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The purpose of this research was to investigate the impacts of vegetation on cellular signal strength. The research was conducted in Buckingham County, VA, located approximately 60 miles west of Richmond, VA. The county is mostly rural. Dillwyn, a small town, serves as the county's major metropolitan area.

Signal strength observations were collected over a nine month period. The first set of samples was collected in September/October 2008 and compared directly to samples taken in January 2009. A third set of samples was collected in May 2009 and compared to predictions from a free-space loss model. Each sample was assigned a National Land Cover Dataset (NLCD) value for Deciduous, Evergreen or Open Area. The Open Area class was used to verify the accuracy of the free-space loss model.

Significant differences between the signal strengths captured in September/October 2008 and January 2009 were observed. The signal strength was stronger in the winter than in the fall. There was no significant difference between land cover classes when all signal strength differences obtained were examined. However, there was a significant difference between the Deciduous/Open areas and Evergreen classes when only the negative signal strength differences were examined. A weak negative correlation was found between distance from the tower and the signal strength difference for the Evergreen class.

ANALYZING THE IMPACTS OF TREE CANOPY

ON CELLULAR RADIO NETWORKS

by

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the Faculty of The Graduate School at
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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Today's society is driven on ever-changing technology. By the time one purchases a high-tech product there is a strong possibility that technology has been replaced or is out-of-date. The current market for telecommunications is characterized by heavy consumer adoption rates representing nearly all age groups. The cellular phones for many of these consumers are used for general voice communication, but there is a rapidly increasing adoption of additional services provided through telecommunications networks such as internet access, texting, daily planning, digital imaging/sharing, and listening/sharing music. Unlike previous alternatives, cellular communications have become the preferred method of voice telecommunication (Wagen & Rizk, 2003). In fact, some people own two cell phones; one for business and a second for personal use, and accessing wireless technology is becoming more of a necessity than a luxury. The networks which support cellular phones must provide operational stability and expansion capacity to accommodate market share growth. Telecommunication providers constantly reconfigure their cellular networks to adapt for fluctuations in demand and geographic size of market areas. A telecommunication company has inherent economic incentives to strategically locate its infrastructure where it optimally benefits communities. The goal of telecommunication providers is to maintain reliable coverage for customers while maximizing return on network investments.

Communities also want reliable coverage but for different reasons. Many local governments and communities depend on reliable access to wireless networks as a means to attract outside businesses to support economic growth. Wireless connectivity for public safety is also another important reason. The propagation of cellular networks, however, is often tempered by land use zoning decisions and the interests of the general public. There are industries that develop master telecommunication plans which provide a blueprint for balancing growth of cellular networks with the interests of both providers and local governments.

Wireless communication is currently beginning its fourth generation of development. Like any technological innovation, wireless communications require a large amount of infrastructure to provide reliable coverage and service to customers. At each site, there is a vertical structure with multiple antennas strategically assembled. There are several different structure types which are used to support antennas (CityScape Consultants, Inc, 2007). The most common is the tower, which is often painted in red and white. An alternative to the common tower is the guyed tower, which has a narrower base and requires cabling to support stability. The third type of structure is the monopole, which requires no additional support, but is usually limited in height. Antennas can also be attached to existing structures, such as street lamps, water towers, inside church steeples, and on roof tops. Multiple antennas are often found on one structure. Cables are used to attach antennas to control centers to provide electrical power and connectivity to electronics. The control center is usually located in a small detached building adjacent to the structure, similar to a homeowner’s shed. The deployment of wireless infrastructure is very expensive and companies only add capacity in areas where demands support investments. Additionally, identifying gaps in the geographic service areas provides opportunities for companies to co-locate antennas, which can help alleviate service coverage problems while reducing costs on investments. Cellular communication networks are designed as a set of overlapping cells to allow for handovers for mobile cellular users (Wagen & Rizk, 2003).

There are external obstructions which inhibit the propagation of radio waves from transmitting devices to the receiving antennas. Some of these factors are anthropogenic while others are naturally occurring. In urban environments, for example, buildings can interfere with radio waves and cause significant signal attenuation (Huang et al., 2006). Natural vegetation in urban areas plays a minor role in reducing the strength of the signal. In the rural areas, however, natural vegetation takes a much more significant role and it is important to determine its magnitude so that planning and locating new tower sites can be improved (Blaunstein et al., 2003).

The need for local communities and wireless communication companies to determine coverage through propagation modules is very important. Public safety has a dominant impact on the growth and advancements of wireless communication. Given the relative ease that we can travel significant distances today, it is imperative that a stable and thorough network of towers be in place to ensure reliable emergency communications. Public safety is a high priority in the densely populated areas of the United States; however, it is the rural areas which require the most work. In these areas, emergencies could go hours or longer before they are noticed if cellular coverage is not sufficient to support a phone call. In cases of natural disasters or accidents, people rely on their cellular phones to contact loved ones to verify their health and safety. If the networks are overwhelmed with calls and people cannot get through, the sense of anxiety can be elevated, leading to a snowball panic effect.

Wireless communication has a significant impact on the economy. This impact extends beyond the telecommunications itself and includes the everyday business deals which are often negotiated using cellular phones. With the fourth generation of wireless technology, emails are no longer sent only from personal computers or laptops. Instead, emails can be sent from a slow moving vehicle in rush hour or in a crowded airport waiting for a departure. Business is no longer on a “9 to 5” schedule. Staying connected all hours of the day has increasingly become a mandatory requirement for professionals such as sales associates, account executives, and senior management.

Personal use of cellular phones contributes to the economy as well. It is not uncommon for people to make plans, order food and even pay bills while on the go using cellular phones. In contrast to years past, most people can be reached at any hour of the day. The general economic impact of the wireless communication industry is substantial and the industry is responsible for supporting the employment of tens of thousands of people across the globe. And without them, our world would be completely different.

The goal of this study is to examine the influence of vegetation on radio wave signal loss for a rural county. This study focuses on the effects of two broad types of trees: deciduous and evergreen. Rather than using theoretical situations and techniques to determine the magnitude of attenuation of the vegetation, an empirical study will be conducted using signal strength samples taken in the field from the study area. The findings of the study will lead to the creation of signal strength loss values for land cover classes as defined by the National Land Cover Dataset (NLCD). The designation of signal loss values by class type provides a way to incorporate the effects of vegetation in rural areas into propagation models. The cellular coverage and signal strength in the study area will be examined using methods for developing clutter loss values for vegetation classes under investigation.

CHAPTER II

LITERATURE REVIEW

Literature Overview

Examining prior research is imperative to conducting effective research. The lessons from past research provide the foundation of best practices based on the mistakes and successes of those who conducted the research. This chapter reviews prior work conducted on attenuation caused by vegetation and examines several important properties of radio waves. This chapter also provides a discussion on land cover datasets used to aid signal strength prediction.

It is important to examine the environment in which radio waves must travel before reaching the receiving antenna so that factors impacting attenuation could be considered and measured (Huang et al., 2006). Rubinstein (1998) stated that losses attributed to land clutter are a significant problem when predicting point-to-area propagation (Rubinstein, 1998). Goldhirsh and Vogel (1987) also identified problems with the “degradation of signals caused by attenuation and multipath from trees and terrain” (Goldhirsh and Vogel (pg. 1), 1987). The effects of trees on radio waves are caused by several factors, such as the type of tree, the shape and size of tree canopy as well as the frequency of the radio wave (Huang et al., 2006). In the Huang et al. (2006) study, attenuation was found to be positively correlated with frequency, i.e. as the frequency increased, so did the magnitude of the attenuation. This study considered free space loss, clutter loss, and terrain loss as major attenuation factors in total signal strength loss and propagation prediction. Other factors such as precipitation and atmospheric absorption were not considered because research has shown that these elements have minimal to no impact on frequencies used for cellular communications (Jacobsmeyer, 2008).

