Methods for Improving Long-Range Wireless Communication between Extreme Terrain Vehicles

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Introduction

Axel is an extreme terrain, two-wheeled rover designed to traverse rocky surface and sub-surface landscapes in order to conduct remote science experiments in hard-to-reach locations. The rover's design meets many requirements for a mobile research platform capable of reaching water seeps on Martian cliff sides. Axel was developed by the Mobility and Robotic Systems section at the Caltech Jet Propulsion Laboratory. Unique design criteria associated with extreme terrain mobility led to a unique rover solution, consisting of a central module, which provides long-term energy storage and space for large-scale science payloads, and two detachable Axels that can detach and explore extreme terrain locations that are inaccessible to conventional rovers. The envisioned mission could involve a four-wheeled configuration of Axel called 'DuAxel' that is able to traverse the benign, flattened terrain of a landing site and approach the edge of the targeted crater or cave where it would deploy anchoring legs and detach one of the Axel rovers [1]. A tether provides a secure link between the Axel rover and the central module, acting as an anchor to allow Axel to descend along steep crater walls to collect data from the scientifically relevant sites along the water seeps or crater ledges. After completing its scientific mission Axel would hoist itself up to the central module and dock autonomously (using its on-board stereo cameras), allowing the once-again recombined DuAxel to travel to another location to repeat data collection.

Figure 1: The Axel Rover Pictured During Arizona Field Testing

Background

Communication between the central module and the detached Axel is essential, and will be implemented in two different ways: long range, low bandwidth command and control communication will be done over the wire through the tether. This will be especially useful when Axel is deep inside a crater or a location far removed from the central module. Power will also be supplied from the central module's energy source (e.g. solar panels) to Axel via the tether. For high bandwidth communication of large data sets such as images or video, Axel will rely on wireless communication. While wireless has a superior throughput, it is limited by range and line-sight-obstructions to the signal.

Currently, Axel is employing IEEE 802.11g wireless ‘WiFi’ technology for development and testing purposes. WiFi is a common, commercially available radio frequency (RF) technology used in home and office wireless networks. It is becoming increasingly popular as new versions are released such as 802.11n and the latest draft edition 802.11ac. One of the components of a WiFi network is the router, which is most often wired via an Ethernet cable to the wide area network; the router communicates wirelessly by broadcasting a signal made up of packets of information that are received by the host’s antenna. The signal quality between the router and the host is a function of distance, obstructions (e.g., buildings, electrical wiring, etc.), and the amount of RF interference that may be present. The 802.11g protocol has an operating frequency of 2.4 GHz with the total bandwidth divided into eleven channels. The total bandwidth of 802.11g is approximately 72 MHz, but because each individual channel has a bandwidth of 20 MHz there is some frequency overlap between adjacent channels, thus there remain only three non-overlapping channels, one, six, and eleven. [2] Like 802.11g, the newer 802.11n has a bandwidth that is split into eleven channels with some overlap; however, there are a number of key advances in technology. The ‘N’ version can operate at either 2.4 or 5 GHz and uses Multiple Input Multiple Output (MIMO) technology, this means N has the capability of using multiple antennas to create a more robust signal thereby increasing effective range.

While WiFi is a proven technology in an office setting, it has been unreliable thus far when paired with Axel. The design of Axel is not conducive for RF communication because of its cylindrical metal body that blocks RF signals (effect known as a Faraday Cage). This creates challenges in antenna placement, because Axel will be navigating geologically harsh, obstacle-filled environments, where the antenna cannot simply protrude from this Faraday Cage as it could be damaged. The Faraday Shield of the body also limits the option of placing the antenna within the body of Axel, thus a unique or creative solution is required such as building the cover of the body out of Plexiglas instead of aluminum.

Members of the Axel team have also looked into communication and power relay options through the tether. The tether is made up of four 26 gauge wires, each having a diameter of 0.0159 inches (0.405 mm) [3], which would be required to conduct the signals for distances up to a kilometer. Large voltage losses are incurred because of the small diameter of the wires and the long length of the tether. These challenges led the team to pursue a high-voltage, low-current ‘trickle charge’ solution to supply Axel with power. The tether conductors are similar to what is used in a standard Ethernet cable, which allows for a technique known as power over Ethernet (PoE) to be employed. Prior to my arrival, the team conducted initial research and testing, all without obtaining conclusive results.

