University of New Hampshire
Broadband Center of Excellence

TELEVISION WHITE SPACES:

Assessing TVWS for Rural Broadband Access

University of New Hampshire Broadband Center of Excellence

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November 2014

Abstract

In this report, the use of Television White Spaces (TVWS) as a promising medium for rural broadband access is examined. The technology assessment trial described is conducted in and around Durham, New Hampshire. Seven clients and two base stations are used to analyze the performance of the TVWS equipment in a suburban/rural environment. Data transmission rates were found to be in the broadband range over distances up to 12.5 km with near line-of-sight links, but losses caused by terrain line-of-sight obstructions were found to have a negative effect on performance. Additionally, some propagation models are examined for their use in predicting performance to simplify installations. Power spectrum measurements were made to explore the propagation of the signals over UHF frequencies and to discern how they correlate to throughput speeds measured by Internet-based broadband speed tests. Some conclusions are presented as to the performance of the system, as well as some areas where more work is needed to fully assess the system.

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1 Executive Summary

In the fall of 2013 the University of New Hampshire Broadband Center of Excellence began field-testing wireless broadband access technology in the area immediately surrounding Durham, N.H. The trial was designed to assess the market readiness of technology and processes tied to delivery of broadband Internet service over license-exempt spectrum normally reserved for television broadcasting — the “TV White Spaces” (TVWS).

Our objective was to determine if current-generation technology is viable for meeting the needs of Americans who live in areas where broadband service is otherwise unavailable. By some estimates, there are up to 30 million U.S. citizens who cannot attain increasingly vital broadband connectivity, typically because they live in rural areas where wireline broadband networks are economically untenable. TVWS presents a potential remedy.

In particular, we hypothesized broadband access equipment operating in the license-exempt TVWS bands would meet needs of end users and Internet Service Providers alike because the frequencies have excellent propagation characteristics and because there are no expensive licenses associated with TVWS.

What we found is TVWS equipment and frequencies have the potential to deliver broadband access service, but the current generation of equipment and planning tools are insufficient to support immediate, large-scale deployment.

Although we found network performance to be adequate and even excellent in certain instances, our conclusion is that the tools and techniques associated with TVWS network installation and management are inadequate to meet real-world deployment demands for reasons that include:

- **Absence of standards-based products.** Current iterations involve proprietary technology, products and backend systems
- **Expensive client devices.** Technology has not been “siliconized” to support affordable scaled deployment.
- **Installation challenges.** TVWS equipment has not yet achieved plug-and-play functionality and instead requires highly skilled/trained personnel to trouble-shoot and perfect.
- **Limited or uneven performance.** Latency and throughput are inadequate or unpredictable across varying deployment scenarios.
- **Susceptibility to interference.** Terrain obstacles, manmade and/or natural, hobble performance predictability.
- **Network management challenges.** A lack of operational observability and diagnostic capability prevent adequate performance monitoring.

In order to be viable, the service must be plug-and-play such that people without extensive expertise in wireless networking can install and operate the service. This includes the end users, but perhaps more importantly, the infrastructure suppliers: ISPs, town managers, librarians or public servants.

Remedying these inadequacies will require that TVWS be elevated to constitute a carrier-class delivery platform, with characteristics that include:

- Auto-correcting intelligence designed into products and end-to-end systems
- A 24 x 7 operational mentality
- Four 9s (99.99 percent) of service availability as the operational objective

Our findings suggest there is a long way to go before TVWS infrastructure and spectrum can be utilized to meet the needs of the underserved. But it is not an impossible task. TVWS can emerge as a viable broadband delivery alternative if:

- Vendors establish carrier-class broadband Internet as system design goals
- Standardization efforts such as IEEE 802.22 or TVWS LTE take hold to create multi-vendor interoperability, standardized back-end management systems and involvement by multiple silicon vendors
- Equipment is plug and play, able to automatically optimize operational parameters
- Testing labs are available that verify product operation and multivendor interoperability
- Regulators including the FCC provide clear guidance on the use of TVWS by unlicensed devices
- A effective mechanism is established and enforced for disparate services coexistence within TVWS spectrum

Long term viability of TVWS for broadband Internet will depend on many factors, but BCoE believes it is a technology with potential. We note that cable modem systems were at a similar state 20 years ago in terms of product maturity, regulations, silicon and standardization. With sufficient motivation and investment by public and private resources an industry can be built around TVWS broadband access.

This report includes a detailed description of the field trials—bringing up the service, identifying antenna locations, measuring output performance over time, ascribing space and frequency and assessing the quality of analytical tools to assist with deployment. It also makes recommendations for next steps.

2 Introduction

Figure 1: Client, Measurement, and Base Station Locations

I. Scope

This report serves as a quantitative analysis of the use of the Carlson Wireless Technologies RuralConnect® equipment for rural broadband applications. This includes throughput and signal-to-noise ratio measurements with the client premises equipment (CPE), in addition to total received power measurements using a spectrum analyzer. These measurements are used to help select which locations will be included in Phase 3 of the trial of TVWS equipment in the Durham, N.H. area. In addition, some analytical path loss models and the Radio Mobile computer software are explored for their use as a prediction tool for future system deployments. These two methods, measurement and computer analysis, are used in tandem to quantitatively assess the RuralConnect equipment for rural broadband access.

Phase 1 of this trial took place between September and December of 2013 as part of the Gigabit Libraries Network initiative to explore the capabilities of TVWS [5] with the results documented in [3]. This report covers Phase 2 of the trial that took place May thru August of 2014.

II. Purpose

Broadband, high-speed Internet access has all but become a requirement in today's connected world. However, millions of people in the United States and billions worldwide do not have access to fixed broadband at their home. As a result, users often must travel to public institutions to gain access. With wired infrastructure unavailable in many rural areas, wireless options deserve to be examined as one of the primary means to extend broadband's reach to these unserved areas. Unused VHF/UHF broadcast television frequencies made available for unlicensed use by the FCC have come to be considered promising for this application. These TVWS frequencies have propagation properties that may be superior in rural areas to other frequencies such as the 2.4 GHz and 5 GHz frequencies used in Wi-Fi routers. TVWS does not require a direct line of sight and can propagate up to 4 times as far as Wi-Fi at the same power [3]. This can allow municipalities and ISPs to provide access to wireless broadband Internet in rural areas.

One company that has begun developing rural broadband equipment is Carlson Wireless of Northern California. The devices used in this trial are the Carlson RuralConnect TVWS Radios [4]. With connection capabilities up to 16 Mbps aggregate, these wireless radios can provide broadband speeds over much larger distances than existing Wi-Fi routers. As of December 2013, the FCC approved the RuralConnect devices for commercial, unlicensed use in the United States. With this authorization, testing in the different environments in which it may be used is necessary to determine the possible suitability for rural broadband. This testing was completed in the Seacoast region of New Hampshire. Results of the Phase 2 characterization are described in this document.

III. Trial Information

The FCC under certain requirements makes TVWS frequencies available for unlicensed use, including accessing a geolocation spectrum database to determine available channels (such as the Google database shown in Figure 2), and restricting the maximum transmit power and the antenna height. The channels are chosen from the available unoccupied spectrum that will offer the best performance, with lower frequencies normally having improved propagation characteristics. The updated Carlson equipment software used in Phase 2 allows frequency sweeping wherein performance can be monitored on different channels. This led to the discovery that channels 22 (521 MHz) and 23 (527 MHz) would provide the best performance. Before this software update occurred, channel 40 (629 MHz) was being used. The maximum transmit power allowed of 36 dBm or 4 Watts, and the maximum height of 30 meters limits the interference to the licensed television broadcast channels. The Carlson RuralConnect radios chosen for the trial have the ability to transmit in different modulation modes, enabling weaker channels to be used reliably. A summary of these modes can be found in Appendix A.

Testing was completed on the UNH campus in Durham, New Hampshire as well as in surrounding towns. The UNH campus fiber-optic network provided the Internet backhaul that supported a trial of this nature. Even though the libraries included in this stage of the trial already have broadband access, the close proximity to the research university allowed the system to be actively monitored and measured to determine if it is a viable solution to the rural broadband problem.

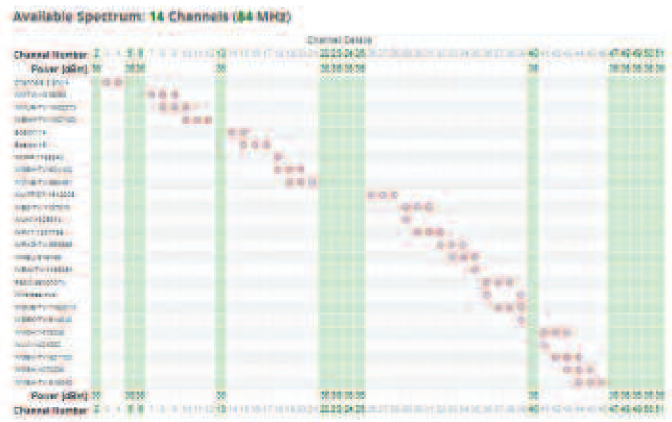


Figure 2: Available TVWS channels in Durham New Hampshire

IV. Initial Deployment and Overall Assessment

Characterization of the system was necessary to determine if it could be used for connecting multiple libraries in the towns surrounding the University of New Hampshire in Durham, NH. The locations selected were Barrington Library, Madbury Library, Durham Library, Lee Library, and three campus locations: the Dimond Library, Thompson Hall, and the UNH InterOperability Laboratory (IOL). The locations are mapped in Figure 1, with coordinates and distances from the base station depicted in Table 1. The Phase 1 trial began with a single base station mounted in a utility penthouse on the roof of one of the taller buildings on campus, Stoke Hall. This dormitory building also houses some university offices and provides a high-speed Internet back haul for the TVWS system. The base station's omni-directional antenna was mounted roughly 1.5 meters above the roof, producing a transmitter height of roughly 27 meters. The orientation of the antennas and radio waves were vertically polarized, meaning the electric field of the wave is oscillating in the vertical direction allowing for maximum isolation of the signal from the remaining local TV broadcast channels that are horizontally polarized. Operation of the base station was on channel 40 (frequency = 629 MHz).

Phase 1 test results had been disappointing as the library clients outside of Durham were unable to connect to the base station and throughput measurements with the operational clients showed lackluster performance. It was noted that use of the lower gain (5.2 dBi), omni-directional base station antenna reduced the reach of the system, and channel 40 seemed to have a higher noise floor, which caused more interference and errors in the system. Additionally, the modulation was set by the Carlson Operation and Management Center (OMC), and could be changed only by manual user intervention, rather than dynamically as the channel performance changed (this capability was added as a software update later in Phase 2). This reduced the throughput levels at the locations that could receive the signal at higher levels.

Due to channel characteristics such as weather and foliage effects that vary over time, the signal-to-noise ratio fluctuated, affecting the performance and underscoring the need for dynamic adjustments to modulation rate and channel use. To continue the trial, improvements would be made to the system to better assess performance of the equipment.

CLIENT	COORDINATES	DISTANCE (BASE STATION)
Thompson Hall	43°08′09.1″N | 70°55′56.6″W	280 m (Kingsbury Tower)
Dimond Library	43°08′08.5″N | 70°56′00.3″W	220 m (Kingsbury Tower)
Durham Public Library	43°08′24.3″N | 70°55′37.7″W	325 m (Stoke Hall)
InterOperability Laboratory (IOL)	43°09′09.6″N | 70°57′11.6″W	2,540 m (Kingsbury Tower)
Madbury Public Library	43°10′01.8″N | 70°56′24.5″W	3,700 m (Kingsbury Tower)
Lee Public Library	43°07′24.1″N | 71°00′39.8″W	6,300 m (Kingsbury Tower)
Barrington Public Library	43°13′09.0″N | 71°02′08.9″W	12,520 m (Kingsbury Tower)

Table 1: Client location coordinates and distance from base station

V. Modifications to Initial Deployment and Resulting Assessment

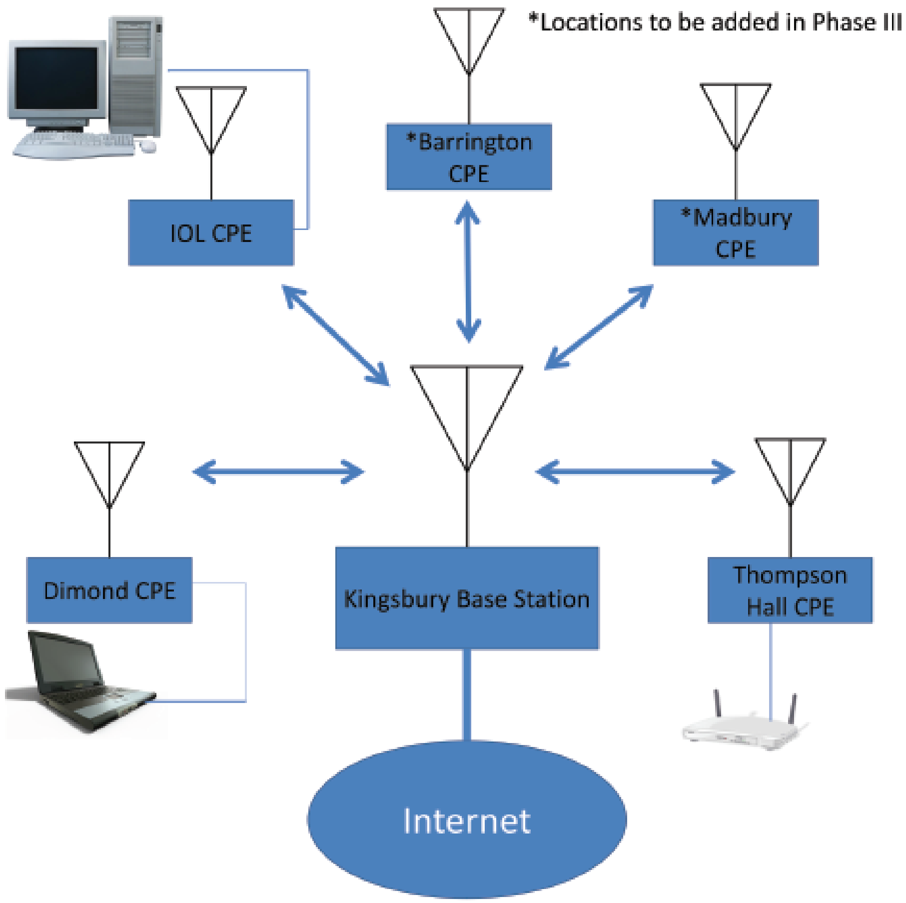


Figure 3: Network diagram showing the clients connected to the Kingsbury Base Station

Phase 2 of the trial began in July of 2014. The goal of Phase 2 was to improve the overall performance of the TVWS system. One of the first improvements was adding a new base station at a different location on campus. This new station was installed on an antenna tower that resides on the roof of the engineering building, Kingsbury Hall. The tower reaches 70 feet above the roof line, which itself is 35 feet above the ground, producing a total height of roughly 105 feet or 32 meters. On the top of the tower is a Yagi antenna used for other research. To avoid interfering with the rotation of this antenna, the TVWS base station antenna was placed roughly 10-12 feet or 4 meters from the top of the tower, giving a transmitter height of 28 meters as seen in Figure 4 (note that the brick wall seen in the image only appears to block the antenna due to angle of camera). This is a small increase over the Stoke transmitter height. Additionally, Kingsbury Hall rests on a higher elevation than Stoke to give the transmitter even more height when taking the elevation into account. Computing the height above average terrain (HAAT) with the Radio Mobile software (see Section 4), it is found that the Stoke transmitter has a HAAT of 6.58 meters while the Kingsbury transmitter has a HAAT of 14.22 meters. This HAAT improvement was anticipated to help the signal propagate to the further client locations that are at higher elevations. These improvements allow this new location to serve most of the trial locations. The network diagram showing the client connections is seen in Figure 3.

