ECE 475 Course Project

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ECE 475: Radio-Wave Systems
July 30, 2022

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1 Abstract

For wireless communication systems, especially in Earth-to-space communications, the antenna is one of the most important components. A good design of the antenna can relax transmitter/receiver design because more of the radiated power is captured and improve overall system performance. In this project, the task is to design a low-profile antenna to be placed on a highly conductive box of that can be placed on top of a truck to communicate with GPS satellite. A microstrip patch antenna was selected and designed in HFSS. First, a simple 1×1 patch antenna was created, and after evaluating we found it did not meet gain specifications and added another patch antenna to create an 1×2 array. All specifications were met at that point and the details of the design will be laid out in the following sections.

2 Introduction

The choice of antenna we decided to go with was a microstrip patch antenna. These antennas are low profile and easily conformable to planar and nonplanar surfaces which is critical if the antenna is to be mounted on top of a truck in a mobile environment, simple and inexpensive to manufacture, and when the particular patch shape and mode are selected, they are very versatile in terms of resonant frequency, polarization, pattern, and impedance [1]. The major disadvantages of the microstrip patch antenna are their low efficiency, low power, narrow beamwidth, and high Q factor which means a small frequency bandwidth. In the context of this project, these disadvantages are not significant and are outweighed by the benefits. Firstly, the patch antenna is narrowband and need only be at resonant at 1575.42 MHz so the lack of bandwidth is not a problem. Secondly, the low gain of a single microstrip patch antenna is alleviated by forming an array. Thirdly, since the antenna will always be facing the zenith, their is a direct LOS path from the antenna to the receiver, so the narrow beamwidth is not relevant. Finally, the low efficiency is resolved by increasing the height of the substrate.

3 Antenna Design

3.1 Physical Dimensions

The substrate was initially set to be the maximum dimensions (25cm × 25cm) that was specified. The substrate RO4350 was chosen with a height of 1.6mm as this is a common material and substrate thickness used in RF production. The dimensions of a single patch antenna at the resonant frequency could then be calculated using the "em: talk" tool: https://www.emtalk.com/mpacalc.php. The length L_p and width W_p of the patch antenna was calculated to be 49mm and 62mm, respectively.

3.2 Inset Length

The length of the inset x_0 was calculated using the formula

$$Z_0 = Z_{\text{in}} \cos^2\left(\frac{\pi x_0}{L_p}\right) \tag{1}$$

Z_{in} is the input impedance of the patch antenna and was obtained with the "em: talk" tool. Z_0 is the desired input impedance. Usually, the desired input impedance would be 50Ω, however, because we anticipated to have 2 or more patch antennas in an array, we set the desired impedance to 100Ω so that the equivalent impedance of 2 antennas in parallel is 50Ω. The calculated inset length is 12.52 mm and a 100Ω microstrip is used to feed the antenna. And finally, the inset gap from the feed line was set to be equal to the width of the feed line itself as this is a rule of thumb.

3.3 Microstrip Lines

The microstrips in our antenna have impedances of either 50Ω or 100Ω. The widths were calculated using the "em: talk" tool: `https://www.emtalk.com/mscalc.php`. The width of 50Ω and 100Ω microstrip lines for RO4350 are 3.52mm and 0.87mm, respectively.

3.4 Antenna Arrays

To satisfy the gain requirement found in Section 6.1, it was found that a single patch antenna was not sufficient. To increase the gain, an additional antenna was added to form a 1×2 array. The spacing between each antenna was set to $3\lambda_e/2 \approx 70$mm. This antenna structure satisfied the specifications (which is discussed more in 4), thus, it was not necessary to create a 2×2 antenna array.

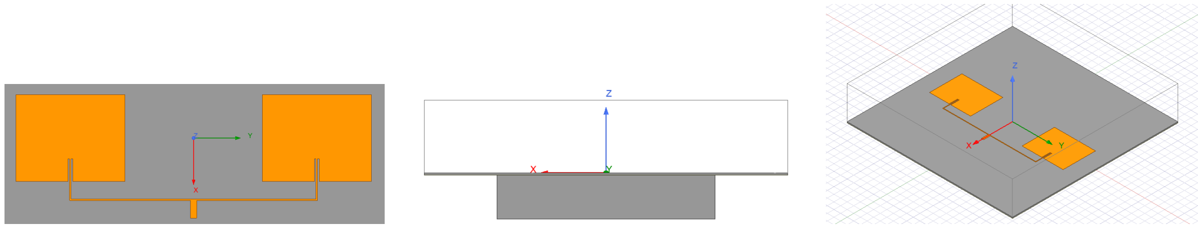
3.5 Conducting Box

To account for the platform which the antenna will sit on, a conducting box was added in HFSS. Because it is assumed that the platform is a highly conducting box, a perfect conductor (PEC) material was used in HFSS. To achieve desired performance, the height of the box was tuned to be 3cm.

