TELEMETRY AND COMMAND LINK FOR UNIVERSITY MARS ROVER VEHICLE

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ABSTRACT

This paper describes a telemetry and command communication link used as part of a rover entered in the University Mars Rover competition. The link is capable of transmitting multiple real time video streams, along with other telemetry data from a rover to a base station approximately one kilometer away, under non-line-of-sight conditions. Low data rate commands are sent to the rover, to control its movement. To simulate conditions on Mars, the link cannot use existing cellular or satellite communication infrastructure. The data link uses the 70 cm Amateur Radio band for transmission in both directions.

Keywords: Telemetry and Command, UHF Systems, Robotics, Remote Sensing

INTRODUCTION

The Mars Society is a private non-profit charitable organization which promotes the exploration and settlement of the planet Mars. Since 2010 the organization has been hosting an annual competition known as the University Rover Challenge (URC). The university teams construct robotic devices, or rovers, which would be capable of operating on the surface of Mars, and are tested at the Mars Society desert research station (MSDRS) near Hanksville, Utah. This paper describes a telemetry and command communication system designed for one such rover.

The rovers must be able to operate without a tether or other device for power communications and control. There is no firm specification on the power source, other than it is able to power the device for one hour, and be able to be operated in the Martian environment. The gross rover mass is limited to 50 kg, although there are no other restrictions on dimensions. Regulations mandate that the rover be assembled from off-the-shelf components, with a total value of no more than 15,000 USD. The rover has a robotic arm which is used to collect soil samples, and perform simple maintenance tasks, such as measuring voltages or removing light debris from solar panels. To aid in navigation and maintenance tasks, the robot is equipped with video cameras.

While the rover may perform some operations semi-autonomously, the higher level decisions are made by humans at a remote location. This necessitates sending telemetry data and video information over a wireless communication link from the rover to the base station, and also requires that command information be sent to the rover over a return link. The wireless link is required to conform to United States Federal Communications Commission standards and regulations. The regulations for the competition does not allow for lighter than air vehicles for observation, but they are allowed to deploy communications antennas or relay devices.

The terrain at the MSDRS ranges from flat to vertical, and the competition guidelines specify that the rover must be able to negotiate slopes up to 15%. From this the team inferred that it will be necessary to have a communication system which can operate in a non-line-of-sight channel.

The system design involved modifying a commercial off-the-shelf 2.4 GHZ Ethernet router so it could operate in the 70 cm / 435 MHz amateur radio band. This was coupled with an omnidirectional antenna structure on the rover, and Yagi base station antenna.

PROPOGATION ANALYSIS

The system design called for all communication on board the rover, and at the command center, to be TCP/IP based. An inexpensive way to accommodate communication between the two locations would be with a commercial Ethernet access point and router hardware. Much of this hardware operates at 2.4 GHz or above. The team had some concerns about the ability of this equipment to operate in a non-line-of-sight environment. To determine if this was a problem, we used a commercial RF modeling program to measure the channel attenuation at the MSDRS site at both 2.4 GHz and 435 MHz, as shown in figure 1.

For antennas approximately 2 meters above the surface, the attenuation at 2.4 GHz appeared to be up to 200 dB. We were concerned that it would be difficult to close the link power budget when facing this much path attenuation. The attenuation in the 70 cm band was less severe, with peak values of approximately 150 dB. Based on this 50 dB difference in link gain, we elected to construct a system that would operate at 435 MHz.

70 CM RADIO OPTIONS

We investigated two options for implementing a 435 MHz TCP/IP router and access point. The first was to use a commercial off-the-shelf (COTS) Ethernet access point, Linksys® model WRT54-G router, shown in figure 2. This device uses spatial diversity through two transmit and receive antennas. It has a Broadcom BCM5354 processor which is clocked at 240 MHz, with 8 MB of RAM and a 2 MB flash memory for firmware. In its original configuration, it can communicate using 802.3, 802.11b and 802.11g wireless Ethernet standards.

