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An Assessment of Path Loss Tools and Practical Testing of Television White Space Frequencies for Rural Broadband Deployments

Braden Scott Blanchette
University of New Hampshire, Durham

AN ASSESSMENT OF PATH LOSS TOOLS AND PRACTICAL TESTING OF TELEVISION WHITE SPACE FREQUENCIES FOR RURAL BROADBAND DEPLOYMENTS

BY

BRADEN SCOTT BLANCHETTE
Bachelor of Science in Electrical Engineering, The University of New Hampshire, 2013

THESIS

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Thesis Director, Dr. Nicholas Kirsch, Assistant Professor of
Electrical and Computer Engineering

Dr. Michael Carter, Associate Professor of
Electrical and Computer Engineering

Dr. Richard Messner, Associate Professor of
Electrical and Computer Engineering

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Original approval signatures are on file with the University of New Hampshire Graduate School.

To my family. Without their support, this would have never happened.

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List of Acronyms

AGL – Above Ground Level

ASK – Amplitude Shift Keying

ASL – Above Sea Level

BCoE – Broadband Center of Excellence

BER – Bit Error Rate

bps – bits per second

BPSK –Binary Phase Shift Keying

CPE – Client Premise Equipment

dB – decibel, representing a ratio

dBi – decibel with respect to isotropic radiator (for antenna gains)

dBm – decibel with respect to 1 milliwatt

dBW – decibel with respect to 1 Watt

DSL – Digital Subscriber Line

E-Field – Electric Field, in this case of an antenna

EIRP – Effective Isotropic Radiated Power

ENB – Equivalent Noise Bandwidth

FCC – Federal Communications Commission

FDD – Frequency Division Duplexing

FEC – Forward Error Correction

FSK – Frequency Shift Keying

FSPL – Free Space Path Loss

GHz – Gigahertz (1 billion cycles per second)

GPS – Global Positioning System

GSM – Global System for Mobile Communications, or Groupe Spécial Mobile

HAAT – Height Above Average Terrain

HDTV – High Definition Television

IEEE – Institute for Electrical and Electronics Engineers

IFSAR – Interferometric Synthetic Aperture Radar

IOL – InterOperability Laboratory

ITM – Irregular Terrain Model

ITU-R – International Telecommunications Union Recommendation

km – kilometers

LED – Light Emitting Diode

LIDAR – Light Detection and Ranging

LMI – Local Management Interface

LoS – Line of Sight

LR – Longley-Rice

m – meters

Mbps – Megabits per second (data rate)

MHz – Megahertz (1 hundred thousand cycles per second)

NED – National Elevation Dataset

ODU – Outdoor Unit

Ofcom – Office of Communications

OMC – Operations and Management Center

OTA – Over the Air

PCS – Personal Communications Service

POE – Power Over Ethernet

PSK – Phase Shift Keying

PTP – Point-to-Point

QAM – Quadrature Amplitude Modulation

QPSK – Quadrature Phase Shift Keying

RBW – Resolution Bandwidth

RMSE – Root Mean Squared Error

RSSI – Received Signal Strength Indicators

RV – Recreational Vehicle

Rx – Receiver

SNR – Signal to Noise Ratio

SRTM – Shuttle Radar Topography Mission

SUI – Stanford University Interim Model

SUV – Sport Utility Vehicle

TDD – Time Division Duplexing

TVWS – Television White Space

Tx – Transmitter

UHF – Ultra High Frequencies (300 MHz to 3 GHz)

UK – United Kingdom

UNH – University of New Hampshire

U.S. – United States

USGS – United States Geological Survey

VHF – Very High Frequencies (30 MHz to 300 MHz)

WiFi – local area wireless computing network using 2.4 GHz or 5 GHz bands

WiMAX – Worldwide Interoperability for Microwave Access

WRANs – Wireless Regional Area Networks

ABSTRACT

AN ASSESSMENT OF PATH LOSS TOOLS AND PRACTICAL TESTING OF TELEVISION WHITE SPACE FREQUENCIES FOR RURAL BROADBAND DEPLOYMENTS

by

Braden Scott Blanchette

University of New Hampshire, September, 2015

Broadband internet has grown to become a major part of our daily routines. With this growth increase, those without direct access will not be afforded the same opportunities that come with it. The need for ubiquitous coverage of broadband Internet is clear to provide everyone these opportunities. Rural environments are an area of concern of falling behind the growth as the low population densities make wired broadband solutions cost prohibitive. Wireless options are often the only option for many of these areas; WiFi, cellular, and WiMAX networks are currently used around the world, but with the opening of the unused broadcast television frequencies, deemed TV White Space (TVWS), a new option is hitting the market. This new technology needs to be assessed before it can be seen as a viable solution.

The contribution of this work is two-fold. First, findings from a real, ongoing trial of commercially available TVWS radios in the area surrounding the University of New Hampshire campus are presented. The trial shows that though the radios can provide Internet access to a distance of at least 12.5 km, certain terrain and foliage characteristics of the path can form coverage holes in that region. The second contribution explores the use of empirical path loss models to predict the path loss, and compares the predictions to actual

path loss measurements from the TVWS network setup. The Stanford University Interim (SUI) model and a modified version of the Okumura-Hata model provide the lowest root mean squared error (RMSE) for the setup. Additionally, the deterministic Longley-Rice model was explored with the Radio Mobile prediction software. It was determined that without extensively tuning the foliage component of the algorithm, the model could produce significant prediction errors, resulting in a trade-off between low cost, un-tuned predictions, and prediction accuracy.

CHAPTER 1

Introduction

Wireless communication systems have seen a boom in development over the last several decades, but, it has been a daily part of human life for thousands of years. Many would not think of it, but wireless communications also exists in the form of speech, hand motions, smoke signals and drums. Focusing on electronic communications, the first wireless transmission is attributed to Guglielmo Marconi in 1898. He was able to transmit a signal from the Isle of Wight to a boat in the English channel using ideas of electromagnetic waves established by the likes of Nikola Tesla, James Maxwell, and Heinrich Hertz [4]. This led to rapid development of wireless telegraphs, television and eventually, bi-directional communications. Claude Shannon developed the idea of error free communications by limiting the data rate based on the signal to noise ratio (SNR). This allows reliable communications to be established in wider areas if the system designer has some knowledge of the characteristics of the propagating channel [5].

The development of reliable, error free communications paved the way for transmitting more than just voice and picture, but any form of data. Communications systems can transmit information anywhere from across the room with Bluetooth devices, to thousands of miles into space for satellite communications. This wide range of communication distances led to a wide range of devices and the increased demand for sending and receiving data at high speeds. With the explosion of the number of Internet capable devices, the demand for wireless Internet connectivity has grown. One of the severely limiting factors to this growth is the limited amount of available spectrum. Wireless spectrum is divided into different bands and assigned to different communication systems. Often a license is required to use the frequencies, allowing only the particular technology to use the bands. Requiring a license allows the user who purchased the license to have limited, controlled interference from other users. Restricting access by a license, however, can lead to underutilized spectrum in areas where the licensed user does not operate. To overcome this, unlicensed users are sometimes allowed to access parts of spectrum that are underutilized. Doing so allows more users access to communications systems in locations where access may not have otherwise been possible.

In today's modern world, broadband Internet connection has become a major part of day to day living. Millions of people in the United States alone have smart-phones that bring broadband access to the palm of your hand. This has evolved greatly over the past few decades from when Internet was limited to a few thousand researchers at an average speed of about 500 bits per second (bps) per person [6]. This connection was limited to as far as a wire could reach, with wireless options only recently becoming commonplace.

Today Internet capacity, or the amount of data transfers per second the global Internet supports also known as bandwidth, is roughly 2 million megabits per second (Mbps) with closer to one billion people having access [6]. Connection to the Internet is commonly associated as a social or leisure activity. The Internet, however, can provide invaluable information to people when they may need it most. Instant access to news and weather alerts can give people a chance to react in emergency situations before it is too late. Broadband Internet access can provide teleconferencing options to connect patients to their doctors and specialists, without having to travel long distances for a checkup. Students can have access to online resources and classes to enable getting a degree while working across the country or even across the globe. The options are endless for those who have broadband access.

Millions of people in the United States and worldwide, however, do not have direct access to broadband Internet. Broadband is currently defined by the Federal Communications Commission (FCC) as 25 Mbps download speeds and 3 Mbps upload speeds due to advancements in technology [7]. This definition leaves 55 million Americans without access to the newly defined speeds considered broadband. This update came in January of 2015, increasing the level from the previous definition of 4 Mbps download speeds and 1 Mbps upload speeds. The FCC also states, however, that 4 Mbps is all that is needed for high definition video conferencing and most other typical uses. Because of this, the 4 Mbps definition will be used throughout this thesis. This level of broadband is still unavailable to many, particularly in rural areas.

While wire-line solutions can provide speeds in excess of 100 Mbps [8] over long distances, the installation of the wires needed to bring the Internet to homes becomes cost prohibitive in low population areas. Telephone lines that provide dial-up access are common in many areas, but with speeds only in the tens of kbps, the technology does not meet the speed requirements necessary for many common uses of the Internet. As this is the only option for many, new technology needs to be developed and tested to help fill the void and make broadband access ubiquitous.

One step towards ubiquitous broadband access has to be connecting underserved and unserved rural areas. Often, wired technologies are not available since rural areas commonly are synonymous with low population densities. The only options may be slower dial-up and DSL, or expensive and limited access from satellites. A low-cost option must be made available to help bring connectivity to all corners of the globe. One such option is the use of Television White Space (TVWS) radios.

The TV white spaces are open frequencies that were made available after the analog to digital switch-over of broadcast television in 2009 [9]. Changing to digital transmissions made a lot of the spectrum for TV broadcasts empty in many areas, particularly so in rural areas. Now available for unlicensed use, new technology is being developed to take advantage of this frequency band. The frequencies available in TVWS are desirable due to their improved propagation characteristics over the higher frequency supported by WiFi and WiMAX. This will be discussed in Chapter 2. As this new technology is developed, the need for trials becomes essential for determining if it can be a viable option for closing the gap in worldwide connectivity.

The contribution of this thesis is two-fold. First, a trial of commercially available TVWS radios is discussed with focus on the connection of local libraries to the University of New Hampshire (UNH) network. Started by the UNH Broadband Center of Excellence (BCoE), the trial worked to connect local libraries in a way that would simulate connection of rural libraries that do not have broadband Internet access. The range of the radios was tested by attempting to establish connection at the distance limit of the radios, as well as in locations where the terrain may make connection difficult. The findings are presented as well as some initial conclusions from the trial. Though these trials are being conducted all over the world [10–12], extending the trials to all types of environments helps explore the viability of new, commercially available solutions.

The second contribution of this work came from the main conclusion of the trial: in order to make truly affordable deployments of TVWS radios a possibility, simple deployment planning tools must be verified. To accomplish this, path loss measurements were made in the same coverage area of the TVWS network explored in the trial to determine which of the studied path loss models can help predict performance of the radios used based on received power thresholds set by the radio manufacturer. Many simulations of path loss models have been run in other studies such as those conducted by Nimvat and Kukarni [13] in the GSM bands, and by Deshmukh et al. for TVWS access in rural areas in India [14]. Some had a focus on improving database coverage such as the work by Achtzehn et al. [15]. Other work had simulations of path loss models and TVWS coverage in other environments such as the work exploring urban deployments discussed by Fitch et al. [16] and Simic et al. [17]. The need for measurements to validate the models in the rural environment, such as that surrounding the UNH campus, is a necessity.

Measurements have been made from television broadcast setups such as the work done by Kasamapalis et al. [18] and Sridhar et al. [19] for TV coverage, and the work by Faruk et al. [20] which was completed with secondary access to TVWS in mind. The use of TV transmitters can hide the effects of low antenna heights that are required for TVWS networks. Because of this, path loss measurements were made in the area surrounding the UNH campus to compare the prediction capabilities of the Okumura-Hata model, the Egli Model, and the SUI model as well as the use of the Longley-Rice model with the Radio Mobile software.

The thesis is divided into four main chapters following this first introduction chapter. In the second chapter, some background information is provided to allow a better understanding of the TVWS requirements and wireless communication principles that can explain the problems that arise in deployment. In addition, the different path loss models and software tools used for the predictions, and the radios used in the trial, are described. The third chapter discusses the findings of the TVWS trial that is taking place on and around the UNH campus. In the fourth chapter, the path loss models are compared to measurements made in the area to determine which model performs predictions best for low power, low antenna height rural broadband installation. In the fifth and final chapter, some conclusions of the findings are presented along with potential areas of future work.

CHAPTER 2

Background and Motivation

2.1 Introduction

In order to better understand the concepts discussed in the contribution of this work, a basic introduction to concepts is presented. The chapter begins with background on the TVWS regulations and ongoing trials that are helping determine the performance of TVWS broadband networks. Next, the engineering concepts of wireless communications will be explained. With this basic understanding, the challenges faced by wireless networks and how those problems can be predicted and compensated can be covered. Finally, the RuralConnect radios [21] used in the trial completed in this research will be discussed with respect to performance and performance monitoring of the radios. For a more in-depth breakdown of the concepts pertaining to wireless communications, the reader is urged to explore the plethora of texts available covering these concepts such as Wireless Communications, Principles and Practice by Theodore Rappaport [1], and Wireless Communications by Andreas Molisch [4].

2.2 Television White Spaces

Analog over-the-air television broadcasts have occupied parts of the very high frequency (VHF) and the lower end of the ultra high frequency (UHF) spectrum bands since the 1940s. It began with black and white television broadcasts, and continued up to the digital switchover in 2009 [9]. Each 6 MHz channel exists in the lower frequencies that provide propagation characteristics that allow the signal to travel long distances with improved propagation through foliage and walls as well as over hills compared to other wireless networks such as WiMAX and WiFi which operate at much higher frequencies. Many of the channels reserved for these television broadcasts are unoccupied. This is particularly so in rural areas. This implies that a lot of spectrum is reserved for a service that isn't using it. In 2008, the FCC voted to open up the available frequencies to unlicensed use for opportunistic users. In order to avoid causing interference to the primary users, strict regulations were established. Since then, industry suggestions have led to a few revisions, with the current regulation being established in 2012.[22]

2.2.1 Regulations for Interference Avoidance

The main regulation established by Part 15 Subpart H of the Radio Frequency Devices rules and regulations involves the use of databases to establish a list of open spectrum allocations in the area of installation. Originally, the FCC ruled that the TVWS radios would require cognitive radio technology to detect whether or not a channel is occupied. Cognitive radio can detect what frequencies are open through advanced detection algorithms, allowing secondary users to access the open frequencies and better utilize the spectrum [23]. At that time, Cognitive radio technology was, and still is, an area in need of development. The FCC decided that a database of available frequencies would take this place [22]. The open frequencies are established by a list of protected contours [24]. This gives a power level which can determine the required separation distance from an occupied channel. Some additional channels are reserved for wireless microphones, and radio astronomy use in every region.

To connect to the database and begin using available spectrum, the radios are required to know their location, either through internal GPS, or by determination from the installer.

Once the location is established, a list of available channels is given by a spectrum database provider, such as Spectrum Bridge and Google [1]. Urban areas tend to be lacking available channels, but these locations also typically have many available options for broadband Internet. Currently, TVWS networks are geared towards rural areas that don't have access to broadband speeds. Work has also been done, however, to assess their use for hotspots and indoor to outdoor networks in areas where the WiFi frequencies are overloaded. Simulations performed by Simic et al. show that urban areas would not see the same benefits of TVWS networks due to high utilization which causes a lot of interference among the radios [17], but the use in rural areas is promising.

Figure 2.1 shows the general availability of channels in the US. There are pockets in urban areas that have no channel availability, but it is clear that the majority of the US has at least 9 available channels for broadband access and other communications.

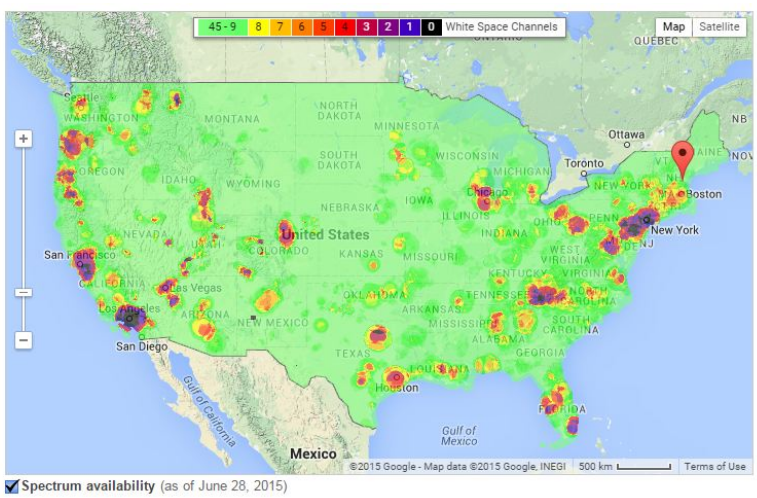


Figure 2.1: Spectrum availability throughout the US according to Google's spectrum database

[1] Spectrum Bridge database can be viewed at `https://spectrumbridge.com/tv-white-space/` and the Google database can be viewed at `https://www.google.com/get/spectrumdatabase/channel/`

In order to further limit the interference to users in channels that are unoccupied in one area, but occupied in areas surrounding the TVWS network, the FCC regulates the allowable power transmitted by the radios. The regulation states that fixed television band devices cannot deliver more than one watt, or 30 dBm per 6 MHz of channel bandwidth. This is based on an assumption of a 6 dBi gain antenna. When a higher gain antenna is used, the difference from the 6 dBi assumed has to be made up by reducing the power transmitted from the radio. The regulation calls for an effective radiated power of 4 Watts or 36 dBm to be the limit. The idea behind this rule is that keeping the power low will reduce the possibility of long distance transmissions that could interfere with licensed TV broadcasts.

As the antenna height can be a major factor in the distance over which the signal can propagate, the regulation gives strict guidelines. The antenna is only allowed to be a maximum of 30 meters above ground. Since the ground elevation can be great, as in the cases on top of mountains, the 30 meter height could be high enough to cause interference to distant receivers of the television broadcasts.

Extreme elevation would reduce the likelihood of terrain and foliage obstructing the path and restricting the distance of propagation. To avoid this issue, the height above average terrain (HAAT) is restricted to 250 meters. The HAAT is calculated by determining the average height of at least 50 points along 8 evenly spaced radials from 3.2 km to 16.1 km from the transmitter. The FCC has a calculator to determine the HAAT, and many software tools do as well [2]. Restricting the height and power allow the users of the TVWS network, who are defined as secondary users of the spectrum, to operate without interfering with the existing broadcast television networks.

[2] https://www.fcc.gov/encyclopedia/antenna-height-above-average-terrain-haat-calculator

2.2.2 TVWS Radio Development

Utilization of the TVWS is becoming a prominent topic for new and existing radio communication technologies, from development of femtocells for cell phone use [25, 26], to Internet use in underserved and underdeveloped areas. The Institute for Electrical and Electronics Engineers (IEEE) is working on a standard for deployment of these radios [27]. While this standard is still in development, radios are becoming commercialized that do not follow this standard (including the ones used in this research). This standard will help make the radios work similarly across all manufacturers, and thus become more affordable. This is similar to what the 802.11 standard has done for WiFi routers. In the meantime, the radios that have been developed and commercialized are part of trials across the world. These trials provide important information to the manufacturers and allows further development of the radios based on the information from real world trials. The Office of Communications (Ofcom) in the UK hosted a TVWS pilot to determine if white space technology can be a viable source of communications [11]. The trial concluded that the coverage region for existing broadcast television was greater than advertised at some places making it desirable to do a spectrum sweep to determine which of the available channels are best for communications. This feature is built into the radios used in this trial, allowing the radio to occupy a channel for a set amount of time, then switch to a different channel and track the results. This enables the user to select the optimal channel for use. Achtzehn et al. suggest using some measurements to help fit the prediction methods utilized by the databases to provide higher accuracy [28]. This could help simplify deployment by reducing the need to run spectrum sweeps to determine which channels function as advertised.

Other smaller scale demonstrations and trials have shown promise for TVWS devices.

Kang and Jeong developed a device to verify the coverage ability of TVWS [29]. Though the performance does not quite compare to the commercial radios seen in trials, the device did show that increased coverage over WiFi can be accomplished even with the use of the simple radio. Similar results were obtained from the report by Mack and Cartmell, where they concluded TVWS would serve well for line of sight backhaul [12]. More trials of the networks are necessary to fully assess performance of commercially available radios. As the trials continue, more knowledge can be gained that will allow the manufacturers to further develop the radios to optimize their use. A contribution of this thesis is to setup and analyze a trial of TVWS radios to further monitor their performance in a rural broadband deployment.

2.3 Path Loss

In any wireless radio communications link, the power of the signal leaving the transmitted antenna will not be the same as the power of the signal as it arrives at the receiving antenna. This reduction in power is known as path loss and must be considered when designing a communications system. The loss in power is governed by the medium over which the transmission occurs. In wired transmissions, loss also occurs, but it is minimal and predictable, caused only by the rated attenuation of the material, and any additional imperfections that could cause reflections. In wireless transmissions, the channel is full of these "imperfections" such as trees, buildings, terrain, people, and even particles in the air that can cause measurable loss at different frequencies. Because receivers have a certain power threshold required for successful reception, the path loss between the transmitter and receiver must be above that threshold or a communications link cannot be established. In communications networks where power is a limited resource, the path loss cannot be overcome by simply turning up the power. This power limitation often occurs due to regulations setting a maximum power limit, equipment power limitations, or in systems operating on battery power.

Predicting where the signal can be received reliably at these power levels is critical for planning a wireless network. The path loss can be destructive to a communications link to a point where the link cannot be established. Understanding what causes path loss is a step towards being able to predict radio connection. There are three main phenomena that cause the path loss which are diffraction, reflection, and scattering. Each phenomena can also explain how communications work in instances where normally they would not.

2.3.1 Diffraction

When an obstruction exists in the radio path, the direct line signal will be blocked and there will be a significant loss of power before reaching the receiver. Because of diffraction, however, the propagating wave can bend around or over the object to still reach the receiver; this is caused by what is known as diffraction. Explained by Christiaan Huygens in 1670, he postulated that every point on a wave front acts as a source for a secondary wave [30]. When this wave hits a sharp edge, like the corner of a building, or the top of a hill, the wave can effectively bend around the obstruction as seen in Figure 2.2. This region blocked by the obstruction is known as the shadowed region, much like when an obstruction blocks a light source. Though there can be significant loss in the shadowing region, potentially making a link unusable, the phenomenon of diffraction allows the signal to be seen even without a line of sight to the source.

This bending of the signal is called refraction when there is no physical obstruction, but still the existence of a barrier of different electrical characteristics in the air. This allows the signal to propagate further around the curved earth as well. If signals only traveled in a straight path, the curved earth would greatly limit how far the signal could travel as it would

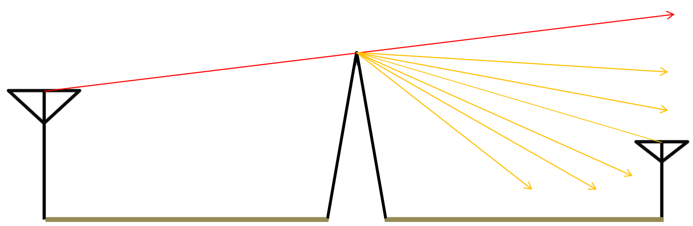


Figure 2.2: Example of diffraction of the top of a hill where the ray can "bend" into the shadow region

just go off into space beyond the horizon. Though this does occur to an extent, diffraction and refraction allow the signal to bend around the earth and travel at much greater distances.

2.3.2 Reflection

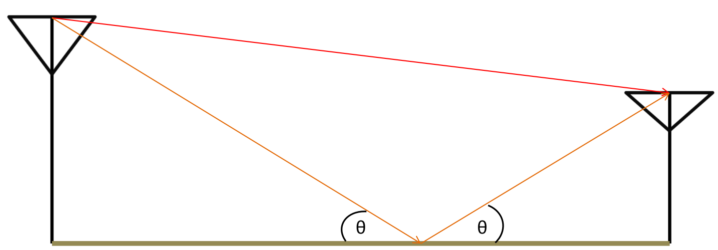
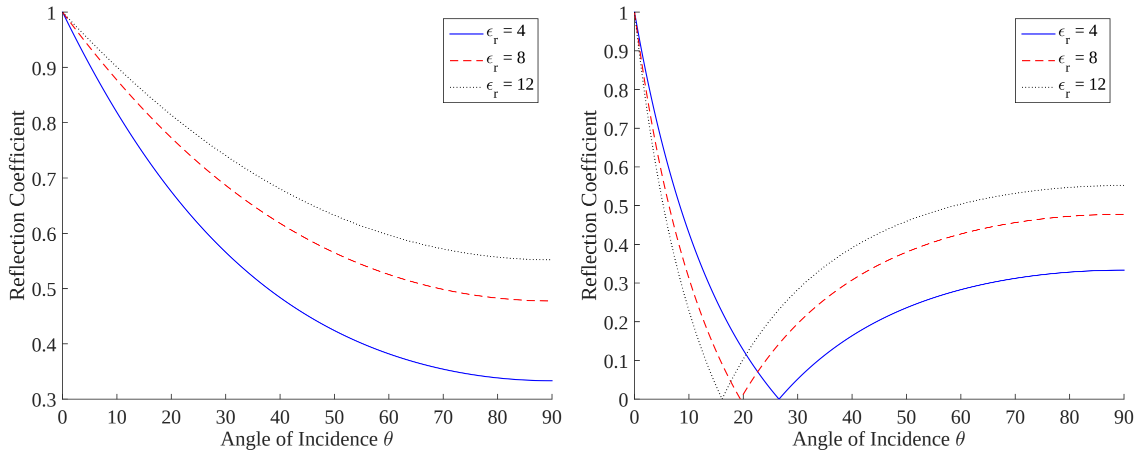


Figure 2.3: Example of the signal reflecting off the ground to arrive at the receiver

When the radio wave encounters a surface with different electrical properties (i.e. the ground or a wall) a portion of the signal will be reflected off the surface at the angle of incidence as seen in Figure 2.3. Some of the signal may be absorbed by the surface, and some will be transmitted into the surface resulting in loss of power in the signal. When considering the ground, total reflection may be desired as any portion transmitted into the ground is going to reduce the signal seen at the receiver. In certain cases, however, the signal can arrive out of phase from the reflection causing loss at the receiver in the form of the signal canceling itself out. Because of this, the ground reflections can cause additional loss, even though more signal arrives at the receiver. Conversely, when considering a wall obstructing the path, more signal is desired to be transmitted into (and through) the wall. The amount of signal reflected versus the signal incident to the surface is known as the reflection coefficient. This coefficient is dependent upon the angle of incidence of the signal as it hits the surface, and the dielectric constant, ϵ_r, of the surface. Figure 2.4 shows the reflection coefficient as the angle of incidence changes for horizontal and vertical antenna polarization. For clarity, vertical antennas are those whose E-Field components are perpendicular to the ground. In this case, the reflection coefficient plots in Figure 2.4 are for ground reflections. For a wall that is parallel to the E-Field from a vertical antenna, the plots would be switched. For vertical antennas, there is an angle where total transmission of the signal into the ground exists. This occurs at a specific incident angle known as the Brewster Angle. Egli presented evidence that antenna polarization has little effect on path loss when the antenna heights are above one wavelength due to the small incident angle [31]. It is seen that for both polarizations the reflection coefficient approaches 1 as the angle approaches 0°. This allows total reflection to be assumed for grazing angles, which can help simplify propagation analysis.

Though this reflection can be either constructive or destructive to the signal, it is useful for having increased signal strength in areas where otherwise the signal would not be seen, or not at those levels.

Reflection is also a contributor to what is known as "ducting". In long distance links, different electrical characteristics in the atmosphere due to varying compositions of gas and



(a) Horizontal Polarization (b) Vertical Polarization

Figure 2.4: Reflection coefficient off flat ground for horizontal and vertical antenna polarization

even weather patterns can cause the reflection off the different layers. This ducting allows signals to travel much further than under typical line of sight (LoS) conditions, since the signal is guided through the atmosphere [32]. A similar case occurs in cities where the "urban canyon" effect takes place. Though the urban canyon term is commonly used to describe the loss of LoS to satellites and other antennas among tall buildings, it can also explain how the signal from a low transmitter can reflect down streets, bouncing off buildings as it travels to the receiver. This can help increase the signal seen at the receiver by using the buildings as a sort of lossy wave guide. Some work has been done to model the buildings as wave-guides with good agreement to measurements [33]. These two cases can help extend communications links to unreachable places, but they may not apply to rural TVWS access as the antenna heights and transmission power limits the ability to utilize an atmospheric duct and there are not typically buildings the could cause the urban canyon in a rural area. Additionally, atmospheric ducts are not a reliable source of communications over long periods of time. Because of this, it is not usually considered in coverage analysis.

2.3.3 Scattering

When a wave hits an object that is much smaller than a wavelength, the wave will be scattered into many different directions. This is observed heavily in rural areas where foliage coverage is great. The leaves on trees causes the signal to scatter as seen in Figure 2.5 and sometimes this can provide significant loss. At higher frequencies (greater than 11 GHz), precipitation can be a significant cause of loss. Rain fade is a concern in satellite communications that operate at these higher frequencies. Though line of sight can be easier to establish with satellite as the transmitter is up in space, well above trees and hills, the rain fade can cause significant loss, reducing the signal even to a point of losing communications. This makes the lower UHF frequencies in TVWS desirable for Internet connectivity over satellite [34].

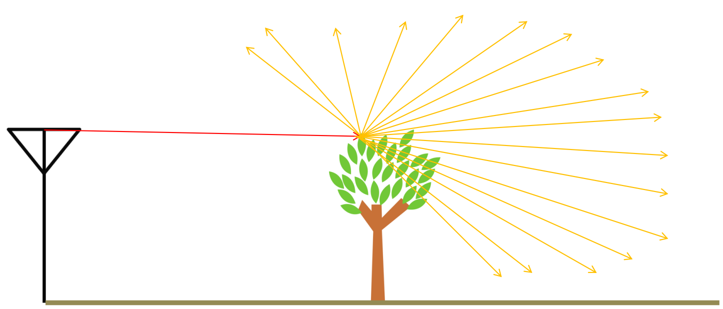


Figure 2.5: Example of the signal scattering off a leaf of a tree and the resultant scattered wave leaving in all directions

This scattering is also seen when a propagating wave hits a rough surface. Reflection is assumed to be perfect when the wave hits a surface at a particular incident angle, resulting in a reflection coefficient of 1. On a rough surface, however, the reflection coefficient is adjusted by the scattering loss factor, ρ_s on the form of (2.1) at the incident angle, since a portion of the signal will now be scattered in other directions.

$$\Gamma_{rough} = \rho_s \Gamma_{smooth} \tag{2.1}$$

This will cause less of the signal to be reflected at the source of the impact. Scattering can actually help the reception of the signal in the same way it can harm reception. Since the signal is scattered in all directions, more energy may reach the receiver than simply from reflections and diffraction. Scattering is an idea that is not considered in this research, as when the angle approaches 0°, the reflection coefficient approaches 1.

2.3.4 Link Budget

To account for every component in the propagation path from transmitter to receiver, the designer creates what is called a link budget. This equation (2.2) takes into account transmit power, P_{Tx}, antenna gains, G_{Tx} and G_{Rx}, component losses, L_{Tx} and L_{Rx} (i.e. from cables and connectors), and the path loss PL which is determined by path loss models or measurement, and gives the predicted receive power P_{Rx}. Using this equation with the performance threshold set by the communications hardware, the fade margin can be determined. The fade margin (M) is a value of power built into the design to allow for statistical variations in the signal. Most empirical propagation models will predict the median path loss and not give any information on statistical variations from differences in terrain, weather and channel variations [1, 2, 35].

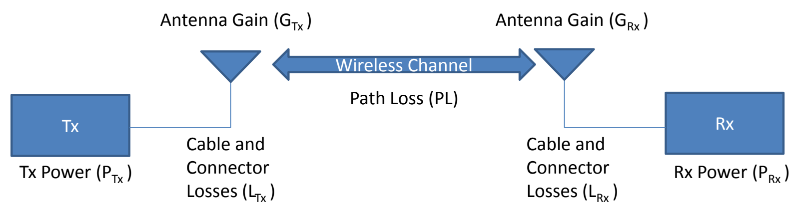


Figure 2.6: Diagram of wireless communications channel

$$P_{Rx}(dB) = P_{Tx} - L_{Tx} + G_{Tx} - PL + G_{Rx} - L_{Rx} - M \tag{2.2}$$

Certain techniques can be used to predict whether the power received at a certain location will be above the performance threshold(s) while taking into account some of the causes of loss discussed here. These tools are known as propagation models. These models have been developed from electromagnetic principles, and/or empirical measurements and have a certain range of valid input parameters. The lower UHF frequencies utilized by TVWS have a handful of well known propagation models that are applicable in the TVWS frequencies and a few are explored here for use in TVWS deployment planning.

2.3.5 Ground Effects

The most basic of propagation models (Free Space Path Loss) assume that the radio wave propagates from the transmitter to the receiver in a straight line with no obstructions. This is referred to as line of sight (LoS) propagation. In LoS propagation, the only loss component is the distance between the transmitter and receiver. The idealized situation of LoS is often not the case. The radio wave will propagate directly between the transmitter and the receiver, but it will also leave the transmitter at other directions resulting in reflections, scattering, and diffraction off buildings, trees and the ground. In the rural environment, buildings are not as common as in the urban environment, but hills and trees are often very dense. There have been ways to account for these effects when considering deployment. Simplifications can be made to create a good prediction of the losses associated with the imperfections in the path.

2.3.5.1 Fresnel Zone

In the International Telecommunication Union (ITU) Recommendation P. 526-13 [36], it is stated that diffraction off obstructions can affect the LoS path loss if the obstruction is within the first Fresnel zone. The Fresnel zones are a set of ellipsoids centered on the direct path of the signal with radii following (2.3).

$$R_n = 550 \left[\frac{n d_1 d_2}{(d_1 + d_2) f} \right]^{\frac{1}{2}} \tag{2.3}$$

In (2.3) n represents the n^{th} ellipsoid or Fresnel zone, d_1 and d_2 represent the distance between the point of interest and the transmitter and receiver in km respectively, and f is the frequency in MHz. The result is the radius of the nth ellipsoid in meters at the particular point. Any obstructions to these zones, be it trees, hills or buildings and other man-made objects, can form destructive or constructive interference to the signal propagation. Outside of the first Fresnel zone, the loss will be minimal and can be neglected. Typically, the rule of thumb is if 60% of the first Fresnel zone is cleared, LoS can be assumed as any reflections will be negligible. Typically, this zone is represented as two dimensional, as it is here, but it is really extended in all three dimensions.

Alternating Fresnel zones will have alternating effects on the signal between constructive interference in the odd Fresnel zones from the signals arriving in phase and adding together, and destructive interference in the even zones as a result of out of phase signals that may cancel. This results from the phase relationship between the direct wave and the reflected wave. The further the path the reflected wave travels results in a phase difference from the line of sight signal. If the phase shift is not a multiple of 360°, there will be a loss of the signal when added with the line of sight signal due to cancellation. This is undesired, but, with restrictions on antenna height, unavoidable, so it should be predicted to determine link availability.