Figure 4: View of the Kingsbury Antenna Tower from the North

In addition to the increase in height introduced at the Kingsbury transmitter, some equipment upgrades were made. The same omni-directional antenna was used, but a reflector was added to direct the signal toward the locations needing more signal power. This effectively doubled the gain in this direction, while reducing the signal that was propagating in directions that do not have clients. In a situation where omni-directional coverage is needed, this is not ideal, but when the area is served by multiple base stations and having the clients exist predominantly in one direction from the base, as in this case, using sectorized antennas can help direct the signal, increasing power and thereby available throughput. Feeding this sectorized antenna was a new base station design that helped reduce line losses to the antenna. The base station on Stoke is an indoor, rack-mounted system that uses a 100-foot coaxial cable to the antenna. This cable, even with its low loss characteristics, introduces about 2dB of loss before the signal can be transmitted. To reduce this loss, the base station now has an outdoor unit (ODU) that mounts on the tower with the antenna. This is powered by the base station controller via a Power over Ethernet (POE) line that delivers power and data to the ODU. This greatly reduces the amount of line loss by reducing the length to about 2 feet. These two equipment upgrades contributed to improvements in the radiated power transmitted to the client locations. To help improve the initial deployment of the base station on Stoke, a sector antenna was used in place of the original omni-directional antenna.

This sector antenna, seen in Figure 5—and much like the reflector on the Kingsbury transmitter – directs the signal toward a specific location, in this case the Durham Public Library. By focusing the signal, the gain in this direction is now around 10 dBi, roughly twice that of the omni-directional antenna. Making this change and with the additional throughput gained by offloading the other clients to the Kingsbury base station increased performance of the Durham Library client.

Figure 5: The new Stoke sector antenna

With the aforementioned changes to the system, the Phase 2 deployment saw varying levels of improvement at all of the client locations. Connection was made to all of the clients in question, including those with little to no signal found in Phase 1. This enabled the trial to move forward with semi-permanent clients at the libraries described here.

3 Measurement Locations and Results

Two measurement techniques were used to quantitatively characterize the Carlson Wireless Rural Connect system used in this TVWS rural broadband deployment:

1. The primary measurement technique utilized the client equipment's (CPE) available software and hardware performance indicators, because in a typical installation these indicators may be the only tools available. The indicators consist of onboard receive signal-strength indicators (RSSI) and software signal-to- noise ratio (SNR) measurements. The RSSI consist of 4 LEDs that provide a basic approximation of the SNR and work well for indicating the potential performance of the client in that location and antenna orientation. They work in the same way as the familiar bars on a cellular phone; more visible lights mean higher signal strength and better performance. They prove helpful not only for finding if there is a signal at the location, but also work well for large-scale antenna direction indications. Rotating the antenna one way or another can increase or decrease the RSSI level, which indicates increased/decreased performance. A description of expected performance based on RSSI LED level is described in Appendix A.
2. A Rohde and Schwarz FS300 spectrum analyzer was used to examine the power spectrum envelope of the signal received at the various locations. This setup is described in Appendix A and the additional losses introduced by the test set-up are factored into the power calculations.

At no time during these measurements were the base stations operating on the same frequency or was the CPE connected to both base stations. This was accomplished through the management platform that has the ability to power cycle and mute transmissions, allowing for isolation of the appropriate device.

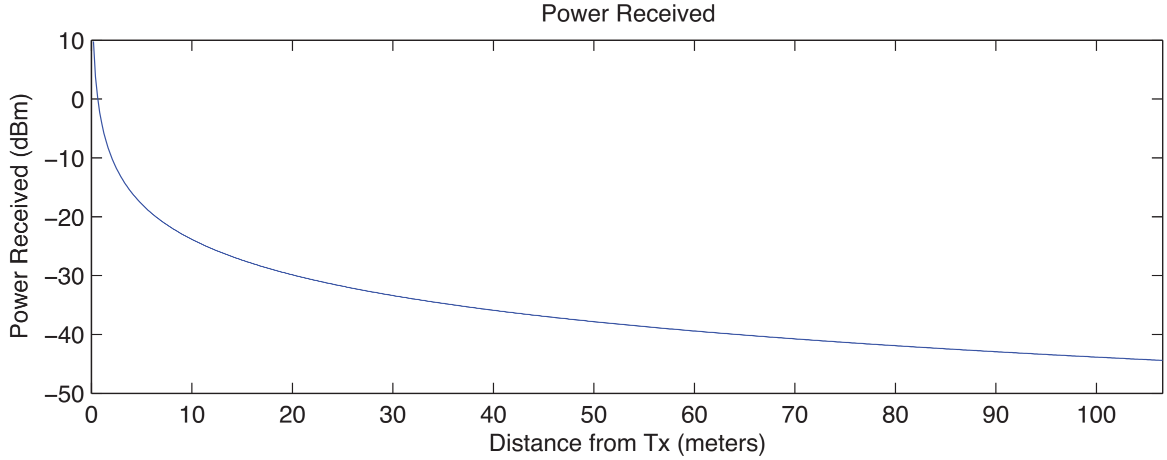
I. On-Campus Locations

From the beginning, the three campus locations in the deployment have shown consistent connection and have been providing insight into the system performance. Measurements were made at the locations, with closer, direct line-of-sight measurement that provides baseline comparisons to the more remote sites. The measurement setup can be found in Appendix A. Additionally, antennas used for measurement and equipment performance specifications can be found in Appendix B and Appendix A respectively.

DATE	JULY 29, 2014
Antenna	High gain
Base information	Kingsbury reflector
Measurement location	Morse Hall parking lot
Antenna hight + direction	2.2 meters, facing Kingsbury
Channel	23
SNR (down-up)	32.5 dB – 33.2 dB
Modulation (down-up)	16 QAM – 16 QAM 3/4
LEDs	4 solid
Throughput (down-up)	7.73 Mbps – 4.58 Mbps
Notes	Could not mount CPE antenna facing Kingsbury base

Table 2: Kingsbury line of sight tabulated throughput results

To provide a better understanding of the new system performance to begin Phase 2, a line-of-sight measurement was made for the Kingsbury base station in the parking pad of Morse Hall, the research building directly west of Kingsbury. The terrain and line-of-sight path can be seen in Figure 6. Note that the path loss plot is an approximation, ignoring possible antenna gains and line losses and as a result, it can vary from what is measured. The measurements were made using the High Gain Log Periodic antenna at a height of 2.2 meters facing the Kingsbury transmitter. The antenna was not aimed directly at the transmitter, due to difficulties changing the elevation angle with the available mounting equipment, but the same setup was used throughout the measurements.



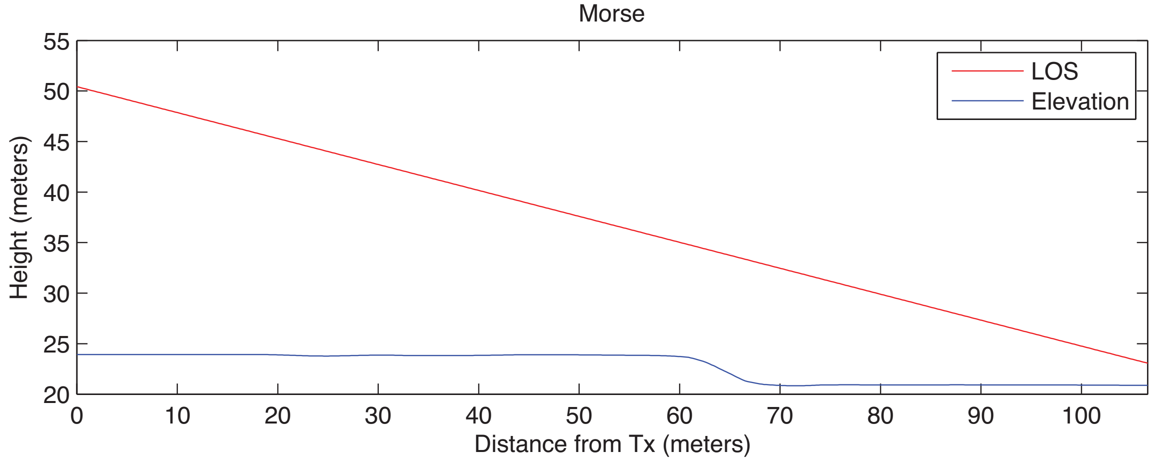


Figure 6: Terrain and line-of-sight path from transmitter to Morse Hall along with approximated Free Space Path Loss

Figure 7: View from test device in the Morse parking pad

Connecting the CPE to the High Gain Log Periodic antenna produced high signal to noise ratio (SNR) values which would be expected given the short distance (roughly 100 meters) and high gain of the antenna (roughly 14dB). This resulted in a measured throughput using the websites www.speakeasy.net/speedtest and www.speedtest.net, of 7.73 Mbps download and 4.58 Mbps upload. These results were measured while the IOL and the Dimond Library clients were active, but not passing user data. It is important to note that available Internet test sites do not always produce consistent or accurate results, but the measurements serve as a good comparison purpose for measuring relative speeds. Using the spectrum analyzer, the received power was measured as seen in Figure 8, and calculated to be -36.7 dBm which is well above the -93 dBm threshold required by the CPE hardware for little to no errors. This measurement was made in peak hold mode to capture the signal in its entirety. The radios use time division duplexing, meaning the base station and clients transmit and receive on the same frequencies, switching between transmit and receive at alternate times.

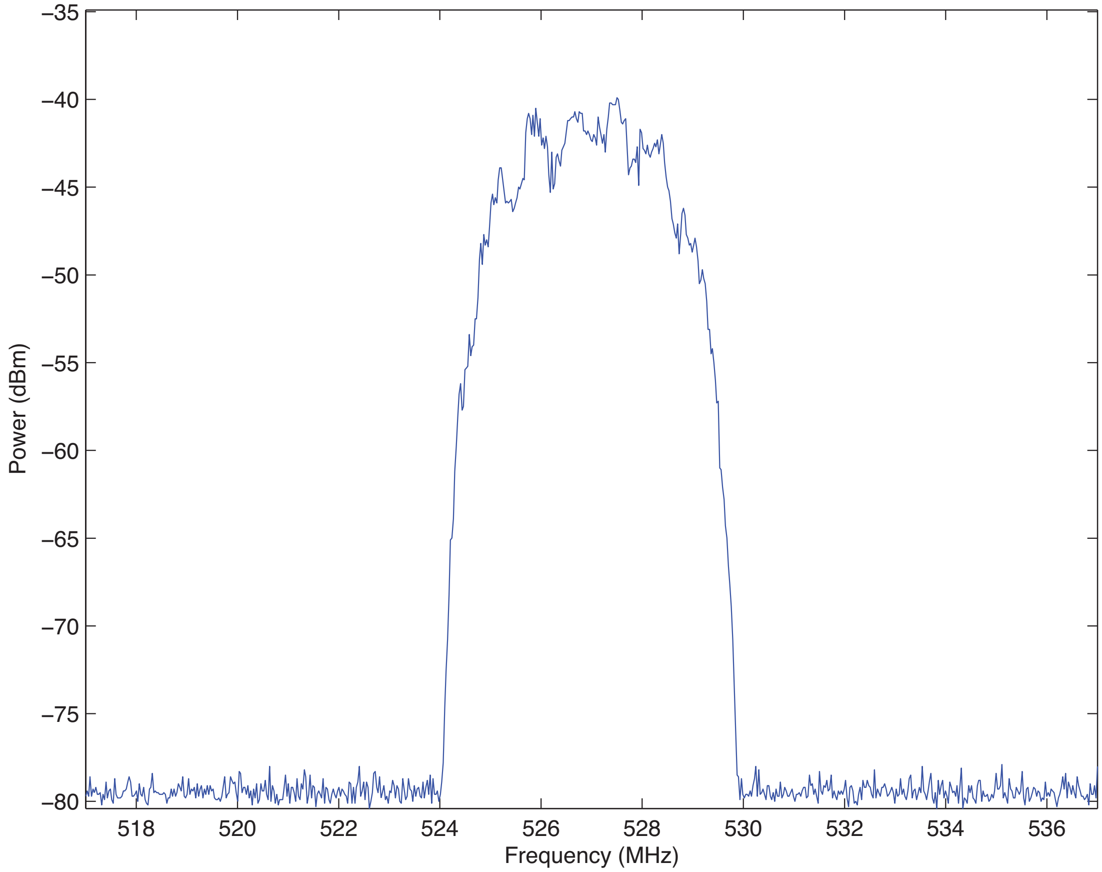


Figure 8: Spectrum measurement in Morse parking lot

A. Dimond Library and Thompson Hall parking lot measurements

DEVICE OR METRIC	JUNE 24, 2014	JUNE 30, 2014
Antenna	Log periodic	Log periodic
Base information	Kinsbury Reflector	Stoke sector facing Durham
Measurement location	Thompson Hall parking lot	BCoE office in Dimond Library
Antenna height + direction	2.2 meters facing Kingsbury	1.7 meters facing Stoke
Channel	22	22
SNR (down-up)	30.4 dB – 30.8 dB	Not recorded
Modulation (down-up)	16 QAM – 16 QAM	Not recorded
LEDs	4 solid	1 solid
Maximum throughput (down-up)	9.4 Mbps – 5.1 Mbps	0.85 Mbps – 0.38 Mbps
Notes	OMC used on Stoke Base Station does not actively display SNR and Modulation information, resulting in it not being recorded	

Table 3: Dimond Library tabulated throughput results, Part 1

DEVICE OR METRIC	JUNE 30, 2014	JUNE 30, 2014	JUNE 30, 2014
Antenna	Log periodic	Log periodic	Log periodic
Base information	Kinsbury Reflector	Kinsbury Reflector	Kinsbury Reflector
Measurement location	BCoE office in Dimond Library	BCoE office in Dimond Library	BCoE office in Dimond Library
Antenna height + direction	1.7 meters facing Stoke	1.7 meters facing out the door, towards East	1.7 meters facing out the door, towards East
Channel	23	23	23
SNR (down-up)	13.9 dB – 17.8 dB	18.0 dB – 23.8 dB	18.0 dB – 23.8 dB
Modulation (down-up)	16 QAM – 16 QAM	Not recorded	
LEDs	2 solid	3 flickering	3 solid
Maximum throughput (down-up)	2.79 Mbps – 1.31 Mbps	4.55 Mbps – 2.52 Mbps	6.67 Mbps – 2.38 Mbps
Notes		Door open	Door closed

Table 4: Dimond Library tabulated throughput results, Part 2

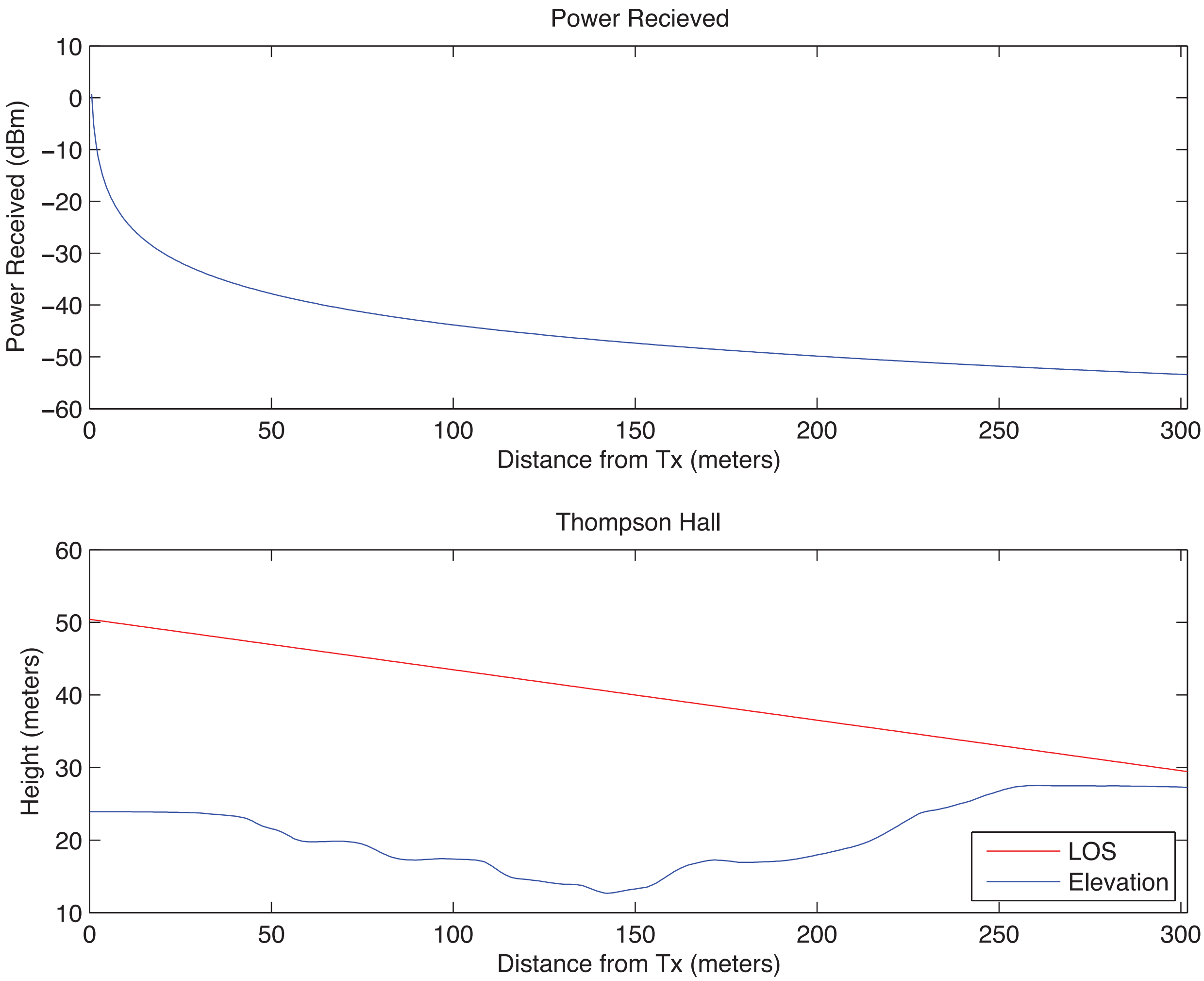


Figure 9: Terrain and line-of-sight path from transmitter to Thompson Hall along with approximated Free Space Path Loss

In addition to being directly next to the Thompson Hall client location, the Thompson Hall parking lot is located adjacent to the Dimond Library where another one of the client stations is currently active. Measurements in this lot yield additional short distance signal comparison baselines to help give a reference point to evaluate the performance at the off-campus libraries. There is not any major terrain variation, as can be seen in Figure 9. The Log Periodic antenna was mounted roughly 2.2 meters off the ground and pointed toward the base station (shown facing the other direction in Figure 10). When facing the Kingsbury base station, the throughput measurements through the CPE were as follows:

- **Test 1→Download:** 9.21 Mbps, **Upload:** 4.67 Mbps
- **Test 2→Download:** 9.46 Mbps, **Upload:** 5.10 Mbps

Considering that the reflector on Kingsbury is directing most of the signal away from this location, some lower throughput values are expected. The close proximity and near line-of-sight signal, however, produces a scenario that shows performance near the maximum of the system, which is rated for 10 Mbps download and 8 Mbps upload speeds.

