Wave Car Racers

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***Abstract*—This paper details the design, simulation, fabrication and test of a four patch antenna array to determine its functionality as a high gain, lightweight antenna that allows for microwave (5.8 GHz) energy harvesting and conversion to mechanical energy. The antenna application is to power a self-designed race car along a race track. The goal is to create an antenna with the aforementioned description, while maximizing peak gain and minimizing weight. The self-designed race car needs to be operable by the small amount of power received via the antenna and the energy harvesting circuit.**

I. Introduction

The goal of this experiment is to design, simulate, and fabricate a high-gain, lightweight antenna that allows for microwave (5.8 GHz) energy harvesting and conversion to mechanical energy in order to propel a small DC motor. The antenna should have a target unlicensed ISM band of operation between 5.725 GHz and 5.850 GHz; it should also maximize peak gain while minimizing weight. After fabrication, the antenna will be measured for S_{11} values, as well as radiation patterns in the H and E planes. The experiment will conclude with the testing of the antenna. The first test the antenna will undergo, is measuring how well the antenna maximizes the parameter in Equation 1. This test determines the antenna's ability to maximize gain and minimize weight. The second test will measure the total distance the antenna can propel a small DC motor attached to a race car when connected to an energy harvesting circuit and powered by a 5.8 GHz 700 Watt continuous wave magnetron. The success of the antenna will be determined based on the two aforementioned tests.

$$\sqrt{Peak\ Linear\ Gain\ /Weight} \quad (Eq.\ 1)$$

II. Design

A. Antenna

A patch antenna, a Yagi Uda antenna, and a horn antenna were considered as potential antenna design choices for this application. All three design options possess relatively good directional gain if the main beam is narrowed. Additionally, all three design options possess a good front-to-back ratio. A Yagi Uda antenna was determined to be too difficult to manufacture properly and a horn antenna was determined to be too heavy. Consequently, a patch antenna was decided upon as the design, because it promised to be lightweight, easy to fabricate, and directional. In order to further increase the directionality of the antenna, a four patch antenna array was designed. The four patch antenna array was symmetrical as showcased in Figure 3; the symmetrical layout creates a narrow beam in both horizontal and vertical direction. The narrow beams are a vital part of the design, as they correlate with high gains in the direction of the main beam.

The original design for the antenna was an edge-fed patch antenna. The design and calculations of all patch and trace dimensions for the edge-fed case were completed, but the PCB mills available were not capable of etching traces as small as the ones calculated. The next design approach was an inset-fed patch antenna with quarter wave transformers to match the antenna to the 50**Ω** SMA connector. This would ensure minimal reflection and hence, maximum power transfer.

B. Energy Harvesting Circuit

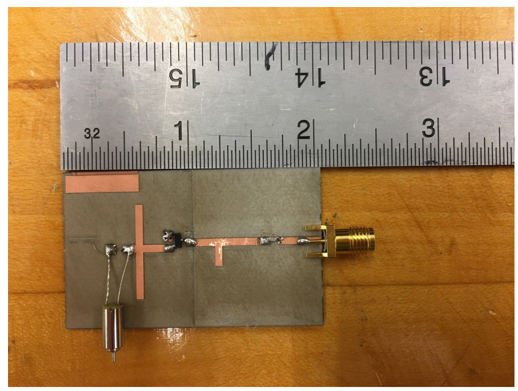


Figure 1. Energy harvesting circuit after assembly with previously provided DC motor.

The energy harvesting circuit and the necessary components were provided as part of the assignment. No alterations were made to the energy harvesting circuit provided as the main goal of the project was to create a properly functioning antenna and race car.

C. Race Car

In order to fulfill the requirements of the project, the antenna and the energy harvesting circuit have to provide enough energy to power a miniature race car along a predefined track.

The main design consideration for the race car is the car chassis. The car chassis should include the following: space for the energy harvesting circuit, a gear box, 2 axles with wheels, a motor, and an area to attach the antenna. The necessary technical drawings of the race car chassis with the aforementioned features were created in CAD utilizing Solidworks 2018. 3D-printing was decided upon for manufacturing of the chassis, as it ensures a good ratio between weight and stability. Additionally, the makerspaces at Georgia Institute of Technology house a vast amount of 3D printers, so the technology was easily accessible.