2.3.5.2 Knife-Edge Diffraction

When an obstruction blocks the LoS path, the signal can still reach the receiver by means of diffraction. Though it is nearly impossible to make precise estimates, it is possible to approximate the loss based on simple geometrical approximation of the terrain. The obstruction can be represented by a single diffracting knife edge as in Figure 2.7

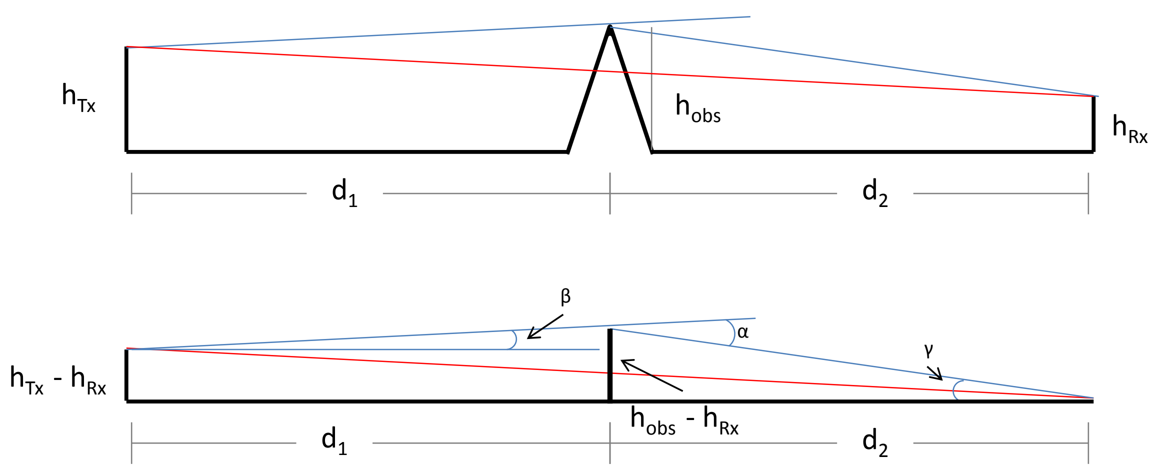


Figure 2.7: Diagram showing how an obstruction can be represented as a diffracting knife edge

In this example, the receiver is in the shadowed region of the obstruction. The diffraction of the signal off the peak of the obstruction will allow the signal to reach the receiver, but with significant loss in power. By subtracting the lower antenna height (either transmitter or receiver) from the rest of the heights, an equation for the Fresnel-Kirchhoff diffraction parameter, ν, can be developed as seen in (2.4) with units following Figure 2.7 and $\alpha = \beta + \gamma$, with β and γ being the departure angle from the transmitter and the arrival angle to the receiver respectively as seen in Figure 2.7.

$$\nu = \alpha \sqrt{\frac{2 d_1 d_2}{\lambda (d_1 + d_2)}} \tag{2.4}$$

The Fresnel-Kirchhoff parameter can be used to normalize the phase difference that is a result of the longer path taken by the wave (traveling over the obstacle versus a straight line path). The phase difference is then $\phi = \frac{\pi}{2}\nu^2$. This diffraction parameter can then be used to calculate the diffraction gain from the Fresnel integral. The Fresnel integral is seen in (2.5) and the diffraction gain is seen in (2.6).

$$F(\nu) = \frac{E_d}{E_0} = \frac{1+j}{2} \int_{\nu}^{\infty} e^{\frac{-j\pi t^2}{2}} dt \tag{2.5}$$

$$G_d(dB) = 20 \log |F(\nu)| \tag{2.6}$$

Due to the complexity of the equation, graphical or numerical solutions are often relied upon to compute the diffraction loss. Simplifying the loss over a range of ν values allows the loss to be approximated. These simplifications of the Fresnel integral can be seen in Table 2.1 from [1].

Approximate Diffraction Gain	**Range of ν**
$G_d(dB) = 0$	$\nu \leq -1$
$G_d(dB) = 20\log(0.5 - 0.62\nu)$	$-1 \leq \nu \leq 0$
$G_d(dB) = 20\log(0.5e^{-0.95\nu})$	$0 \leq \nu \leq 1$
$G_d(dB) = 20\log(0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2})$	$1 \leq \nu \leq 2.4$
$G_d(dB) = 20\log(\frac{0.225}{\nu})$	$\nu > 2.4$

Table 2.1: Table of approximated diffraction gains [1]

Using this approximation, one of the locations of interest in this trial is examined. The Lee Library, located 6.3 km from the UNH campus has a large terrain obstruction blocking the LoS path from the base station. This obstruction has a height of roughly 76 meters at a distance of 4.76 km from the base station. With (2.4)-(2.5) and Table 2.1, computer simulations are used to compute the approximate loss to be roughly 13.87 dB from this terrain obstruction. This will prove to be significant loss as will be discussed in Section 3.6.3. This loss is greatly reduced from what would be seen at higher frequencies. If 2.4 GHz, the frequencies used for WiFi, were used for this sort of connection, the same calculation would result in a predicted loss of roughly 25 dB. This 11 dB decrease in loss is huge and shows the value of the lower UHF frequencies and TVWS.

2.3.5.3 Multiple Knife-Edges

In very hilly or urban areas, and in longer communications links, it is not uncommon to have multiple obstructions in the path. There have been various simplifications developed to account for the different obstructions [4]. To accurately predict the loss from multiple obstructions is very difficult and no exact solution exists. These few simplifications, however, can help understand the loss that will be seen.

Bullington's Method: In this method, each of the obstructing knife edges are replaced by a single, equivalent knife edge. This knife edge is found by the intersecting lines from each of the Tx and Rx to the knife edge with the steepest tangential lines respectively. This will typically give an optimistic, under-prediction of the loss that will be seen as it is effectively ignoring the obstructions that do not have the steepest tangential lines. These obstructions could be the tallest obstructions at times, which would normally have an effect on propagation. This simplification, though, requires minimal computation effort and can be used with some understanding of the potential errors.

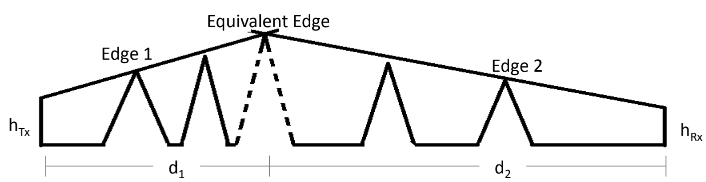


Figure 2.8: Equivalent screen representation of multiple knife edges proposed by Bullington

The Epstein-Peterson Method: Since the Bullington Method has inherent inaccuracies due to only using two obstructions to establish the loss, other methods have been derived. One of those known as the Epstein-Peterson Method. This method will compute the loss seen by each knife edge individually, by assuming the transmitter and receiver to lie on the tip of the knife edges to the left and right of the obstruction. Each individual edge loss is then added together to compute the total diffraction loss from all edges. This result is generally an improvement over the simplified Bullington method. Significant errors, however, can arise if the edges are close together as the electromagnetic and physical principles behind the derivation of the knife edge model begin to lose accuracy. Figure 2.9 shows an example of the Epstein-Peterson Method.

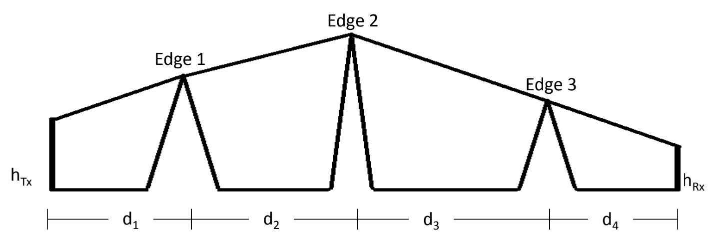


Figure 2.9: Representation of edges for the Epstein-Peterson and Deygout methods for multiple knife edges

Deygout's Method: Deygout's method is similar to the Epstein-Peterson method as shown in Figure 2.9, as each edge is taken into consideration. When complete, however, only the edges with the greatest impact on the loss are considered. First, the loss from every edge is determined as if it was the only edge present. The edge with the highest loss is taken as the main edge. Then the loss from the Tx or the Rx to the main edge based on other edges between the obstruction and the Tx or Rx is found taking the largest as the secondary edges. This is continued until each edge is considered in the loss. At this point, all of the losses are added (in dB) to find the total loss.

The Epstein-Peterson method and Deygout's method can require significant computations to determine the loss. Meeks performed work conducting measurements in VHF frequencies and it was determined that using the Deygout method, only 2 edges were needed to provide good prediction results [37]. Any more would not improve the prediction results enough to validate the extra computation time.

Each of these methods provide an improvement over the single knife edge approximation. In this study, there were no locations where multiple edges could be analyzed. This situation may arise in other, more hilly areas, but the reduced coverage range from the low power and low antenna heights makes it not as common an occurrence as in long distance communications.

2.3.6 Foliage Loss

Another major factor of loss in rural areas is determined to be that from trees. Foliage in trees will act as diffracting, reflecting, and scattering sources. TVWS signals are said to be able to propagate through trees at minimal loss compared to the higher frequencies of WiFi. This is mostly due to the size of the leaves with respect to wavelength. The wavelength of a TVWS signal is on the order of 0.5 meters. A WiFi signal operating at 2.4 GHz has a wavelength of 0.125 meters. This will cause the branches, tree trunks, and leaves to act more like reflecting sources in WiFi than like scatterers in TVWS. This results in increased loss as explained by foliage loss models.

There are three main, widely used loss models for estimating foliage loss with some variations discussed here. They have been developed from empirical measurements at different frequencies and can give the additional loss due to propagation through forests. [38–40]

2.3.6.1 Weissberger's Modified Exponential Decay Model

This model is used for situations where propagation occurs through a forest with dense dry leaves versus over the top of trees [41]. There is agreement with the model at many different frequencies and heights as described in the report. The model shown in (2.7) gives the loss through a path of dense, dry, in leaf trees up to a distance of 400 m. For antenna heights below the treeline at both the receiver and the transmitter, this may not be enough

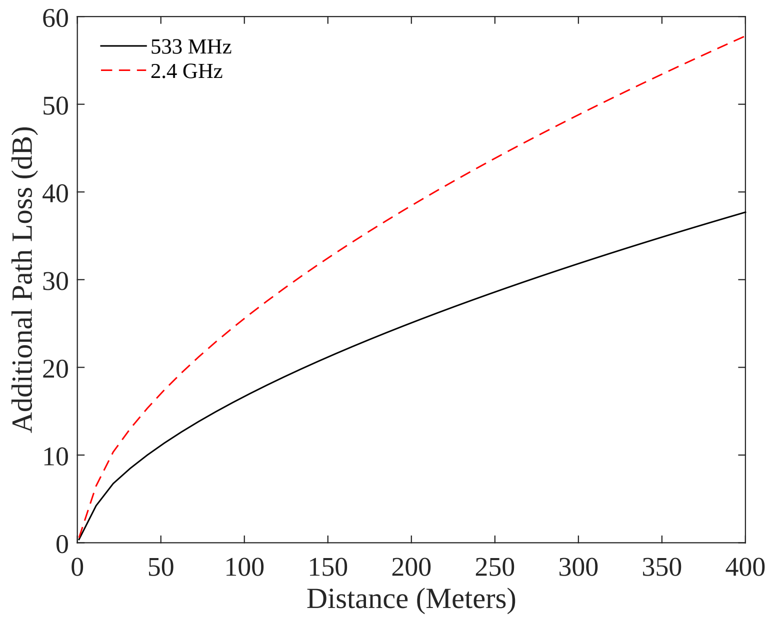


Figure 2.10: Loss due to foliage as predicted by the Weissberger Model

distance, but when one of the antennas can be placed above the treeline, the distance limits may be sufficient. There is an obvious frequency dependency involved with the formula as is also seen in Figure 2.10 where the measurement frequency in this study of 533 MHz is compared to 2.4 GHz used in WiFi. It is clear that TVWS frequencies suffer much less loss through extensive stretches of foliage.

$$L_{Weiss} = \begin{cases} 1.33xf^{0.284}d^{0.58} & 14m < d < 400m \\ 0.45xf^{0.284}d & 0m < d < 14m \end{cases} \tag{2.7}$$

2.3.6.2 ITU-R Model

Like Weissberger's model, the ITU-R Model was developed for forest depths of under 400 meters. It was designed from measurements in the UHF frequencies where the majority

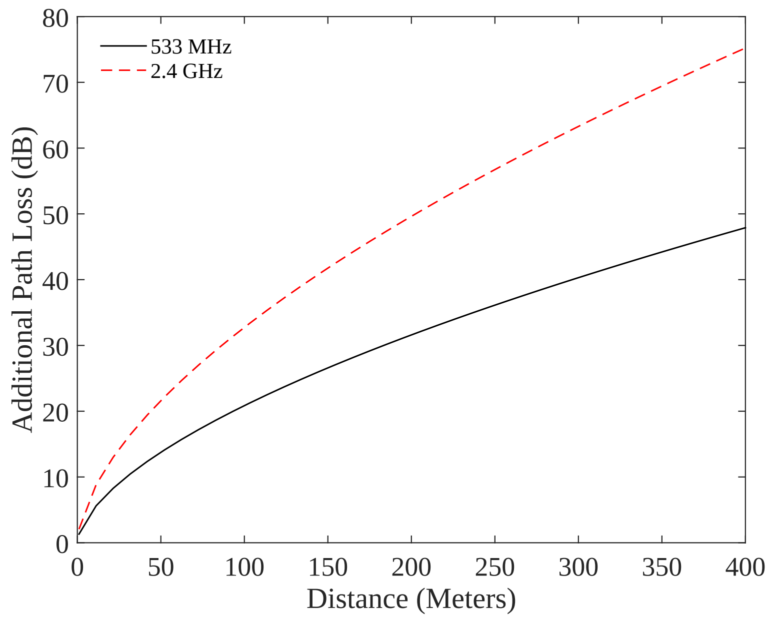


Figure 2.11: Loss due to foliage as predicted by the ITU-R Model

of the signal near the transmitter or receiver travels through the trees. This model is not broken up into different distances like the Weissberger model. Though they are very similar in result for short distances, they begin to diverge as the distance increases as is apparent in Figure 2.14. Like the Weissberger model though, it shows that the lower frequencies in TVWS show less loss than WiFi which is consistent with other studies. This can be seen in Figure 2.11.

$$L_{ITU-R} = 0.2xf^{0.3}d^{0.6} \tag{2.8}$$

2.3.6.3 Fitted ITU-R Model

To account for variations from measurements seen in research, the fitted ITU-R model was developed. This model helps improve the predictions for the measurements made at higher frequencies of 11.2 GHz and 20 GHz. This results in a lower loss found when dis-

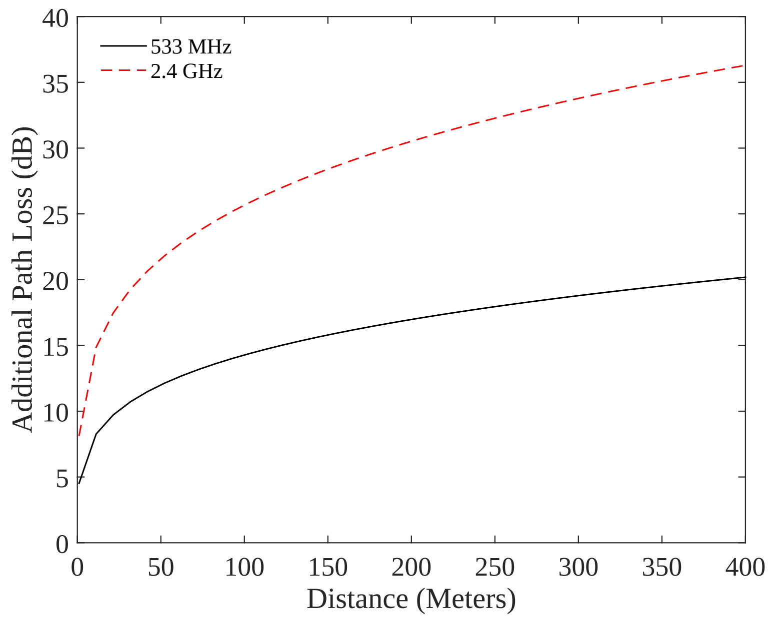


Figure 2.12: Loss due to foliage as predicted by the Fitted ITU-R Model

tances increase compared to the Weissberger and ITU-R model. At shorter distances, however, it predicts a higher loss. This model is designed for higher frequencies based on the measurements made to form the model [42] but extension to other frequencies is possible [40].

2.3.6.4 Fitted ITU-R Model considering the Lateral Wave

Since the model described previously are for shorter distances, Meng et al. fit data from longer distance measurements to a new model [40]. They found that as distance increases at low frequencies, the lateral wave that travels over the top of the trees becomes dominant. This results in a reduced effect from the foliage at larger distances as the dominant signal traveled over the top of the trees as opposed to through them. Figure 2.13 shows how with the lateral wave, the foliage loss that is addition to the predicted path loss almost plateaus as distance increases. This model was designed for VHF frequencies where the lateral wave

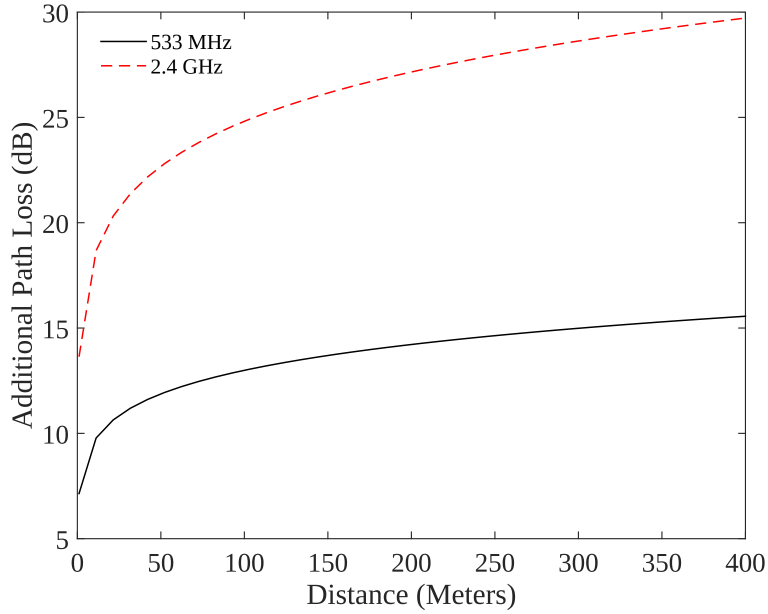


Figure 2.13: Loss due to foliage as predicted by the Fitted ITU-R Model that accounts for the lateral wave

takes greater effect, but could be applicable in the lower UHF bands as well. This would need to be verified, but is outside of the scope of this work.

$$L_{LITUR} = 0.48f^{0.43}d^{0.13} \tag{2.9}$$

Each of the previous foliage models shown can help explain how propagation in forested environments can provide excessive loss, even at the lower frequencies of TVWS. A comparison of each of the models in Figure 2.14. In this research, foliage loss specifically was not a focus, but using these models, the variations seen with other propagation models can be explained.

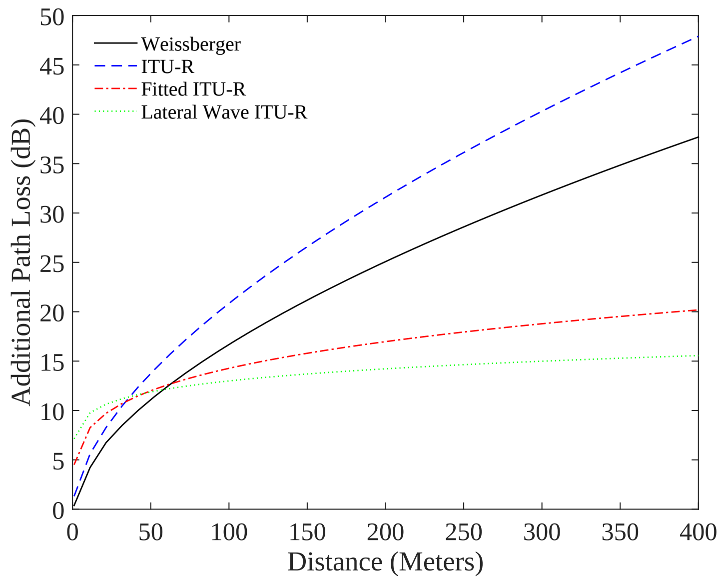


Figure 2.14: Loss due to foliage as predicted by each of the models discussed at 533 MHz

2.3.7 Multipath Fading

In the wireless environment, the propagating ray will typically arrive at the receiver from a number of different directions. If there is a LoS view to the transmitter, a single ray will be the dominate ray seen at the receiver. Except for wide open areas or very high antennas, however, the ray will come from multiple paths at similar power levels. This is due to reflections and scattering off objects in the propagation path. Since the ray will bounce off one or more objects, it will travel over a longer path to get to the receiver. This will cause a phase shift to be seen, as well as a reduction in power from the signal being split up at the point of impact on the object. This phase shift can add with the dominate ray and form constructive or destructive interference. If the rays are in phase, they will add together and provide more power than the direct ray alone. If they are out of phase they will cancel out part or even all of the signal. This is what is referred to as multipath fading and also called small scale fading (vs the large scale fading of terrain variations etc.) [1]. Fading can change over short periods of time and over short distances due to the varying channel from objects such as cars and branches moving and changing orientation based on the signal path. It is also seen when the receiver is moving with respect to the transmitter. This is a major concern in mobile systems, but in this research, only stationary receivers were explored. Because of this, the main concern is the multipath variations.

Each propagation channel has what is known as a coherence bandwidth. This is the maximum bandwidth of a signal that can propagate through the channel and see flat loss over the entire frequency span of the signal. When signals of larger bandwidth than the coherence bandwidth are used in the channel, it will suffer frequency selective fading which will appear as nulls in the signal spectrum. Frequency selective fading will create inter-symbol interference (where one portion of the transmitted signal interferes with another portion) and cause errors from the lost information. In order to overcome this in a receiver, equalization techniques must be used. Equalization can allow signals suffering this multipath loss to still be received and function as if the loss was not seen. These equalization techniques come in many forms, and the radios used in this study utilize proprietary techniques that can provide improved reception for the 6 MHz bandwidth signal in the multipath environment that exists with low antenna heights in the wireless environment.

2.4 Propagation Models

In order to predict path loss and therefore communication performance, propagation models have been developed. The simplest models are known as empirical models and are developed by fitting actual measurements in different environments. These models can help predict the median path loss at a given distance in different environments similar to the environment in which they were developed. They are sometimes referred to as point-to-area models since they will predict the path loss from a single point to a distance, covering a particular area. More advanced models that can predict the path loss to a specific point are known as deterministic models. These point-to-point models use electromagnetic wave theory to calculate the loss due to actual terrain and clutter in the propagation path. The accuracy of the deterministic models is heavily influenced by the quality of the terrain and clutter data that is used with the models. Getting accurate data can be cost prohibitive and may not be an option in low cost deployments of TVWS networks. Using empirical models and freely available deterministic models is the best and most affordable option for these deployments. A few popular models are described here.

2.4.1 Free Space Path Loss and the Two-Ray Model

The model behind all ideas of propagation is the Free Space Path Loss Model [43]. Developed from the Friis free space equation, the Free Space Path Loss model is the basic path loss equation. It only accounts for the reduction in power due to the distance between the transmitter and receiver and the frequency of operation. The Friis model (2.10) shows a dependency on wavelength λ and antenna gains, G_t and G_r, as well as a system loss factor, L, which is not related to propagation. As the gains of antenna and wavelength are frequency dependent, it shows how frequency can affect loss at the receiver and transmitter. Since the Free Space model (2.11) is a logarithmic representation of the Friis equation and only considers distance and frequency and not other loss factors in the path, it is used here only for a basic comparison,where d is the distance in meters and f is the frequency in GHz.

$$PL_{Friis} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2.10}$$

$$PL_{FreeSpace} = 20\log(d) + 20\log(f) + 32.4 \tag{2.11}$$

To account for a single ground reflection in addition to the line of sight ray, the Two-Ray model is used [1]. Much like the Free Space model, this basic model will give a baseline prediction, accounting for a single, dominant reflection off of the ground as discussed in Section 2.3.2. At longer distances, typically measured as $d > \frac{20h_t h_r}{\lambda}$, the incident angle will be small and near perfect reflection will occur when scattering is ignored. This will result in the path loss increasing with distance to the fourth power. With the free space model, which only accounts for one direct ray, the path loss increases with distance squared. This extra reduction from the interfering reflected wave can be modeled by (2.12). It does not account for reflections off of buildings and trees or statistical variations like some of the more advanced models, but it can give a baseline approximation for path loss. The Two Ray model contains only the parameters d, the distance in meters; h_t, the transmitter height in meters; and h_r, the receiver height in meters.

$$PL_{TwoRay} = 40\log(d) - 20\log(h_t) - 20\log(h_r) \tag{2.12}$$

This equation holds for large distances, but closer to the transmitter free space may be the dominant loss factor since the reflection coefficient will be reduced and the free space model may best approximate this loss. These models will be a good base level approximation for TVWS trials. When there is terrain that is not perfectly flat, or if there is a lot of clutter in the path, these models begin to lose accuracy quickly. Using empirical models that were designed from measurements in more lossy terrain and land cover, or software tools such as Radio Mobile that take the terrain into account, will better predict the performance in urban and dense forested rural areas.

2.4.2 Egli Model

The Egli model was designed from measurements in areas along the eastern seaboard of the U.S. in the late '50s [31]. These measurements were made at the UHF and VHF frequencies from television broadcast towers. The model is useful for point-to-area coverage in areas with similar terrain irregularities and foliage coverage. The model was designed as an extension to the two-ray or plane earth model. This model, as described above, is only truly valid in flat areas with no clutter [44]. This model provides an improvement over the Two-Ray model by incorporating empirical measurements to include terrain and clutter which can have a significant effect on path loss. The model (2.13) has components of the two ray model, with the d^4 loss component, and the frequency dependency of the free space model. Additional loss factors are included to account for the fact that terrain variations and foliage can become a contributing factor. The model works well for the TV broadcast systems over which the measurements are made. Since they are the same frequencies, the model holds well for TVWS use. Since the antennas are lower, however, some accuracy may be reduced from the model as explored in this research.

$$P_R = \left(\frac{40}{f}\right)^2 \frac{(h_t h_r)^2}{d^4} P_T G_T G_R \tag{2.13}$$

where f is the frequency in MHz, h_t and h_r are the transmit and receive antennas respectively, both in meters, d is the distance in meters, P_T is the transmission power in Watts and G_T and G_R are the transmit and receiver antenna gains in linear terms.

2.4.3 Okumura-Hata Model

Early on in communications planning, field strength curves were developed from measurements under different system parameters. The curves developed by Okumura in the 1960s were used to give engineers a tool to predict the signal strength at a given distance in certain terrain and clutter categories with graphical methods. As these graphical methods may have been simple to use for spot measurement in the field, using them for many separate locations was not as efficient once computers grew in computation ability. Hata made an empirical formulation of the graphical methods established by Okumura [35]. This model, aptly named the Okumura-Hata model, was widely used for propagation predictions in the UHF frequencies. The Hata formulation follows (2.14) where f_c is the operating frequency valid in the range of 150-1500 MHz, h_b is the base station height from 30-200 m, R is the receiver distance from 1-20km, h_m is the receiver height and $a(h_m)$ is the correction factor for the receiver height in different environments. The correction factors are given in (2.15) and (2.16)

$$PL_{HATA} = 69.55 + 26.16\log(f_c) - 13.82\log(h_b) - a(h_m) + (44.9 - 6.55\log(h_b)\log(R) \quad (2.14)$$

For a medium to small city:

$$a(h_m) = (1.1\log(f_c) - 0.7)h_m - (1.56\log(f_c) - 0.8) \quad (2.15)$$

For a large city:

$$a(h_m) = \begin{cases} 3.2(\log(11.75h_m))^2 - 4.97 & \text{if } f_c \geq 400 \text{ MHz} \\ 8.29(\log(1.54h_m))^2 - 1.1 & \text{if } f_c \leq 200 \text{ MHz} \end{cases} \tag{2.16}$$

Correction factors are also included for suburban and rural areas. These areas are defined as having quasi-smooth terrain and minimal clutter compared to the urban areas. This gives a reduced loss from the urban environment and should be considered. These terms given in (2.17) and (2.18) are subtracted from the loss in (2.14).

For a suburban area:

$$K_r = 2\left(\log\left(\frac{f_c}{28}\right)\right)^2 + 5.4 \tag{2.17}$$

For a rural area:

$$K_r = 4.78(\log(f_c))^2 - 18.33\log(f_c) + 40.94 \tag{2.18}$$

2.4.4 Okumura-Hata Model Modifications

In research performed by Mumtaz et al., measurements were made with the TVWS planning in mind [45]. It was found that the Okumura-Hata model produced accurate median results in their field strength tests in Germany. Their rural application involved mostly near-LoS links. Not all rural areas can have mostly LoS links. The TVWS trial conducted around the UNH campus involves many non-LoS links, so certain terrain and dense foliage conditions have to be considered. Modifications have been based on measurements conducted in what is described as similar rural environment[2]. The authors, Medeisis and Kajackas, found that the urban model, seen in (2.19), can have significant errors in rural predictions. Breaking the model down to its separate parts, as seen in (2.20)-(2.22), the constants pertaining to the channel (E_0 and γ) can be fit to the data at different frequencies.

The Okumura-Hata Urban Model is used where E_R is in $dB(\mu V/m)$ with variable explanations in Table 2.2.

$$E_R = 35.55 + P_{BS} - 6.16log(f) + 13.82log(h_{BS}) + a(h_{MS}) - (44.9 - 6.55log(h_{BS}))log(R^{\gamma}) \tag{2.19}$$

Parameter	**Definition**
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)
γ	1

Table 2.2: Variables used in the Okumura Hata Model

$$E_0 = 35.55dB(\mu V/m) \tag{2.20}$$

$$E_{SYS} = P_{BS} - 6.16\log(f) + 13.82\log(h_{BS}) + a(h_{MS}) \tag{2.21}$$

$$\gamma_{SYS} = -\gamma(44.9 - 6.55\log(h_{BS})) \tag{2.22}$$

Combining the equations, the new form of the Okumura-Hata model is seen in (2.23). This allows for fitting coefficients to the measured data. Through the author's measurements, the adjusted coefficient were found for VHF and UHF frequencies shown in Table 2.3

$$E_R = a + b * \log(R) \tag{2.23}$$

$$a = E_0 + E_{SYS} \tag{2.24}$$

$$b = \gamma_{SYS} \tag{2.25}$$

	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 2.3: Calculated empirical parameters for the modified Okumura-Hata model[2]

The terrain in the measurement campaign in their work is similar to the UNH area, which allows these corrections to be compared to measurements in this research. The frequency used in their work is slightly lower than that here so some errors may arise. The difference is not so great, however, that the equation should become invalid.

2.4.5 Stanford University Interim (SUI) Model

The Stanford University Interim (SUI) model was developed to improve prediction results from models like the Okumura-Hata model for cases with lower antenna heights and different terrain categories [46, 47]. The model, shown in (2.26), 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).

$$PL = A + 10\gamma \log(d/d0) + s; \quad for\ d > d0 \tag{2.26}$$

Parameter	Definition
A	$20\log(\frac{4\pi d_0}{\lambda})$
λ	wavelength in m
γ	$(a - bh_b + \frac{c}{h_b})$ (the path loss exponent)
h_b	height of the base station antenna in m between 10 m and 80 m
d_0	100 m

Table 2.4: Variables used in the SUI Model

For the definitions in Table 2.4, a, b, and c, are constants that are dependent on the terrain category, as seen in Table 2.5

The formulation also includes a shadowing component. This component (s in (2.26)) will account for Doppler spread and multipath delay, among other loss factors. The typical standard deviation from the shadowing component is between 8.2 and 10.6 dB. The shadowing was determined by the test data that developed the model, and can be expressed as:

$$s = 10x\sigma_\gamma \log\left(\frac{d}{d_0}\right) + y\mu_\sigma + yz\sigma_\sigma \tag{2.27}$$

where x, y, z are Gaussian random variables, $\mathcal{N}[0,1]$. 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 severe terrain and foliage differences in the path as well as weather variations, movement of cars and tree branches into the propagation and reflection paths, etc. The shadowing statistical values from Table 2.5 are defined to work from 1GHz to 4GHz by the authors of the paper [46], so this shadowing term is not used in this research. With enough measurements, however, a similar formulation of the statistical parameters could be developed to better describe the varying channels. This is outside of the scope of this report, but should be considered for future work as communication networks in TVWS become available.

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 2.5: Constant values for SUI model

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

$$PL_{modified} = PL + \Delta PL_f + \Delta PL_h \tag{2.28}$$

where PL is the path loss given in (2.26), ΔPL_f (in dB) is the frequency correction term (2.29)

$$\Delta PL_f = 6 \log \left(\frac{f}{2000} \right) \tag{2.29}$$

where f is the frequency in MHz, and ΔPL_h (in dB) is the receive antenna height correction term ((2.30) and (2.31))

$$\Delta PL_h = -10.8 \log \left(\frac{h}{2} \right) \quad \text{for Type A and B} \tag{2.30}$$

$$\Delta PL_h = -20 \log \left(\frac{h}{2} \right) \quad \text{for Type C} \tag{2.31}$$

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 in every case. This is the downfall of the empirical mean path loss models, that can be overcome by point-to-point models. The accuracy of the average loss can give a good idea of the general coverage area.

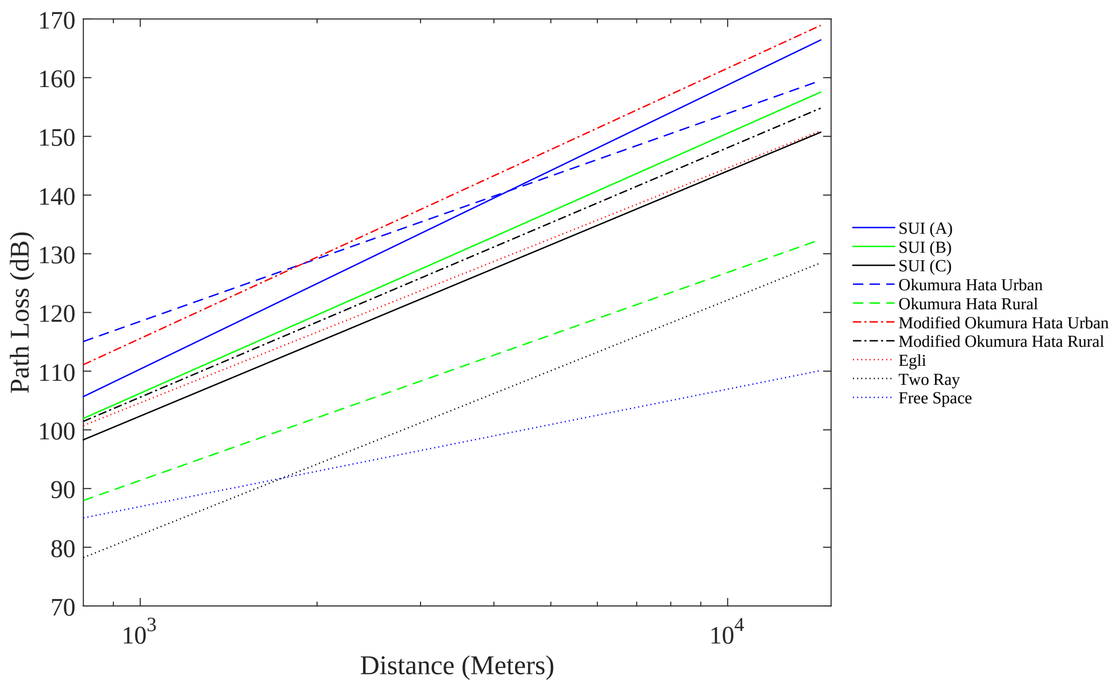


Figure 2.15: Comparison of the different path loss models

2.5 The Longley-Rice or Irregular Terrain Model

While the empirical propagation models listed in the prior section can give a good approximation for path loss in different environments, being able to incorporate terrain data in a deterministic model is essential in rural applications. Models such as the SUI model provide a couple of options to consider terrain effects, but selecting the appropriate terrain category is not always easy to do. Using accurate terrain data will allow a better consideration of certain obstructions in the propagation path that could hinder signal propagation. High accuracy ray tracing models are available, but knowing the precise location of every obstruction in the ray path is required to provide the accuracy. Freely available models such as the Longley-Rice model can be used to provide affordable deterministic predictions at the cost of decreased accuracy.

