Applied Physics Capstone Report: Implementation of a Robust Communications System for Robotic Mars Rover Application

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Abstract

It is difficult to optimize communications systems when they must work in a variety of environments. Such is the challenge presented by the Mars Society each year during the international University Rover Challenge. This report describes the journey taken by the communications sub-team of the 2018 BYU Mars Rover Team in order to build a reliable communications system capable of communicating between a stationary base station and a moving rover both in and out of line-of-sight. First, we took time to analyze and understand the competition rules, ensuring that our design would meet all the necessary specifications. Then we considered how the design would affect other sub-teams. Then, we decided on a communications plan and purchased antenna hardware in order to implement it. We soon modified this plan to use only two 900 MHz antennae. In the last stage of development, we created a rotating antenna mount. We tested our design at several intermediate points and finally at the University Rover Challenge held May 30–June 2.

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Introduction

Background

The BYU Mars Rover Team has held a strong presence in the University Rover Challenge (URC) since 2007, placing in the top three for 5 of the last 11 years, and placing in the top five for 10 of the last 11 years. Since the main purpose of the team is to compete in the URC, the team's design is bound by the competition's many requirements and constraints. These are published online here: http://urc.marssociety.org/home/requirements-guidelines. The rules include weight and cost constraints, and some of the rules specify what the rover will be expected to do during each task of the competition. For example, this year the rover was required to travel over several types of terrain, make its way autonomously through a rigorous course, pick up and deliver payloads, and take and analyze soil samples. In each of these tasks, communication between the rover and the base station is an absolutely essential aspect of the rover design. Without a working communication system, the rover would not be able to complete any of the required tasks.

Last year, the team competed with a 2.4 GHz communication setup. One directional antenna was kept at the base station while one omni-directional antenna was attached to the rover. Though last year's system performed well overall, it experienced a number of communication failures, some of which occurred at critical points during last year's competition. These communication failures occurred mostly when the rover went out of line-of-sight of the base station antenna, but also occurred at other unpredictable times. These difficulties led us to reconsider the communications system this year.

DEFINITIONS

Since these terms will be used throughout the paper and are rather cumbersome to write, I will employ the following abbreviations:

OLOS = Out of Line-of-Sight

ILOS = In Line-of-Sight

LOS = Line-of-Sight

COMPETITION OVERVIEW AND COMMUNICATIONS REQUIREMENTS

The University Rover Challenge has been in operation for more than 10 years. The goal of the competition is to "design and build the next generation of Mars rovers that will one day work alongside astronauts exploring the Red Planet" (URC Website). Each year, the competition was composed of four tasks: autonomous terrain traversal, equipment servicing, science cache, and extreme retrieval and delivery. Each task poses a distinct challenge for the rover's communication system. The main measures of communication challenges are distance and number of degrees OLOS. Another important factor is bandwidth, the amount of data the antenna is able to transmit in a set amount of time. The following are our estimates of the communications requirements, broken down by task:

Autonomous Terrain Traversal

The rover is expected to travel up to 1 kilometer and transmit signals at greater than 60 degrees OLOS. The bandwidth does not need to be very high since the rover performs most of its algorithms onboard (and therefore doesn't have to transmit much data back to the base station).

Equipment Servicing

The rover is expected to travel close to the base station and handle a variety of objects. Distance and LOS are not a concern. The drivers can better control the rover and manipulate objects when they see more camera feeds; however, sending camera feeds over the antenna requires more of bandwidth, making this a big concern in this task.

Science Cache

The rover is expected to travel close to the base station inside a natural bowl. Distance and LOS are not a concern. We now have to account for interference in the bowl, because last year it made the rover lose communication at seemingly random spots. Bandwidth is also a concern, since, like the equipment servicing task, many camera views help the drivers to manipulate the rover's science subsystem.

Extreme Retrieval and Delivery

The rover is expected to travel up to 1 kilometer away from the base station and transmit signals at greater than 60 degrees OLOS. The rover is also expected to carry a variety of objects, so several camera views (and hence a large amount of bandwidth) are preferable.

SUMMARY

From these requirements, we easily saw that the main factors that would determine the success of our communications system would be its ability to work at large distances, to transmit data at large degrees OLOS, and to allow sufficient bandwidth.

Motivation

Communications is an integral subsystem of the rover. If there is a complete comms failure, the rover won't be able to complete the task, and the team will be docked (probably very many) points. It is critical that the comms system work reliably so that the team can earn the most points in each task possible.

Last year's team reported that their 2.4 GHz system lacked consistency. Sometimes, the rover would lose signal when it went out of line of sight, and sometimes it would lose signal when the rover was just a few feet away. This kind of communications problem happened several times at the competition last year and forced the team to restart the rover, costing them precious minutes and giving them less time to complete the task. Our main motivation this year is to create a robust communications system that overcomes the weaknesses of last year's system while following the competition rules and requirements set forth in the introduction.

Context

Communications systems are prevalent in today's society. However, the type of communication required by the University Rover Challenge is different from many of the applications we see today. For instance, the frequencies we are using correspond to the same frequencies by Wi-Fi routers and cell phone towers. However, for our application, the rover must travel much further from the base station than most Wi-Fi systems are capable of. Cell phone frequencies are able to transmit signals quite far and cover a wide range, which is partly because the frequencies are broadcasted from huge towers loaded with several sets of antenna. The size and weight constraints mean that our team can't broadcast frequencies in this way. Another factor that makes our application unique is that the rover is a moving target. It is impossible to calibrate the antenna to face just the right direction, since that "right direction" changes almost immediately as the task starts.

Methods

Here I describe the physical resources allocated to the Mars Rover Team and the mindset of the Capstone team.

RESOURCES

This year, the BYU Mars Rover Team was over 20 people strong. It was led by Dr. Killpack from the Mechanical Engineering department. We did most of our work in the BYU Motor Sports Lab, but also utilized several ME and EE shops on campus.

In addition to these resources, the team also has significant financial resources. The URC rules place a $17,500 limit on the cost of the rover and base station, and the majority of this funding comes from the departments of Mechanical and Electrical engineering. Other funding comes from corporate team sponsors such as Nvidia, IntertialSense, Protocase, and NASA.

The team also has electronic resources. Some of these include access to the Mechanical Engineering Department's J Drive, on which many of the teams files and videos are stored. Additionally, the team has access to ShareLatex online software and space on

Google Drive. Most of our testing procedures and results documents were created, edited, and approved using Google Drive.

