# ECE 475 Project: Antenna Transmitter Design

Ahsen Qureshi, 20964433
Addison Henikoff, 20968149

August 4, 2025

## 1 Introduction

To justify the choice of our antenna, we tried a number of designs, most based on $\lambda/2$ dipoles, oriented so that the broadside of the dipole is facing upwards, and positioned $\lambda/4$ above the conducting box, to maximize the use of image theory. Approximating the top of the conductive box with an infinite sheet of PEC, the "image dipole" is $\lambda/2$ below the actual dipole, and has opposite polarity, so the radiation of the image dipole reinforces the actual dipole, increasing gain and directivity. Figure 1 below represents our $\lambda/2$ dipole element.

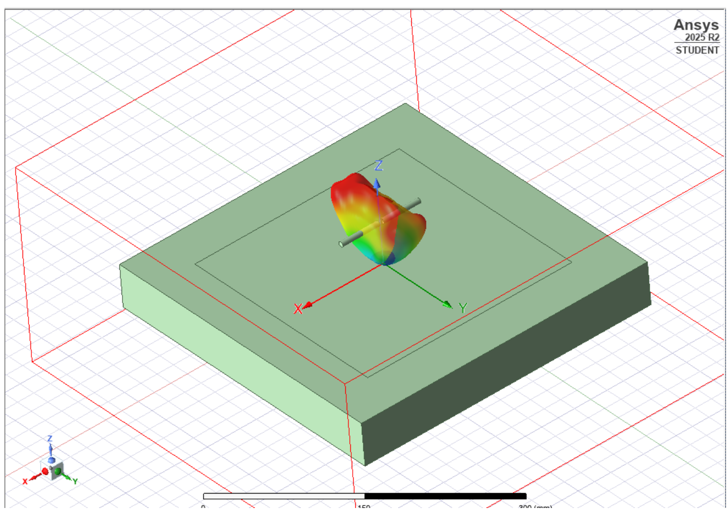


Figure 1: $\lambda/2$ Dipole Element

The $\lambda/2$ dipole served as the foundational radiating element in several array configurations that we modeled and analyzed in HFSS. These configurations included a series layout, where dipoles were placed beside one another, and a parallel layout, with dipoles arranged front and back of each other. Each design was evaluated for gain and radiation pattern performance. Ultimately, we selected the configuration that lowered half-power beamwidth (HPBW), slightly improving the antenna's directivity and gain in the Zenith, which is critical for maintaining a strong link with a satellite 20,200 km away.

Our finalized design is shown in Figure 2 below, which is the array layout that we found to have the highest gain.

We also simulated microstrip patch antenna configurations, assuming it would show higher directivity and gain as the element purely faces the Zenith direction. Figure 3 and Figure 4 below is a single microstrip patch antenna, along with a 2-element array, with the patch antenna as the element.

While the patch antenna demonstrated higher directivity as an element compared to the dipole, we encountered challenges when arraying them in a configuration that maintained a strong main lobe directed toward the Zenith.

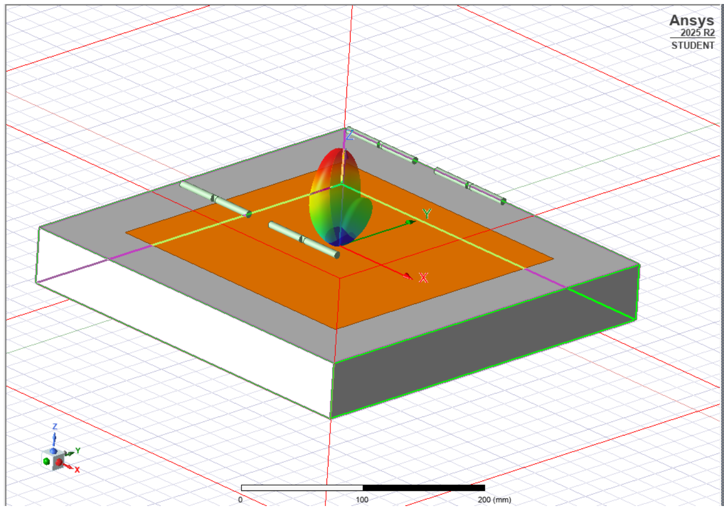


Figure 2: 2x2 Array of $\lambda/2$ Dipoles.

