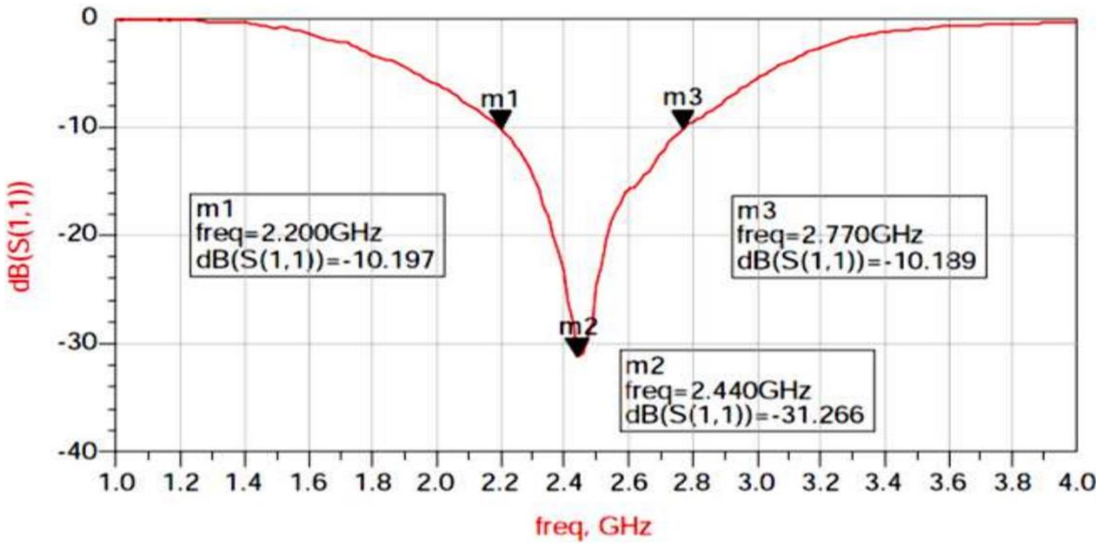

Figure 12: Return loss graph. [13]

Horizontal orientation type A antenna layout, which can be seen in figure 13, offers narrow bandwidth (239MHz) with -18.144dB return loss, as seen in figure 14. This option might be considered if **no metal zone** has to be narrow.

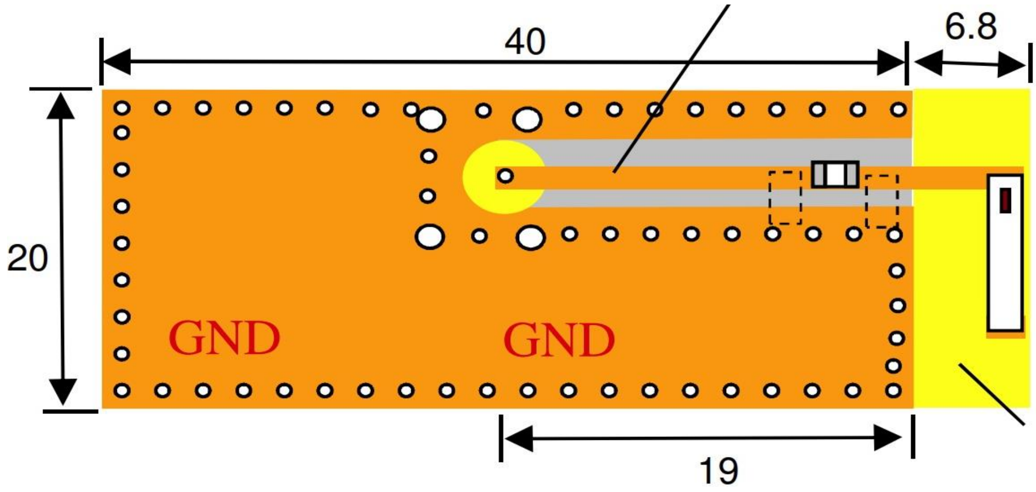

Figure 13: Horizontal orientation type A [13]

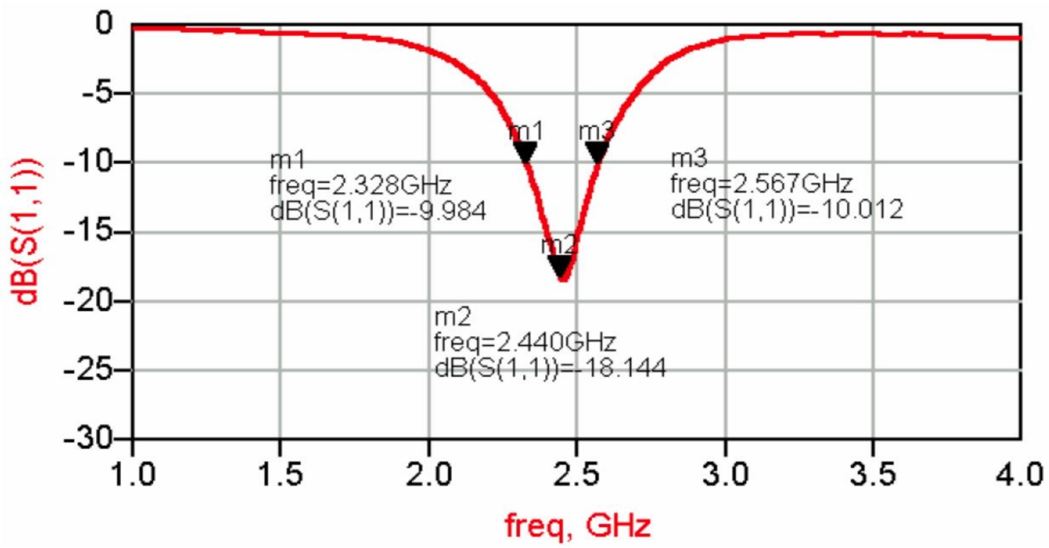

Figure 14: Return loss graph [13]

Horizontal orientation type B antenna layout, which can be seen in figure 15, offers mid narrow bandwidth (350 MHz) with -35.776 dB return loss, as can be seen in figure 16. This option might be considered if return loss aimed to be minimum.