PRODUCT DEVELOPMENT MINDSET

Throughout my experience on the Mars Rover Team, I was also enrolled in the mechanical engineering capstone course: ME 475/476 Integrated Product and Process Design. The class is focused on teaching the fundamentals of product development, and requires each team to progress through several stages of development, each with its own requirements and approval processes. The four principles central to the product development process are

1. A successful design is one that is desirable and transferable.
2. A successful design must evolve.
3. Designs can only evolve as the result of a team using design activities.
4. Optimal design evolution occurs when the team customizes and coordinates design activities with the goal of making the design more desirable and transferable.

Much of the process of designing and building the rover was done with these product development principles in mind. Now I will define "desirable and transferable."

In most of the capstone projects, team members work to produce a product that will be placed on the market for sale. A desirable design, for them, is one that customers want to buy; it must include abilities and features that are attractive to the customer. But we are not trying to sell our rover design to anybody. Our definition of a desirable design is one that (1) obeys all of the competition rules and regulations without incurring penalties and (2) allows the team to score the most points possible in each of the competition tasks. If our design is able to complete these two objectives, then the design is desirable.

A transferable design is one that allows other parties to completely understand how to machine or buy all of the product's parts, how the parts fit together, and generally how to build the product from scratch. A transferable design can only happen if the design is well documented: requirements are written down and prioritized, procedures for approval are recorded, and part drawings are kept up to date.

When a design is sufficiently desirable and transferable, it is done. We kept these two indicators in mind throughout our work on the communications system and on the rover in general.

Timeline

Here is a summary of our work, organized chronologically.

COMMUNICATIONS MARKET REQUIREMENTS AND PERFORMANCE MEASURES

Our first step was to determine the “market requirements” for the communications subsystem. After carefully considering the URC rules, we determined that the following were essential requirements for the entire rover system:

MR 1 - Rover can be set up and switched between tasks quickly
MR 2 - Rover’s batteries last the entire competition task
MR 3 - Rover’s electrical components and wiring are robust
MR 7 - Rover base station interface is intuitive and reliable
MR 8 - Rover has versatile imaging capabilities
MR 11 - Rover starts up reliably
MR 12 - Rover transmits and receives data reliably
MR 13 - Rover withstands the competition environment
MR 15 - Rover meets competition weight requirements
MR 18 - Rover design is well-documented

The market requirements I selected here were those that we determined would be affected by the communications system in some way. For example, “MR 8 - Rover has versatile imaging capabilities” is on the list because our communications system must have enough bandwidth to send and receive video reliably.

These “market requirements” and corresponding “performance measures” show how we measured the desirability of our design. Throughout the process we used these requirements to determine if our ideas and tests were leading us toward a desirable design.

SELECTION OF A ROVER ANTENNA

The previous year’s team recommended we switch to include a 900 MHz setup. We decided to test the option using a leftover base station antenna given to us for free from Ubiquiti. After deciding to test 900 MHz, we then had to find an acceptable rover antenna compatible with 900 MHz. The following were factors in our decision:

Cost: Cost was a factor for obvious reasons. We needed a good, robust system, but one that was affordable and allowed us to stay within the project budget. The Electrical Budget was $4500; however the communications budget was only a portion of that. Because the antennas are a huge part of the communications budget, we were prepared to spend a few hundred dollars on a good rover antenna.

Weight: Weight was a huge factor in our decision. The rover’s weight limit was 50 kg. Last year, the rover was overweight for some of the competition tasks. So we knew that whatever antenna we chose had to be light enough to avoid putting the rover over the weight limit. We looked for an antenna that was less than 5 kg.

Directionality: Omnidirectional antennae are nice since they are nearly isotropic in the horizontal direction. They don't require any adjustment or rotation when the rover moves far to the left or right. However, the omnidirectionality comes at a price—generally omnidirectional antennae transmit less power than directional ones, meaning less distance receiving reliable communications. We looked for an omnidirectional antenna since a directional one would cause balance issues and possibly be difficult to control when attached to the rover.

Size (especially height): We looked for a taller antenna rather than a shorter one, since taller antenna are better able to catch signals from the base station, especially when it is far away and/or behind objects. We looked for an antenna that was several feet tall.

Compatibility: The base station was a Ubiquiti antenna, which came with a compatible Ubiquiti Rocket radio. The rocket makes the antenna very easy to use—almost "plug and play." Additionally, the Rocket provides a simple GUI that allows operators to change many settings, including frequency band, which is a requirement for the competition. For these reasons we looked for an antenna that would also be compatible with a Ubiquiti Rocket.

A spreadsheet listing these and other factors can be found in the Appendix.

First, we created a list of many possible antenna options. After considering these factors, we narrowed the list down to two or three viable options. Then we talked with Dr. Long of the BYU Electrical Engineering Department. These two antenna options were nearly identical, but one was much cheaper than the other. We asked Dr. Long if the price reduction was any indication of a quality reduction. He responded that the antennae were probably actually identical, and that the price difference didn't indicate any difference in quality. So we went with the cheaper of the two.

TESTING

After implementing the 900 MHz system, we conducted several rigorous tests. Test reports can be found in the appendix.

Testing locations

We tested the communications setup at several different locations.

Our first test site was on BYU campus. There are sufficient areas to test LOS and OLOS communication on campus, as well as opportunities to communicate over large distances. However, there are many buildings on campus, and many other signals bouncing around. This results in interference, which makes campus a less-than-ideal test site for the rover.

We also tested the rover at the entrance to Rock Canyon. There we kept the base station antenna in the parking lot and were able to test OLOS as we moved the rover setup deeper and deeper into the canyon.

Later we tested at Rock Canyon Park. At Rock Canyon Park there is a huge bowl-shaped area with high walls, again allowing for OLOS tests. We placed the base station outside of the bowl, and placed the rover antenna at various locations on top of and inside of the bowl.

Additionally, team members tested the antenna at test sites close to the competition area in Hanksville, Utah, and at a gravel site in Provo owned by BYU. Each offered a unique environment to test the communications system.

In all cases, the 900 MHz system performed quite well, transmitting and receiving signals across large distances and over and around barriers.

Creating a mobile testing apparatus

We decided to create a mobile testing apparatus for several reasons. The first of these was the sheer difficulty of loading equipment to the test site. We thought that carrying two laptops plus antennae would be much preferable to loading the "full setup," which includes the entire rover, a generator, and the base station equipment. Another reason was that often several team members wanted to use the rover at the same time, and our testing time with the full setup was limited. The final reason was that the rover had many bugs (not having to do with the communication system), that would impede our tests when we tried to go with the full setup.