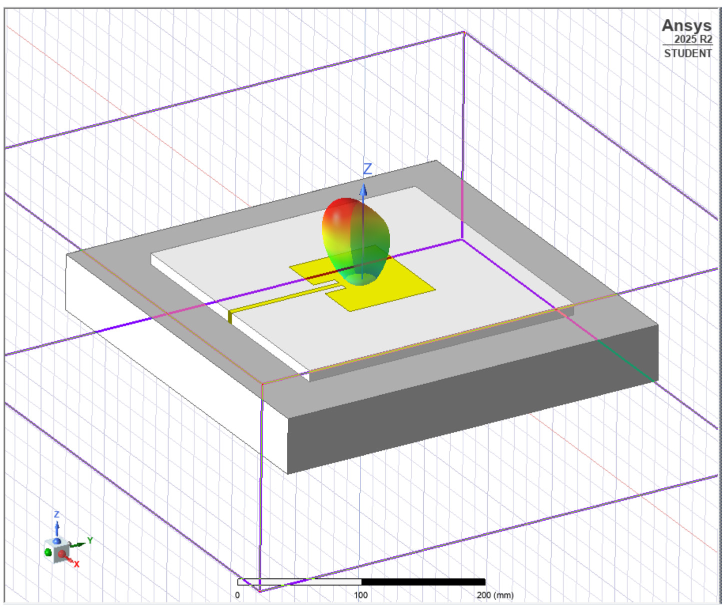


Figure 3: Microstrip Patch Antenna

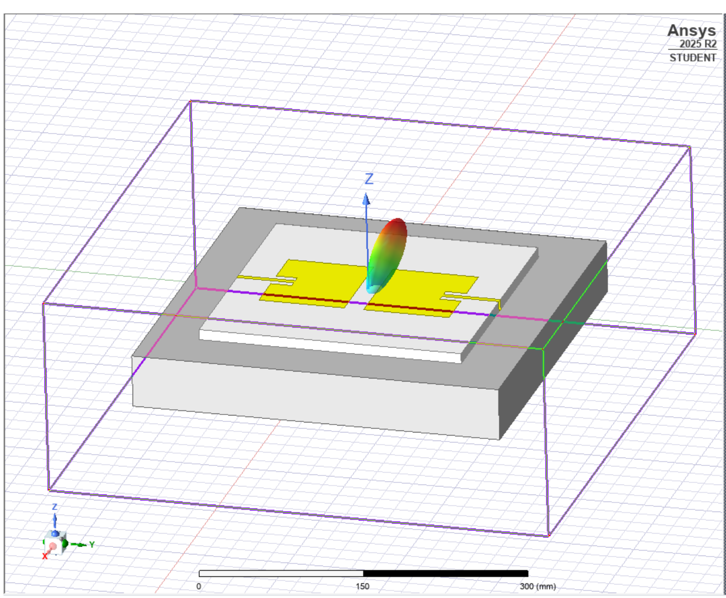


Figure 4: Microstrip Patch Antenna Array

# 2 Design Methods

## 2.1 Structure Parameters

The values in the Table 1 were defined using the HFSS "Design Parameters" module, allowing for easy changes to simulate different configurations throughout the project.

The dipole length and height above the ground plane were initially set around theoretical values based on $\lambda/2$ and $\lambda/4$, respectively, then adjusted to maximize gain and impedance matching.

Additionally, the horizontal and vertical spacing were parametrized to observe their influence on mutual coupling and beam shape, which we then ultimately settled on $\lambda/2$ spacing to preserve constructive interference and direct the main lobe toward the Zenith.

Our dipole diameter was also included as a parameter, but reducing its values led to meshing issues that were similar to Homework 3. Therefore, this dimension was kept constant.

The footprint was evaluated as a dependent parameter, constrained by the spacing given to us in the project outline of 25cm x 25cm. This parametric approach allowed iterative tuning that yielded a higher gain and a more focused radiation pattern. The table below shows our final values.

| **Parameter** | **Value / Description** |
|---|---|
| Dipole Length | 79.238 mm (optimized for gain and impedance matching) |
| Dipole Diameter | 6 mm |
| Height Above Ground Plane | $\lambda/4 = 47.62$ mm (based on image theory for constructive interference) |
| Horizontal Spacing (X-axis) | 105 mm |
| Vertical Spacing (Y-axis) | $\lambda = 190.48$ mm |
| Footprint | 18.43 cm $\times$ 19.65 cm $\times$ 5.07 cm |

Table 1: Key Design Parameters for Dipole Antenna Array

## 2.2 Real Time Considerations

As we wanted to simulate the transmission antenna in its intended environment, we created a mounting platform that was modeled as a solid rectangular Perfect Electric Conductor (PEC) prism with dimensions 35cm $\times$ 35cm $\times$ 5cm in HFSS. This platform was then centered at the origin, directly beneath the antenna, which is designed to face the zenith under the assumption that the satellite is directly overhead.

To simplify the simulation environment, the truck structure and the surrounding ground were excluded. In the project design, we were not provided with the truck's height or electromagnetic properties, and therefore could not model them accurately. However, since the PEC platform acts as a strong reflector, only minimal energy is radiated downward toward the truck or ground. As a result, their influence on the antenna's performance was assumed to be negligible and unlikely to affect the accuracy of the simulation.