Approaches to Research

Like in other scientific specialties, there were several ways to approach a study: empirically, semi-empirically and theoretically (Huang et al., 2006). These approaches range from using formulas derived from gathering field data and samples to using mathematical equations derived from theories and laws. Each approach brings its own advantages and disadvantages, and researchers need to determine which approach best fits the purpose of their study. For instance, empirical and semi-empirical studies, while being simple and easy to implement are only good if measured datasets exist or can be readily acquired through field work (Huang et al., 2006). Similarly, Wagen & Rizk note that empirically based studies require large numbers of repeated observations at strategically sampled geographic locations. Studies have indicated the accuracy of current empirical models generally increases with increasing distance from an antenna source (Wagen & Rizk, 2003). The main problem with empirical models; however, is that they do not explicitly capture the effects of human and natural phenomena on signal attenuation. They simply measure the outcome. This limits the empirical models to geographic regions that are very similar in nature. Models developed for a particular rural area, for example, might be useful for other similar rural areas, but the prediction accuracy for dissimilar regions such as urban areas is likely to be poor.

Other approaches, such as stochastic models focus on randomness rather than observation measures at sampled locations. In contrast to deterministic models which use existing laws or rules, stochastic models use a series of random events to determine the outcome (Abhayawardhana et al., 2005). Stochastic models are less accurate and their use depends on the situation. On the other hand, stochastic models require less data and computer processing. Although, the specific attenuation of vegetation had been examined in the past for differing portions of the radio wave spectrum, many studies were conducted empirically using idealized situations which do not fully represent the natural environment.

Attenuation due to Vegetation Research

Vogel and Goldhirsh conducted a study at NASA Wallops Flight Facility on Wallops Island, Virginia where they used a small aircraft with a transmitter and a vehicle on the ground with a receiver (Vogel and Goldhirsh, 1986). The frequency used in the study was 869 MHz. The aircraft and land vehicle were separated by trees of various species which were adjacent to the runway. A series of 47 flybys were conducted with a signal strength reading taken for each flight. The signal strengths were strongest in areas that had gaps between trees and weakest where the aircraft, tree, and land vehicle were all aligned. Additionally, the study showed higher angles from the aircraft to the land vehicle resulted in smaller signal strength decreases. This impact was a result of shorter travel distances of radio waves through trees. The authors concluded that attenuation of radio waves was about 10-20 decibels (dB) for single trees along the runway. This study demonstrated that groups of trees result in significant attenuation of radio waves, but the impact was minimal when only one tree was considered. For general propagation modeling, the attenuation of one tree was insignificant for predicting signal strengths for large areas.

One year later, Goldhirsh and Vogel conducted a similar study in Central Maryland using a helicopter equipped with a transmitter and a land vehicle with a mounted receiver (Goldhirsh and Vogel, 1987). To test the frequency of 870 MHz and the impacts of vegetation, the mounted transmitter and receiver were separated by trees. Instead of a closed site similar to the study at Wallops Island, their research was conducted on public roads, such as Maryland state routes 32, 108, and 295. The study areas consisted of significant tree stands and were a minimum distance of 15 km long along public roads with tree density varying by species. The trees along the study sections were mostly deciduous with some evergreens. The deciduous trees included in the study were Callery Pear, Pin Oak, Norway Maple and Sassafras while the evergreen trees were Scotch Pine and a pine grove. The results of the study showed the median attenuations were between 6-15 dB, which directly correspond to the varying levels of tree density along study sections. The tree with the densest leaves, such as the Callery Pear, had the most extreme attenuation (above 18 dB). The authors noted that the moisture content of deciduous trees is the highest in the early spring after the leaves have achieved full growth. Significantly, Goldhirsh and Vogel's (1987) study provided attenuation measurements by tree type while considering limitations from previous work on propagation studies.

Research on the interplay between attenuation and vegetation is not limited to the United States and there are several other studies that have included other regions of the world. Tewari et al. conducted a study on the effects of vegetation on the radio waves in rain forests of India (Tewari et al., 1990). Unlike the work done by Vogel and Goldhirsh, the majority of trees studied in India were evergreens. Specifically, the research was conducted in three different forests: subtropical pine, tropical moist deciduous and tropical wet evergreen. Three different frequencies, 200, 500 and 800 MHz, were used in the study. The signals were transmitted from a fixed mast which could have its height changed from 3.95 to 16.45 meters and signals were received using a field-strength meter at different distances from the transmitting location.

The data collectors noticed significant changes in the signal readings during periods of increased winds. In order to account for the effect of the wind, the field strength meter was allowed to stabilize for two minutes prior to a reading was taken. Another finding was that the magnitude of attenuation becomes greater as distance increases from the source up to a distance of 0.4 km. The path which the radio wave must travel through the vegetation at shorter distances may have had a different impact than a radio wave traveling a longer distance. Paths traveling greater distances from the source may follow a path above the vegetation for the majority of the distance and through vegetation for shorter distances. The magnitude of attenuation decreased as the height of the transmitting or receiving antennas increased because an increase in antenna height on either end allowed the radio waves to travel above obstacles more easily.

A notable conclusion by the authors was the effects of moisture on the signal strength readings. The overall loss was greater in the wet season compared to the dry season. The change in electrical constants between the two seasons caused the differences in the observed losses. In the end, the foliage loss was determined to be a major factor when measuring the difference between path loss through vegetation and the expected path loss (as measured without vegetation given the same parameters). Given that free space loss was easily calculated, the issue of measuring signal loss lies with accounting for terrain and clutter losses (Jacobsmeyer, 2008).

Propagation Research

The loss along a path referred to the ratio of the transmitted power to the received power (Abhayawardhana et al., 2005). There had been significant research developing various equations which could be used to predict the magnitude of attenuation. Friis developed the following free-space transmission loss equation (Longley et al., 1968):

$$L\ (dB) = 32.44 + 20 * \log_{10} f + 20 * \log_{10} d \qquad (1)$$

L = loss in dB
f = frequency (MHz)
d = distance (km)

The free-space equation only takes into account the distance and frequency in space without clutter while utilizing a distance decay function to calculate the signal strength for a given distance. Friis' equation captures the positive correlation between frequency and distance. An increase in frequency and/or distance results in an increase in the magnitude of the loss.

Because the free-space equation accounts for distance and frequency, the equation is useful for line-of-sight calculations.

Frequency and distance are not the only factors that impact the propagation of radio waves. Reflection, diffraction and scattering also contribute to the attenuation of cellular radio waves (Rappaport, 2002). These effects are not mutually exclusive. Trees, for instance, can cause both a scattering and diffraction effect (Blaunstein et al., 2003). When a radio wave comes into contact with a large surface relative to its wavelength, the radio wave reflects off the surface. Depending on the specific electrical properties of the surface, the amount of reflectance and transmittance can change. If the surface was a perfect dielectric, then part of the radio wave would be reflected and part would be transmitted into the surface. However, if the surface was a perfect conductor, then all of the radio wave would be reflected off the surface. Typical surfaces for radio wave reflectance are the bare earth and buildings. Reflectance from bare earth is accounted for by using the two-ray model. This model captures both the line of sight path, from the transmitting to receiving tower, as well as, the reflected path back to the receiving tower. Total signal strength received is equal to the sum of the two different paths (Figure 2.1) (Rappaport & Milstein, 1992). In Figure 2.1, h_t and h_r represented the heights of the transmitting and receiving towers, respectively. The distance between the base of the two towers is represented by d, and the distance between the tops of the two towers is computed as d_d. Lastly, the distance from the transmitting antenna to the point where the radio waves contacted the Earth's surface is denoted as d" and the distance from that point to the receiving antenna is calculated as d'.

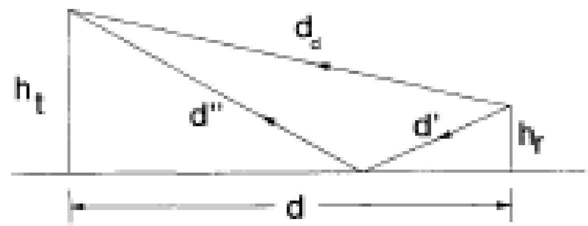

Figure 2.1 Ground Reflection (Two-Ray) Model (Rappaport & Milstein, 1992)

The presence of obstacles between the transmitting and receiving towers is accounted for by predicting diffraction, which simulates radio wave propagation around or over barriers (Rappaport, 2002). Diffraction is also used for long range propagation where the earth's curvature becomes an issue for line of sight propagations. Although the signal strength may have been drastically reduced in these cases, there was often a strong enough signal in the line of sight blind spots for successful communications. In modeling diffraction, it can be generally accepted that obstacles are usually modeled as a knife edge rather than rounded or smooth objects (Adamy, 2007). There are two important distances involved in calculating diffraction. d_1 is the distance between the transmitter and the obstacle, while d_2 is the distance between the obstacle and the receiver (Figure 2.2). In Figure 2.2, T and R represent the transmitting and receiving antennas, respectively, while H represents the vertical height of the obstacle impeding the radio wave. If d_1 is greater than d_2, the receiver is located in a blind spot and a signal will not be received. Single obstacle diffraction losses have been estimated to be close to actual losses. In mountainous regions, diffraction is an important factor which allows service providers to successfully build quality networks (Rappaport, 2002). One significant drawback of diffraction is the overwhelming complexity which results from multiple obstacles interfering with radio wave propagation.