3.6 Summary of Calculated Parameters

Table 1: Calculated Parameters

λ_0	ε_r	H_{box}	h	λ_e	L	W	L_p	W_p	x_0	$W_{50\Omega}$	$W_{100\Omega}$	Spacing
190 mm	3.66	3 cm	1.6 mm	90 mm	25 cm	25 cm	49 mm	62 mm	12.52 mm	3.52 mm	0.87 mm	140 mm



(a) Top-view (b) Side-view (c) Angled view

Figure 1: Physical structure of the antenna

4 Design Parameters

The following are the main parameters which were considered in our design.

4.1 Gain

Because an explicit requirement was not given for the receiver antenna gain and power on the satellite, a perusal of the current literature on modern GPS receiver antennas gives a lower bound on the power as around -140 to -150 dBm before the signal is considered as noise [2] and the gain as around 6 to 9 dBi. By using the Friis Transmission Equation, we can solve for the required gain of our designed antenna G_t where $P_t = 1W$, $\lambda = 0.1903m$, and $d = 20220km$.

$$\begin{aligned} P_r &= P_t \frac{G_r G_t \lambda^2}{(4\pi d)^2} \\ P_r(dB) &= P_t(dB) + G_t(dBi) + G_r(dBi) + 20\log\left(\frac{\lambda}{4\pi d}\right) \\ -140dBm &= 30(dBm) + G_t + 6 - 180 \\ G_t &= 4dBi \end{aligned}$$

It was calculated that the patch antenna must have a gain of at least 4 dBi to be able to deliver at least $-140dBm$ of power to the satellite. A single patch antenna cannot provide a gain this high. Thus, we experimented with patch antenna arrays to achieve a higher gain.

4.2 Directivity

An ideal isotropic antenna is 0dB or 1. Highly directive antennas, such as horn and dish antennas, have values of 10dB and upwards [3]. So, in our design we aimed to achieve a directivity near 10dB. Such directivity cannot be obtained with a single patch antenna, so we experimented with 1×2 and 2×2 array designs to achieve an optimal value.

4.3 Efficiency

The efficiency of the antenna is specified to be 50% or greater. By having high gain and high directivity, decent efficiency can be obtained.

4.4 VSWR

A rule of thumb is that the VSWR should be under 2, but ideally, close to 1. To achieve a good VSWR, the impedance at the waveport should be matched at 50Ω. To account for this, we tuned our antenna parameters in HFSS to get the S_{11} notch at the resonant frequency, 1.57542GHz. When we instead designed each patch to have an input impedance of 100Ω, we achieved much better gain and matching at the port.

5 Design Challenges

5.1 Patch Dimensions and Microstrips

With antenna design, sometimes the mathematical model does not translate into a functioning real model. The majority of the initial design of the antenna was through mathematical equations, however, they did not always produce great results when simulated in HFSS. For example, there are many different equations that can be used to design the gap of the inset and feed line, but some provided mediocre results. To get around these issues, antenna dimensions were tuned in HFSS to yield acceptable results.

Because we used two patch antennas, there has to be a certain amount of spacing between them to perform well (about $3\lambda/2$ is the typical distance). As microstrips become longer, they are more lossy, and this gave issues when connecting the patch antennas in our design. To achieve optimal results, we tuned the distance between patch antennas in HFSS.

5.2 Achieving High Gain and Correct Matching

A single patch antenna was not able to provide a high gain, so we had to try using 2×1 or 2×2 arrays. We encountered issues when we designed each patch antenna to have a 50Ω input impedance and quarter-wavelength transformers were used to bring it to 100 Ohms. We instead designed the inset of each patch antenna such that the input impedance was 100Ω and this prevented the need for a quarter-wave transformer for the 2×1 array. The results obtained with this array satisfied the gain specifications.