Objectives

An early task of mine was to develop further the communication and power transmission through the tether; I began by speaking with engineers and technicians who had previously worked on the tether to get up to date on the state of the effort. I learned about the severe constraints caused by the wire size and limited number of conductors present within the tether. Consequently, this part of my project was de-scoped to allow more time to focus on the wireless communication aspect.

The main focus of my work this summer has been to create a robust wireless communication system for the Axel rover, which is both an important and difficult problem. Timely advancement of Axel’s maturity requires the ability to communicate with the rover to conduct tests and to aid in the development of other systems. Currently, communication must be done using an auxiliary Ethernet cable, which is inconvenient and the cable can become tangled during tests. To improve the wireless performance I needed to study and understand the current system, its properties, and its flaws. By noting these attributes, I could focus my attention on what needed to be improved, and simply reuse the existing equipment and policies that already performed satisfactorily.

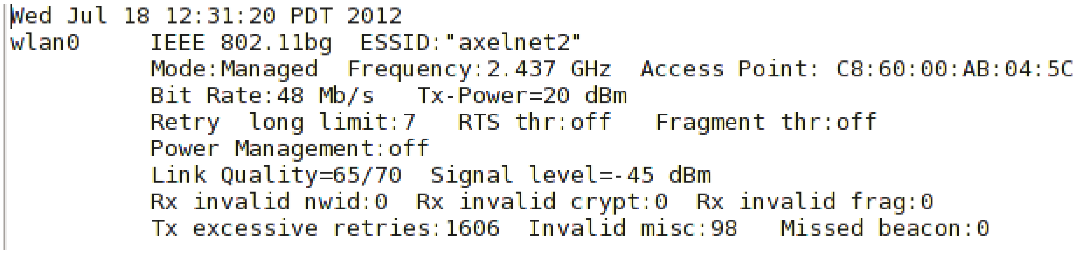
Another key objective of my work this summer has been optimizing antenna placement on Axel; as stated earlier, this was both an important and difficult problem for the team. I wanted to provide the team with a clear picture of the behavior of the wireless system under differing circumstances including the effects of range, the antenna type, and the frequency being used. I also needed to look into how enclosing the antenna in different materials such as Plexiglas or aluminum would affect the wireless signal and recommend modifications to Axel based on these results.

Approach

Conducting tests on the actual Axel rover would be difficult due to its size, weight, and usage by other students doing their respective tests. Thus, the setup of the experiments was designed to simulate the actual scenario as closely as possible using a bench top model of Axel. This bench top is equipped with the same central processor and operating system image that is being deployed on the rover, as well as the same motor control features and IO ports, but in a much more compact form. This allows it to be transported more easily while still giving results similar to what would be obtained on the vehicle; it also has the added bonus of not being in high demand by other team members. By researching the available versions of 802.11, I could see what advantages the latest editions had over the current system. My task was to find the most capable technology that would easily interface with existing Axel hardware and software. Once I selected the best technology, I was to conduct tests to compare the new system with the old one.

For the WiFi hardware the team used an Asus router; this router had a multitude of programmable features such as the WiFi version of the standard being utilized, the channel number, and in the case of the 802.11n standard, the bandwidth. I could change these settings by simply connecting to the router via an Ethernet cable. This capability of broadcasting 802.11g or 802.11n allowed me to switch easily between the versions to compare their effectiveness. On the other end of the wireless link, I used Alfa long-range USB adapter cards which were interfaced to my laptop; this allowed for a very mobile setup conducive for carrying out outdoor testing while being practical for eventual migration to the Axel rover. The cards and router also came equipped with RF antennas, but to improve performance, larger antennas were attached. These antennas are classified based on their gain in units of decibels isentropic (dBi). This is the ratio of the power produced by the antenna from a far-field source on the antenna's beam axis to the power produced by a hypothetical lossless isotropic antenna [4], or more simply stated it is a measure of how efficiently the antenna converts radio waves to usable electrical signals. The Alfa brand is favored by the Axel team due to previous experience with the company's products and positive consumer reviews.