Figure 10: Thompson Hall parking lot setup

Additionally, various throughput tests were performed with the active client in Dimond Library, with the best results displayed in Tables 3 and 4. These results will continue to be monitored and updated as the trial continues.

B. InterOperability Laboratory (IOL), Durham, NH

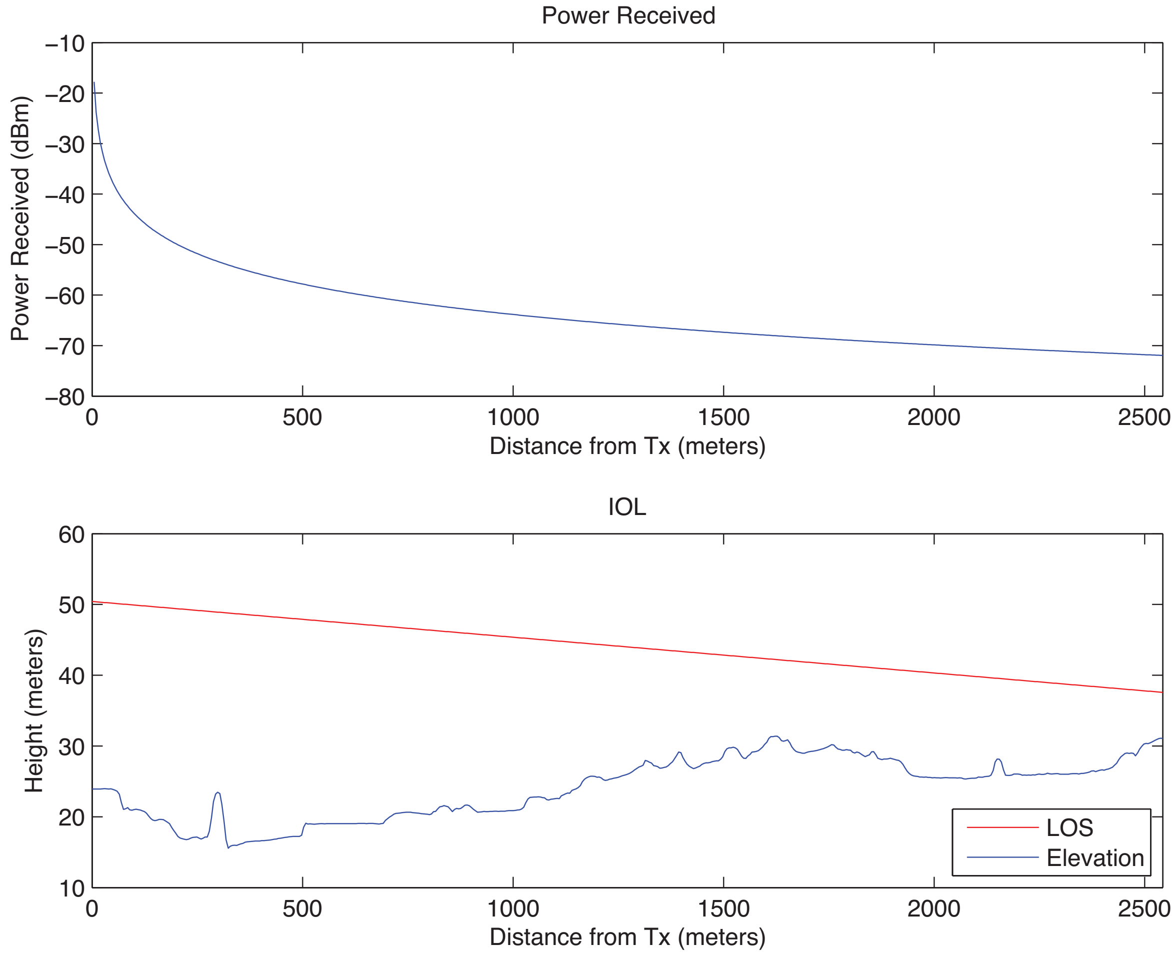


Figure 11: Terrain and line-of-sight path from transmitter to the IOL along with approximated Free Space Path Loss

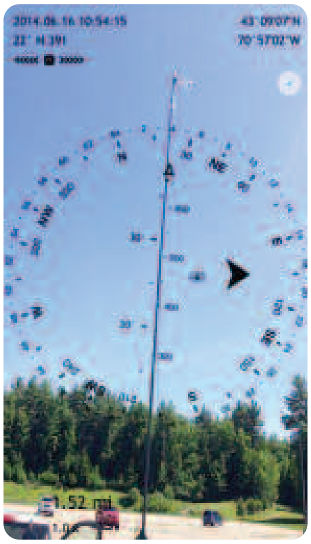


Figure 12: IOL parking lot setup

An additional CPE has been placed at the InterOperability Laboratory for testing. Throughput performance at this location has been recorded in the past; these measurements show the received signal envelope from the original Stoke Omni-directional antenna, with the setup shown in Figure 12. In order to provide full analysis, measurements were made with the CPE on and downloading a large file to inject traffic into the system (Figures 14- 16), and also with the CPE off (Figure 13) to compare channel power in the two cases. Variations in the envelope, such as seen between the ”smoother” envelope in Figure 16 and a more fragmented envelope, as in Figure 13, are due to the differences in relative path loss, and signal fading at the location. Over distances, even short ones with minimal terrain variations as between Stoke and the IOL seen in Figure 11, the signal will degrade due to foliage and reflections off the ground resulting in these jagged envelopes. The close proximity to the transmission (both from the active CPE in the IOL and the base station on Stoke) provides a higher power envelope due to the lower loss, compared to the off-campus locations. Signal power relative to the noise level and the receiver sensitivity will indicate a good link as is the case in all of the IOL measurements. The calculated total power for Figure 13 is -67.6 dBm, Figure 14 is -64.8 dBm, Figure 15 is -62.6 dBm, and Figure 16 is -51.3 dBm. The variation between these measurements shows the importance of proper antenna orientation to obtain the best results. The IOL serves as a test location for the system so performance changes with the base station changes have not been monitored due to heavy consideration placed on the other active sites. These measurements provide a marker for future work.

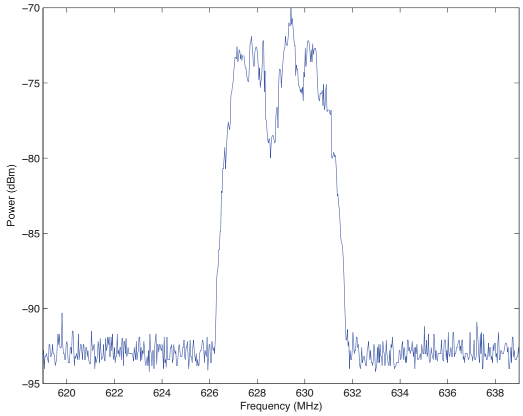


Figure 13: Power envelope of the signal received after a system reboot, effectively turning off the CPE and traffic.

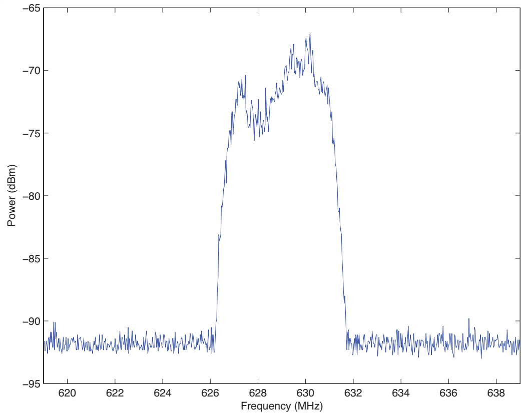


Figure 14: Power envelope of the signal received some time after a system reboot, giving the CPE time to turn back on.

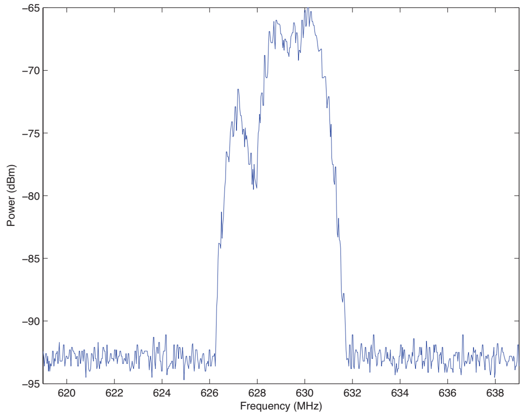


Figure 15: Channel power envelope facing the transmitter with antenna height of 3.25 meters.

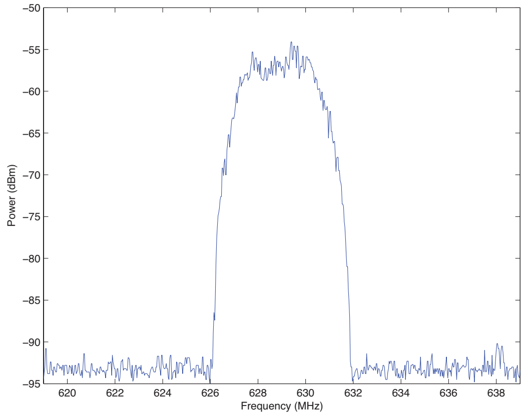


Figure 16: Channel power envelope facing the IOL CPE with antenna height of 3.2 meters.

II. Off-Campus Locations

A. Barrington Public Library

DEVICE OR METRIC	JUNE 24, 2014	JUNE 24, 2014	JUNE 24, 2014	JULY 11, 2014
Antenna	High gain	High gain	High gain	High gain
Base information	Kinsbury Reflector	Stoke Omni	Stoke Omni	Kinsbury Reflector
Measurement location	Behind adjacent town hall	Behind adjacent town hall	Behind adjacent town hall	Library entrance
Antenna height + direction	3.3 meters, towards base station	3.3 meters, towards base station	3.3 meters, towards base station	6.6 meters, towards base station
Channel	22	22	40	23
SNR (down-up)	18.3 dB – 9.1 dB	n/a	n/a	19.6 dB – 11.5 dB
Modulation (down-up)	16 QAM 3/4 – QPSK 3/4	n/a	n/a	16 QAM 3/4 – QPSK 3/4
LEDs	2 solid	1 flashing	0	3 solid
Maximum throughput (down-up)	5.66 Mbps – 1.87 Mbps	n/a	n/a	3.29 Mbps – 0.86 Mbps
Notes		No sufficient signal	No signal found	Near height of mast

Table 5: Barrington Library tabulated throughput results

Stoke Omni-directional Antenna Measurements

Barrington Public Library is on the fringes of the expected operating range of the system. Even though there are no geographical obstacles between the Stoke antenna and the CPE location as seen in Figure 17, the distance between the two locations initially seemed to be too great for the signal to propagate. Using the spectrum analyzer, power measurements were made to view the spectrum occupancy as seen in Figure 18. No signal was detected in the channel however there were signals observed at lower frequencies, but at relatively low power. A full frequency span of the antenna captured in Figure 19 shows some high power signals in the higher frequencies, most likely due to the TV broadcast channel 33 which, according to tvfool.com, is broadcast from an antenna roughly 17 miles from the location. This is at a high enough frequency that it should not affect performance. The measurements taken were only recorded at a height of 7.65 meters, but the results were the same for other heights.

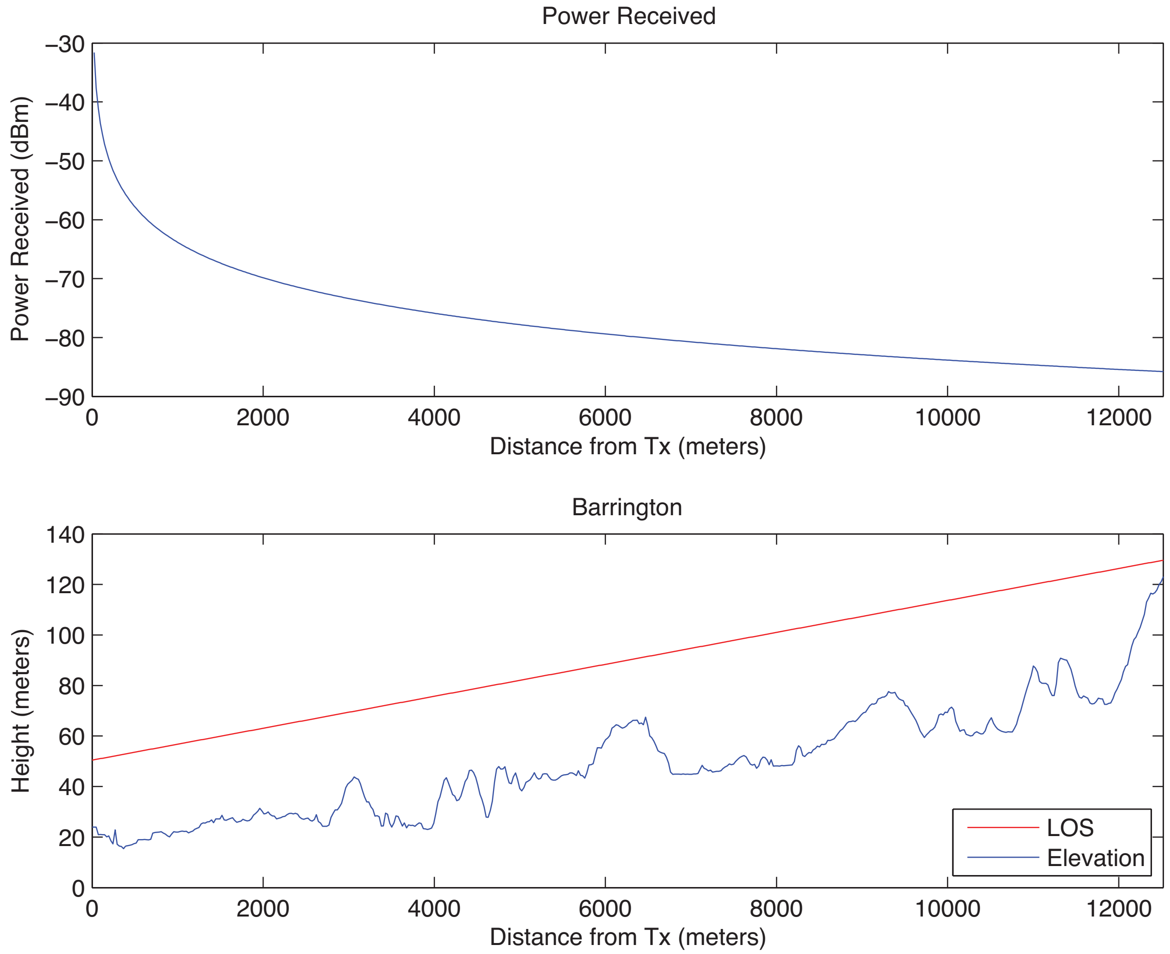


Figure 17: Terrain and line-of-sight path from transmitter to Barrington Library along with approximated free space path loss.