5.3 Conducting Box

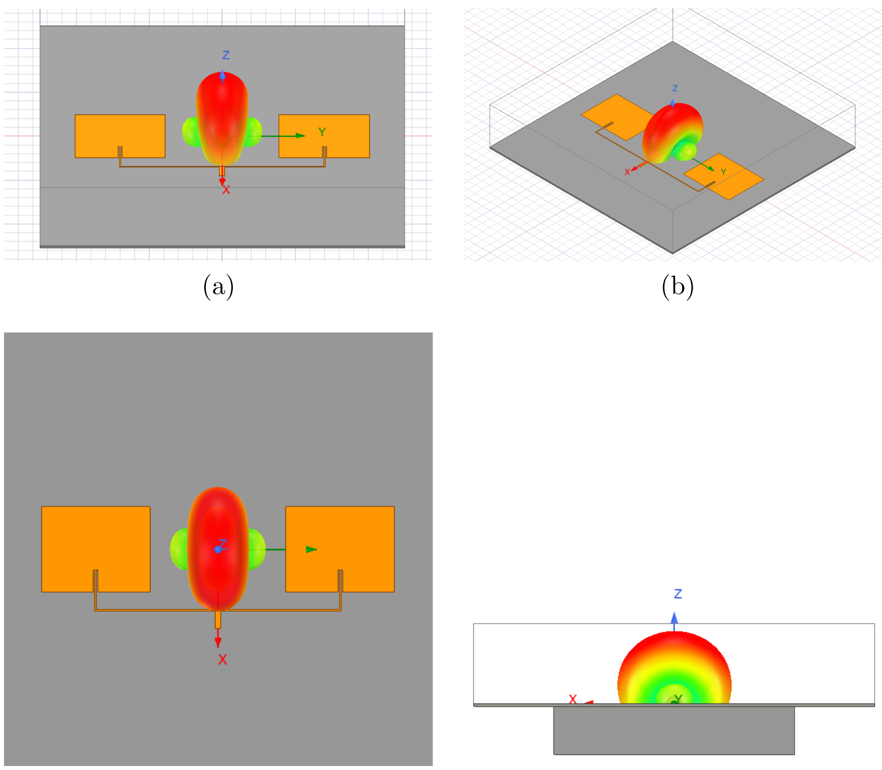
The surface of the antenna provided disturbance to its performance. To simplify the designing process, we first designed the antenna in HFSS without any surface. Then, once the antenna design was complete, we added the surface and used tuning in HFSS to modify the box height until we achieved the desired performance. Overall, the added conducting box did reduce the gain and efficiency, but the specifications were still met.

6 Presentation of Results and Interpretation

The antenna design was simulated in HFSS using a driven terminal.

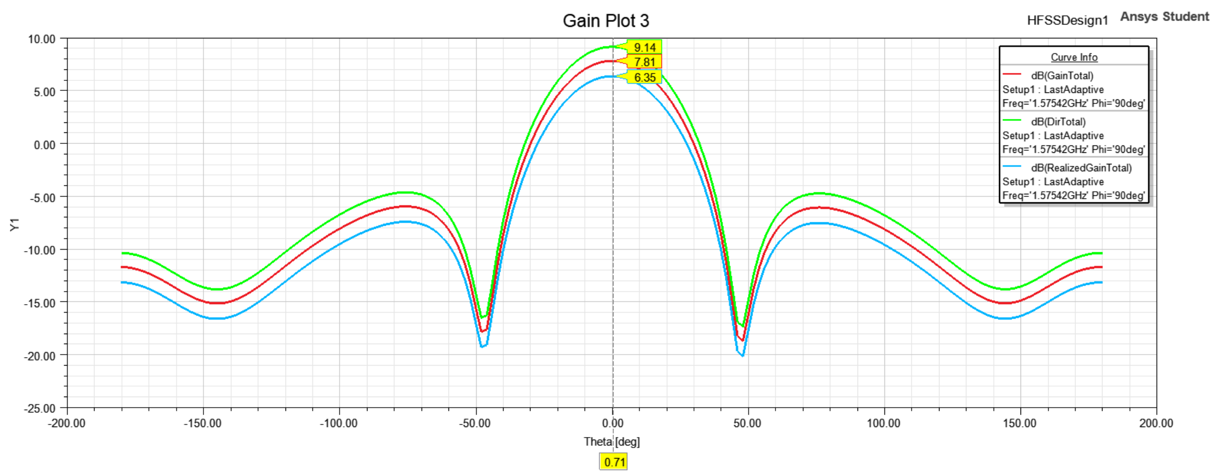
6.1 Antenna Gain and Directivity

In Figure 2, 3D polar plots of the radiated power are shown. In Figure 3, it is seen that the peak gain is 7.81dB, the realized gain is 6.36dB, and the directivity is 9.14dB. Therefore, the gain and directivity requirements are satisfied.