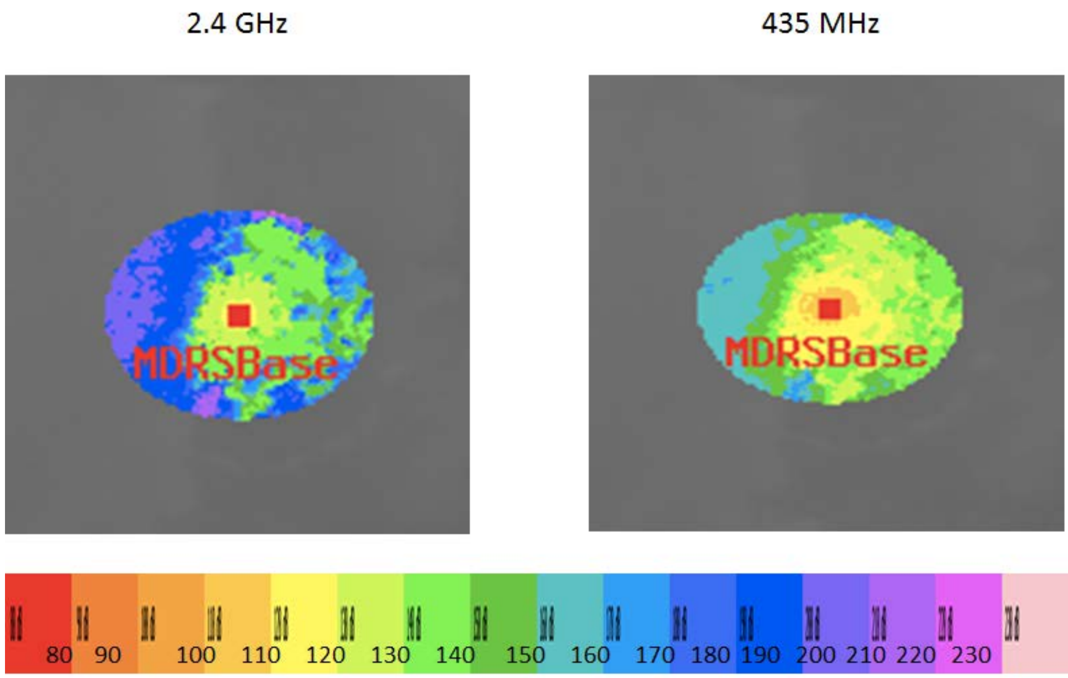

Figure 1 Propagation Analysis at Mars Society Desert Research Station Competition Site

Perhaps the most appealing aspect of this particular router, is that the manufacturer released the firmware source code under the terms of the GNU General Public License [1]. This has allowed third parties to write software for the routers, including OpenWRT [2], Tomato [3], and DD-WRT [4]. For this project we elected to use OpenWRT. This is a GNU/Linus based firmware for devices such as gateways and routers. It was quite easy to load the routers used on both the rover and the base station with OpenWRT and establish point-to-point communications between them using wired connections.

