ECE 4370
Final Project Report

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Design

All aspects of the design focused on keeping the vehicle as lightweight as possible, while maximizing gain in the direction of the source. The antenna was handmade and the chassis was assembled from purchased components. The provided RF-to-DC conversion circuit and DC motor were used without modifications.

Antenna

Most of the design effort focused on maximizing the gain of the antenna while minimizing weight. A Yagi-Uda array was chosen for the high front-to-back ratio and simplicity of design. V-dipoles were chosen over straight dipoles to minimize space and material used and to maximize bandwidth. The narrow bandwidth of a straight Yagi-Uda array would prove risky, especially for a handmade array which was more likely to deviate from design and simulation results.

Two V-dipole Yagi-Uda arrays were used as shown in Figure 1 below. The dimensions and spacing between each component are specified in Table 1. All components share the same angle alpha. The top array was identical to the bottom array. Individual values were optimized using 4NEC simulation.

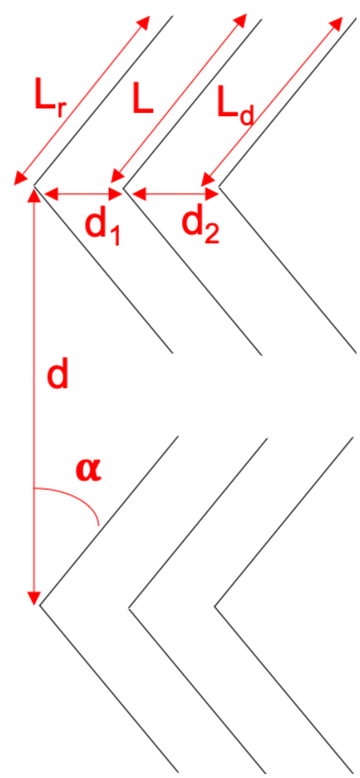

Figure 1. Array built from two V-dipole Yagi-Uda arrays with dimensions used for optimization labeled in red. The top and bottom arrays are identical, and lengths and angles for each component are symmetric.

Table 1. Antenna Dimensions		
Dimension	**Value**	**Description**
Lr	0.0391765 m	Length of reflector
L	0.0384435 m	Length of driver
Ld	0.035465 m	Length of director
alpha	44.30387°	Angle
d	0.068555 m	Distance between arrays
d1	0.012204 m	Distance between reflector and driver
d2	0.0007148 m	Distance between the driver and director
r	0.00051 m	Wire radius

Chassis

The chassis needed to be stable enough to support the antenna in the correct position while minimizing weight. Two potential designs were generated using Autodesk Tinkercad by varying the placement of the antenna and PCB as shown in Figure 2.

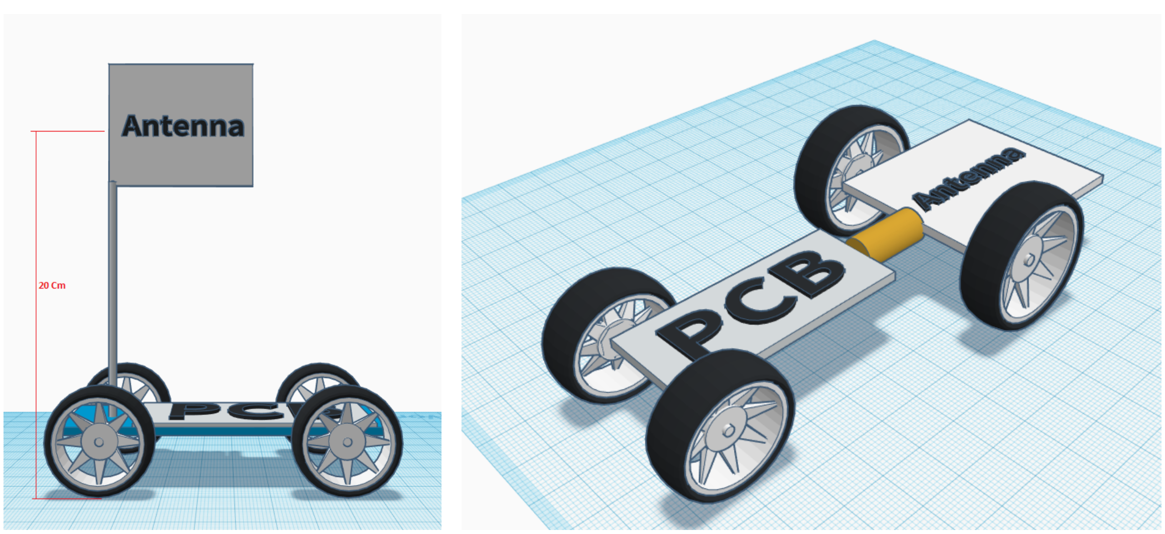

Figure 2. Two potential chassis designs. The left design has the antenna upright as a “flag” whereas the right design has the antenna laid flat alongside the PCB.