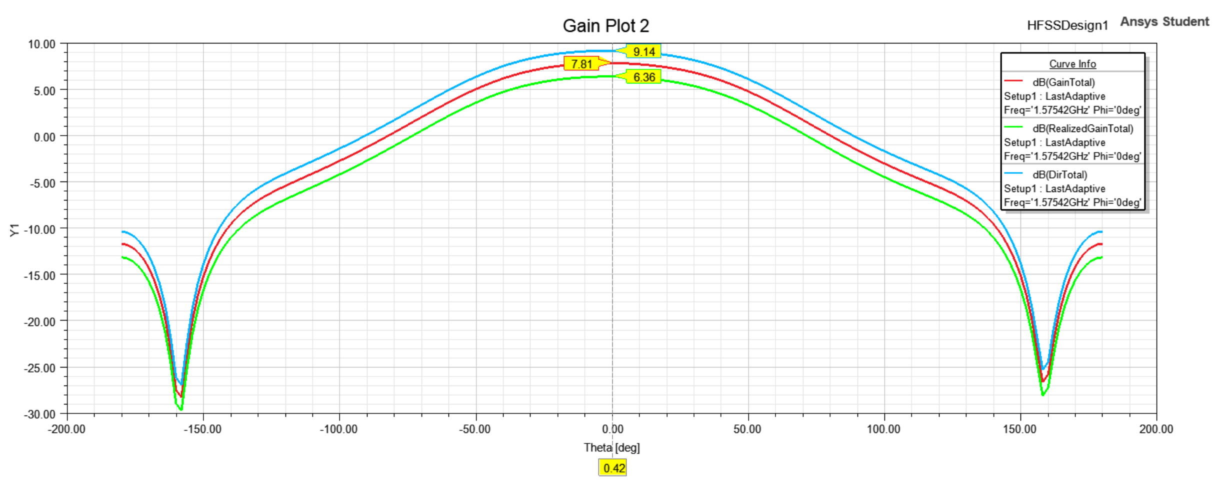


(a) (b) (c) (d)

Figure 2: Radiated power of the patch antenna array



(a)



(b)

Figure 3: Gain and directivity of the patch antenna array

6.2 Efficiency

The efficiency is calculated as

$$e = \frac{\text{Gain}}{\text{Directivity}} = \frac{10^{6.36\text{dB}/10}}{10^{9.14\text{dB}/10}} = 52\% \tag{2}$$

This calculation is verified in HFSS.

	Freq [GHz]	RadiationEfficiency Setup1 : LastAdaptive	TotalEfficiency Setup1 : LastAdaptive	SystemEfficiency Setup1 : LastAdaptive	dB(PeakDirectivity) Setup1 : LastAdaptive	dB(PeakGain) Setup1 : LastAdaptive	dB(PeakSystemGain) Setup1 : LastAdaptive
1	1.575420	0.736124	0.526441	0.526441	9.149182	7.818690	6.362675

Figure 4: Parameters calculated in HFSS

The efficiency is 52% which is relatively low, but it still satisfies the specification of being over 50% efficient. The cause for the low efficiency is the conducting box which disturbs the overall radiation pattern of the antenna. Without the conducting box, an efficiency of 74% was achieved.

6.3 VSWR

The S_{11} response is plotted in Figure 5. At the resonant frequency, 1.57542 GHz, S_{11} is -16.5dB.

