ETEN10 Antenna Technology: Design and measurements of patch antennas

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I. INTRODUCTION

Patch antennas have a large part in wireless communications in today's society. This is because the ease of manufacturing and the low profile of the antennas. Another advantage is that it is good to use in array designs because of its profile and directivity. The purpose of this report is to make two patch antennas where one is designed for frequency of 2.402 to 2.480 GHz and matched to a 50 Ω. The second antenna was designed to be a circular polarized patch antenna operating at 2.4 GHz with an axle ratio of 3 dB or less for a cone of 60 degrees. [1] The following steeps were taken to get a good design for the two antennas:

1) A theoretical design for the two antennas were made to get a good starting point to later refine.
2) The design were improved using the FEKO simulation software.
3) The antennas were made and then altered according to the measured data collected by a VNA to get the desired characteristics.

After the antennas were finished they were measured in an anechoic chamber to get the gain pattern and also the polarization for the circular polarized antenna.

II. ANTENNA DESIGN 1

A. Theoretical design

The received wavelength for the antenna is

$$\lambda_\varepsilon = \frac{\lambda_0}{\sqrt{\varepsilon_r}} = \frac{c_0}{f_0\sqrt{\varepsilon_r}} \tag{1}$$

were f_0 is center frequency, c_0 is the speed of light and ε_r is relative permittivity. This gives the length of the patch to half a wavelength and the width to 3/4 wavelength. With f_0 = 2.441 GHz and ε_r = 4.4 and (1) this gives the length of 29.2 mm and a width of 43.9 mm.

$$L_{new} = \frac{f_1}{f_0} L \tag{2}$$

$$x = \frac{L}{\pi} \arcsin(\sin(\frac{\pi x_1}{L}) \sqrt{\frac{R(x)}{R(x_1)}} \tag{3}$$

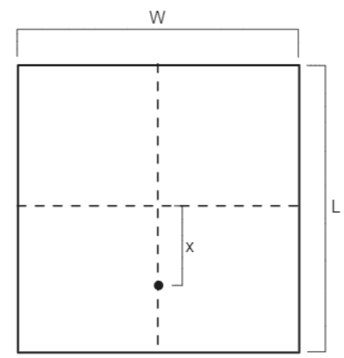

Fig. 1. The design variables of the first antenna.

B. Simulations

To refine the design, FEKO simulations were used base on the method of moments as well as calculation based on the cavity model and started with a feed for the patch at a distance 8.9 mm. First the original design were simulated and the center frequency was 2.38 GHz. With this the a new length of 28.48 mm was calculated using (2) and the resistance of this patch were 34.6 Ω. To get a new feed point such that it's matched to 50 Ω (3) was used and the the new feed point was 12.8 mm. After this to get the final simulated design the optimization function in FEKO was used. The optimization parameters that were used was the length, width and feed point distance. The optimization was looking to minimize the reflection coefficient at 2.441 GHz and the resistance to be 50 Ω. This final simulated design was a length of 27.3 mm a width of 43.9 mm and a feed point at 10.18 mm. the reflection coefficient can be seen in Fig. 2 and the resistance can be seen in Fig. 3 for this finalized design. The directivity is 7.28 dBi which can be seen in the far field of this design in Fig.4 with one cut in the H-plane and one in the E-plane. The finalized design parameters and the originally calculated ones can be seen in Table 1.

C. Refinement

The patch antenna were created by putting a pice of electrical tape according to the design on a 70 mm x 70 mm x 1.55 mm dielectric plate. A VNA was connected to the manufactured patch and the reflection coefficient and

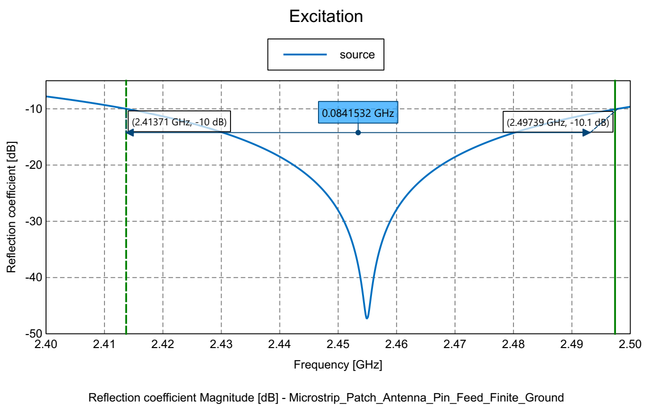

Fig. 2. Reflection coefficient of the antenna 1 design.