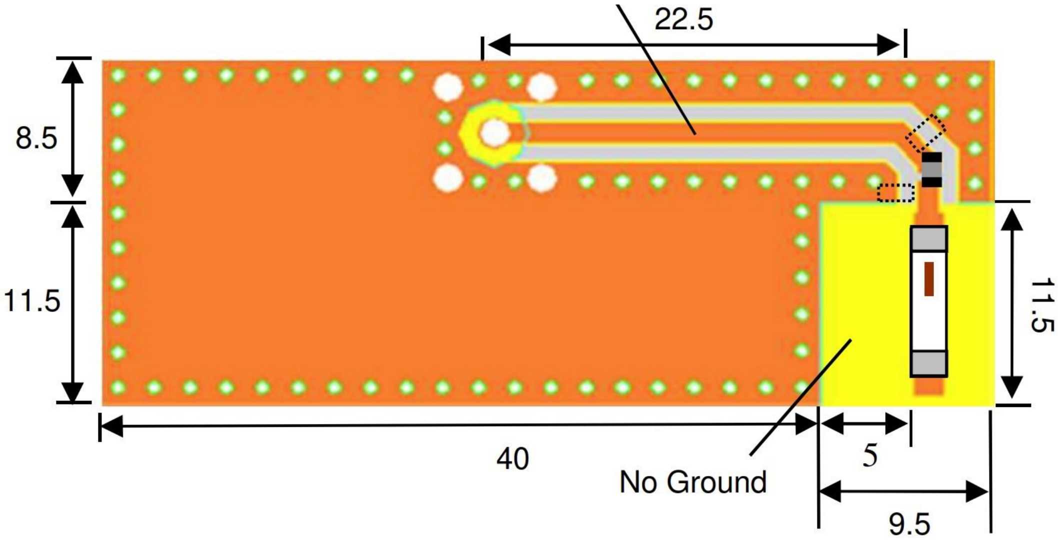

Figure 15: Horizontal orientation type B [13]

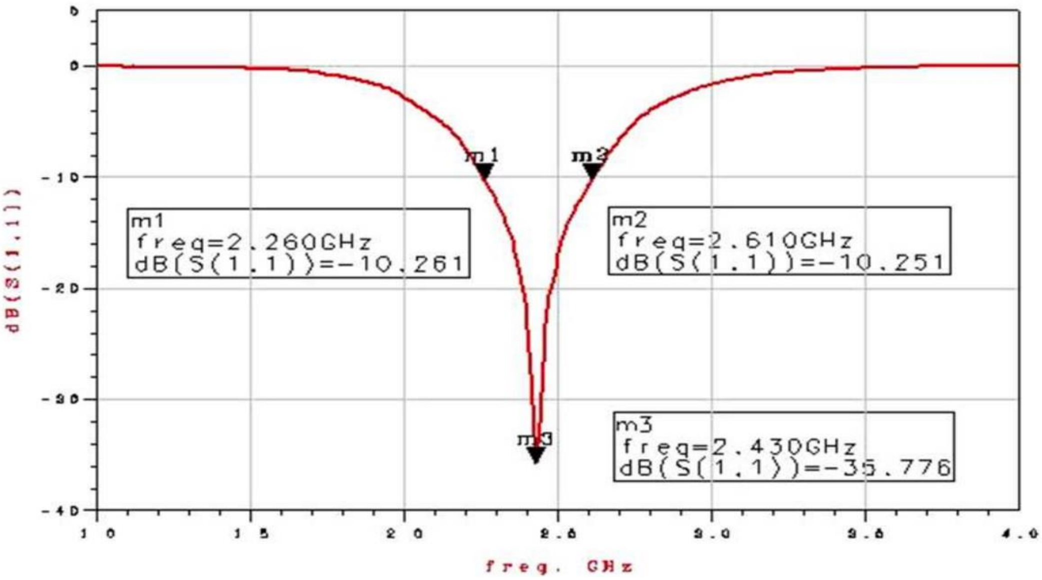

Figure 16: Return loss graph [13]

Antenna PCB was designed, as seen in figure 17, according to vertical orientation evaluation board. Board dimensions are clear on the data sheet of the antenna but track and gap width needed to be adjusted as mentioned according to grounded coplanar waveguide calculations. On the evaluation board SMA connector is used but for this project UFL connectors were better suited. For matching components PCB needed to have slots for a “pi” (or shunt-series-shunt) network, as clearly seen in figure 18.