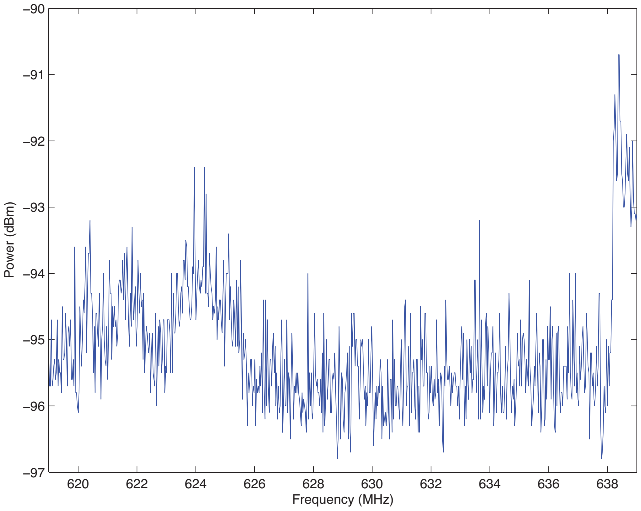


Figure 18: Power measurement made over 20 MHz span showing no visible signal.

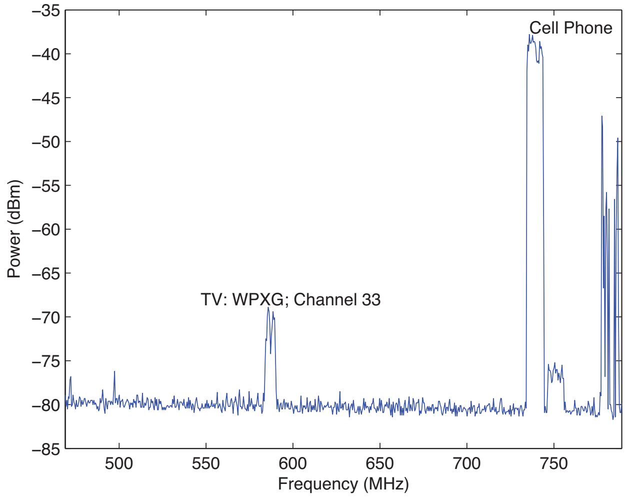


Figure 19: Full frequency span of the antenna showing out-of-channel signals.

Kingsbury Tower Omni-directional Antenna with Reflector Measurements

After the Kingsbury base station installation, measurements were again made, this time using the High Gain Log Periodic CPE antenna and the CPE itself. Here, the CPE connected to Kingsbury showed 2 solid LEDs of RSSI when connected on channel 22 (frequency = 521 MHz). This corresponds to a measured SNR of 18.3 dB and uplink SNR of 9.1 dB. When connected to the Stoke base station on this channel, only 1 LED was occasionally seen. A speed test at this location while connected to the Kingsbury base station on channel 22 produced the following throughput results:

- **Test 1→Download:** 4.65 Mbps, **Upload:** 1.68 Mbps
- **Test 2→Download:** 5.45 Mbps, **Upload:** 1.82 Mbps
- **Test 1→Download:** 5.66 Mbps, **Upload:** 1.87 Mbps

These values are lower compared to the Thompson Hall parking lot, but are within the range of what most consider broadband, and are encouraging based on the distance between the base station and client (roughly 12.6 km or 7.8 miles). Measurements were not made at the library but at the adjacent town hall parking lot but do show the general signal strength in the area and show that with the proper equipment, a strong connection can be made with the Barrington Library.

A spectrum analyzer and an inexpensive coax amplifier designed to boost TV signals were used to make power measurements. The amplifier introduces an additional 12-24 dB of gain with a variable control and roughly 12 dB of gain from a signal booster that helps one see the lower power signals at these distant locations. With the boost off, and the variable gain all the way up, the power was measured to be -66.7 dBm, which after removing the amplifier gain, is roughly -90.7 dBm with the envelope shown in Figure 20. This is a low power signal, but it is above the receive threshold of the CPE (-93 dBm) which according to the manufacturer, will result in better than 10−6 BER at lower modulation rates.

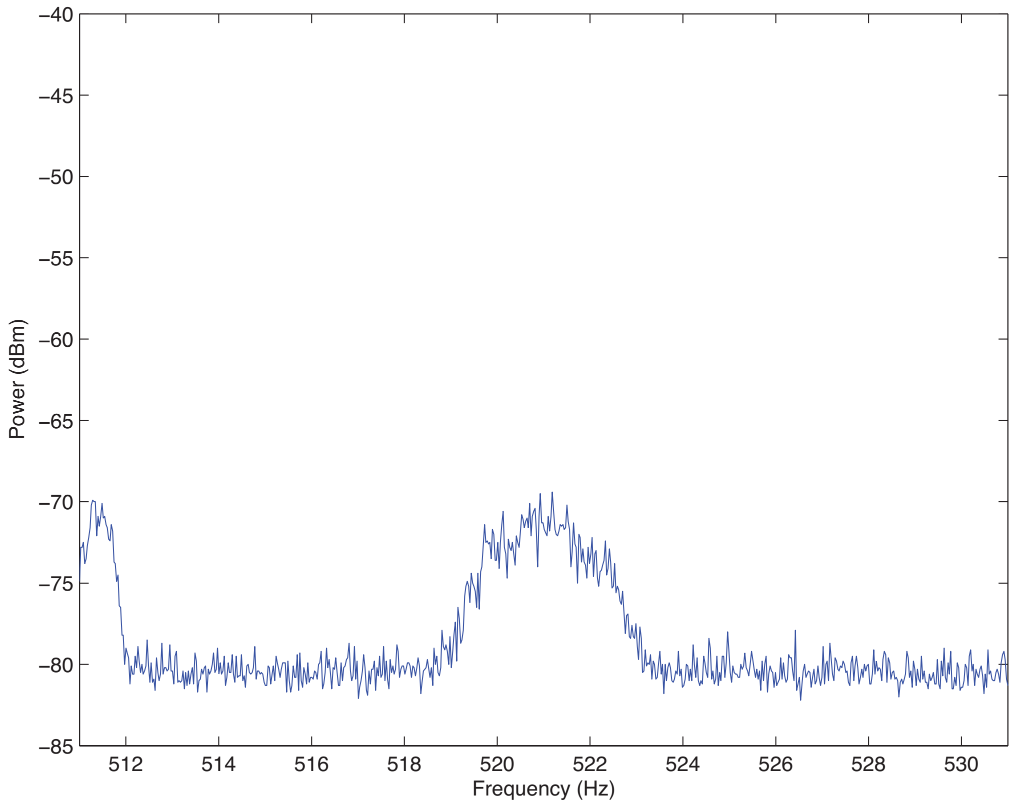


Figure 20: Power measurement from the Kingsbury transmitter

To verify actual performance at the library measurements were taken at a later date placing the antenna as close as possible to the projected mounting location (on a mast above the entrance) as shown in Figure 21. The mounting location is at a height of roughly 7.65 meters off the ground. When connected to the Kingsbury base station the base station measured a SNR of 19.6 dB downlink and 11.5 dB uplink. This resulted in speeds a little lower than measured in the adjacent parking lot but still in the broadband range. The results are as follows:

- **Test 1→Download:** 3.23 Mbps, **Upload:** 1.85 Mbps
- **Test 2→Download:** 3.29 Mbps, **Upload:** 1.86 Mbps
- **Test 1→Download:** 2.70 Mbps, **Upload:** 0.73 Mbps

Variations of these results could reflect a variety of influences. A link of this distance in this area has a high probability of passing through trees, which could affect the link if there is any significant wind changing the orientation relative to the propagation path. These trees can cause reflections that could further degrade the signal. Additionally, the second set of measurements was made on channel 23 (527 MHz). Though just a 6 MHz difference in frequency, there could be additional loss (and occasionally gain) posed by the foliage and geographical features in the link path. Foliage effects have been studied in greater depth and summarized in [6] among others and will be considered in future work. Values could also fluctuate with weather conditions and time of year. A summary of the measurements is seen in Table 5. Here we can see that the throughput measurements and SNR measurements do not always correlate, in that improvement in one did not always show improvement in the other. This could possibly be from the inconsistencies in the Internet tests, but is certainly worth noting for future study.

Figure 21: Measurements at the mounting location at the Barrington Library

B. Lee Public Library

DEVICE OR METRIC	JUNE 30, 2014	JUNE 30, 2014	JUNE 30, 2014	JUNE 30, 2014
Antenna	High gain	High gain	High gain	High gain
Base information	Stoke sector facing Lee	Stoke sector facing Lee +10-degrees clockwise	Stoke sector facing Lee +10-degrees counter-clockwise	Stoke sector facing Lee +20-degrees counter-clockwise
Measurement location	Library parking lot	Library parking lot	Library parking lot	Library parking lot
Antenna height + direction	3.3 meters, facing Stoke	3.3 meters, facing Stoke	3.3 meters, towards base station	6.6 meters, towards base station
Channel	22	22	22	22
SNR (down-up)	Not measured	Not measured	Not measured	Not measured
Modulation (down-up)	Not measured	Not measured	Not measured	Not measured
LEDs	1 solid	1 solid	1 solid	1 solid
Maximum throughput (down-up)	0.99 Mbps – 0.85 Mbps	0.98 Mbps – 0.64 Mbps	0.98 Mbps – 0.86 Mbps	0.7 Mbps – 0.6 Mbps
Notes	Only measured throughput for these tests			

Table 6: Lee Library tabulated throughput results

Stoke Omni-directional Antenna Measurements

Lee library has a significant hill blocking the line of sight signal as seen in Figure 22 in the form of Wednesday Hill. This seems to be a significant loss point as no signal was seen at this library location (Figure 23). The measurement was taken at antenna heights between 7.65 meters and 3.25 meters (in increments of 1.1 meters) with no signal visible.

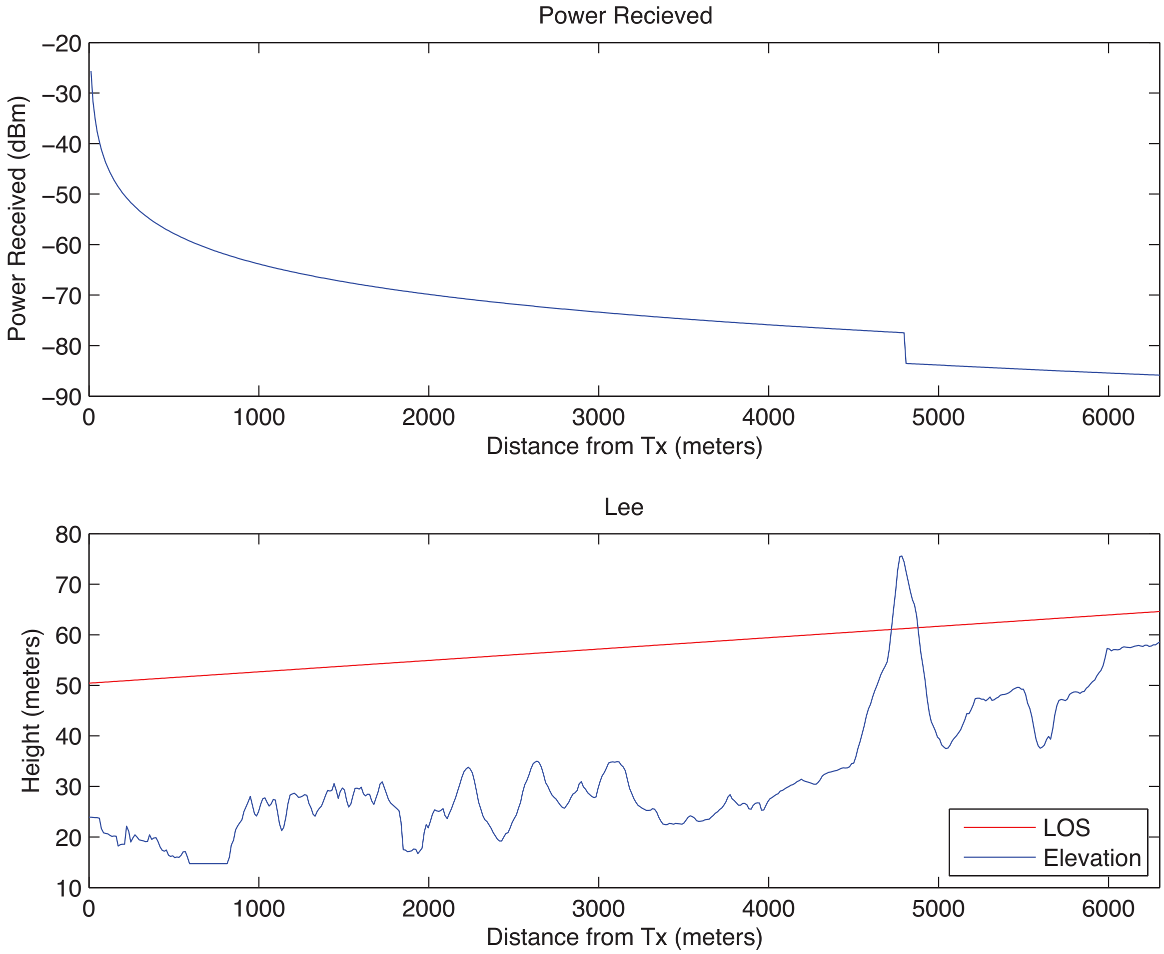


Figure 22: Terrain and line-of-sight path from transmitter to Lee Library along with approximated Free Space Path Loss with diffraction loss [1]

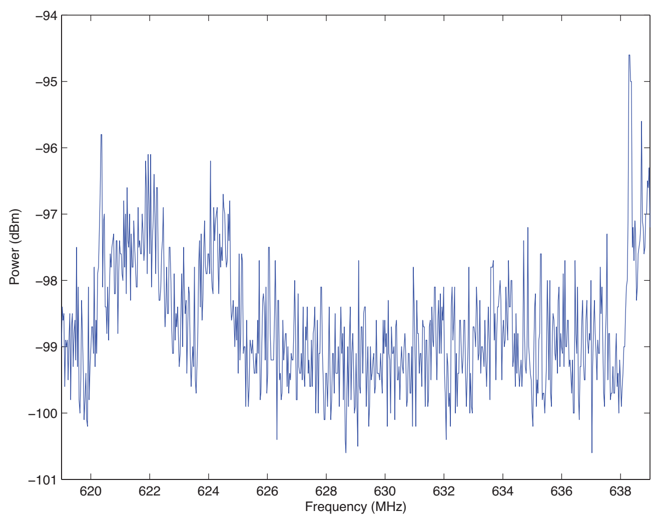


Figure 23: Signal measurement at the library location facing the transmitter

Kingsbury Tower Omni-directional Antenna with Reflector Measurements

The next measurements were made at the Lee Library to see how the Kingsbury system was able to improve the link. Directing as much energy towards Lee Library as possible is essential for an improved link due to the hill blocking the line of sight. Previously at this location, no signal was noted using the log periodic antenna, either through the CPE RSSI LEDs or with a spectrum analyzer. The new tests were performed using the Yagi antenna that gives an increase gain and when using an antenna height of roughly 5.45 meters, a value of 6 dB SNR was found. This is a vast improvement over not seeing signal before. Additionally worth noting, the measurements were taken behind and above an SUV as seen in Figure 24 which seemed to act as a ground plane, showing a small drop in SNR when the vehicle was moved. The measurements were done on channel 22. When the channel was changed, there was a significant drop in measured SNR:

- **Channel 23 →** -1 dB
- **Channel 24 →** ranged from -5 dB to 0.5 dB
- **Channel 25 →** ranged from -2 dB to 1.5 dB

None of the higher channels allowed connection of the client to the base station, inviting the conclusion that operation should be on channel 22 due to the higher noise level on the other channels relative to channel 22. Signals were not observed on a spectrum analyzer, most likely due to the noise floor of the analyzer being above the signal.

