NAVIGATION IN RADIO FREQUENCY LANDSCAPES USING AUTONOMOUS VEHICLES AND MULTIPLE ANTENNA SYSTEMS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Navigation in Radio Frequency Landscapes Using Autonomous Vehicles and Multiple Antenna Systems

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Autonomous, or self-driving, vehicles have been making headlines in recent years as new technologies develop. While they are increasingly used for human transportation, it frequently remains important for autonomous rovers to maximize connectivity as they move. There have been recent developments in antenna technologies, called reconfigurable antennas, which allow reconfiguration of the radiation pattern through electromagnetic, rather than physical, means. This project focuses on engineering a control strategy which decides how to use omnidirectional, directional, and reconfigurable antenna systems while navigating an autonomous rover. We start with a path-planning algorithm optimizing signal strength by selecting the best path, then expand the algorithm to evaluate possible antenna configurations and choose when to use the appropriate configuration while traversing the optimal path. After running a series of tests using a number of metrics to make decisions in the control strategy, a control strategy has been developed with multiple optimization functions which would apply best to differing scenarios.

ACKNOWLEDGEMENTS

I would like to thank Dr. Huff for his guidance & support throughout the course of this research. He has been a great resource and I have been glad to be able to work with him this last year. Thanks also go to my fellow students in Huff Research Group for their support in the completion of the project.

Finally, I would like to acknowledge Sarah Raines, a fellow Undergraduate Research Scholar working in Huff Research Group for allowing me to use data and an image (Figure 4) she generated from Wireless InSite (Remcom) software in the development of my project. She is publishing a thesis titled “Modeling and Evaluation of Received Signal Strength Using Reconfigurable Antennas in Complex Urban Environments.”

NOMENCLATURE

dB	Decibel
GHz	Gigahertz
GPS	Global Positioning System
MHz	Megahertz
RF	Radio Frequency
RSS	Received Signal Strength
RSSI	Received Signal Strength Indication
SNR	Signal-to-Noise Ratio
TAMU	Texas A&M University

SECTION I

INTRODUCTION

Antenna Radiation Patterns

There are a number of antenna technologies in use today. Three configurations which will be discussed here are omnidirectional, directional, and reconfigurable antenna systems. Omnidirectional antennas have a radiation pattern which distributes signal strength equally in all directions on a flat plane. They are widely used in systems where it's difficult to tell where the receiver will be, so signals could be expected from any direction. In these types of systems, it is easy to observe basic properties of electromagnetic signals, such as how proximity to the transmitter will greatly increase the signal strength. Similarly, high frequency signals will attenuate faster than low frequency signals and so overall have a lower signal strength.

Directional, or horn, antennas have a highly directed radiation pattern, where the signal is much stronger in the direction the antenna is pointing and weaker elsewhere. Orientation awareness is critical for these types of antennas to understand sensor input of communication systems on mobile platforms. This process integrates physical characteristics of the device into the information processing algorithms [1].

As reconfigurable antenna systems develop, they become a more viable technology for mobile computing devices such as smartphones and laptops. These antennas allow for modifications to their radiation patterns, thus changing the communication channels they use. As seen in [2], there is evidence to support the idea that this type of antenna can improve communication system performance.

Decision-Making Algorithms for Autonomous Vehicles

Antenna systems are used on a number of different platforms, such as cell phones and vehicles. We will focus on antenna systems for autonomous rovers as they investigate their environment. These types of vehicles are useful as a mechanism for collecting data and to test various innovations. There are examples of autonomous robots being used to measure the radio signal strength of an area. One such example in [3] demonstrates a technique used to get data in real time, showing that a robot can make a precise RF map of an environment.

The purpose of this project is to use an autonomous robot to study the propagation of electromagnetic waves through complex environments and to engineer the controls for an autonomous system which can optimize its received signal. The groundwork has been laid for the development of an autonomous robot which can measure the radio signal environment and for the establishment of a reconfigurable antenna system. This project will go on to develop a control strategy to examine current RSS at different frequencies for a given location and determine what configuration an antenna system should be in to maximize RSS of the vehicle while navigating through a path.