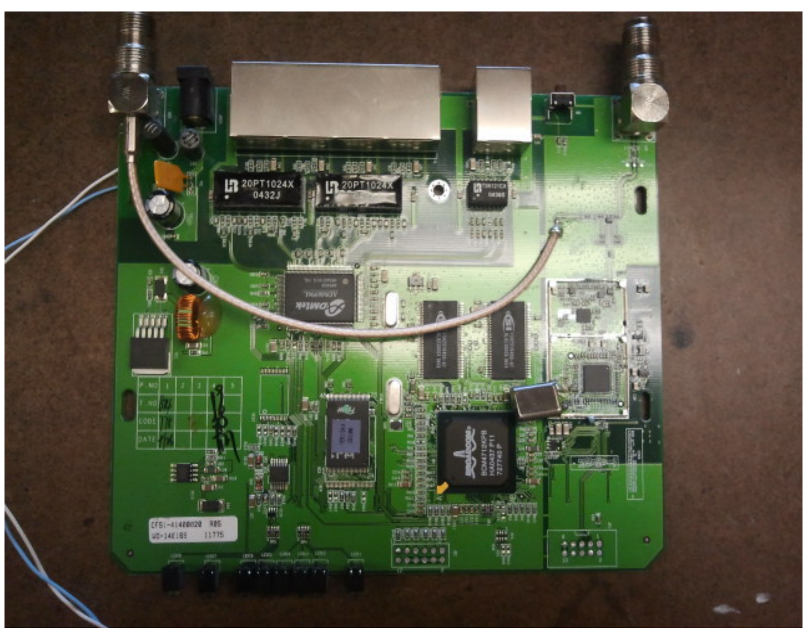

Figure 2. Initial Router Solution

We then established wireless communication between the devices using the MadWiFi [5] drivers specified by the wireless card manufacturer. However, despite the radios being able to see each other, we were unable to get an Ethernet link through the wireless connection. This was a problem with the protocol we were using. The protocol we used was a simple master-client connection. This is similar to the protocol used by any wireless device when connecting to a network. We ended up having to switch to a different master-client protocol which emulates a wired Ethernet bridge. This allows both sides of the link to see through the link.

Once we established communication at 2.4 GHz, we went about modifying the WRT54-G to allow it to transmit in the 435 MHz / 70 cm band. This involved replacing a crystal oscillator and reprogramming a PLL to move the carrier frequency. While we were successful at changing the oscillator frequency, the device started to exhibit instability during booting. We began researching that problem, and see no reason theoretically why it cannot be overcome – however we failed to fully debug the router prior to the deadline for the competition.

Because of time constraints and the difficulties encountered with modifying the inexpensive router, we exercised an option to use a more expensive off-the-shelf radio solution which was originally intended for the 70 cm band. The DL435 radio shown in figures 3 and 4 transmits up to 600 mW of power at 435 MHz. We chose to load the OpenWRT router and MadWiFi linux kernel drivers on the device, making it appear identical to the original solution to network devices.

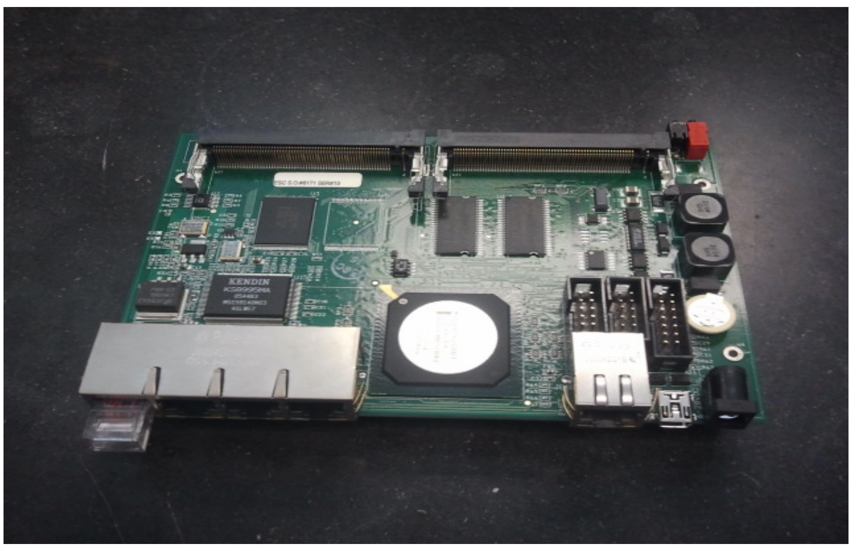

Figure 3. Alternative Router Design

The telemetry, video and command link required connection speeds up to 5 Mbps. We were originally concerned about this, since Part 97 of FCC regulations [6] limit data rates to 100 kbps in this band. However after researching this issue we found that we could legally transmit 5 Mbps using orthogonal frequency division multiplexing (OFDM) modulation.