The Longley-Rice (LR) model [48], also known as the Irregular Terrain Model (ITM), developed by the National Telecommunications and Information Administration at the Institute for Telecommunications Sciences, used electromagnetic theory and terrain features along with empirical measurements to develop an algorithm to predict propagation loss. The prediction is designed to be valid over a large range of input parameters seen in Table 2.6.

Model Parameter	**Range**
Antenna Heights	0.5m - 3000 m
Frequency	20MHz - 40GHz
Distance	1km - 2000km
Surface Refractivity	250-400 N-units

Table 2.6: Longley-Rice Input Parameter Ranges

The power of the LR model is its use of terrain path profiles to predict how scattering, diffraction and reflections affect the signal power at the receiver. If terrain path profiles are unavailable, the model operates in point-to-area mode, and has the ability to predict the losses based on average terrain height for similar environments. These average heights are seen in Table 2.7.

Terrain Type	**Δ h (m)**
Water or very smooth plains	0-5
Smooth plains	5-20
Slightly rolling plains	20-40
Rolling plains	40-80
Hills	80-150
Mountains	150-300
Rugged mountains	300 - 700
Extremely rugged mountains	>700

Table 2.7: Longley-Rice Terrain Height Difference Approximations

Δh is computed as the difference in height between the lower 10% and higher 10% heights of the terrain.

The LR model has two modes of operation. Area mode is where the exact terrain is unknown. The average terrain height values, showing in Table 2.7, are used to incorporate terrain loss factors along with the climate variations. These average values can vary greatly from location to location, so this is not as powerful as when the precise terrain path is known. When this path is known, the LR/ITM model operates in point-to-point (PTP) mode, where loss is calculated from the transmitter to the receiver, taking actual path data into consideration in the algorithm. Knowing the precise path proves useful for calculating more accurate diffraction losses.

2.6 Radio Mobile

There are many software tools available to help with radio network planning. Many are paid subscription services that offer a restricted number of maps and paths to be analyzed. Some are freely available, at the cost of difficulty in setup, which is the responsibility of the user, as well as potentially a loss of accuracy from freely available terrain and clutter data. These free versions can be powerful tools for a low cost installation, if they provide accurate results. Radio Mobile, developed by Roger Coudé, is intended for use by amateur radio enthusiasts and other users who do not want or need to spend money on a paid service. Software such as Radio Mobile will incorporate the terrain data and determine if there are obstructions in the propagation path. If obstructions are found, the LR/ITM model is used for predicting path loss. In cases where 60% of the first Fresnel zone is cleared, the Two-Ray model is used to provide a free space loss while incorporating a reflected ray off the ground. In many rural areas, there will not be a direct LoS path between the transmitter and receiver, so the use of LR/ITM in PTP mode is more effective at computing path loss [49].

2.6.1 Site Settings

There are a number of settings used in Radio Mobile and the LR/ITM algorithm. Some of the important parameters for determining the propagation of signals are the atmosphere and ground related parameters. For example, the more conductive the terrain, the greater the risk of attenuation or fluctuations in the radio signal as an effect of the ground. Other important parameters are surface refractivity, ground conductivity, relative ground permittivity, and the climate settings. The surface refractivity is measured in N-units. This value decreases with altitude, and is a major component in determining the ability of the radio wave to bend with the earth. The default value is 301 N-units. Ground conductivity is more important at lower frequencies (30kHz - 3MHz), where the surface wave is a dominant component of propagation. This value is measured in Siemens per meter. The default value for conductivity is 0.005 S/m. The relative ground permittivity is measured in Farads per meter, and the default value is 15 F/m. General values are seen in Table 2.8.

Ground attribute	**Ground Conductivity** σ_r	**Relative Ground Permittivity** ϵ_r
Average ground	0.005	15
Poor ground	0.001	4
Good ground	0.02	25
Fresh water	.01	25
Sea water	5	25

Table 2.8: Values of electrical characteristics of ground used in Radio Mobile

Another important parameter that can be set in Radio Mobile is the climate settings. These will consider the atmospheric conditions in the LR/ITM algorithm. This is important in the software's determination of the the refractive index, which determines how well the signal bends around the curved earth, as well as fading properties. There are 7 options for climate type: equatorial, continental sub-tropical, maritime sub-tropical, desert, continental temperate, maritime temperate over land, and maritime temperate over sea. Without a clear description of each climate type, it is recommended for most users to use the continental temperate. It is generally recommended that in the absence of real data, the default values should be used for all of these settings.

2.6.2 Modes of Variability

A way to statistically account for variations in the mean predicted values is what is called modes of variability. Radio Mobile uses three different modes to account for various variations in the received power. These confidence measures will give a median value that the received power can expect to be greater or equal to for the percentage of time selected. Generally speaking, a higher percentage will give a lower power value, but there will be more confidence that the power will be above this value at any given time.

Time variability is what accounts for variations of hourly median power values as the attenuation changes due to slower changes in atmospheric refraction, for example. Selecting a value such as 50% would state that 50% of the time the value will be greater than or equal to the median value. The location variability accounts for variations in long-term statistics that occur from path to path due to differences in terrain. The last value, situation variability, deals with hidden variables, including things like the individual's ability to take field strength readings. This covers other statistical variations that either cannot be directly explained, or are simply ignored. The situation variability is the measure that is most commonly referred to as the confidence interval. Setting the situation variability value accordingly will give a certain confidence with the calculated values. For example, if the value is set to 70%, the user can have confidence that the 70% of the values measured will be equal to or higher than the prediction. Avez et al. determined that these variability values and the confidence interval that they make up are the main method to tune the LR model [50]. Improving the accuracy of the actual terrain data and land cover files used, however, can help fit the data to the model as well.

2.6.3 Terrain Data

There are multiple options for terrain data to use for the Longely-Rice model in Radio Mobile, but for use in the U.S., the two under consideration in this study are the 30 meter resolution Shuttle Radar Topography Mission (SRTM) data and the 10 meter resolution

National Elevation Dataset (NED) data [3]. The 10 meter 1/3 arc second data is from the U.S. Geological Survey (USGS). The USGS NED data is taken from LIDAR measurements for some areas and cartographic contours for others. The vertical root mean squared error (RMSE) of 25,310 reference points of the data is 1.55 meters. It is acknowledged, though, that accuracy may be better in some areas than others. The 30 meter resolution data used in Radio Mobile is from the SRTM missions of 2000. This data comes in a maximum resolution of 30 meters, and has a vertical RMSE of 10 meters based on the mission specifications. The mission used Interferometric Synthetic Aperture Radar (IFSAR) to detect elevation of 80% of the earth. This data typically includes land cover in the height as well as bare earth terrain heights that the NED data covers. This can be good for propagation predictions when the model does not handle land cover well in the prediction. When using prediction tools with higher accuracy in terms of land cover losses, the 10 meter resolution would be desired to give the highest accuracy of terrain coverage.

	NED	**SRTM**
Source Data	Photogrammetry/Aerial Data/Digitized Contours/Lidar/Ifsar Data	Ifsar datatd>
Source Resolution	High resolution, 10m and 30m DEMs	30-m
Source Dates	1925-Present	February, 2000 Space Shuttle Endeavour
Source Type	Digital Elevation Model	Digital Surface Model
Vertical Accuracy	1.55 m RMSE Measured	10-m RMSE (Mission Specification)

Table 2.9: Comparison of the NED and SRTM data [3]

2.6.4 Land Cover

To account for losses due to buildings and trees, software models like Radio Mobile typically have the option to incorporate land cover into the calculations. This data is also from the NED data but only comes in a maximum resolution of 30 meters [51]. This can cause some overlap of categories into locations where they do not apply. For example, an urban area would cause a significant increase in loss compared to a grassy field. It is possible, however, for these categories to be adjacent to one another, and the overlap of either would cause some error in the loss prediction. The loss from the different clutter categories, seen in Figure 2.16, is determined from a combination of empirical methods and wave theory, but errors can arise from the use of average heights for calculations. Since these values are given as a default, they will need to be updated for each area the model is used. This can be difficult in areas where studies of average tree and building height has not been completed. Because of this, the model was tested both with the default heights and with simple "common sense" adjustments, based on comparison of tree heights surrounding buildings on the UNH campus. This will not give as much accuracy as a thorough study of tuning heights and densities of forests, but can give an idea of how well the model performs without extensive tuning of every parameter.

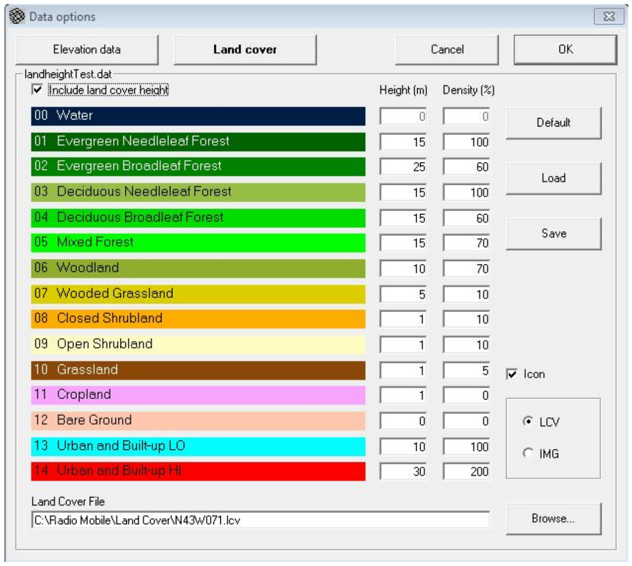


Figure 2.16: Comparison of default and adjusted clutter files

2.6.5 Planning Tools in Radio Mobile

One of the main benefits of Radio Mobile over other Longley-Rice software implementations is the inclusion of various planning tools that can help visualize the propagation along the specific paths. Some are as simple as a HAAT calculator, where the range of terrain is variable. Though HAAT calculators are readily available online, including one in the software can simplify planning. The inclusion of the features described in this section in Radio Mobile makes it an invaluable resource for low cost system planning.

2.6.5.1 Antenna Patterns

While most software tools can incorporate common antennas into the path loss, Radio Mobile allows the user to input the radiation pattern of the antenna being used in the network through a ".ant" file. This file can be created through a text editor, such as Notepad in Windows systems, and saved with the .ant extension. The file lists the attenuation of the antenna with respect to 0° in the horizontal and vertical planes. Starting with 0° , the file lists the attenuation at the horizontal angles in 1° increments , each on a separate line. Once all of the horizontal angles are covered, the vertical angles are listed, starting at + 90° and going to -89° [52]. This information is then incorporated into the calculation of gain, based on the rated gain of the antenna. Additionally, the pattern can be viewed in with the antenna viewer within Radio Mobile, shown in Figure 2.17. If the radiation pattern is correct, the antenna gain in any direction can be correctly calculated, allowing for higher accuracy in the prediction.

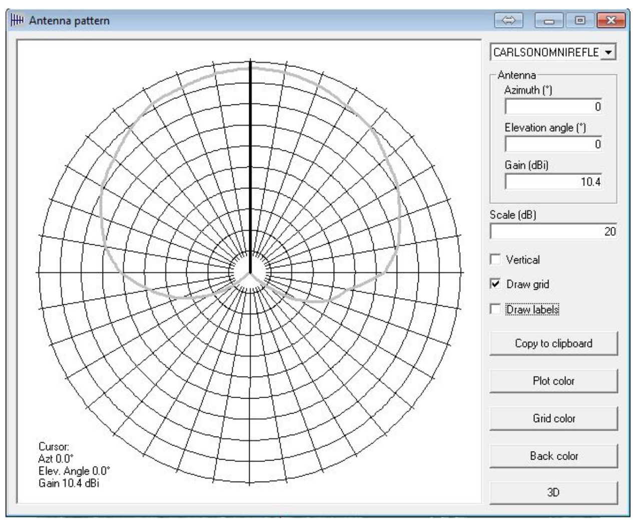


Figure 2.17: Antenna viewer window as seen within Radio Mobile software

2.6.5.2 Radio Link View

When dealing with stationary radios, the desire to know details about the propagation path arises. Radio Mobile includes a tool to show the path profile in the Radio Link window, seen in Figure 2.18. In this radio link window, the path profile is given, showing the terrain profile and clutter distribution (when enabled) that contribute to the path loss calculation. The obstructing terrain and clutter is highlighted by the inclusion of the first three Fresnel zone ellipsoids. This shows the terrain and clutter that will have an impact on the path loss. Since TVWS networks use low antenna heights, it is typically seen that most of the path is inside this first Fresnel zone. Radio mobile shows how much loss the path contributes to the total path loss, listed at the top of the window as "Obstruction" loss. This is then broken up into an Urban portion, if the path travels through buildings, and a Forest portion, if the path travels through trees.

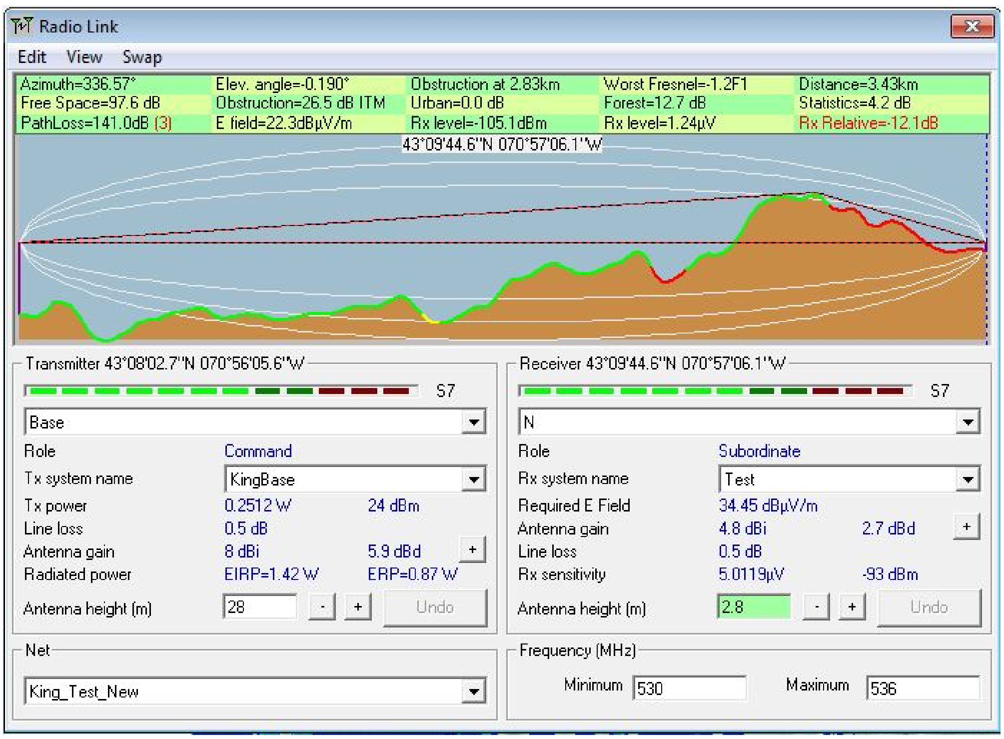


Figure 2.18: Radio Link window as seen within the Radio Mobile software

The parameters of the link can also be seen in this window. On the transmitter (Tx) side, the transmit power, gain, and line loss of the Tx radios are included. These are what is used to calculate the radiated power in the link direction by the program. The Rx side uses similar information use to calculate the Rx sensitivity for an acceptable link. This is established by the Rx thresholds of the radio that can be included in the system setup. If the the link is some adjustable dB value over the threshold, which will be called "X" here, the line showing the path will be green; if it is within $\pm X$, the line will be yellow; and if it is XdB below the threshold, the line will be red. Figure 2.18 shows a link that is more than 3 dB below the threshold, so the line is red.

These visual cues are useful for understanding the link, but one powerful tool within the window is the ability to change the antenna height of either the Tx or Rx antenna. This will adjust the prediction based on the new clearance of the terrain and clutter. Though the results are not explored in this research, this can give an idea of how raising or lowering the antenna can affect the path loss and, therefore, connection quality.

2.6.5.3 Coverage Maps

Once the desired performance is achieved from the Radio Mobile predictions, the radio settings can then be used to create coverage maps. These maps can show where the radio can receive the signal at specific locations on the map, and what power can be expected. This can be a powerful tool for quick planning of coverage, since coverage holes can be visualized quickly. An example coverage map is seen in Figure 2.19. In this coverage map, the dark blue is -100 dBm, which is below the threshold for connection based on the radio thresholds discussed in Section 2.7. With a higher gain antenna than what this map was created for (a 5 dB ominidirectional antenna), however, connection could be established at this level.

Though there may be locations in this map that do not perform to the expected power level, it can help point out particular areas that have obstructions in the path quickly which will make planning a deployment much simpler.

Each of the tools described in this section can help simplify deployment planning for the user. Since it is free software, it may not have been tuned as extensively as paid use

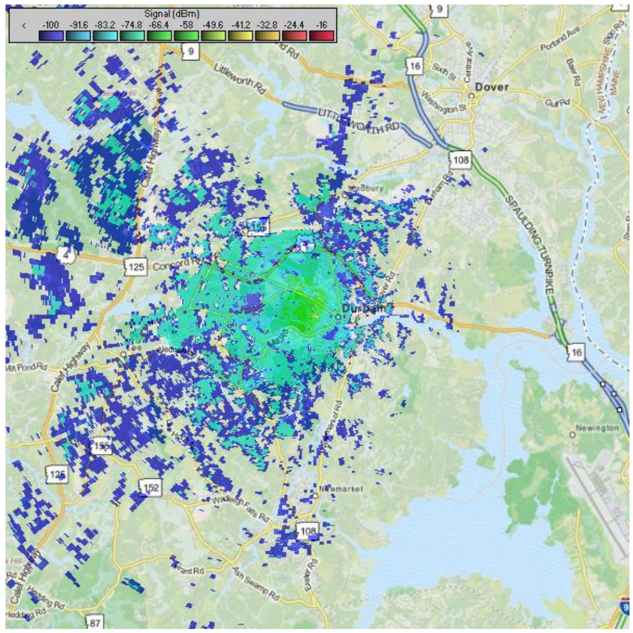


Figure 2.19: A coverage map generated by Radio Mobile

options. With some acceptance of error, however, it can be used to give the installer a basic understanding of the coverage areas of the radio network, with minimal training necessary.

2.7 RuralConnect Radios

As the concept of TVWS networks comes into the limelight more and more options for radios become available. The radios used in this trial are not part of the developing IEEE 802.22 standard [27] but were one of the first FCC certified radios available on the market since December of 2013. Since that time, software and firmware updates have improved performance, but the basic functionality described here remains in place with the current edition.

For this TVWS trial, radios made by Carlson Wireless of Northern California were utilized [21]. With connection capabilities up to 16 Mbps aggregate, these wireless radios can provide broadband speeds over much larger distances than existing WiFi routers. As of December 2013, the FCC approved the RuralConnect devices for commercial, unlicensed use in the United States [53]. The radios utilize proprietary equalization schemes to help overcome fading caused by multipath interference. This allows higher throughput at lower signal thresholds, which is essential for low power communications.

In order to more efficiently share the limited spectrum, time division duplexing (TDD) is used to share the channel among all the radios in the network. The upstream and downstream traffic will be separated in time, whereas with frequency division duplexing (FDD) the upstream and downstream occur on different frequencies. The main advantage of TDD over FDD is the ability to have the ratio of downstream to upstream traffic adaptive to the demand, and still have full channel utilization since the full frequency band will be occupied. TDD enables more efficient spectrum utilization when the traffic is not proportional, which is common, since most users do not require as much upload throughput as download. [54] The TDD method requires the use of a guard time between transmissions, which will adversely affect latency. Still there is no need for a guard band, as all transmissions are on the same frequency, allowing the entire spectrum to be utilized. This is important in cases, like TVWS, where there are a limited number of available frequencies, making the increased latency a necessary trade off. Latency is typically on the order of 120 ms, which is still much faster than satellite, which is on the order of 600 ms. [8]

Latency is also adversely affected by the distance the information has to travel. Since TVWS networks using the RuralConnect radios are typically limited to around 15 km, the links are much closer than satellite links and do not suffer the extreme latencies. There is, however, a more limited spectrum available to TVWS users, so getting higher data rates is accomplished by the different modulation modes.

2.7.1 Radio Signal Modulation

The data that is sent over the wireless links is made up of a string of binary numbers, 1s and 0s. This digital bit-stream then needs to be modulated to transmit the information at the carrier frequency of the radios. The digital signal has significant power at low frequencies, and to transmit these baseband signals as is would require antenna sizes that are unfeasible, since an antennas dimension is usually related to the wavelength. Because lower frequencies result in a larger wavelength, transmission would require a larger antenna. [55] Because of this, the baseband signal must be shifted to higher transmitting frequencies using some form of modulation.

When modulating a baseband signal, the information is grouped into sets of symbols. These symbols are made up of 1 or more bits. When more bits are used, more information can be sent over the same amount of time and bandwidth. When a fixed bandwidth is used, transmitting more symbols is the only way to increase the data rate. Decoding these symbols with more bits, however, requires more signal power to be able to discern between different symbols. This means a higher SNR is required to achieve high data rates.

There are two families of baseband modulation: amplitude modulation and angle modulation. With amplitude modulation, or amplitude shift keying (ASK), the baseband signal controls the amplitude of the carrier sinusoid. The amplitude of the carrier sinusoid is changed as the symbols change in the bit stream with each amplitude level representing a different symbol. At the receiver, the changes in amplitude are mapped back to the transmitted symbols. It is very susceptible to noise since the different symbols are represented by different amplitude levels, which are easily shifted by noise and other interferers. This requires a very high SNR to be able to accurately demodulate the signal so it is not the best choice for high information rates required in wireless Internet access where many amplitude levels would be needed, and lower power is expected. Angle modulation refers to any modulation scheme that affects the angle argument of the carrier sinusoid. This either is the frequency or the phase. In frequency shift keying (FSK), there is a set of sinusoids at orthogonal frequencies that each represent one of the M symbols. This requires a large portion of spectrum to be able to effectively transmit at high data rates. When frequency spectrum is at a premium, FSK is often avoided. In these cases, phase shift keying (PSK) is a better option. With phase shift keying, the phase of the carrier signal is varied with each discrete phase variation representing a different symbol. PSK has the advantage of lower bandwidth requirement than FSK, and a lower susceptibility to noise than ASK making it appealing for low power, limited spectrum applications such as with these TVWS radios.

There are 3 basic phase modulation modes available for use with the Rural Connect radios; binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and 16 symbol quadrature amplitude modulation (16-QAM), which is a combination of phase shift keying and amplitude modulation.

2.7.1.1 Binary Phase Shift Keying

Phase shift keying is a modulation mode that involves altering the phase of the carrier based on the symbol being sent. In BPSK, only one bit is sent per symbol. Since the bits can be either a 0 or a 1, only two options are needed for symbols, and only two different representative phases are needed. This allows the maximum phase difference of 180° to be used in the transmission. This makes it easier to discern between the two phases even with low SNR since the two phase representations are the maximum distance from each other on the phasor plot seen in Figure 2.20a. Since only one bit is sent for each symbol, the bit rate is limited severely by the bandwidth as the two are proportionally related. In order to increase the amount of information that can be sent from a BPSK signal, increasing the bandwidth would be required. In communications systems, particularly so with wireless systems, the bandwidth of the signal is restricted by the channel bandwidth. In TVWS channels in the US, the channels are strictly limited to 6 MHz, our symbol rate is limited as well. In order to send more information, more bits need to be sent for each symbol. This is done with additional phases.

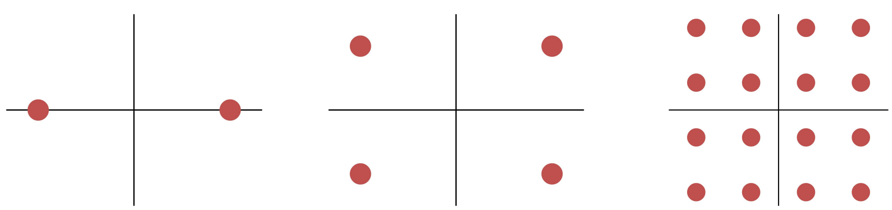
2.7.1.2 Quadrature Phase Shift Keying

In order to double the data rate, while keeping the same symbol rate as BPSK, 2 bits need to be sent for each symbol. This is accomplished with QPSK modulation. Instead of phase variation of 180^o, 90^o increments are used. This makes the signal much more susceptible to noise, as a smaller phase shift can cause the decoder to not be able to determine which phase was sent. Figure 2.20b shows how the phases are closer together on the phasor constellation map. Noise will cause the data-point to be mapped somewhere away from the constellation point. If the noise is great enough to shift the point closer to another point on the constellation, the symbol will be decoded in error. In order to minimize the effect of noise on the decoded symbol, a higher SNR is required. If a high enough SNR is available, greater data rates can be achieved by sending even more symbols.

2.7.1.3 Quadrature Amplitude Modulation

Since speed is the main desire for broadband Internet connection, the radios need to find a way to best utilize the channel. To continue increasing the data rate, more bits need to be sent for each symbol. The next step for the RuralConnect radios is to utilize 16 QAM modulation. Quadrature amplitude modulation is a combination of phase shift keying and amplitude modulation. This is accomplished by sending two orthogonal signals simultaneously through the channel referred to as the inphase and quadrature signal. Orthogonal signals can be easily detected from each other since they are 90° out of phase. This allows the two signals to be sent, doubling the data rate. To continue to increase the data rate, these two orthogonal signals undergo amplitude modulation to send more bits per symbol, and allow higher data rates to be achieved. Just as QPSK required more signal power than BPSK to be able to detect the symbol, even more signal power is needed for 16 QAM. Now, four times as many constellation points are needed since two more bits are being sent. This allows four bits to be sent in one symbol, giving four times the data rate of BPSK.

To keep increasing the data rate, higher levels of QAM are used. In higher power systems, this is possible, but with the power restrictions set on TVWS systems, the signal does not need to travel far before it approaches SNR values that would limit the ability for the decoder to discern between different symbols in higher order QAM. Because of this, 16-QAM is the limit for the RuralConnect radios.



(a) BPSK:
One bit per symbol
Symbol Rate = Bit Rate

(b) QPSK:
Two bits per symbol
Symbol Rate = $\frac{1}{2}$ Bit Rate

(c) 16 QAM:
Four bits per symbol
Symbol Rate = $\frac{1}{4}$ Bit Rate

Figure 2.20: Comparison of the different modulation modes phasor diagrams

2.7.2 Forward Error Correction

For channels that may not perform well enough for one of the higher modulation modes, but would be underutilized by the lower modulation modes, forward error correcting coding

(FEC) can be used. In Non-LoS and distant links, noise and interference will cause lower SNRs to be achieved and errors in the decoding when higher modulation modes are used. To help overcome this, without reducing the modulation mode and giving up all of the speed advantages, FEC is used to insert bits into the stream that can be used to determine what bits were actually sent. Various methods of error correcting codes have been developed over the years, but the main method used in these radios is Convolutional codes [56].

Convolutional codes add bits to the stream by means of convolution. A block diagram example in Figure 2.21 shows how for each information bit, U, two output bits $C^{(1)}$ and $C^{(2)}$ are generated. Since each pair of output bits are based on the current information bit and the two prior bits in this example, the successive pairs of codes become unique for a sequence of bits. This allows the decoder to find an input sequence that has what is called a maximum likelihood of occurring. This means, from the sequence of coded bits, there are multiple possibilities, but one will stand out as being the most likely to have been sent. This can help overcome errors that may occur from noise and interference when the SNR drops. Since more bits need to be sent for each information bit, the data rate is reduced. In the typical convolutional code, the rate reduction is 1/2. In the RuralConnect radios, this is shown as BPSK 1/2, QPSK 1/2 and 16QAM 1/2. With this, the data rate is cut in half but error correction is improved, and more reliability on the data link can be achieved.

In order to further improve the data rate, and still maintain some error correction, punctured convolutional codes were formed. These are convolutional codes with a 1/2 rate where within a sequence, 1 or more of the coded bits are deleted and not sent. This is done following a predetermined puncturing pattern so the decoder will know which bits from the sequence have been removed. For example, the puncturing code below will result in a 3/4 rate code where the top row of the matrix are the bits sent from $C^{(1)}$ and the bottom row from $C^{(2)}$. Where a 1 exists means the coded bit is sent, and a 0 shows a deleted code bit, increasing the data rate.

$$P_{3/4} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix} \tag{2.32}$$

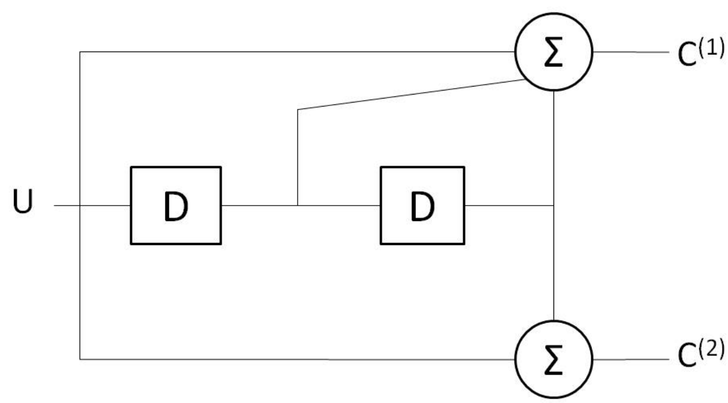


Figure 2.21: A simple block diagram of a convolutional code tapped delay line example

Figure 2.21 shows a block diagram of a simple form of the convolutional codes and puncturing patterns shown here, and may not be representative of the patterns used in the radios, but the concept is the same. The punctured codes are represented by BPSK 3/4, QPSK 3/4, and 16QAM 3/4. These modes can be set by the radio management interfaces.

2.7.3 Radio Performance Monitoring

The base station controller for the RuralConnect radios has an on-board local management interface (LMI). Previous versions of the radios utilized a cloud based operations and management center (OMC). These management services provide the ability to select available TVWS channels, modulation modes, and both versions would provide uplink and downlink signal to noise ratio (SNR) values to monitor performance over time. The OMC has since been discontinued, with the LMI taking over as the sole control interface. Phase I of the trial discussed in Chapter 3 used the OMC which only provide a means to control the radios and very little performance indicators. There was a plot of the SNR values the radios measured over the previous 24 hours, but this was not updated continuously. The LMI improvements include real time modulation mode and SNR updates as well as a more intuitive user interface. The LMI will archive the radio information such as SNR and channel information allowing past incidents to be recalled. With this update to the management interface, the radios have the ability to actively adapt the modulation modes to match the channel performance and better utilize the wireless channel.

2.7.3.1 External Radio Performance Monitoring

Out in the field, the radios have on-board received signal strength indicator (RSSI) LEDs that can give an idea on the link performance at any given time. This would allow to manually set the modulation mode to match channel performance to reduce the number of packet and bit errors in the data link. These 4 RSSI LEDs have 3 settings, flickering, steady blinking, and remaining solidly lit. These settings indicate an approximate SNR and can help the installer determine where the strongest signal is coming from. Table 2.10 shows the approximate SNR values for each RSSI level. The modulation modes listed follow the original edition of the radio. In the current edition, the modulation settings are limited to BPSK, QPSK and 16QAM, each with the optional 1/2 and 3/4 convolutional codes. These are listed as “Conv”, and “Conv Punct” respectively. The table should hold with relative accuracy and can be used as a way to monitor performance with the radios themselves.

Number of LEDs	LED Behavior	Approx. SNR	Mod. Type	Error Correction
1-2	Flickering or Blinking	2-10	BPSK	Conv
2	Solid	12	BPSK	Conv Punct
3	Flickering	16	QPSK	Conv
3	Blinking	18	QPSK	Conv Punct
3	Solid	20	QPSK	Conv Punct
4	Flickering	24	16 QAM	Conv
4	Blinking	27	16 QAM	Conv Punct
4	Solid	30+	16 QAM	None

Table 2.10: Relation of RSSI LEDs to SNR

Since the noise power is usually mostly due to instrument noise, different receiver (Rx) power threshold levels can be established for 10^{-6} BER performance of the radios based on an expected SNR. With these thresholds, seen in Table 2.11, the different approximate OTA data rates can be achieved based on the modulation and FEC modes shown in Table 2.12.

Modulation (FEC Rate)	Rx Power Sensitivity
QPSK (1/2)	-93 dBm
16QAM (1/2)	-86 dBm
16QAM (None)	-80 dBm

Table 2.11: Rx threshold $10^{-6}BER$ performance for important modulation modes

Modulation (FEC Rate)	OTA Data Rate Mbps
BPSK (None)	4
QPSK (1/2)	4
QPSK (3/4)	6
QPSK (None)	8
16QAM (1/2)	8
16QAM (3/4)	12
16QAM (None)	16

Table 2.12: OTA Data Rate for the various modulation modes

These sophisticated radios were chosen for use in the TVWS trial. Their performance as a wireless broadband Internet network is being monitored, with some findings shown in Chapter 3. Using the information presented in this background chapter, the findings from the trial as well as the measurement campaign to explore possible path loss models can be better understood. These steps are essential in moving forward with TVWS networks towards ubiquitous broadband coverage.

CHAPTER 3

The Trial

3.1 Introduction

Beginning in September, 2013, the Television White Space (TVWS) trial at the University of New Hampshire (UNH) began work monitoring the performance of a real TVWS network. The trial started as part of the Gigabit Libraries Project, which was an initiative to provide broadband Internet access to unserved and underserved communities through public libraries [57]. The intent was to connect the libraries of towns surrounding the UNH campus to the UNH fiber network through wireless links operating in open ultra high frequency (UHF) television frequencies. The Carlson RuralConnect Radios were chosen for the trial as they are commercially available.

Surrounding the town of Durham, New Hampshire, where the UNH main campus is situated, are the towns of Madbury, Lee, and Barrington. These towns were chosen for client locations. One advantage of these locations is that each of them, along with the town of Durham, have their own, small, public library that are already connected to high speed Internet through wired options. The distance and terrain between the towns, however, mimics rural areas with heavy foliage and few buildings; it would not be uncommon for these rural libraries to have no wired broadband options, and a wireless link may be the only solution to providing broadband access. In addition, it is important to test the devices in an area where system outages would not be as critical an issue due to the existing connectivity. This is another advantage of this test-bed location. The fiber network that serves as the back-haul for the TVWS network will provide adequate speeds to see how well the radios function without speed limitations.

To further test the network under a larger load, client devices that are not accessible to the public were installed at the InterOperability Lab (IOL), in the Broadband Center of Excellence (BCoE) office in Dimond library, as well as in Thompson Hall, an office building on the university campus. The different base station and client locations considered in this trial are seen in Figures 3.1 and 3.2.