Before developing a path planning algorithm, previously created strategies must be considered. This project will implement a path planning algorithm which uses the average RSS over various paths to evaluate which path will be optimal. Dijkstra's Algorithm [4] is frequently used to find the shortest path between two nodes. The "k shortest paths" [5] algorithm could also be useful to find multiple solutions to analyze to determine the optimal path. For these algorithms, the function determining the length (weight) of the path between nodes can be modified to represent other factors, instead. For example, instead of looking for the shortest path, the path with the highest average speed or strongest average received signal strength indication (RSSI) could be found.

These two algorithms will be used in the development of the path planning algorithm which navigates an autonomous vehicle in such a way as to maximize RSS along a given path. The strategy will then be further modified to develop a control system using prior data for a given GPS location to determine which configuration of an antenna system should be selected to optimize RSS. The data will be collected to establish a RF map of a complex environment for omnidirectional, directional, and reconfigurable antennas, allowing the control system to analyze signal strength at various frequencies and antenna configurations during its navigation of the vehicle.

SECTION II

METHODS

The necessary materials to complete this project were provided through the Huff Research Group laboratory, including autonomous vehicles, various antennas, computing resources, and simulation models. The overall strategy used was to first collect or generate data for signal strength in complex environments. Next began development of a path planning algorithm maximizing signal strength while considering a number of other factors. Finally, a control strategy which examines GPS-tagged data and configures the system as appropriate was determined for the autonomous vehicles.

Collecting and Generating Data

Data is required to develop the path planning algorithm, as both a proof-of-concept and for further testing. This project uses data from a number of sources.

Generated Data using Friis Transmission Equation

The Friis Transmission Equation, in decibel (dB) form, describes the power of an antenna in space as a function of a number of antenna characteristics, such as antenna directivity and wavelength. Equation 1 can be used to generate data sets for omnidirectional antennas, allowing for simple test cases to be used in the development of the path planning algorithm.

$$P_r = P_t + D_t + D_r + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) \qquad \text{Equation 1}$$

When using Equation 1 to generate data for the omnidirectional antennas, we assumed that the directivity, D_t and D_r, of the transmitter and receiver could be ignored since on the horizontal plane of interest, the antenna will radiate evenly in all directions.

Simulated Data

A fellow Undergraduate Research Scholar in Huff Research Group, Sarah Raines, used a simulation software called Wireless InSite (Remcom) to generate data for simple use cases and to simulate propagation in complex environments, such as the engineering buildings on Texas A&M University's campus. The simulated models are used to generate an understanding of how radiation patterns should exist on campus, allowing for the path planning algorithm and autonomous rover control strategy to fill in the gaps where collected information may not exist. The software has been verified to have similar results to a real-time setup [6].

Path Planning Algorithm

The data generated in the previous steps contributes to the development of the path planning algorithm for the autonomous rovers, which performs an analysis on the data to determine which route is optimal under a set of constraints. The algorithm is based off Dijkstra's Algorithm, which finds the shortest path between two nodes.

The path planning algorithm determines a series of transfer functions between possible start and end points, allowing for the optimal path to be chosen once the primary constraints are considered. A graph approach is required due to the nature of the problem, which represents the environment as a series of nodes connected by path segments, each with its own properties [7].

Autonomous Rover Control Strategy

Once the path planning algorithm is complete, it may be expanded to accommodate the possibility of controlling the antenna systems of the autonomous rover. This means it becomes possible to change antenna configurations while travelling along the path, thus changing the costs associated with traversing each path. This portion of the algorithm determines the optimal antenna configuration to maximize connectivity at each point, and its end goal is to provide a series of configuration commands for the autonomous rover.

It is possible to use various cost functions while optimizing the antenna setup, so four different metrics were employed. Different purposes for operation of the autonomous rover might find more use from one metric than another.

SECTION III

RESULTS

This project required the completion of a number of technical tasks in succession. First, the data from the Friis Transmission Equation was used to develop the path planning algorithm optimizing signal strength. Then, the data from the simulation software was used for the creation and optimization of the autonomous rover control strategy. Various metrics were used to compare the antenna configurations, and these have been evaluated for overall effectiveness.

Development of the Path Planning Algorithm

To begin this project, the Friis Transmission Equation was used to generate a data set for simple test cases of the path planning algorithm. A heat map was developed, as seen in Figure 1, and multiple path segments evaluated to determine their signal strength.