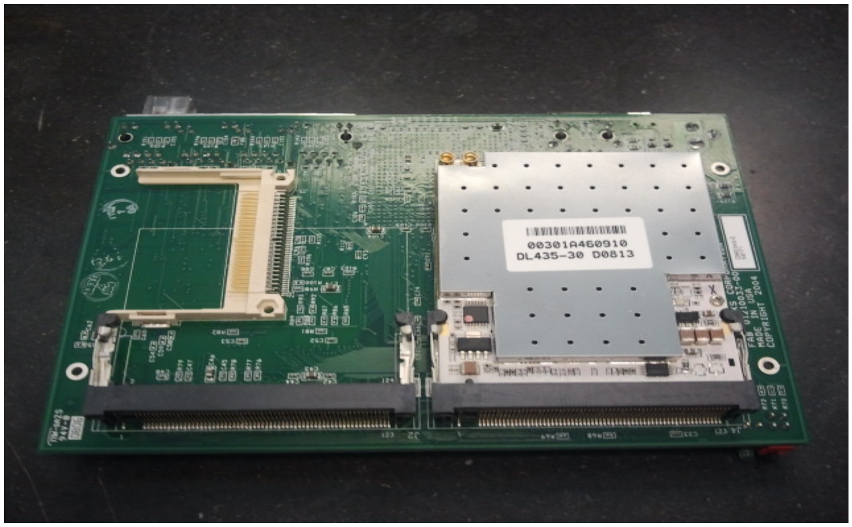

Figure 4. Alternative Router Design

To verify a connection could be established at the required data rates, we configured a simulated base station and rover. The rover was a completely isolated system that was only connected to the radio. The base station used a conventional internet service provider to a laptop computer. To verify we could achieve the necessary data rate, we streamed recorded video from the rover. After establishing we could stream multiple video channels, we set about measuring the link throughput. The first program we tried is called Netcast, however it appeared to give us some false readings. We then tried a program known as Iperf and its associated graphical user interface Jperf. This program running as a client and server connection was able to get an average bandwidth of 11.2Mbps.

ANTENNA DESIGN

We needed to design an antenna system for both the rover and the base station. We had initially hoped to use omnidirectional antennas at both ends, to simplify overall system design. However we were unable to obtain a sufficient signal to noise ratio to close our communication link. Further analysis indicated that a directional antenna at one end, and an omnidirectional antenna at the other should be sufficient. To minimize the complexity of the rover, we chose to place the omnidirectional antenna on it. The competition rules allow the use of a directional antenna at the base station, and also allow a user to control the direction of this antenna. That, in addition to the mathematical analysis and simulation, made us suspect that other teams had encountered similar difficulties, and that we were probably proceeding in a reasonable manner.

Our first attempt at an omnidirectional antenna for the rover was to use a quarter wave dipole vertical/whip antenna. These antennas radiate in all horizontal directions, but do not radiate well vertically. The competition parameters indicated the rover would never be more than 15 degrees from horizontal, so our antenna would never be more than 15 degrees from vertical. This gave us some concern, especially when the antenna was tipped away from the base station. A classic vertical antenna is placed on an infinitely large ground plane, and the antenna does not radiate a signal below this plane. The rover would not provide an infinite ground plane; we expected that we would still get some radiation below that plane.

The biggest problem turned out not being that the ground plane was too large, but that it was too small. We determined that it would be difficult to establish a significant ground plane at the elevated position that the antenna was located on the rover assembly. We expected that it would be difficult to obtain the correct loading impedance for the antenna, and that its radiation pattern would not be acceptable with a very small ground plane.

Our next attempt was to use a half wave dipole antenna design. The difficulty with a dipole is that it has excellent broadside gain, but deep nulls at either end, as illustrated in figure 5. Since we were not concerned about radiating the signal vertically, we considered mounting the dipole vertically on the rover. However it appeared it would be difficult to obtain the proper matching impedance for the radio transmitter when we configured the antenna and transmission cable in that orientation.