# 3 Results

## 3.1 Efficiency

In Figure 5, the impedance of our four dipoles in our antenna array is show. The elements are each driven by equal-length 76 Ohm transmission lines, which are joined in a series-parallel configuration, results in a total input impedance of $76.16 + j1.01\,\Omega$.

To improve impedance matching, a quarter-wave transformer is employed (a $61.71\,\Omega$ transmission line, 47.62 mm long). At the feed point, the final measured input impedance is $49.99 - j0.66\,\Omega$.

Based on these values, the reflection coefficient $\Gamma$ is calculated, allowing us to evaluate the return loss and associated efficiency.

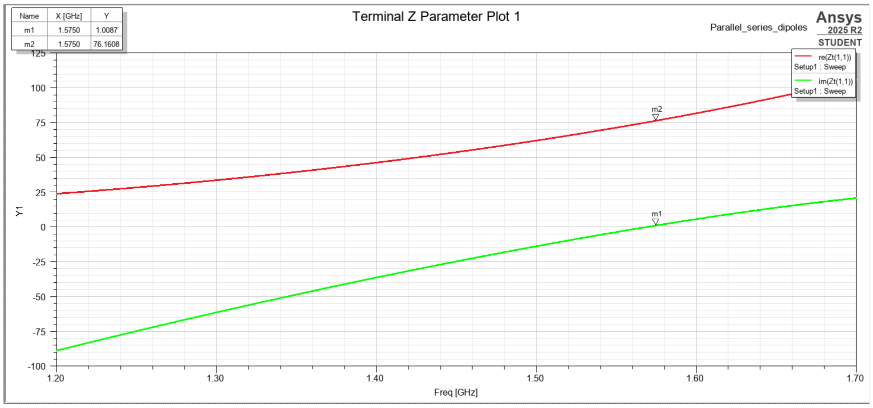


Figure 5: Input Impedance at 1.575 GHz

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{(49.99 - j0.66) - 50}{(49.99 - 0.66j) + 50} = -0.0000219 - j0.0066$$

The efficiency due to return loss is given by:

$$(1 - |\Gamma|)^2 = 98.68\%$$

Assuming the dipoles are constructed from copper, conductive losses are expected to be minimal. Additionally, dielectric losses are negligible, as the medium between the dipoles and the surrounding conductive enclosure is air.

## 3.2 Realized Gain

Figure 6 below shows the gain pattern of our antenna array as a function of the elevation angle $\theta$.

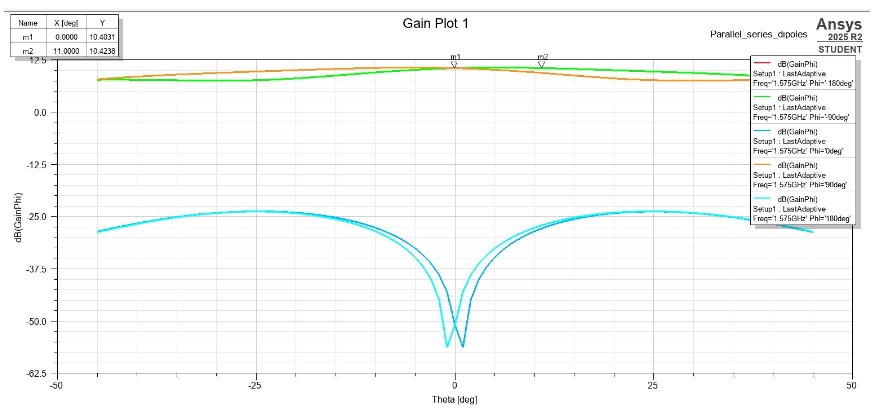


Figure 6: Antenna Gain versus $\theta$.

We know that gain quantifies the antenna's ability to focus energy in a particular direction compared to an isotropic radiator. For communication with a satellite located 20,200 km away, having a high gain at zenith is crucial to maximize the received or transmitted signal power. The raw gain at zenith ($\theta = 0°$) is 10.413 dBi. Incorporating the effects of return loss, the realized gain is calculated as:

$$G_{\text{realized}} = 10^{\frac{10.413}{20}} \times (1 - |\Gamma|)^2 = 10.8233 \approx 10.34 \text{ dBi}$$

To account for power lost due to impedance mismatch between the antenna and the feed line, we calculate the realized gain, which incorporates the return loss effect. The realized gain is approximately 10.34 dBi, indicating efficient radiation of power in the desired direction after considering practical losses. This level of gain is suitable for ensuring strong communication links over the long distance to the satellite, particularly for a mobile platform such as a truck, where maximizing signal strength is essential to overcome path losses.

## 3.3 Power Density

The power density S at the satellite's location is a key parameter indicating how much power per unit area is available for communication. It depends on the input power to the antenna, the realized gain, and the distance R between the antenna and the satellite.