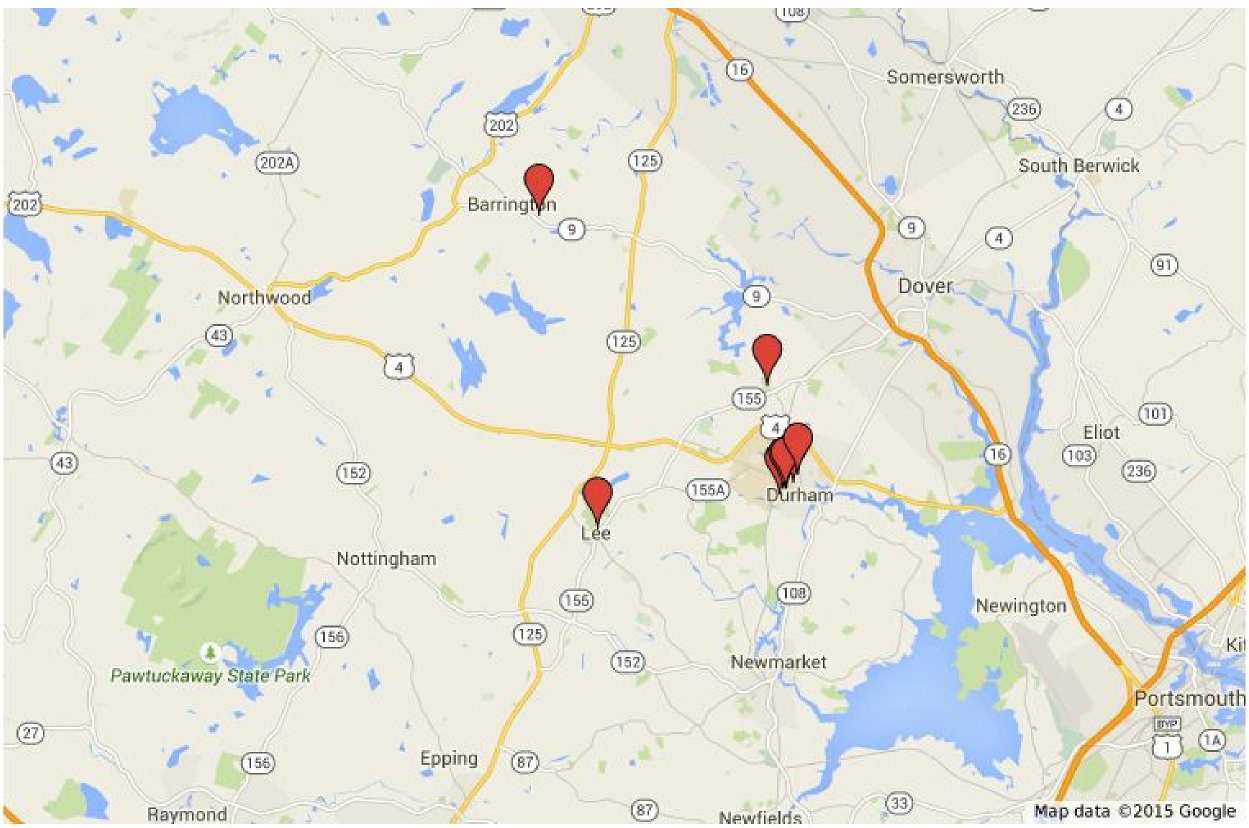


Figure 3.1: Client and base station locations from Google Maps

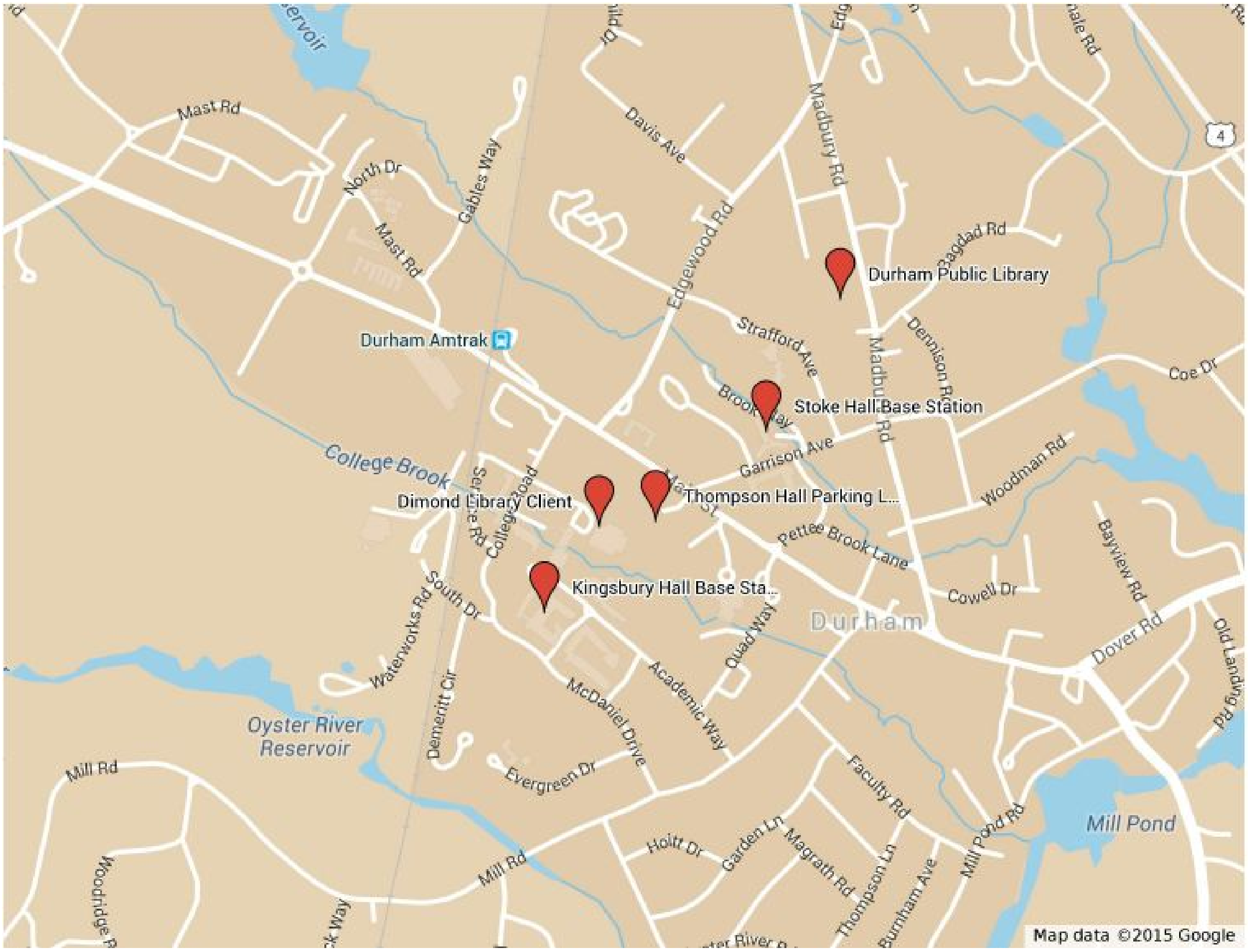


Figure 3.2: On campus client and base station locations from Google Maps

Client	**Coordinates** Longitude|Latitude	**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 3.1: Client location coordinates and distance from base station

Each of the locations that were chosen as part of the trial were tested with a temporary setup of a RuralConnect radio client premise equipment (CPE). The CPE was connected to the base station that provided the best coverage of the location. Different antenna heights were used, but focus was placed on antenna heights that would be close to the actual mounting of permanent CPEs. The trial was conducted in two phases. Phase I was the initial installation on Stoke Hall on the UNH campus. This phase used an omnidirectional antenna to give 360° coverage of the base station and is discussed first in this chapter. Next, is the discussion of Phase II, which involved an installation of a second base station on Kingsbury Hall across campus. Following the presentation of the background of the two phases of the trial are reviews of the measurements at the different client locations. This involves confirmation of modulation modes at the locations, as well as some basic online speed test measurements to get a better idea of the connection capabilities of the network. Finally, is a presentation of some conclusions of the first two phases of this ongoing trial.

3.2 Phase I: Initial Deployment

The first stage of the trial began with a base station on Stoke Hall, an eight story dormitory building that also houses some university offices. There is a penthouse on the roof of Stoke Hall that serves as a good location for installing the base station. The first antenna on Stoke Hall was an omnidirectional antenna that had equal gain in all directions, providing uniform coverage. This antenna, developed by Carlson Wireless, had a 5.2 dBi gain, making an effective isotropic radiated power (EIRP) of roughly 29 dBm (ignoring cable losses); this EIRP is well below the limit of 36 dBm set by the Federal Communications Commission (FCC). The height of the building provides an easy installation point that gets the antenna close to the maximum height allowed. The antenna was mounted roughly 1.5 meters above the roof, giving an antenna height of 27 meters above ground. Stoke Hall is on ground with an elevation of about 17 meters above sea level according to Google Earth. This is lower than a lot of the surrounding area. Taking this into consideration, the height above average terrain (HAAT) of the Stoke Hall antenna is calculated to be 9.76 meters[1]. Initially, channel 40 (center frequency of 629 MHz) was utilized for the communication link.

During this phase of the trial, the only library with a permanent installation accessible to the public was the Durham Public library. The IOL and BCoE office in the Dimond Library also had permanent installations that were used as additional testing and monitoring points. In order to test the connection at the other library locations, a temporary client radio and laptop were used. It was found that the link performance at each of the locations did not meet the requirements for a broadband network. The main cause for the poor performance was the modulation settings of the RuralConnect radios being limited by the weakest link. As a result, BPSK was used for each link, which severely limited performance. Connection was not established between the base station and the portable clients at Barrington and Lee. The client at Madbury had connection but that was lost after moving the base station antenna location to another location on the Stoke Hall rooftop. It was determined that use of a lower gain omnidirectional antenna would not provide the necessary coverage in this environment. Though not mountainous, the Durham area does have rolling hills and dense forests that can inhibit the signal propagation due to diffraction and scattering of the signal [1]. Increasing the gain of the transmit antenna to bring the power right to the regulated limit would be essential for improving performance.

Another cause of the reduced performance is due to non-automatic modulation selection. The signal to noise ratio (SNR) of the channel varied greatly over time as seen in Figure 3.3.

[1]HAAT was calculated using the Radio Mobile Software which is discussed in Chapter 2.6

This was attributed to varying channel characteristics (moving branches, cars, etc.) as well as the possible interference from other unknown users. The radios at the time did not have the ability to adaptively change the modulation and forward error correcting (FEC) codes to match the performance of the channel. This caused excessive errors when the SNR would drop below the performance threshold for a set modulation. Conversely, if the modulation was set too low to make up for these drops in SNR, the channel would not be utilized to its full potential when the SNR improved. This indicated the need for adaptive modulation to maximize the efficiency of the channel, or a way for the radios to detect the potential interferers and change to a different available channel. The latter cognitive approach is an idea under heavy consideration currently [16, 58, 59] but, was not approached in this research. Adaptive modulation was a software improvement that was introduced during the transition from the limited functionality, cloud based operations and management center (OMC) to the improved on-board, local management interface (LMI) used with the Kingsbury Hall base station. This occurred in Phase II.

Figure 3.3: Screen capture of OMC SNR measurements over a 24 hour period

3.3 Phase II: Kingsbury Hall Base Station and the Stoke Hall Sector Antenna Installation

The second phase of the trial that began in July 2014, attempted to improve performance of the network through a number of changes. First, a new base station was installed that would allow sector antennas to be used, which would increase the gain and, therefore, the coverage range of the base stations. The new base station antenna was installed at Kingsbury Hall, on a tower whose top reaches 21 meters above the roof. The roof itself is 11 meters above ground. To stay out of the way of other antennas, the TVWS antenna was placed 4 meters below the top of the tower. This gave the antenna a height of 28 meters. Taking into consideration that Kingsbury Hall is at a slightly higher elevation than Stoke Hall (Google Earth puts it at 24 meters above sea level (ASL)), the HAAT was calculated to be 16.65 meters. This elevation increase, even though it is slight, would prove to help the signal propagate farther to the various client locations by raising the antenna above some potential obstructions.

The antenna used for this installation is the same as the omnidirectional antenna that was used on Stoke Hall. This mount, however, included a reflector that directs the signal in one direction. This modification reduces the 1 dB beamwidth to 120^o, which allows the signal to propagate only where the signal is desired (there are no clients to the direct east of Kingsbury Hall). The reduced beamwidth also increases the gain of the antenna to 10.4 dBi, which results in an EIRP of 33 dBm; much closer to the 36 dBm limit.

In addition to this base station, the omnidirectional antenna on Stoke Hall was replaced with a sector antenna seen in Figure 3.5. This antenna has a a gain of 9 dBi averaged over the 90^o 3 dB coverage range, and was placed facing the Durham Library client as this was

Figure 3.4: Kingsbury Hall omnidirectional antenna with reflector

the only active, public client, and it would benefit from the increased gain. Using sector antennas allows both the use of multiple base stations to cover a geographical area more efficiently, as well as more clients to be included in the networks. This trial did not require multiple base stations based on the number of CPEs, but utilizing two base stations allows for better coverage.

Another improvement for the Kingsbury Hall base station was the introduction of an outdoor unit (ODU) with the indoor rack-mounted controller. The base station on Stoke Hall utilizes a 100 foot run of 75Ω coaxial cable to deliver the signal to the antenna. This long length of cable causes increased loss in the transmission. Rated at 0.02 dB/ft, the loss equates to 2 dB. The new Kingsbury Hall base station, however, uses a power over Ethernet (POE) connection from the base station controller to the ODU, which then is connected to

Figure 3.5: The new Stoke Hall sector antenna

the antenna via a much shorter coaxial cable, about 2 feet in length. This greatly reduces the loss associated with the cabling as it is rated at 0.055db/ft, which, for a 2 foot lead, is roughly 0.11 dB of loss. When dealing with low powers and a lossy propagation environment, this small dB gain can prove to be the difference between establishing a reliable link.

3.4 TVWS Trial Analysis Tools

In the trial, two measurement techniques were used to characterize the system in this deployment. The primary technique used was the software and hardware performance indicators utilized by the CPE. This was done to emulate what may be a typical deployment scenario, where these may be the only tools at the disposal of an amateur installer. The on-board hardware performance indication consists of 4 received signal strength indicator (RSSI) LEDs as seen in Figure 3.6. This gives the user a basic approximation of the SNR seen at a given antenna orientation. The RSSI LEDs work the same way as the bars on a cell phone; more LEDs activated means higher signal strength and improved performance. The RSSI LEDs can be helpful for determining the quality of signal at a location and for determining how coarse antenna orientation adjustments affect the received signal. In addition to the RSSI LEDs, the LMI on the Kingsbury Hall base station can give real time updates of modulation modes and SNR values for both the uplink and downlink. These can be used to monitor channel performance during installation.

Figure 3.6: Close up of RSSI LEDs

The second tool was to make spectrum analyzer measurements with the client antennas and 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 that would introduce errors in the measurement, allowing a higher accuracy in the spectrum measurement. The matching pad is rated at a maximum loss of 5.7 dB over a frequency range of DC to 1 GHz. A laptop was used to control the analyzer and to save the various spectrum traces as an ASCII file. This was then plotted using MATLAB computing software and included in this thesis. For the measurements, the spectrum analyzer had a set configuration to keep measurements consistent: 0 dB internal attenuation, a resolution bandwidth (RBW) of 200 kHz, a center frequency set to operation channel, a 20 MHz span to capture the channel in question, as well as adjacent channels, and the peak hold mode setting on the spectrum analyzer was set to "Max" to capture the time division duplex (TDD) signal. By keeping these settings consistent, measurements can be compared to one another with more simplicity. Synchronizing the analyzer for TDD measurements with the FS300 analyzer is very difficult. Peak hold mode gave an optimistic view of the received spectrum, displaying the maximum power values over a number of sweeps. Even in these outdoor slow fading channels with stationary units, there is commonly still a fluctuation in signal power due to changing conditions within the path and sporadic interference and noise. The use of the peak hold mode on the analyzer will not account for this. Displaying the maximum power over time will be used to give a general idea of the relative power spectrum received at each location and the shape of the spectrum can indicate the amount of frequency selective fading seen at a particular stationary antenna location.

Throughput tests in this trial were only available using free online speed tests. These tests can have inherent inaccuracies due to not knowing the exact path chosen to the test server as well as other downloads occurring on the computer. This can provide results that can vary due to unknown traffic between the server and the client user. They are, however, used in this research to help analyze the connection, and to create traffic between the base station and client in order to allow the adaptive modulation to best fit to communication in the channel. To help reduce the possibility of error, the tests were performed on two different sites [2]. Both sites allow selection of a server location, and, to stay consistent, the Washington D.C. server was chosen, as this was the closest location available from both sites that provided the most consistent results. To use these speed tests for comparison, the average value of the throughput recorded using the online speed tests is listed throughout this chapter, unless otherwise specified.

Modulation was set to adaptive for all of the tests once this option was made available

[2] `www.speedtest.net` which is advertised as the "worlds most popular Internet speed test" by the provider Ookla, and `www.speakeasy.net/speedtest` provided by Mega Path

(after the Kingsbury Hall base station installation). Modulation was recorded from the LMI, but not available from the OMC used on the Stoke Hall base station. When available, the modulation mode used was recorded, following the names as seen in Section 2.7.3.1

3.5 Active Client Locations

During the duration of the trial, there were 4 active clients and 3 additional prospective client locations. The active clients were chosen based upon the ability to have a seamless installation without having to get special permission from any town governments. The clients are all within 3 km from their respective base stations. This does not push the limits of the distance of a TVWS network, but it gives a suburban deployment scenario where wall losses and building wave-guides can occur. Monitoring performance in these cases can give insight to the overall performance of a TVWS network.

3.5.1 Dimond Library and Thompson Hall

The on campus clients were located at the Dimond Library and Thompson Hall, two UNH buildings centrally located on campus; which are roughly 200-300 meters from the Kingsbury Hall base station and 350-400 meters from the Stoke Hall base station. This close proximity allows these locations to be an ideal candidate to monitor the radios in a suburban installation. The scope of this work was for the use of the network in rural broadband, as this predominately makes up the area surrounding the UNH campus. These radios are intended for use in any environment, however, so it is useful to include these locations as a more thorough analysis of the radios' capabilities.

The client in the Dimond library is in an office closed to unsolicited traffic, so it was not a public installation. Similarly, the Thompson Hall client is in another UNH office, making it another private installation. These two radios are mostly used for demonstration purposes to show interested parties how the network works but were two of the four permanent installations in the trial.

Measurement Location	Thompson Hall Parking Lot	BCoE Office	BCoE Office
Base Information	Kingsbury Reflector	Stoke Sector Facing Durham Library	Kingsbury Reflector
Antenna	Log Periodic	Log Periodic	Log Periodic
Antenna Height-Direction	2.2 meters facing Kingsbury	1.7 meters facing Stoke	1.7 meters, various orientations
Channel	22	22	23
Average SNR (Down-UP)	30.4 dB - 30.8 dB	Not Recorded	16.7 dB - 21.6 dB
Typical Modulation (Down-Up)	16 QAM - 16 QAM 3/4	Not Recorded	QPSK 3/4 - 16 QAM 1/2
LEDs	4 Solid	1 Solid	3 Flickering
Average Throughput (Down-Up)	9.3 Mbps - 4.9 Mbps	0.84 Mbps - 0.54 Mbps	3.70 Mbps - 1.57 Mbps
Throughput Standard Deviation (Down-Up)	0.18 Mbps - 0.31 Mbps	0.21 Mbps - 0.22 Mbps	1.67 Mbps - 0.77 Mbps
Notes	–	Management software on Stoke doesn't clearly display SNR and Modulation	Various antenna directions where tested

Table 3.2: Dimond Library and Thompson Hall average performance results

3.5.1.1 Phase I: Omnidirectional Antenna on Stoke Hall

During the Phase I of the trial, testing was limited to the CPE in the BCoE office. This was a permanent installation that allowed easy access for monitoring the network. The bulk of testing from this phase was not performed for this thesis work, but can be seen in the BCoE report on the initial findings [60]. The modulation was restricted to BPSK for this initial part of the trial. Restricting the modulation would result in reduced throughput performance in locations that have higher SNR.

3.5.1.2 Phase II: Kingsbury Hall Base Station

Thompson Hall Parking Lot: The installation of the second base station at Kingsbury Hall allowed the network testing at the Dimond Library and Thompson Hall to continue to monitor the network improvements. To extend the testing to the more common case of outdoor antenna installations, a test radio was placed in the parking lot next to the two buildings. The results of this testing are included in Table 3.2. Modulation was consistently 16 QAM in the downlink and 16 QAM 3/4 in the uplink at this location, with SNR maintaining above 30 dB. The throughput speeds recorded from the online speed tests averaged 9.3 Mbps downstream and 4.9 Mbps upstream. There is minimal terrain variation between the test antenna and the Kingsbury Hall base station, but it is apparent that buildings and some trees block the LoS path. This would cause some additional attenuation over LoS path loss. Further, the Thompson Hall parking lot is behind the reflector at the Kingsbury Hall antenna. Since it is within a close range of the base station, and since the reflector will not completely eliminate signal propagation in this direction, it is understandable to get the modulation and SNR that was seen. This would indicate good performance for the TVWS radios as an extension of WiFi networks for short range coverage.

BCoE Office: Additional tests were run on the client in the BCoE office in the Dimond Library. This client resides in an office centrally located within the building, with no windows in the room. Typically, directional antennas will provide the best signal when aimed at the base station antenna. At this location, however, the client radio showed the best performance when the antenna was pointed out the door of the office, towards the nearest window across the hall. This would indicate that the signal was propagating down the sidewalks of campus, using the buildings as a sort of wave-guide [33]. The frequencies used in TVWS networks have better wall penetration than the frequencies used in WiFi networks. The direct signal from the Kingsbury Hall base station, however, would have to propagate through multiple brick walls and floors. In this case, the reflected path of the buildings around the library appears to provide less loss than the direct path through the walls of the library. Table 3.2 shows the average SNR and typical modulation modes seen in the BCoE office. The average SNR was recorded as 16.7 dB downlink and 21.6 dB uplink. The average speeds seen had a greater standard deviation, since different antenna orientations and locations were tested. The speeds ranged from 1.75 Mbps-6.67 Mbps download and 0.78 Mbps- 2.52 Mbps upload. The modulation mode ranged from QPSK 1/2 to QPSK on the downlink and QPSK 3/4 to 16 QAM 1/2 on the uplink, which explains the range of speeds seen.

When connected to Stoke Hall base station, the results were very limited, measuring speeds consistently around 0.84 Mbps download and 0.54 Mbps upload. These speeds could not be verified by the modulation mode as the OMC does not report modulation. The Stoke Hall base station was facing away from the BCoE office so the slow speeds are not unexpected. The sector antenna on Stoke Hall provides much less signal outside of the coverage range than the antenna on the Kingsbury Hall base station, which would greatly limit the propagation to the BCoE office. This makes the Kingsbury Hall base station the best choice for connection.

3.5.2 InterOperability Laboratory (IOL)

Early in the trial, a client was installed at the InterOperability Laboratory just off of the UNH campus. The client was mounted on the roof of the three story building, providing a near line of sight path to the original Stoke Hall base station. In addition, with the client located in an UNH affiliated lab, testing was able to be performed by the lab during Phase I. During Phase II, the CPE was connected to the Kingsbury Hall base station, but since the lab is restricted to employees only, access to the client was limited. Further testing was done in the parking lot outside of the laboratory to help monitor network performance.

3.5.2.1 Phase I: Omnidirectional Antenna on Stoke Hall

Speed tests were performed when connected to the Stoke Hall base station in the first phase, with results seen in the BCoE report [60]. The speeds seen in the early phase of this trial were collected from the Stoke Hall omnidirectional base station setup of Phase I of the deployment. At the time of the test, only BPSK modulation was used, which severely limited performance. As upgrades to both the software and the hardware have been made to the system, the performance has improved.

3.5.2.2 Phase II: Kingsbury Hall Base Station

In the scope of this research, access to the installed client has been limited, due to its residence in a private testing facility affiliated with UNH. Additional speed tests on this client radio as the trial progressed have not been performed, but the modulation modes and the SNR has been monitored from the client through the LMI on the Kingsbury Hall base station. An SNR improvement to roughly 26.4 dB downlink and 21 dB uplink has been seen from the roughly 16 dB downlink and uplink tested in Phase I of the deployment

[60]. These SNR values were averaged over a one-week period, immediately following the installation of the Kingsbury Hall base station. During this time, different channels were tested for performance in an attempt to determine which would be the best channel to use. It was determined that channel 23 (center frequency 527 MHz) provided the best performance. SNR values from a one week period in mid October, 2014 averaged around 27 dB downlink and 23 dB uplink. These values were seen while the Dimond and Thompson Hall clients were active and on the same channel; channel 23. Modulation modes on the channel were typically 16 QAM with 1/2 and 3/4 rate FEC and with occasional drops to QPSK. This is not surprising as the antenna is mounted on a near line of sight to the base stations.

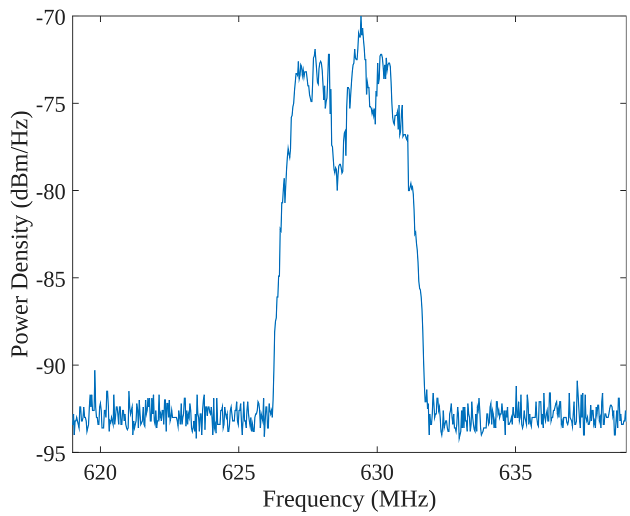


Figure 3.7: Power spectrum of the TDD signal received on peak hold mode at the IOL

Using the FS300 spectrum analyzer, the signal was captured on peak hold mode from the Stoke Hall base station in Phase I, as seen in Figure 3.7. This was done with the same antenna that is used on the CPE, only from the parking lot next to the building, since the CPE is not accessible. The trace was recorded using a height of 7.7 meters. The dips seen in Figure 3.7 are a product of frequency selective fading, resulting from multipath propagation as discussed in Section 2.3.7. The antenna was held stationary so these peaks remained the same for the duration of the measurement. From the trace, a roughly -63 dBm power is calculated. This shows a high-power signal that would be expected from a nearly LoS link. Though it cannot be fully evaluated due to the peak hold mode used, it is presented in this section as a reference point for the other measurements.

3.5.3 Durham Library

The Durham Public Library was chosen as one of the locations for a client station installation. This library is in the same town as the UNH campus, and because of this close proximity, alternatives to costly roof antenna installations could be explored. The client was installed using a simple Winegard Flatwave HDTV window antenna that is commonly used for broadcast television reception. Radiation patterns as well as the gain and beamwidth values were not available for this antenna, but it was approximated to be roughly 2 dBi, which is low compared to the other roof mounted options. The ability to simply place it in a window, however, allows for a quick and easy installation that may be desired by users who may be close enough to the base station to tolerate the low antenna heights and gains. The window in which the antenna was mounted does not face Stoke Hall directly. This window is on the back side of the building and was used based on its proximity to a desk capable of holding the test computer for the trial.

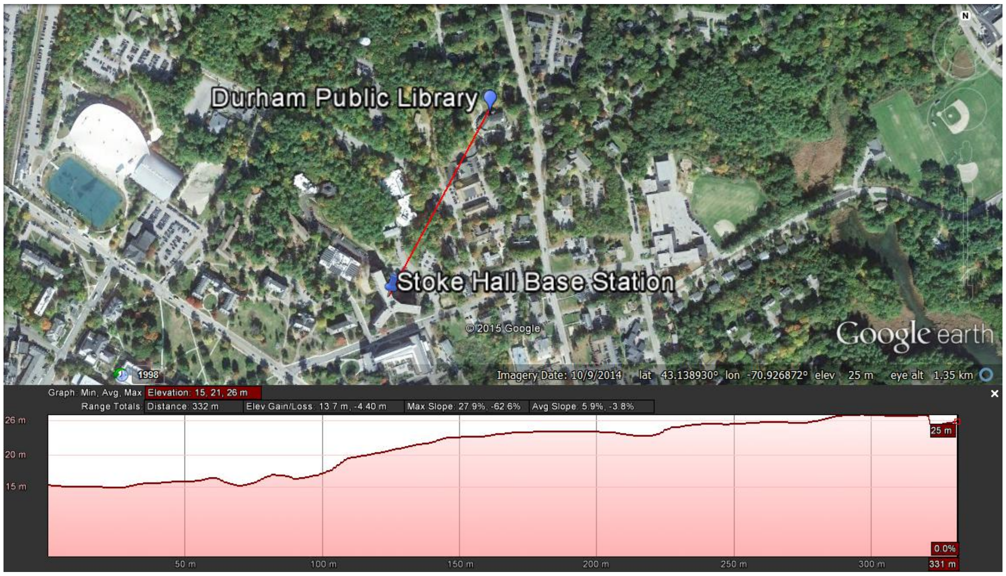


Figure 3.8: Map from Google Earth of the Stoke Hall base station and the Durham Library

Base Information	Stoke Omni	Stoke Sector Facing Durham
Antenna Height-Direction	0.75 meters towards West	0.75 meters towards South
Channel	40	22
Average SNR (Down-UP)	Not Recorded	28 dB - 17.2 dB
Typical Modulation (Down-Up)	Not Recorded	Not Recorded
LEDs	2 Flickering	3 Flickering
Average Throughput (Down-Up)	1.04 Mbps - 0.90 Mbps	3.97 Mbps - 1.70 Mbps
Throughput Standard Deviation (Down-Up)	N/A	1.28 Mbps - 0.69 Mbps
Notes	Early demonstration, not enough data collected for statistics	Modulation mode not available from OMC

Table 3.3: Durham Library average measurement results

3.5.3.1 Phase I: Omnidirectional Antenna on Stoke Hall

The window in which the antenna was initially mounted faces west, which is not facing away from the Stoke Hall base station, but part of the library itself would block the LoS from the base station, providing additional loss. Typically, one would want to have the antenna face the base station to provide the best results, but in the case of a plug-and-play network in someone's home, this desired mounting may not always be available.

Initial results with the Stoke Hall omnidirectional antenna were lackluster. Speeds above 1 Mbps were rarely seen in this Phase I deployment. It was found that the window antenna worked better slightly offset from the window as opposed to taped directly to the window. Mounted on a stand on the sill of the window provided speeds closer to the 1 Mbps mark. The loss through the buildings between the Stoke Hall base station and the Durham Library client was excessive, greatly reducing performance. The OMC that monitored the system at the time did not provide real-time SNR values, but the RSSI LEDs were always limited to 2 flickering LEDS. This indicates an approximate SNR of roughly 8-10 dB, according to Table 2.10 which is consistent with the average SNR graph the OMC does provide, seen in Figure 3.3.

These building losses are significant and detrimental to the connection. The signal from Stoke Hall would have to travel through multiple walls to reach the window antenna. Outdoor mounting is ideal to minimize this loss, but utilizing the window mounted antenna helps explore other simple options. Outdoor mounting can help avoid wall losses, which is typically assumed to be 6 dB per wall for lower UHF frequencies [17, 61]. Mounting the antenna in a window, however, can be much simpler and come at a reduced cost.

Spectrum analyzer measurements from the parking lot of the Durham Library were taken with the log periodic client antenna at a height of 2.2 meters. The power spectrum seen in the general vicinity is shown in Figure 3.9. This does not incorporate the losses associated with the signal traveling through the library to the CPE, but the effect of the building next to the library blocking the LoS is seen. A fair amount of multipath fading from the building and other buildings in the path exists, as is shown by the nulls in the power spectrum. The received power at this location is calculated to be roughly -71 dBm, which is fairly low, considering the proximity to the base station. Considering the weak signal seen at the CPE, this power measurement does correlate. A direct correlation is difficult to make without a measurement at the CPE antenna location, though, so it should only be taken as a relative measurement, just as was the IOL measurement.

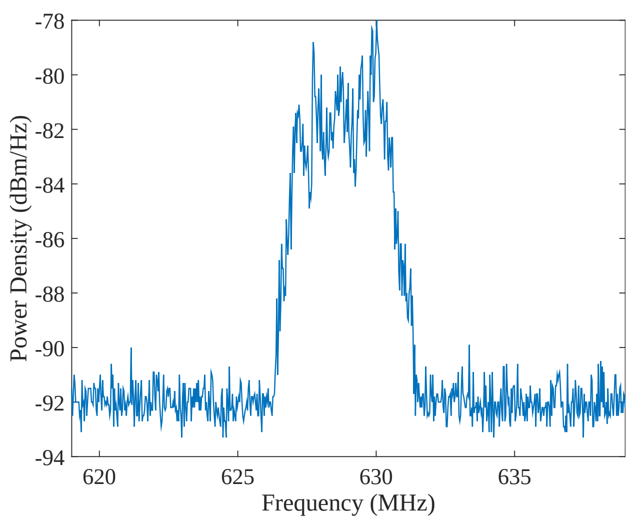


Figure 3.9: Power spectrum of the TDD signal received on peak hold mode at the Durham Public Library

3.5.3.2 Phase II: Sector Antenna Installation on Stoke Hall

Installing the new antenna on Kingsbury Hall involved the inclusion of a reflector to direct the signal toward the weaker client location at Lee Library (see Section 3.6.3). This put the Durham Public Library outside of the coverage range of this base station installation. To improve the performance at the Durham Library, a directional, higher gain antenna was installed on Stoke Hall. Additionally, the window antenna was moved, in an attempt to further improve the connection. It was found that placing the antenna in the window on the perpendicular wall, next to the original installation window, provided better connection. The antenna would now face a more southern direction (window faces north, but antenna is bi-directional), and more towards Stoke Hall.

These two changes were shown to greatly improve the link. SNR improved from 8-10 dB in Phase I to the 28 dB downlink and 17 dB uplink from the Kingsbury Hall base station. Speed tests were also performed and found to be around 3.97 Mbps download and 1.7 Mbps upload, which is a vast improvement over the 1 Mbps/0.9 Mbps measurements seen from the omnidirectional antenna used in Phase I.

Spectrum analyzer measurements with the same setup as in Phase I of the deployment showed a significant improvement with the sector antenna. Again, measuring with the building blocking the path, the trace is seen in Figure 3.10. The received power at this location is measured to be roughly -59 dBm. This verifies the significant improvement over the -71 dBm, seen at the same location. This improvement is not seen solely by the gain improvement from the base station, but also the use of the directional antenna can cut down on some of the multipath effects that may have reduced the power. Additionally, a lower frequency was used (channel 22-521 MHz), which would result in slightly improved propagation characteristics.

To verify that the loss and multipath fading was, in part, a factor of the building next to the parking lot, the antenna was moved to another location to avoid the building blockage. This measurement trace is seen in Figure 3.11. There is significant reduction in the multipath, frequency selective fading that was seen in Figure 3.10. The received power at this location was measured to be roughly -48 dBm, showing an improvement in overall power that comes with removing a building from the signal path.

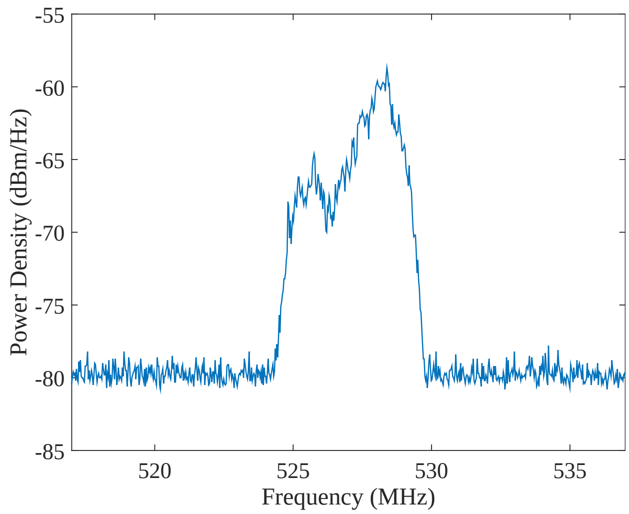


Figure 3.10: Power spectrum of the TDD signal received on peak hold mode at the Durham Public Library showing loss of building blocking LoS

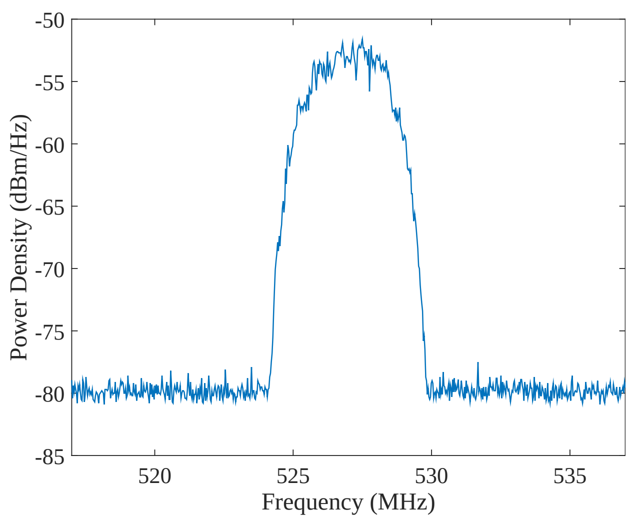


Figure 3.11: Power spectrum of the TDD signal received on peak hold mode at the Durham Public Library showing improvement away from building

3.6 Prospective Client Locations

The following locations do not have any permanent clients installed. This is due to difficulty getting permission to install on the typically older buildings in which these libraries reside, along with the increased cost of installing a roof mount antenna that would be needed at these distant locations. Because of this, initial performance monitoring was needed to show the potential of the network. Unless otherwise stated, the recordings during Phase I were done with the smaller log periodic antenna and Phase II results were from the higher gain log periodic antenna. The findings are described in the proceeding sections.