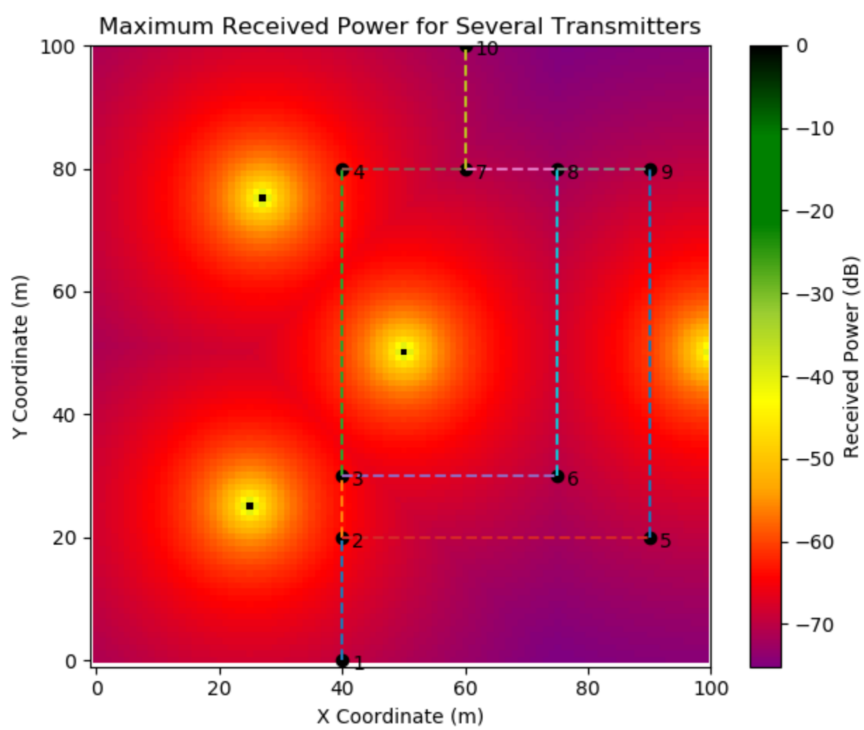

Figure 1. Simulated Dataset from the Friis Transmission Equation

Figure 1 shows a series of three possible paths from point 1 to 10, each going through areas of varying signal strength. The black points show the locations of omnidirectional transmitters in the field of interest. All of the transmitters use the same frequency. When choosing routes with this heat map, a higher received power value is desired. This means that the green and yellow end of the spectrum is preferred over the red and purple areas.

Another consideration for the early path planning algorithm was maximizing the Signal-to-Noise Ratio (SNR), which is a factor which remains important in actual data collection and evaluation. Figure 2 shows an example with three transmitters, one which interferes with signal received from the other two. For this heat map, the green areas are preferred over the red because it means that the signal from the noisy transmitter is much weaker than the other signals.