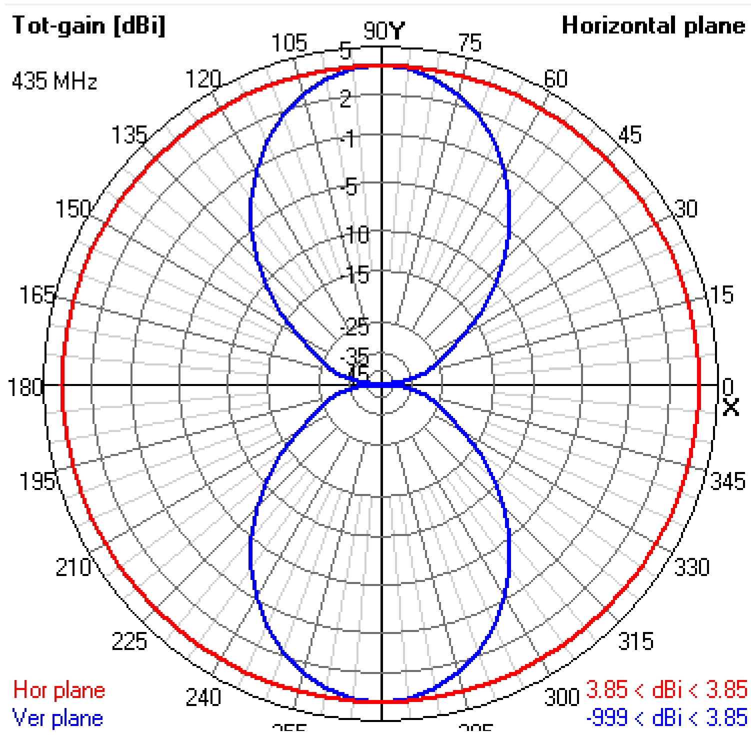

Figure 5. Simulated Dipole Radiation Pattern

Our final solution for the rover antenna was to use an array of two horizontal dipole antennas, rotated 90 degrees from each other, as shown in figure 6. It is a bit difficult to see one of the dipole antennas in this figure, as it points directly at the camera directly below where the transmission line enters the structure.

For the base station antenna design, we considered a parabolic dish and Yagi design. The dish was going to be difficult and expensive to fabricate, mount, and steer, so we opted for a Yagi antenna. We calculated the element lengths for both a 3 director and 4 director antenna array.

For the three director antenna we found

- Antenna Length=0.8λ=0.69*0.8=55.2 cm
- Reflector Length=0.482 λ=0.482*0.69=33.26 cm
- Emitter Length=0.424 λ=0.424*0.69=29.69 cm
- Length of each Director=0.428 λ=0.428*0.69=29.53 cm
- Distance between Elements=0.2 λ=0.2*0.69=13.80 cm

And for the 4 director antenna we found

- Antenna Length=1.2 λ=1.2*0.69=82.8 cm
- Reflector Length=0.482 λ=0.482*0.69=33.26 cm
- Emitter Length=0.420 λ=0.420*0.69=29.53 cm
- Length of each Director=0.428 λ=0.428*0.69=28.98 cm
- Distance between Elements=0.25 λ=17.25 cm
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We wanted all the directors to be the same length, so the measurements above are not exactly the same as the ideal calculations gave. It also appears that we needed a tolerance of 0.03 λ which we did not think we could achieve with the inexpensive fabrication method we planned to use.

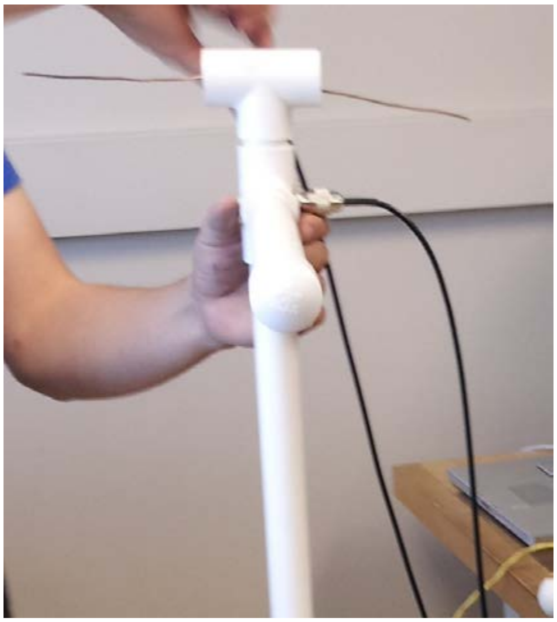

Figure 6. Rover Dipole Antenna Array

We used a commercial program known as YagiCAD to analyze both the 3 and 4 director designs, along with a number of others. There did not appear to be significant advantage to using 4, 5 or 6 directors, when compared to our base design of 3 directors and 1 reflector. The final radiation pattern of our antenna design is shown in figure 7, and one of the antennas we constructed is shown in figure 8.