The design on the left was chosen to minimize the initial distance between the transmitter and receiver to maximize initial received power.

Additional Components

The provided RF-to-DC conversion circuit was used. This included a rectifier circuit which converts RF energy to power a 3V DC motor. A copy of the circuit schematic is provided in Figure 3.

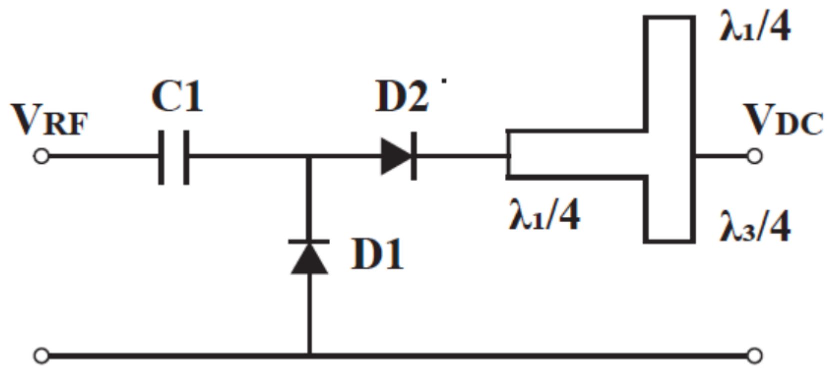

Figure 3. RF-to-DC conversion circuit schematic. This includes an RF capacitor (C1) and two Schottky diodes (D1, D2) which reflect high-order harmonics back into the device for improved efficiency.

A low-powered DC motor was provided, which took the converted DC voltage from the rectifier circuit and converted this to mechanical energy to spin the wheels of the car. The provided DC motor had specifications outlined in Table 2 below.

Table 2. DC Motor Specifications	
Parameter	**Value**
Voltage	3.0 Volts
RPM	70000 RPM
No-load Current [1]	30 mA

Simulation

The antenna was simulated using NEC. The geometry of the antenna was captured in 2D and 3D within NEC as shown in Figure 4. Plots of the antenna patterns are shown in Figure 5 below. The maximum gain was 12.6 dBi, and front-to-back ratio was 14.6 dB.

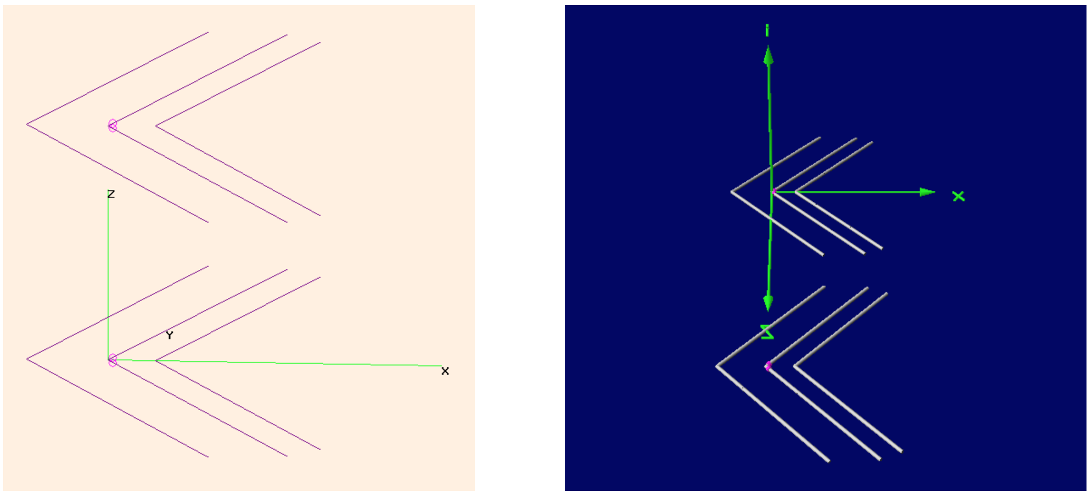

Figure 4. Screenshots in 2D (left) and 3D (right) of 4NEC's antenna geometry.