Conducting accurate and consistent tests was enabled by using Linux Gentoo operating system to create Bash shell scripts in the Linux kernel. Multiple scripts were written, each with a specific test to run and data to collect, when it was time to collect data I simply invoked each script and let it run its programmed task, which greatly simplified the testing. One tool used in testing was the ping command, using ping data could be collected on various parameters, but I chose to concentrate on packet-loss information. A script was also created to collect RF signal information using the 'iwconfig' tool from the Linux wireless toolbox. Iwconfig allows access to signal quality, received signal strength and bit rate; an excerpt of the iwconfig output is shown on the next page.



```
Wed Jul 18 12:31:20 PDT 2012
wlan0     IEEE 802.11bg  ESSID:"axelnet2"
          Mode:Managed  Frequency:2.437 GHz  Access Point: C8:60:00:AB:04:5C
          Bit Rate:48 Mb/s   Tx-Power=20 dBm
          Retry  long limit:7   RTS thr:off   Fragment thr:off
          Power Management:off
          Link Quality=65/70  Signal level=-45 dBm
          Rx invalid nwid:0  Rx invalid crypt:0  Rx invalid frag:0
          Tx excessive retries:1606  Invalid misc:98   Missed beacon:0
```

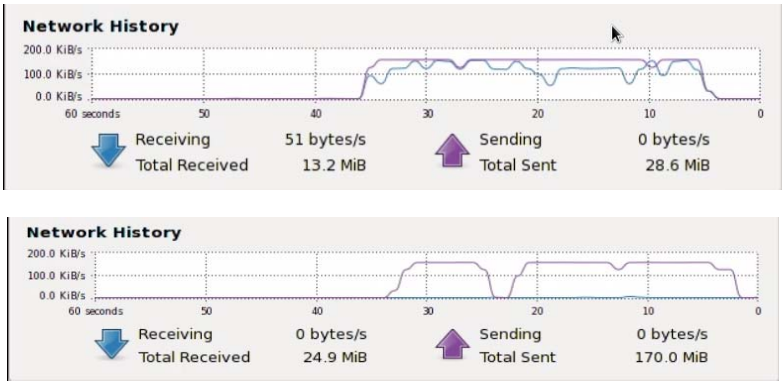
Figure 2: iwconfig Output

To get accurate figures on data transfer rates I used secure copy utility to transfer a two megabyte file from my laptop to the bench top via wireless. The router and bench top were connected by Ethernet to test only one leg of the wireless transfer this removed the second wireless connection between the router and the bench top, helping eliminate an extra, unneeded variable from the trial.

The data was collected in a series of experiments where several parameters were varied including the 802.11 version, channel number, and distance. The first test that was conducted was a basic ping to prove that the test system was functioning properly. My first action after the problem issues were worked out of the system was to test antenna types by running short-range indoor tests between two antennae with attenuated power to simulate long distance. Once the raw data had been collected, it needed to be filtered and reduced to a more manageable size of only relevant information. To accomplish this, more scripts were written using the Bash shell to extract the valuable information and store it in a comma separated value (CSV) text-based file format; from here, the data points could be easily understood and used to create useful graphs. Another tool that was utilized was a WiFi spectrum analyzer to search the available channels and show the amount of traffic on each. This allowed selection of the least noisy channel, which maximized the WiFi performance.

Results

To demonstrate the effect the metal body had on the RF signal I conducted a test using 802.11g by doing a simple ping between the router and an Alfa 9 dBi antenna. The top image of Figure 3 shows the relatively strong reception when the antenna is resting uncovered on the Axel body. After placing an aluminum plate over the antenna, enclosing it in the body of the rover, I repeated the test and had essentially 100% signal loss. This clearly shows the importance of improving the wireless communication system on Axel.



Receiving 51 bytes/s
Total Received 13.2 MiB
Sending 0 bytes/s
Total Sent 28.6 MiB

Receiving 0 bytes/s
Total Received 24.9 MiB
Sending 0 bytes/s
Total Sent 170.0 MiB

Figure 3: Faraday Effect

The data shown in Figures 4 – 8 was collected during tests that were conducted using 802.11n over the same geographical area using an identical system configuration. Figure 4 shows the results of a test conducted to study the amount of data being lost in the wireless transmission as a function of the distance separating the transmit and receive antennas. As would be expected, the data loss increases with distance and becomes nearly 100% at a range of roughly 90 to 100 meters.