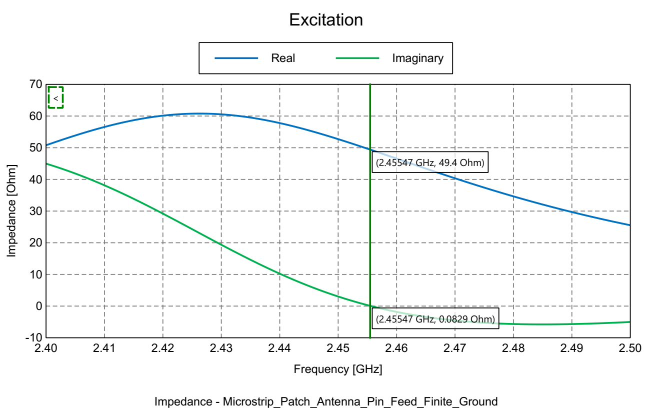

Fig. 3. Radiance resistance for antenna design 1.

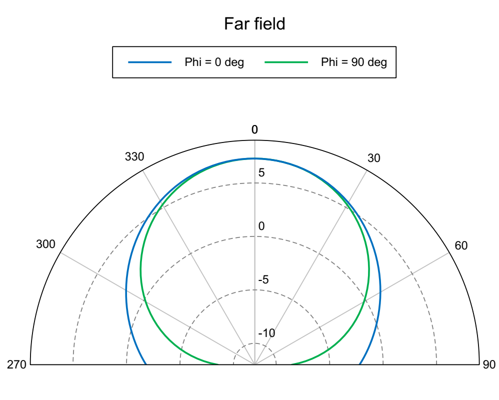

Fig. 4. The far field of the antenna 1 design, in the E-and H-plane.

resistance were measured. The center frequency was 2.47 GHz and the resistance was 70 Ω. To refine the patch to the desired frequency and resistance a small pice of tape was added to the side close to the feed. This resulted in a too large patch which was shaved down until the resistance and frequency was 49.43 Ω and 2.44 GHz which can be seen in Fig. 5 and Fig. 6. The patch bandwidth was measured to 820 MHz and the lowest reflection was -38 dB which can be seen in Fig. 6.

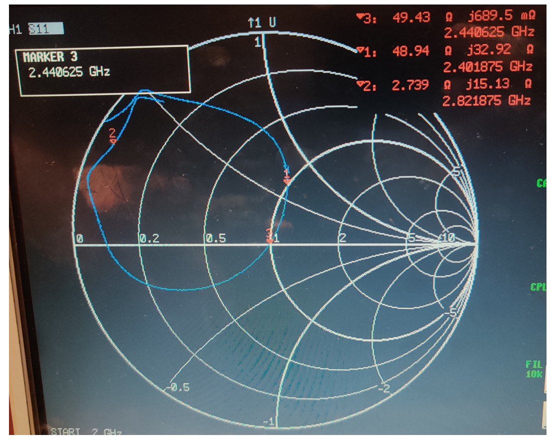

Fig. 5. Measurement of impedance in the polar plot of the antenna 1 on the VNA

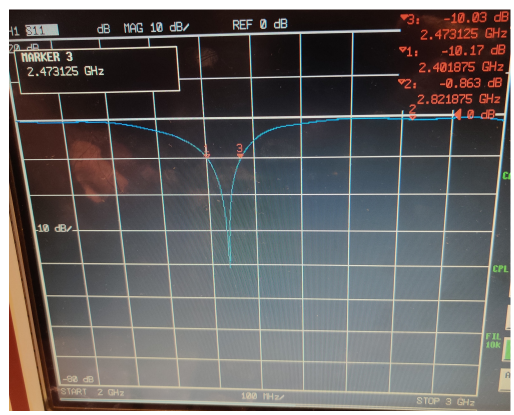

Fig. 6. Measurement of reflection coefficient of the antenna 1 on the VNA

TABLE I
COMPARISON OF CALCULATED VS. CHOSEN VARIABLES AFTER SIMULATION AND REFINEMENT

Variable	**Values**	
	Calculated	***Chosen***
f_0	2.441 GHz	2.445 GHz
L	29.28 mm	27.3 mm
W	44.0 mm	43.9 mm
x	8.9	10.18
R	43 ohm	55.5 ohm
$BW_{-10\text{dB}}$		0.084 GHz

III. ANTENNA DESIGN 2

A. Motivation

For the second antenna design, a RHC-polarized antenna was chosen. The design aims for a center frequency of 2.4 GHz and a wide band as large as possible. The requirements states that the axial ration should have a magnitude of less than 3 dB for a cone of opening 60°.