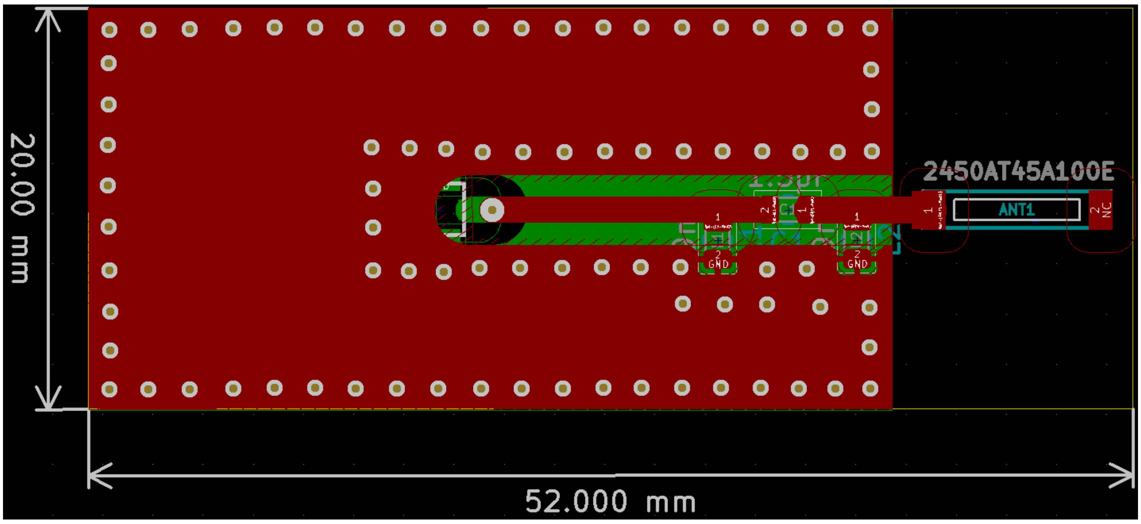

Figure 17: Antenna PCB design using KiCAD

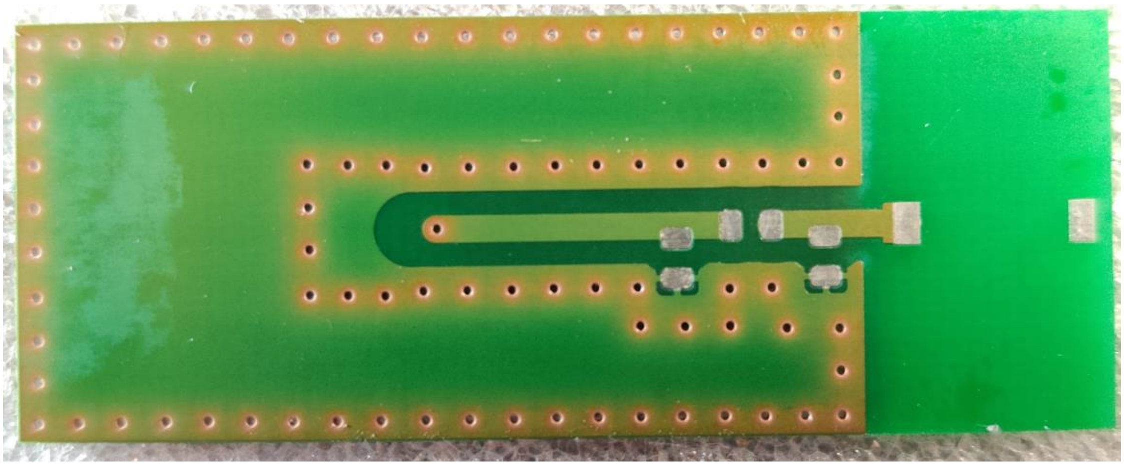

Figure 18: Printed Antenna PCB

3.3.2 Design of Secondary Antenna PCB

Johanson Technologies offers for this particular antenna two different antenna evaluation layout according to customers need and orientation.

Layout 1 antenna layout, which can be seen in figure 19, offers very wide bandwidth (960MHz) with -25.619 dB return loss, as can be seen in figure 20. This option might be considered if bandwidth needs to be very wide. Layout 1 is not considered to be the best option for this project since needed frequencies must be between 2401MHz and 2483MHz according to wi-fi frequency bandwidth.

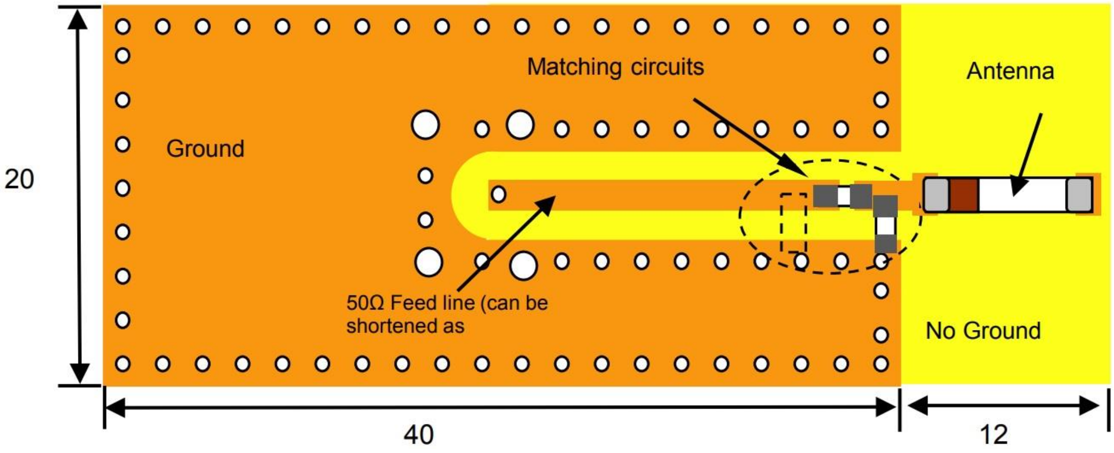

Figure 19: Layout 1 [14]

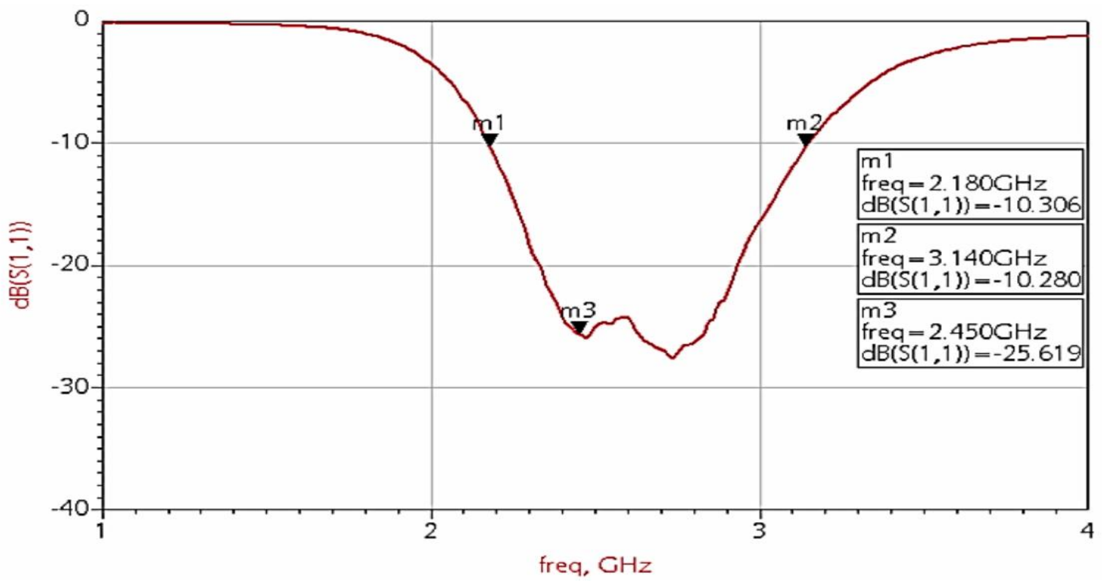

Figure 20: Return loss graph [14]

Layout 2 antenna, which can be seen in figure 21, offers narrow bandwidth (185MHz) with -37.746 dB return loss, as can be seen in figure 22. This option might be considered if return loss aimed to be minimum. Layout 2 was decided to be the most useful for this project.

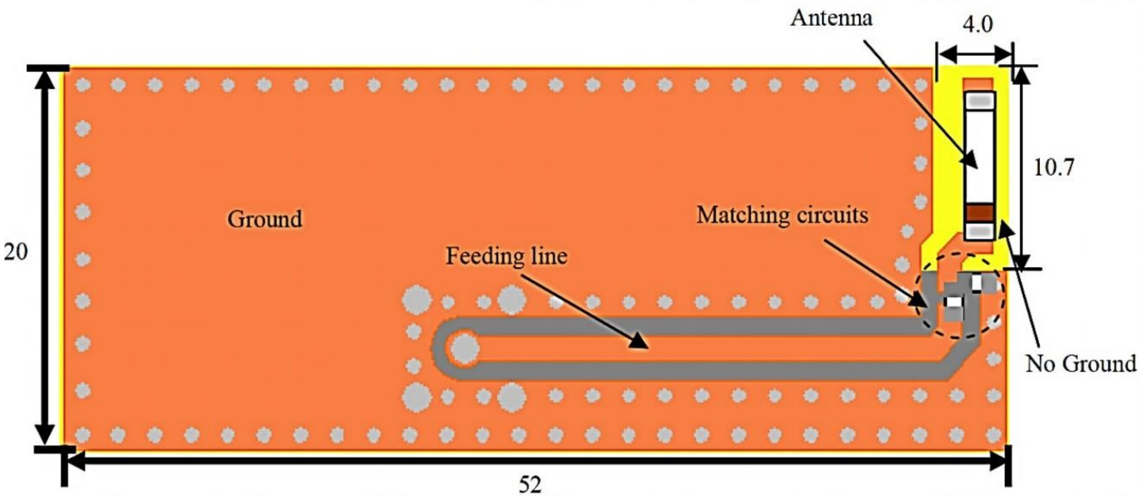

Figure 21: Layout 2 [14]