For these reasons, we worked to create a simple mobile setup. To do this we used two lithium polymer battery connectors, and asked a member of the electronics team to solder on a new head joining the two connectors. The two batteries gave us a mobile power source, capable of powering the antenna. The setup consisted of two of these sets of LiPo batteries, two POE adapters, two laptop computers, and, of course, two antennae.

The mobile setup made it much easier to perform communications tests without advanced notice and without taking the rover away from the rest of the team.

REPORTED LAG

In some tests of the full rover-base station system, the operators reported lag, even at close quarters. This lag could have been due to several factors:

1. Attempting to transmit high-quality video over the link. If future teams need to transmit high-quality video, then 900 MHz might not provide enough bandwidth. For our applications, however, we determined that we didn't need to transmit high-quality video often enough for it to be an issue. The only time that high-quality camera feed is required by the competition is during the science task, where the drivers must take a few high-resolution frames of the soil and the surrounding area. Since we never had to send high-quality video, only high-quality frames, we decided that the advantages of being able to maintain

communications at large distances and behind obstacles outweighed the advantages of being able to send high-quality video this year. Additionally, we performed several tests proving that the setup could transmit multiple video feeds at a lower quality that the antenna could handle, but that would still be sufficient to help the drivers navigate, pick up and manipulate objects, and read text.

2. Running into interference with other signals. This was mainly a problem when testing on BYU campus. Luckily, the competition requires that teams adhere to strict frequency regulations, limiting interference during the actual competition. Future teams may determine that more is required in order to limit interference; however, we determined it wasn't a priority, especially since the Ubiquiti software already implements algorithms to reduce interference, and I'm not sure what more could be done to mitigate the problem.
3. Other factors. Often lagging problems were hard to track and not very repeatable. Several times operators would report lag after one test, but no lag after the next. These problems could have been caused by myriad factors, including software issues and low batteries. Perhaps a more detailed analysis could be done to determine all the causes of slow or stopped communications.

BUILDING AN EFFECTIVE ANTENNA ROTATOR

Since any useful 900 MHz base station antenna is directional, we decided we needed some means of rotating the antenna. We considered using a strong servo motor, but decided that a stepper motor would be better since stepper motors allow for tighter control over position. We decided that a geared-up stepper motor would be able to handle the torque required to overcome the inertia of the antenna, as well as the friction of the lazy Susan and the torque caused by strong winds. In order to verify this, we performed several calculations that ensured the stepper motor would be able to handle the load.

For our rotator setup which included the lazy Susan, a long square bar, a short cylinder, and the antenna, we get the following:

$$\tau_{servo} = I * \alpha + \tau_{bearing} + \tau_{air}$$

where I is the moment of the inertia of the entire setup:

$$I = I_{plate} + I_{square\ bar} + I_{cylinder} + I_{antenna}$$

Here I have taken the axis of rotation to be the center of the lazy Susan, 6 inches from the end of the square bar. I determined a rudimentary value for $\tau_{bearing}$ by hanging masses with known weights on the corner of the lazy Susan and determining what weight was required to move the bearing. A teammate performed calculations based on predicted windspeed and the geometry of the rotator to provide a value for τ_{air}.

Knowing this and the geometry of each element of the system, our calculation for τ_{servo} was

$$\tau_{servo} = 1.5\ Nm$$

assuming we need an angular acceleration of $\alpha \approx 2$ degrees per second.

Since the motor we purchased was rated for 4 Nm, we determined it would be able to do the job.

Results and Discussion

TEST RESULTS

After performing several tests, we determined that the 900 MHz system would have sufficient bandwidth and ability to communicate from over 1 kilometer and transmit signals at greater than 60 degrees OLOS. These results are indicated in the Test Results documents included in the appendix.

THE UNIVERSITY ROVER CHALLENGE COMPETITION

The culmination of the Capstone project occurred during the University Rover Challenge, which took place from May 30 to June 2, 2018. The competition is composed of 4 challenging tasks. Communications plays an integral role in each of these tasks. Here I will provide a review of the performance of the communications system for each task.

Science

For the science task, we set up the base station antenna at the ridge of a natural, bowl-shaped depression in the desert. Even though the rover stays relatively close to the antenna throughout the task, because of the bowl shape and natural walls or ridges in the terrain, the task does require some OLOS communication that was challenging in past years. This year, there were no communications issues. The rover maintained communications throughout the task, even though it traveled to several different locations inside the bowl.

Equipment Servicing

This task was perhaps the least requiring of the communications system. The antenna was set up on one side of a road in the desert, and the rover performed the task on the other side of the road, in perfect LOS. The only possible communications issue that we were considering here is that the rover had to have enough bandwidth to manage a large number of camera feeds. In this task there weren't any problems with bandwidth. In all, there were no communications issues for this task.

Autonomy

The communications system worked quite well during the autonomy task. For the task the rover had to go very far away from the base station and pass behind huge boulders. The rover didn't lose communications throughout the task.

Extreme Retrieval and Delivery

Extreme Retrieval and Delivery was the most requiring of the communications system. For this task, the rover started near the antenna, but followed a winding course that took it about 1 km away and required it to pass OLOS many times. The communications system performed admirably well during the entire task. One example of extreme OLOS operation during this task was that the rover had to pick up a hammer and drop it close to an astronaut, who was situated right behind a hill. At one point during the task, the drivers reported a lag; however, they were able to correct it by rotating the antenna a few degrees. This halted the lag, and the drivers were able to perform well throughout the remainder of the task. This shows that our rotating antenna system was successful during the competition.

In summary, the communications system performed remarkably well in each of the competition tasks. The 900 MHz directional setup allowed the rover to maintain communications even when far from the base station, behind large objects, and in areas of possible interference (like the bowl during the science task). The rotating antenna setup also proved itself effective, especially during the Extreme Retrieval and Delivery task.

Conclusions

The team will probably continue to use a 900 MHz system in future years. It has proven effective for us this year, allowing us to maintain reliable communications throughout each of the tasks of this year's competition.

In product development terms, I believe we have proven that our design is desirable: it is one that meets the market's needs. In other words, it allows the team to obey the competition rules and to score as many points possible.