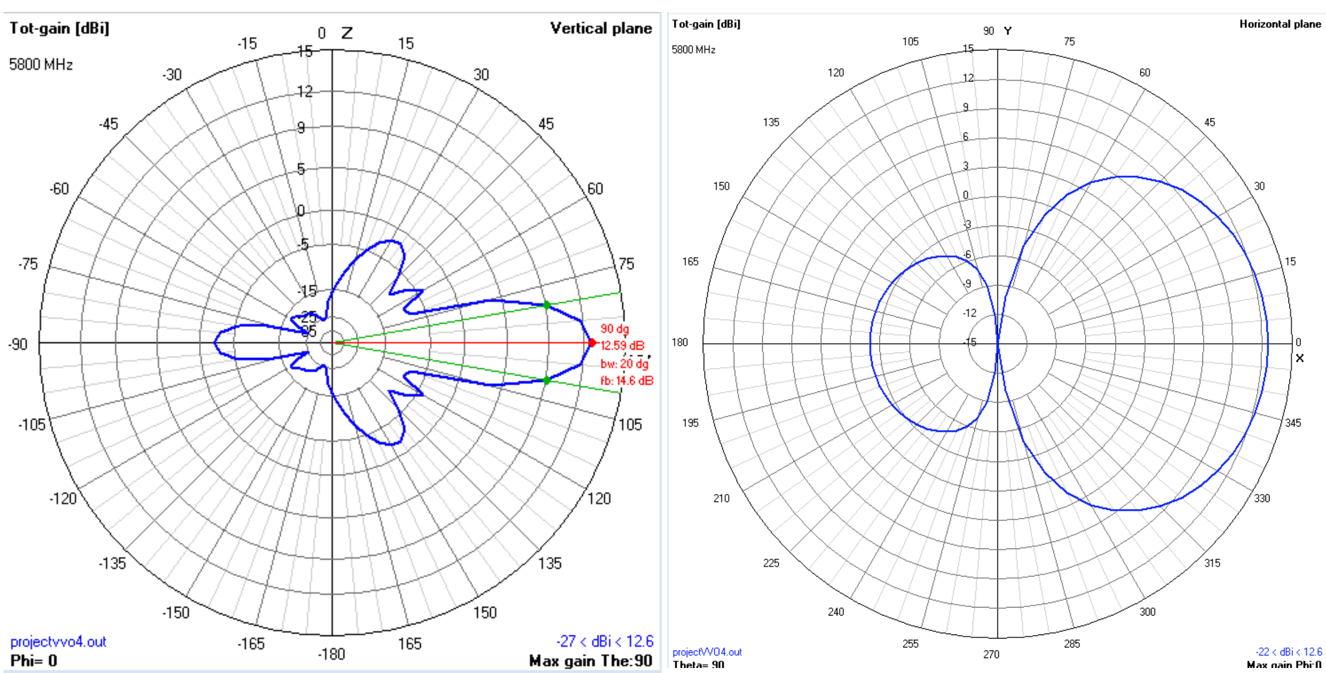

Figure 5. The vertical plane antenna pattern is shown on the left, and horizontal is shown on the right. Front to back ratio of 14.6 dB is visible on the plot on the left.

This simulation also showed antenna resistance as about 22 Ohms, with a small reactance less than 1 Ohm as shown in Figure 6.

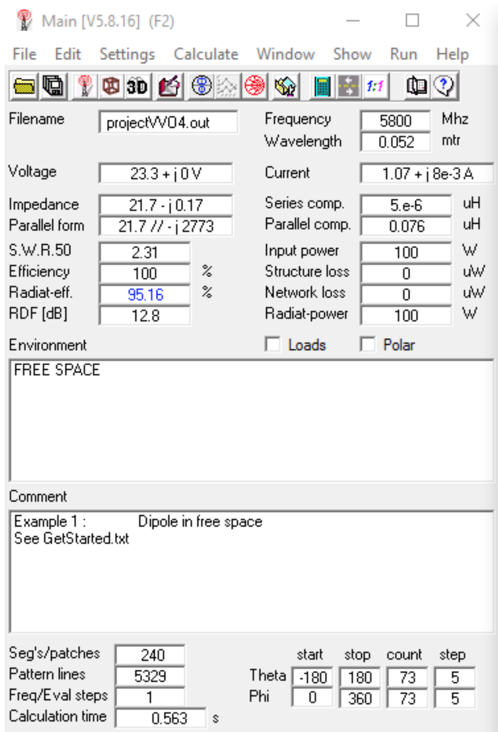

Figure 6. Antenna parameters, including impedance of 21.7 - j0.17 Ohms.