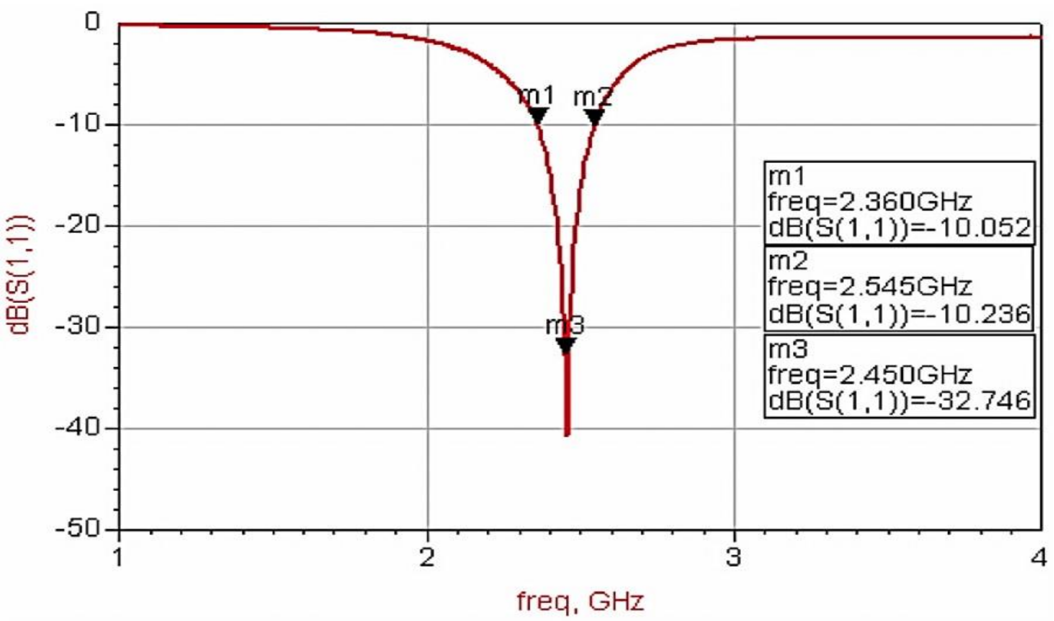

Figure 22: Return loss graph [14]

Antenna PCB was designed, as seen in figure 23, according to vertical orientation evaluation board. Board dimensions are clear on the data sheet of the antenna but track and gap width needed to be adjusted as mentioned according to grounded coplanar waveguide calculations. On the evaluation board SMA connector is used but for this project UFL connectors were better suited. For matching components PCB needed to have slots for a “pi” (or shunt-series-shunt) network, as clearly seen in figure24.

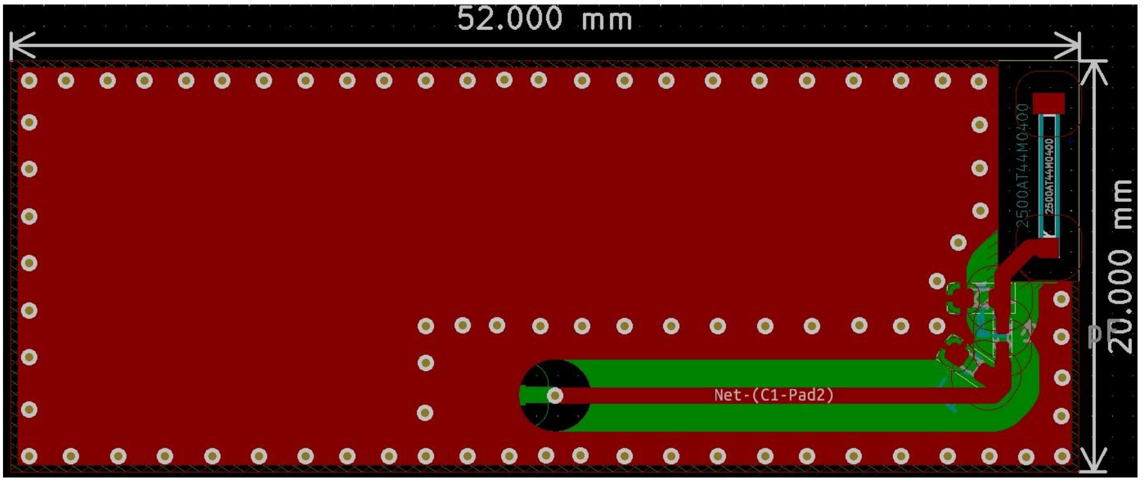

Figure 23: Antenna PCB design using KiCAD

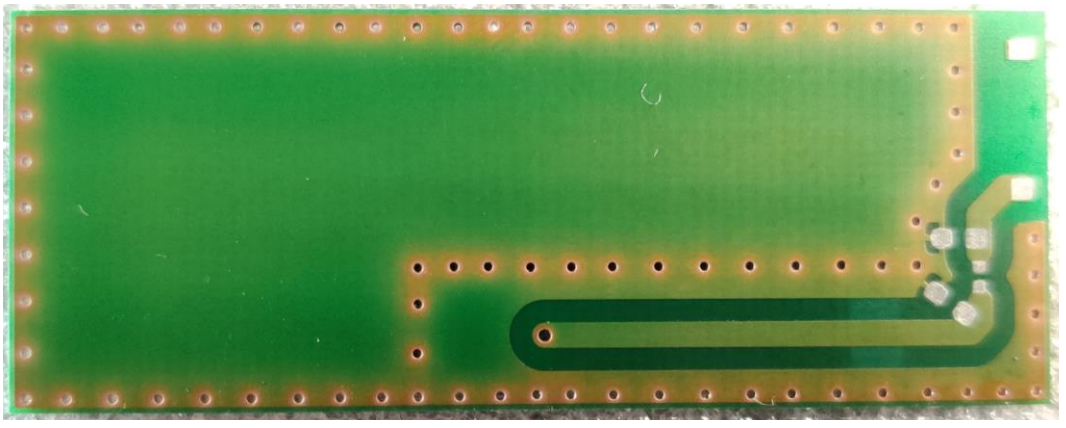

Figure 24: Printed Antenna PCB

3.4 Matching Circuit and Implementation

To be able to calculate which matching components antenna PCB needs for matching and analyse how well it performs without the matching components, antenna PCB needs to have a zero ohm resistor or a direct link from source to chip antenna itself, which can be seen in figure 25 and 26.