Therefore, using the realized gain, and knowing the transmitter provides 1 Watt to the antenna, the power density at a distance $R$ is computed by:

$$S = \frac{P_{\text{in}} \cdot G_{\text{realized}}(\theta, \phi)}{4\pi R^2} = \frac{1 \times 10.8233}{4\pi(20,200 \times 10^3)^2} = \frac{10.8233}{5.123 \times 10^{15}} \approx 2.11 \times 10^{-15}\,\text{W/m}^2$$

Although power density is relatively low, it is typical given the vast distance involved; however, the antenna's gain effectively focuses the transmitted power to ensure a usable signal strength at the satellite. Accurately assessing power density is essential for evaluating the overall communication system performance and guaranteeing that the satellite receiver can reliably detect and process the incoming signal.

## 3.4 Voltage Standing Wave Ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) is a measure of how well the antenna impedance matches the transmission line impedance. The VSWR of the antenna is given by:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = 1.013$$

As we know, a VSWR close to 1 indicates good impedance match, minimizing power reflections back toward the source. Here, with the help of a quarter-wave transformer, a VSWR of 1.013 shows ideal matching, meaning almost all input power is radiated rather than reflected. This is especially important for a mobile antenna on a truck, where maintaining efficient power transfer despite environmental changes and movement is challenging. Low VSWR improves overall system efficiency and reduces potential damage to the transmitter.

## 3.5 Bandwidth

The antenna's operational bandwidth is defined as the frequency range over which the return loss is better than 10 dB. Figure 7 below shows that for this antenna array, the 10 dB bandwidth extends from 1437.4 MHz to 1649.5 MHz, which corresponds to a fractional bandwidth of about 13.5%.

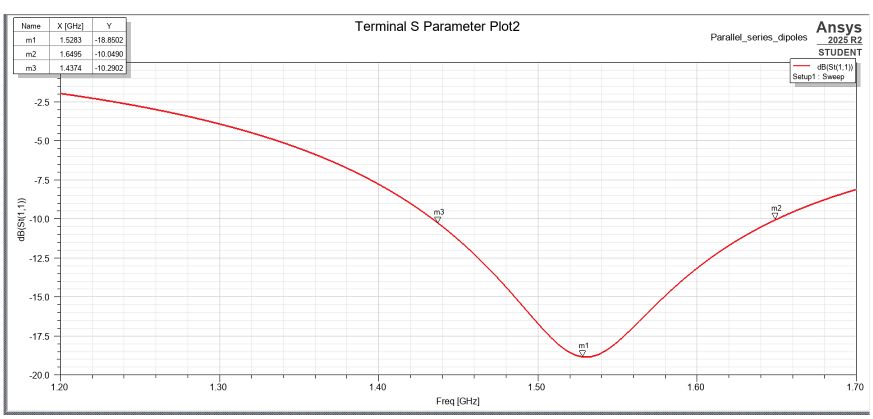


Figure 7: S-parameters of the antenna array used to determine bandwidth.

A wide bandwidth is beneficial for satellite communication because it allows the antenna to support multiple frequency channels or adapt to frequency shifts caused by Doppler effects as the truck moves. It also ensures the antenna maintains good performance across the satellite's allocated frequency band, providing reliable data transmission without frequent retuning. The 13.5% bandwidth balances gain, size, and frequency coverage for the dipole array in this application.

# 4 Challenges

As mentioned above, we tried to investigate the effect of dipole diameter, but got HFSS errors when we reduced the diameter below 6mm. So, we used our results from homework 3 to deduce that this parameter wouldn't have dramatically changed the results of the simulation around our center frequency.

While testing different array element designs, we tried a microstrip patch antenna. While the gain and directivity were promising, we struggled to array the patch antenna. As a result, we decided to go with the $\lambda/2$ dipole as our array element, due to its well-understood dispersion pattern and predictable arrayability.

# 5 Summary

We now summarize the overall layout and key specifications of our final antenna design.

The antenna consists of a 2D, 2x2 array of $\lambda/2$ dipole elements, positioned $\lambda/4$ above a conductive box. This spacing allows us to exploit image theory, effectively turning the conductive surface into a reflector that enhances the array's metrics. The design was tuned for optimal performance using HFSS, with an emphasis on gain, impedance matching, VSWR, efficiency, and bandwidth.

The key performance metrics of the final design are listed below:

| **Parameter** | **Value** |
|---|---|
| Realized Gain (Zenith) | 10.34 dBi |
| Radiation Efficiency | 98.68% |
| VSWR | 1.013 |
| Bandwidth | 212.1 MHz (13.4%) |
| Height Usage | 51% of max allowed |
| Footprint Area | 30% of max allowed |

Table 2: Summary of Key Antenna Specifications