Fabrication

The antenna and chassis frame were built by Group 9. Other components, including the PCB and DC motor, were selected from supplied ECE 4370/1 materials.

Antenna

The antenna was fabricated using copper wire on a paper-like substrate as shown in Figure 7. The copper wires were bent and cut to the specified dimensions in Table 1, with each driver fed in parallel to a coaxial cable. Figure 8 shows a detailed view of the connections. A quarter wavelength baluns was used to balance the signal.

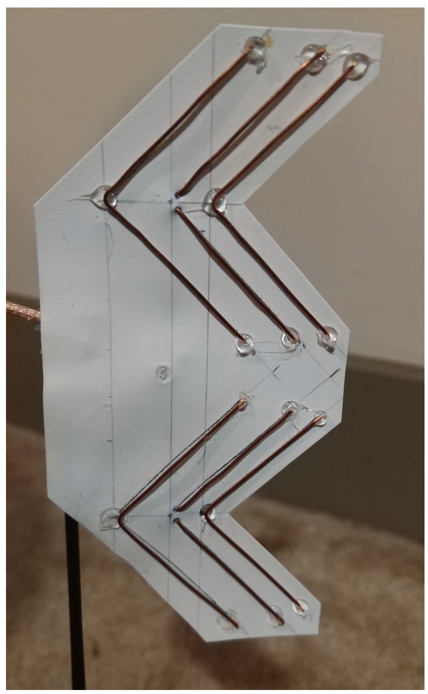

Figure 7. Physical construction of the V Antenna Stacked Yagi Array design from Figure 1 with tracings.

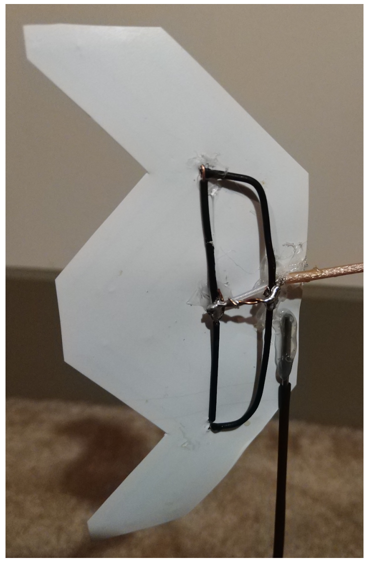

Figure 8. Connections on the back of the antenna array to both drivers, including quarter wavelength baluns and direct soldering to coaxial cable.

Chassis

The chassis included a plastic base, plastic wheels, metal axles, two gears, the DC motor, and a metal rod that raised the antenna to 20 centimeters from the ground in accordance with the design shown in Figure 2. The basic frame parts (plastic base, wheels, gears, pole for antenna) were purchased through Amazon [2,3]. A gear ratio of 50:8 was used, and a detailed view of the DC motor connection is shown in Figure 9.

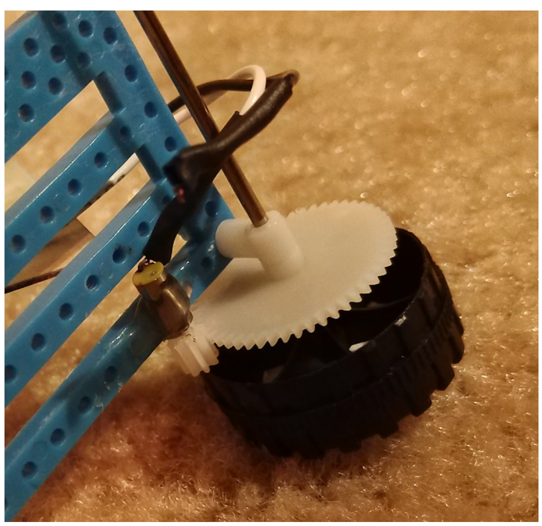

Figure 9. Detail of the DC motor and two gears connected to the front axle.

Integration

All parts were assembled and integrated as demonstrated in Figure 10.