It was possible to 3D print the car chassis, but not the necessary gears as the 3D printer accuracy is limited to 0.5 mm. Therefore, the axles, wheels, and gears were purchased as a set. The car chassis width was determined to be approximately 8 cm based on the purchased axles and gears. The 3V DC motor provided with the energy harvesting circuit was not utilized; it was replaced by a Uxcell 3.7V coreless motor. The Uxcell motor has a larger shaft and lower RPM value at the expected operating voltage. The new motor's power demand is similar to that of the DC motor provided and the motor operates at very low voltages.

The main beam of the power transmitting antenna is approximately 20 cm above ground level. As the antenna is designed to have maximum gain values at elevation angle Θ=0, the antenna needs to be attached to the chassis 20 cm above ground level. Due to this fact, the car chassis was designed to include 2 large poles, approximately 20 cm in height, for the purpose of attaching the antenna to the car.

No predesigned model could be utilized for the project application, as none of the models met the project requirements. The finished model is displayed in Figure 2a and 2b. The chassis has a basic design due to time constraints. The most important design aspects of the race car were antenna attachment area and space for the energy harvesting circuit. An additional feature of the chassis design is the mounting necessary for all shafts of the car drivetrain; the mountings ensured design robustness and durability.

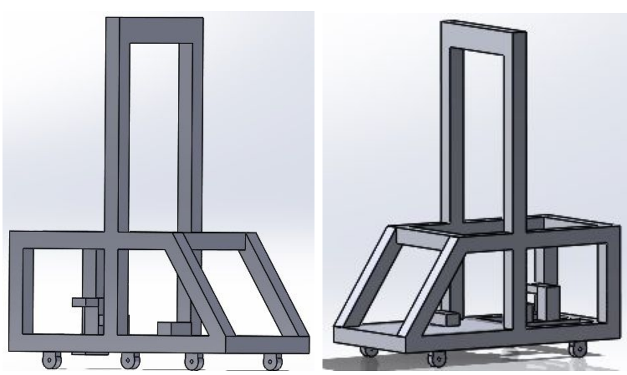


Figure 2. View of the model of the racecar
a): View from the front left corner, b): View from the front right corner

Operated at 3V, under no load conditions, the utilized DC motor averages approximately 40,000 RPM. In order to prevent spinning wheels, the gear box must be designed according to the Equation 2, where u is the gear ratio.

$$u = \frac{n_1}{n_2} = \frac{number\ of\ teeth\ on\ gear\ 1}{number\ of\ teeth\ on\ gear\ 2} (Eq. 2)$$

A gear ratio of 0.31 was determined necessary to avoid spinning wheels, but still provide the necessary torque to move the race car. An additional motor coupler was manufactured due to the fact that the diameter of the DC motor's shaft was too small to be directly attached to the gears.

III. SIMULATIONS

HFSS was selected as the software to simulate the antenna. It was selected based on ease of use and its ability to export gerber files.

A. Antenna Dimensions

The parameters of a single patch antenna are shown in Table 1.

Table 1. Dimension of a single patch antenna	
Patch Width	15.7 mm
Patch Height	11.79mm
Dielectric Constant	4.4
Dielectric Thickness	1.5mm

Equations 3 and 4 were used to calculate the parameters that are shown in the Table 1.

$$Width = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}}; \quad \varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

$$Length = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right)$$

Equation 3. Patch antenna width equation
Equation 4. Patch antenna length equation.

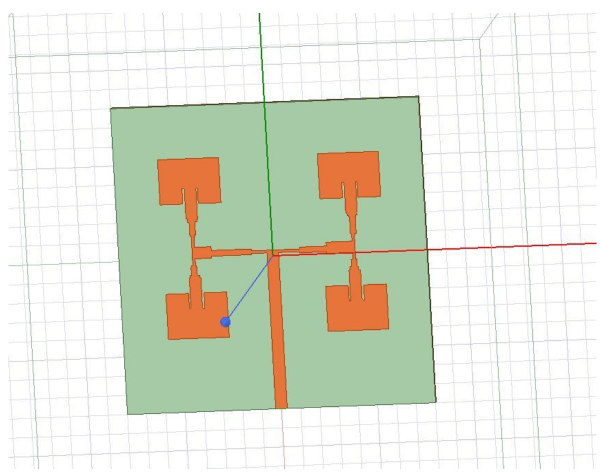
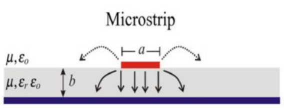


Figure 3. HFSS patch antenna design.