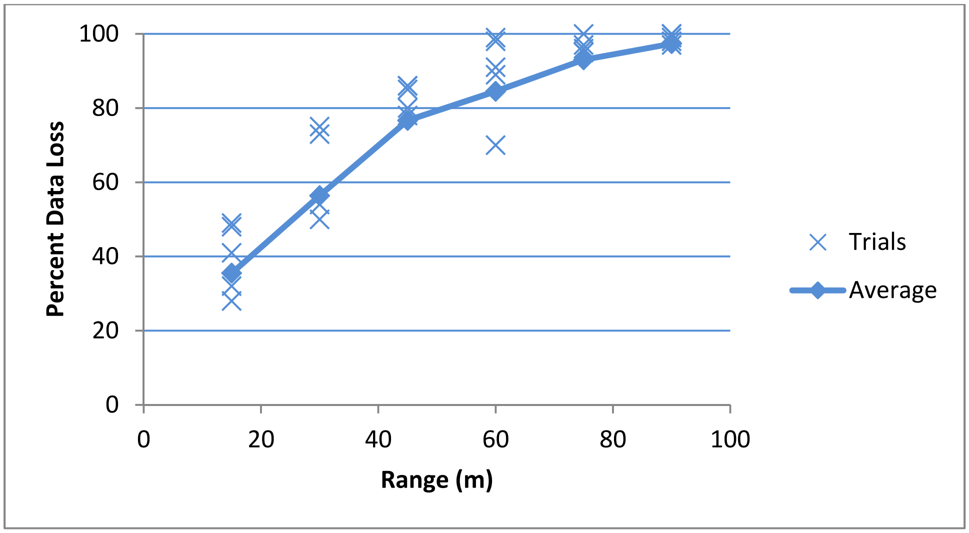


Figure 4: Transmission Packet Loss

The following chart shows the strength of the router's signal received by the Alfa antenna versus the distance that separates them. The data was collected using the iwconfig tool and the plotted points are the average of 100 readings taken at each location at a rate of one reading per second. An unexpected result is the increase in signal strength between 60 and 75 meters, this could be due to a decrease in RF noise at the time the 75 meter readings were taken or because the change in location created an environment that was more conducive to RF signals.

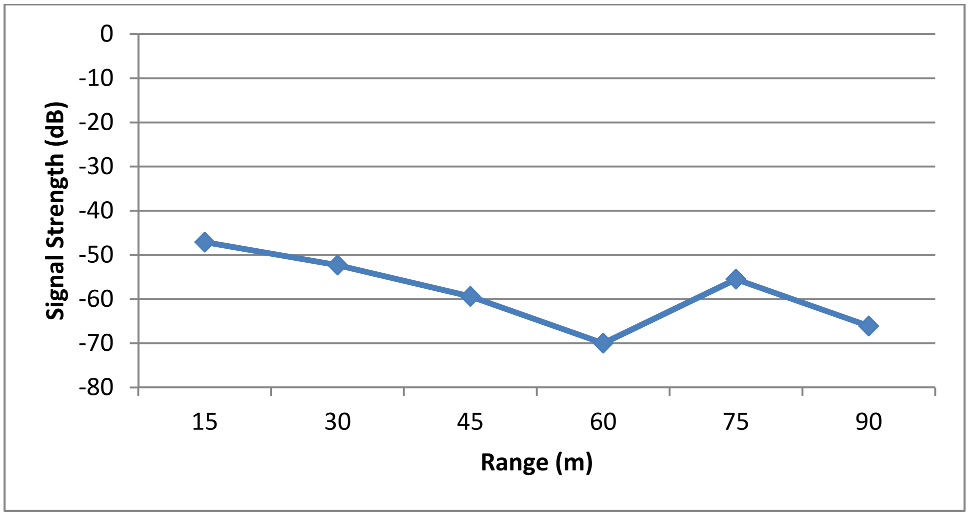


Figure 5: Signal Strength

The iwconfig tool was also used to collect the data that is displayed in Figure 6. Here again the data points are the mean value of 100 readings taken from 15 to 90 meters in 15-meter increments. What this plot shows is that 802.11n had a relatively stable transfer rate from 15 to 75 meters, but began to decrease beyond this distance. The wireless connection was intermittent at 90 meters and no relevant measurements could be attained beyond this range.