A design of the type shown in Figure 3(a) in the Laboratory manual [1], was chosen. This design seemed the easiest to implement and simulate in FEKO. With the specified center frequency $f_0 = 2.4$ GHz, the received wavelength of the antenna, λ_ϵ, was calculated to be 59.6 mm according to (1), giving us a initial guess for the length of the antenna $L = \lambda_\epsilon/2 = 29.8$ mm.

For this design we wanted to explorer how well FEKO could optimize the variables of our design. The width (W) was initially set to be the same as L. The initial offset (x) was set to the same final value for the first antenna design. We also included a offset in the y direction, initially set to 0 mm. The variable "edge", responsible for the cut of corners, was at first simply set to be $1/4$ of the length. For a full view of the design and different variables, see Fig. 7.

The simulations in FEKO decide the final values for the variables. The simulation hade multiple goals. The antenna should resonate at the frequency of f_0 and preferable have a radiation resistance R matched to 50 Ω. The far field goals was set to have a Axial ration as close as possible to 0 dB, both in the E-plane and the H-plane.

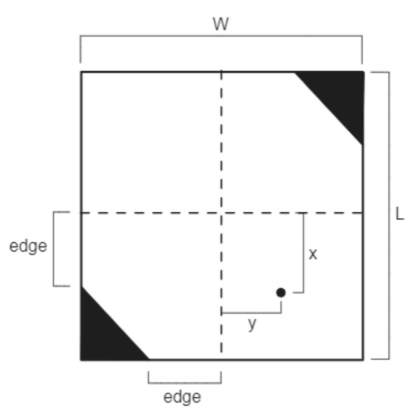

Fig. 7. The design variables of the second antenna.

The results of the optimization in FEKO and the chosen variables for the second antenna can be seen in TABLE II. The table also includes some values from the simulation.

B. Simulations

The design of the second antenna was then simulated in FEKO. The figures 8 trough 11 shows the simulated results. In Fig. 8 it is clear that the design has a higher resonant frequency than preferred, around 2.42 GHz. In Fig. 9 the radiation resistance at this resonant frequency is shown to be around 60 Ω, a bit higher than the wanted 50 Ω.

TABLE II
THE OPTIMIZED DIMENSIONS FOR THE SECOND ANTENNA DESIGN AND SIMULATION RESULTS

Parameter	Optimized Value
edge	10.4 mm
L	28.6 mm
W	29.1 mm
x	9.85 mm
y	2.76 mm
f_0	2.42 GHz
R	60 Ω
BW_{-10dB}	0.13 GHz

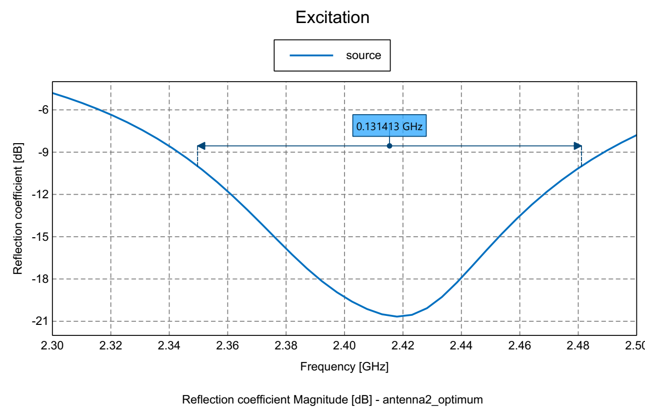

Fig. 8. The simulated reflection coefficient of the second antenna design.

A design requirement was that the antenna should have an axial ratio no less than 3 dB inside a 60 °cone. In Fig. 10 we see that the axial ratio meets these requirements. The directive can be seen in Fig. 11. The optimized FEKO design achived a high directivity, completely concentraded inside a 60°cone.