3.6.1 Madbury Library

The Madbury Library lies just 3.7 km north of Durham and the UNH campus. It is on a slight hill, allowing a reduced amount of foliage to obstruct the path, and is across the street from a recreational field, which provides a good clearing for the signal. This small building has few options for antenna mounting, so testing was done in the parking lot, with effort to get close to the corner of the building where an antenna may most easily be mounted. Connection to the Stoke Hall base station was not achieved during Phase I of the trial, but with the improvements of Phase II came one of the stronger broadband links seen in the trial, making this a great location for future work in the BCoE trial.

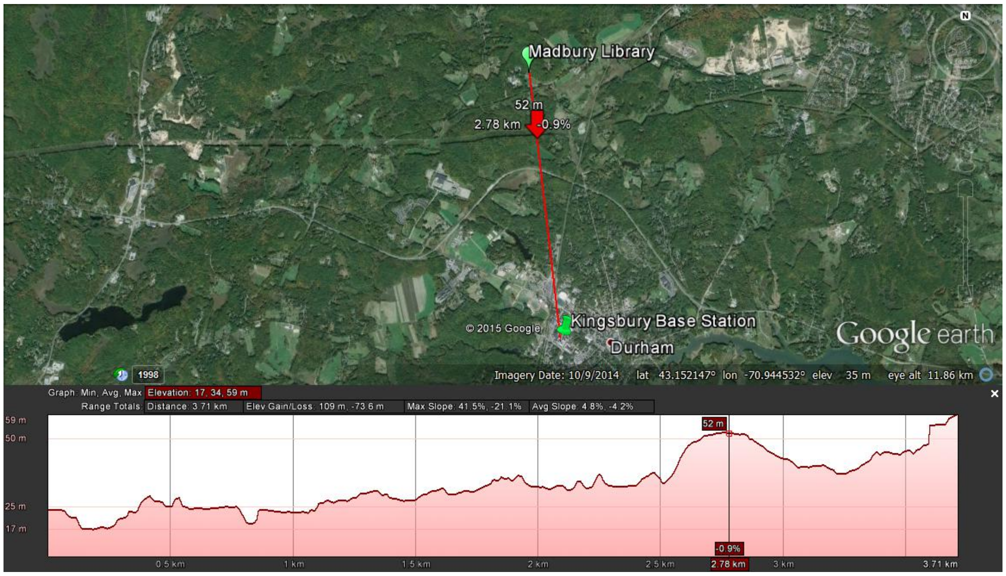


Figure 3.12: Map from Google Earth of the Kingsbury Hall base station and the Madbury Library

Base Information	Kingsbury Reflector	Kingsbury Reflector	Stoke Sector	Kingsbury Reflector	Stoke Sector
Antenna Height-Direction	3.3 meters facing Kingsbury	6.6 meters facing Kingsbury	6.6 meters facing Stoke	7.7 meters facing Kingsbury	7.7 meters facing Stoke
Channel	22	23	22	23	22
Average SNR (Down-UP)	25.4 dB - 16.6 dB	26.4 dB - 14.9 dB	8.6 dB - 8.7 dB	26.4 dB - 15.0 dB	9 dB - 9 dB
Typical Modulation (Down-Up)	16 QAM - 16 QAM 1/2	16 QAM - QPSK	Not Recorded	16 QAM - QPSK 3/4	Not Recorded
LEDs	4 Solid	4 Solid	3 Flickering	Too high in the air to read	Too high in the air to read
Average Throughput (Down-Up)	8.47 Mbps - 2.54 Mbps	3.86 Mbps - 1.56 Mbps	1.01 Mbps - 0.83 Mbps	6.79 Mbps - 2.63 Mbps	0.98 Mbps - 0.81 Mbps
Throughput Standard Deviation (Down-Up)	0.86 Mbps - 0.12 Mbps	1.79 Mbps - 0.54 Mbps	0.024 Mbps - 0.10 Mbps	0.75 Mbps - 0.45 Mbps	0.058 Mbps - 0.12 Mbps

Table 3.4: Madbury Library average measurement results

3.6.1.1 Phase I: Omnidirectional Antenna on Stoke Hall

During the early setup of the original Stoke Hall network performed before this study, the library was able to connect to the Stoke Hall base station with reportedly good results (the results were not recorded as this was just part of the initial feasibility tests). The base station, however, was moved to another part of the Stoke Hall roof to make room for other antennas, and at this point, the connection to the Madbury library was lost. Man-made obstacles introduced between the base station and the client after the movement of the antenna, and the 2 meter height loss that came with it, could be a cause for the lost signal, or additional foliage loss that may also have been introduced. The exact cause of the loss is unclear from the tools available. It does not appear there were any complete terrain blockages introduced, but since 60% of the first Fresnel zone is not cleared, reflection off the ground is a possible cause for loss [36]. To begin, the connection may have been marginal where a slight change, introducing even minimal loss, could have removed the possibility of connecting.

Two different locations were tested within the parking lot of the Madbury Library in an attempt to locate the signal. During this test, client heights between 3.3 and 7.7 meters were checked (in increments of 1.1 meters), and it was determined that no feasible antenna height would make the connection at this location.

3.6.1.2 Phase II: Kingsbury Hall Base Station

With the newly installed base station at Kingsbury Hall, connection was again seen at the Madbury Library. A higher gain log periodic antenna was used for testing that gave a roughly 4 dB improvement over the log periodic antenna used in the Phase I testing (See Appendix A). Furthermore, even though the library is out of the main lobe of the reflector antenna, the gain is estimated to be roughly 7 dBi in this direction. This gives a minimum of roughly 6 dB improvement from antenna gains alone. Combined with reduced cable loss from the use of the ODU, this shows a significant improvement from the hardware. Additionally, the software was upgraded at this time, which advertised improved filtering and signal detection capabilities. All of these improvements led to the connection with SNR around 26 dB downlink and 15 dB uplink.

Testing at different antenna heights close to the projected mounting locations gave a range of throughput values, as seen in Table 3.4; it was found that the 3.3 meter height provided the best throughput performance though modulation mode and SNR values remained consistent. At this location, the average throughput seen was 8.48 Mbps download, and 2.45 Mbps upload. This occurred with the LMI reading an SNR of 25.4 dB downlink and 16.6 dB uplink. When testing at the heights of roughly 6.6 meters and 7.7 meters, it was found that the SNR was roughly the same (within 1-2 dB difference). The throughput measured from the online speed tests, however, fluctuated in the downlink direction. With the same SNR, and modulation modes (16QAM), it would appear that the online speed tests may be giving some wide-ranging results. The modulation and SNR values are trusted, as they did not fluctuate during the testing like the throughput results did. The speed tests are used just to give further verification of the connection, and the results show that broadband speeds can be expected over this link at the tested antenna heights with a high gain antenna.

Running a spectrum trace at the library, using the antenna height of 3.3 meters, resulted in the trace seen in Figure 3.13. A low-cost UHF antenna pre-amplifier was used to help boost the signal to bring it well above the noise floor. The amplifier gave an additional gain of 25 dB. Taking this into account, the power was measured to be roughly -83 dBm. This is right around the Rx threshold for the 16 QAM modulation which correlates with the

LMI recordings. Additionally, it is worth noting that there is minimal frequency selective fading seen in this measurement. This can be explained by the near LoS signal to the library and a lack of buildings in close proximity to the library, like what was seen at the Durham Library. This further shows the strong signal that can be achieved at this library location which should provide consistent high throughput speeds for the CPE.

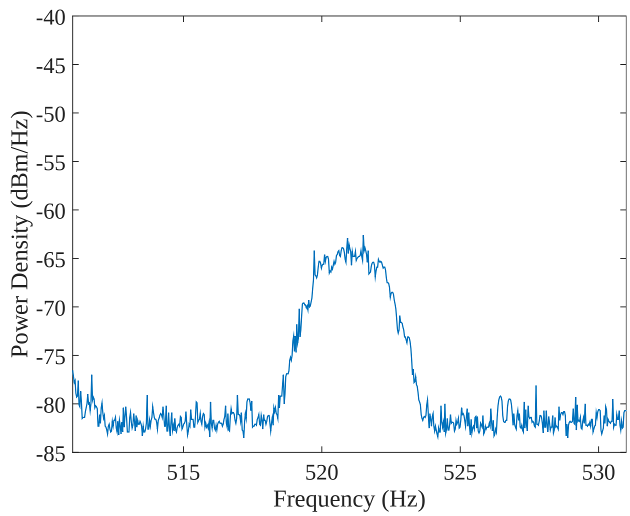


Figure 3.13: Power spectrum of the TDD signal received on peak hold mode at the Madbury Library

The promising results seen from the high gain antenna led to the decision to test a low-cost installation with a window antenna, similar to the setup at the Durham Library. At the Madbury Library, there are several south-facing windows that would be ideal for placing a window antenna, as the direction leads to the UNH campus. Tested at several different locations in the windows, the results were fairly underwhelming, with the SNR at an average of 11 dB download and 3.87 dB upload. At these values, the modulation for the downlink and uplink were QPSK 1/2 and BPSK 3/4, respectively. From this experiment, the speeds were recorded to be roughly 1.31 Mbps download and 0.56 Mbps upload. These modulation recordings can provide close to the older definition of broadband speeds (1.5 Mbps T1 lines [62]), but significantly slower than what was seen with the higher gain antennas, showing the importance of proper antenna use and installation at the more distant client locations.

3.6.1.3 Phase II: Sector Antenna Installation on Stoke Hall

During the beginning of Phase II of the trial, the connection was tested at Madbury from the newly installed sector antenna to see how performance improved from the old directional antenna. Tests were taken on channel 22 (center frequency of 521 MHz) at the antenna heights of 6.6 meters and 7.7 meters. At both heights, the SNR was seen to be roughly 9 dB in both the downlink and uplink direction. A throughput measurement was made resulting in roughly 1 Mbps seen in both the download and upload. This test was performed connected to the Stoke Hall base station, which does not display instantaneous modulation when set to adaptive modulation. From these speeds, SNR value, and using Table 2.10, however, it is fair to guess that the modulation was BPSK 3/4. This performance might be acceptable if it was the only option, but since we know SNR far exceeding these values can be achieved by the link from the base station on Kingsbury Hall, it is clear that the latter is the optimal choice.

3.6.2 Barrington Library

At the time of Phase I of the deployment, the TVWS radios were advertised to provide Internet access over links typically to about 10 km and only rarely up to 15 km if terrain and land cover allowed. The Barrington Public Library rests on top of a hill, roughly 12.6 km from the Stoke Hall base station. This location on the fringes of the connection range was an optimistic location from the beginning due to the initial use of lower gain antennas on the CPE and base station. The redesign of the system for Phase II with the new base station would reinvigorate the hopes that connection could be seen at this distance. Most of the measurements were made at an adjacent parking lot due to the difficulty of accessing the mounting location at the library. The connection, however, was verified at the projected mounting location, with modulation modes recorded.

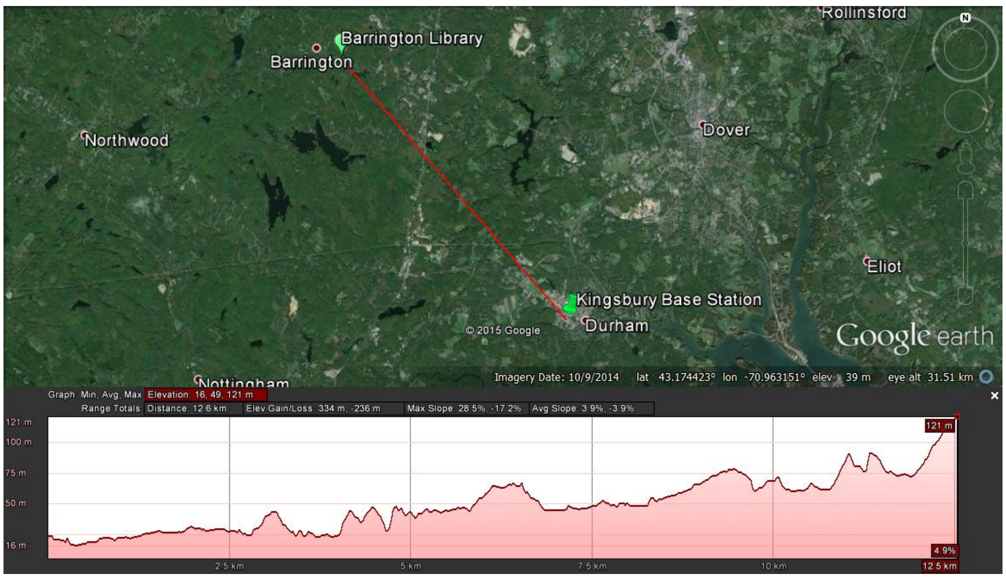


Figure 3.14: Map from Google Earth of the Kingsbury Hall base station and the Barrington Library

Base Information	Kingsbury Reflector	Kingsbury Reflector
Measurement Location	Behind Adjacent Town Hall	Library Entrance
Antenna Height-Direction	3.3 meters - Towards Base Station	7.7 meters - Towards Base Station
Channel	22	23
Average SNR (Down-UP)	18.2 dB - 8.5 dB	18.5 dB - 7.9 dB
Typical Modulation (Down-Up)	16QAM 3/4 - QPSK 3/4	16QAM 3/4 - QPSK 3/4
LEDs	2 Solid	3 Flashing
Average Throughput (Down-Up)	5.25 Mbps - 1.79 Mbps	3.07 Mbps - 0.81 Mbps
Throughput Standard Deviation (Down-Up)	0.53 Mbps - 0.099 Mbps	0.33 Mbps - 0.072 Mbps

Table 3.5: Barrington Library average measured results

3.6.2.1 Phase I: Omnidirectional Antenna on Stoke Hall

Since the Barrington Library is roughly 12.6 km from the UNH campus and the expected coverage range of the RuralConnect radios is 10 km, it was predicted that the link to Barrington would not be strong enough to support a broadband Internet connection. No connection was achieved at antenna heights between roughly 3.3 meters and 7.7 meters on channel 40. To improve the link, testing was done with a higher gain antenna (the High Gain Log Periodic with 13 dBi gain) instead of the smaller antenna (Log Periodic with 9 dBi gain), which did show slight improvement when the base station was changed to channel 22. An occasional RSSI LED would light at the 3.3 meter height. This flickering LED is an indication of an SNR of around 2 dB according to Table 2.10. The flickering LED was intermittent, which did not result in any Internet connection being established.

3.6.2.2 Phase II: Kingsbury Hall Base Station

Just like the other locations explored, Barrington Library had a lot to gain from the improvements introduced in Phase II. Since there was a small indication of signal seen at the Library from Phase I of the deployment, it was hoped that increasing base station antenna gain would help establish connection. The measurements made with the CPE showed 2 LEDs on the RSSI meter when connecting to the new Kingsbury Hall base station on channel 22. The LMI measured the SNR on average to be 18.2 dB on the downlink and 8.5 dB on the uplink. Modulation was stated to be 16 QAM 3/4 downlink and QPSK 3/4 uplink. This is a vast improvement over the lack of connection from the Stoke Hall base station, and further demonstrates the desire for high gain antennas and tuned installations.

Since these measurements were made at the adjacent parking lot (roughly 100 meters east of the projected mounting location), the measurement was made again, closer to the mounting location. This could only be done during hours in which the library was closed due to the mounting's location directly above the entrance (see Figure 3.15). The height was set to 7.7 meters, and when connection was established, an SNR of 18.5 dB downlink and 7.9 dB uplink was achieved, with the 3rd LED lit occasionally. This is similar to what was seen in the parking lot measurements. The same modulation was recorded (16 QAM 3/4 downlink and QPSK 3/4 uplink), but the speed test results showed a slight reduction of download throughput. The measured speeds were completed on a different day from the parking lot test, and showed a large variation. Based on other test locations, it can be reasonably attributed to the use of the online tests, which have shown fluctuations. The takeaway from this test, however, was the ability to achieve good SNR values and consistent modulation modes that should provide at least near-broadband speeds.

Figure 3.15: Measurement by the projected mounting location at the Barrington Library

Using the same antenna setup as the connection test for the 3.3 meter height and including the pre-amp that was used in Madbury, the power signal was measured, as seen in Figure 3.16.

Calculating the power from the trace results in roughly -87 dBm. This is right around the range for the 16 QAM 1/2, which is not the modulation that was recorded at the time of the connection test. Slight antenna movements which could have occurred during the disconnect of the CPE, however, could be a cause of the different predicted modulation, as the threshold for 16 QAM 1/2 and 16 QAM 3/4 are within a couple of dB. The difference in modulation could also be due to the radio's decision on setting the modulation. The algorithm utilized in adaptive modulation mode is not reported, and could be a decision based on more than just a power threshold, with those numbers providing simply a general idea of performance.

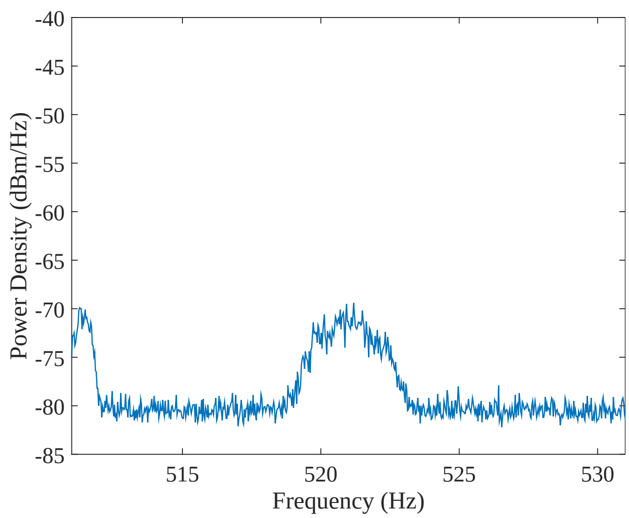


Figure 3.16: Power spectrum of the TDD signal received on peak hold mode at the Barrington Library

3.6.3 Lee Library

At roughly 6.5 km from the UNH campus, Lee Library lies within the theoretical maximum operating range of the TVWS network. This particular location, however, introduces one of the many challenges that face rural propagation. There is a hill in the path between the base station and the Library, causing severe loss. TVWS is heralded as being capable of propagating over hills. What this really means is the loss due to diffraction over a hill as described in Section 2.3.5.2 is less than that of higher frequencies. The result of this is a greater possibility of signal being seen in the region shadowed by the hill. The loss can still occur at a level that makes connection difficult. Measurements were taken at different phases of the trial and showed this occurrence.

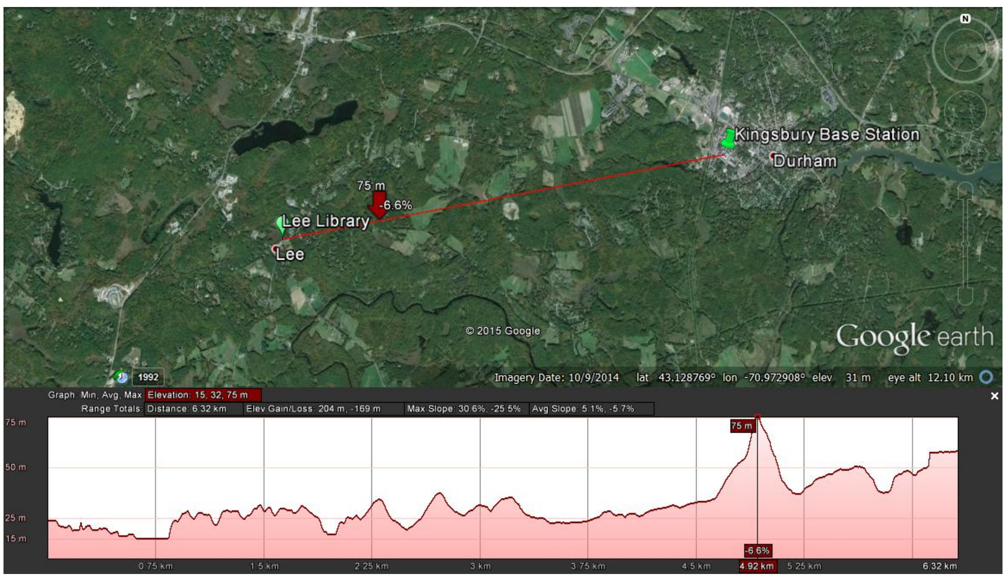


Figure 3.17: Map from Google Earth of the Kingsbury Hall base station and the Lee Library

Base Information	Stoke Sector Facing Lee	Stoke Sector Facing Lee +10 deg Clockwise	Stoke Sector Facing Lee +10 deg Counter-CW	Stoke Sector Facing Lee +20 deg Counter-CW
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 facing Stoke	3.3 meters facing Stoke
Channel	22	22	22	22
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 - 0.85 Mbps	0.7 Mbps - 0.60 Mbps

Table 3.6: Lee Library average measurement results, only interested in throughput at the time of the test

3.6.3.1 Phase I: Omnidirectional Antenna on Stoke Hall

During Phase I of the deployment, no signal was seen at the Lee Library from the Stoke Hall base station. Since this library is within the advertised 10 km operating range, having no knowledge of the terrain and clutter between the base station and CPE would lead to questioning the advertised range. Wednesday Hill as shown in Figure 3.18 is a large blockage, and it is clear that this causes loss in excess of what the system can handle. Measurements were made with the lower gain antennas, which are designed for clients closer to the base station, and higher gain would be needed in an effort to see signal in the shadowed region.

Figure 3.18: Google Terrain Map showing Wednesday Hill in relation to Lee Library

3.6.3.2 Phase II: Kingsbury Hall Base Station

The installation of the reflector at Kingsbury Hall was optimized in an effort to connect Lee, by directing the main lobe in this direction. This would provide the maximum gain from this base station antenna to attempt to connect this library. Measurements at the library were made with a Yagi antenna, which gives an improved gain of roughly 10.8 dBi. This was chosen instead of the high gain log periodic with 13 dBi gain to see if the base station improvements would be enough to connect this CPE without significant gain difference in CPE antenna. Different heights and orientations were explored with the intention to determine if connection could be achieved.

Using software provided by Carlson, the SNR alone could be monitored, which is particularly useful when a constant connection to the base station and LMI cannot be made due to low SNR values. When the antenna was placed above an SUV, the highest SNR value of 6 dB was seen (this value is the downlink SNR measured at the CPE). This can be explained by the SUV acting as a ground plane, effectively increasing the gain of the CPE antenna. Moving the SUV further away saw the SNR drop to 4-5 dB, but still gave positive values. These values were recorded on channel 22. Changing to other prospective channels in the area saw the following SNR values:

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

When any other channels were tested, no signal was detected by this software, indicating that channel 22 would be the best option for attempting connection. When connecting to the base station to run a speedtest, the truck was moved in order to provide a more realistic installation scenario. Connection was established between the base station and CPE, but the LMI indicated SNR values of 4.7 dB in the downlink and -3.3 dB in the uplink. This negative SNR shows the signal lost in the noise floor at the base station. When this happens, the radio cannot reliably complete communications, which was seen anytime an Internet connection was attempted.

3.6.3.3 Phase II: Sector Antenna on Stoke Hall

The sector antenna at the Stoke Hall base station is directed at Durham Library, the opposite direction of the Lee Library, which would make connection to this base station impossible. In order to determine if antennas that are more directional on the base station can further improve performance, the antenna was temporarily aimed towards Lee. Connection was established in this setup, as with the Kingsbury Hall setup, but this time, Internet connection was more reliable, allowing speed tests to be run. With the high gain client antenna at a height of roughly 3.3 meters (same setup and location as when connected to the Kingsbury Hall base station), speeds were seen in the 0.9-1 Mbps downlink, and 0.85-0.9 Mbps uplink range. These speeds are below what many consider to be broadband, and were recorded using the online speed tests that have been shown to fluctuate at times. They do show, however, that connection can be established, which is promising for clients that may be shadowed by hills in a closer range where the diffraction loss can be tolerated. Testing at different CPE antenna heights would cause the signal to be lost, indicating that the 3.3 meter height was ideal, based on the test set up. This further indicates the need for a tuned installation at these extreme locations.

3.7 Trial Conclusions

Through the tests performed in this trial, it is determined that this current generation of the TVWS radios used do not always work as advertised. The low antenna heights and low power limits set by the FCC makes even relatively small terrain variations, and the dense forests associated with this rural area, induce propagation loss that can make the difference between making a connection or not even over short distances. The distances are certainly much better than WiFi, but in some locations the automatically selected modulation modes limit the throughput speeds to be lower than the newly adopted definition of broadband. In areas even as distant as the Barrington Library, however, the speeds can rival, and even exceed, what can be expected from many DSL and Satellite links. In certain cases within the range defined by Carlson, like seen in Lee, terrain and foliage caused the signal to be marginal at best. Using the range definition set by the manufacturer can cause locations to be included in the coverage zone that cannot actually establish connection.

Since the throughput speeds were measured with free, online speedtest software, using accurate hardware measurement devices or recording multiple tests over longer periods of time will give a better idea of the speeds available at these locations. This is an area for future work as the trial progresses. The speeds presented here are used to give more understanding of the connection quality at each location. The modulation modes and SNR values recorded by the LMI are what has been used to determine connection quality at each location, with the speed tests used as a secondary measurement, as well as to help classify when the modulation and SNR information was not readily available.

This leads to the conclusion that path loss models should be chosen that can give a prediction of signal power at certain locations. These models can give a better understanding of the coverage area than the advertised maximum coverage range that is intended for a "typical" coverage area. Because it is hard to define a typical rural area, since each has varying degrees of terrain undulations and foliage coverage, the specialized path loss models can give a better prediction of where the radios will work, and where they will not. This will be discussed in the next chapter.

CHAPTER 4

Predicting Radio Performance

4.1 Introduction

During the trial deployment of the TVWS radios, it was found that certain propagation path characteristics, such as terrain and ground clutter, may play a larger role in the RuralConnect radio's performance than originally advertised. The radios are said to operate with a general coverage range of 10 km with the ability to propagate through foliage and around hills. As it was seen at Lee Library, however, a combination of dense foliage and large hills may prove to provide more loss than the link budget can allow. Though it is well-known that radio communication systems will typically not operate at the maximum advertised performance levels and ranges except in ideal situations, it is important when planning deployment to be able to predict the performance. In any communication system, even small losses can have a serious effect on link performance. Propagation models were developed for various applications to help predict the median path loss at a given distance. They are, however, limited in accuracy by ranges of operating parameters such as distance and antenna height.

A significant factor in propagation losses are the terrain undulations and foliage losses. The lower UHF frequencies used in TVWS networks have lower losses diffracting over hills and propagating through trees than the higher frequencies used in other wireless technologies, such as WiFi and WiMAX [38]. TVWS networks are required by the FCC to maintain low antenna heights to avoid interference to primary users (broadcast television receivers and wireless microphones that have their own designated channels) [22]. This makes even seemingly small terrain variations have an adverse effect on networks, potentially causing shadowing of the CPE antenna, which is typically mounted well below the 30 meter limit.

It was found in the TVWS trial in Chapter 3 that shadowing by hills could make a link nearly inoperable, even if the distance was well within the expected operation range. For a network to become plug-and-play, much like WiFi networks are today, performance-restricting channel characteristics and the models using them should be easy for a layperson to understand. While prior studies have investigated path loss models in TV frequencies for use in TVWS networks [20, 63], making measurements with a real TVWS network setup is of interest to see how the models can predict path loss in a real situation. The verification of the models was previously done with high power, high elevation TV broadcast towers. This gives a good idea of the performance, but when lowering the power and antenna height, which is necessary for TVWS networks, it is crucial to see if these simple models can still provide acceptable accuracy for deployment of a TVWS network. Part of the contribution of this work is to see if these models provide accuracy in the area where the BCoE TVWS trial took place without needing extensive (and therefore expensive) tuning.

The chapter will begin by explaining the measurement campaign, where relative power measurements were made with a spectrum analyzer to compare to the prediction made by path loss models. The comparison is then made to the empirical models used in this analysis. The models investigated in this research were chosen for their applicability to rural wireless area networks. The models used were the Egli Model [31], which was built from measurements in the VHF and UHF television frequencies; the Okumura-Hata Model [35], which is commonly used for UHF predictions; a tuned version of the Okumura-Hata Model [2], which was developed for improved accuracy in rural areas; and the Stanford

University Interim (SUI) Model [46], which is developed for higher UHF frequencies, but to overcome the shortfalls of the Okumura-Hata Model when lower antenna heights are used. These empirical models are designed to predict the median path loss in different environments and with various system parameters. Additionally, the Longley-Rice model [48] is used through the Radio Mobile prediction software. Finally, measurements were made with the RuralConnect radio at the corner cases from the initial measurement campaign, which provide a few representative terrain and foliage cases for a rural environment. This will help verify prediction accuracies and inaccuracies and is discussed along with a few conclusions from the campaign.

4.2 The Measurement Campaign

The TVWS broadband wireless network trial discussed in this research was performed at the University of New Hampshire and the surrounding towns. This campus is surrounded by forest and terrain that is very similar to what would be found in a typical rural area where these radios would be used. In order to help assess empirical propagation models, measurements were conducted using the base station setup at Kingsbury Hall that is being used for the trial. The measurements were made in two ways. The first part of the campaign made spectrum measurements at 40 different locations in Durham, NH and the surrounding towns, shown in Figure 4.1. Once the measurements were made and analyzed, thirteen locations were chosen to represent the typical rural area because of their location behind hills or in heavy tree cover.

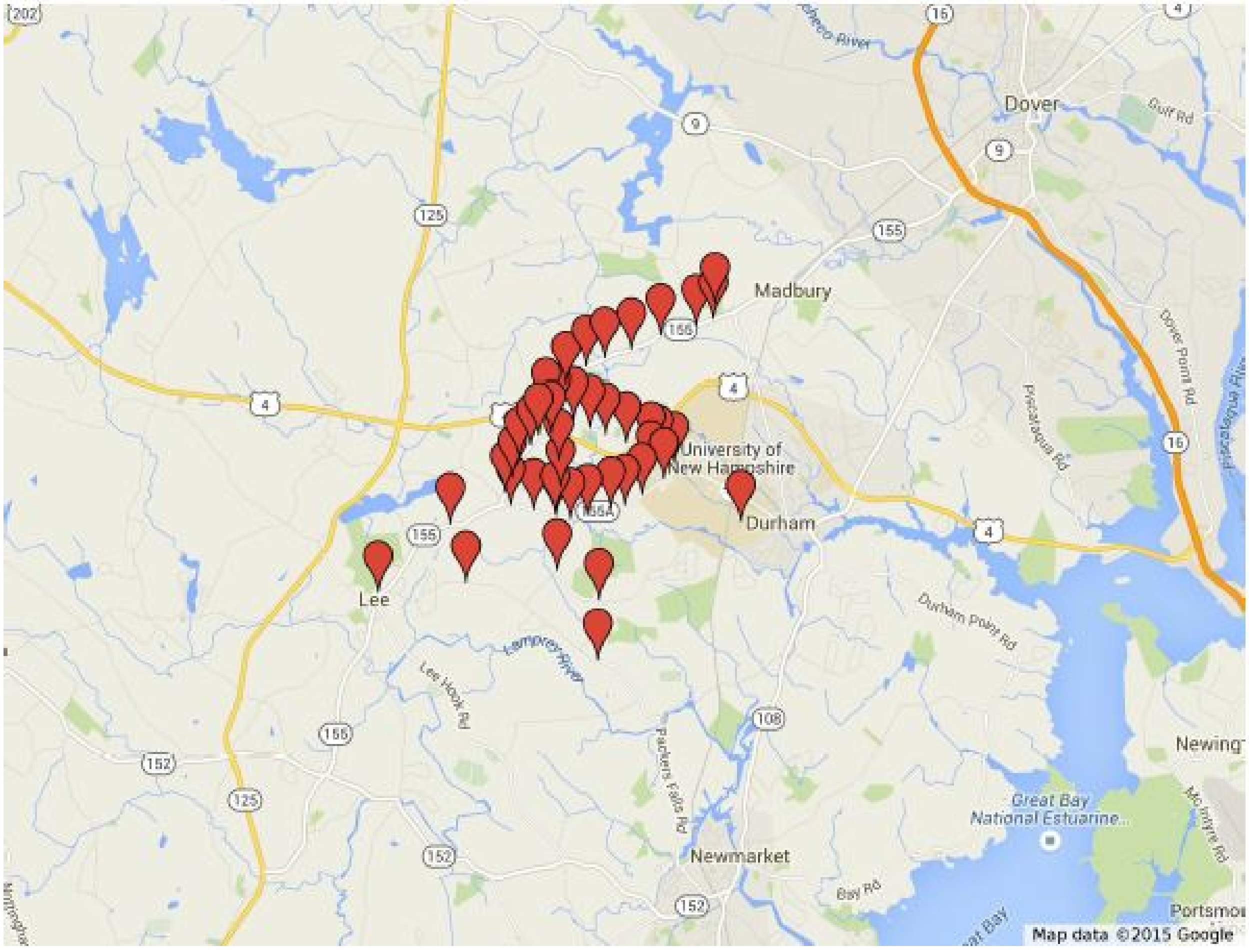


Figure 4.1: Map from Google Maps showing measurement locations (Barrington Library off the northeast corner of the map)

4.2.1 Spectrum Measurements

The surrounding area has a series of roads where the measurements were made within the coverage of the directional base station antenna on Kingsbury Hall. The directional base station antenna has a 120^o beamwidth that covers a portion of Routes 155 and 155A, where the majority of the measurements were made. The locations were logged by a GPS unit with an Arduino to ensure more accuracy in the location recording. The traveled roads provided a combination of radial measurements, where the distance was increased with each location, and measurements along a road that travels a similar distance from the base station. This was done in order to give more measurements at a similar distance covering different terrain and foliage cases.

The receiver measurements utilized an omnidirectional antenna, mounted at a height of 2.8 meters. This keeps the antenna a few wavelengths above ground while allowing comparison to a non-ideal case of antenna mounting that may be done by a subscriber. Typically, to reduce the negative effect of terrain and foliage, it is desired to mount the antenna of a stationary receiver at a higher point. The mounting equipment used during the test made mounting at these more ideal antenna heights difficult when making a large number of measurements. Additionally, this height is not too far off from mounting on a vehicle or RV, which could be of interest for mobile use.