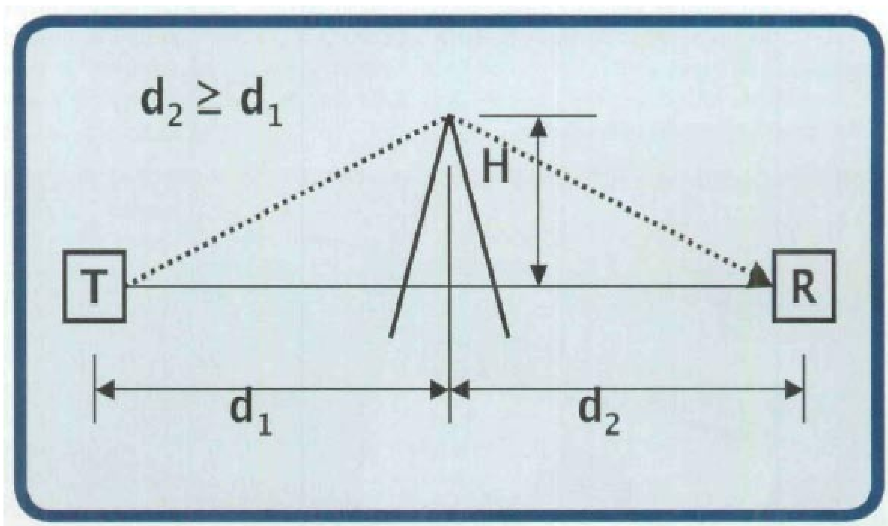

Figure 2.2 Knife-edge Diffraction (Adamy, 2007)

Unlike reflection which occurs when the impeding surface is larger than the wavelength of the radio wave, scattering occurs when the impeding surface is smaller than the wavelength (Rappaport, 2002). In scattering, there are many impeding surfaces in an area, whereas; in reflection, there are only a few, which can produce large amounts of scattering. Small, rough, or irregularly shaped objects can cause scattering of the radio wave. Objects such as foliage, street signs, and lamp posts are examples of surfaces that can scatter radio waves in all directions. Diffraction and reflection, in most cases, add to the signal strength at the receiving tower, whereas, scattering can add or subtract from signal strength depending on the impeding surface as well as its relative location to the receiving tower. Jacobsmeyer (2008) determined that radio wave propagation is not usually line-of-sight and argued instead, that received signal strength consists of a combination of diffracted and reflected radio waves (Jacobsmeyer, 2008).

Okumura-Hata Propagation Model

The Okumura-Hata propagation model is based upon measurements taken in and around Tokyo, Japan in 1968. The equation is (Parodi et al., 2007):

$$\text{Loss (dB)} = 46.3 + 33.9 * \log_{10}(f) - 13.82 * \log_{10}(hb) - 1.22 + (44.9 - 6.55 * \log_{10}(hb)) * \log_{10}(r) \quad (2)$$

f = frequency (MHz)
hb = transmitting antenna height
r = distance from antenna

For macrocellular environments, the Okumura-Hata is considered to be the most popular model for signal strength prediction (Ranvier, 2004). The model can be used for frequencies between 500-1500 MHz, with transmitting antenna heights greater than 30 meters, and receiving antenna heights between 1 and 10 meters. The distance between the transmitting and receiving antennas must be between 1 and 10 kilometers (Erceg et al., 1999; Ranvier, 2004). The original model was created for urban areas. In order to account for suburban and rural areas, correction factors were developed. Although the model is applicable for areas ranging from urban to rural, it is not best in hilly, heavily wooded areas (Ranvier, 2004). This study used the Okumura-Hata model, in part, as a baseline for propagation prediction.

CHAPTER III

METHODS

Study Area

The study area is located in Buckingham County, Virginia, approximately 60 miles west of Richmond, VA (Figure 3.1). Buckingham County has 581 square miles and a population of 15,623 as of the year 2000 (Census, 2008). The two primary industries in the county are logging and mining. Two United States highways, U.S. 15 and U.S. 60, intersect in the town of Dillwyn. With the exception of Dillwyn, much of the county is extremely rural with sparse population. The northern part of Buckingham County is largely covered by deciduous, evergreen, and mixed forest, while the southern landscape is characterized by open fields. The county's topography is dominated by rolling hills with three mountains in the west and southeast of the county.

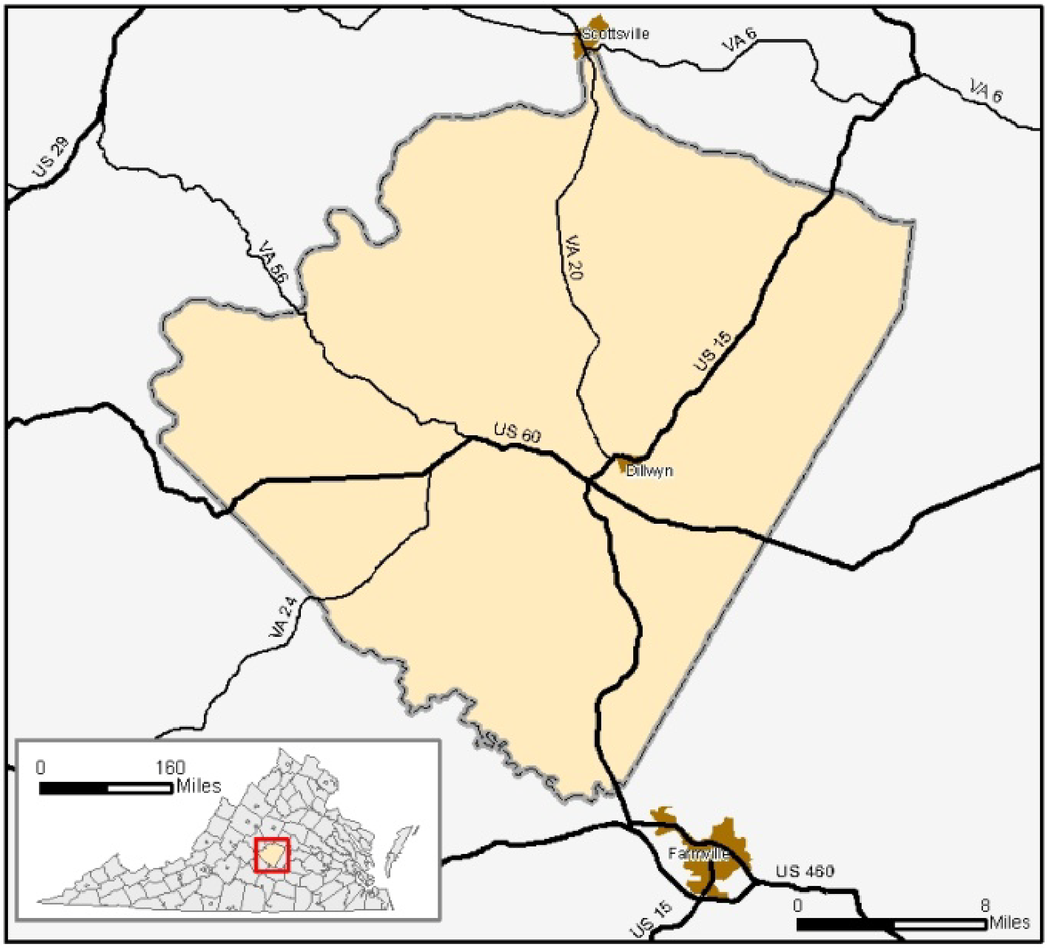

Figure 3.1 Location of Buckingham County, VA

There are approximately 30 transmission towers located within the county. Only three of them are used in this study because those are the only ones belonging to the provider for this study (CityScape Consultants, Inc., 2008) (Figure 3.2). Each provider has its own portion of the radio wave spectrum. The three towers are part of the United States Cellular Corporation network and they operate at a frequency of 879.4 MHz (FCC, 2008). One tower is located north of Dillwyn near the intersection of County Road 1014 and Gold Mine Street (37.55° N, 78.46° W). The site elevation is 198 meters above mean sea level (AMSL) and the height of the tower is 125 meters. Another tower is located on Tower Road off of County Road 607 near Gladstone (37.53° N, 78.77° W). The site elevation is 209 meters AMSL and the tower height is 78 meters. The third tower is located in the northernmost part of the county off Virginia Route 20 on County Road 747 near Scottsville (37.78° N, 78.49° W). The site elevation is 126 meters AMSL and the tower height is 106 meters (CityScape Consultants, Inc, 2008) (Figure 3.2).