C. Optimization

The the reflection coefficient and radiation resistance of the second antenna was measured with a VNA in a lab. Surprisingly the antenna design was perfect, without the need of any further tweaks. In Fig 12 the resonant frequency can

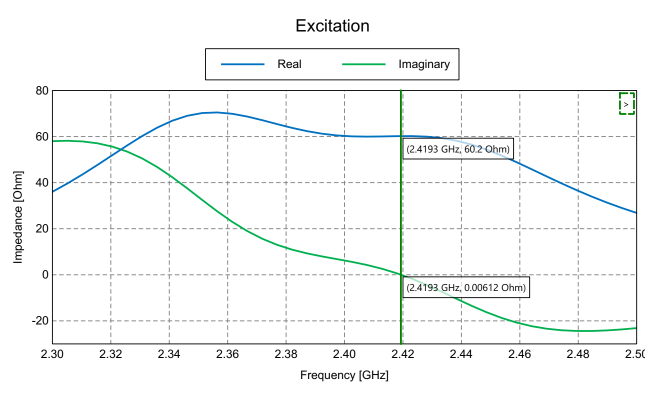

Fig. 9. The simulated Radiation resistance second antenna design.

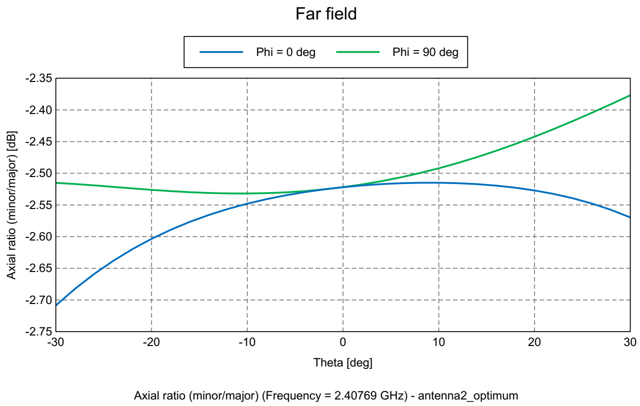

Fig. 10. The axial ratio from the simulated second antenna design.

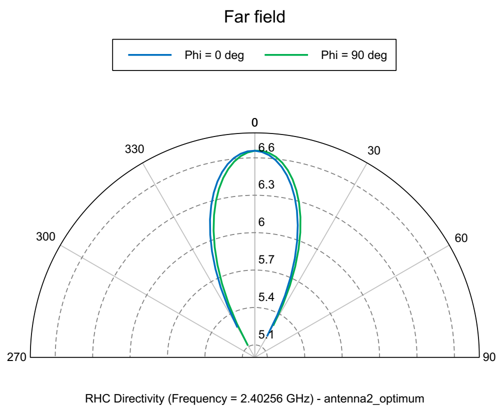

Fig. 11. The simulated RHC polarization part of the far field of the second antenna in the E-plane and the H-plane.

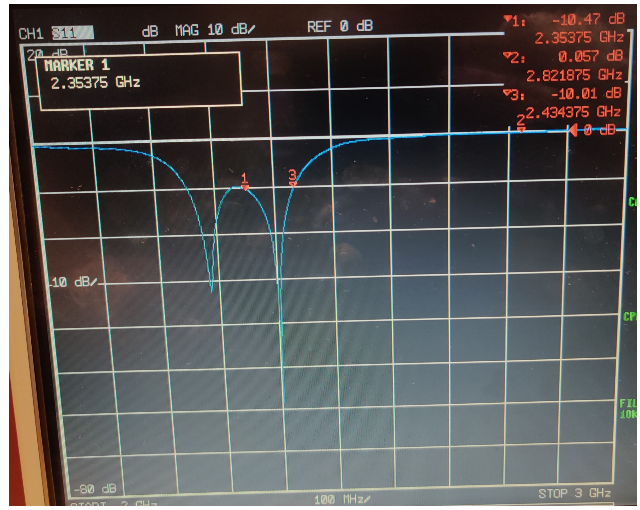

Fig. 12. The output of the VNA when measuring the reflection coefficient of the second antenna design.