To help eliminate the effects of multipath fading, both time and spatial averaging were utilized in the measurements. While transmitting a continuous signal, the 100 individual spectrum traces at each antenna location were saved to a computer with a LabVIEW program for processing to incorporate the averaging. To calculate the total power of the signal, (4.1) is used to take the individual power measurements saved in the trace and convert to total channel power. [64] This is the method utilized in more sophisticated spectrum analyzers that have a channel power measurement option. Summing the sample points of the power envelope and normalizing to the number of data points ($N = (n_2 - n_1) + 1$) produces the channel power.

$$P_{ch} = \frac{B_s}{B_n} \frac{1}{N} \sum_{i=n1}^{n2} 10^{\frac{P_i}{10}} \tag{4.1}$$

In this equation, Bs is the specified bandwidth, and Bn is the equivalent noise bandwidth (ENB). The ENB comes from the sweep filter used. This is additionally set by the resolution bandwidth (RBW) of the spectrum trace. The conversion factor is based on the type of filter, with the digital spectrum analyzer used having a ENB of $1.056RBW$. This equation is what is used internally in channel power measurements on more sophisticated spectrum analyzers, and is the suggested method of measurement from the FCC for the TVWS radio testing. [65] The measurements were made with standard deviation ranging from roughly 1 dB in the near line of sight cases to roughly 3.5 dB in a couple of the more distant locations. The span of the spectrum analyzer was chosen to give 110% of the RBW separation between data points. Since the analyzer was set to 700 data points, this would put a data point at every 11 kHz. Doing this would reduce the effect of overlap of the filter, causing a higher power reading. This was confirmed using a signal generator to test this theory at different RBWs and measurement frequency spans. The result was consistent using this method. Since the channel bandwidth is 6 MHz, the smallest RBW was desired that would span the entire channel, which turned out to be the 10 kHz RBW. This would give the shortest sweep time of the available RBW settings, thereby allowing for reduced measurement time. 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 signals above the noise floor of the spectrum analyzer. To match the 75Ω antenna and cable used to the 50Ω spectrum analyzer, a matching pad was used. This will reduce the possibility of reflections from the impedance mismatch causing an effect on the power measurement. This incorporated a loss of 5.7 dB but would allow for flat performance over the entire frequency range of the device, which was DC to 1 GHz. The measurement setup is summarized in Table 4.1.

Base Station Antenna Height (AGL)	28 meters
Base Station Antenna Gain	10.4 dBi
Base Station Antenna Beamwidth	120^o
Center Frequency	533 MHz
Measurement Antenna Height (AGL)	2.8 meters
Measurement Antenna Gain	5.2 dBi
Pre Amp Gain	12.5 or 25 dB
Spectrum Analyzer Used	Rohde and Schwarz FS300
Resolution Bandwidth	10 kHz
Span	7.7 MHz
Cable and Connector Losses	7 dB

Table 4.1: Measurement setup used

4.2.2 Modulation Measurements

To help verify the power measurements and predictions made by the path loss models used in this study, the measurement campaign included using the RuralConnect radios at the corner cases of the power measurement locations. This determined the modulation modes that were achievable. Measurements were made at thirteen of the original spectrum power measurement locations to see if the measured loss corresponded to the modulation modes seen. The radios were connected to a laptop, where the throughput can be measured via the online speed test sites used in Chapter 3. There are many variables in online tests, such as the traffic on the users' network in addition to the traffic on the network connecting the test servers. A wireless connection like this will fluctuate over time and location due to the varying effects on all of the clients. Website tests, however, are a good basic measurement device and were used as a relative performance marker since this is typically what a customer would use to measure their connection speeds. SNR and modulation was recorded by the

Carlson Local Management Interface (LMI) for the Kingsbury Hall Base Station. The LMI is hosted locally on the base station, and is what is used to control the radios' connection and monitor performance over time. Connection to the LMI cannot be done by the client radios connected to the base station, so this was accomplished through a mobile phone data connection. The modulation modes achieved when in adaptive modulation mode are what is used to help verify the measurements, based on the power thresholds established by the manufacturer. The best modulation mode is chosen based on the received power at the radio, and can therefore help verify the predicted and measured path loss.

The locations were spread throughout the measurement area to investigate performance over a range; they represent the various cases seen in this campaign. The naming of the locations are in order of the measurements with A-Z and then AA, BB, CC, through MM. The naming is used in this section for consistency, but for exact location, refer to the map in Figure 4.2. Following the link budget seen in Table 4.2, the applicable modulation can be seen for a certain amount of loss. This result can vary with more loss allowed which would result in an increased BER. To obtain consistent, higher accuracy performance, though, this threshold should be met.

Modulation Setting	QPSK 1/2	16 QAM 1/2	16 QAM
Tx Power	24 dBm	24 dBm	24 dBm
Tx Cable Loss	0.5 dB	0.5 dB	0.5 dB
Tx Antenna Gain	10 dB	10 dB	10 dB
Rx Antenna Gain	9 dB	9 dB	9 dB
Rx Cable Loss	0.5 dB	0.5 dB	0.5 dB
Rx Threshold	-93 dBm	-86 dBm	-80 dBm
Allowable Loss	135 dB	128 dB	122 dB

Table 4.2: Link budget for the modulation measurements

Modulation recordings were made with the same tripod setup used in the path loss

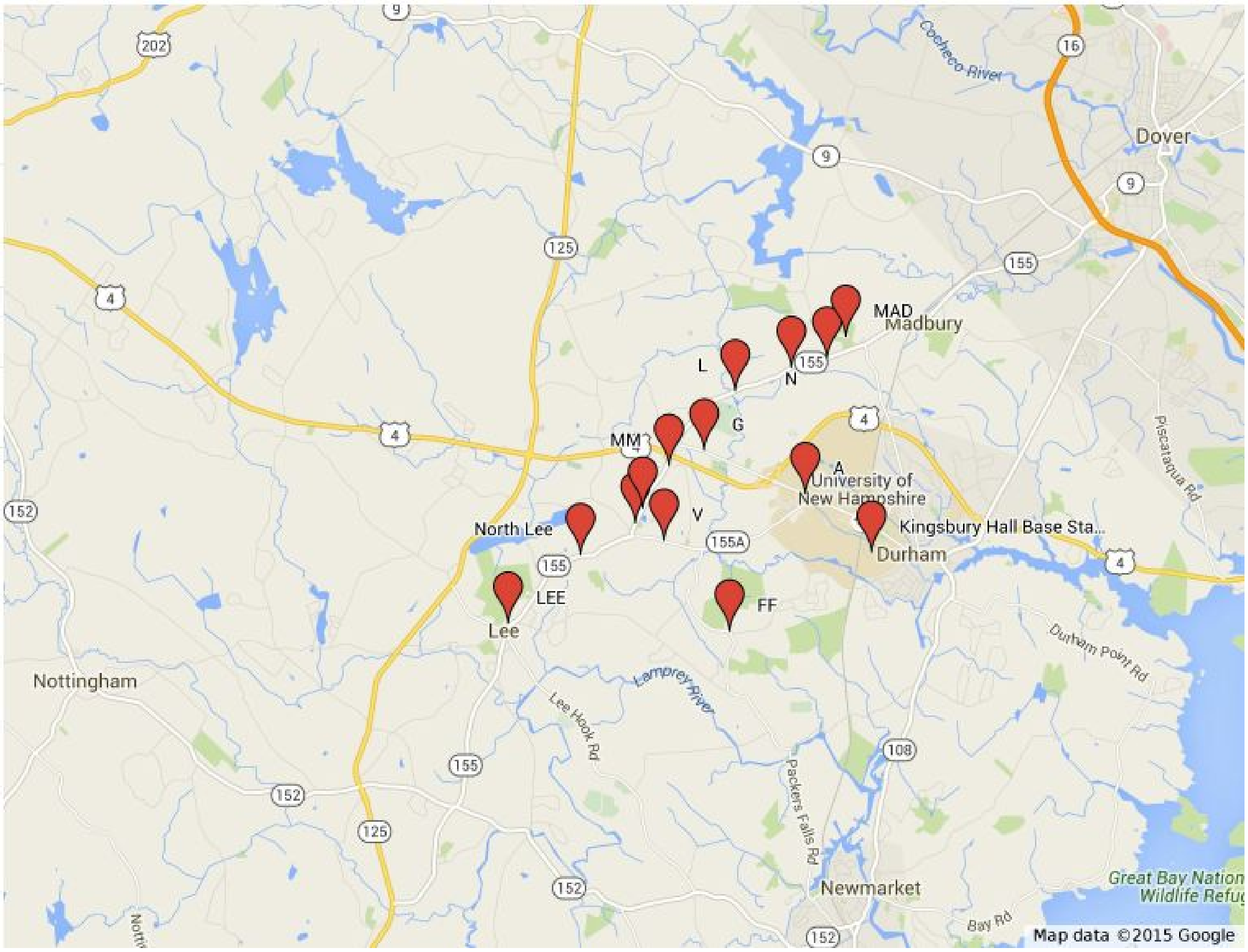


Figure 4.2: Google Maps image of measurement locations where modulation was recorded to verify path loss measurements (Barrington Library off the northeast corner of the map)

measurements, but the Log Periodic antenna was used instead of an omnidirectional antenna seen in Figure 4.3. This gives a higher gain (9 dB) and more directional beam, which helps reduce multipath effects. Additionally, the size of the antenna makes the effective mounting height roughly 2.2 meters. This could cause the results to vary slightly between the speed and path loss measurements, but this will give an idea of the relative accuracy of the measurements, as well as the ability to predict performance from the power measurements.

(a) Spectrum power measurement setup (b) Radio modulation measurement setup

Figure 4.3: RuralConnect radio and spectrum power measurement setups used in the measurement campaign

4.2.3 Performance Metrics

Before presenting the comparison, the metrics used to evaluate the models are discussed. One metric used to evaluate performance of these models is the root mean squared error (RMSE) of the path loss prediction compared to the measurement result. The equation for the RMSE is shown in (4.2), where $\epsilon_{m,i}$ is the prediction error of a given model at location i. The RMSE is commonly used to help determine the overall prediction performance of a path loss model. Additionally, the average error, which helps determine if the loss is generally being under-predicted or over-predicted, and the standard deviation of the error are given to help fully analyze each model's performance compared to the path loss measurements made in this study.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|\epsilon_{m,i}|^2} \tag{4.2}$$

4.3 Comparison of the results to Empirical Models

In this section, each of the empirical path loss models' performance results will be covered. The settings used for each model as well as an explanation for how the model fits with the environment and data collected is presented. Once each model is examined for its strengths and weaknesses, a comparison of the results from each model is given, concluding which path loss model(s) predicted the mean path loss with the most accuracy in this measurement campaign.

4.3.1 Egli Model

The Egli Model [31] was developed in 1957 from measurements made along the eastern seaboard in the U.S. It is generally accepted as an improvement in path loss prediction over FSPL and the Plane Earth Model for areas with similar terrain. The model is designed for predicting coverage for a mobile user moving over irregular terrain. It is used in this study for its applicability to the frequency band, as well as the similarity between the terrain over which the model was developed and the Durham, NH area. Generally, the model under-predicts the path loss, giving a mean error of 3.2 dB, despite a low RMSE of 6.47. This shows the applicability to the region, but the low antenna heights used introduces a greater effect of foliage and terrain loss. The Egli model gives a good baseline, but the other models can give a better idea of the path loss in the TVWS system when set up correctly.

4.3.2 The Okumura-Hata Model, and the Tuned Okumura-Hata Model

Figure 4.8 shows that the rural (open area) version of the Okumura-Hata model severely under-predicts the path loss in most cases. The Okumura-Hata models are well defined for open areas where there is not significant cause of loss from terrain and or foliage. The model in open areas assumes a "quasi-smooth" terrain and large base station antenna heights (> 30m). The transmitting antenna for the measurements made in this study is located 28 meters above ground, which is below the applicable range for the Okumura-Hata model, and is located at a slightly lower elevation than many of the measurement locations. These two factors can cause even minor terrain variations to have a greater effect on the link. The increased effect of terrain variations over the measurements made in Japan was recognized by Medeisis and Kajackas [2], where the Okumura-Hata model was fitted to measurements in both urban and rural areas. Using these corrections in this research has shown better agreement for many of the measurement locations, as seen in Figure 4.4a.

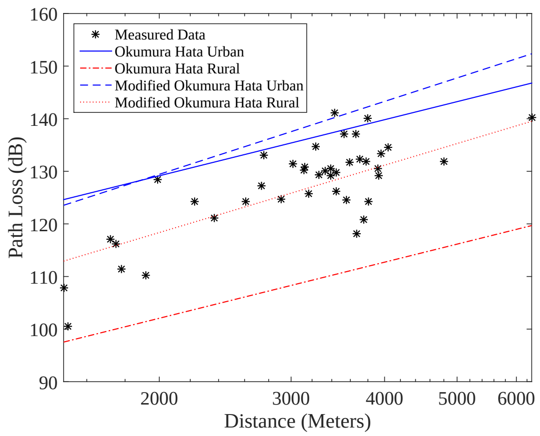
When using the Okumura-Hata model, the antenna height is not usually taken as simply the height above ground. The height above average terrain (HAAT) is used to incorporate the fact that higher elevation at the receiver or transmitter can play a significant role in varying the path loss. In the case of the Kingsbury base station, the HAAT averaged from 3-15 km (as suggested by [2] for use with their tuned model) is 17.91 m. Using this height, the path loss models are run again, with the results seen in Figure 4.4b. These results show an increased RMSE across each of the Okumura-Hata models. These values are heavily affected by the inclusion of the Barrington Library data in the analysis. This library location is more than twice the distance of the other measurement locations in this research.

The measurement at this location can be omitted from the calculation of the RMSE, since there were not enough measurements made in close proximity to allow it to represent the distance. The comparison has been limited to the distance of Lee Library (6.3 km) to have a more thorough coverage of the area in question. This leads to the desire to adjust the HAAT used. Since the measurements now only extend to Lee, the definition of the effective antenna height in ITU-R P.1546 [66] was used. This states that when the terrain is known for point-to-area predictions, the HAAT can be computed from a distance span of 0.2d-d, where d is the coverage radius. This changes the range for HAAT computation to be from 1.26 km - 6.3 km. The standard HAAT definition that assumes that terrain in the first 3 km does not play a significant role in coverage is designed for systems (particularly TV and FM radio) that have a very large coverage area. TVWS networks are much more limited in coverage, so this adjusted definition may be better suited. Computing the HAAT in Radio Mobile with this new range (still using 50 points) results in an effective antenna height of 27.89 m. This height difference from the assumed 28 m is minimal, but using this to compute the path loss from the different Okumura-Hata models does in fact slightly reduce the RMSE for the modified rural model.

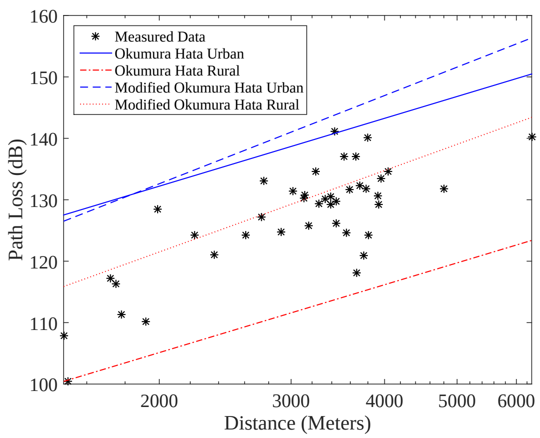
The RMSE results seen in Table 4.3 show how adjusting the perspective of the effective antenna height can change the prediction results. Using the HAAT for the range of 3-15 km may give better overall results if the measurements were made throughout the coverage area to that distance. Due to the noise floor of the spectrum analyzer limiting the measurement area, however, the measurements were mostly distributed out to 6.3 km. In this range, the HAAT of the base station is not significantly changed from the height above ground level (AGL). The elevation begins to rise beyond this distance, which effectively lowers the base station antenna compared to the distant points. Including the measurement results from

Barrington does show an improvement in the rural Okumura-Hata model as this location was in a clearing at a high elevation. This brings the link closer to a near-LoS path that is expected from "quasi-smooth" terrain.

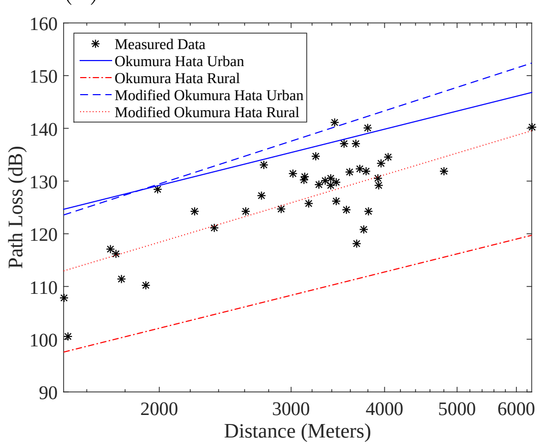
Removing the measurement results from Barrington, again, due to it being an outlier in distance, improves the prediction results for the Modified Okumura-Hata model, as stated before. The results can be seen in Table 4.4. Worth noting with the RMSE is the average error, which will incorporate whether the model is generally over-predicting or under-predicting path loss. For the AGL height and the HAAT for the reduced distance, the average error is below 1 dB. This means that on average, the model does a good job predicting the mean path loss. The maximum error is evenly distributed as well, with the maximum over-prediction and under-prediction being roughly 12.7 dB for the AGL and reduced distance antenna height. Though this large spread could be a problem for predicting performance in marginal locations, it is not unexpected. Previous work, such as that by Faruk et al. [20], has acknowledged that standard deviations of measurements on the order of 10-15 dB is not at all unusual in rural areas where terrain and foliage can play a large role in power. The RMSE for the urban models actually goes up slightly, when using either of the calculated HAAT antenna heights. This is an improvement in this case since the Durham, NH area is a very rural area by all accounts. So, the urban model should over-predict path loss, due to fewer buildings, which cause increased loss compared to foliage. Though the models should be further evaluated with a drive test throughout the entire coverage area, these few measurements show that the modifications presented by Medeisis and Kajackas [2] help improve prediction performance for areas with similar terrain. With enough measurements of the coverage area, a similar tuning method, as discussed in their report, can be taken to further improve performance for predicting the mean path loss for the TVWS network.



(a) Results using AGL antenna height



(b) HAAT correction for 3-15km



(c) ITU-R P.1546 recommendation for effective antenna height

Figure 4.4: Comparison of measurement results using different effective antenna heights

Propagation Model	RMSE for Htx = 28 m	RMSE for HAAT = 17.91 m	RMSE for HAAT = 27.89 m
Okumura-Hata (Modified Urban)	13.01	16.18	13.04
Okumura-Hata (Modified Rural)	6.39	7.06	6.38
Okumura-Hata (Urban)	10.90	13.74	10.92
Okumura-Hata (Rural)	19.25	16.15	19.22

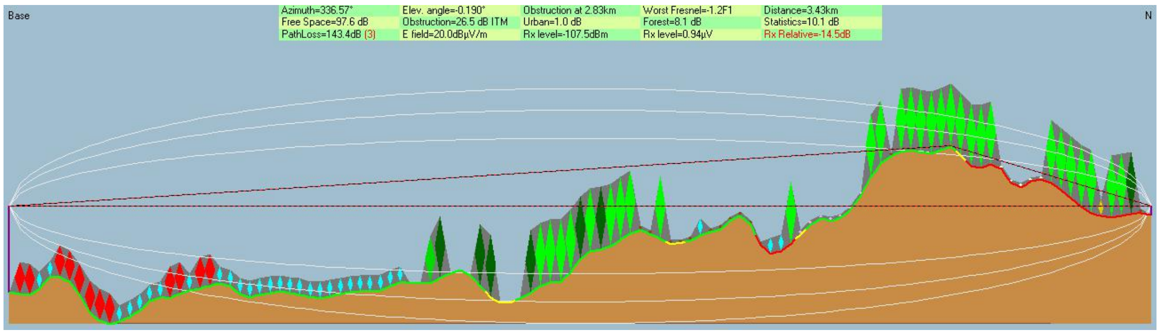
Table 4.3: RMSE after HAAT adjustment including results from Barrington

Propagation Model	RMSE for Htx = 28 m	RMSE for HAAT = 17.91 m	RMSE for HAAT = 27.89 m
Okumura-Hata (Modified Urban)	12.06	15.24	12.09
Okumura-Hata (Modified Rural)	5.65	6.05	5.64
Okumura-Hata (Urban)	10.31	13.14	10.33
Okumura-Hata (Rural)	19.47	16.34	19.45

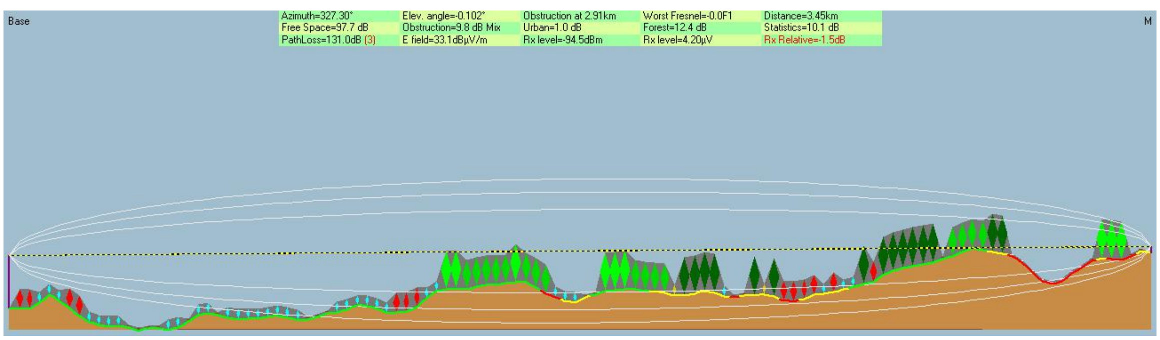
Table 4.4: RMSE after HAAT adjustment without including results from Barrington

4.3.3 SUI Model and Terrain Categories

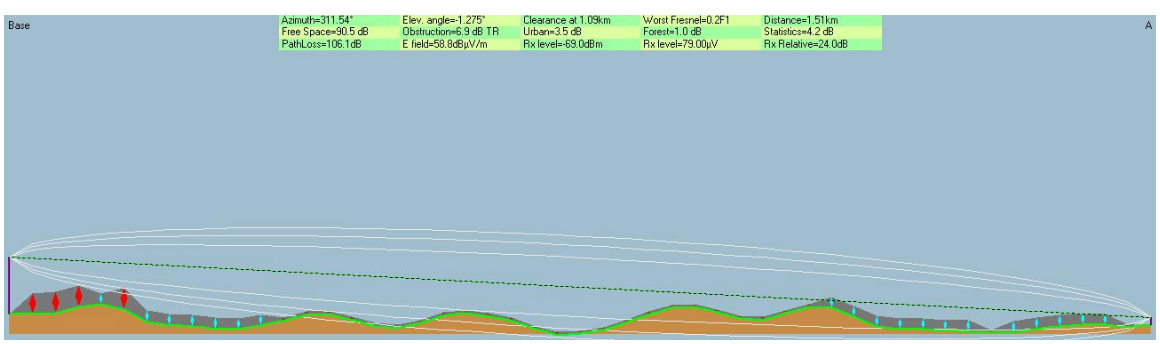
Incorporation of terrain considerations can improve performance of the path loss predictions. The Stanford University Interim (SUI) model that was established for the IEEE 802.16 Broadband Wireless Access working group does just that. The model is divided into three terrain categories: A, B, and C. Category A is defined as hilly terrain with moderate to heavy tree densities. Category C is relatively flat terrain with light tree densities. Category B is what falls in between those two categories as either being flat with heavy tree densities, or hilly with light tree densities. The terrain and foliage around Durham, NH where the trial takes place primarily falls within this middle category B. Some sites, however, are shadowed by hills that are high in comparison to the antenna heights. This loss caused by diffraction over the hill can be detrimental to the connection. In these locations, the power is better predicted by category A. Conversely, some locations exhibit more direct propagation paths that would be best described by category C. These differences are shown in Figure 4.5, where three different paths in the three categories are shown. Grouping all of the measurement locations by which category gives the closest prediction is displayed in Figure 4.6.



(a) Category A: hilly terrain and heavy tree densities seen at measurement location "N"

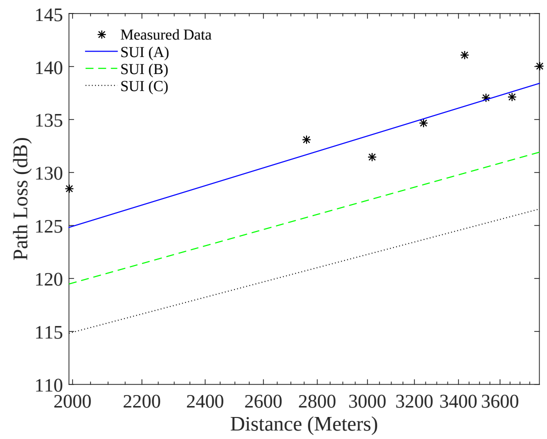


(b) Category B: hilly terrain or heavy tree densities seen at measurement location "M"

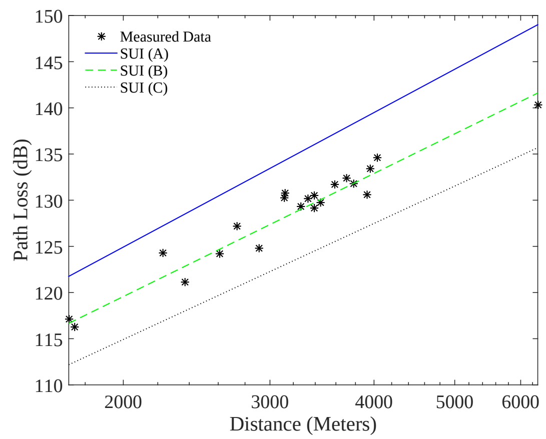


(c) Category C: flat terrain and light tree densities seen at measurement location "A"

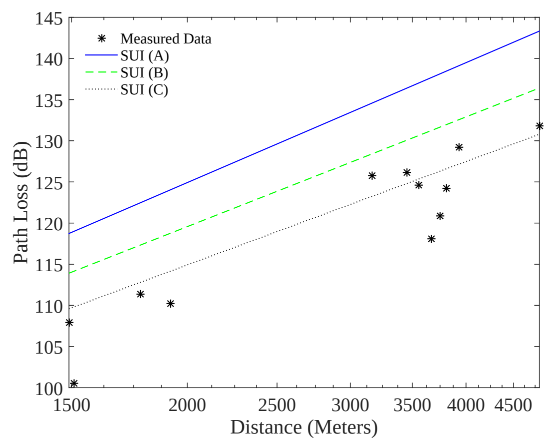
Figure 4.5: Comparison of measurement locations in different terrain categories obtained from the Radio Mobile software



(a) Category A: hilly terrain and heavy tree densities



(b) Category B: hilly terrain or heavy tree densities



(c) Category C: flat terrain and light tree densities

Figure 4.6: Comparison of measurement results for the different terrain categories

Grouping the locations by RMSE gives a good match to the actual terrain and foliage that exist in the path when considering antenna heights. When computing the terrain irregularity parameter Δh that is commonly used to describe terrain type, the A category is the highest, but only at 19 meters. According to Table 2.7, this only equates to the high end of smooth plains. This does not really fall under the hilly category that qualifies as A. With the low antenna heights used in these tests, however, even this seemingly small fluctuation of terrain can cause significant loss. Additionally, when a single obstruction exists in a path, the terrain irregularity parameter may not be as affected as when multiple obstructions occur. A single obstruction can still cause significant loss due to the signal diffraction over the edge.

Terrain Category	Δh
A	19.7 m
B	16.3 m
C	14.3 m (16.9 m with Barrington)

Table 4.5: Terrain irregularity parameter for each group of measurement categories

The terrain irregularity parameter is lower for B and C: 16.3 m and 16.9 m respectively. The fact that the category C terrain difference is higher than that of B is slightly misleading in this case. The results from Barrington were included in this calculation. Barrington Library is at an elevation of roughly 125 meters. This is almost 100 meters higher than the elevation at the base station on Kingsbury. This large elevation difference greatly alters the terrain irregularity parameter. If Barrington is omitted, the parameter drops to 14.25 m, which follows an expected trend to category C.

The effective antenna height is computed as either the height above ground level or the height above average ground level by (4.3) [67]. Determining the effective antenna height this way was not used for the prediction, but it can help explain the results. The mean effective antenna height of the receiver shows the potential shadowing in each case. The effective height increases as the category goes from A to C. With a low effective height for category A, the even seemingly small terrain variations can cause significant loss along the path. As the antenna height increases and the terrain irregularity decreases, the diffraction from the terrain would cause less loss.

$$h_{eff,i} = max[h_{gi}, h_{gi} + h_a(x_i) - h_{ref}(x_i)]i = t, r \tag{4.3}$$

h_{gi} = height above ground (AGL)

$h_a(x_i) = h_{ref} + h_s$

h_{ref} = average terrain height

h_s = Local ground height - average terrain height

Terrain Category	**Mean** $h_{eff,r}$
A	10.2 m
B	12.6 m
C	16.3 m

Table 4.6: Average effective receiver antenna height for each group of measurement categories

The density of the forests in the area also seem to play a significant role in these measurements. The antenna height is well below the tree canopy in most cases. Since a lot of the locations are at a higher elevation, the signal must propagate a significant distance through the trees. This puts a vast majority of the measurements in category B, which will incorporate heavy tree densities. Even though the TVWS frequencies have improved propagation characteristics through trees, the loss can still be significant as described in Section 2.3.6.

There are some cases that do not seem to fall in the category determined by the RMSE.

One of these cases is the measurement location shown in Figure 4.7. At this location, there does not appear to be any significant terrain obstructions to the LoS signal, yet the path loss measured at this location exceeds the prediction of category A (though only by 1.5 dB). This could be from the significant path through the trees to this location. Verification was made with the CPE, and the predicted performance from path loss matches what was seen, which will be discussed further in Section 4.5.

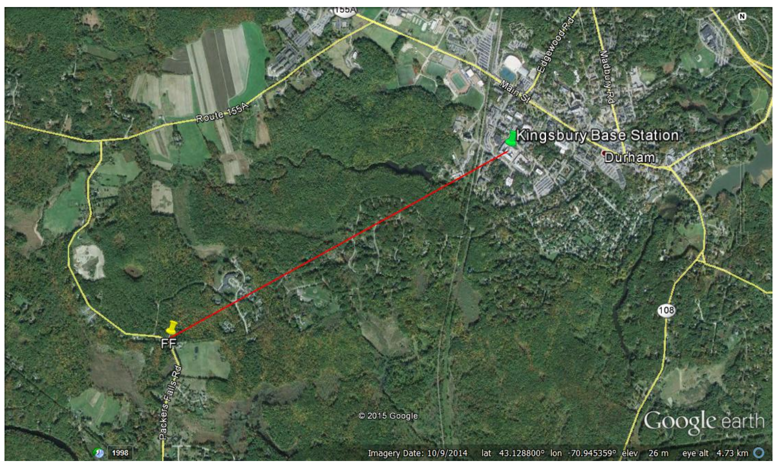


Figure 4.7: Google Earth image of measurement location FF showing the large span of forest between the transmitter and the location

Just as with the Okumura-Hata model, the results from Barrington are omitted in this section due to the lack of measurements made out to that distance to allow the result to quantify the mean path loss. Using the 6.3 km distance to Lee as the range, the results from the SUI model show that category B has the best fit. The mean error is within 1 dB of the estimation, showing this model does well at predicting the mean path loss. The range of error goes from overestimating loss by roughly 14 dB, to underestimating by roughly 11 dB. The standard deviation about the mean is roughly 5 dB; well within the range listed in the work by Faruk et al. [20], showing even better results than the Okumura-Hata model. As the SUI model was developed to help overcome the errors in the Okumura-Hata model seen at low antenna heights, this result is expected. The SUI model, however, was developed at higher frequencies than TVWS (around 1.9 GHz used in Personal Communications Services (PCS)). Before the SUI model can be accepted at these lower frequencies, more measurements in different terrain environments should be made to confirm the acceptability of each category. These results indicate that the model can provide good prediction results in the B category in areas similar to that of this trial.

4.3.4 Empirical Model Prediction Performance

For a full comparison, the overall RMSE results are seen in Table 4.7. These show that from the measurements made in the area surrounding the UNH campus, the best prediction results come from the SUI model with terrain category B, as well as the Modified Rural Okumura-Hata model. These two models were created from measurements in environments similar to the area surrounding the UNH campus, namely areas with slightly varying terrain and extensive foliage coverage. The low RMSE seen by these models is complemented by a mean error below 1 dB. Figure 4.8 shows that the models very nearly split the measured path loss values in half. Using the link budget in Table 4.2 as a reference, 128 dB of loss can be used as the tolerable loss for the network if 16 QAM 1/2 is the minimum modulation mode accepted. The SUI model would predict the distance where the average path loss in the area would occur as roughly 3.1 km. The modified Okumura-Hata rural model would predict the distance to be 3.4 km. At this distance, it is reasonable to assume that 50% of the radios utilizing the measurement antenna height would perform at or above this modulation threshold. The terrain and land-cover in the location of the network play a large role in which an empirical model should be chosen to give an idea of the coverage range.