Measuring the downlink and uplink SNR separately registered 4.7 dB down and -3.3 dB up. This negative SNR in the uplink will provide problems passing data from the client to the base station and should be considered in gauging the viability of using TVWS to provide broadband connectivity for Lee Library with the current system configuration. More measurements at different locations in the parking lot should be made before confirming or denying Lee as a broadband capable client site.

Figure 24: Lee parking lot setup with SUV "ground plane"

Stoke Sector Antenna Measurements

The high-gain directional sector mounted on Stoke was aimed in the direction of Lee Library to test if the connection could be improved (this was not a permanent solution, as the antenna is normally aimed at Durham Library, in the opposite direction to Lee) and measurements were taken to detect any improvement over the Kingsbury link. With the high gain client antenna at a height of roughly 3.25 meters, 1 LED of signal was received as before. However, when running a throughput test, the following results were obtained:

- **Stoke antenna facing Lee:**

  Test 1→Download: 0.91 Mbps, **Upload:** 0.89 Mbps

  Test 2→Download: 0.96 Mbps, **Upload:** 0.88 Mbps

  Test 1→Download: 0.99 Mbps, **Upload:** 0.85 Mbps

- **Stoke Antenna rotated clockwise 5–10 degrees from facing Lee:**

  Download: 0.98 Mbps, **Upload:** 0.64 Mbps

- **Stoke Antenna rotated counter-clockwise 5–10 degrees from facing Lee:**

  Download: 0.98 Mbps, **Upload:** 0.85 Mbps

- **Stoke Antenna rotated counter-clockwise 15–20 degrees from facing Lee:**

  Download: 0.7 Mbps, **Upload:** 0.6 Mbps

It can be seen from these throughput values, that the sector antenna on Stoke provides improved throughput considering the geographical path between the base station and CPE. However, when attempting to raise the antenna to test additional heights, the signal was lost and would not reconnect until the height was lowered to the original 3.25 meters. This could be due to signal reflections off terrain and other structures causing the maximum signal to be received at this height. Antenna direction was also very critical, as slight rotation off center would result in a drop in upload throughput. This further shows that though signal is received at this location, the signal is weak, and the heavy reliance on the antenna height and location makes it difficult to use this site for deployment. For the measurements made to date, a summary is seen in Table 6.

C. Durham Public Library

DEVICE OR METRIC	MAY 19, 2014	MAY 30, 2014	JUNE 30, 2014
Antenna	Window antenna	Window antenna	Window antenna
Base information	Stoke omni	Stoke omni	Stoke sector facing Durham
Measurement location	Client setup in Library	Client setup in Library	Client setup in Library
Antenna height + direction	0.75 meters towards Stoke	0.75 meters towards Stoke	0.75 meters towards Stoke
Channel	40	40	22
SNR (down-up)	Not recorded	Not recorded	22 dB – 28 dB
Modulation (down-up)	Not recorded	Not recorded	Not recorded
LEDs	2 flickering	1 solid	3 flickering
Maximum throughput (down-up)	0.81 Mbps – 0.15 Mbps	1.04 Mbps – 0.90 Mbps	4.96 Mbps – 1.57 Mbps
Notes	Early demonstration; not a full test	Early demonstration; not a full test	Management software on Stoke doesn't clearly display SNR and Modulation

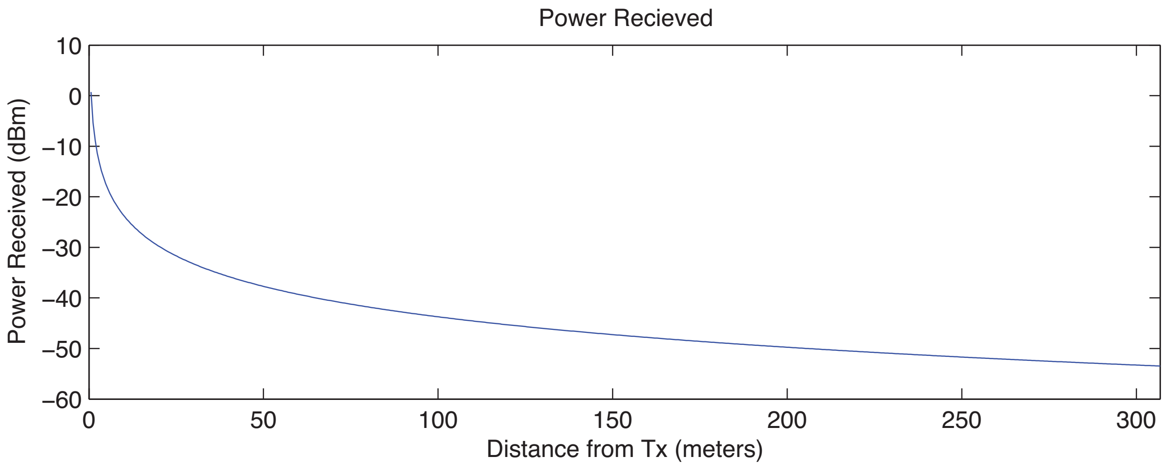
Table 7: Durham Library tabulated throughput results

Stoke Omni-directional Antenna Measurements

The Durham Library has an operational CPE used by library patrons. Currently, a window-mounted TV antenna with a gain of 2 dBi behind a tinted window is being used. While this may not provide the client with the best performance, it does allow for an unobtrusive and low profile installation. During Phase 1, performance was very limited with throughput measured as low as 0.81 Mbps download and 0.15 Mbps upload. This is very low considering the close proximity to the Stoke base station (roughly 0.31 km or 0.19 miles) and could be the result of using this type antenna mounted indoors when compared to the higher gain (9-13 dBi) client sector antennas mounted outdoors at other locations. There are no major terrain differences (Figure 25) however the tinted window has different propagation characteristics than a clear window, which could introduce reflections, resulting in signal attenuation.

Additionally, the close proximity to campus means close proximity to other buildings that could degrade the signal. Even though UHF radio waves have lower loss through walls than Wi-Fi frequencies, loss still occurs due to the change in electrical characteristics of the walls relative to free space and will result in reflections off the surface and absorption as the wave propagates into the material. Both will reduce the power of the signal received once it propagates through the material. The degree of loss is dependent on the material the signal is penetrating, whether it is brick, wood, or a glass window. Lower frequencies have better penetration capabilities through building materials, but reflections, and therefore loss, are not eliminated. An investigation into wall losses in the 600 MHz range can be seen in [7].

Spectrum measurements were made with the log periodic client antenna with the results shown below.



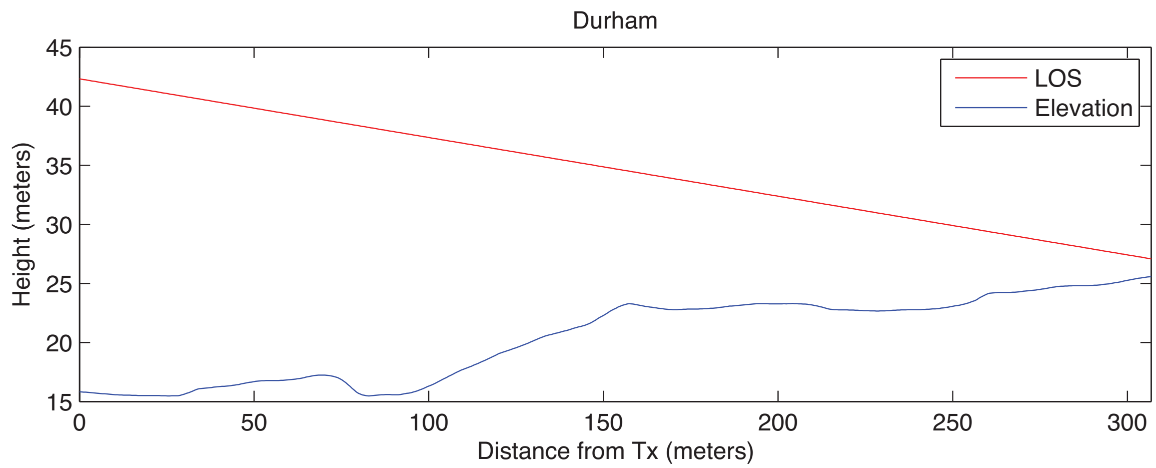


Figure 25: Terrain and line-of-sight path from transmitter to Durham Public Library along with approximated Free Space Path Loss

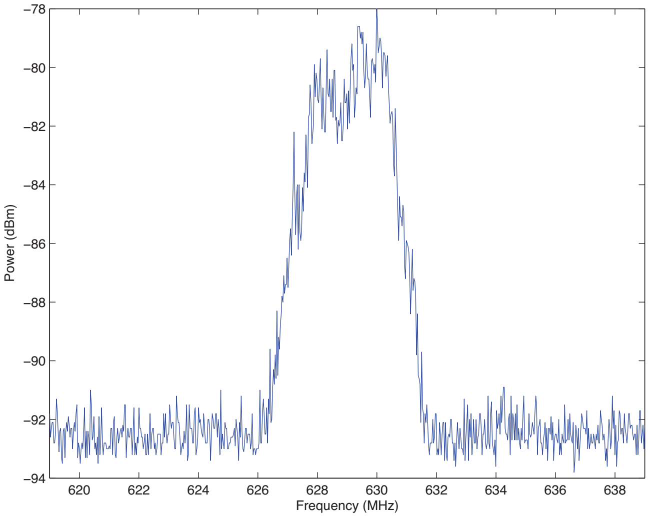


Figure 26: Power envelope facing the transmitter with the client “on”

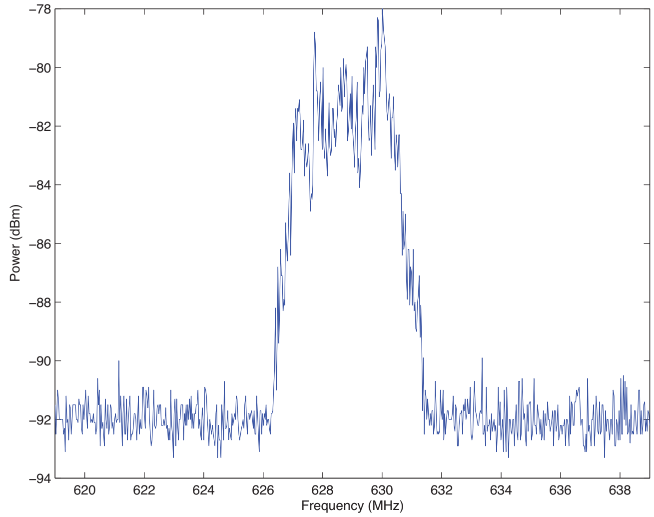


Figure 27: Power envelope facing the transmitter with the client “off”

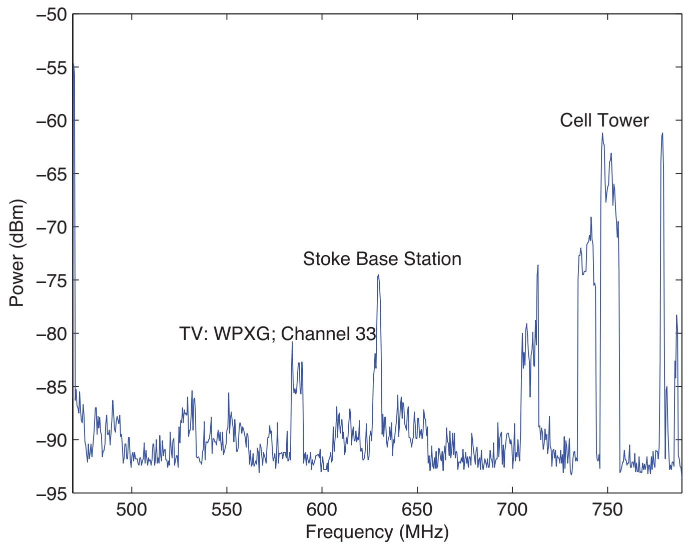


Figure 28: Full spectrum of measurement antenna with height of 3.25 meters

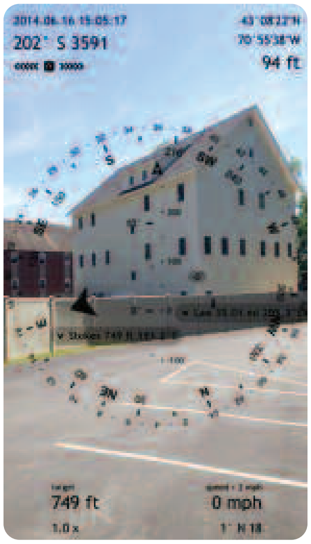


Figure 29: Building blocking the line of sight to the transmitter

These measurements were made with a building blocking the line of sight to the base station as seen in Figure 29. Measurements were made with the client both turned on and off at the library (Figures 26 and 27 respectively). Even with the building, the spectrum measurement results show a strong link in the area with a power measurement of -75.3 dBm for the case seen in Figure 27. Figure 28 shows the prominence of the signal from the base station relative to adjacent channels. A broadcast television station, transmitting from roughly 20 miles away according to tvfool.com, occupies channel 33. However, with the throughput results being less than desired, improvements to the system were deemed necessary. The Durham Library is not in the area of coverage provided by the Kingsbury base station as it is behind the Kingsbury reflector therefore the Stoke base station omni-antenna on Stoke roof was replaced by a sector antenna, focused on the library.

Stoke Sector Antenna Measurements

With the sector antenna now focused on Durham Library new measurements were taken. The antenna change greatly improved the throughput to around 4.4-4.9 Mbps download and 1-1.5 Mbps upload. There was a downlink SNR of roughly 23 dB and an uplink SNR of roughly 28 dB during these tests. Throughput measurements are summarized in Table 7. These results show a strong broadband connection at this library and demonstrate that a window antenna could be used in certain installations.

To help assess the signal at Durham Public Library another spectrum measurement was made, this time in another location of the parking lot to avoid the building that is blocking the line of sight. The received envelope is shown in Figure 31, where the power was measured to be -48.1 dBm. Measuring again in the middle of the parking lot gives the envelope shown in Figure 30, where the power was now measured to be -57.3 dBm. This demonstrates that buildings have an effect on the received signal, even if it may be more apparent at higher frequencies.