My time on the Mars Rover Team gave me many problem-solving opportunities. I not only worked with the communications system, but also spent time on rover hardware, software, and electronics. I feel that I was able to apply what I've learned about circuits from my physics classes and what I've learned about computer science from my experience there. In addition, I had several opportunities to create and complete documentation including many test procedures and reports. In addition to these activities, I spent many hours debugging and attended many planning and prioritization sessions. I am grateful for the opportunity to be on the Mars Rover Team and am proud of what we accomplished.

Acknowledgements

During the course of my time on the Mars Rover Team, I saw myriad advantages to working with such a talented, multidisciplinary team. Most of the work done on the rover, and on the antenna system, was done as a team. I could not have had success on the communications sub-team without the help of many other team members. For example, the communications team lead, Jace Rozsa, was the driver for many of the accomplishments mentioned here. Particularly, Jace performed tests, created the PCB for the rotating antenna servo, and wrote several bits of code to read data from the antenna hardware and for the rotating system.

I thank Andrew Delacruz for his help brainstorming and putting together the hardware for the antenna rotating system, Nefi Oliva for his help with the antenna rotation hardware and software, Tucker Wilkes for the antenna rotation software, Matt Pope for his help integrating the communications software with ROS, Zach Brock for teaching us how to wire up stepper motors, and all of the other members of the team for their help.

I also thank Dr. Marc Killpack for his experience, advice, and encouragement.

References

Mars Society. (2018). About-URC. Retrieved from http://urc.marssociety.org

Mattson, C. A., & Sorensen, C. D. (2015). Fundamentals of Product Development.

Appendix A – Test Procedures

MDR-TP-EC12 Antenna Switch Time Test Procedure

Written by:	Tyler Averett	Revision and Date:	1.3, 03/08/2018
Checked by:	Zachary Brock	Approval Date:	03/08/2018

1. Objectives

The communications team is currently planning to use two separate antenna configurations. So, there will be some point in between competition tasks in which the team must switch one antenna configuration out for the other. Since time between competition tasks is limited, the team should ideally show that any equipment switching (including antenna switching) can be performed in a time period which is shorter than the maximum wait time between tasks.

The most challenging switch will occur between the Equipment Servicing and Autonomous Traversal tasks. There will be 10 minutes after Equipment Servicing ends before Autonomous Traversal begins.

Therefore, we wish to show that any antenna switch (especially switching from 2.4 GHz to 900 MHz, as will be the case for the Equipment Servicing-Autonomous Traversal transition) can be completed in less than 10 minutes.

1. Audience

This test procedure is for operators of the BYU Mars Rover. The test may be performed by members of the communications sub-sub-team, or by any other members of the team. The testers should have an understanding of how the antennas are physically connected as well as a knowledge of how to test for connection once both antennas are up and running. Theoretically, this test procedure will be explicit enough that any member of the team can perform the test by closely following these procedures.

2. References

For antenna troubleshooting issues, see the Antenna Troubleshooting Guide, found in the Google Drive->Mars Rover 2018->Electrical->Communications->Capstone Documentation.

1. Requirements Traceability

This test correlates directly to the following system-level market requirement:
MR 1 - Rover can be set up and switched between tasks quickly.

Additionally, the test correlates to the following electrical sub-system-level market requirement:
MR 1 - In-field Rover setup time

3. Testing Details

1. Required Hardware/Software

The following hardware is required to be able to perform this test:

- Rover w/ charged LiPos
- Rover 2.4 GHz Antenna

- Rover 2.4 GHz Rocket
- Rover mounting equipment for 2.4 GHz setup
- Rover 900 MHz Antenna
- Rover 900 MHz Rocket
- Rover mounting equipment for 900 MHz setup
- Base station laptop
- Base station Ethernet cords
- Base station USB-Ethernet converter
- Base station antenna stand
- Base station 2.4 GHz Antenna
- Base station 2.4 GHz Rocket
- Base station 900 MHz Antenna
- Base station 900 MHz Rocket
- Base station 900 MHz servo (for rotation the 900 MHz Yagi)

The following software is required to be able to perform this test:

- Ubiquiti AirMax GUI

2. Documentation Instructions and Fault Reporting

Document this test using the Mars Rover Test Report Template. A “Pass” means a switch time of 10 minutes or less and indicates adequate preparation for competition. A “Fail” is a switch time of more than 10 minutes and indicates a need for more practice or a need to rethink our communications concept. After completion of the test, inform a communications subteam member of the test results.

3. Testing Preparation

Perform the following to prepare for the antenna switch test:

1. Attach the 900 MHz Antenna and Rocket to the rover.
2. Attach the 900 MHz Antenna and Rocket to the base station.
3. Power on antennas and the base station computer.
4. Power on the rover by releasing the red Emergency Stop switch.
5. Power on the Jetson computer by pressing its power button.
6. Make sure a network link exists between the base station computer and the rover computer. To do this, ping the rover IP (192.168.1.99).

4. Testing Procedure

Perform the following to proceed with the antenna switch test:

1. Start timer.
2. Exit out of the network connection.
3. Turn the rover off by hitting the emergency stop.
4. Unplug ethernet cord from base station Rocket.
5. Unplug ethernet cord from rover Rocket.
6. Undo mounting for base station antenna and Rocket.
7. Undo mounting for rover antenna and Rocket.
8. Mount new base station antenna and Rocket.
9. Mount new rover antenna and Rocket.
10. Plug in ethernet cord to new base station Rocket.
11. Plug in ethernet cord to new rover Rocket.
12. Turn the rover back on by unlatching the emergency stop, waiting 20 seconds, and pressing the restart button on the Jetson.
13. Wait for connection lights to appear on the Rockets.

14. From the base station laptop, ping the rover IP (192.168.1.70).
15. Stop timer and record switch time. Complete a test report using the Mars Rover Test Report Template.

5. Expected Test Results

Expected result should be a simple measurement of time in minutes and seconds. If the antenna do not establish connection after 10 minutes, the result is a “Fail.”

6. Special Instructions

This test is most helpful in conjunction with other switch time measurements. For example, other tests measuring the time required to switch between the science and arm modules should also be completed.

MDR-TP-EC01 Minimum Throughput at 1 Kilometer Test Procedure

Written by:	Tyler Averett	Revision and Date:	1.1, 03/21/18
Checked by:	Jace Rozsa	Approval Date:	3/22/2018

1. Objectives

The purpose of this test is to prove that the rover and base station can stay connected at large distances of up to 1 km. The competition indicates that the rover will never have to go farther than 1 km from the base station

1. Audience

This test should be performed by two or more members of the Communications sub-team. Testers should know how to hook up the antennas, troubleshoot, and work with the Rocket GUI.