In order to minimize reflections, the four patch antennas were matched to the 50 **Ω** input impedance of the SMA connector. Two quarter wave transformers were used to reduce reflections in the splitting branches of the antenna array.

B. Matching Network

The impedance of a microstrip is a function of its width, dielectric height, and dielectric constant. Equations 5 - 9 can be used to calculate the impedance of a microstrip.



$$Z_0 = \begin{cases} \frac{1}{2\pi}\sqrt{\mu/\varepsilon_{eff}}\ \ln\left(\frac{8b}{a}+\frac{a}{4b}\right), & a<b \\ \sqrt{\mu/\varepsilon_{eff}}\ \frac{1}{a/b+1.393+0.667\ln(a/b+1.444)}, & a>b \end{cases}$$

$$\varepsilon_{eff} = 8.854\times10^{-12}\left[\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12b/a}}\right]\ \text{F/m} \qquad v_p=\frac{1}{\sqrt{\mu\varepsilon_{eff}}} \qquad L=\frac{Z_0}{v_p} \qquad C=\frac{1}{Z_0 v_p}$$

Equation 5. Input impedance, Z_o, equation
Equation 6. Effective dielectric constant, ε_{eff}, equation
Equation 7. Propagation velocity, v_p, equation
Equation 8. Inductance, L, equation
Equation 9. Capacitance, C, equation

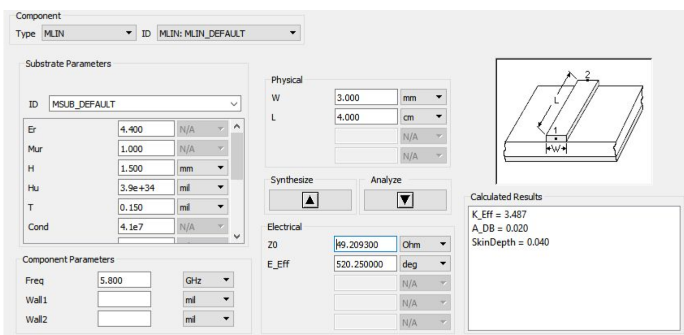


Figure 4. Linecalc software screenshot

The Linecalc software, pictured in Figure 4, does not use Equations 5-9, but it eases the calculation process by allowing the user to input parameter values. The Linecalc software determined the proper width of the dielectric after all parameters were entered.

C. Radiation Patterns

The antenna radiation pattern is shown in Figure 5. The main lobes are present towards the front of the antenna, which indicates that the antenna has a good front to back ratio.

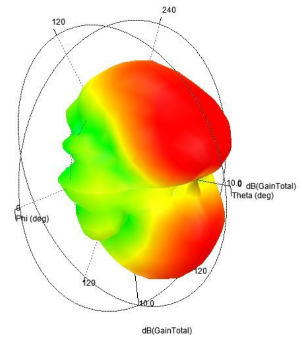


Figure 5. 3D radiation pattern of the patch antenna array.

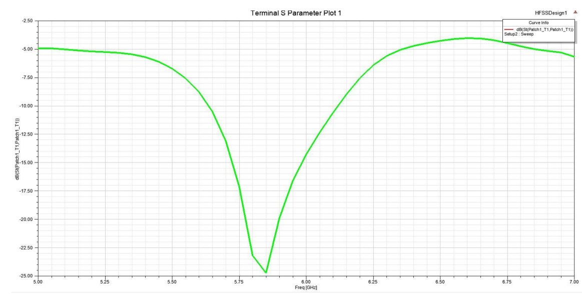


Figure 6. HFSS S11 Pattern of the patch array antenna.

The center frequency of the S_{11} plot is at 5.8 GHz with a minimum S_{11} value of -25 dB value, as shown in Figure 6. Minimum S_{11} values below -10 dB can be considered good power transfer and have low reflection. The bandwidth of this antenna would be 5.6 GHz to 6.1 GHz. The peak gain for both the H plane and E plane radiation patterns is located at zero degrees as indicated by Figure 7 and Figure 8.