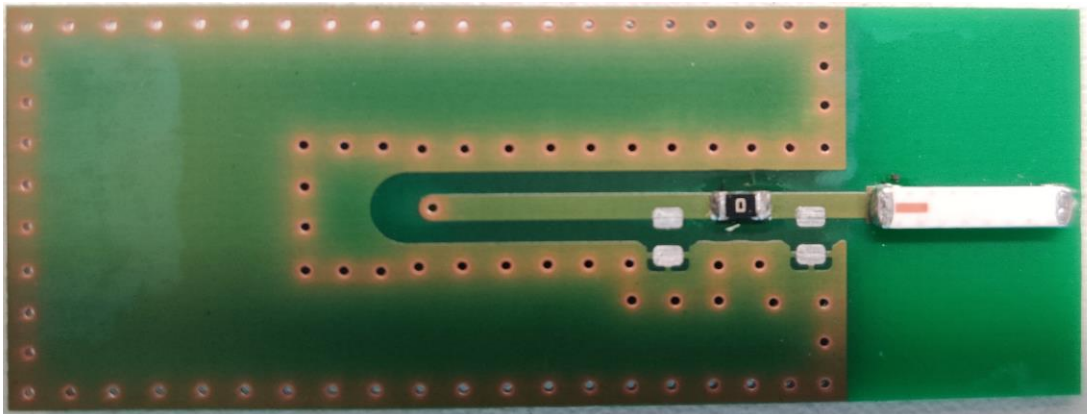

Figure 25: Primary antenna with direct link

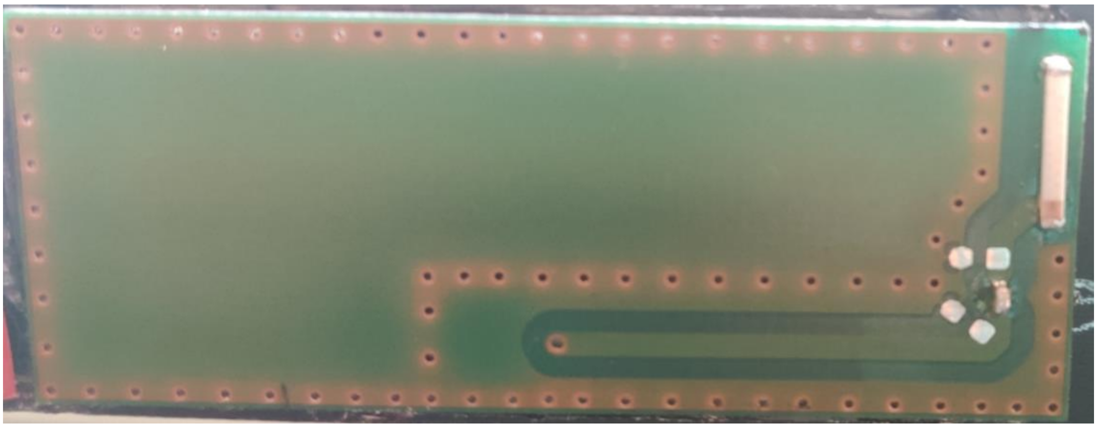

Figure 26: Secondary antenna with direct link

Determining the return loss of the antenna designs, a network analyser needs to be used. Network analysers always has to be calibrated in the frequency ranges which PCB is aimed to work and with the cables and adapters which are attached to the PCB. Network analyser's frequency range is set to be between 2.1GHz and 2.7GHz and markers are set to be on 2.412GHZ, 2436GHz and 2.472GHz. With the help of the analyser, it is found that, primary antenna has -20.255dB return loss and 42.4-j4.75 ohms load impedance which is 0.848-j0.095 ohms as normalized impedance and 0.0233 + j0.00261 siemens admittance, as can be seen in figure 27. Considering the components found in the laboratory shunt capacitor, series inductor and shunt capacitor found to be the best solution for matching the circuit.