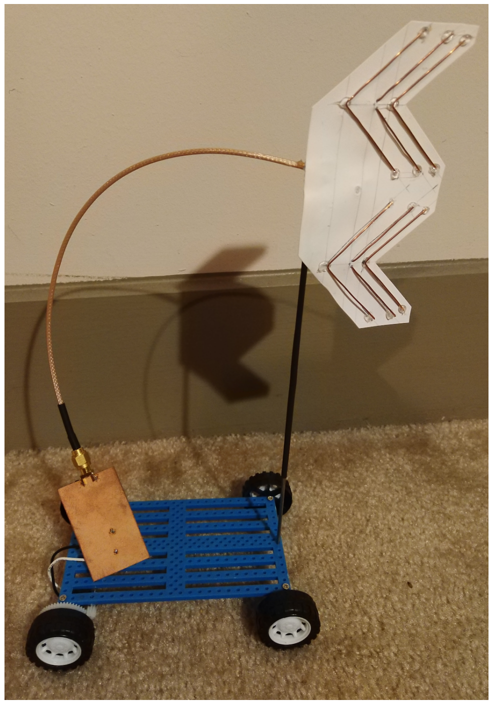

Figure 10. Complete assembly of all components including the antenna, chassis, wiring, PCB, motor, and supporting components.

Measurement

Impedance of the antenna was measured using a network analyzer. These results are shown in Table 2. Additional measurements from LV-DAM software verified the antenna pattern and related parameters. These results are shown in Table 3 and Figures 11 - 14.

Table 2. Network Analyzer Measurements

Parameter	**Value**
Antenna Impedance	-8.66 dB @ 5.87 GHz
Bandwidth	155 MHz

Table 3. Rooftop Range Measurements

Parameter	**Value**
Peak Gain	-18.46 dB
Half-Power Beamwidth	88.69
Sidelobe Level	N/A, no lobes

The received gain was calculated through the link budget using Equation 1:

$$P_R = P_T + G_R + G_T - 20\log_{10}\left(\frac{4\pi}{\lambda}\right) - 20\log_{10} r \tag{1}$$

With inputs and received power values shown in Table 4, where MSL of =-18.46 dB was used for received power.

Table 4. Received Gain Calculations

Input	**Value**	**Output**	**Value**
P_T	30 dBm	G_R	-0.6 dBi
P_R	-18.46 dB		
G_T	5.1 dBi		
λ	0.05172 m		
r	1.83 m		

V Stacked Yagi Array.ant

	MSL (dB)	MSP (°)	HPBW (°)
E	-18.46	333	88.69
H	-30	0	0

Figure 11. Max Signal Level (MSL) in decibels with associated angle and half power beam width (HPBW) in degrees from LV-DAM measurement.