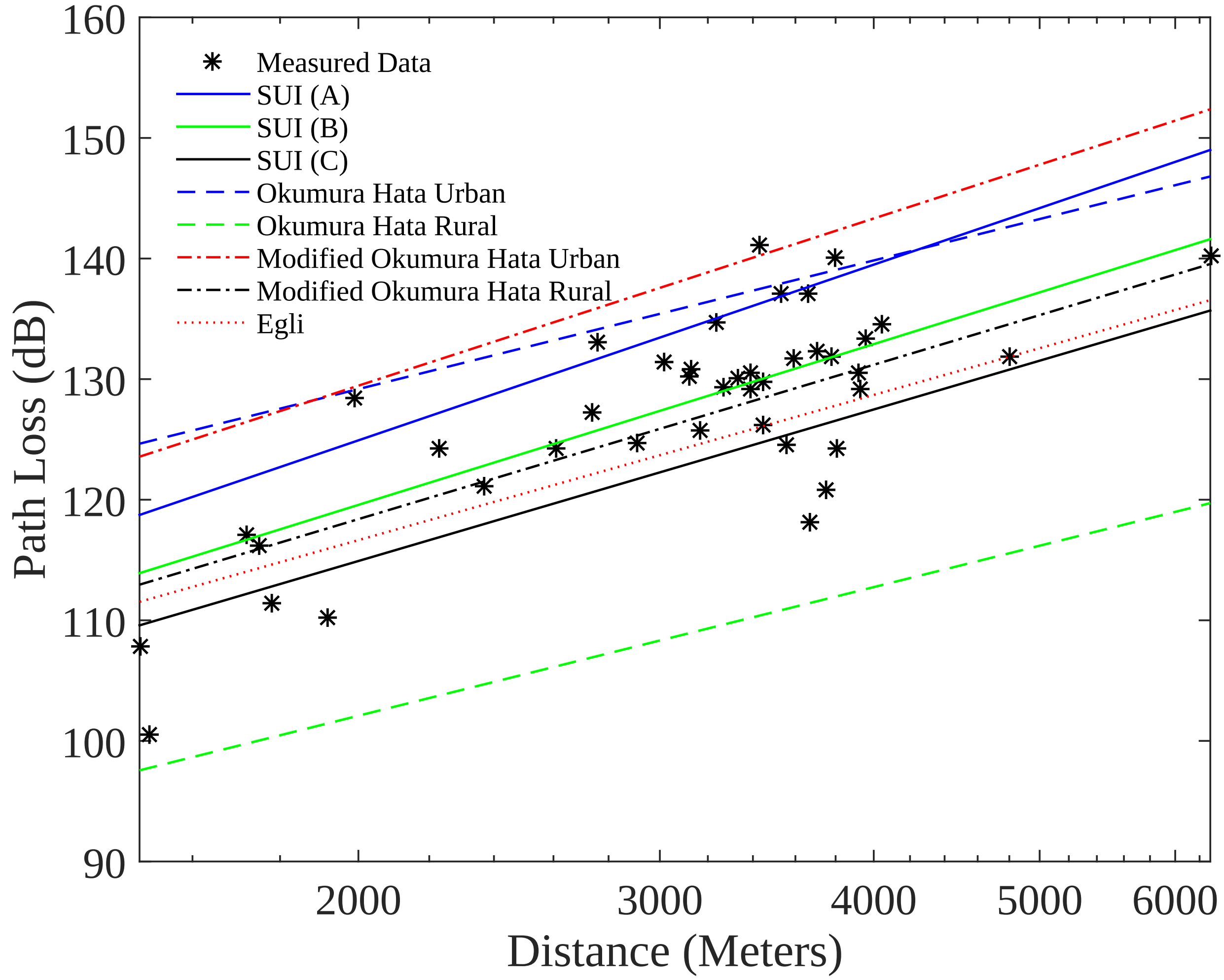


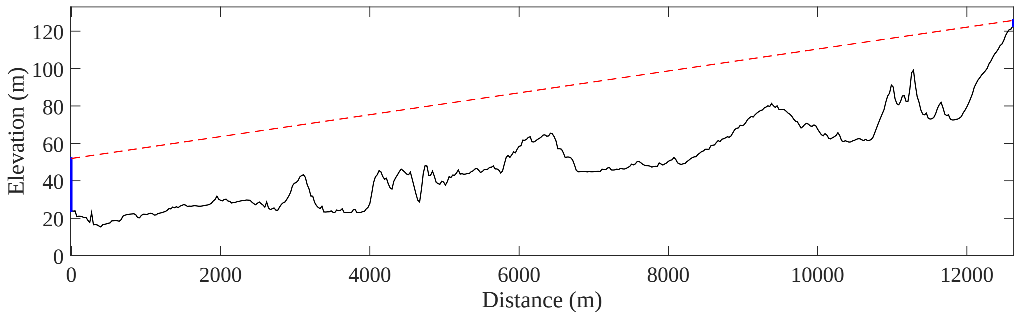
Figure 4.8: Comparison of the measurement results to various path loss models

Propagation Model	RMSE	Mean Error	Standard Deviation
SUI (Category A)	8.62	-6.66	5.54
SUI (Category B)	5.56	-0.55	5.60
SUI (Category C)	7.22	4.57	5.66
Okumura-Hata (Modified Urban)	12.09	-10.76	5.56
Okumura-Hata (Modified Rural)	5.65	0.95	5.64
Okumura-Hata (Urban)	10.33	-8.53	5.90
Okumura-Hata (Rural)	19.45	18.56	5.90
Egli	6.47	3.16	5.71

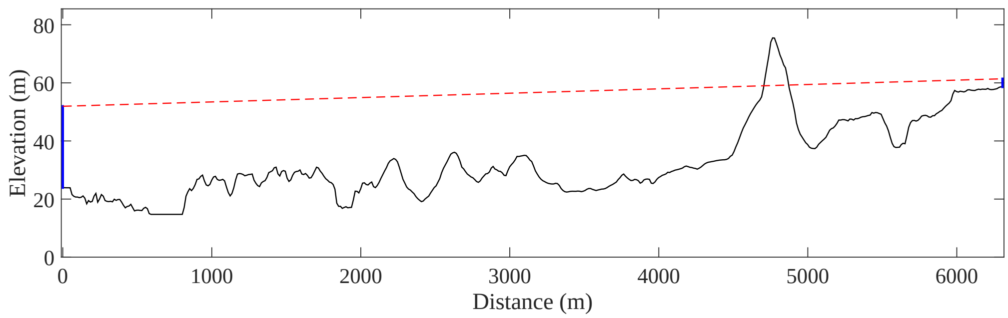
Table 4.7: General RMSE for each empirical model explained in this chapter

4.4 Radio Mobile and the Longley-Rice Model

The previously discussed empirical path loss models give a mean path loss value for a given distance and frequency. As is clear from the measurements, however, terrain and ground clutter effects can cause large variations from the predicted value from location to location. The SUI model breaks terrain up into three different categories, which provides better accuracy than models that cover a more strict terrain definition. These models, however, are best suited for mobile users where the user can overcome coverage holes as he or she changes location and orientation. For the case of TVWS rural broadband networks, the client will generally be stationary. This increases the desire to be able to predict the received power in a specific location in order to predict typical performance. Incorporating the use of accurate terrain data is important in order to understand how the terrain profile may influence transmission. For example, the Lee Library location did not provide consistent connection during our trial, even though the Library is only about 6 km from the base station while connection at broadband speeds was seen at Barrington Library 12.6 km away. This can be attributed to the terrain between the two locations. The Lee Library lies in the shadow of a hill that sits between Kingsbury and Lee. The loss from this hill can be approximated using knife edge diffraction methods. A calculation determines that this hill alone will provide a loss of roughly 14 dB (see Section 2.3.5.2). There are other terrain factors that enter the 60% cutoff of the first Fresnel zone, and, additionally, ground clutter plays a role, resulting in loss that makes the link inoperable.



(a) Barrington Library



(b) Lee Library

Figure 4.9: Terrain paths showing clearance for Barrington and Wednesday Hill obstructing path to Lee

Knowing all of the causes of loss along a path can become difficult and time and resource consuming. This is why the use of available software solutions to make the predictions becomes necessary. Many commercially-available software products can use available terrain information to provide more accurate predictions of performance at any location, using diffraction theory. In order to keep the cost of the deployment as low as possible, utilizing freely available software tools may be desired. Radio Mobile is one such tool that was explored in this research. The trade-off with the freely available tools may come with reduced accuracy. Paid services have more accurate terrain and clutter data as well as have tested and tuned the models used for different environments. This task of tuning is left up to the user of tools such as Radio Mobile. In this research, the investigation is into the use of the tool without extensive tuning for prediction of path loss at specific locations.

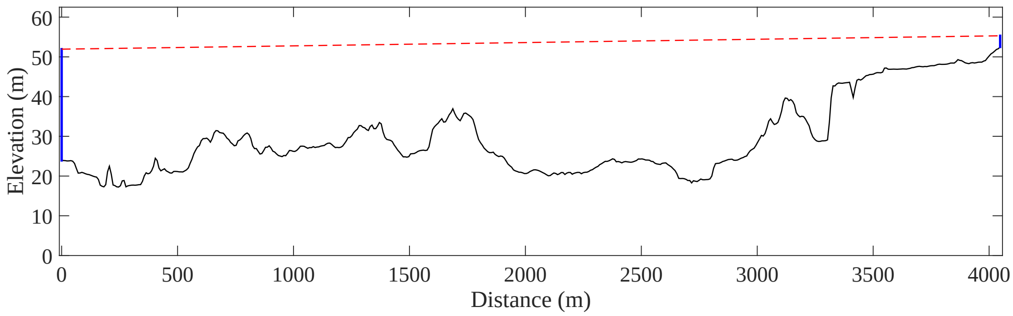
4.4.1 Reliability and Statistical Parameters

Radio Mobile uses the Longley-Rice model, as described in Section 2.6. Using different statistical variations, the Longley-Rice model can predict the path loss value that can be accepted for a certain percentage of parameters. The IEEE 802.22 working group that is developing the standard for TVWS wireless regional area networks (WRANs) suggests using 99.9% time availability and 50% location availability [27]. This will provide estimates that may vary greatly from the measured value, but when looking over the entire coverage area, the planning tool should provide estimates that show connection can be made in hard to reach areas. The standard does not discuss the incorporation of the situation availability setting that is included in Radio Mobile. This statistical measure can account for additional loss that may occur as the situation varies from where the measurements that tuned the model were made. For example, the Longley-Rice model used was developed from measurements with sparse ground cover [68]. The area around the UNH campus has significant foliage coverage, and this can create additional loss that can be accounted for by the situation variability.

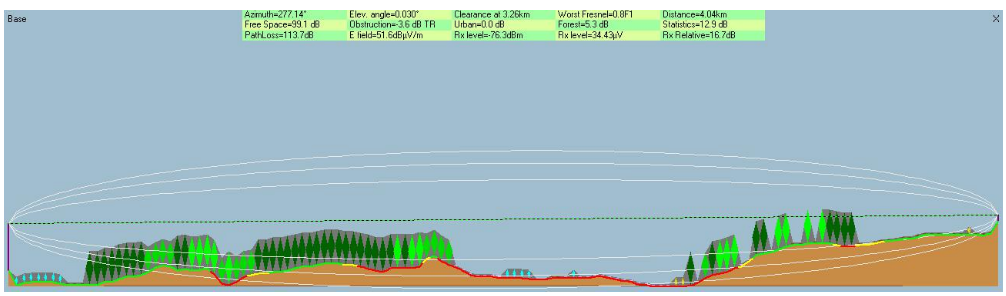
4.4.2 The Use of Accurate Terrain and Clutter Data

For terrain data, the minimum resolution suggested by the IEEE 802.22 working group is 30 meters, but for the U.S., 10 meter resolution data is also available. Both the 30 meter resolution and 10 meter resolution terrain is examined in this section with and without the 30 meter clutter information provided by the Radio Mobile Software. The 30 meter data incorporates clutter into a lot of the height measurements taken from the SRTM missions

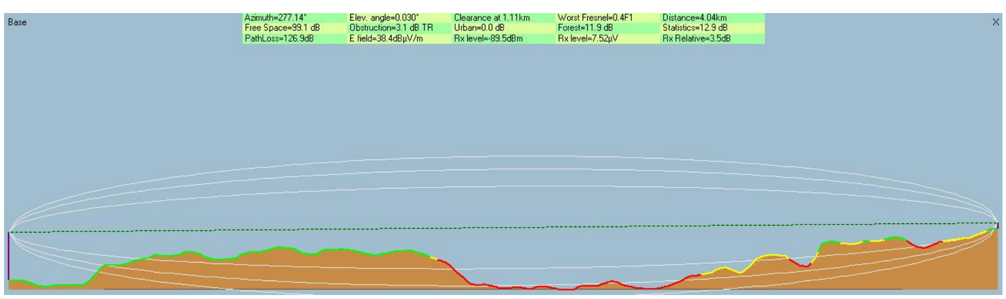
[69]. The 10 meter, 1/3 arc second resolution data is from the National Elevation Dataset (NED), which is accepted as being bare earth elevations [3]. Figure 4.10 shows the 10 meter data closely resembles that in Google Earth, and how the 30 meter includes the clutter height in most of the heights. The improved resolution can reduce errors seen by the software. Error 3 in the Longely-Rice Model applies to internal calculation of parameters, mostly involving the radio horizon distance and angle. This seems to be caused by the LoS signal grazing off terrain that does not go above the direct path but comes right up to it. In a report on the use of Longley-Rice for TV coverage [70], the FCC states that the path loss predicted with these errors should be accepted as accurate. For the 30 meter resolution, 50% of the locations came up in error, and for the 10 meter resolution, only 14% came with the error. There is not much documentation on the cause of this error in Radio Mobile, so it is assumed that it is most likely from the increased elevations seen from the inclusion of clutter height in the terrain data for the 30 meter resolution. Another option with Radio Mobile is to use an additional loss factor from forests and urban clutter, and to not use the mixed clutter data set. The foliage loss models explored in Section 2.3.6 show that for just 25 meters of foliage obstruction, the loss could be from 7-10 dB. This can be added to the loss from terrain by including a 60% forest loss. Increasing this percentage will increase the loss. This was explored as an option, with results seen below.



(a) Terrain path to measurement location X (see Section 4.5.1) taken from geocontext.org, matches the Google Earth terrain path data



(b) Terrain path to measurement at location X taken from Radio Mobile with 10 meter resolution



(c) Terrain path to measurement location X taken from Radio Mobile with 30 meter resolution

Figure 4.10: Comparison of 30 meter and 10 meter resolution to Google Earth terrain data

4.4.3 Environmental and Network Settings

The Longley-Rice model includes electrical characteristics of the environment to predict loss. Generally, when certain environmental parameters are not known (as is the case in this research) the default values are chosen, and in this case, these settings are for "average" cases. For Radio Mobile, this follows the parameters seen in Table 4.8. These settings are described more on the Radio Mobile help site [49].

Parameter	**Value Chosen**
Surface Refractivity (N-Units)	301
Ground Conductivity (S/m)	0.005
Relative Ground Permittivity	15
Climate	Continental Temperate
Mode of Variability	Broadcast

Table 4.8: Radio Mobile settings

4.4.4 Results from Radio Mobile

Clutter Setting	**Situation Variability**	**RMSE**	**Mean Error**	**Standard Deviation**
No Cover	95% Situation Variability	8.74 dB	3.9 dB	7.91 dB
1 m Mixed Cover	90% Situation Variability	9.95 dB	0.25 dB	10.07 dB
30% Forest Loss	70% Situation Variability	11.12 dB	7.9 dB	7.89 dB
80% Forest Loss	70% Situation Variability	7.79 dB	0.02 dB	7.89 dB

Table 4.9: Radio Mobile RMSE for 30 m terrain resolution

Clutter Setting	Situation Variability	RMSE	Mean Error	Standard Deviation
No Cover	99% Situation Variability	12.37 dB	8.5 dB	9.06 dB
Default Cover	95% Situation Variability	14.53 dB	9.9 dB	10.75 dB
Default Cover	99% Situation Variability	11.58 dB	4.6 dB	10.76 dB
Adjusted Cover	99% Situation Variability	10.63 dB	0.97 dB	10.71 dB
80% Forest Loss	99% Situation Variability	9.85 dB	-4.11 dB	9.06 dB
80% Forest Loss	97% Situation Variability	8.96 dB	-0.62 dB	8.96 dB

Table 4.10: Radio Mobile RMSE for 10 m terrain resolution

With the 30 meter terrain resolution from the SRTM missions, the mode of variability and ground cover are adjusted to determine the best settings for improved prediction performance. With no cover, the situation variability was increased to 95% to account for the missing forest cover. The RMSE was found to be 8.74 dB with a mean error of 3.9 dB. This prediction error is small considering that foliage is not taken into account. Since the terrain height includes clutter height, the diffraction over the top of the trees is included as terrain diffraction, thus adding to the loss and bringing the prediction closer to the measurement result. Switching to the 10 meter terrain resolution would presumably provide more accurate results due to more accurate terrain data. Since this does not include any clutter height, however, the loss is severely under-predicted in most cases. Even increasing the situation variability to 99% only provides an RMSE of 12.37 dB, with an average error of 8.5 dB. This shows that the Longley-Rice model utilized in Radio Mobile does not predict the path loss in a heavily wooded rural area, such as that in this trial, without incorporating additional foliage loss.

Introducing the clutter in Radio Mobile will require tuning the default clutter file to account for the foliage heights and type in the coverage area. As this information is not

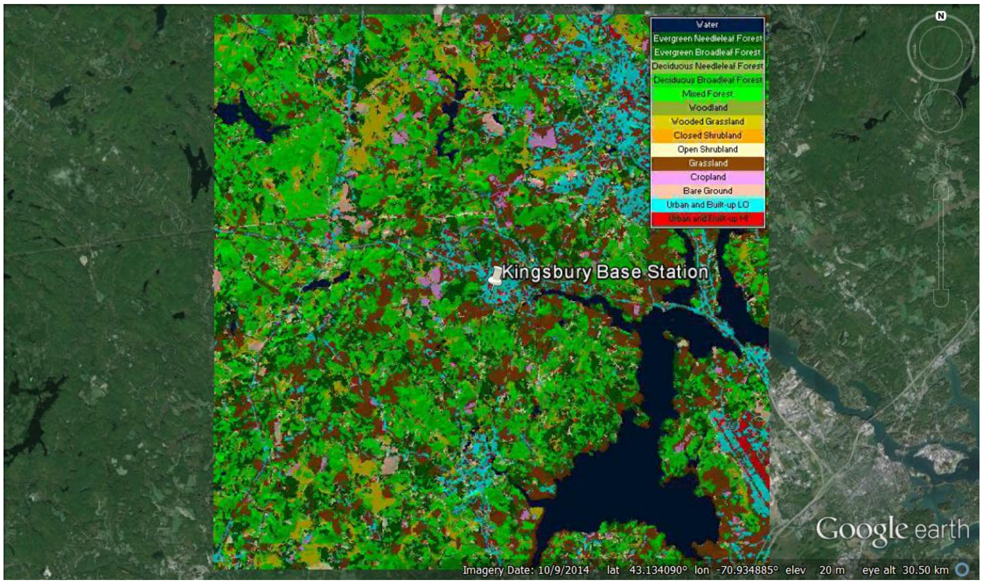
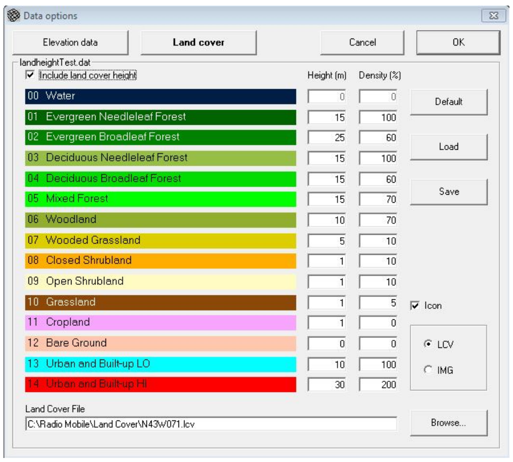


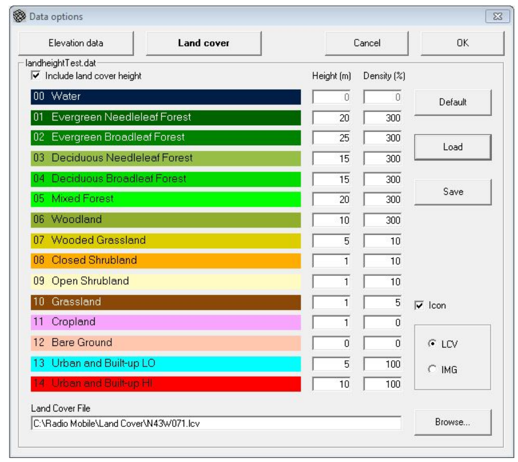
Figure 4.11: Clutter map provided by Radio Mobile viewed in Google Earth

always readily available, testing the default settings with some minimal tuning can help show the performance of the prediction. Utilizing the clutter file that is available through Radio Mobile will incorporate a distribution of clutter that should match what is seen in the area, and this is confirmed in Figure 4.11.

Zooming in on part of the UNH campus shows that the clutter descriptions are fairly accurate, but the 30 meter resolution causes some overlap of certain categories where they do not apply. The images are not included due to the lack of resolution to view in a print copy, but in some cases the "urban" category that the campus falls under will extend over wooded areas and even grassy fields. Though these cases do not occur everywhere, if a radio path were to pass through what is thought to be an urban area, but is really a grassy field, additional loss may be predicted that is not actually seen. Additionally, the height of the clutter can play a significant role. The urban category defaults at an average height of 30 meters. In a truly urban area, this actually may be low, but on the UNH campus there are only a couple of buildings that even come close to this height. Simple adjustments to the file were made to account for these height differences and to increase the foliage density in an attempt to bring the predictions closer to the measurements.



(a) Default clutter file data



(b) Adjusted clutter file used for analysis

Figure 4.12: Comparison of default and adjusted clutter files

Since the 30 meter terrain resolution file includes clutter height in most of the data, a method to incorporate foliage loss was suggested and verified by amateur radio enthusiast Remko (PE1MEW) [71]. Measurements were made in the Netherlands in urban and forested areas, and the best results came from setting all foliage and urban heights to 1 m. This will allow the model used in Radio Mobile to include foliage loss at heights within the tolerance of the SRTM missions. These measurements were made at VHF frequencies and the results really only apply to similar situations. It is strongly suggested to perform a similar verification to give best results. The settings used by Remko are included in this analysis to give an idea of how improvements can be made. Since the measurements were made at the VHF frequencies, the same results obtained in his study [71], with average error of 0.08 dB and standard deviation of 5.2 dB, do not show the same accuracy in this study.

With the same terrain and clutter settings, the RMSE achieved is only 9.96 dB, but the average error is low at 0.26 dB. The spread was large compared to the VHF study [71], with a standard deviation of 10.1 dB. This was only accomplished by increasing the situation variability to 90% to attribute more loss seen in this test. Though still a large error, this was an improvement over the use of the terrain without the clutter file, which would indicate the desire to further tune the model to the forest type and density of the coverage area for best results. Looking at the terrain heights, some of the area does not include the foliage height in the terrain data when referenced to the Google Earth data. This shows the inconsistencies that can come with the freely available data. Improvement in the prediction can be seen with other settings.

With the 10 meter resolution data, clutter height is not included in the terrain. This means an average height for each general type of foliage and building clutter needs to be included to incorporate additional losses by land cover. The losses predicted to occur from the foliage and building types is a combination of empirical measurements and wave theory. Since averaging of the clutter is done, there are going to be unavoidable errors in some locations. The default clutter file was used initially, and an RMSE of 11.58 dB and a mean error of 4.6 dB was obtained. This was again with 99% location variability, so it is clear that the losses associated with foliage are not accurately estimated with the low antenna heights at these frequencies. The adjustment of the clutter file, seen in Figure 4.12, was done to make the heights and foliage densities more appropriate for the UNH area. This was done by simply estimating tree height based on the height of surrounding buildings. These corrections led to the improvement of the RMSE to 10.63 dB and the mean error to 0.97 dB.

The results show that inclusion of clutter in the loss predictions reduces the prediction error in all cases. The clutter file, however, does not provide enough of an improvement when the default heights and densities are used. Tuning can be done to improve the results, but the tuning can be difficult and cost prohibitive.

Radio Mobile offers another solution that adds a uniform loss to all locations, allowing the mean prediction error to be reduced. In some locations that have minimal tree coverage, this will cause the software to over-predict the loss. Since these cases of minimal tree coverage in rural areas typically are of shorter distance and are close to line of sight, the link will generally work when within the coverage range. For example, Radio Mobile was calibrated in a location in Canada where forest coverage was minimal. It was found that using a forest loss of 30% and a situation variability of 70% provided the best results in the calibration location [72]. Using the same situation variability, different coverage percentages were explored to determine which gave the best fit in this trial. With the 30 meter resolution and the suggested 30% forest loss, the RMSE is 11.12 dB and the mean error is 7.9 dB. Since this high mean error shows the loss is generally under-predicted, the forest loss is increased to 80%. Doing so results in the RMSE being reduced to 7.79 dB and the mean error is reduced to 0.02 dB. Increasing the foliage loss is valid in this case, where many of the measurements were made on roads with heavy tree cover. The use of 80% foliage loss, which is 12.7 dB of loss, does a very good job at predicting the path loss compared to the other settings.

Using the 10 meter resolution terrain data again does not predict the loss as well as the 30 meter data, but using the uniform loss from the foliage coverage provides the best results for the 10 meter resolution. Since the closest prediction for the 30 meter resolution data was seen with the 80% foliage coverage, this setting was chosen again for the 10 meter resolution data. Since 99% situation variability gave the most accurate results in the previous settings, this was again chosen for these predictions. In this case, the loss was over-predicted on average, with an RMSE of 9.85 dB and mean error of -4.11 dB. To improve these results, the situation variability was reduced to 97%. Doing so improved the RMSE to 8.96 dB and the mean error to -0.62 dB. This again is not as accurate as using the 30 meter resolution data, as was the case seen with every setting. The 10 meter resolution data should be more accurate, but it appears that the foliage loss is under-predicted by Radio Mobile for this area. The inclusion of the clutter height in the terrain heights used in Radio Mobile seems to add to the loss, in a way that improves the prediction results.

The use of the Longley-Rice/ITM model in this study shows some good results, as well as a few outlier cases. The results of the Radio Mobile predictions show the importance of accurate terrain and clutter information in low power, low antenna height systems, as was the case in this campaign. The RMSE values are heavily influenced by the choice of variability statistics used in the predictions. This requires a thorough understanding of the area as it relates to the locations where the model was developed. The IEEE standard defines the time and location reliability settings, but the situation variability can be altered to better fit the location. In fact, any choice of these reliability measures can provide some extreme variations between the predictions and the results. In cases where the network connection is being sold to the consumer, a more accurate prediction may be required that may not be achievable from freely available software tools and an untrained network planner. When the service may be offered for free through government and municipality programs, low cost predictions may give enough accuracy to fit the needs of the users, and keep the cost down, allowing these TVWS radios to be used in areas where other options are not economically viable.

The Radio Mobile software has the ability to create coverage maps based on a typical receiver setup. This setup can be selected from one of the clients input into the network when the prediction was made. Using the setting that gave the best RMSE and mean error results, the coverage map in Figure 4.13 was made and overlaid on a Google Earth map.

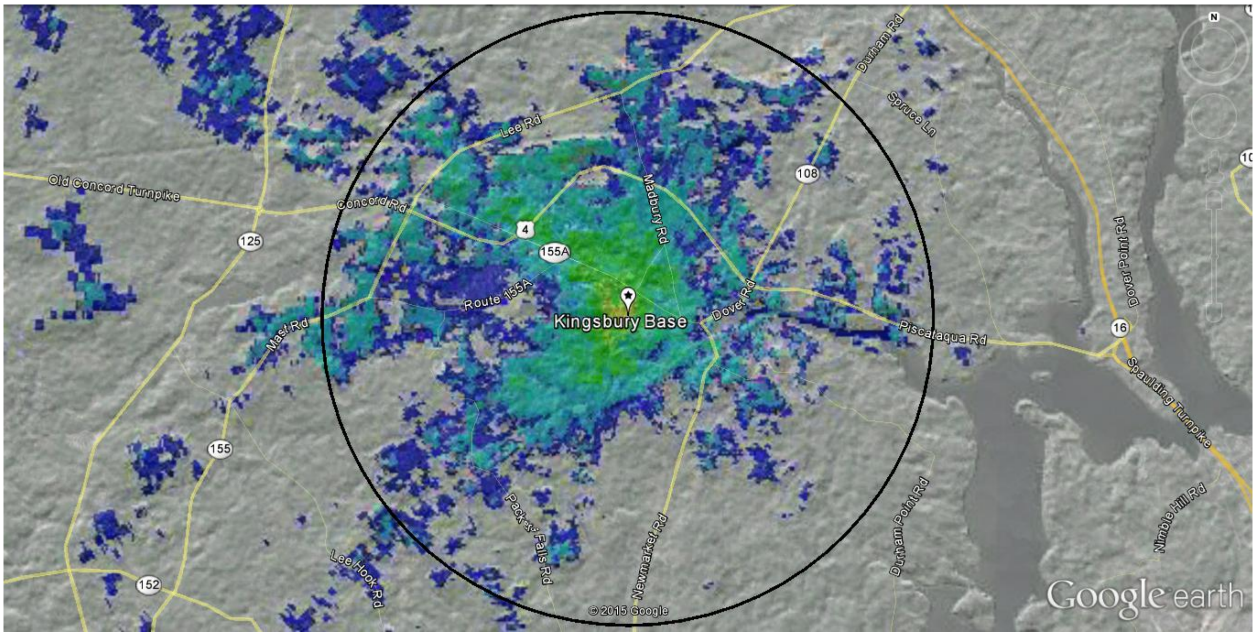


Figure 4.13: A coverage map generated by Radio Mobile, overlaid on a Google Earth map

Whereas the empirical models give a distance where the mean path loss is expected to be some value, the deterministic model used to make this map can give a general idea of the power levels that would be seen with the same antenna setup, and a better indication of coverage holes. The black circle seen in the figure shows the distance that SUI model predicts that roughly 137 dB of loss would be seen on average, 5 km. The coverage indicated by the dark blue from Radio Mobile is for a -100 dBm received power threshold with the path loss measurement setup, with lighter colors indicating a higher received power. In the main lobe of the antenna, which is to the west of Kingsbury Hall, the -100 dBm threshold would equate roughly to 137 dB of loss as well. This shows how Radio Mobile can give a better idea of the actual coverage of the base station than a standard radius. Improvements in the model may be needed to give better accuracy, but the map will provide a good visual tool for planning the TVWS network at minimal cost.

4.5 Using Path Loss to Predict Performance

Knowing the path loss with some confidence from either the empirical models or the Longley-Rice Model can help predict the performance of the radios in the deployment. If the path loss can be predicted accurately by one of the aforementioned models, the performance of the radio can be predicted as well, based on the advertised modulation rates and speeds, seen in Table 4.11, and the SNR threshold values in Table 4.12.

Modulation (FEC Rate)	OTA Data Rate Mbps
BPSK (None)	4
QPSK (1/2)	4
QPSK (3/4)	6
QPSK (None)	8
16QAM (1/2)	8
16QAM (3/4)	12
16QAM (None)	16

Table 4.11: OTA Data Rate for the various modulation modes

Modulation (FEC Rate)	Rx Power Sensitivity
QPSK (1/2)	-93 dBm
16QAM (1/2)	-86 dBm
16QAM (None)	-80 dBm

Table 4.12: Rx threshold 10^{-6} BER performance for important modulation modes

The thirteen locations examined in this part of the measurement campaign are chosen as representative of the area. Some of them represent the largest error from the Radio Mobile predictions, while others show good correlation to the predictions. The Radio Mobile setting used for comparison is the 30 meter resolution terrain data with the 80% foliage loss. This setup provided the best results with the lowest RMSE and mean error closest to 0 among each of the Radio Mobile settings explored. This gives a specific loss for each location as opposed to the distance-based loss from the empirical models, which makes it the better choice for comparison. The downlink modulation is of interest as this is based on the received power level, which would relate to the path loss measured in the first part of the campaign.

4.5.1 Locations Where Path Loss is Underpredicted

The locations grouped in this section had a higher path loss measured than what Radio Mobile predicted. Underestimating the path loss could result in thinking a link would work when it would not, or even simply thinking it would work better than it would. This is undesirable and verification of the path loss by means of the radio performance is used to confirm that the loss is being underestimated.

4.5.1.1 Location FF

This location was discussed in Section 4.3.3 as having more path loss than predicted for the SUI terrain category. Radio Mobile also provided an underestimation of the loss, which was predicted to be roughly 125 dB. Based on the allowed loss from our link budget in Table 4.2, this would indicate some form of 16 QAM modulation, likely with some forward error correction to help overcome demodulation errors that would arise from the lower SNR likely seen. The path loss measurement, however, showed 133 dB of loss which would indicate QPSK modulation with some FEC to help eliminate errors. As mentioned, this location is right next to a large stretch of forest that lies between the base station and the measurement location. This would imply that the radio path travels through many trees, resulting in more loss than what what was predicted by Radio Mobile. Connecting the client radio at this location shows the modulation starting at BPSK 1/2 and then fluctuating between QPSK 3/4 and 1/2 as speed tests are run. This correlates well with the measured loss of

133 dB, and shows how the Radio Mobile prediction will be off in some cases, particularly when there is a lot of foliage in the path.

Measurement Parameter	Trial 1	Trial 2	Trial 3	Trial 4
LEDs	2	2	2	2
Downlink SNR (dB)	7.4	9.4	10.1	13.4
Downlink Modulation	BPSK 1/2	QPSK 3/4	QPSK 1/2	QPSK 3/4
Uplink SNR (dB)	2.1	3.3	3.3	5.8
Uplink Modulation	BPSK 1/2	BPSK 3/4	BPSK 1/2	BPSK
Ping Time (ms)	275	191	195	198
Download Speed (Mbps)	1.31	1.14	1.2	1.33
Upload Speed (Mbps)	0.44	0.67	0.57	0.74

Table 4.13: Measured throughput speeds at measurement location “FF”

4.5.1.2 Location V

This location has similar terrain and clutter characteristics as FF. There are no significant terrain undulations in the path, but the terrain does bring the foliage up to block a significant portion of the radio signal path. Radio Mobile, via the Longley-Rice model, does not do as well to predict loss through foliage as it does loss due to terrain. This is shown by the prediction from Radio Mobile only accounting for 123 dB of loss. The measured value was roughly 137 dB. This would correspond to QPSK 1/2 and BPSK modulation modes. The measurements with the RuralConnect radio confirm this prediction, which displays a mix of the QPSK and BPSK with the 1/2 FEC while running speed tests. This further shows the improvements needed from Radio Mobile when predicting loss over heavily forested coverage areas.

Measurement Parameter	Trial 1	Trial 2	Trial 3	Trial 4
LEDs	1	2 flickering	1	1
Downlink SNR (dB)	10.5	9.1	9.6	7.7
Downlink Modulation	QPSK 1/2	BPSK 1/2	QPSK 1/2	BPSK 1/2
Uplink SNR (dB)	1.4	1.6	1.4	1.6
Uplink Modulation	BPSK 1/2	BPSK 1/2	BPSK 1/2	BPSK 3/4
Ping Time (ms)	174	173	201	176
Download Speed (Mbps)	1.2	0.62	1.3	0.92
Upload Speed (Mbps)	0.18	0.5	0.23	0.31

Table 4.14: Measured throughput speeds at measurement location “V”

4.5.1.3 Location X

Similarly, the measurement location X shows Radio Mobile under-predicting the loss. This location is roughly 4 km from the base station, and the majority of that stretch is through forested areas. The trees along the path causes loss that does not seem to be accurately predicted by Radio Mobile without more extensive tuning. The prediction from Radio Mobile is roughly 119 dB of loss, which corresponds to a modulation selection of 16 QAM. The measurements with the RuralConnect radio came up with QPSK 1/2 as the highest modulation achieved, which would correlate to the roughly 135 dB of loss that was measured.

Measurement Parameter	Trial 1	Trial 2	Trial 3	Trial 4
LEDs	1	1	1	1
Downlink SNR (dB)	9.9	10.4	9.3	9.3
Downlink Modulation	QPSK 1/2	QPSK 1/2	BPSK	QPSK 1/2
Uplink SNR (dB)	5.9	5.3	4.9	3.7
Uplink Modulation	BPSK 3/4	BPSK 3/4	BPSK 3/4	BPSK 3/4
Ping Time (ms)	176	199	198	181
Download Speed (Mbps)	1.24	1.14	0.97	1.38
Upload Speed (Mbps)	0.04	0.51	0.46	0.58

Table 4.15: Measured throughput speeds at measurement location “X”

4.5.1.4 Location G

Location G was examined for accuracy to further demonstrate the potential inaccuracies of the Radio Mobile predictions in areas with heavy foliage cover. This location is one under heavier tree cover along the road. Only 113 dB of path loss was predicted by Radio Mobile at this location, which would correspond to 16 QAM modulation and likely high throughput speeds. The path loss measurement, however, indicated a loss of 130 dB, similar to the other under-predicted locations discussed. Path loss of 130 dB would correspond to QPSK or QPSK 3/4 modulation, which is was what was seen by the RuralConnect radio at this location.

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	2	2	2
Downlink SNR (dB)	13.8	14.1	13.6
Downlink Modulation	QPSK 1/2	QPSK 3/4	QPSK 3/4
Uplink SNR (dB)	8.7	7.4	9.2
Uplink Modulation	BPSK 3/4	BPSK	BPSK
Ping Time (ms)	124	122	124
Download Speed (Mbps)	1.69	1.88	1.92
Upload Speed (Mbps)	1.09	0.88	1.22

Table 4.16: Measured throughput speeds at measurement location “G”

In each of the locations where modulation modes were recorded to verify the path loss where Radio Mobile under-predicted the loss, the modulation modes correlate with the path loss measured. Nearly all of the measurement locations were in a dense tree cover along the roads surrounding the UNH campus. It appears in some cases that Radio Mobile comes up a little short when predicting foliage loss for this test setup. Looking through online forums discussing Radio Mobile and some other guide sites [71], the accuracy of the foliage loss in Radio Mobile can be questioned at frequencies above VHF when specific predictions in small coverage areas are needed. Though the UHF frequencies used in TVWS networks are on the lower end of the band, there are clearly some inaccuracies in the default foliage heights and loss predictions. Using a default loss improves the RMSE and average error, but it will under-predict the loss in some cases, which can cause problems when attempting to predict performance. This is something that would have to be accepted in lower accuracy, freely available prediction tools.

4.5.2 Locations Where Path Loss is Overpredicted

Just as the path loss at some locations will be under-predicted when using a default foliage loss value, there will be instances of over-predicting the loss. These locations are typically in clearings, with minimal terrain variations between the base station and client. There is also the possibility of inaccuracies in the terrain data that can cause errors in the predictions. These two cases are discussed in this section.