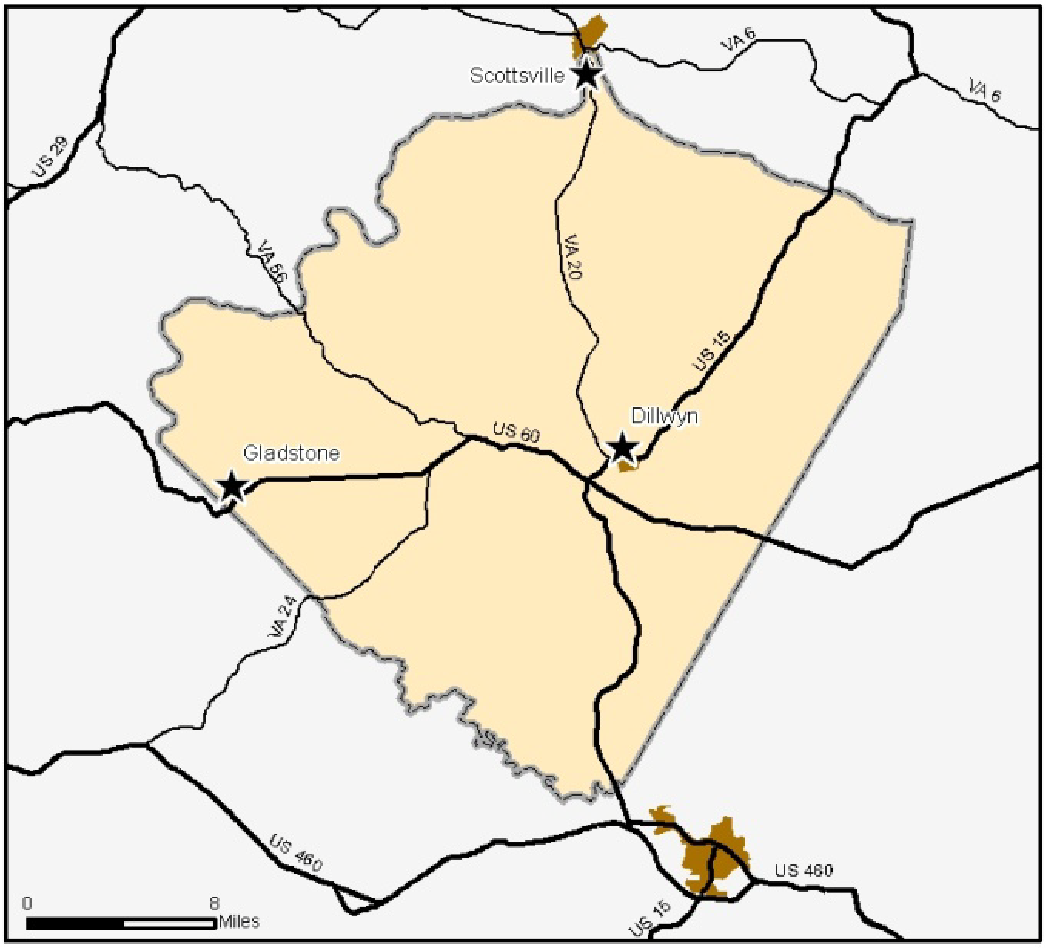

Figure 3.2 Locations of Three Towers Used in the Study

The county itself presented significant issues with the field work. The road network consisted of many small, unpaved roads with numerous turns and elevation changes which made stopping to take samples not only difficult, but dangerous. Additionally, many long driveways were initially selected as potential sample sites but were not entered because they were privately owned property. This limited the number and the spatial distribution of sample readings. The distribution of the deciduous and evergreen trees also presented problems. It was noticed, after several trips to the county, that the evergreen trees existed as tree stands and not an as evenly distributed phenomena throughout the county as originally interpreted by visual inspection of the NLCD imagery. The clusters of evergreen trees did not allow for the sampling of varying distances from the tower. The deciduous trees were evenly distributed throughout the entire county which allowed a wide range of distances from the towers.

Research Design – Sampling

Two sampling schemes were used in the study. The first involved a systematic sampling based on a regular grid to determine the locations of sampling sites (Figure 3.3). The grid consisted of cells that were three by three miles and it was rotated so that the right side of the grid was parallel to and just outside of the eastern county line. Sampling began at the sites labeled as even column sites and moved to a random selection of odd column sites since the time constraints did not allow for all odd column sites to be sampled. The odd column sampling sites were selected by using a random number generator. A total of 40 random odd column sampling sites were selected. These points were then obtained in the order in which they were generated, i.e. the first number generated was the first point attempted. Similar to the even column sample locations, if a point was unobtainable for any reason, it was abandoned. In the end, only 11 of the 40 randomly selected odd column sites and 108 even column sites were sampled for a total of 119 samples using this sampling scheme given each site was sampled once (Figure 3.4).