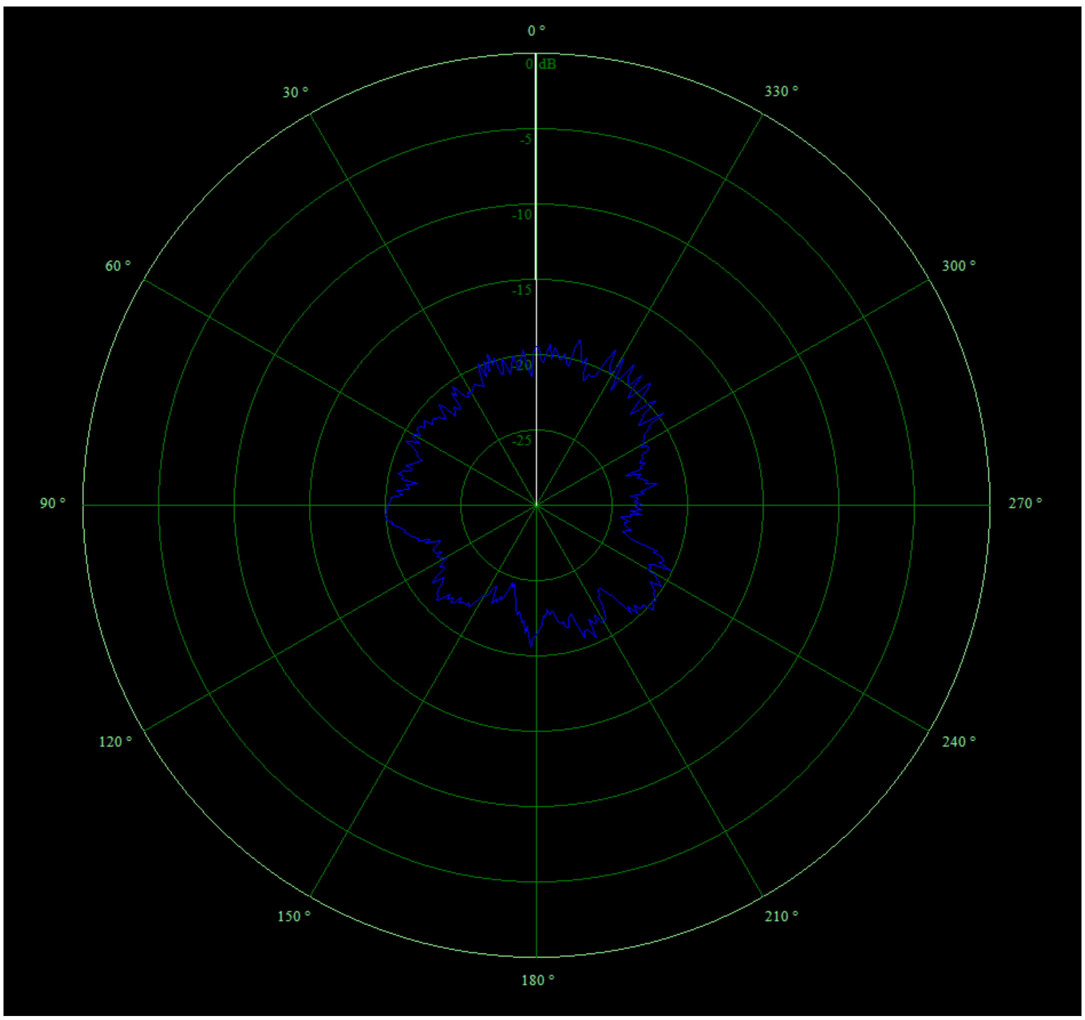

Figure 12. Antenna radiation pattern from LV-DAM measurement.

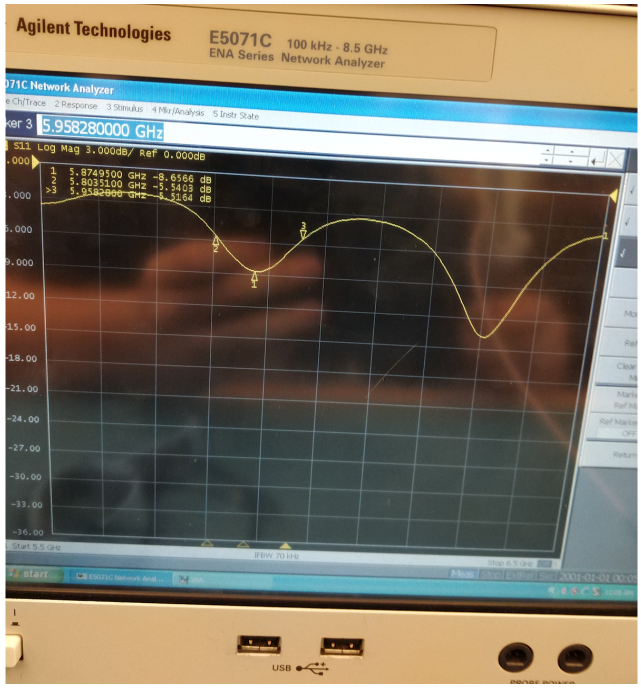

Figure 13. Impedance pattern from network analyzer.

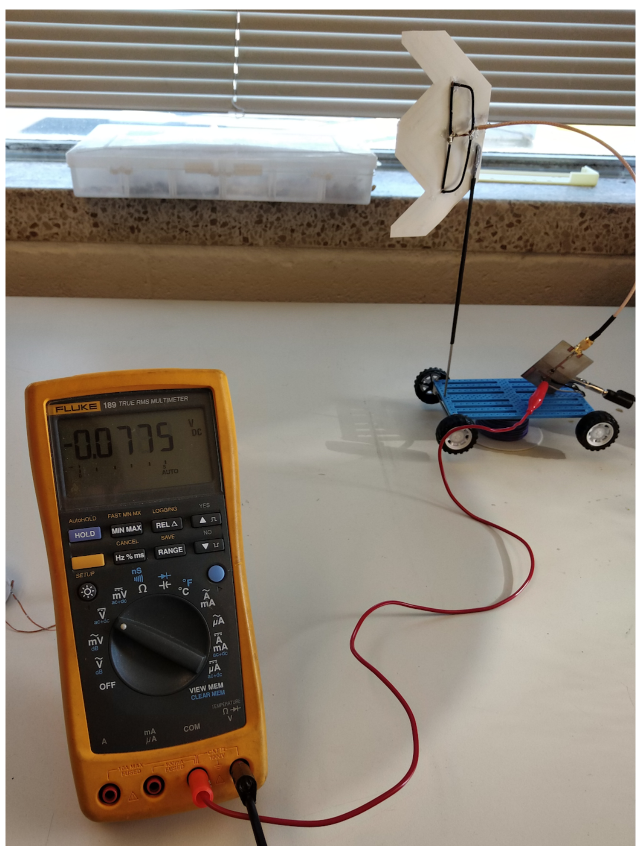

Figure 14. Multimeter measurements showing 77.5 mV received power.