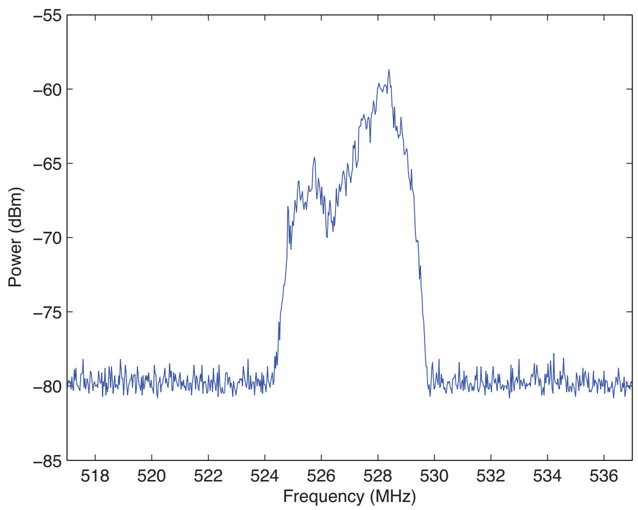


Figure 30: Power measured in the middle of the Durham Library parking lot to show the affect of blockage of building

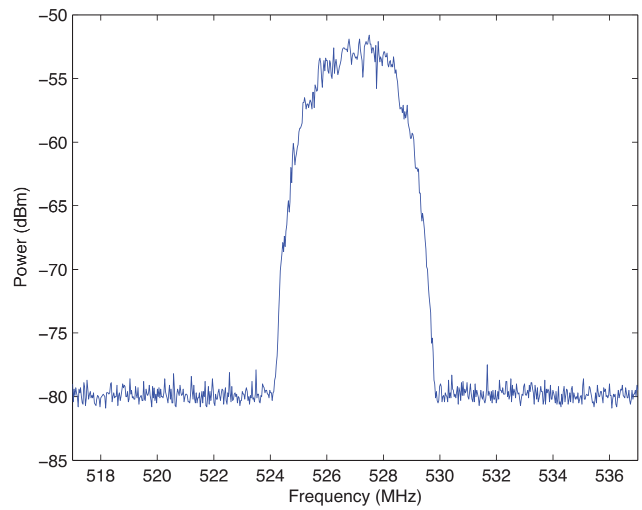


Figure 31: Power measured in the back of the Durham Library parking lot to avoid blockage of building

D. Madbury Libarary

DEVICE OR METRIC	JUNE 24, 2014	JUNE 24, 2014	JUNE 24, 2014	JULY 11, 2014
Antenna	High gain	High gain	High gain	High gain
Base information	Kingsbury reflector	Stoke omni	Stoke omni	Kingsbury reflector
Measurement location	Library parking lot near entrance	Library parking lot near entrance	Library parking lot near entrance	Library parking lot near corner of building
Antenna height + direction	3.3 meters, facing Kingsbury	3.3 meters, facing Stoke	3.3 meters, facing Stoke	6.6 meters, facing Kingsbury
Channel	22	22	40	23
SNR (down-up)	2.56 dB – 16.6 dB	Not measured	Not measured	2.66 dB – 15.0 dB
Modulation (down-up)	16 QAM – 16 QAM 1/2	Not recorded	Not recorded	16 QAM – QPSK 3/4
LEDs	4 solid	1 flickering	0	4 flashing
Maximum throughput (down-up)	9.27 Mbps – 2.36 Mbps	Not measured	Not measured	5.3 Mbps – 2.05 Mbps
Notes		No connection	No connection	

Table 8: Madbury Library tabulated throughput results, Part 1

DEVICE OR METRIC	JULY 11, 2014	JULY 11, 2014	JULY 11, 2014
Antenna	High gain	High gain	High gain
Base information	Stoke sector facing Durham	Kingsbury reflector	Stoke sector facing Durham
Measurement location	Library parking lot near corner of building	Library parking lot near corner of building	Library parking lot near corner of building
Antenna height + direction	6.6 meters facing Kingsbury	7.7 meters facing Kingsbury	7.7 meters facing Kingsbury
Channel	22	23	22
SNR (down-up)	8.6 dB – 8.7 dB	26.3 dB – 14.9 dB	9.0 dB – 9.1 dB
Modulation (down-up)	Not measured	16 QAM – QPSK 3/4	Not measured
LEDs	2 solid	Elevation too great to discern	Elevation too great to discern
Maximum throughput (down-up)	1.04 Mbps – 0.9 Mbps	7.93 Mbps – 3.07 Mbps	1.04 Mbps – 0.92 Mbps
Notes	Management software on Stoke doesn't clearly display SNR and Modulation		Management software on Stoke doesn't clearly display SNR and Modulation

Table 9: Madbury Library tabulated throughput results, Part 2

Stoke Omni-directional Antenna Measurements

Figure 32: Initial Madbury Library antenna test setup

At the Madbury Public Library, two locations were used for the measurements. In the Phase 1 deployment a signal was originally received at these locations however after the base station antenna on the roof of Stoke was moved the signal was lost. There do not seem to be any significant terrain variations or obstructions between the base station and this client location (Figure 33), so losing the signal could have been due to man-made obstructions. In the measurements seen in Figures 34 and 35, the Stoke base station was operating on channel 40 and the IOL CPE was downloading a file to produce traffic. Location one measurements were done with the 7.65 meter setup as seen in Figure 32. Due to the location in relation to level ground and power lines, the measurement at location two was only made with an antenna height of 6.55 meters. The measurement was checked at heights between 7.65 meters (or 6.55 meters) and 3.25 meters (in increments of 1.1 meters) with no signal apparent.

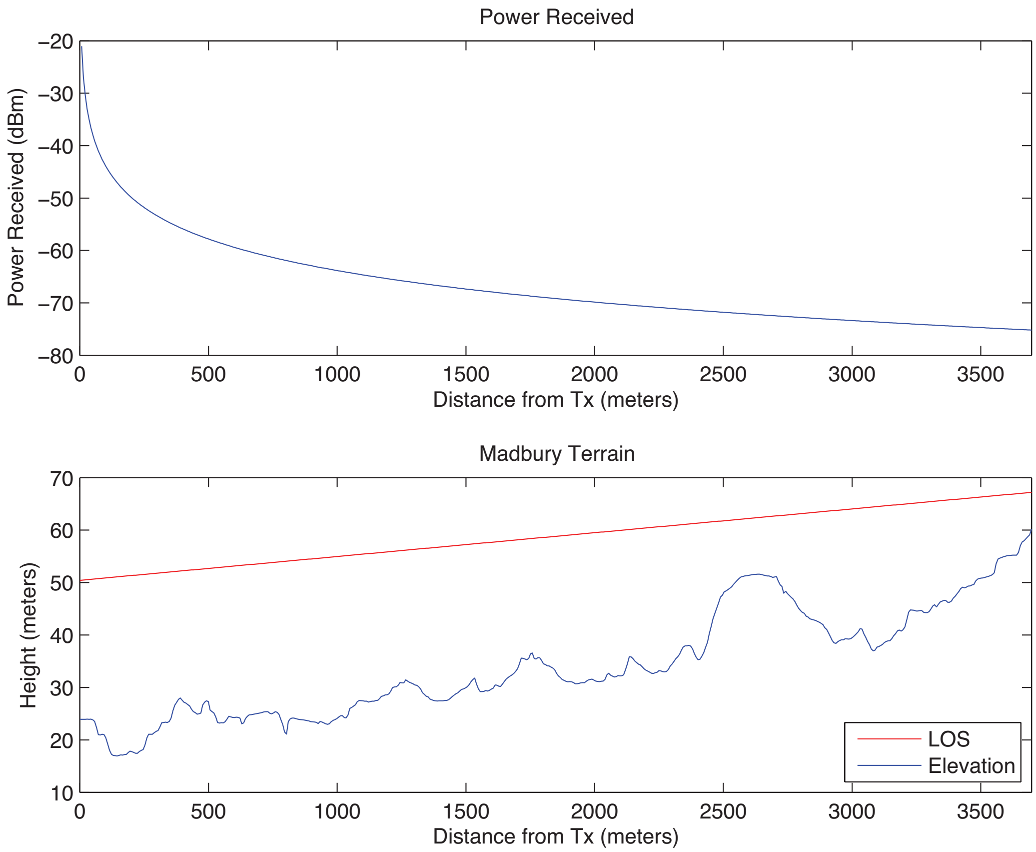


Figure 33: Terrain and line of sight path from transmitter to Madbury Library along with approximated Free Space Path Loss

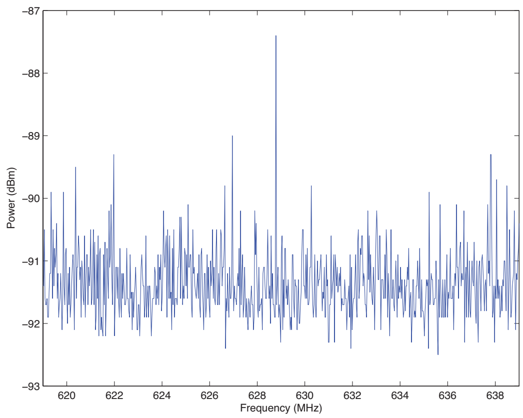


Figure 34: Power measurement at location 1

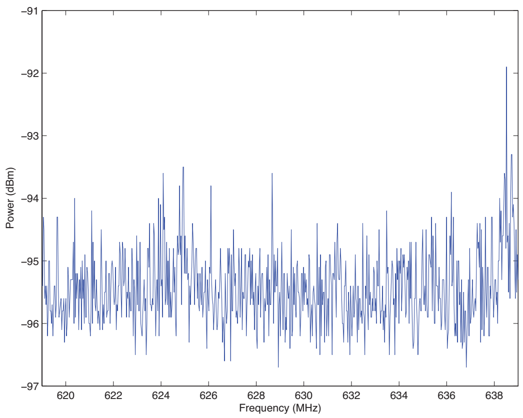


Figure 35: Power measurement at location 2

Kingsbury Tower Omni-directional Antenna with Reflector Measurements

After the Kingsbury installation, measurements were made again at Madbury, this time using the High Gain antenna. Connectivity was established with the Kingsbury base station on channel 22 with four LEDs illuminated. This corresponds to a downlink SNR of 25.6 dB and an uplink SNR of 16.6 dB. Changing the client to the Stoke base station on channel 22, one LED was seen occasionally, and when on channel 40, no LEDs illuminated. The speed test results for Kingsbury base station on channel 22 were as follows:

- **Test 1→Download:** 7.56 Mbps, **Upload:** 2.41 Mbps
- **Test 2→Download:** 9.27 Mbps, **Upload:** 2.36 Mbps
- **Test 3→Download:** 8.60 Mbps, **Upload:** 2.59 Mbps

These results show real promise for connectivity at this library moving forward. To analyze the signal further, the spectrum analyzer was used at the same height of 3.3 meters. The resultant power envelope can be seen in Figure 36, and was measured as -59.3 dBm with the amplifier having the signal boost on (additional gain of 24 dB). This results in an actual received power of -83.3 dBm, which is well above the threshold, confirming the location to be an acceptable link

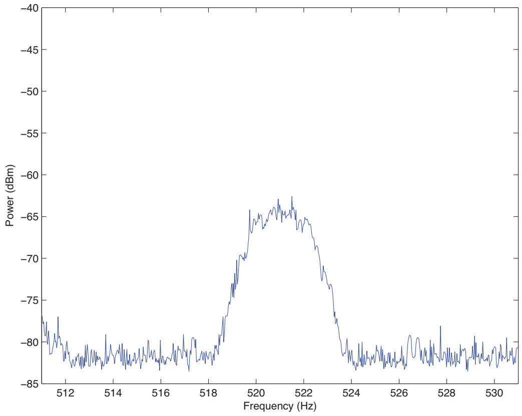


Figure 36: Madbury power measurements from Kingsbury transmitter

To verify the link at the probable mounting location of the client antenna, additional measurements were made at a later date, closer to the projected placement of the mount. The channel of operation was set to 23 from the Kingsbury base station and the SNR was again measured by the base station to be roughly 25.8 dB downlink and 15.2 dB uplink. Using an antenna height of 7.65 meters resulted in the following throughput values:

- **Test 1→Download:** 1.47 Mbps, **Upload:** 1.94 Mbps
- **Test 2→Download:** 4.82 Mbps, **Upload:** 1.02 Mbps
- **Test 3→Download:** 2.40 Mbps, **Upload:** 0.92 Mbps
- **Test 4→Download:** 5.30 Mbps, **Upload:** 2.05 Mbps
- **Test 5→Download:** 5.30 Mbps, **Upload:** 2.05 Mbps

These results showed more variation then before so more speed tests were run to find any correlation. The link quality is reduced somewhat from the previous measurements, possibly again due to location, weather variations and the different operating channel, but still sufficient for broadband Internet at this location.

Since the actual mounting location at this library had not been verified, measurements were made again, this time at an antenna height of roughly 8.75 meters to test if height could effect the throughput measurements. With the results shown below, it could be surmised that the increased height did have a positive effect on the throughput, however SNR remained roughly the same (measured by the base station to be 26.3 dB downlink and 14.8 uplink) indicating a possible variation between runs of the Internet based speed tests.

- **Test 1→Download:** 7.93 Mbps, **Upload:** 3.07 Mbps
- **Test 2→Download:** 7.51 Mbps, **Upload:** 2.92 Mbps
- **Test 3→Download:** 6.65 Mbps, **Upload:** 2.98 Mbps
- **Test 4→Download:** 6.42 Mbps, **Upload:** 2.35 Mbps
- **Test 5→Download:** 6.32 Mbps, **Upload:** 2.53 Mbps

At either height, the link was fairly strong, indicating that this library will be a good client location for the trial. Since the link was very strong, a window antenna, like the one used in the Durham Library, was also tested. The results were fairly underwhelming, with a maximum throughput of 1.41 Mbps download and 0.58 Mbps upload. Since this is significantly lower then what was measured with the High Gain Log Periodic antenna, and on the lower end of what is considered broadband, the High Gain antenna should be used for installation at this location.

Sector Antenna Measurements

With the sector antenna on Stoke facing Durham Library, Madbury Library lies within its coverage area and therefore was also tested for link performance with it. To characterize this link, throughput tests were taken on channel 22 at antenna heights of 7.65 meters and 8.75 meters, as was the case with the Kingsbury link. The results of the speed tests were:

At 7.65 meter antenna height:

- **Test 1→Download:** 1.04 Mbps, **Upload:** 1.90 Mbps
- **Test 2→Download:** 1.03 Mbps, **Upload:** 1.91 Mbps
- **Test 3→Download:** 0.98 Mbps, **Upload:** 0.67 Mbps
- **Test 4→Download:** 1.00 Mbps, **Upload:** 0.79 Mbps

At 8.75 meter antenna height:

- **Test 1→Download:** 0.97 Mbps, **Upload:** 0.70 Mbps
- **Test 2→Download:** 0.90 Mbps, **Upload:** 0.71 Mbps
- **Test 3→Download:** 0.99 Mbps, **Upload:** 0.89 Mbps
- **Test 4→Download:** 1.04 Mbps, **Upload:** 0.92 Mbps

Though this configuration does provide close to broadband speeds, connection to Kingsbury base station clearly provides the fastest link as can be seen in the measurement summary in Tables 8 and 9. Re-aiming both base station antennas to better distribute the client locations may improve overall throughput, and will be considered in future work.

4 Propagation Analysis

To help predict the performance of the system, certain analytical tools can be used. The combination of computer software and previously designed propagation models can be added to the installer's toolbox to help decide if a location is reachable with TVWS based technology. An analysis of some of these tools, as it pertains to the Durham area installation, follows.

I. Radio Mobile software

Using freely available tools such as Radio Mobile created by Roger Coudé can further help with prediction of the performance of additional future client locations. Using available digital terrain data, foliage coverage databases, and electrical characteristics of the ground, the software utilizes the Longley-Rice propagation model to predict path loss. The Longley-Rice model uses statistical models to determine a range of values one could expect to see at a given location. Changing the variability of different parameters will change how strict the user needs the results to be based on the required performance. A higher variability will give the user more confidence that the power will be above a certain level. For this analysis, 75% was chosen, meaning in 75% of the measurements taken, the measured value will be greater than or equal to the predicted value [8].

Additionally, the tool allows the user to raise/lower the antenna height to help predict the ideal height at a given location. This can be beneficial for a user to determine if an installation is possible at a given location when the antenna height can be variable. As discussed for the Lee client location, antenna height can play a large role in receiving a borderline signal. To help with the planning, the antenna files containing the radiation patterns of the antennas used can be imported to the software to help account for gain variations at different elevation and azimuth angles.

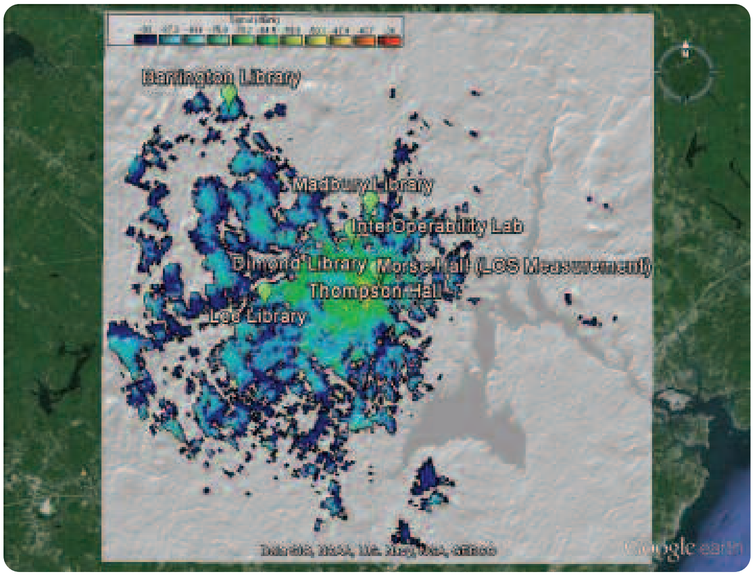


Figure 37: Coverage map created with the Radio Mobile software tool, overlaid on Google Earth Map to see client locations

Certain visual tools are used in the software such as coverage maps and path plots. The coverage maps, like the one seen in Figure 37 can help with planning a larger scale deployment. When zooming in on the map at the Lee Library in Figure 39, a location with notably poor connection, it is seen that the signal power is in the dark blue range. The legend shown in Figure 38 indicates the signal is approximately -93 dBm, which is the lowest receive threshold for 10−6 BER (see Appendix A). This correlates to the measurements taken at Lee showing an existing but weak link. Using the software to simulate raising and lowering the antenna height shows the signal power going up and down independent of whether the antenna was raised or lowered. This correlates with the observation that raising and lowering antennas at the client locations seemed to frequently change the SNR or throughput, but not always as expected. The hypothesis is that the antenna height will affect the phase difference between the primary incoming signal and the secondary signal arriving from reflections. This phase difference can cause either constructive or destructive interference that in turn raises or lowers the received signal power. This is an area that warrants further study and field-testing.