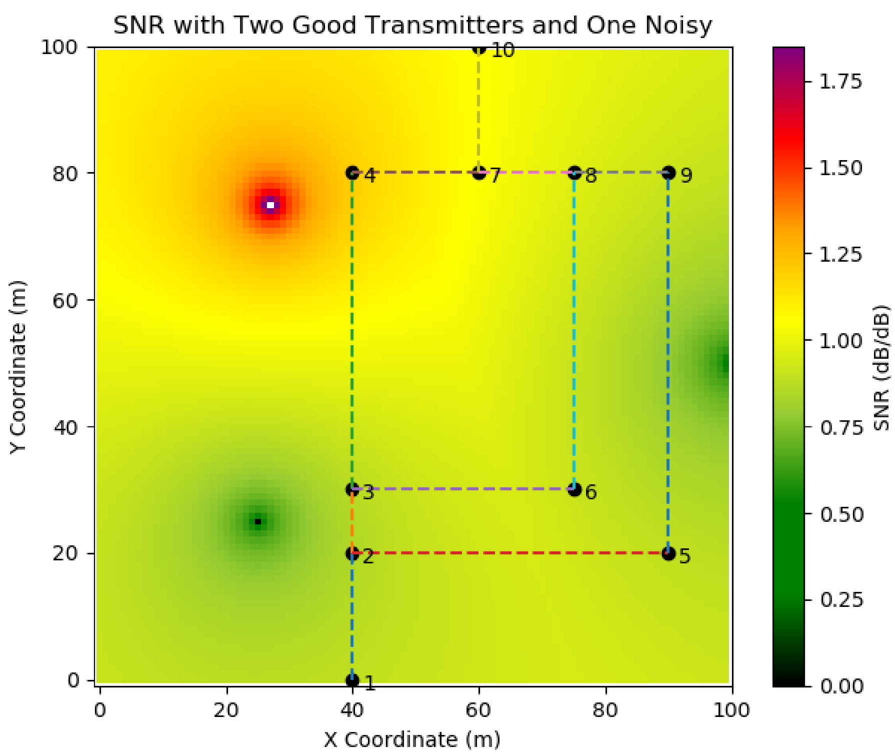

Figure 2. Simulated SNR Dataset from the Friis Transmission Equation

The path planning algorithm itself developed as a modification to Dijkstra's Algorithm, which determines the shortest path using a cost function measuring the length of each path segment. Instead of using a length-based cost function, the modified algorithm sums the signal power values in dB along the path, thus evaluating both signal strength and path length in the same metric. Figure 3 shows the simulated data which would be integrated over to compare the paths. When evaluating the SNR, the modified algorithm instead sums the SNR values along each path segment, again evaluating both SNR and path length with the same metric. For the simulated data, SNR would be computed by comparing one transmitter against another.