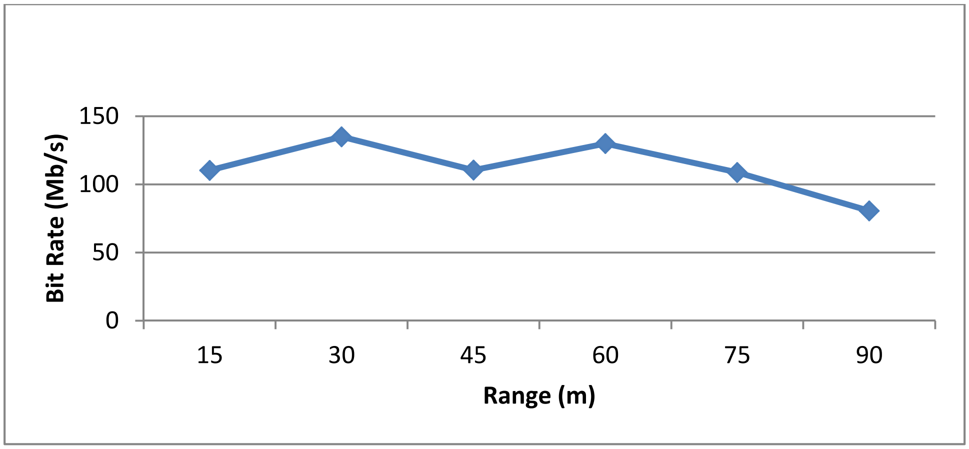


Figure 6: Bit Rate Reported from Router

Using the same process as in Figures 5 and 6, Figure 7 shows signal quality versus distance between the transmit and receive antennas. This is used primarily as an indicator of the strength of the WiFi signal and is a simply an integer value, with 70 being a theoretically perfect connection.

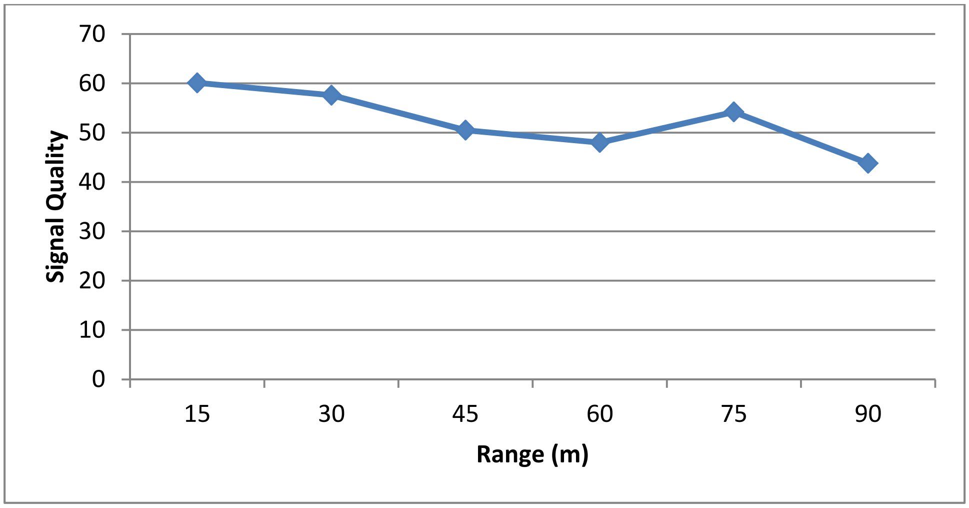


Figure 7: Link Quality between Host Antenna and Asus Router

To get accurate data on the actual wireless transfer rates, a 2 MB file composed of random data was transmitted wirelessly using the secure copy protocol and the transfer rates were measured. The test was repeated five times at each distance and the results are plotted on the next page. As the figure shows, the results were in accordance with IEEE 802.11n specification out to 30 meters, but then degraded rapidly. The file could not be transferred from a distance of 90 meters as the process was either unable to start or would stall before completion, resulting in recorded bit rates of 0 kB/s.