Figure 38: Legend for the Coverage Map

Figure 39: Coverage at Lee Library

The path plots, such as seen in Figure 40 help the user determine causes for signals that are weaker than expected. Other software such as Google Earth can do this, but Radio Mobile combines the visual effects with loss due to different sources. The white elliptical lines mark the Fresnel zones. These zones help determine if terrain will cause additional attenuation to the signal. It is quite obvious in this case where the line of sight signal is blocked by the hill, but in other cases it might not be as obvious. This can prove useful in the task of planning installations.

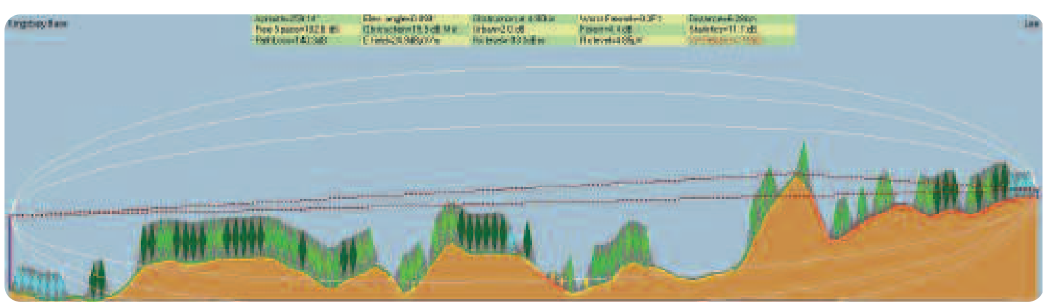


Figure 40: Terrain Path and foliage coverage between Kingsbury and Lee Library

The use of the Longley-Rice algorithm, and therefore the Radio Mobile software, is limited by certain parameters, one of which is that the distance between the base station and the client needs to be at least 1 km. The on campus locations are all within 1 km so the results of this tool could be potentially inaccurate for these locations. This should be verified in future work, but does not really cause much of an issue since in most cases, locations within 1 km would be close enough for the UHF radio wave to propagate with enough power and not require this software analysis.

II. Propagation Models

a. Free Space Path Loss/Plane Earth

Developed from the Friis free space equation, the Free Space Path Loss model (from [9]) is the basic path loss equation. It accounts only for the reduction in power due to the distance between the transmitter and receiver, and the frequency of operation. It is used here for a basic comparison.

$$PL_{FreeSpace} = 20\log(d) + 20\log(f) + 32.4 \quad \textbf{(1)}$$

Where:

d is the distance in meters;

f is the frequency in GHz;

To simply account for a single ground reflection, the Two-Ray or Plane Earth model is used [1]. Much like the Free Space model, this basic model will give a baseline prediction, accounting for reflection off of the ground. It does not account for reflections off of buildings and trees or statistical variations like some of the more advanced models, but can give a baseline approximation for path loss.

$$PL_{PlaneEarth} = 40\log(d) - 20\log(h_t) - 20\log(h_r) \quad \textbf{(2)}$$

Where:

d is the distance in meters;

h_t is the transmitter height in meters;

h_r is the receiver height in meters;

These models will be a good base level approximation for the TVWS trial. However, when there is terrain that is not perfectly flat, these models begin to vary. Using software tools such as Radio Mobile that takes the terrain into account, will better predict the performance.

b. Okumura-Hata Model

The Okumura-Hata propagation model is widely used throughout different applications to predict propagation in urban environments. More recently, work has been done to update the model to apply to rural areas. In their studies [2], Medeisis and Kajackas found that the urban model, seen in Equation 3, can have significant errors in rural prediction. However, breaking the model down to its separate parts, as seen in Equations 4-6, the constants pertaining to the channel (E0 and γ) can be fit to the data at different frequencies.

The Okumura-Hata Urban Model where E_R is in $dB(\mu V/m)$:

$$E_R = 35.55 + P_{BS} - 6.16log(f) + 13.82log(h_{BS}) + a(h_{MS}) - (44.9 - 6.55log(h_{BS}))log(R^{\gamma}) \quad \textbf{(3)}$$

Where:

P_{BS} — radiated power of the transmitter, dBW

f — operating frequency, MHz

h_{BS} — effective height of the transmitter antenna, m, above average terrain in the range 3–15 km

h_{MS} — height of the receiver antenna, m; $a(h_{MS}) = (1.1 * log(f) - 0.7) * h_{MS} - (1.56 * log(f) - 0.8)$

R — distance from the transmitter, km

$\gamma = 1$

$$E_0 = 35.55dB(\mu V/m) \quad \textbf{(4)}$$

$$E_{SYS} = PBS - 6.16\ log(f) + 13.82\log(h_{BS}) + a(h_{MS}) \quad \textbf{(5)}$$

$$\gamma_{SYS} = -\gamma(44.9 - 6.55\log(h_{BS})) \quad \textbf{(6)}$$

Combining the equations, the new form of the Okumura-Hata model is seen in Equation 7. This allows for fitting coefficients to the measured data. Through the author's measurements, the adjusted coefficients were found for VHF and UHF frequencies shown in Table 10.

$$E_R = a + b * \log(R) \quad \textbf{(7)}$$

Where:

$a = E_0 + E_{SYS}$

$b = \gamma_{SYS}$

To compare with the measurements made in the TVWS trial, the closest frequency from Medeisis and Kajackas' work (450 MHz) was chosen for analysis. To best fit the coefficients, using the measurement data collected in this trial would provide best results, and could help future predictions.

	160 MHz		450 MHz		900 MHz	
	URBAN	RURAL	URBAN	RURAL	URBAN	RURAL
E_0	40	40	40	50	35	60
γ	1.25	1.20	1.30	1.20	1.00	1.25

Table 10: Calculated empirical parameters for the updated Okumura-Hata model in [2]

c. Stanford University Interim (SUI) Model

Found in [10, 11], the SUI model was developed to improve path loss models to account for statistical parameters in the channel that many other models ignore. This shadow component (in Equation 8) will account for Doppler spread, multipath delay among others. The typical standard deviation of the shadow component is between 8.2 and 10.6 dB. The model is designed for use in three different terrains, hilly terrain with moderate to heavy tree densities (Category A), mostly flat terrain with light tree densities (Category C), or a combination of the two (Category B).

$$PL = A + 10\gamma \log(d/d_0) + s; \text{ for } d > d_0 \quad (8)$$

Where:

$A = 20 \log(^{4\pi d_0}/_{\lambda});$

λ is the wavelength in m

$\gamma = (a - bh_b + {}^{c}/_{h_b})$ is the path loss exponent;

h_b is the base station in m between 10 m and 80 m;

$d_0 = 100$ m

For the equation above, *a, b,* and *c,* are constants that are dependent on the terrain category, as seen in Table 11. The shadowing as determined by the test data that developed the model can be expressed as:

$$s = [10x\sigma_\gamma \log(d/d_0) + y\mu_\sigma + yz\sigma_\sigma] \quad (9)$$

where x, y, z are Gaussian Random Variables $N[0,1]$. Including this part of the equation will account for the potential shadowing that could cause variations on the path loss value. This can come from weather variations, movement of cars and tree branches into the propagation and reflection paths etc.

MODEL PARAMETER	TERRAIN TYPE A (HILLY WOODS)	TERRAIN TYPE B (HILLY OR WOODS)	TERRAIN TYPE C (FLAT AND OPEN)
a	4.6	4	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20
σ_γ	0.57	0.75	0.59
μ_σ	10.6	9.6	8.2
σ_σ	2.3	3.0	1.6

Table 11: Constant values for SUI model

There are some correction terms to account for varying antenna heights and frequencies. The model was initially designed based on the higher microwave frequencies (1.9 GHz) and receiver heights of about 2 meters, but can be used for other frequencies and heights with the following corrections:

$$PL_{modified} = PL + \Delta PL_f + \Delta PL_h \quad (10)$$

Where PL is the path loss given in Equation 8, ΔPL_f (in dB) is the frequency correction term (Equation 11)

$$\Delta PL_f = 6 \log {}^{f}/_{2000} \quad (11)$$

Where f is the frequency in MHz, and ΔPL_h (in dB) is the receive antenna height correction term (Equations 12 and 13)

$$\Delta PL_h = -10.8 \log {}^{h}/_{2} \text{ for Type A and B} \quad (12)$$

$$\Delta PL_h = -20 \log {}^{h}/_{2} \text{ for Type C} \quad (13)$$

Where h is the receive antenna height between 2 m and 10 m. These corrections should translate the model into frequencies used in this TVWS trial. Ignoring the shadowing effect for now will provide a path loss that may not match well, but if it is within a certain threshold, the statistical variation could be to blame.

d. Comparison to test results

Applying the path loss models at the various distances and antenna heights shows how well available path loss models predict the loss in the TVWS environment. Only a couple of measurements were made, but it can be seen that in the trial situation, free space path loss most closely approximates the path loss seen between the base stations and the clients (Figures 41 and 42). In this case, the base station is situated at a lower elevation then the clients and at a high enough antenna height that free space loss is the predominant cause of loss between the units. There is an effect due to foliage and ground reflections, but in the off-campus locations, the distance between the units is the biggest loss factor. In the case of the Barrington unit, the path loss is best modeled by the Plane Earth or Two Ray model. In the case of the Durham Library, the path loss is found to be much greater. This could be due to the close proximity to buildings and trees between the Stoke base station and this measurement location. Seeing a higher power measured when avoiding the building blocking the line of sight shows this to be apparent (see Section 3). Though TVWS signals in the UHF frequencies have less loss through buildings and trees then compared to Wi-Fi, propagation through buildings does cause more loss then through air as one would expect. This is why the measurement here most closely matches the SUI model, which was designed with data taken in suburban and urban environments, taking into account the reflections and losses due to buildings. This is why the environment in which the system is deployed will have a large effect which models should be used to predict the range and performance of the system.

Because a small number of measurements were made, no firm conclusion can be drawn about which models are most applicable to TVWS in a rural environment. Small-scale fading, or shadowing, can result in variations between measured values that can greatly affect the measured path loss value. Taking many measurements and finding an average path loss is important to be able to assess the models' use. The variation in shadowing can be seen in Figure 43. Here, the SUI model is shown with the predicted shadowing effect. It is seen that the lower path loss predictions come much closer to the measured results than when shadowing is not considered. In order to account for this in the measured values, more measurements will need to be taken, and will be done so in future work.

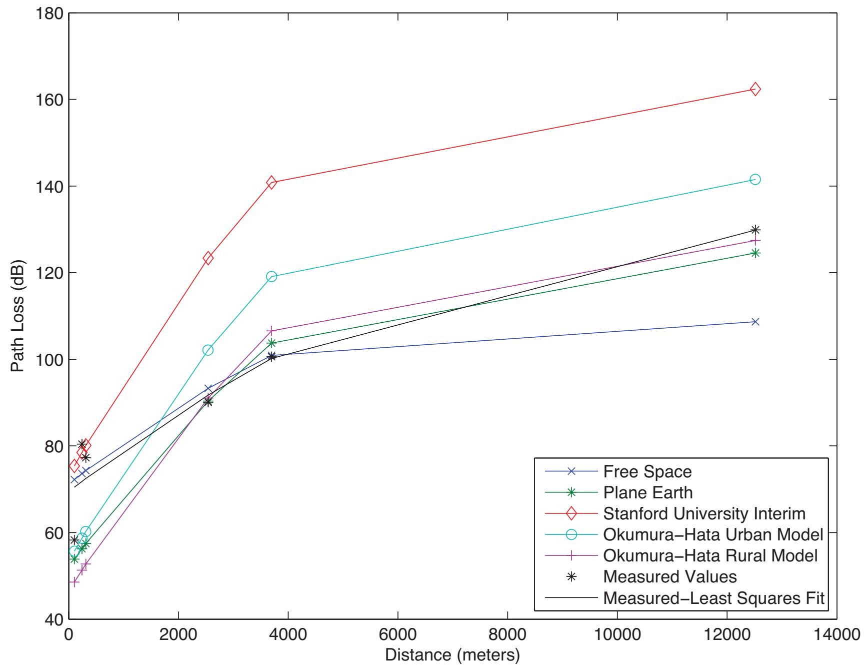


Figure 41: Plot of Path Loss models discussed, compared to initial measurements

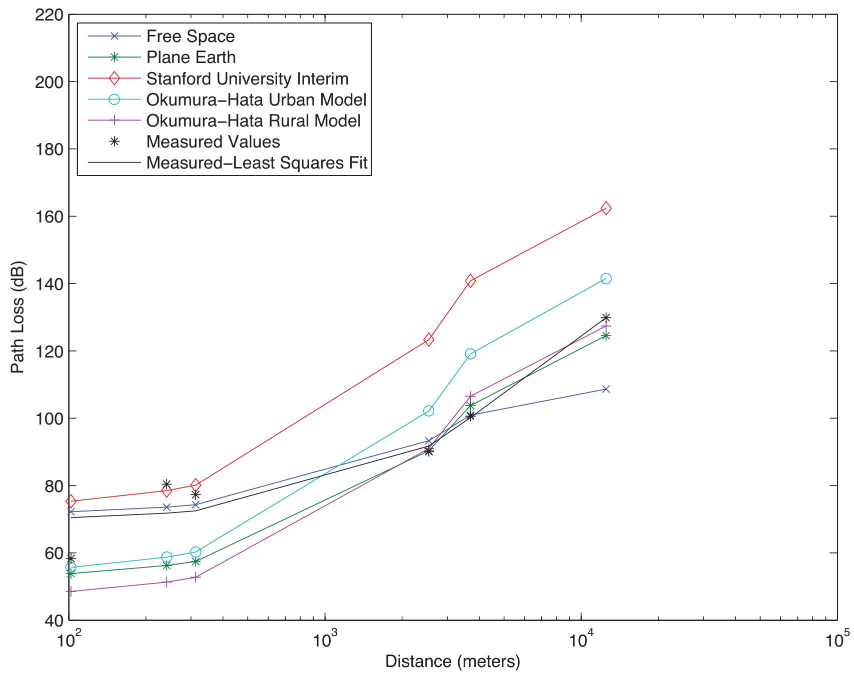


Figure 42: Plot of Path Loss models discussed, compared to initial measurements with distance in log scale

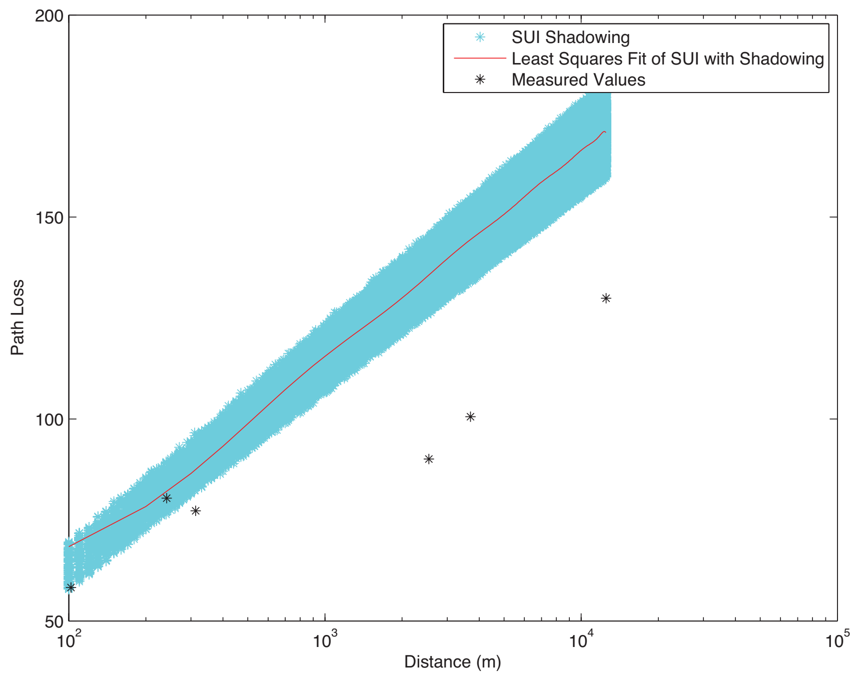


Figure 43: The Effect of Small Scale Fading (Shadowing) on Path Loss Predictions

5 Phase 3 Work

To continue the trial and help determine whether TVWS spectrum can support the speeds and reliability necessary for broadband access, additional work still needs to be done. Testing the Carlson equipment to insure it meets the specifications will be useful for verifying the analysis that has been completed. This was not done initially due to the short amount of time between receiving the devices, and the scheduled installation. Since the installation itself is not complete, continued performance monitoring is necessary to determine if the network still performs as expected when additional full time clients are added. Currently, Barrington and Madbury have yet to be installed. Doing so will complete the setup and let the trial truly commence. Once the installation is complete, additional testing will be necessary to further confirm some of the statements made in this document. For example, the measured values used in the propagation studies were taken using peak hold mode on the spectrum analyzer and this, combined with the small sample number of measurements, result in an average signal that does not fully take into account the shadowing. Many more measurements are needed to fully account for this, and allow a decision to be made on which propagation model, if any, can be used for prediction of performance. Along with more measurements needed, studying the effects of foliage can help make the available models more accurate in the forest environment indigenous to this area of New Hampshire. To continue the analysis of the equipment, additional trials in other locations with varying terrain and forest characteristics would be beneficial. This is outside of the scope of this specific trial, but to further confirm the performance, investigation in all types of environments is essential.