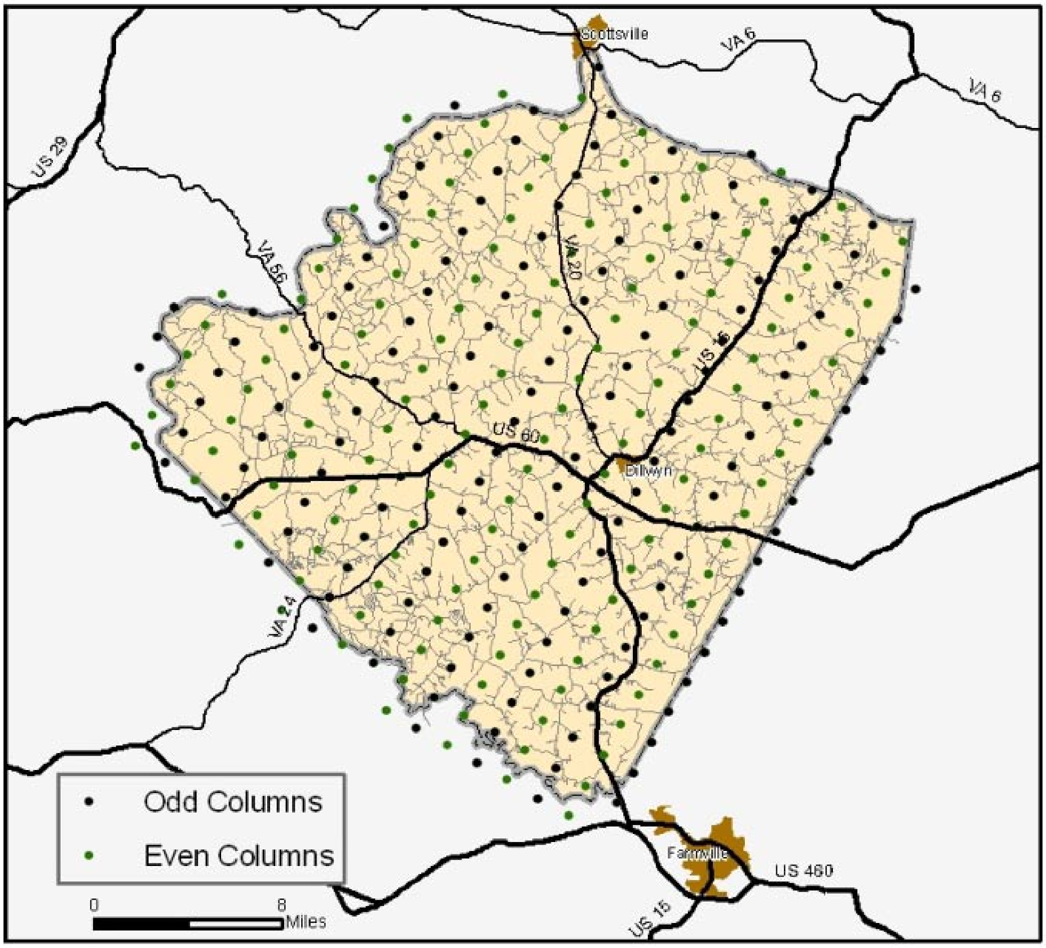

Figure 3.3 Original Sampling Grid

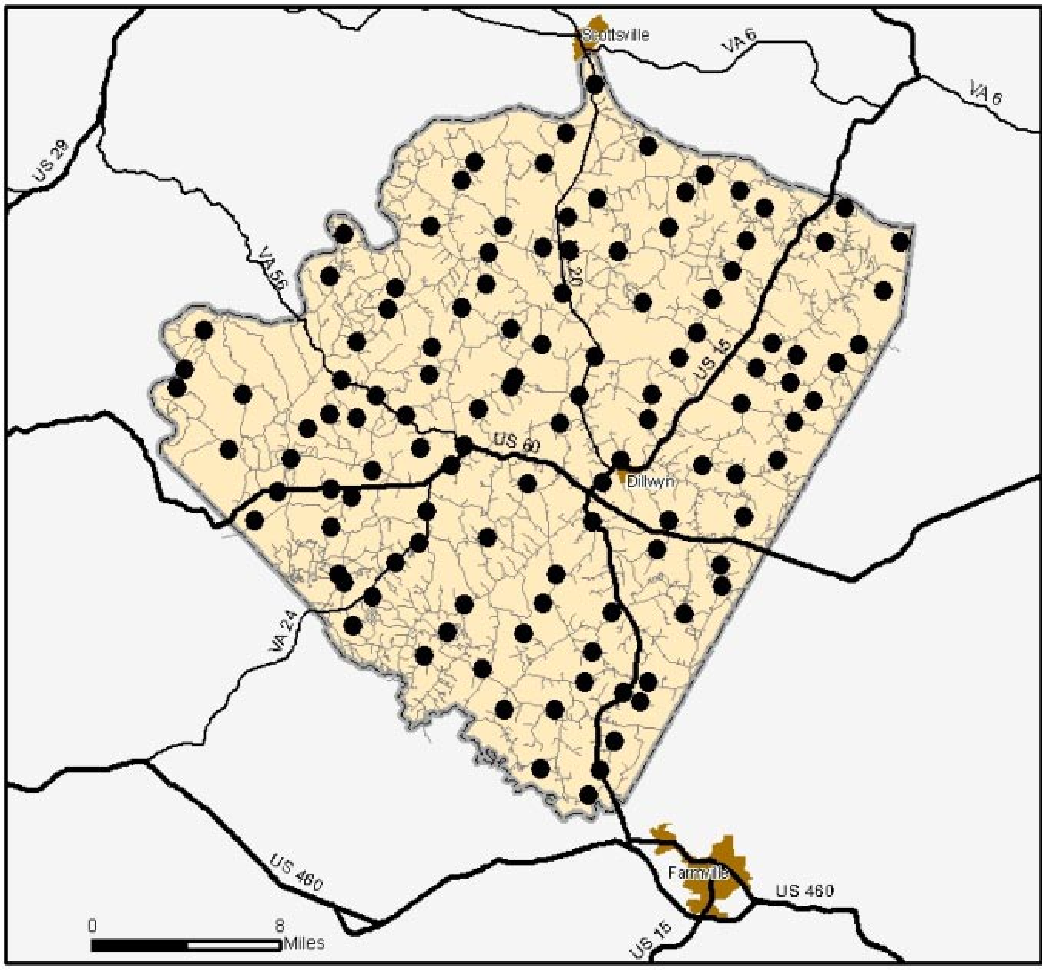

Figure 3.4 Samples Collected from Original Sampling Grid

Given the grid was constructed apart from the map and arbitrarily placed on the map to align with a straight edge and with no concern for point placement, the sampling scheme was free of user-introduced bias. Without such precaution, it would have been easy to select only sites with significant vegetation cover or at an irregular spacing, producing samples which would have been more clustered throughout the study area. The pre-determined sampling sites allowed the team to obtain the results without worrying about unintentional bias of the samples. Although radio waves can only travel a specific distance for a given frequency, samples were taken throughout the county using the grid to ensure that all areas receiving a signal were included in the study.

Two sets of samples were gathered using the systematic sampling scheme for this study. The first was taken while the trees were in full bloom in late September and early October of 2008. The second set was taken after the leaves had fallen in the middle of January 2009. The locations for both sets of samples were the same with only one exception. One location was not accessible in January because it was behind a locked gate. Some of the samples showed no signal strength, likely resulting from being outside of the range of a tower and they were removed from the subsequent analyses. In addition, a coverage zone was placed around each tower post data collection (Figure 3.5). The radius distance for each tower was calculated using the Okumura-Hata formula and the height of the transmitting and receiving antennas (Table 3.1).

Table 3.1 Size of Coverage Zone of Each Tower Estimated by Okumura-Hata Model

Tower	Dillwyn	Scottsville	Gladstone
Radius of Coverage Zone (meters)	12,971	11,663	9,310

The coverage zones were used as estimated distances from each tower where the signal would not be significant enough to register on the spectrum analyzer. There were 45 samples taken outside of the coverage zones which had no signal. Samples outside of the coverage zones were not used in the subsequent analyses. The final data set had 62 sites/samples from September/October and 61 sites/samples from January (Figure 3.6).

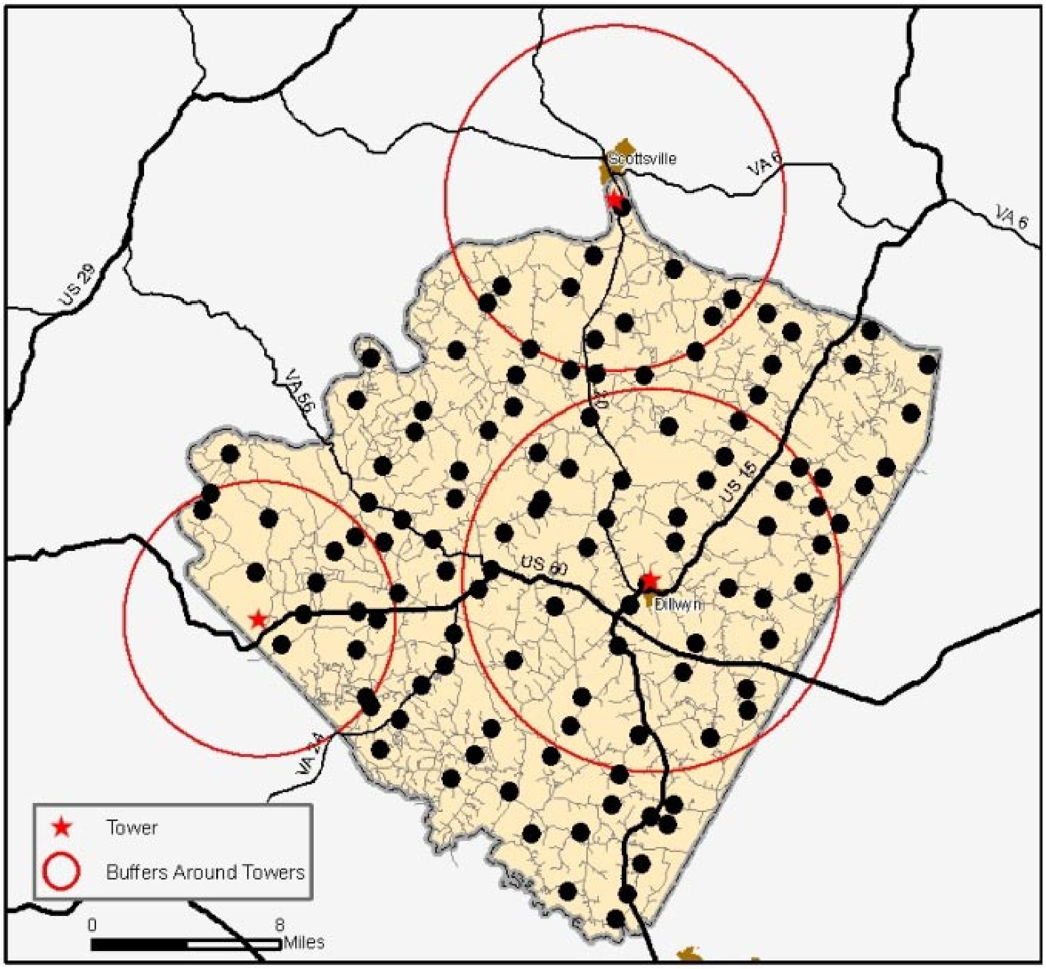

Figure 3.5 Actual Sampling Sites based on the Original Sampling Grid. The Circles represent the coverage zones of the cell towers estimated by the Okumura-Hata model.