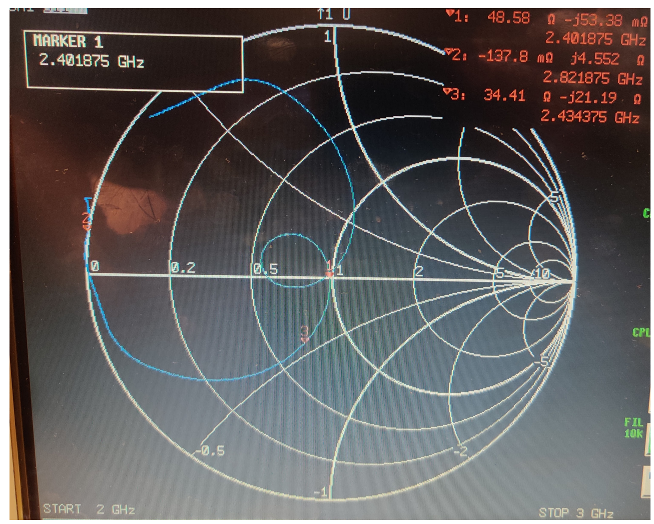

Fig. 13. The output of the VNA when measuring the input impedance of the second antenna design.

be measured to 2.4 GHz. The radiation resistance at this frequency was measured to 48.6 Ω (Fig. 13), an almost perfect match.

The polarization of our antenna cannot directly be measured with the VNA. To verify that we succeed in making a RHC polarized antenna, we measured the power received of two helix antennas with different circular polarizations. We verified that the received power was much higher for the RHC polarized antenna than for the LHC antenna, verifying that our antenna is indeed RHC polarized.

IV. Construction

A simple way to increase the directivity of an antenna is to make a reflector to direct the radiation. To study this effect a reflector was design for a quarter wave monopole antenna operating at 2.44 GHz. The reflector was made with a parabolic design in one dimension. The diameter should be much larger than the wavelength of 3 cm so a diameter of 20 cm was chosen [2]. To get the dimensions for the reflector the parabola formula was plotted and printed out on Geogebra

$$y^2 = 4F(F + z) \tag{4}$$

where F is the focal point distance [2]. The printed curve was cut out of two pieces of cardboard and a 6 cm wide cardboard strip was clad with aluminum foil and put in the cutout. Testing this reflector in the anechoic gave a increase of 6 dB which was the same as the provide reference antenna form the lab manual [1] which shows the reflector works as expected.

V. Final performance

A. First antenna design

The final measurements of the antenna were made in an anechoic chamber. To be able to calculate the gain of the antenna a quarter wave monopole antenna was tested as a reference antenna with its peak reaching -50 dB. To get the same scale as in the simulations 50 dB was added to get to $dB_{monopole}$ and 5.15 dB was added to get the dBi that the simulation used. The antenna 1 peak in the E-plane was measured to 7.7 dBi and the difference between the E and H-plane was 24.8 dB which is shown in Fig. 14. The

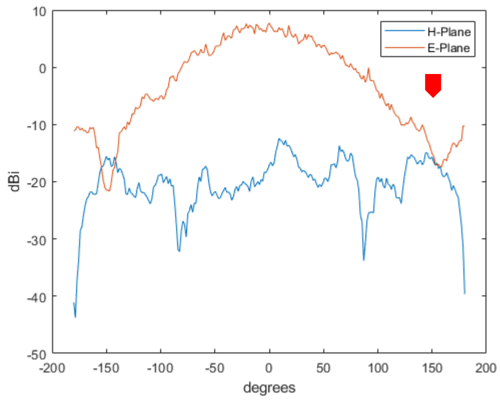

Fig. 14. Far field for The H and E-plane

shape of the radiation pattern for this antenna can be seen in Fig. 15, which shows that most of the energy is radiated orthogonal to the surface. The antenna was also tested to see

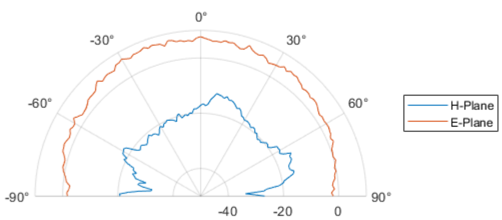

Fig. 15. Polar plot for the far field of the H and E-plane

if it could be used as an antenna for Bluetooth in an acoustic anechoic chamber. It was able to work as an antenna and only when the transceiver and the antenna were facing different directions and were covered did it lose connection. In the acoustic anechoic chamber it was also shown how an antenna array works with interference and face trough the use of two speakers. It was possible to see how two sources interfere with one another based on distance, frequency and phase.