2. References

1. Requirements Traceability

This test procedure will measure the rover's performance for System PM 20, "Minimum Throughput at 1 kilometer."

3. Testing Details

1. Required Hardware/Software

Required hardware:

- Two laptops with static IP addresses configured
- 4 LiPo batteries
- 2 jerry-rigged POE battery adapters
- 2 long ethernet cords
- 2 working USB-Ethernet adapters
- Dollies/carts for mounting antennas on
- Antenna pair you wish to test with Rockets and corresponding connecting wires

Required software:

- Airmax GUI included with the Rockets

2. Documentation Instructions and Fault Reporting

Document this test using the Template found in Mars Rover 2018 >> Team Organization >> Capstone Documentation >> Testing. Record test results as well as any relevant notes.

3. Testing Preparation

Perform the following to prepare for the "Minimum throughput at 1 kilometer test."

1. Drive to some location that has approximately uninterrupted line-of-sight for at least one kilometer (.62 miles).

2. Set up one antenna at one site, drive .6-.7 miles, and set up the other antenna there.
3. To set up each antenna:

a. Mount the antenna to the dolly/stand/cart, using nuts and bolts if necessary.

b. Mount the antenna's Rocket. Ensure that the antenna and Rocket are connected correctly (one RP-SMA to N connection for the 900 MHz rover antenna, two RP-SMA to RP-SMA connections for all the other antennas).

c. Connect 2 batteries to a POE converter. (Alternatively, plug the converter into a generator.)

d. Connect the POE converter to one of the computers (through the Ethernet to USB adapter, if necessary).

e. Connect the POE converter to the Rocket.

f. Ensure that the computer shows a connection to the Rocket. See troubleshooting guide (forthcoming) for details.

g. Log in to the Rocket GUI by typing the Rocket IP address into a web browser. username and password are both "ubnt."

h. Ensure that the antennas have found each other and have established a connection. They should do this automatically when both antennas receive power. You know that the antennas are connected if the signal lights on the Rocket light up. If the Rocket signal lights do not light up, see the troubleshooting guide for help.

4. Testing Procedure

To perform the "Minimum throughput at 1 kilometer test," do the following:

1. Have one of the testers open up a "Speed Test" window on his or her computer by clicking on the drop-down list in the Rocket GUI and selecting "Speed Test."
2. Enter the IP address of the far Rocket, and click to initiate the test.
3. Wait for the test to finish.
4. Record the given result for "Total."
5. Repeat the test several (at least 3) times.

5. Expected Test Results

The result should be a measurement or list of measurements of throughput in megabits per second. For in line-of-sight tests, expect values of around 2 megabits per second. A result of 2 megabits per second is a "Pass."

6. Special Instructions

MDR-TP-EC11 Max Weight of Rover Antenna Test Procedure

Written by:	Tyler Averett	Revision and Date:	1.1 03/14/18
Checked by:	Jace Rozsa	Approval Date:	3/22/2018

1. Objectives

The rover is limited to 50 kg. Since surpassing this weight requirement means significant point reductions to our team, it is crucial for us to choose and design solutions that are weight-efficient. Our target value for this parameter is 2 kg.

1. Audience

This test may be performed by any member of the Mars Rover Team.

2. References

List any documents (standards, Mars Rover documentation, etc.) that are referenced in this test procedure.

Document ID	Document Name	Revision No.
https://docs.google.com/spreadsheets/d/1wvfUs2zY4Kju8N7JJ3GHX39qTHhvlQt w0le1OL3GSjg/edit?usp=sharing	Electrical Subsystem Requirements Matrix	17-11-10
http://urc.marssociety.or g/home/requirements-guidelines	URC Rules	2018

1. Requirements Traceability

This test will help evaluate the electrical system’s performance measure 15: Max Weight of On-Rover Antenna, which pertains to the electrical system’s market requirement 10: Max (rover) weight in any competition configuration. This affects the rover’s market requirement 15: Rover meets competition weight requirements.

3. Testing Details

1. Required Hardware/Software

The following hardware is required to be able to perform this test:

- Rover antenna and rocket subject to test
- Relevant mounting equipment (all brackets, bolts, nuts needed to secure the antenna and rocket)
- The ethernet cord required to connect the rocket to the POE adapter
- NOT the POE adapter. Since we’ll need a POE adapter for any antenna configuration, we’ll keep the POE adapter as part of the Electrical weight budget and not count it as part of the antenna weight.
- A scale capable of measuring up to 5 kg with a good degree of certainty
- A flat platform that may be used to make weighing easier

No software is required for this test.

2. Documentation Instructions and Fault Reporting

Document the results of this test using the Mars Rover Test Report Template. Currently, a “fail” is any weight above 2 kg. A “pass” is any weight 2 kg or below. Notify a communications sub-team member of the results.

3. Testing Preparation

Perform the following to prepare for the antenna weight test:

1. Gather all of the hardware listed above.

4. Testing Procedure

Perform the following to proceed with the antenna weight test:

1. Weight the antenna, rocket, and cables.

a. If necessary, use the flat platform to hold all of the equipment,

b. If necessary, weigh the parts one at a time.

2. Record the total weight.

5. Expected Test Results

The antenna configuration weights 2 kg or less (Pass/Fail).

6. Special Instructions

Please be careful with the antenna.

Appendix B – Test Results

MDR-TR-0013 900 MHz Antenna Test

Date	Subsystem	Related Desirability Goal	Pass/Fail
February 21, 2018	Electrical: Communications	Extreme Out of Line of Sight Communication	Pass

Names of persons conducting test

Tyler Averett	Jace Rozsa		

Approval

Approver Name:	Zachary Brock	Approval Date:	2/26/2018

Purpose

During two of the competition tasks, the team is not guaranteed line-of-sight between the base station and the rover. Additionally, we know that the rover will have to traverse unpredictable terrain and navigate a wide variety of obstacles. Accordingly, we must prove that our communications concept is robust enough that the rover and base station networks will stay connected in spite of these obstacles. Additionally, the connection must have enough bandwidth to reliably transmit camera feeds, GPS location, and other data.