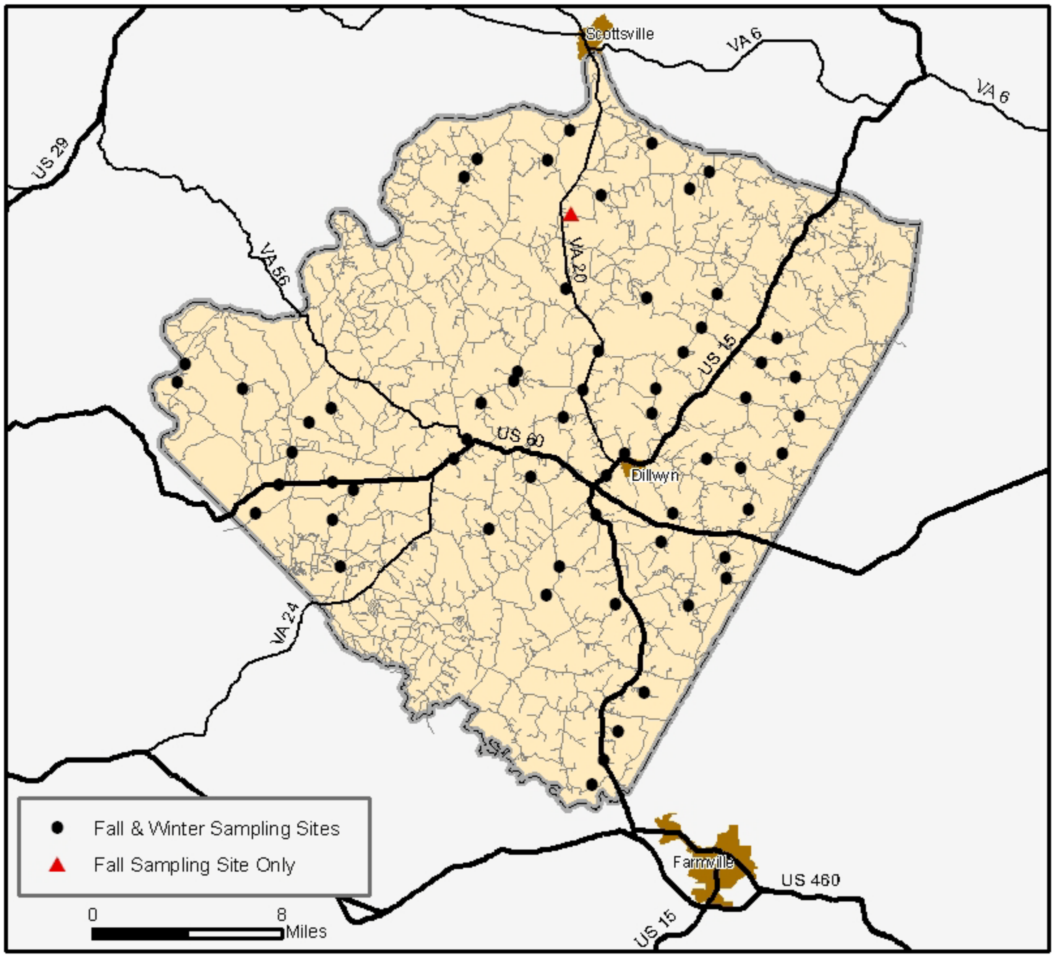

Figure 3.6 Sampling Sites that Fall within the Coverage Zones

The use of the sampling grid allowed the data collection team to understand some of the limitations of the county and ways to overcome them. For instance, the clustering of the evergreen stands was unknown prior to sampling and hence adjustments were made to the second sampling scheme. Additionally, a fourth tower was located in Cumberland County, VA which provided coverage to the southeast region of Buckingham County. Although the fourth tower had an impact, time did not allow for its inclusion in the sampling from the second sampling scheme and therefore it was not included in the study. It was believed that the first sampling scheme was important in the evolution of the study and without the complications realized early on; the study would not have been completed. The sixty one samples taken both in September/October and January were used to provide direct analysis between leaf-on and leaf-off conditions.

The second sampling scheme involved collecting points, which were randomly selected within the area of interest. The area of interest was determined by using the intersection of the same coverage zones around the towers determined using the Okumura-Hata formula shown in Table 3.1 and a 50 foot buffer of the road network. Fifty feet was chosen for the buffer distance based upon knowledge that sometimes samples could be taken further off the roads as well as to limit the distance so the sample team was always within view of the road. Only those roads with names were used for the buffer because of field knowledge that those were the only accessible roads in the county. This process produced polygons where the two layers were coincident and therefore represented accessible areas within the propagation range of the study towers. Using a random point generator, points were placed throughout the newly created polygons with a minimum separation of 200 feet between points. Two hundred feet was chosen as the separation distance to allow some separation between the samples while maximizing the number of random points generated within the study areas. A total of 385 random points were placed in the polygons (Figure 3.7).