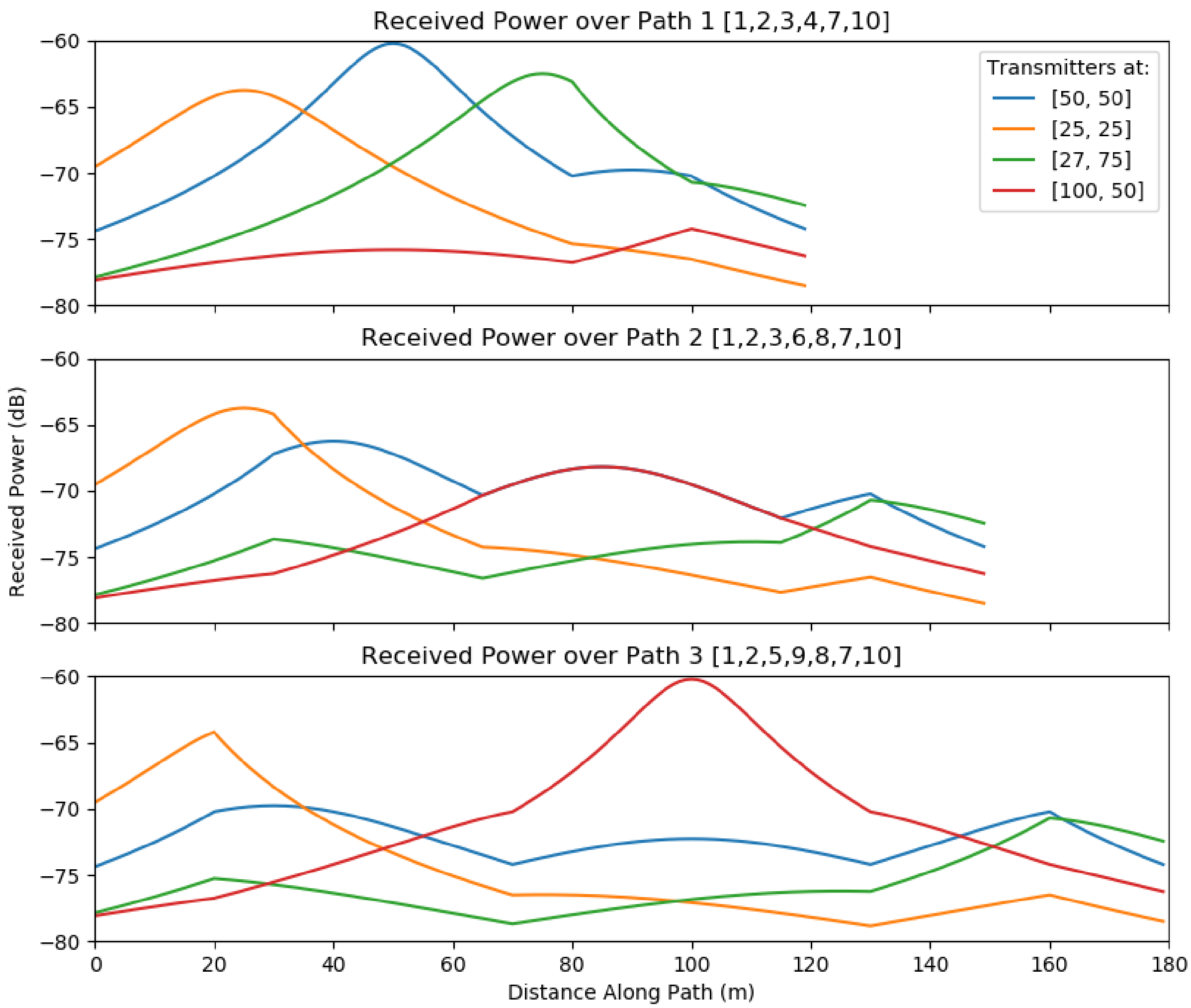

Figure 3. Received Power Data Simulated by Friis Transmission Equation

Implementation of Dijkstra's Algorithm requires the description of the problem as a graph with a series of nodes connected by segments with directionalities, called edges. Each segment can have a set of characteristics, such as a series of coordinates describing the route, or single values of parameters like the frequency used for the segment. The cost function identifies which edge is being queried, allowing for the return of a value which is summed with the other edges to determine the optimal path. In the end, the algorithm decides which path is best for the rover to take.

Development of the Autonomous Rover Control Strategy

After developing the path planning algorithm using the generated test data sets, data from simulation software was used to further develop the algorithm into a control strategy for the rover. The data was modelled at the Engineering Quad at Texas A&M University (TAMU) using Wireless InSite (Remcom) software, over three paths as described in Figure 4.

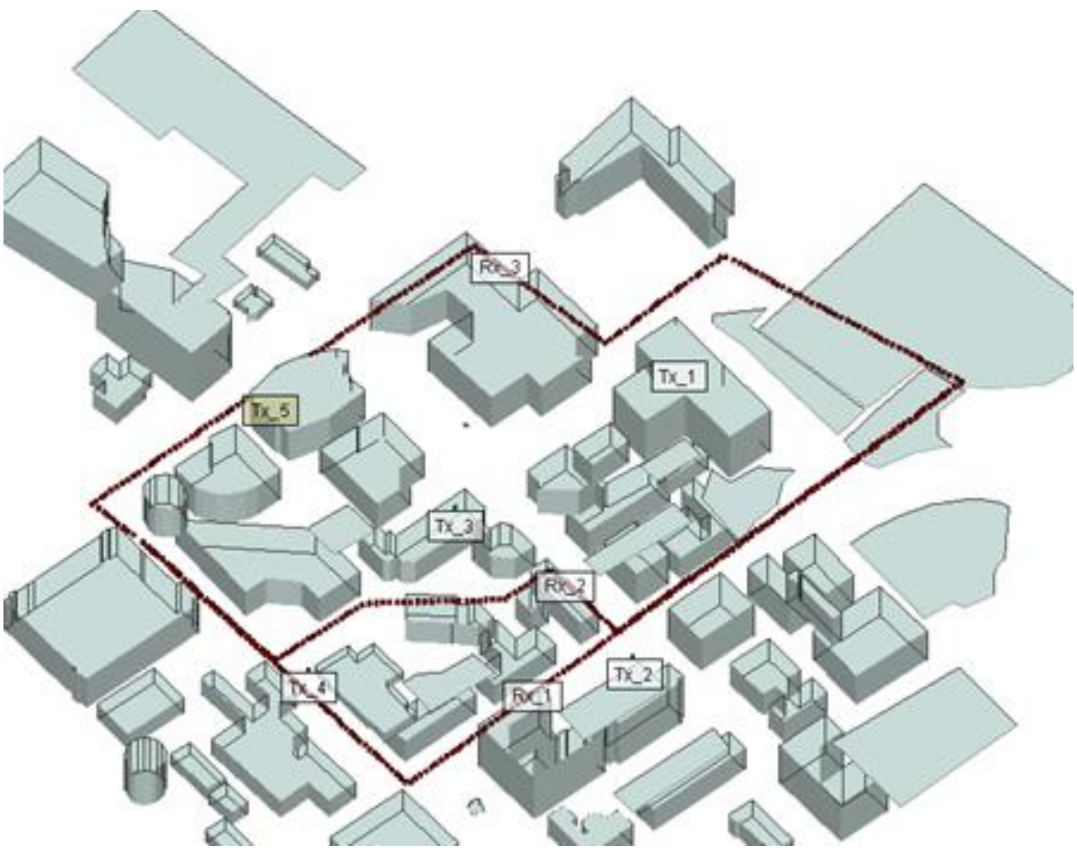

Figure 4. Simulated Routes across the TAMU Engineering Quad

Note: This image was generated by Sarah Raines as mentioned in Acknowledgements.