Method

We performed this test at and around Rock Canyon Park in Provo, UT. We set up the base station at the corner of E 2620 N and N 1200 E, pointing towards the “bowl” in the center of Rock Canyon Park. For this test, the base station consisted of a 900 MHz Yagi antenna and Ubiquiti Rocket, 2 LiPo Batteries, the base station laptop, a dolly to mount the antenna on, and relevant connectors. We then set up the rover station, which was configured just like the base station except using a 900 MHz Omnidirectional antenna rather than a 900 MHz Yagi.
We used dollies rather than the actual base station and rover because the dollies are much more portable, and we figured that the tests we were going to run would vary only according to the environment (landscape, obstacles) and not according to what the antennas would be mounted on.

We tested varying degrees of out of line-of-sight by placing the rover antenna at six positions inside of the “bowl,” on the side of the hill opposite to the base station antenna. Approximate locations are described below, and are listed in approximate order of decreasing line of sight. For example, the rover location “Halfway down” means that the rover was halfway down the hill on the inside of the bowl. “30 ft from edge” means that the rover was at the bottom of the bowl, 30 feet away from the slope of the hill.

After booting up both the rover and base station antennas and ensuring a connection, we performed "Speed Tests" to measure connection strength. The test is offered as a standard for Ubiquiti Rocket Software, and can easily be performed by clicking the appropriate places on the Rocket's GUI. The GUI may be accessed by typing the Rocket's IP Address into a web browser. The Speed Test was performed on the base station (192.168.1.30) and tested connection to the rover station (192.168.1.20). The test gives rates for TX, RX, and Total. Total speeds are shown below. Occasionally, the test would give a "timeout" (TO) error. However, this problem was solved by waiting a few seconds and attempting the test again. We hope that the timeout error is an artifact of running repeated speed tests and not a result of lacking bandwidth.

Results

The results of the test are summarized in the following table. Speed test results are in Mb/s.

Rover Location	Speed Test (Total) Results	Rover Location	Speed Test (Total) Results	Rover Location	Speed Test (Total) Results
15 feet down	1.75	Halfway down	2.27	10 ft from bottom	1.88
15 feet down	TO	Halfway down	1.34	10 ft from bottom	1.99
15 feet down	TO	Halfway down	TO	10 ft from bottom	TO
15 feet down	1.98	Halfway down	TO	10 ft from bottom	TO
15 feet down	2.45	Halfway down	TO	10 ft from bottom	1.26
		Halfway down	1.82		

Rover Location	Speed Test (Total) Results	Rover Location	Speed Test (Total) Results	Rover Location	Speed Test (Total) Results
Bottom of hill	1.35	30 ft from edge	0.98	100 ft from edge	1.62
Bottom of hill	TO	30 ft from edge	1.39	100 ft from edge	1.99
Bottom of hill	TO	30 ft from edge	0.94	100 ft from edge	1.65
Bottom of hill	0.73				
Bottom of hill	1.12				

Conclusion

From the given data, we conclude that 900 MHz is indeed a good frequency band for out of line-of-sight applications. Our minimum speed for all (non-timeout) tests was 0.73 Mb/s, which we believe is more than enough to send camera footage and other data between the rover and the base station. Additionally, this test shows the communications system's capability to communicate even when in severe out of line-of-sight conditions; since we transmitted from one side of the hill to the other, we've shown that the rover can communicate at at least 90 degrees out of line-of-sight. In the future, we plan to perform more tests to further confirm the robustness of the 900 MHz setup. Next time, we hope to use the actual rover and base station and get a better understanding of exactly how much data is being sent between the rover and the base station.

Revision 1.1, Updated 3/29/2018

MDR-TR-0031 Minimum throughput at 1 km

Date	Subsystem	Related Desirability Goal	Pass/Fail
3/20/2018	Communications	Minimum throughput at 1 km	Pass

Names of persons conducting test

Jace Rozsa	Tyler Averett		

Approval

Approver Name:	Zachary Brock	Approval Date:	03/22/2018

Purpose

The purpose of the test was to see if our communications network created a strong enough link at the maximum distance stated by the competition rules (1 km).

Method

We followed the Procedure for Minimum Throughput at 1 km (MDR-TP-EC01), found in the Google Drive in BYU Mars Rover 2018 >> Testing >> Procedures. We performed the test along Timpview Drive in Provo, Utah, and used the 900 MHz yagi and the 900 MHz omni. We used the black mars rover computer and Jace’s laptop.

Results

We took three measurements at a distance of slightly over 1 kilometer (it was hard to park at exactly 1 kilometer). We got 2.8 Mbps, 2.66 Mbps, and 2.13 Mbps; averaging 2.53 Mbps.

Conclusion

Our measured value for throughput was about 2.5 Mbps, which is higher than our target value of 2 Mpbs. The system passes.

Revision 1.0, Updated 03/22/2018

MDR-TR-0029 Minimum throughput at 1 km 60 degrees out of line of sight

Date	Subsystem	Related Desirability Goal	Pass/Fail
2/21/2018	Communications	.7 Mbps	Pass

Names of persons conducting test

Jace Rozsa	Tyler Averett		

Approval

Approver Name:	Zachary Brock	Approval Date:	03/22/2018

Purpose

The purpose is to verify the throughput at 60 degrees out of line of sight.

Method

See Minimum throughput at 1 km 60 degrees out of line of sight test procedure. The test was performed at rock canyon park. We situated the base station on the east side of the park down 2620 N and put the rover antenna at the top of the bowl in the park and varied how far down the bowl we went, measuring the throughput at each point.

Results

Position in bowl	**Throughput**
15 feet from top rim	2.45 Mbps
Halfway between top and bottom of bowl	1.6 Mbps
10 feet from bottom of bowl	1 Mbps
Bottom of bowl	1.12 Mbps

30 feet from edge of slope inside bowl	1.17 Mbps
100 from edge of slop inside bowl	1.75 Mbps

Conclusion

The minimum throughput we had was 1 Mbps which is well beyond our target value.

Revision 1.0, Updated 03/22/2018

MDR-TR-0037 Antenna Weight Test Report

Date	Subsystem	Related Desirability Goal	Pass/Fail
Mar 14, 2018	Electrical: Communications	Max Weight in any Competition Configuration	Pass

Names of persons conducting test

Tyler Averett			

Approval

Approver Name:	Zachary Brock	Approval Date:	4/2/2018

Purpose

The purpose of this test is found in “Antenna Weight Test Procedure,” which may be found in the Google Drive in the Mars Rover 2018 >> Testing >> Procedures folder.

Method

I followed the test procedures found in “Antenna Weight Test Procedure,” which may be found in the Google Drive in the Mars Rover 2018 >> Testing >> Procedures folder.