4.5.2.1 Location A

Location A is the closest measurement location explored in this study. At 1.5 km, this location is just off the UNH campus and is surrounded by the open fields on the outside of campus. Including the default foliage loss incorporates more loss than what is actually seen at the location. Radio Mobile predicts loss of 114 dB when using the default loss. Measurement of the path loss was roughly 100 dB. Though this 14 dB could cause severe error in performance prediction, when this close to the base station, and this low level of loss, the 14 dB would not change the performance prediction significantly. The threshold for 16 QAM modulation and the highest performance of the radios is 122 dB. 114 dB is well enough below this level to expect good performance, even when 100 dB is the actual loss. At other, more distant locations, this offset can cause more severe prediction error.

Measurement Parameter	**Trial 1**	**Trial 2**	**Trial 3**
LEDs	4	4	4
Downlink SNR (dB)	29.4	29.3	29.5
Downlink Modulation	16 QAM	16 QAM	16 QAM
Uplink SNR (dB)	26.9	26.8	27.4
Uplink Modulation	16 QAM	16 QAM	16 QAM
Ping Time (ms)	122	122	126
Download Speed (Mbps)	6.13	5.94	6.43
Upload Speed (Mbps)	2.95	2.62	3.05

Table 4.17: Measured throughput speeds at measurement location "A"

4.5.2.2 Location L

As the distance between the base station and the client increases, the importance of accurately predicting the loss increases as well. When small changes in the loss could result in drops in performance, predicting the loss in error could result in suggesting one performance level while achieving another. In the case of over-predicting, this could mean thinking that the client location would not work, while it really could. This was seen at location L. Located at the bottom of a hill, this location was next to a clearing of trees for power lines. The clearing next to this location means a reduced amount of foliage for the signal to propagate through compared to the locations in thicker tree cover. Radio Mobile predicted 142 dB of loss, which would typically be too much to make a connection with any reliability. The path loss was actually measured to be 132 dB. This would not provide broadband access, but should be a low enough loss to provide some reliable Internet access. Testing with the RuralConnect radio confirmed this with QPSK 1/2 modulation being selected, which according to the manufacturer corresponds to roughly 135 dB of loss. This correlates well with the measurement. Prediction error like this could cause a client to be told that service is not available when it really is possible. This is a sacrifice that would need to be made when using low cost prediction options.

Measurement Parameter	**Trial 1**	**Trial 2**	**Trial 3**
LEDs	2 Flickering	1	1
Downlink SNR (dB)	11.7	10.2	11.1
Downlink Modulation	QPSK 1/2	QPSK 1/2	QPSK 1/2
Uplink SNR (dB)	3.2	2.8	4.6
Uplink Modulation	BPSK 3/4	BPSK 3/4	BPSK 3/4
Ping Time (ms)	124	125	124
Download Speed (Mbps)	1.76	2.14	2.21
Upload Speed (Mbps)	0.46	0.65	0.64

Table 4.18: Measured throughput speeds at measurement location “L”

4.5.2.3 Location BB

In some cases, the foliage loss may not be the cause of prediction error. The resolution of the terrain (and of the GPS measurements) also can cause error. Location BB is shown to be in the shadow of a hill that would cause enough loss to eliminate the possibility of making connection. This location is beyond the edge of the hill as seen in Figure 4.14, so errors in resolution from the GPS and the terrain itself could compound to increase the loss. Radio Mobile predicts 143 dB of loss on this path, which like location L, would correspond to no connection. The path loss, however, was measured to be 131 dB. This 12 dB difference could easily be from assumed diffraction over the hill that is thought to block the path. Testing with the RuralConnect confirmed the 131 dB loss measurement as modulation choices QPSK 1/2 and QPSK 3/4 were recorded, again showing roughly 135 dB loss.

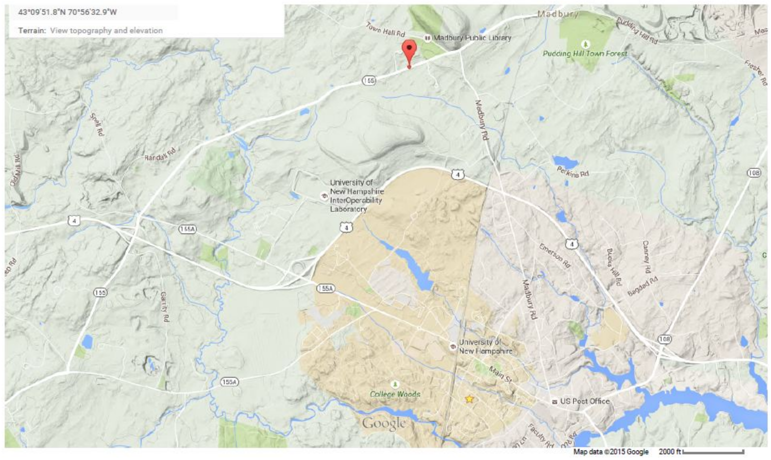


Figure 4.14: Google Maps image of measurement location BB showing the location of the hill that may not actually be in the propagation path

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	2 Flickering	2 Flickering	2 Flickering
Downlink SNR (dB)	11.9	11.1	11.8
Downlink Modulation	QPSK 1/2	QPSK 3/4	QPSK 1/2
Uplink SNR (dB)	6	7.5	7.6
Uplink Modulation	BPSK 3/4	BPSK 3/4	BPSK 3/4
Ping Time (ms)	185	186	177
Download Speed (Mbps)	1.47	1.55	1.39
Upload Speed (Mbps)	0.55	0.55	0.93

Table 4.19: Measured throughput speeds at measurement location "BB"

4.5.3 Locations Where Path Loss is Accurately Predicted

While there were inherent inaccuracies in the path loss prediction from Radio Mobile, many locations did have path loss predicted accurately. These locations had terrain loss better predicted by Radio Mobile, and the foliage loss that was added to the predictions better matched these locations. While 75% of the predictions were within 10 dB of the measured loss, the locations discussed in this section had the smallest prediction error.

4.5.3.1 Lee Library

As the only location chosen in the BCoE TVWS trial where connection was unsuccessful, and a major cause for the realization of the necessity of accurate prediction models, the Lee Library was chosen as a verification location. This location is in the shadow of Wednesday Hill, which causes enough loss to make the system inoperable. The path loss was measured to be roughly 140 dB at this location. Radio Mobile predicts the loss to be roughly 142 dB, which is in very good agreement with the measurement. This is below the threshold for connection in the measurement setup used, and was confirmed to be the case. To further confirm the accuracy of the prediction, a connection speed measurement was made roughly 1.5 miles to the north along Rt. 155 (labeled as North Lee in Figure 4.2), to get out of the shadow of the hill. Path loss was not measured, but the radio selected modulation was recorded, with a modulation mode of 16 QAM with either the 3/4 or 1/2 FEC seen. This would correspond to roughly 128 dB or less of loss. Adding this location to the Radio Mobile prediction shows a loss of 124 dB, which correlates well with the modulation modes seen. This indicates that in locations with terrain obstructions, Radio Mobile does well to predict the loss. Lee Library is in a more open area than some of the measurement locations, which results in reduced foliage coverage in the path. Radio Mobile was shown to predict the loss with some improved accuracy in locations with less foliage coverage over those locations with more forest obstructions.

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	3	3	3
Downlink SNR (dB)	24.1	24	23
Downlink Modulation	16 QAM 3/4	16 QAM 1/2	16 QAM 1/2
Uplink SNR (dB)	16.4	14.8	15.1
Uplink Modulation	16 QAM 1/2	16 QAM 1/2	16 QAM 1/2
Ping Time (ms)	174	176	173
Download Speed (Mbps)	4.26	3.53	3.1
Upload Speed (Mbps)	1.58	0.88	1.19

Table 4.20: Measured throughput speeds at measurement location north of Lee Library

4.5.3.2 Location N

Located in the shadow of another hill, the measurement location N is predicted to have a loss of 141 dB by Radio Mobile. This is in fact what was measured, further showing the accuracy of the Longley-Rice model and Radio Mobile when terrain obstructions are the dominant cause of loss. To confirm that this loss would make the radio link inoperable, the RuralConnect radio connection was attempted. As predicted, no connection was achieved with this setup, confirming the result.

4.5.3.3 Madbury Library

Similar to Lee Library, Madbury Library is in a forest opening with a recreation field directly adjacent and along the radio path. This clearing of trees reduces the foliage loss in the path, and allows the strength of the Radio Mobile prediction to show. The loss at this library was measured to be 118 dB and Radio Mobile actually predicted the loss to be 119 dB. This would indicate the ability to achieve 16 QAM modulation and high data rates, as seen in Table 4.21.

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	4	4	4
Downlink SNR (dB)	27.3	27.3	27
Downlink Modulation	16 QAM	16 QAM	16 QAM
Uplink SNR (dB)	23.2	23.4	24.5
Uplink Modulation	16 QAM	16 QAM 3/4	16 QAM 3/4
Ping Time (ms)	123	122	122
Download Speed (Mbps)	7.67	7.08	7.23
Upload Speed (Mbps)	3.56	3.23	3.81

Table 4.21: Measured throughput speeds at the measurement location at Madbury Library

4.5.3.4 Location Y

Since one of the locations with poor accuracy was location X, which is in very close proximity to location Y, it was desired to confirm the accuracy of prediction at this location. The terrain and clutter in the two radio paths are very similar, resulting in what one would expect to be very similar loss predictions and measurements. As the loss was measured to be 133 dB, very similar to location X at 135 dB, this idea is confirmed. Radio Mobile does well with the prediction of location Y, however, predicting 134 dB of loss. Unfortunately, a connection to read the modulation from the LMI was not achieved at this location, so the exact modulation used is unknown. The connection speeds recorded in Table 4.22 indicate either BPSK or QPSK 1/2 modulation based on measured results in Appendix B.2. This would correspond to 135 dB of loss, and is very similar to what was seen at Location X. This shows that Radio Mobile is capable of predicting the loss in the heavy tree cover, but the overall accuracy may not be as high as desired. This is a trade-off that keeps coming up with the use of freely available, un-tuned software solutions that has to be weighed by the user.

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	1	1	1
Ping Time (ms)	124	180	191
Download Speed (Mbps)	1.51	1.28	1.16
Upload Speed (Mbps)	0.53	0.11	0.16

Table 4.22: Measured throughput speeds at measurement location “Y” (No connection to LMI to record SNR or modulation)

4.5.3.5 Location MM

This location is a combination of different cases. At 3.8 km, it is one of the more distant locations, but it is at a higher elevation than many. This allows the signal path to stay above the tree line for much of the way, resulting in lower loss and improved prediction accuracy. The measured loss at this location is only 121 dB. Radio Mobile predicts the loss to be 120 dB. This correlation is confirmed with 16 QAM modulation achieved, further indicating that Radio Mobile does well for predictions in areas where foliage cover is not as dense in the immediate proximity of the antenna.

Measurement Parameter	Trial 1	Trial 2	Trial 3
LEDs	4 Flicker	4 Flicker	4 Flicker
Downlink SNR (dB)	24.8	24.6	25
Downlink Modulation	16 QAM	16 QAM	16 QAM 3/4
Uplink SNR (dB)	17.5	16.3	16.2
Uplink Modulation	16 QAM 3/4	16 QAM 1/2	QPSK
Ping Time (ms)	178	177	189
Download Speed (Mbps)	4.06	3.75	4.05
Upload Speed (Mbps)	1.17	1.3	1.29

Table 4.23: Measured throughput speeds at measurement location “MM”

4.6 Conclusions

There are several main takeaways from the analysis of the propagation models. First, the models were developed in similar environments to where the TVWS trial measurements were made in the area surrounding the UNH campus, but since the models do have some variations in settings, it is important to verify their functionality in this actual use. Empirical propagation models are expected to work well when it comes to making predictions in situations very similar to those of the measurements from which they were developed. For example, the Egli and Okumura-Hata models are known to provide good accuracy for UHF communications in terrain categories similar to those from which they were developed. Typically, predictions with these models are for systems with higher antennas and high power transmissions. When low power and low antenna heights are used, like in TVWS networks, the variation of terrain and foliage cover can provide increased loss from what may be seen in the typical case of broadcast television, for example. This was acknowledged by Medeisis and Kajackas [2], where the Okumura-Hata model was tuned for areas that have more terrain variations than the "quasi-smooth" terrain in the Okumura-Hata model rural area definition. It was found that this tuning provided better prediction results for this TVWS network. Using the HAAT definition from ITU-R P.1546 [66] makes more sense for a TVWS network where the coverage range will not typically exceed the distance for the standard HAAT definition (3 km-15 km range). Using the HAAT definition from ITU-R P. 1546 provided the highest overall prediction accuracy for all models. The Egli model itself was developed in similar terrain, so the RMSE was low, but the loss was generally under-predicted as the model was developed from measurements with higher antennas.

To account for the reduced antenna heights, as well as varying terrain and clutter categories, the Stanford University Interim (SUI) model was developed to help overcome the shortfalls of other UHF prediction models. The middle category B, which covers areas with hilly terrain or dense forests, describing well the UNH area, provides very accurate mean path loss prediction. Since the model was developed from measurements at higher frequencies, the other terrain categories should be confirmed before the whole model is accepted for use in TVWS predictions. When it comes to mean path loss predictions in TVWS networks, the SUI B model and the tuned Okumura-Hata model from Medeisis and Kajackas [2] provide the best results, and can be used in similar terrain and ground clutter situations to the UNH area to give a basic idea of loss expected in TVWS networks.

When deploying a TVWS network, predicting exactly where a CPE will work, and roughly how well, will be important moving forward. Since point-to-area empirical models only provide the mean path loss, extreme variations can be expected when terrain or foliage obstructions exist in one path while another exhibits closer to LoS characteristics. Point-to-point models can provide a better understanding of the loss expected at specific locations. These models take terrain and ground clutter into consideration to predict the loss along a specific propagation path. Since TVWS networks will mostly be used in underserved areas, low cost deployments are a must. This means using low cost and even free propagation modeling software to provide predictions. Free software models may not have the best accuracy because they only use freely available terrain and clutter information, and accurate tuning that comes from paid services is left up to the user. Testing Radio Mobile has been completed for this trial area with the default settings and some simple adjustments to see if it can provide accuracy without having to either pay for a drive test to tune the model, or perform extensive terrain and clutter verification. It was found that using the IEEE 802.22 variability recommendation [27] and the 30 meter resolution with 80% foliage cover provides the best results for prediction in the measurement campaign. The default clutter file requires accurate tuning for the area to provide acceptable accuracy, so finding the mean foliage loss and including it as a standard loss value will provide the best average results. Using this setting, more than 75% of the predictions are within 10 dB in this campaign area. This would provide fairly accurate prediction with a few outliers. This same result has been seen from the Longley-Rice Model in other research on the use for TVWS predictions [15]. In a paid service, the prediction would need to be more accurate. In low cost deployments, however, this value of 75% within 10 dB may provide acceptable accuracy for understanding the loss and, therefore, the radio performance in the area. More success will come from tuned models based on drive tests in similar areas. This should be done to really allow low cost TVWS deployments by untrained professionals to become a simple and viable option for providing broadband Internet access to underserved rural areas.

CHAPTER 5

Conclusions and Future Work

Television White Space radios are a promising new technology that can be used to help fill the broadband Internet void that exists in underpopulated rural areas in the United States and around the globe. The available frequencies in the lower UHF bands have superior propagation characteristics to WiMAX and WiFi, thus allowing wider coverage ranges to be achieved. As it is still early in the technology's existence, the necessity to set up trials of the available devices to determine if they can support real rural broadband deployments is clear. In order to assist in this development, the first main contribution of this thesis was to present the findings from an ongoing trial in the Durham, NH area of commercially available RuralConnect Radios from Carlson Wireless. By connecting local town libraries to the University of New Hampshire network, it has been shown that coverage of clients at least to a distance of 12.6 km is possible, with modulation rates allowing upwards of 4 Mbps download and 1 Mbps upload speeds to be achieved. This is not 100% coverage to this distance, however, with coverage holes being found much closer to the base station. Even when a connection was achieved with 4 Mbps download and 1 Mbps upload speeds, these speeds are below the newly defined level of broadband set forth by the FCC in January of 2015 [7] which is 25 Mbps download and 3 Mbps upload. The 4 Mbps/1 Mbps that are achieved from the modulation modes recorded, however, would provide access to basic broadband Internet tasks such as videoconferencing and streaming media, if only on a few devices. Development of the technology is still needed to begin approaching the FCC definition of broadband.

For the deployment of a network of TVWS radios in rural areas to be economically feasible, simple, low cost tools are needed to help with determination of radio coverage, which leads to the second contribution of this work. These tools are readily available for other technologies operating in the same frequencies in rural environments, but in order to confirm that the tools can be used in a TVWS network, verification needs to be done with a typical TVWS network setup, namely with low antenna heights, and low transmission power. The measurement campaign described in this research offers some indication of the performance of empirical path loss models that offer a mean coverage range, as well as simple deterministic modeling software, that can predict the path loss to a particular point in the coverage area of the radios.

In this research, the Egli Model, the Okumura-Hata Model and the Stanford University Interim (SUI) model, which are three of the most popular path loss models for rural networks in the UHF frequency bands, were explored. The Okumura-Hata Model performed well when simple tuning completed by Medeisis and Kajackas [2] was applied for a rural area with a similar terrain profile, and at a similar frequency, resulting in a root mean squared error (RMSE) of 5.65 dB and a mean error of 0.95 dB.

Additionally, the SUI model, which can be split up into three different terrain and foliage categories, performed well for the terrain category B, resulting in a RMSE of 5.56 dB and a mean error of -0.55 dB. Category B is defined as a combination of either hilly terrain or dense foliage coverage, which is the environment surrounding the University of New Hampshire campus where the TVWS trial takes place. These empirical models will give a distance at which it can be assumed that the path loss of the radios will be equally distributed about the predicted path loss. This will mean approximately 50% of the radios at this distance will work at, or above, the predicted performance level in deployment locations with similar characteristics to the Durham, NH area. This is useful for general coverage planning of a TVWS network.

Since these empirical models offer only a mean path loss to a particular distance, the use of a deterministic model is beneficial to be able to predict coverage to a specific client location. Many deterministic models are available at a monetary cost to the deployment as they offer finely tuned models and algorithms that were designed by trained experts in the field. In order to eliminate this cost, the freely available Radio Mobile software, which utilizes the Longley-Rice Model, was explored. Comparison to measured path loss in the TVWS network shows that the Radio Mobile software produced some significant errors with different application settings. Due to the deterministic nature of the algorithm, there are a number of settings that can be adjusted to fit the prediction to the location best. Adjusting these settings found the best RMSE and mean error results when using the IEEE 802.22 requirements [27] and the 30 meter resolution terrain data with 70% situation variability, and a flat 80% foliage loss. These settings resulted in a prediction RMSE of 7.79 dB and a mean error of 0.02 dB. The increased RMSE of the Radio Mobile prediction over the empirical modified Okumura-Hata and the SUI models was attributed to the use of the terrain and foliage data without tuning. Just as accurate terrain and foliage data can provide improvements in prediction from deterministic models over the use of empirical models, inaccuracies in the terrain and foliage data can greatly reduce performance. The tool can be used, however, to give a good basic understanding of coverage variations in specific locations due to terrain, as well as provide coverage maps showing expected coverage holes.

5.1 Future Work

This research took a step towards providing verification of tools to assist with a low cost deployment of a TVWS network. There is still more work to be done, however. The trial has been conducted with temporary client setups outside of the library locations. This does not provide the typical deployment scenario where the clients would be online at the same time. In order for the trial to move forward, permanent installations at the library should be completed to monitor network performance with many simultaneous users. Doing so will give a better idea how the network works as a whole, whereas this research showed how the radios work at each location individually.

Rural areas where these networks would be installed come in all different environments. The measurement campaign completed in this research was not an extensive coverage of all rural areas. Some areas may be flat desert where there is minimal terrain and foliage obstructions; others will be similar to the Durham, NH area with large forests and rolling hills between the locations, while others will be in extreme conditions with mountainous terrain and very thick forests. Testing the models described in this research in all of these different terrain and different foliage types comparing deciduous and coniferous foliage, as well as in different seasons, will further validate the models' use for TVWS networks.

To improve the deterministic model's prediction accuracy, tuning should be completed to fit to a typical TVWS network setup with low antenna heights in various rural areas. This is not something that would be feasible for a municipality to perform at a low cost as it typically involves extensive drive tests to provide a large number of measurements in a coverage area. Drive tests, however, could be performed in academic studies similar to this one, in order to tune the models and software for use in low cost deployments. This is an area of interest for possible continuation of this work.

The trial and validation of models performed in this research was completed in an effort to assess commercially available radios and freely available tools for a low cost TVWS rural broadband Internet network. In their study, Fitch et al. suggest that 12 Mbps out to 8 km would be needed to make TVWS networks economically viable [16]. The performance of the radios at the tested client location does not indicate this is achievable with the current generation of radios, which would necessitate the further development of the technology. The ability to connect clients as far as Barrington Library 12.6 km away, however, does show great promise in the ability to help make Internet coverage ubiquitous worldwide. The rate at which wireless communications has grown the past few decades show that the TVWS radio technology can be developed into the solution to the rural broadband coverage problem.

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APPENDICES

APPENDIX A

A Summary of the Antennas Used

For the testing and eventual installation of the TVWS network used in the trial, seven main antennas were used, three for the base stations and four for the client stations and measurements:

- 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 2 dBi

All of these antennas, except the Winegard window antenna, were purchased through Carlson Wireless. More information can be found on their site [73]. 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 A.1.

Location	**Base Station**	**Antenna**	**Phase of Trial Installed**
Kingsbury Hall	N/A (Base Station)	Omni-directional with Reflector	Phase II
Stoke Hall	N/A (Base Station)	Sector	Phase II (Omni-directional Antenna used in Phase I)
Barrington Library	Kingsbury	High Gain Log Periodic	Phase III (Upcoming)
Dimond Library	Kingsbury	Log Periodic	Phase I (Switched from Stoke BS to Kingsbury BS Phase II)
Durham Library	Stoke	Winegard Window	Phase I
InterOperability Laboratory	Kingsbury	Log Periodic	Phase I (Switched from Stoke BS to Kingsbury BS Phase II)
Madbury Library	Kingsbury	High Gain Log Periodic	Phase III (Upcoming)
Thompson Hall	Kingsbury	Winegard Window	Phase II

Table A.1: Base Station and Client Location Antennas

APPENDIX B

Additional Measurement Information

B.1 More Measurement Location Maps

Figure B.1: Client and base station locations

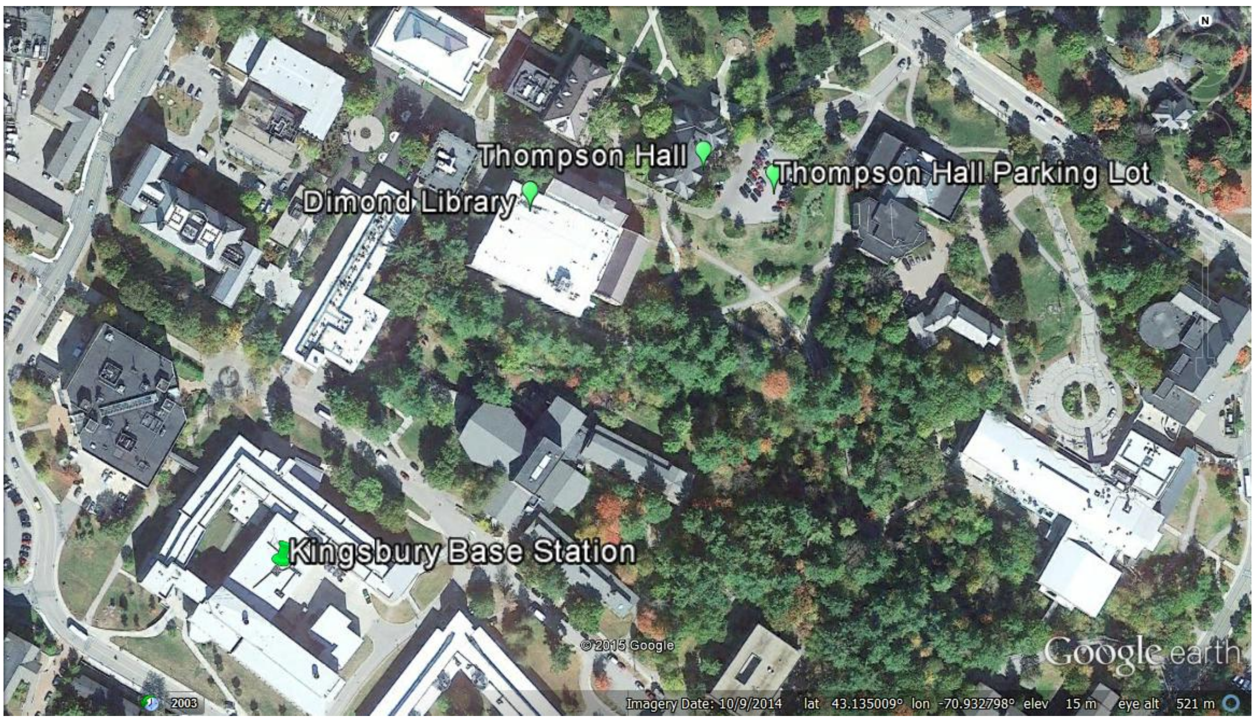

Figure B.2: Map from Google Earth of the UNH campus showing the test locations

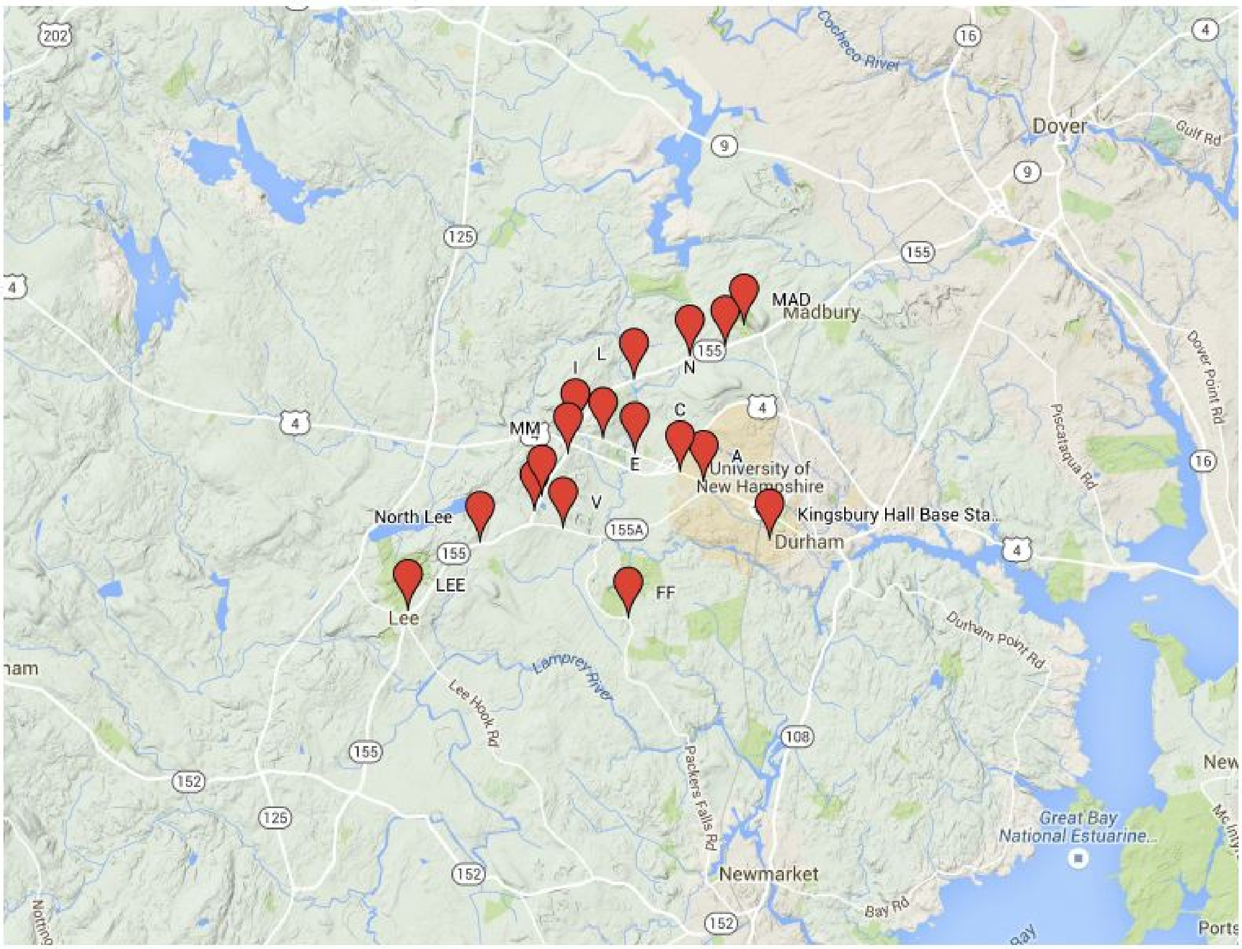

Figure B.3: Map from Google Maps showing modulation measurement locations and terrain

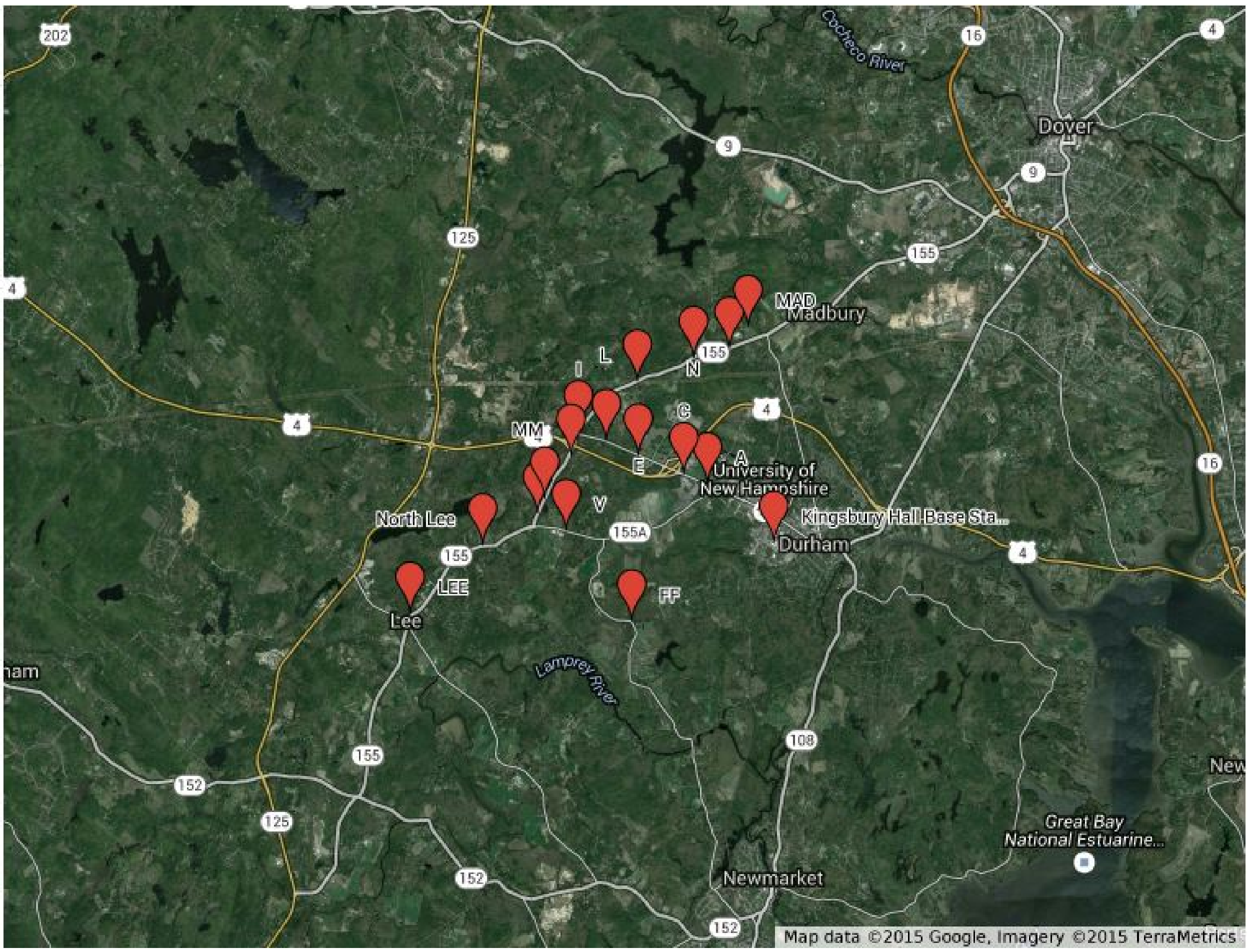

Figure B.4: Map from Google Maps showing modulation measurement locations and land cover

B.2 A Note on Speed Test Results

To determine the speeds expected from the RuralConnect radios at each modulation setting, speed tests were run with adaptive modulation turned off to be able to manually choose the setting used. The test was performed in a lab in Kingsbury with the antenna facing out the window towards the base station antenna. This would eliminate performance limitation from reduced SNR. However, saturation was not a concern as the CPE was outside of the main lobe of the base station antenna. Even with the close proximity to the base station, the power was reduced enough to be below the -16 dBm threshold for full linearity of the receiver. The results of the test are seen in Table B.1.

A few observations should be made from these results. First, even on the maximum rate modulation mode, the advertised speeds of the radios are not met. It was seen that speeds surpassed these values at the Thompson Hall Parking Lot (Section 3.5.1). Even with these values not being at the maximum, the general bit rate range can be seen. As expected, 16 QAM 1/2 and QPSK have roughly the same bit rates as the FEC 1/2 will cut the rate in half. This effectively makes 16 QAM 1/2 have equal data rate to 4 QAM, which is the same rate as QPSK. It is seen that for each of the modulation modes, the use of 1/2 FEC does (roughly) cut the rate in half. The inaccuracies of the online speed tests can be to blame for not giving exactly half, but taking the results as relative speeds, shows the trend as the modulation modes are adjusted. This also shows that broadband speeds are achievable as long as QPSK or better modulation is used. However, the reduced rate QPSK and BPSK options are available to provide Internet access with these radios to marginal locations that don't have other provider options. These speedtest results are only used to give additional indication into the performance of the radios, though testing that is more accurate than variable online speed tests should be performed to verify performance.

	Uplink	**Downlink**	**Ping**
Modulation	**Adaptive: 16 QAM**	**Adaptive: 16 QAM**	–
Measured Speed	6.12 Mbps	8.24 Mbps	121 ms
Modulation	**16 QAM**	**16 QAM**	–
Measured Speed	5.81 Mbps	8.05 Mbps	123 ms
Modulation	**16 QAM 3/4**	**16 QAM 3/4**	–
Measured Speed	5.11 Mbps	7.13 Mbps	124 ms
Modulation	**16 QAM 1/2**	**16 QAM 1/2**	–
Measured Speed	3.37 Mbps	4.4 Mbps	120 ms
Modulation	**QPSK**	**QPSK**	–
Measured Speed	3.64 Mbps	4.6 Mbps	123 ms
Modulation	**QPSK 3/4**	**QPSK 3/4**	–
Measured Speed	2.7 Mbps	3.54 Mbps	125 ms
Modulation	**QPSK 1/2**	**QPSK 1/2**	–
Measured Speed	1.56 Mbps	2.19 Mbps	124 ms
Modulation	**BPSK**	**BPSK**	–
Measured Speed	1.37 Mbps	1.41 Mbps	124 ms
Modulation	**BPSK 3/4**	**BPSK 3/4**	–
Measured Speed	0.91 Mbps	0.93 Mbps	124 ms
Modulation	**BPSK 1/2**	**BPSK 1/2**	–
Measured Speed	0.71 Mbps	0.77 Mbps	126 ms

Table B.1: Modulation Modes in LoS without SNR restrictions