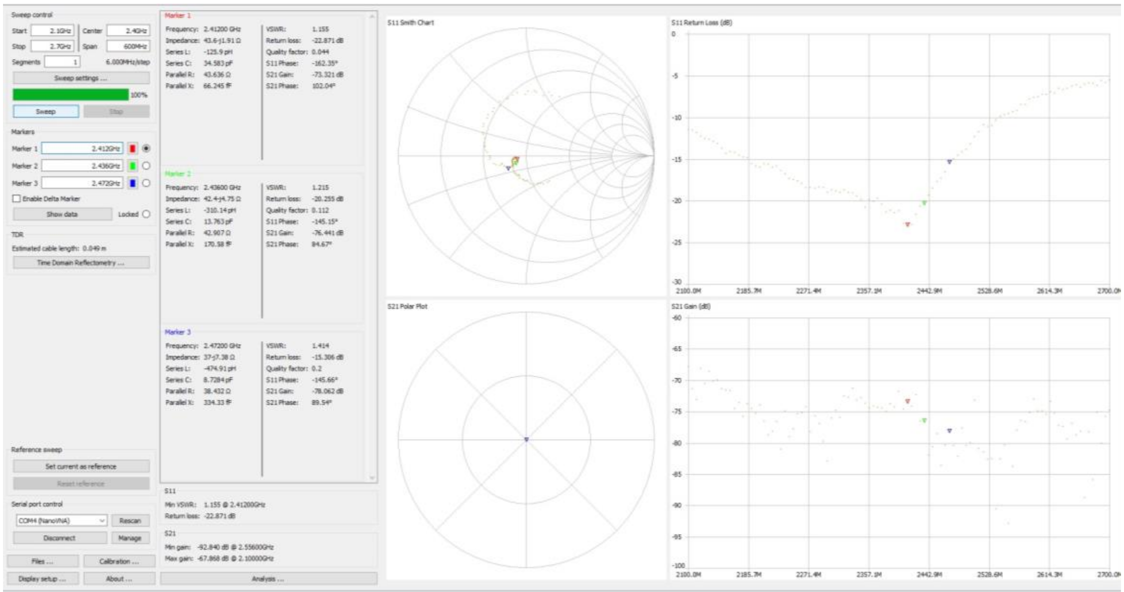

Figure 27: Primary antenna unmatched

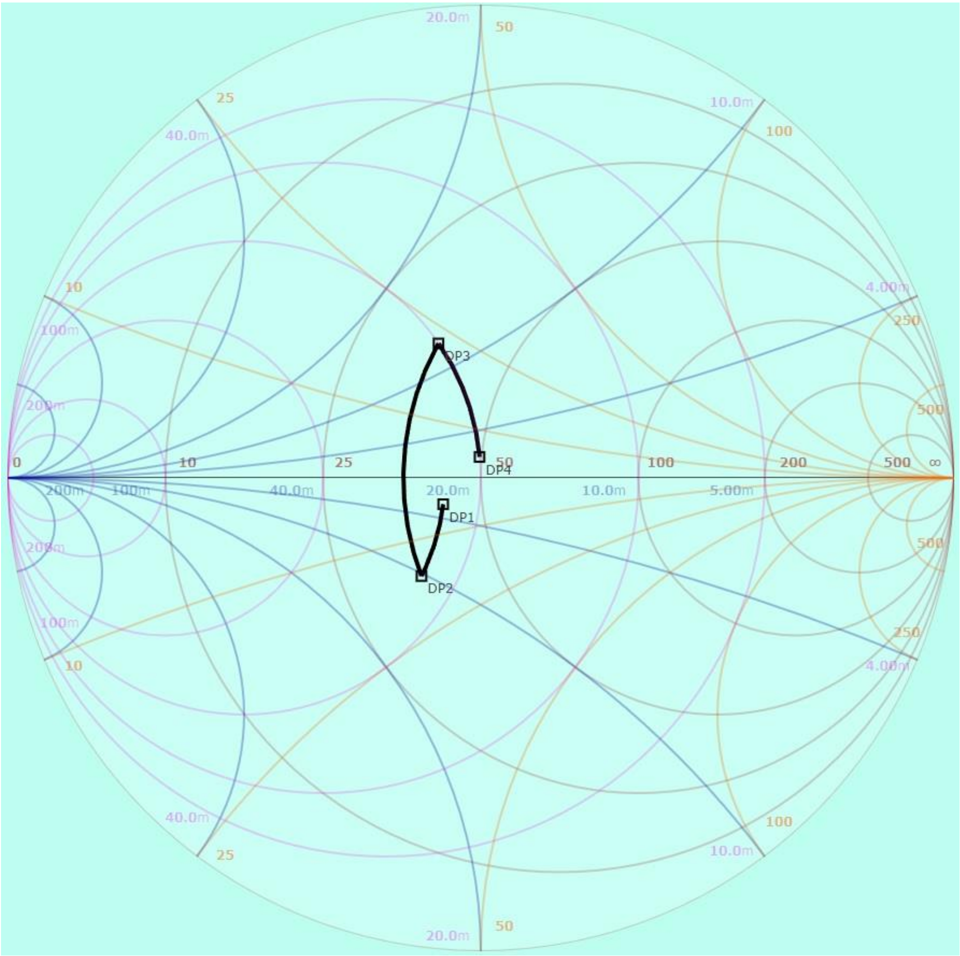

Figure 28: Primary antenna Smith chart matching [15]

To be able to get point from DP1 to DP2 on the admittance circle which is 0.0233+j0.0103 siemens a 0.5pF shunt capacitor needed to be added. To be able to get point from DP2 to DP3 on the impedance circle, which is 0.72+j0.448 ohms a 2.5nH series inductor needed to be added. Finally, from point DP3 to DP4 on the admittance circle, which is 0.200-j0.00178 siemens a 0.7pF shunt capacitor needed to be added. All the matching points can be seen clearly in the figure 28, and the network analyser result can be seen in figure 29.

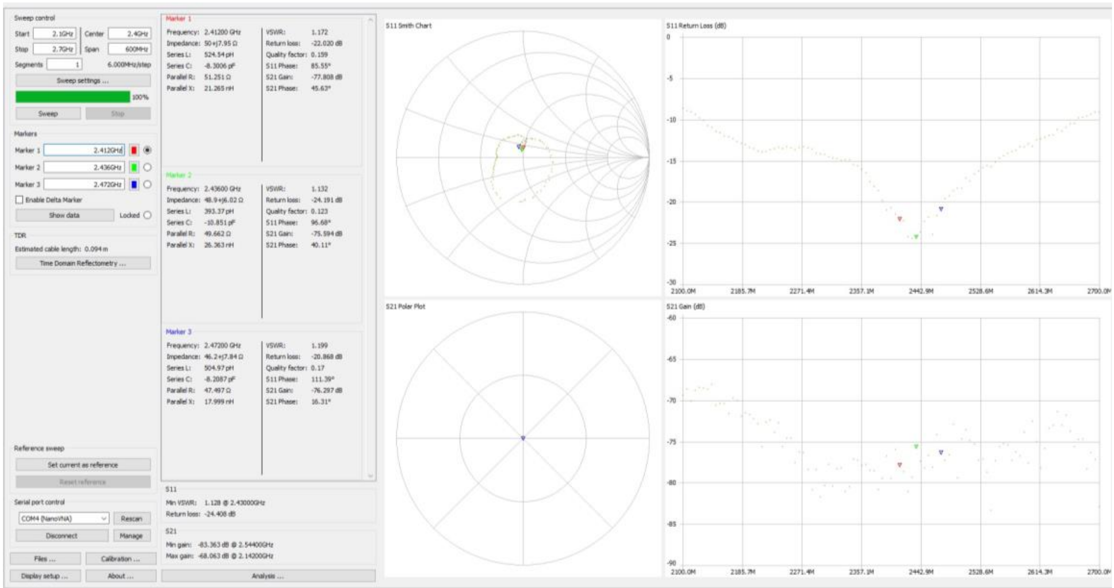

Figure 29: Primary antenna matched

With the help of the analyser, it is found that primary antenna has -6.860dB return loss and 112+j44.1 ohms load impedance, which is 2.24+j0.882 ohms normalized impedance and 0.0773 -j 0.00304 siemens admittance, as can be seen in figure 30. Best solution for matching the circuit was found to be shunt capacitor, series inductor and shunt inductor.