Results

The test was performed on both the 2.4 GHz omnidirectional Ubiquiti rover antenna and on the 900 MHz omnidirectional rover antenna.

M900 Rocket: .250 kg (guess)
900 Antenna: .704 kg
900 Ethernet cord:.02 kg
Total: .974 kg ---> Pass

M200 Rocket: .250 kg
200 Antenna: 1.672 kg
200 Ethernet cord: .02 kg
Total: 1.942 kg ---> Pass

Conclusion

Since both of the setups weigh 2 kg or less, both setups earn a “Pass.”

Revision 1.0, Updated 3/14/2018

MDR-TR-0027 Secure Connections Test

Date	Subsystem	Related Desirability Goal	Pass/Fail
Mar 19, 2018	Electrical	PM 5 and MR 4 for the Electrical Subsystem PM4 and MR 3 for the System	Pass

Names of persons conducting test

Tyler Averett			

Approval

Approver Name:	Zachary Brock	Approval Date:	03/22/2018

Purpose

Any faulty connection may make the rover stop functioning properly, and ultimately may render the rover unusable. It becomes necessary then to ensure that most (if not all) of the connections on the rover are secure.

Method

The test should be conducted as follows:

1. For the main rover (w/o arm or science)

a. Examine each electrical connection. Determine if each connection is secure. If it is a latching connection or otherwise difficult to remove by hand, count it as secure. If it can be pulled out easily, count it as not secure.

b. Record how many secure connections and not-secure connections you find.

2. Repeat (a) and (b) for the arm.
3. Repeat (a) and (b) for the science module.
4. Use the measurements from 1–3 to obtain a percentage of secure connections.

Results

w/o arm or science module (900 MHz): 247 secure, 9 not secure
w/o arm or science module (2.4 GHz): 249 secure, 9 not secure
Arm: 17 secure, 3 not secure
Science: 5 secure, 10 not secure
Total (900 MHz): 269 secure, 22 not secure. Percentage: 92.44%

Total (2.4 GHz): 271 secure, 22 not secure. Percentage: 92.49%

Conclusion

Since for both setups the percentage of secure connections is over the ideal value of 80%, this test is definitely a pass. However, more can still be done. This test only measures electrical connections, and does not check for faulty wires or soldering. Checking these two things will help the rover to have better, more reliable performance.

Revision 1.0, Updated 03/22/2018

Attachments

Connection breakdown found here:

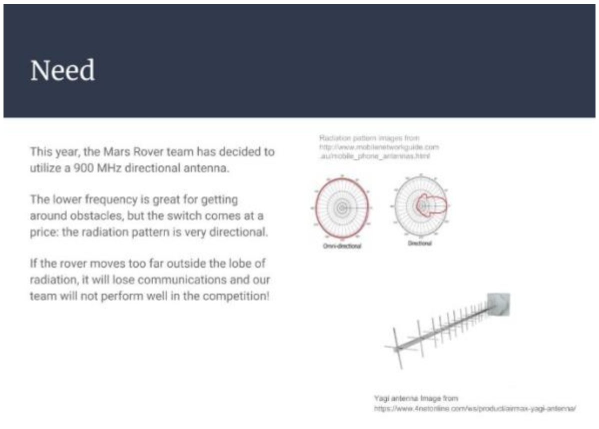
https://docs.google.com/spreadsheets/d/18pmeKVg40O6VPQduX4CQWYy25C-JHV78kHSnCakXfqw/edit?usp=sharing

Appendix C – Design Skill Portfolio

Tyler Averett

Design Skill Portfolio

Skill 1: Modeling



Need

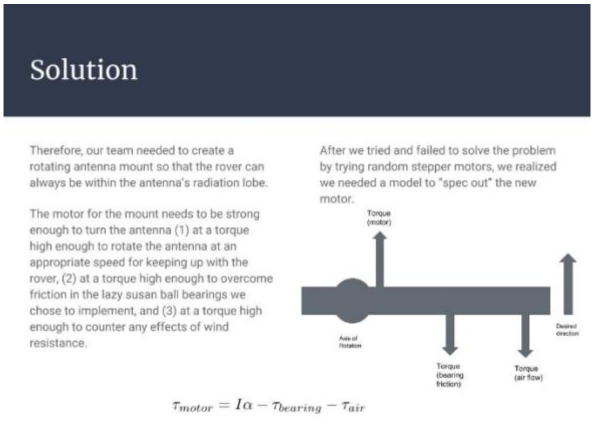
This year, the Mars Rover team has decided to utilize a 900 MHz directional antenna.

The lower frequency is great for getting around obstacles, but the switch comes at a price: the radiation pattern is very directional.

If the rover moves too far outside the lobe of radiation, it will lose communications and our team will not perform well in the competition!

Radiation pattern images from http://www.mobilenetworkguide.com.au/mobile_phone_antennas.html

Yagi antenna Image from https://www.4netonline.com/ws/product/airmax-yagi-antenna/



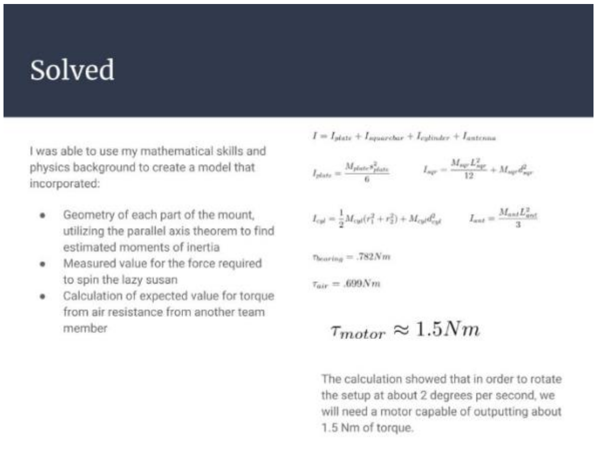
Solution

Therefore, our team needed to create a rotating antenna mount so that the rover can always be within the antenna's radiation lobe.

The motor for the mount needs to be strong enough to turn the antenna (1) at a torque high enough to rotate the antenna at an appropriate speed for keeping up with the rover, (2) at a torque high enough to overcome friction in the lazy susan ball bearings we chose to implement, and (3) at a torque high enough to counter any effects of wind resistance.