B. Second antenna design

The second antenna was also tested in an anechoic chamber in the same way as the first design. The far field of the second antenna design can be seen in Fig. 16. It is clear from the figure that the goal of creating a circular polarized antenna was a success, having a noticeable gain in both the E-and H-plane. The antenna had a maximal gain of 3.5 dB in the E-plane, much lower than the 6.7 dB of the theoretical design. The beam of the theoretical design was completely concentrated within a 60 °cone. The implemented design hade a much wider beam. The axial ratio is plotted in Fig. 17. The final performance of the antenna did not succeed in keeping the axial ration above 3 dB in a 60 °cone, having a axial ration of -3 dB straight ahead, meaning our design is more of a elliptical polarized antenna.

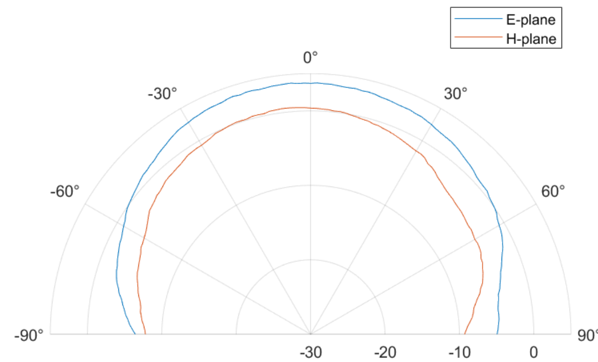

Fig. 16. The measured far field of the second antenna design.

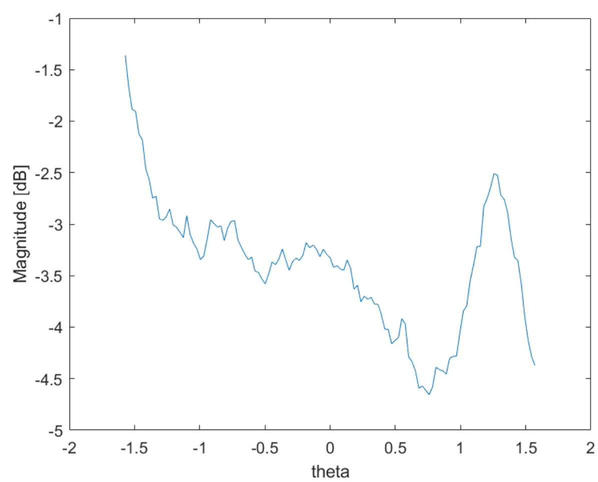

Fig. 17. The measured axial ratio of the second antenna design.

VI. SUMMARY AND CONCLUSIONS

Throughout three laboratory sessions, we have learned the basic workflow of designing patch antennas. We learned that although theoretical formulas provide a good starting point for determining the dimensions, there is still much fine tuning to be made to get a design that matches design requirements perfectly. This fine tuning is often too complex to calculate by hand, and we have learned how computer software, such as FEKO, can be used to simulate and optimize designs.

We implemented our antennas for real and measured and fined tune them in real time using a VNA. Showing that theoretical formulas and simulations cannot fully describe how the antenna will perform in practice, and that the antenna is always in need of further testing and tuning in real life.

In designing the second antenna, we explored the complexities of circular polarization. We learned that achieving a perfect axial ratio is hard an very sensitive to multiple variables, like the position of the feed point and the symmetry of the patch. Although we did not succeed in making a perfect circular polarized antenna, the process taught us how to design for circular polarization and how to measure it.

Our experiments with the parabolic reflector demonstrated how a simple geometric structure can help increase the directivity of an antenna.

We also studied how external factors affect our designs. While non-conductive materials like cardboard had little impact, touching the antenna with human tissue (touching it with your hand) significantly altered the reflection coefficient and often eliminated the resonance. Furthermore, we tested the interaction between two antennas. We found that signal transfer is highly dependent on alignment: the antennas communicated effectively when oriented the same way, but the signal nearly disappeared when one was rotated 90 degrees. This confirmed that antenna orientation (polarization) is critical for successful transmission.

Finally, the tests in the acoustic anechoic chamber made it easy to understand wave interference. By using two speakers, we could hear the interference patterns with our own ears, which gave us a real feel for how antenna arrays work. The project ended with a practical Bluetooth test. Successfully sending data through our built antennas proved that our designs and tuning resulted in a working antenna.

References

[1] A. Pallaris, Y. Cao, and A. J. Johansson, *ETEN10 Antenna Technology: Design and measurements of patch antennas, Laboratory manual*, Lund University, Oct. 2025.

[2] D. SJÖBERG, *ETEN10 Antenna Technology Lecture 11: Aperture, horn, slot, and reflector antennas*, Lund University, Dec. 2025