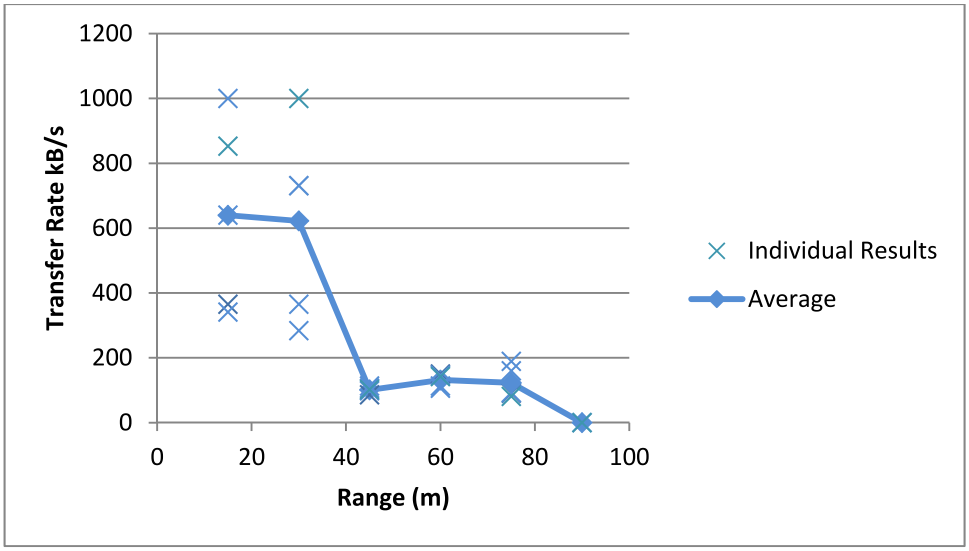


Figure 8: Secure Copy Transfer Rates

Early tests of the 802.11n system were disappointing for a number of reasons, one of which was the USB WiFi adapter driver instability; because this technology is relatively new, the software still had a few bugs, which led to the driver crashing and not recovering. Recovering from a driver failure required resetting the system, which was a time consuming process. It was later found that this driver crash was partially caused by the particular Gentoo software script I was running that was not compatible with this driver; by updating the iwconfig script this problem was largely eliminated. During the first round of testing, interference limited the range to well below the manufacture's advertised effective distance; this strong interference was caused by the electrical system surrounding the test range. Along with the interference from the other WiFi networks in the area, it was discovered that an electrical box used to power the router during outdoor testing produced this interference. This noise could be largely mitigated by moving the router as far away from the box as cord length would allow. Another interesting discovery was finding that one of the Alfa antennas had an internal fault and may have been partially to blame for previous inconsistencies in the data. While performing tests on the different frequency channels available with WiFi it quickly became apparent that channel #11 performed unsatisfactorily. Using the RF spectrum analyzer I was able to confirm my theory that channel #11 was highly utilized by other networks and therefore ill-suited for our needs.

Discussion

This has been an exciting project and I have learned much about the scientific research process while at JPL. I have operated as an individual and with a team and have seen firsthand the importance of communication between team members. I was also exposed to business operations and administrative procedures as conducted in an advanced research company such as JPL, which I found very interesting. On the technical side, I attained a great introduction to the Linux operating system, which was largely new to me. I also learned a great deal about the details of computer networking and specifically IEEE 802.11 protocol, which is a valuable skill in today's job market.

Conclusion

Robust wireless communication is a difficult, non-trivial challenge. While progress was made on this project, the inconsistencies due to noise in the results will require many more tests to be performed before a pattern will begin to emerge. Future work will focus both on testing new draft versions of 802.11 as they are released to exploit the latest advances in technology and also on antenna configuration to maximize performance. The collected data shows that, if carefully configured, WiFi is a capable and feasible technology for use on Axel. Although the existing system is not currently meeting all of its desired field-test requirements, the rapid pace of advancements in the field of wireless communication means that with a proper combination of hardware and software components, we can achieve great gains in wireless communication for Axel and other extreme terrain vehicles.

Acknowledgements

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Bibliography

[1] Jet Propulsion Labratory, "Axel and DuAxel Rovers for the Sustainable Exploratoin of Extreme Terrains," *Journal of Field Robotics,* 2011.

[2] Encyclopedia Britannica Inc, "Wi-Fi," 2012. [Online]. Available: http://www.britannica.com/EBchecked/topic/1473553/Wi-Fi. [Accessed 6 August 2012].

[3] "American Wire Gauge," 2 August 2012. [Online]. Available: http://en.wikipedia.org/wiki/American_wire_gauge. [Accessed 5 August 2012].

[4] "Antenna gain," 14 July 2012. [Online]. Available: http://en.wikipedia.org/wiki/Antenna_gain. [Accessed 1 August 2012].

[5] D. Suess, "Testing," Johnson Co., Pasadena, 2012.