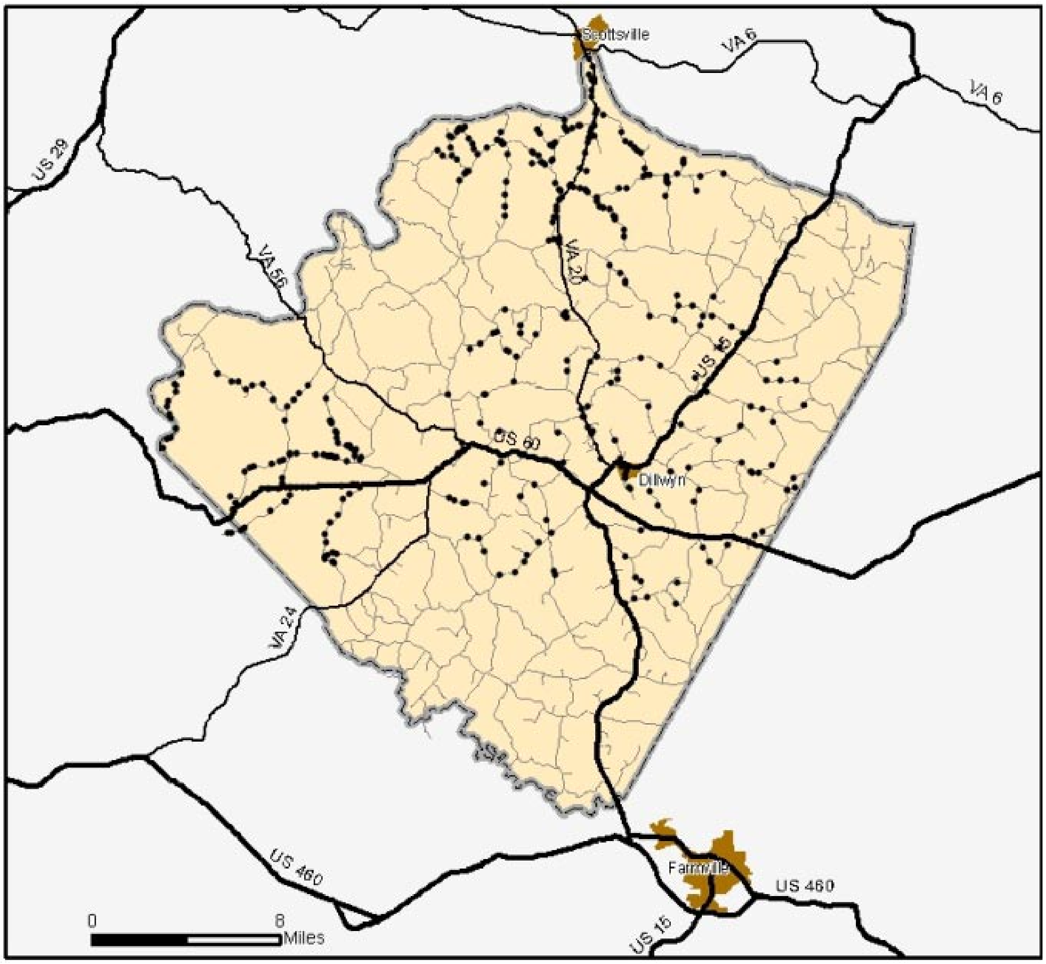

Figure 3.7 Distribution of Preselected Sites for Sampling in May 2009

Signal strength readings were taken at these randomly selected locations over a three-day period in late May 2009 when the trees were in full foliage. These sites were used as a guide rather than the exact locations for sampling. The sampling team attempted to take a sample as close as possible to the preselected sites as they navigated throughout the county. If a location could be found and was not on private property, but the sample could not be taken safely due to traffic or other concerns, the location was abandoned without any sample taken. On the other hand, there were areas which were originally thought to be not accessible based upon the GIS road layers used, but were open to traffic so additional samples were taken in those areas. The sampling team made a special effort to take readings in locations where a significant amount of evergreen trees were found to ensure that there would be enough readings for this type of land cover, given the clustered nature of the evergreen stands and the limited number of evergreen samples taken in the first sampling scheme. In total 236 sites were sampled from the 385 randomly identified locations throughout the county (Figure 3.8).

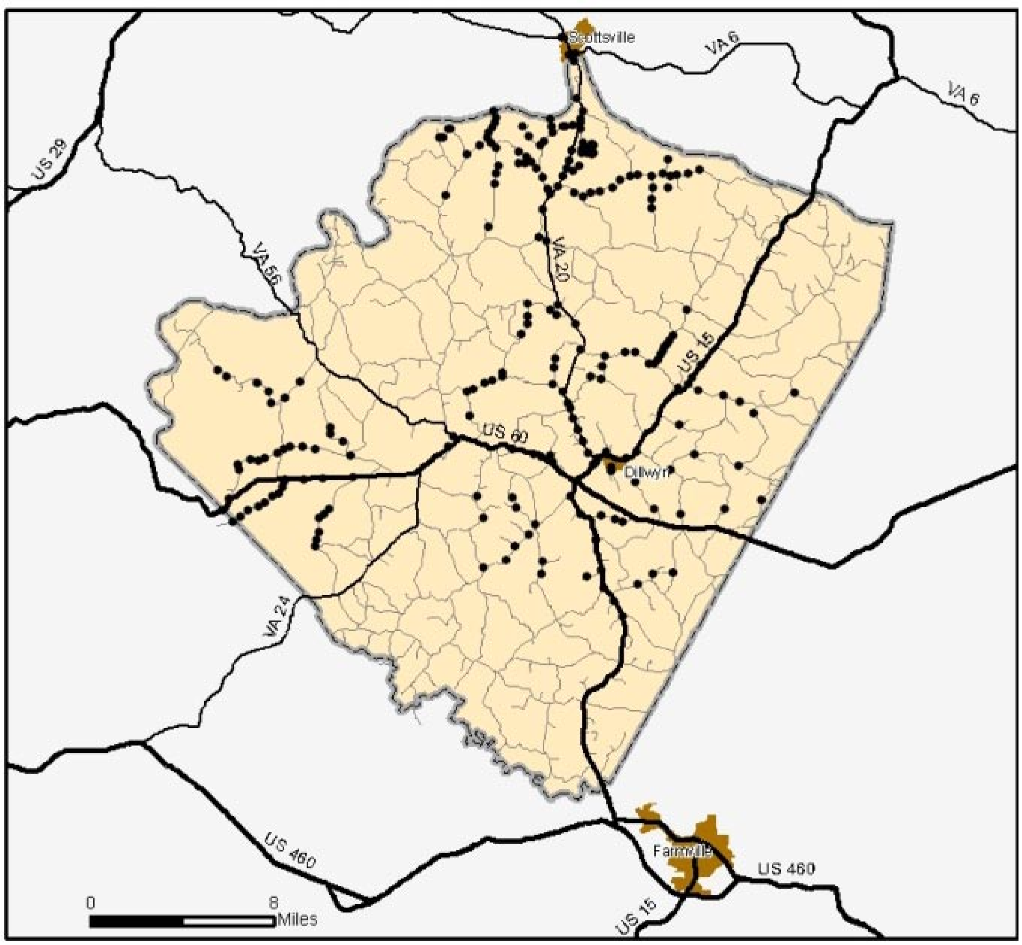

Figure 3.8 Distribution of Sites Actually Sampled in May 2009

The signal strength in dBm was measured at a height of 1.47 meters using a BK Precision Handheld 3.3 GHz Spectrum Analyzer (Model # 2650) with a dipole antenna (Model # AN 301) at each sample location that could be found and was not on private property. A dBm represented the ratio of power in decibels relative to one milliwatt (ATIS, 2007). The decibel (dB) represented a magnitude of intensity relative to a given reference unit such as a watt or milliwatt. In addition to signal strength, the latitude and longitude of the location were recorded using a Trimble GPS Pathfinder ProXH receiver to allow the sample distribution to be mapped and examined.

Research Design – Land Cover Data

In 1998, Rubinstein conducted a study using the Land Use/Land Cover (LULC) dataset created by the United States Department of the Interior, Geological Survey (USGS) to develop clutter losses for the various vegetation types (Rubinstein, 1998). The LULC dataset's classification scheme was developed by Anderson et al. in 1976 using remotely sensed data. Although the dataset was not developed for use in radio wave propagation, the dataset is useful for representing ground clutter in the entire United States. Three frequencies were used in the study: 162, 460, and 860 MHz. In order to include the largest number of LULC classifications in the study and be representative of the vegetation found throughout the majority of the United States, four study areas were selected. The locations were San Diego, Los Angeles, Atlanta, and Whatcom County, WA progressively becoming more rural. Given San Diego's and Los Angeles' commonalities, the two were combined for the analysis and treated as one study area called Southern California. Using a variation of Okumura's algorithm including the "Open" correction factor, signal strength predictions were made for all three study frequencies. After comparing the predicted values to the observed samples, Rubinstein (1998) determined clutter losses for those classifications which had at least 30 samples in them after data processing (Table 3.2). Rubinstein (1998) recommended using the values he determined in radio wave propagation modeling for the United States only, and suggested that additional studies be conducted around the world to determined appropriate values in those regions.

Table 3.2 Recommended Clutter Loss Values by LU/LC Codes (Rubinstein, 1998)

Category	**Description**	**860 MHz Signal Strength Difference (dB)**		
		Southern CA	**Northwest WA**	**Atlanta**
11	Residential	18.77	21.15	25.59
12	Commercial & Services	17.08		24.37
13	Industrial	13.03		
14	Transportation, Communications & Utilities	18.55		25.78
16	Mixed Urban or Built-up Land	17.25		
17	Other Urban or Built-up Land	17.71	19.88	
21	Cropland & Pasture		17.61	
24	Other Agricultural Land		18.32	
32	Shrub & Brush Rangeland	19.25		
41	Deciduous Forest Land		25.30	
43	Mixed Forest Land		26.28	25.72
76	Transitional Areas	16.22		

The Multi-Resolution Land Characteristics Consortium (MRLC) developed the National Land Cover Dataset (NLCD) 2001 with the goal of having a nationwide land cover product which could be used for various studies and research (Homer et al., 2007). Suggestions were taken from the user feedback of the NLCD 1992 to develop guiding principles to be used to create the NLCD 2001. Suggestions included creating a product which was flexible to be used by multiple users, with the capability for the users to access intermediate files allowing local applications. Additionally, the team developing the NLCD 2001 wanted to ensure that the methodology was consistent and repeatable while also being simple and intuitive resulting in a standardized product that could be easily updated. Lastly, the team wanted to develop a product which was compatible with the NLCD 1992. By doing so, the NLCD 2001 provides a “land cover database that is reasonably objective, consistent, and able to accommodate a variety of potential users and producers” (Homer et al., 2004, p. 830). However, the NLCD 2001 was not easily compatible with the NLCD 1992 and therefore comparisons were not advised.