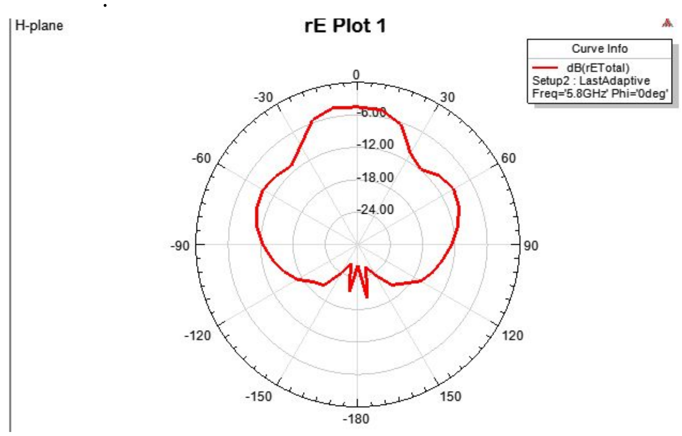


Figure 7. H-Plane radiation pattern of patch antenna array.

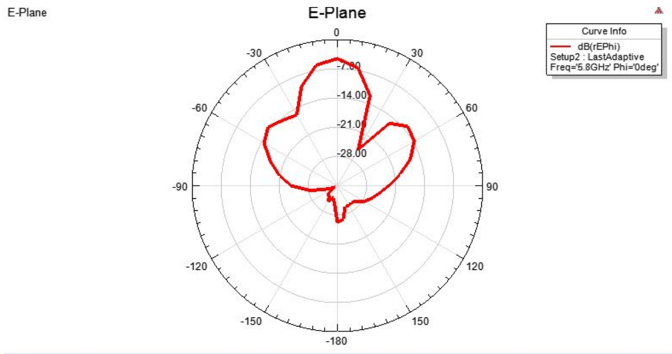


Figure 8. E-Plane radiation pattern of patch antenna array.

IV. Fabrication

A. Antenna

The Antenna was etched with the use of a laser PCB mill at the Georgia Institute of Technology Interdisciplinary Design Commons. The original plan was to mill the antenna at the Senior Design Lab, as it accepts Gerber files (Figure 9) generated by the HFSS software. However, the Senior Design PCB mill started experiencing technical difficulties. Due to the technical difficulties and limited resources, the original dielectric material, FR-4 with thickness 1.6 mm, was no longer available. However, a substitute for the FR-4 was provided to serve as the dielectric for the antenna. The substitute material possesses a similar dielectric constant and thickness compared to the original FR-4. Therefore, the substitute material was similar to the originally simulated material, but did not provide a perfect match to the SMA connector. The fabricated antenna is featured in Figure 10.

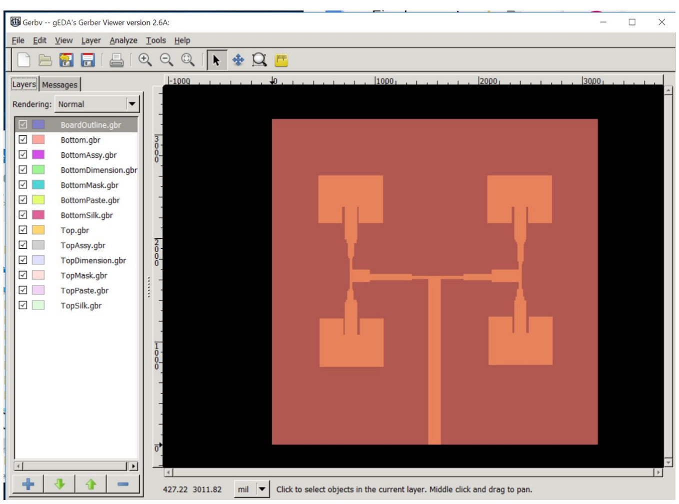


Figure 9. Gerber view of the HFSS.

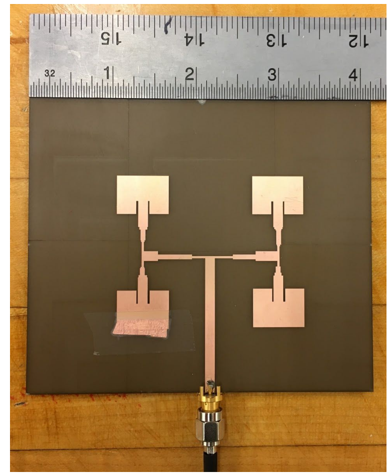


Figure 10. Patch antenna PCB.