Unofficial results including the distance traveled and weight measurements were summarized in Table 5.

Table 5. Unofficial Competition Measurements	
Parameter	**Value**
Distance Traveled	0
Weight of Antenna	.005 kg
Peak Linear Gain	0.87
[Peak Linear Gain]/[Weight]^0.5	12.317

Analysis

A simplified analysis calculated the received power and converted this to an estimate of the distance the car at 7.382 meters from the starting position. This result was higher than predicted, as simulated gain was used as opposed to measured gain and thus this analysis did not account for physical imperfections of the real antenna. Appendix A has a full copy of the Matlab code.

Inputs

Inputs included given parameters, simulation results, and design decisions as summarized in Table 6.

<table>
<tr><th colspan="6">Table 6. Analysis Inputs</th></tr>
<tr><th>Given Parameter</th><th>Value</th><th>Simulation Result</th><th>Value</th><th>Design Decision</th><th>Value</th></tr>
<tr><td>Transmitter height</td><td>0.02 m</td><td>Received gain</td><td>12.6 dBi</td><td>Antenna height</td><td>0.02 m</td></tr>
<tr><td>Transmit power</td><td>700 W</td><td rowspan="3">Antenna impedance</td><td rowspan="3">12.7+0.17j Ohms</td><td>Total weight</td><td>0.055 kg</td></tr>
<tr><td>Transmit gain</td><td>20 dBi</td><td>Wheel diameter</td><td>0.03175 m</td></tr>
<tr><td>Frequency</td><td>5.8 GHz</td><td>Gear ratio</td><td>50:8</td></tr>
</table>

Several assumptions were made to complete calculations that were not directly based on Group 9's own measurements or simulations. Given that very highly optimized RF-to-DC converter has an efficiency around 80%, the conversion circuit used in this project is assumed to have only about 50% efficient [4]. Internal efficiency of the DC motor itself was assumed to be about 50%, based on similar low-voltage DC motors with a maximum efficiency ranging from 60-70% [5]. Impedance of the motor was calculated using a no-load current of 30 mA [1]. Acceleration due to gravity was a constant 9.8 meters per second, and coefficient due to rolling friction between rubber and concrete was assumed to be 0.015 [6].

Calculations

First the link budget was calculated using the same formula as used for measurement from Equation 1:

$$P_R = P_T + G_R + G_T - 20\log_{10}\left(\frac{4\pi}{\lambda}\right) - 20\log_{10} r \qquad (1)$$

with each of the variables defined as inputs stated in the previous section. Received power was then converted from dB back to Watts.

Voltage across the antenna was calculated using the formula in Equation 2:

$$V_A = \frac{2|Z_M|\sqrt{2R_A P_R}}{|Z_A+Z_M|} \tag{2}$$

again where the variables were all defined as inputs in the previous calculation, with the exception of received power which was calculated using Equation 1. Voltage across the antenna was reduced based on the efficiency of the RF conversion circuit, which was then used to calculate the power going into the motor.

Additional loss was due to the efficiency of the DC motor itself, as shown in the torque calculation in Equation 3:

$$\tau = \frac{60 I_M V_M \eta}{\text{rpm} * 2\pi} \tag{3}$$

The torque from the motor was then converted to torque to the wheels as shown in the conversion in Equation 4:

$$R_G = \frac{\tau_W}{\tau_M} \tag{4}$$

and then into forward force of the wheels as shown in Equation 5:

$$F_M = \frac{\tau_W}{D/2} \tag{5}$$

Frictional force was calculated using Equation 6:

$$F_f = mg\mu \tag{6}$$

Then net force was calculated as the difference between the force of the wheels and frictional force, and used to determine the distance traveled as shown in Equation 7:

$$\Delta d = \frac{P_M}{F_{net}\Delta t} \tag{7}$$

The analysis stopped when either the additional gain in distance or received power became too small, and resulted in a total distance traveled of 7.382 meters in a span of 15 seconds.