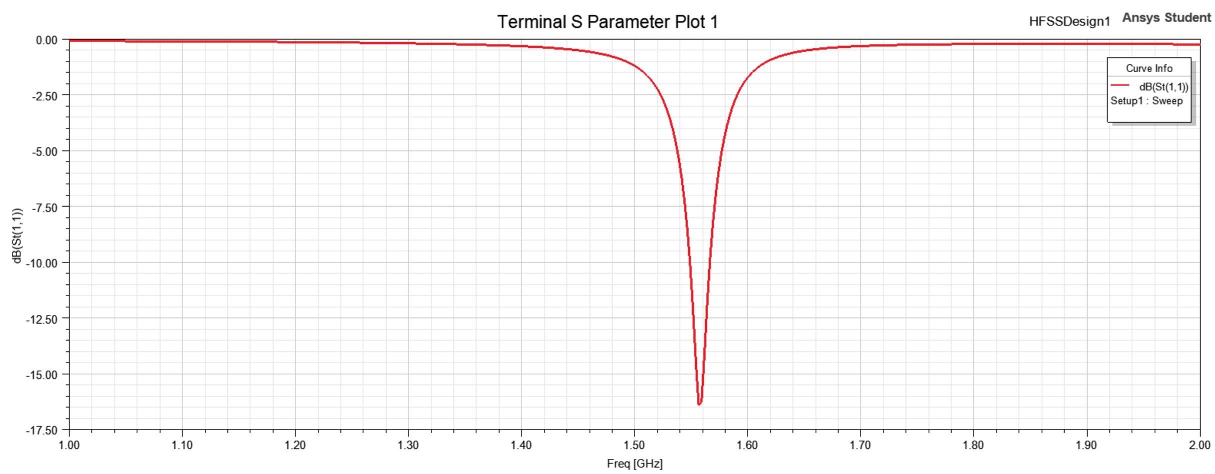


Figure 5: Parametric sweep of S_{11}

A value of $S_{11} = -16.5\text{dB}$ corresponds to a ratio of $10^{-16.5/20} = 0.15$. Because this is a one-port network, S_{11} is also the reflection coefficient Γ. The VSWR is then calculated to be

$$\text{VSWR} = \frac{1+\Gamma}{1-\Gamma} = 1.35 \tag{3}$$

As a rule of thumb, the VSRW should be less than 2 for the frequency range of interest and this requirement is met.

6.4 Bandwidth

From the S_{11} response in Figure 5, the bandwidth is measured with respect to when S_{11} is below -10dB. The two points on the edge of this boundary are (1.549 GHz, -10dB) and (1.579GHz, -10dB). The bandwidth is

$$BW = 1.579\text{GHz} - 1.549\text{GHz} = 0.03\text{GHz} = 30\text{MHz} \tag{4}$$

A 30MHz bandwidth is acceptable because satellite transponders operate at 30MHz and upwards [4].

6.5 Summary of Measured Parameters

Table 2: Measured parameters of patch antenna design

S_{11}	VSWR	Peak Gain	Realized Gain	Directivity	Efficiency
-16.5dB	1.35	7.81dB	6.36dB	9.15dB	52%

6.6 Power Received by a Satellite

Using the Friis equation and our simulated gain of $G_t = 6.36dB$ for the transmitter

$$\begin{aligned} P_r &= P_t \frac{G_r G_t \lambda^2}{(4\pi d)^2} \\ P_r(dB) &= P_t(dB) + G_t(dBi) + G_r(dBi) + 20 \log \left(\frac{\lambda}{4\pi d} \right) \\ P_r(dBm) &= 30(dBm) + 6.36dB + 6 - 180 \\ P_r &= -136.64dBm \end{aligned}$$

This is above the noise floor of a typical satellite receiver of around -150 to -140 dBm so the received power is high enough so that our signal is recognized.

7 Executive Summary

A patch antenna array was designed with mathematical equations from electromagnetic theory and tuning in HFSS. The antenna structure is low-profile with a 25cm×25cm footprint and mounted on a conducting box with height 3cm; the height of the entire antenna is under 5cm. A 2×1 antenna array proved to be sufficient to meet the specifications. The final design achieved 50Ω matching at the waveport. The gain, directivity, and efficiency satisfied the application requirements.

References

[1] Constantine A Balanis. *Antenna theory: analysis and design*. John wiley & sons, 2015.

[2] European Space Agency. Antenna Gains. https://gssc.esa.int/navipedia/index.php/Antennas. [Online].

[3] Directivity. https://www.antenna-theory.com/basics/directivity.php. [Online].

[4] Belintersat. Satelite Footprints. https://belintersat.com/en/system-2#:~:text=The%20satellite%20carries%2038%20transponders,4%20x%2054%20MHz%20bandwidth. [Online].