After we tried and failed to solve the problem by trying random stepper motors, we realized we needed a model to "spec out" the new motor.

$$\tau_{motor} = I\alpha - \tau_{bearing} - \tau_{air}$$



Solved

I was able to use my mathematical skills and physics background to create a model that incorporated:

- Geometry of each part of the mount, utilizing the parallel axis theorem to find estimated moments of inertia
- Measured value for the force required to spin the lazy susan
- Calculation of expected value for torque from air resistance from another team member

$$I = I_{plate} + I_{squarebar} + I_{cylinder} + I_{antenna}$$

$$I_{plate} = \frac{M_{plate}s_{plate}^2}{6} \qquad I_{sqr} = \frac{M_{sqr}L_{sqr}^2}{12} + M_{sqr}d_{sqr}^2$$

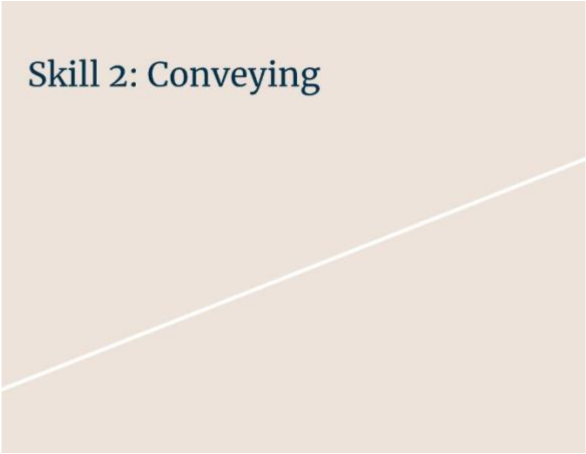
$$I_{cyl} = \frac{1}{2}M_{cyl}(r_1^2 + r_2^2) + M_{cyl}d_{cyl}^2 \qquad I_{ant} = \frac{M_{ant}L_{ant}^2}{3}$$

$$\tau_{bearing} = .782Nm$$

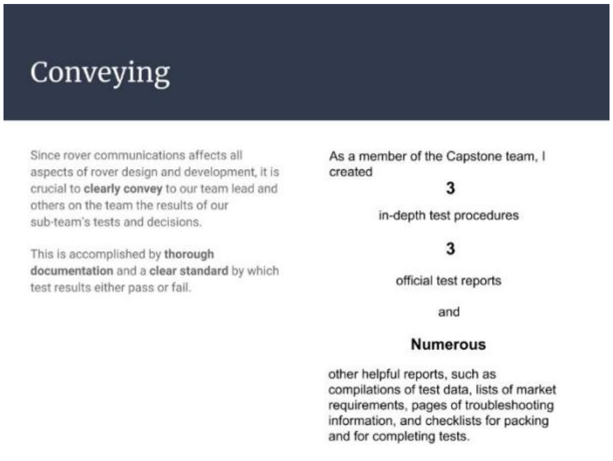
$$\tau_{air} = .699Nm$$

$$\tau_{motor} \approx 1.5Nm$$

The calculation showed that in order to rotate the setup at about 2 degrees per second, we will need a motor capable of outputting about 1.5 Nm of torque.



Skill 2: Conveying



Conveying

Since rover communications affects all aspects of rover design and development, it is crucial to **clearly convey** to our team lead and others on the team the results of our sub-team's tests and decisions.

This is accomplished by **thorough documentation** and a **clear standard** by which test results either pass or fail.

As a member of the Capstone team, I created

3

in-depth test procedures

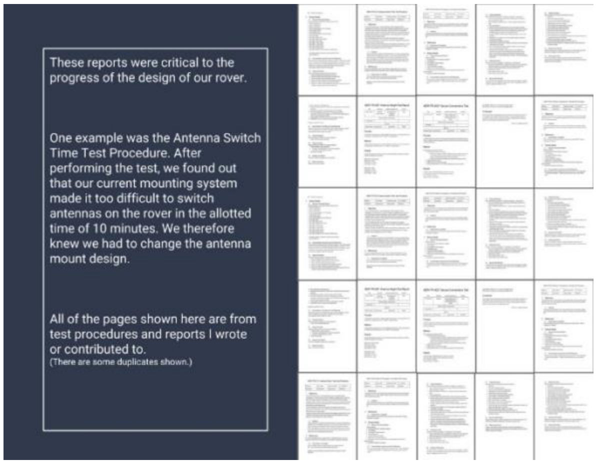
3

official test reports

and

Numerous

other helpful reports, such as compilations of test data, lists of market requirements, pages of troubleshooting information, and checklists for packing and for completing tests.



These reports were critical to the progress of the design of our rover.

One example was the Antenna Switch Time Test Procedure. After performing the test, we found out that our current mounting system made it too difficult to switch antennas on the rover in the allotted time of 10 minutes. We therefore knew we had to change the antenna mount design.

All of the pages shown here are from test procedures and reports I wrote or contributed to.
(There are some duplicates shown.)

Appendix D – Frequency Switching Information

Frequency Switching Information.

See URC rule 2.e.

900 MHz requirements:
- Max frequency bandwidth is 8 MHz. We have decided to set the bandwidth to 5 MHz.
- Must be able to switch among Low, Mid, and High bands. The competition schedule will notify teams which sub-band may be used for each task. Teams must be able to switch to other sub-bands immediately before tasks too.
  - Low = 902-910 MHz, use 907 MHz for center frequency. Frequencies used will be 907 +- 2.5 MHz.
  - Med = 911-919 MHz, use 914 for center frequency. Frequencies used will be 914 +- 2.5 MHz.
  - High = 920-928 MHz, use 924 for center frequency. Frequencies used will be 924 +- 2.5 MHz.
  - How to change center frequency (bandwidth should already be set to 5 MHz):
    - Log in to UBNT GUI on the rover using username and password “ubnt.”
    - Go to the “Wireless” tab
    - There should be a drop-down menu for “Frequency, MHz.” Choose the desired center frequency.
    - Click “Change” (found at the bottom of the page).
    - A box should come up with the option to “Apply.” Click “Apply.”
    - The GUI should restart and prompt you for another login. Log in again.
    - Go back to the “Wireless” tab and ensure the change was made successfully.
- No limit on number of 900 MHz channels. (Can we take advantage of this?)
- They will use spectrum monitoring to make sure we are following the rules.

2.4 GHz:
- Must use center frequencies that correspond to channels 1-11 of the IEEE 802.11 standard for 2.4 GHz.
- Max frequency bandwidth is 22 MHz.
- Must be able to switch channels. The competition schedule will notify teams which channels may be used for each task, and teams must be able to shift to other channels as required.
- Limit of 3 channels in the 2.4 GHz band.