B. Race Car

As mentioned previously, the race car was fabricated through the utilization of a 3D printer. The Solidworks CAD drawing was converted to a necessary STL-file to match the data type requirements of available 3D printers. Final assembly of the overall drive train was a smooth process. Difficulties arose in manufacturing the motor coupler due to the small diameter of the motor shaft. Additionally, the initially provided DC motor broke during the initial power up of the car for unknown reasons. After the motor coupler was manufactured and added to the drive train, the antenna and the energy harvesting circuit were hot glued to the chassis; hot glue ensures the necessary robustness for the application. The antenna was attached to the chassis poles at a height of 20 cm above ground, facing backwards, to account for the energy transmitting magnetron. The energy harvesting board was placed on the base of the chassis. The complete miniature race car after manufacturing is displayed in Figures 11 a) and b).

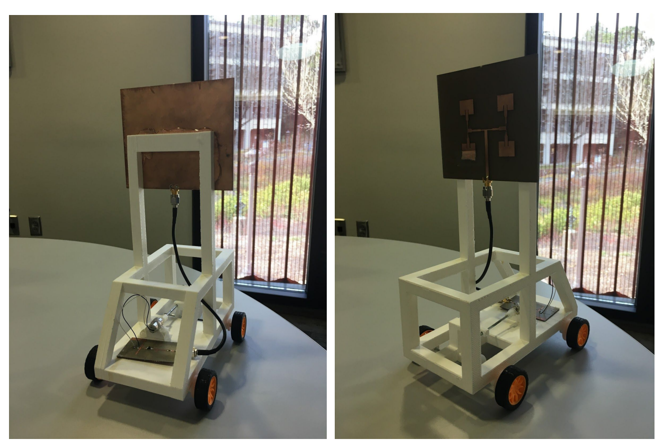


Figure 11. View of the manufactured racecar
a): View from the front right corner, b): View from the back right corner.

V. MEASUREMENT

Once the patch antenna array was milled, the S_{11} measurement of the antenna was collected as shown in Figure 12. This was done after adding a small strip of copper tape to tune the antenna to 5.8 GHz. This was necessary because the the resonance frequency was measured to be 6 GHz. Figure 12 shows a minimum S_{11} measurement of -57.6 dB at 5.8035 GHz for the initial measurement.

The gain patterns in the E plane and H plane were plotted manually during measurements using a spectrum analyzer, a stepper motor and an RF signal generator. A 5.8 GHz reference patch was connected to the RF signal generator and used to radiated power out at 25 dBm. E plane and H plane power values of the milled patch antenna array were recorded from the spectrum analyzer, at 10 degree intervals using the stepper motor. The resulting gain charts are shown below in figure 13 and figure 14.

The peak gain of the antenna was measured using the three antenna test with 3 different 5.8 GHz patch antennas, found in the ECE 4371 Laboratory. The peak gain of the milled four patch antenna array is 7.09 dB according to the three antenna test completed in the lab. The HPBW of the E plane of the patch antenna array is approximately 31.1 degrees. The HPBW of the H plane of the patch antenna array is approximately 45 degrees.

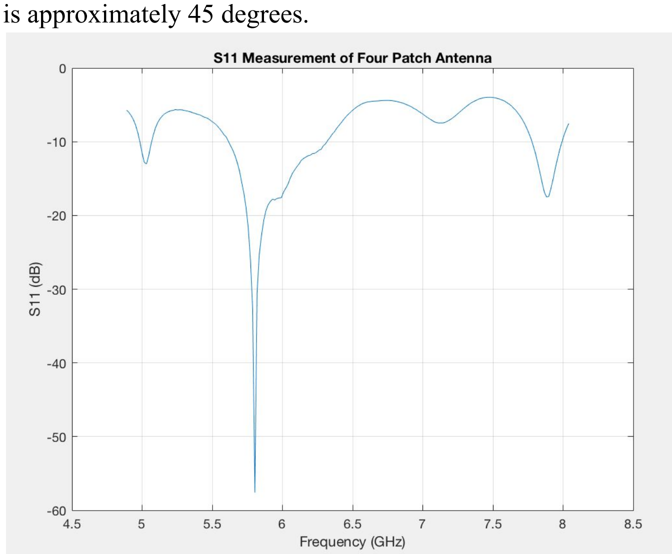


Figure 12. S11 Measurement of patch antenna array.