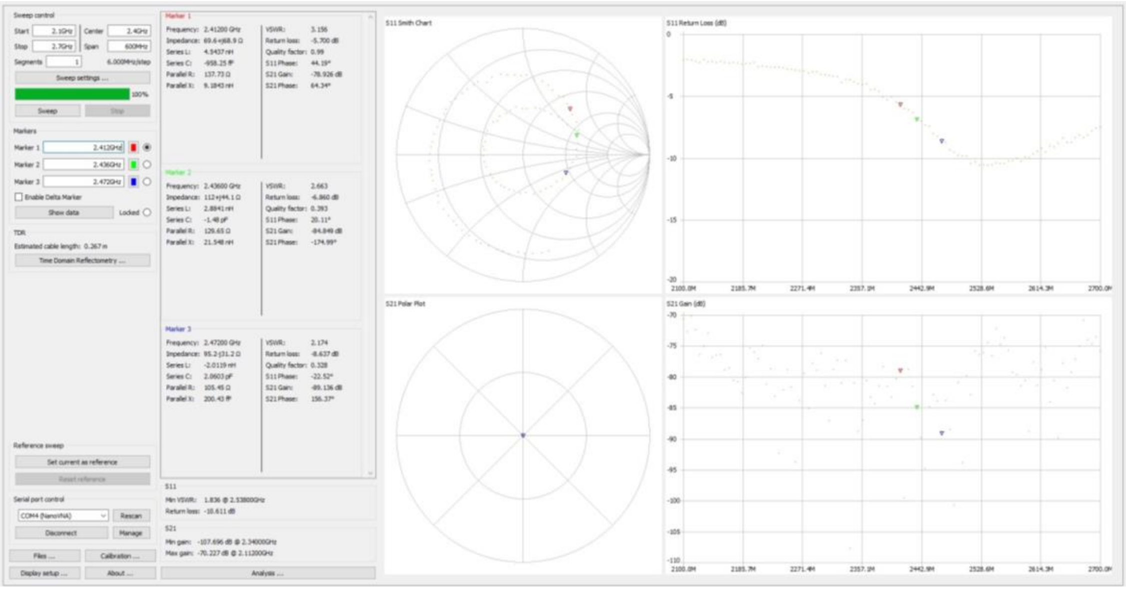

Figure 30: Secondary antenna unmatched

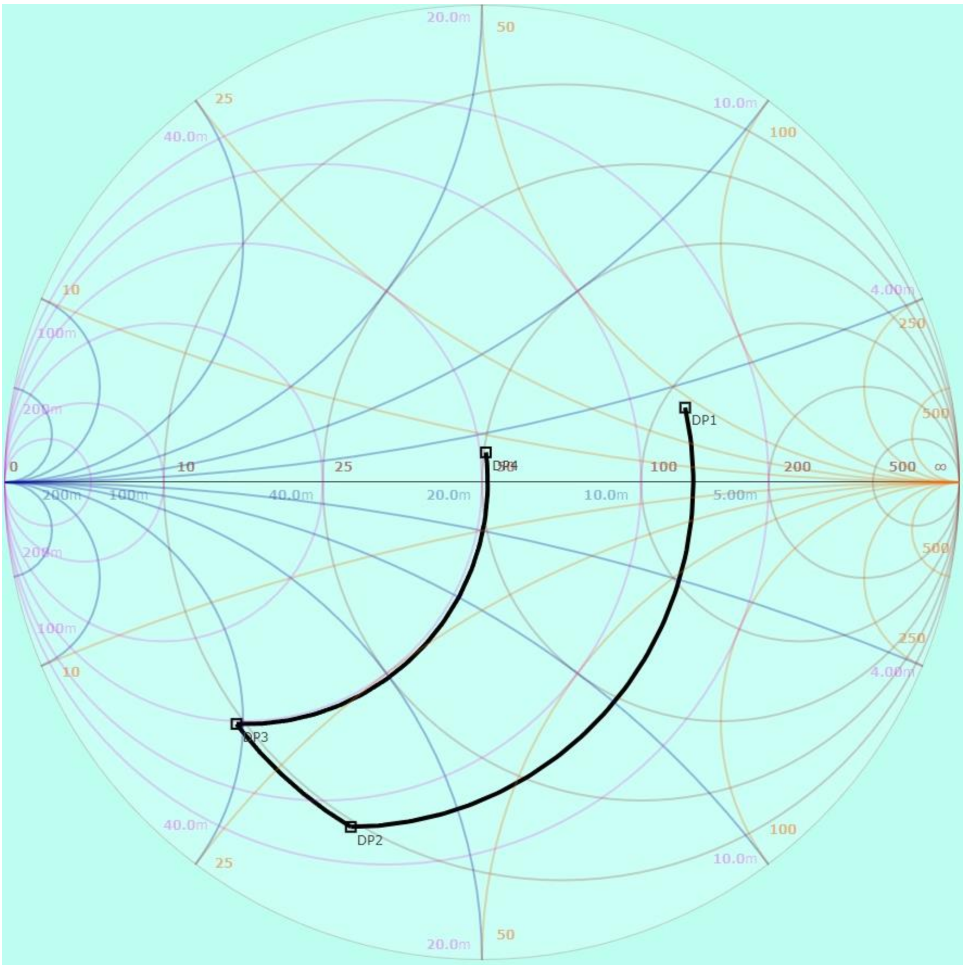

Figure 31: Secondary antenna Smith chart matching [15]

To be able to get point from DP1 to DP2 on the admittance circle which is 0.0773+j0.0276 siemens a 2pF shunt capacitor needed to be added. To be able to get point from DP2 to DP3 on the impedance circle which is 0.0195+j0.0411 ohms a 0.9nH series inductor needed to be added. Finally, from point DP3 to DP4 on the admittance circle which is 0.0195-j0.00246 siemens a 1.5nH shunt inductor needed to be added. All the matching points can be seen clearly in the figure 31. Final result can be seen in figure 32, and impedance is 50.4+j6.36 ohms which is not the ideal but due to restricted laboratory components that is accepted.