The simulated data included three path sets, each with multiple antenna types, transmitter radiation frequencies, and transmitters. These data sets were used in the development and evaluation of the rover control strategy, where both the path and antenna configurations were chosen by the algorithm.

The path planning algorithm grows into a control strategy when considerations are added to evaluate the best antenna configuration at each point along the path, then allowing a path to be chosen. This updated algorithm essentially provides a control setting to the rover, instructing it on which antenna configuration to use at each point. Implementation of this strategy requires analyzing the data for each path using a metric to decide which antenna configuration is optimal at each point. A number of metrics were used in the development of this algorithm. Figure 5 shows the resulting control waveform over the paths when four different metrics are used.

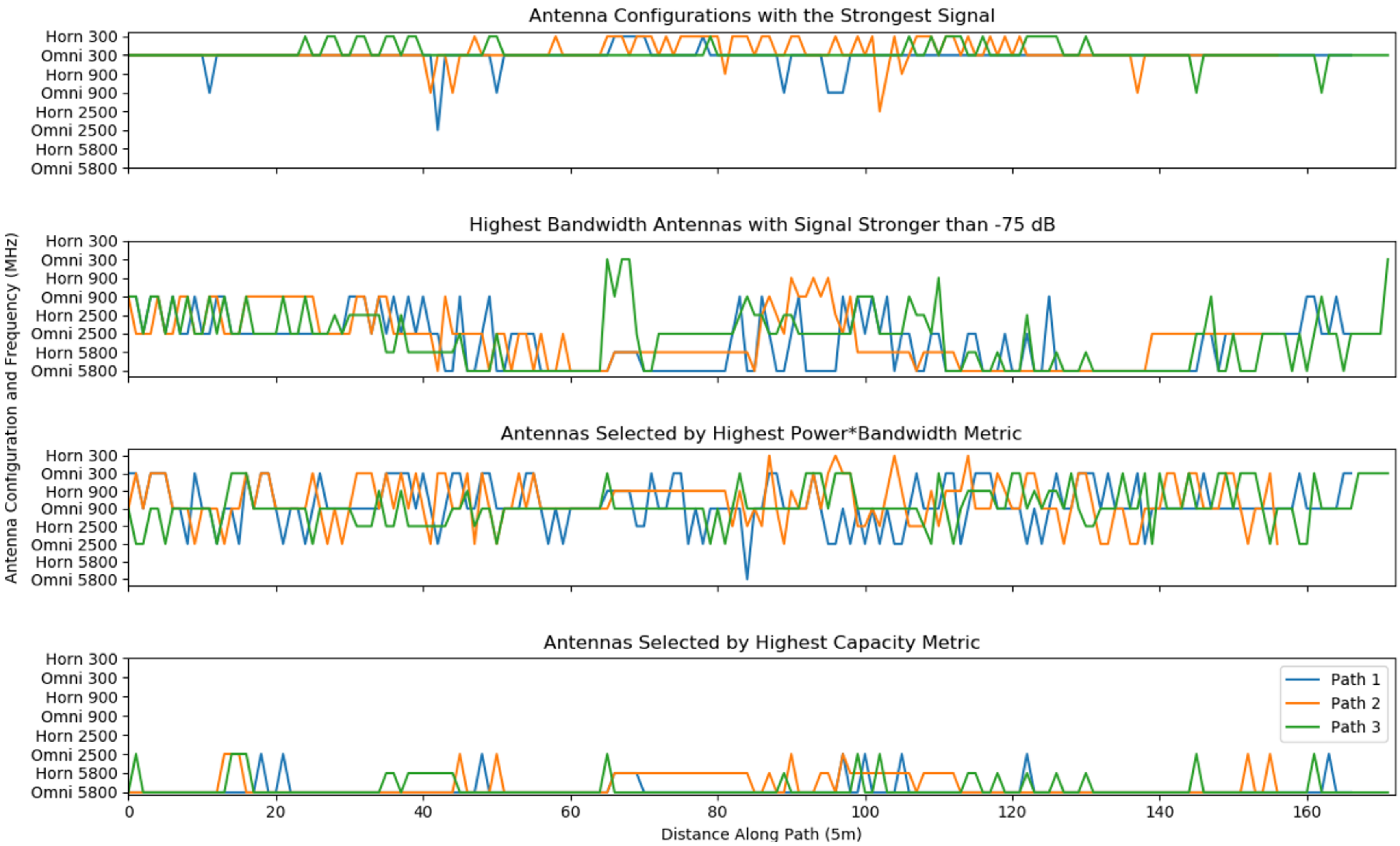

Figure 5. Antenna Configuration Selection at each point along Engineering Quad Paths