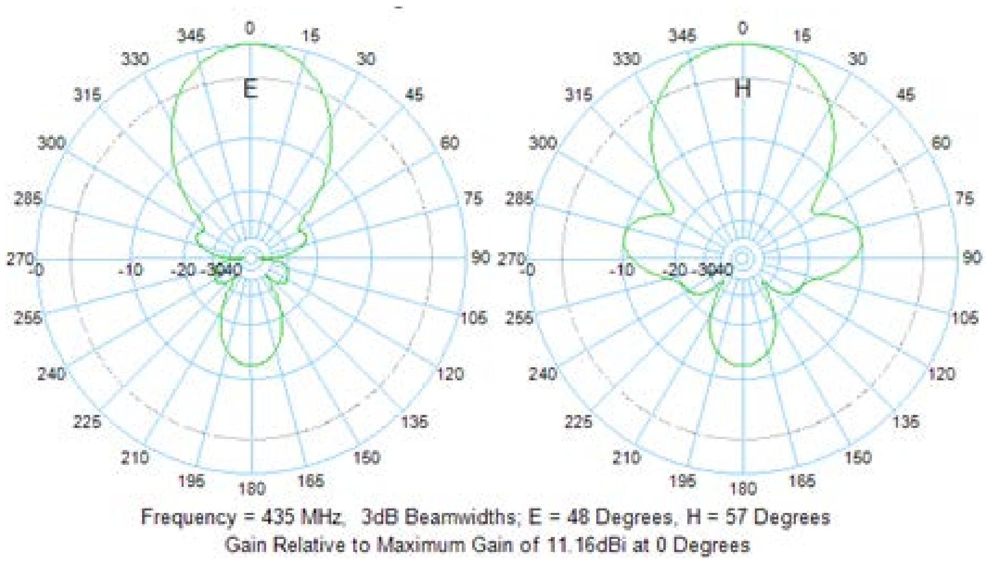

Figure 7. Yagi Radiation Pattern

We expect multipath reflection may be an issue when this system is used, which is why we only looked at radio solutions that allowed the use of two transmit and two receive antennas. We constructed two Yagi antennas to be used at the base station. While they could be mounted on a common mast, it would be better if they were displaced both vertically and horizontally from each other, as illustrated in figure 9.

The MadWiFi radio driver has the ability to switch between antennas to select the one with the highest signal to noise ratio at any moment. We could have used more advanced technology, such as multiple-input multiple-output modulation techniques. However it appeared that simply using the highest SNR was sufficient for our application, and did not involve modifying the radio modulation and demodulation software.

To verify the beam width of the Yagi antennas, we connected a frequency generator to one Yagi, and a dipole antenna to a spectrum analyzer approximately 10 meters away. We rotated the Yagi 360 degrees, and recorded the power level registered on the spectrum analyzer. The mathematical analysis indicated that we should have a 3 dB beam width of 48 degrees, and our measurements indicated it was approximately 40 degrees. We considered these to be in close enough agreement to allow us to use this design in the competition.

Figure 8. 1 Reflector, 3 Director, 435 MHz Yagi

Figure 9. Spatial Diversity

CONCLUSION

We successfully designed and implemented a two way digital radio communication link to download video and telemetry data from a rover to be used in the Mars Society University Rover Challenge. Commands can be uploaded to the rover from the base station using the same system. The system appears to be a TCP/IP router to the external hardware, and operates in the 70 cm amateur radio band. It uses an omnidirectional antenna array on the rover and a pair of Yagi antennas at the base station.

REFERENCES

[1] Free Software Foundation, “GNU General Public License”, http://fsf.org/, Boston, MA, 2007

[2] Open WRT Development Team, https://openwrt.org/

[3] Polarcloud, “Tomato Firmware”, http://www.polarcloud.com/tomato

[4] NewMedia-NET GmbH, “dd-wrt”, http://www.dd-wrt.com/site/

[5] MadWiFi Project, http://MadWiFi-project.org/

[6] Government Printing Office , “Title 47 CFR Part 97”, http://www.gpo.gov/fdsys/pkg/CFR-2009-title47-vol5/pdf/CFR-2009-title47-vol5-part97.pdf