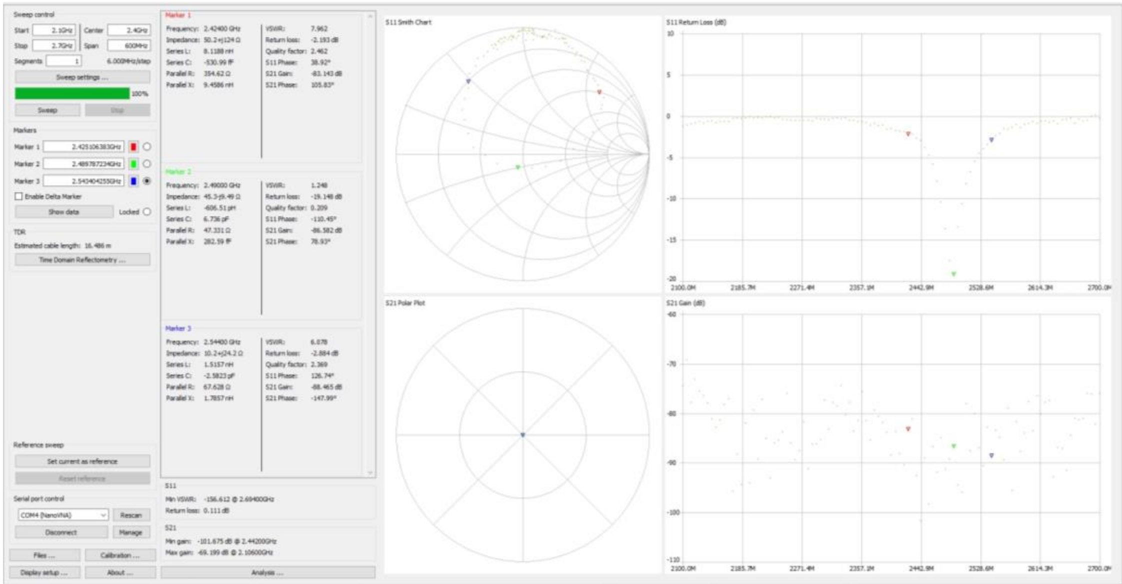

Figure 32: Secondary antenna matched

4 Conclusions and Future Developments

This thesis project was about the design of two types of antenna PCBs for x-ray panels. One has wider bandwidth with higher return loss (primary antenna) and the other has narrow bandwidth with lower return loss (secondary antenna).

Design of the primary antenna PCB was simpler than the secondary antenna and performance of the antenna was fairly good even when it was unmatched. When antenna was matched bandwidth was at the desired frequencies and return loss was -4dB lower, as seen in the appendix 2. In the process of primary antenna matching components values are found to be fairly small. Therefore, tolerance of the components plays an important role. Network analyser tests showed that primary antenna is efficient enough for the next generation panels which is under development. Second antenna PCB design was more challenging, and it did not perform like an antenna without matching circuit. When antenna was matched bandwidth was 12MHz higher than desired frequencies but return loss improved -13dB, as seen in the appendix 3. Secondary antenna needs better matching components which could bring working frequencies to the desired bandwidth. In order to get better matching last inductor's value needs to be increased to 1.6nH and result could have changed, as shown in the figure 33, and below:

Impedance: 51.1 -j1.24
Reflection coefficient: 0.0100 -j0.0122
VSWR: 1.03

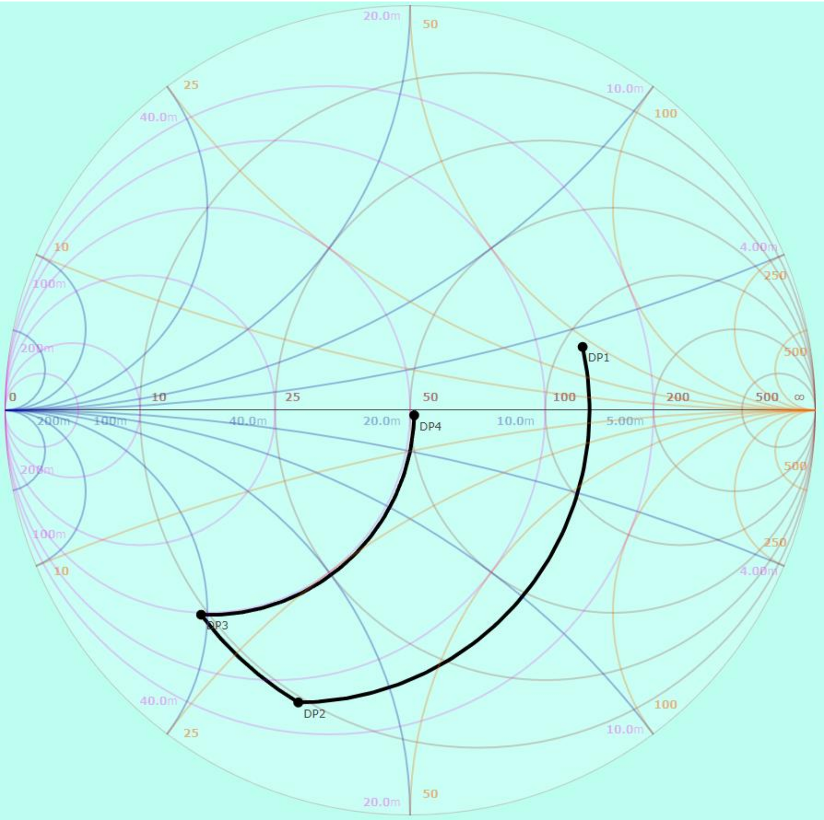

Figure 33: Secondary antenna Smith chart improved matching [15]

To be able to have more precise results both antennas need to be inspected with spectrum analyser in a RF laboratory.

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Appendix 1.

Dipole antenna

	Marker 1	**Marker 2**	**Marker 3**
Frequency	2.412GHz	2.436GHz	2.472GHz
Impedance	64.4-j12.6 Ω	49.2-j21 Ω	31.9-j13.2 Ω
VSWR	1.399	1.524	1.739
Return Loss	-15.580dB	-13.654dB	-11.375dB

Appendix 2.

Antenna 2450AT45A100 unmatched

	Marker 1	Marker 2	Marker 3
Frequency	2.412GHz	2.436GHz	2.472GHz
Impedance	43.6-1.91 Ω	42.4-j4.75 Ω	37-j7.38 Ω
VSWR	1.155	1.215	1.414
Return Loss	-22.871dB	-20.255dB	-15.306dB

Antenna 2450AT45A100 matched

	Marker 1	Marker 2	Marker 3
Frequency	2.412GHz	2.436GHz	2.472GHz
Impedance	50+j7.95 Ω	48.9+j6.02 Ω	46.2+j7.84 Ω
VSWR	1.172	1.132	1.199
Return Loss	-22.020dB	-24.191dB	-20.868dB

Appendix 3.

Antenna 2500AT44M0400 unmatched

	Marker 1	**Marker 2**	**Marker 3**
Frequency	2.412GHz	2.436GHz	2.472GHz
Impedance	69.6+j68.9 Ω	112+j44.1Ω	95.2-j31.2 Ω
VSWR	3.156	2.663	2.174
Return Loss	-5.700dB	-2.663dB	-8.637dB

Antenna 2500AT44M0400 matched

	Marker 1	**Marker 2**	**Marker 3**
Frequency	2.424GHz	2.490GHz	2.544GHz
Impedance	50.2+j124 Ω	45.3-j9.49 Ω	10.2+j24.2 Ω
VSWR	7.962	1.248	6.078
Return Loss	-2.193dB	-19.148dB	-2.884dB