The numbers at the end of the labels on the vertical axis represent the frequency of the selected antenna configurations, while the horizontal axis represents the length of the paths. The four subplots each correspond to a different evaluation metric.

The first evaluation metric used is the same employed in the development of the preliminary path planning algorithm: the strongest signal. However, since the strength of the signal is inversely proportional to its frequency, it was found that this metric highly favored signals at lower frequencies around 300 MHz. This comparison method does not consider the bandwidth of signals, so the signals chosen may not be able to communicate data very efficiently.

The second evaluation metric shown in Figure 5 chose the antenna with the highest bandwidth, as long as the signal strength was over a minimum threshold. In the case shown, a middling threshold was chosen so the results didn't significantly favor either low or high frequency antennas. If the signal strength was required to be higher, the control waveform would choose more low-bandwidth antennas. The opposite applied for lax signal strength requirements. This metric is useful to ensure that the signal chosen has a relatively high SNR if we assume a certain level of background noise.

The third evaluation metric multiplies the received signal power, converted from dB, with the bandwidth of the antenna. The bandwidths increase with the signal frequency, meaning that antennas at 2.4 GHz can communicate more data at the same time than antennas at lower frequencies. This metric seems to prioritize signal strength over bandwidth more than the previous comparison method.

The fourth and final evaluation metric computes the capacity of each antenna at each point along the path using Shannon's Capacity Formula, shown in Equation 2. The bandwidths used for this computation are derived from the allowed channel bandwidths of common communication protocols using each of the provided antenna frequencies. A constant noise value of -100 dB was assumed for the calculations, which computed the SNR using the signal power of the data sets.

$$C = B \log_2(1 + SNR) \qquad \text{Equation 2}$$

This final metric was found to strongly favor high-bandwidth signals over the signal strength of the various transmission frequencies. Table 1 shows the average wait time if the rover stopped at each point along the path until it transmitted 1 Megabit of data. The values were computed using the formula in Equation 3.

$$Average\ Time = \frac{\sum_{path} \frac{1\ Mbit}{bandwidth\ [Mbit/s]}}{path\ length} \qquad \text{Equation 3}$$

Table 1. Average Time Required to Transmit 1 Megabit of Data by Four Metrics

	Strongest Signal (sec)	**Highest Bandwidth with Threshold (sec)**	**Highest Power * Bandwidth (sec)**	**Highest Capacity (sec)**
Path 1	0.549	0.0132	0.171	0.00679
Path 2	0.547	0.0136	0.169	0.00681
Path 3	0.565	0.0249	0.126	0.00680

The results demonstrate how strongly each metric prioritizes choosing high-bandwidth antenna configurations, with average times for each metric frequently an order of magnitude different from one another. It is clear to see that the metric prioritizing signal strength would have the slowest connections, while the final metric prioritizing capacity would have the fastest.

SECTION IV

CONCLUSION

Over the course of this project, two algorithms were developed to determine the path planning and antenna configuration of an autonomous rover as it transmits data in the RF environment. Dijkstra’s algorithm proved to be an effective method of implementing path planning when the cost function of each segment of the path can be modified to accommodate prioritization of connectivity.

Four metrics for comparing antenna configurations in the control strategy were evaluated, showing that each one has varying results and thus would be applicable to different use cases. The metric prioritizing signal strength would be useful for applications where the autonomous rover needs to transmit small amounts of data over long distances as it moves. On the other hand, the metric prioritizing capacity would be more useful if the rover needed a high bandwidth for something like streaming video as it drives around.

The control strategy developed could be used for a wide range of scenarios, from testing of reconfigurable antennas or other antenna systems to evaluate their effectiveness to collection of real-time data. Future steps to consider are implementing an expansion of the algorithm to both consider historical data for the location and current data from the antennas in its configuration decisions. This way, the control strategy would have feedback and would be a closed-loop control scheme, rather than the current open-loop implementation.

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