6 Conclusions

The trial of the TVWS equipment that began in September 2013 had a primary goal of analyzing the performance of wireless Internet devices, and specifically the Carlson RuralConnect radios, as they are used for connecting undeserved areas with broadband Internet. Though the trial is ongoing, some conclusions can be made. First, due to the devices being new technology, setup and installation is not always easy. Having trained professionals assist in the technical aspects of the installation, at least initially, seems necessary to maximize performance. The devices are not at the true plug and play level that current Wi-Fi routers are, however it must be noted that over the course of the trial software upgrades to the base station have made the equipment easier to deploy.

It was found that of the initial intended libraries in Barrington, Durham, Lee, and Madbury, and the on-campus locations in Dimond Library, Thompson Hall, and the IOL, only the Lee Library was determined to not be accessible with the current setup. The propagation path from either base station has to go over Wednesday Hill which proved to cause too great of a reduction in power in the form of diffraction. The signal found at Lee was weak enough that antenna placement played a large role in whether any connection could be made. When a connection was made, speeds were measured below what many consider broadband levels and led to the conclusion that Lee Library location would not continue to be used in the trial. Measurements made at the other potential clients sites close to the projected antenna heights showed good speeds to continue the trial and test the system under a heavier load. Phase 3 of the trial will involve monitoring the system since all clients are connected to their perspective base stations.

PHASE	PHASE 1	PHASE 2	PHASE 3
Base station location(s)	Stoke Hall	Stoke Hall Kingsbury Hall	Stoke Hall Kingsbury Hall
Base station antenna	Carlson omni-directional	Sector antenna Carlson omni with reflector	Sector antenna Carlson omni with reflector
Active client locations	Durham Library, IOL Dimond Library	Durham Library, IOL Dimond Library Thomson Hall	Durham Library, IOL Dimond Library Thomson Hall Barrington Library Madbury Library

Table 12: Trial phases

TVWS is heralded as a non-line of sight capable medium due to its improved propagation characteristics over those with higher-frequencies. In our testing this has shown to be true in most cases, as even with long distances and through heavy tree densities the signal propagated very well as demonstrated by the Barrington Library tests. Though further testing will be necessary to determine if this can be a reliable broadband link over the longer term, initial findings are encouraging. However, signals in the TVWS spectrum do not seem to travel as well over hills and rock outcroppings as perhaps one might be led to believe. Lee Library is blocked by Wednesday Hill and though the signal was not lost completely, it was attenuated sufficiently to become heavily dependent on antenna type, height and location to provide even marginal data connectivity. This will not make installations at multiple sites by lesser trained individuals simple in the way Wi-Fi has become. Though more work is needed to monitor performance in different seasons and with a full load of clients, the potential of TVWS spectrum to help deliver broadband Internet access to rural areas continues to be promising.

Appendices

A. Test setup

I. Spectrum analyzer

To make the spectrum analyzer measurements, the client antennas were used with a Rohde and Schwarz FS300 analyzer. To connect the 75 ohm antennas to the 50 ohm spectrum analyzer, a matching pad was used to avoid the impedance mismatch. This mismatch would introduce unnecessary loss in the system due to reflections that occur. The matching pad still introduces loss and reflections, but at a much lower level, and at a flat rate over wide frequencies. The matching pad used is rated at a maximum loss of 5.7 dB. A laptop was used to control the analyzer and save the various spectrum traces as an ASCII file. This setup can be seen in Figures 44 and 45. The spectrum trace was then plotted using MATLAB computing software and included in this report. For the measurements, the spectrum analyzer had a set configuration to keep measurements consistent:

- 0 dB internal attenuation
- Resolution bandwidth (RBW) = 200 kHz (would adjust if signal called for it, labeled plots separately)
- Center frequency set to operation channel
- 20 MHz span to capture channel in question as well as adjacent channels
- Peak hold mode to Max to capture the time division duplex (TDD) signal

By keeping these consistent, measurements can be compared to one another more easily. To calculate the total power of the signal, equation 14 is used to take the individual power measurements saved in the trace, and convert to total channel power. [12] Adding the individual power measurements and normalizing to the number of data points $(N = (n_2 - n_1) + 1)$ produces the channel power.

$$P_{ch} = \frac{B_s}{B_n} \frac{1}{N} \sum_{i=n1}^{n2} 10^{P_i/10} \qquad (14)$$

In this equation, B_s is the specified bandwidth, and B_n is the equivalent noise bandwidth (ENB). The ENB comes from the sweep filter used. This is additionally set by the RBW of the spectrum trace. The conversion factor is based on the type of filter as seen in Table 13.

FILTER TYPE	APPLICATION	ENB/RBW
4-pole sync	Most SAs analog	1.128 (0.52 dB)
5-pole sync	Some SAs analog	1.111 (0.46 dB)
Typical FFT	FFT-based SAs	1.056 (0.24 dB)

Table 13: RBW to ENB conversion factor for spectrum analyzer

Additionally, a TV band pre-amplifier was purchased for the weaker signals. This can add up to 36 dB of gain to help overcome cable losses and was used to help raise the weaker signal above the noise floor of the spectrum analyzer.

Figure 44: Drawing of the spectrum analyzer power measurement setup

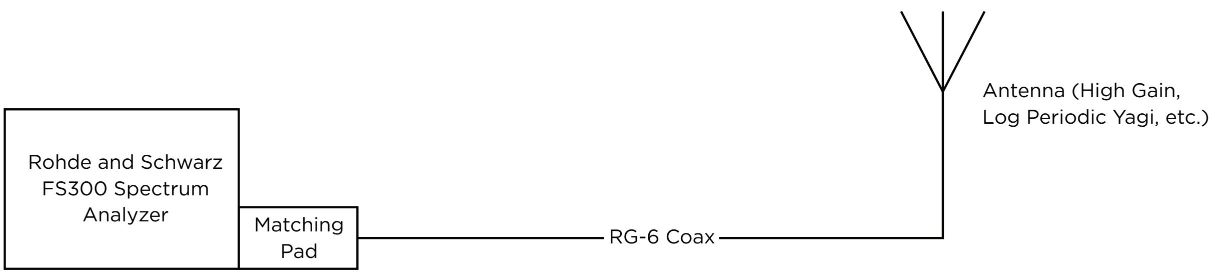


Figure 45: Block diagram showing spectrum analyzer measurement setup

II. Client equipment with Carlson software

The CPE in the system was used for throughput measurements in the setup illustrated in Figures 46 and 47. The CAT5 data connection is sent to a laptop where the throughput can be measured via online speed test sites such as speedtest.net and speakeasy.net/speedtest. There are many variables in online tests such as the traffic on the user's network in addition to the traffic on the network connecting the test servers. When run back to back on a wired link on the network that provides the backhaul for the base stations, speedtest.net indicates a speed of 93.27 Mbps download and 95.93 Mbps upload, while immediately after, speakeasy.net gives 85.62 Mbps download and 80.48 Mbps upload. This large variation on what should be a relatively consistent network shows the variability of the sites. To further examine the tests, running multiple tests at different times throughout the day while connected to the ports serving the base stations would be useful. However, lack of direct access to the locations of the base stations makes accomplishing this task difficult. Also worth noting, a wireless connection like this will fluctuate over time and location due to the varying effects on all of the clients. However, these website tests are a good basic measurement device, and will continue to be used to give a relative performance marker.

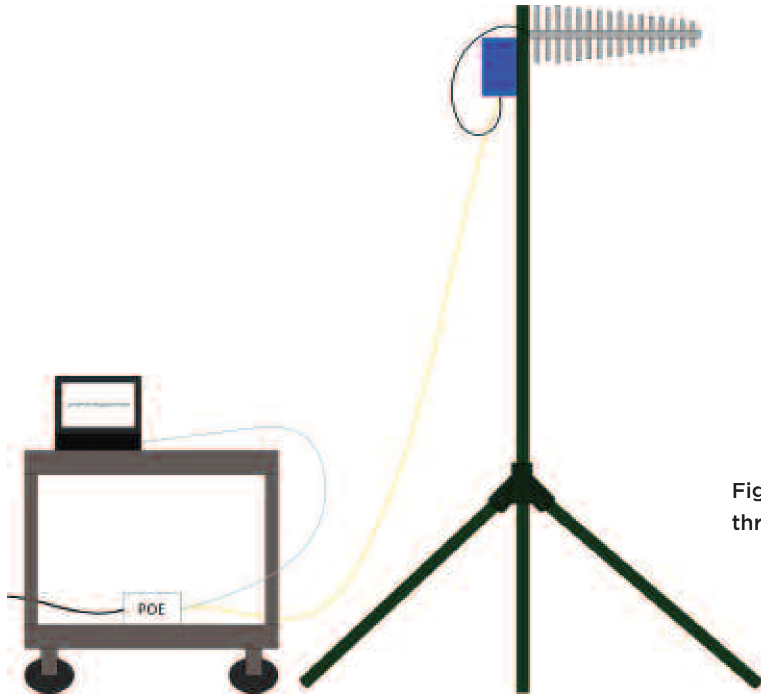


Figure 46: Drawing of the throughput measurement setup

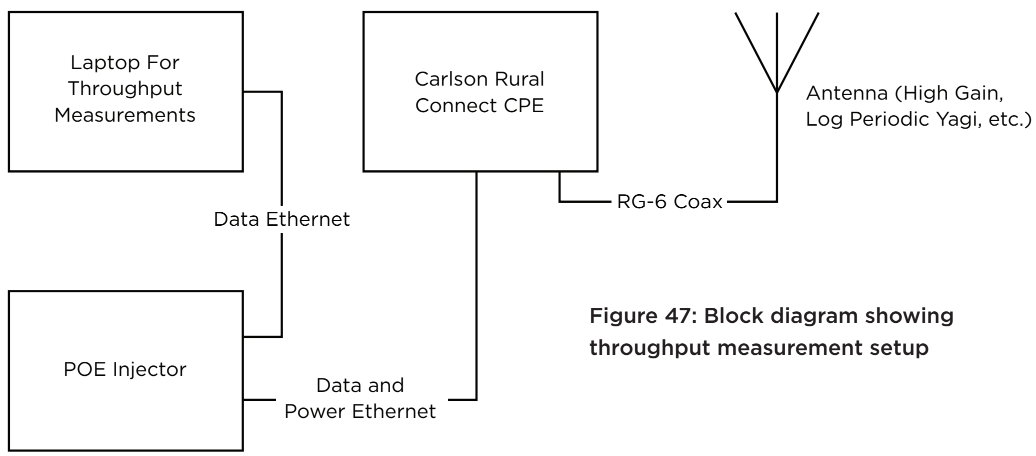


Figure 47: Block diagram showing throughput measurement setup

SNR is measured by the Carlson Operation and Management Center (OMC) for the Stoke Hall Base Station and the Carlson Local Management Interface (LMI) for the Kingsbury Hall Base Station. The OMC is a cloud-based software that can control the base station operation channel and monitor the health and statistics of the system. The LMI is similar software that, as the name suggests, is hosted locally on the base station. Both will track the SNR and modulation mode of the CPEs and were used for measurements at the client locations. However, the OMC does not give SNR and modulation in real time which is why these measurements were often omitted when connected to the Stoke base station. Along with the software, SNR can be approximated by the CPE RSSI LED lights seen in Figure 48. The SNR, along with the recommended modulation mode, can be evaluated based on Table 14.

NUMBER OF LEDS	LED BEHAVIOR	APPOX. SNR	MOD. TYPE	ERROR CORRECTION
1	Flickering	2	BPSK 4	Conv
1	Blinking	4	BPSK 4	Conv Punct
1	Solid	6	BPSK 2	Conv
2	Flickering	8	BPSK 2	Conv Punct
2	Blinking	10	BPSK 1	Conv
2	Solid	12	BPSK 1	Conv Punct
3	Flickering	16	QPSK 1	Conv
3	Blinking	18	QPSK 1	Conv Punct
3	Solid	20	QPSK 1	Conv Punct
4	Flickering	24	QAM 16 1	Conv
4	Blinking	27	QAM 16 1	Conv Punct
4	Solid	30+	QAM 16 1	None

Table 14: Relation of RSSI LEDs to SNR

This table was provided by Carlson Wireless and has not been verified, but serves well for approximation. In the new software update the available modulation rates are BPSK, QPSK, and 16QAM, each with the ability to have 1/2 or 3/4 error correction. This is slightly different from the modulation modes listed in Table 14, but follows the same ability to apply error correction on the weaker channels.

Figure 48: Close up of CPE RSSI LEDs

The following are additional system specifications for operation of the RuralConnect radios taken from the Carlson Wireless website [4]:

- **Frequency Bands:** UHF 470-698 MHz (US)
- **Channel Spacing:** 6 MHz (US)
- **Modulation:** 16QAM, QPSK, BPSK
- **OTA Data Rates:** 4, 6, 8, 12, and 16 Mb/s
- **RX Sensitivity:**
  - -93 dBm for 10^{-6} BER using QPSK 1/2 (10^{-6} BER means one error in 10^{-6} bits)
  - -86 dBm for 10^{-6} BER using 16QAM 1/2
  - -80 dBm for 10^{-6} BER using 16QAM
- **RX Max Signal:** -16 dBm with full linearity
- **Operating mode:** Time Division Multiplexing (TDD)

B. Antennas used

For the testing and eventual installation of the system, seven main antennas were used, three for the base stations and four for the client stations and testing. Specifications for these antennas beyond the gain listed here including radiation patterns and beamwidth can be found on the Carlson website [4].

Base station antennas:

- **Carlson Omni-directional Antenna —** Gain: 5.2 dBi
- **Carlson Omni-directional Antenna with Reflector —** Gain: 10.4 dBi
- **Sector Antenna —** Gain: 9 dBi averaged over 90 degrees

Client station antennas:

- **Log Periodic Directional UHF Antenna —** Gain: 9 dBi
- **High-Gain Log Periodic Directional UHF Antenna —** Gain: 13 dBi
- **Yagi Directional UHF Antenna —** Gain: 10.8 dBi
- **Winegard Flatwave Window Antenna —** Gain: Roughly measured to be 2dBi

In order to increase performance, the higher gain antennas were chosen for future installations. The breakdown of antennas used at each client station and base station can be seen in Table 15.

LOCATION	BASE STATION	ANTENNA	PHASE OF TRIAL INSTALLED
Kingsbury Hall	n/a (base station)	Omni-directional with reflector	Phase 2
Stoke Hall	n/a (base station)	Sector	Phase 2 (omni-directional antenna used in Phase 1
Barrington Library	Kingsbury	High Gain Log Periodic	Phase 3
Dimond Library	Kingsbury	Log Periodic	Phase 1 (switched from Stoke base station to Kingsbury base station (Phase 2)
Durham Library	Stoke	Winegard Window	Phase 1
InterOperability Library	Kingsbury	Gain Log Periodic	Phase 1 (switched from Stoke base station to Kingsbury base station (Phase 2)
Madbury Library	Kingsbury	High Gain Log Periodic	Phase 3
Thomson Hall	Kingsbury	Winegard Window	Phase 2

Table 15: Base Station and Client Location Antennas

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