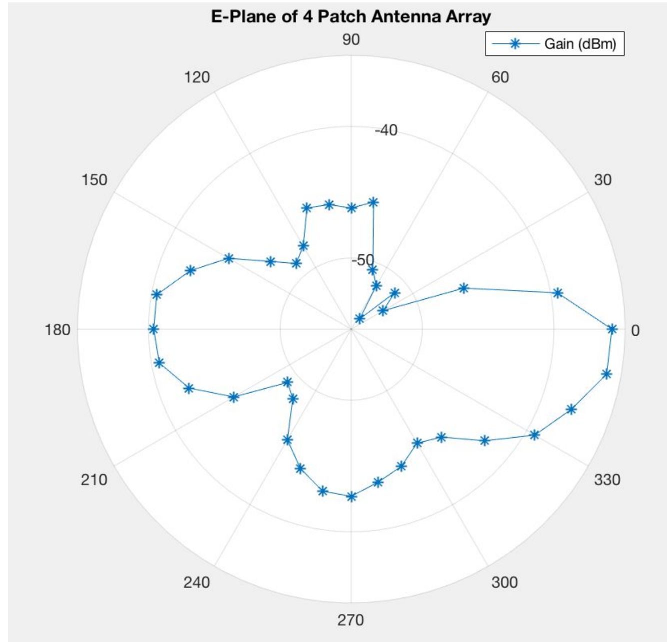


Figure 13. Experimental E-plane gain pattern of four patch antenna array.

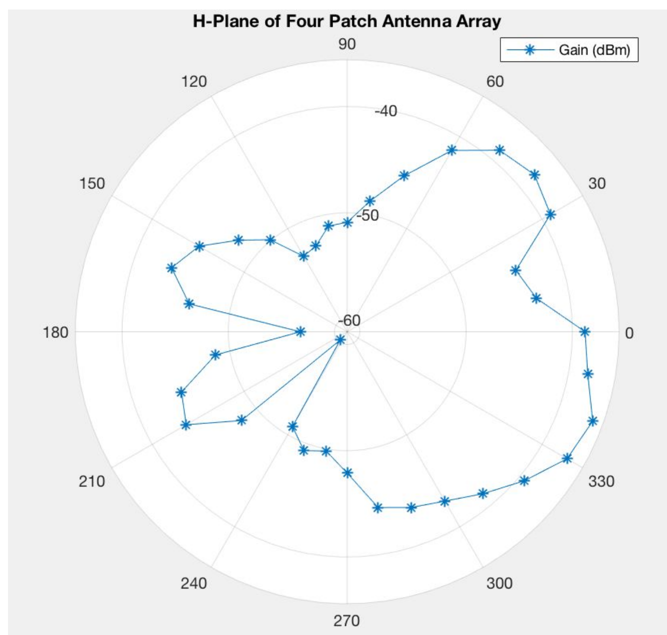


Figure 14. Experimental H-plane gain pattern of four patch antenna array.

VI. ANALYSIS

$$P_r = P_t + D_t + D_r + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right)$$

Equation 10. Friis Logarithmic equation

Table 2: Values of quantities of Friis Logarithmic equation for track environment.		
Quantity	**Values in 1m distance**	**Values for min. needed power**
P_t	700W / 58.45 dBm	700W / 58.45 dBm
D_t	20 dBi	20 dBi
D_r	9.6 dBi	9.6 dBi
λ	0.0517 m	0.0517 m
d	1 m	**1.898 m**
P_r	**10.8 W / 40.33 dBm**	3 W / 34.77 dBm

Table 2 shows the values for the different quantities in the Friis Logarithmic equation. The first column displays the expected power output of the antenna at the starting point of the race track. As the information about the efficiency of the energy harvesting circuit is not readily available, a worst-case scenario is assumed. The motor was assumed to have a low total efficiency of only 33.33%. As a result, it is assumed to have 3.6 W powering the car at the starting point.

The second column states the maximum distance the car will be able to travel. The car needs approximately 1W to power up; the antenna must therefore provide 3W power. This minimum power will be received at a distance of 1.898m away from the antenna. Based on these calculations, the car should be able to travel approximately 0.898m or 2.95 feet.

The racecar and antenna were tested with the magnetron prior to the race. When the vehicle and antenna were tested, the wheels of the racecar did not spin. Potential causes of this result include power losses in the energy circuit, as well as a lack of torque and voltage to move the car due to its weight. Once the magnetron was turned on, the voltage output of the energy harvesting circuit only amounted up to 0.02 V. This was only 10% of the voltage required to spin the initially provided motor under no load conditions. Thus, even the provided motor could not have been operated at this voltage, if it had been attached to the drivetrain of the car.

VII. References

G. Durgin. “Antenna Project.” Georgia Institute of Technology, Atlanta. 11-Nov-2018.