References

[1] Motorhouse online store, "5PCS 4mm*8mm DC 3V 70000RPM High Speed Micro Ultra Mini Tiny Coreless Motor Toy," *ebay.com.* [Online]. Available: https://www.ebay.com/itm/5PCS-4mm-8mm-DC-3V-70000RPM-High-Speed-Micro-Ultra-Mini-Tiny-Coreless-Motor-Toy-/192194090835?hash=item2cbfa91753. [Accessed Nov. 28, 2018].

[2] YGDZ online store, "YGDZ 92 Plastic Gear Package Kit DIY Gear Assortment Accessories Set Plastic Gear Package Kit DIY Gear Assortment Accessories Set", *Amazon.com*. [Online]. Available: https://www.amazon.com/dp/B07JVF54JX/ref=cm_sw_r_cp_awdb_t1_iEZbCbS7S2T9X.

[3] uxcell online store, "uxcell 5 Pcs 2mmx200mm Metal Solid Round Rod Bar for DIY RC Model Car,"*Amazon.com.* [Online]. Available: https://www.amazon.com/uxcell-2mmx200mm-Metal-Solid-Round/dp/B01913RHT8/ref=redir_mobile_desktop?_encoding=UTF8&psc=1&ref=yo_pop_mb_pd_title

[4] Chaour I, Fakhfakh A, Kanoun O., "Enhanced Passive RF-DC Converter Circuit Efficiency for Low RF Energy Harvesting," *National Center for Biotechnology Information*, Mar. 2017. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5375832/

[5] Johnson Motor, "Standard DC Series Motors," Standard DC Series - Low Voltage DC Motors datasheet. [Online]. Available: http://www.contact-evolution.ch/files/DC_motors.pdf

[6] Engineering ToolBox, (2008). *Rolling Resistance*. [Online]. Available: https://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html [Accessed Dec. 1, 2018].

Appendix A: Matlab Analysis Code

```
%% ECE 4370 Final Project
% Group 9

clear all; close all;

%% Inputs

% Given parameters
hTx = 0.20; % Height of transmitter [meters]
PtW = 700; % Transmit Power [Watts]
Gt = 20; % Transmit Gain [dBi]
lambda = 3e8/5.8e9; % Wavelength [meters]

% Simulation Results
Gr = 12.6; % Received Gain [dBi]
Za = 21.7 + 1i*0.17; % Antenna Impedance [Ohms]
Ra = real(Za); % Antenna Resistance [Ohms]

% Measurements/Design Parameters
hRx = 0.20; % Height of receiver [meters]
gearr = 50/8; % Gear ratio between motor and wheels
wheeld = 0.03175; % Wheel diameter [meters]
mass = 0.055; % Mass of the car [kilograms]

% Assumptions
effRF = 0.5; % Assume rectifier circuit is about 50% efficient
effm = 0.5; % Assume motor is about 50% efficient
Zm = 3/30e-3; % Impedance of load (motor) (3 V / no-load 30 mA)
g = 9.8; % Acceleration due to gravity
mu = 0.015; % Coefficient of rolling friction


%% Calculations

Pr = 0; % Start with everything discharged
d = 1; % Start 1 meter away from source
deltat = 15/500; % Time step

for t = linspace(1,15,500)

      % Link Budget
      r = sqrt((d)^2 + (hTx-hRx)^2); % 2D distance from Tx to Rx in meters
      Pr = 10*log10(PtW) + Gr + Gt - 20*log10(4*pi/lambda) - 20*log10(r);
      PrW = 10^(Pr/10); % Convert back to Watts
```

```
        % Voltage to DC Motor
        Va = 2*abs(Zm)*sqrt(2*Ra*PrW)/abs(Za+Zm); % Voltage across antenna
        Vm = effRF*Va; % Voltage across load (motor)
        Im = PrW/Vm; % Current across load (motor)
        Pmotor = Vm*Im; % Power to wheels

        % Force to Wheels
        rpm = (abs(3-Vm)/3)*70000; % 3V DC motor, 70000 rpm
        torqueM = (Im*Vm*effm*60)/(rpm*2*pi); % Torque from motor
        torqueW = gearr*torqueM; % Torque to wheels considering gear ratio
        Fmotor = torqueW/(wheeld/2); % Forward force of wheels
        Ffriction = mass*g*mu; % Frictional force
        Fnet = Fmotor - Ffriction; % Net force

        % Distance Traveled
        deltad = Pmotor / Fnet * deltat; % Distance gained

        if isnan(deltad) || PrW < 1e-8
        break
        else
        d = d+deltad;
        end

end

sprintf('Distance traveled is %f meters.', d-1)
```