Using Landsat 5 and Landsat 7 multi-season data and the use of a commercial decision tree (DT) software package called C5 the developers were able to establish 16 different land cover classifications (Table 3.3). The United States was broken into 65 mapping zones using the protocols developed by Homer et al. (2004). Although no formal accuracy assessment has been completed, estimates derived from cross validation of the mapping zones range from 70-98%, with an average for the entire area of 83.9% (Homer et al., 2007). Upon completion of Alaska, Hawaii, and Puerto Rico the NLCD 2001 would be the first nationwide land cover produced at the 30 meter resolution. In addition to developing a land cover database, the MRLC team developed several additional layers including impervious surfaces and tree canopy (Homer et al., 2004, 2007). Both of these additions contain the spatial distribution of the interested areas as a continuous variable from 1 to 100 percent, thus providing additional usefulness for the NLCD 2001 database.

Table 3.3 NLCD Classifications (Homer et al., 2007)

Category	**Description**
11	Open Water
12	Perennial Ice/Snow
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
31	Barren Land
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
52	Shrub/Scrub
71	Grassland/Herbaceous
81	Hay/Pasture
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

Data Analysis

The information for the antennas used in the first sampling scheme was obtained from the licensing information on the FCC's Universal Licensing System (ULS) website. Using the ULS geosearch for all cellular services in Buckingham County, the call sign

KNKN675 was found and determined to be assigned to U.S. Cellular Corporation. For each location, the tower specifics of interest included the height to tip above ground level (AGL) in meters and the transmitting Effective Radiated Power (ERP) in watts. The exact location of the tower was already determined by field work conducted by Cityscape Consultants. Since the ERP is an estimation of the transmitter power which took into account the transmitting antenna gain, the values had to be converted into estimates that could be put into the models. Antenna gain refers to the intensity of an antenna in a specific direction compared to the intensity from a hypothetical isotropic antenna. The transmitted powers in watts were converted to dBm using the following formula,

$$\text{Power (dBm)} = 10 * \text{Log}((\text{power (watts)})/0.001) \qquad (3)$$

The results were then compared to the ERP on the FCC license and adjustments were made to the input powers until the result matched the ERP for the antenna.

In Equation 3, the power in watts is divided by 0.001. The logarithm of the result is then multiplied by 10 to calculate the power in dBm. The difference between dB and dBm is that dB is a relative measure, whereas, dBm is an absolute measure of power using milliwatts as the reference base. The three towers located in Buckingham County were used for both leaf-on and leaf-off propagation modeling.

Attempts to verify the source and methods used in determining the data, such as the number of antennas and the power for each for a specific tower on the FCC website, did not succeed. Information on the specific antenna used on the towers to identify the antenna gain was also unsuccessful. Accurate propagation predictions could be made only when the input data (terrain, buildings, base stations, antennas) were correct. As such, the accuracy of the data needed to be verified (Wagen & Rizk, 2003). In this study, the terrain and location of the base stations were known to be accurate (Cityscape Consultants, Inc, 2008). However, the accuracy of data on the antennas and the input power was of concern.

Because of the problems related to the uncertainty of the information on the transmitting towers, the original data from the FCC was not used as the transmitted power from the towers in the analysis. Instead, a received power reference formula was used to estimate the signal power at a given distance from the tower as an alternative (Rappaport, 2002).

$$P_r(d)\ \text{dBm} = 10*\log[P_r(d_o)/0.001\ \text{W}] + 20*\log(d_o/d) \qquad d \geq d_o \qquad (4)$$

$P_r(d_o)$ = power (watts)
d_o = reference distance
d = sample distance from tower

This modified equation took a known power, using watts, from a location at a specified distance (d_o) from the source and predicted the power ($P_r(d)$) in dBm at another location of a different distance (d) from the source. The first part of the equation converts watts to dBm where the second part of the equation estimates difference in power between the reference point and the sample point. This reference power formula accounted for the free-space path loss of signal strength at a distance from the reference point.

Two reference distances were used to collect reference samples: 1.0 and 1.5 kilometers from each tower (Figure 3.9). The distances for the equation above can be any magnitude; however, the greater the distance becomes, the further samples have to be taken from the tower. Given the assumption that radio waves will not travel forever, the reference distances needed to be kept minimal. Additionally, using knowledge of the county, several distances were examined for practicality with 1.0 and 1.5 kilometers showing the best possibility for obtaining reference samples. This was determined using the logic that samples could only be taken along or near the road network at the given distance from the tower. Several signal strength readings were taken at these two distances from each tower (Table 3.4). There were more readings taken at a distance of 1.5 km because there were more locations accessible from the towers than at 1.0 kilometers. The averages of signal strength readings taken at the distance of 1.5 km from each tower were then used in the received power reference formula (Table 3.4).

Table 3.4 Signal Strength Reference Points (dBm)

	Signal Strength Reference Samples (dBm)					
	Dillwyn		**Scottsville**		**Gladstone**	
Distance	1.0 km	1.5 km	1.0 km	1.5 km	1.0 km	1.5 km
Samples	-80.8	-75.2	-89.2	-86	-85.6	-87.6
	-83.6	-78.8	-99.6	-87.6	-86.8	-92.4
	-90.8	-80.8		-89.2	-90	-93.6
		-86		-92.4		
		-92.4		-96		
		-93.2				
Average	-85.1	-84.4	-94.4	-90.2	-87.5	-91.2

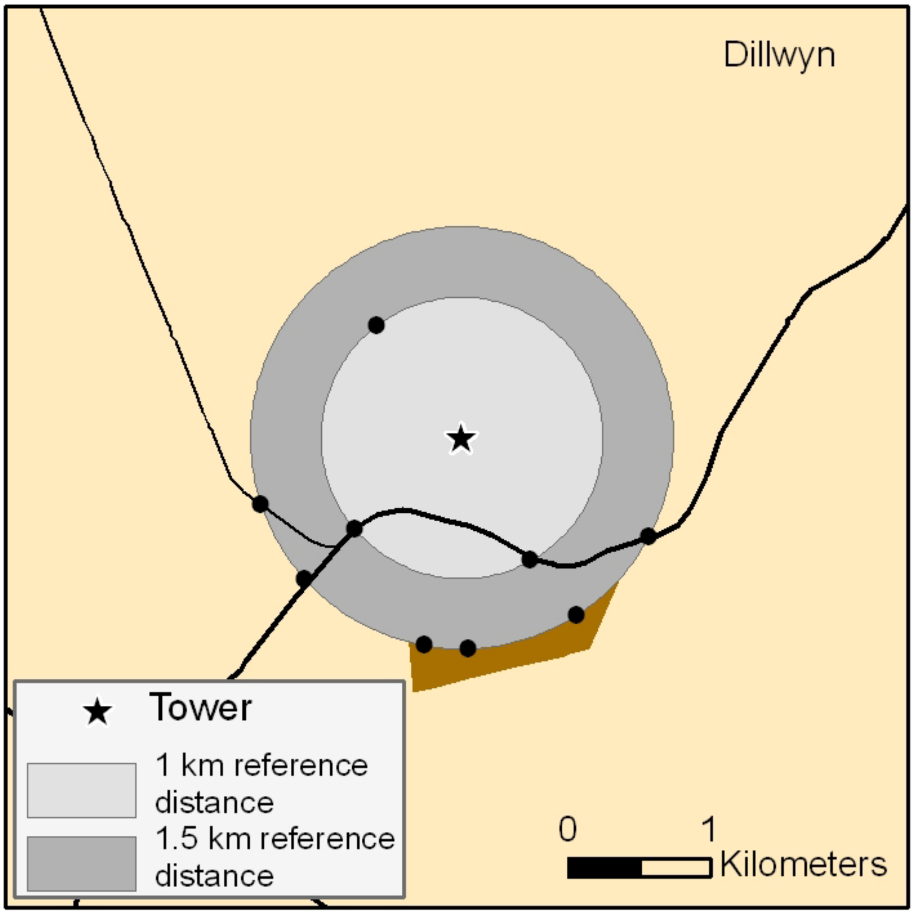

Figure 3.9a Reference Sampling Sites for the Tower near Dillwyn

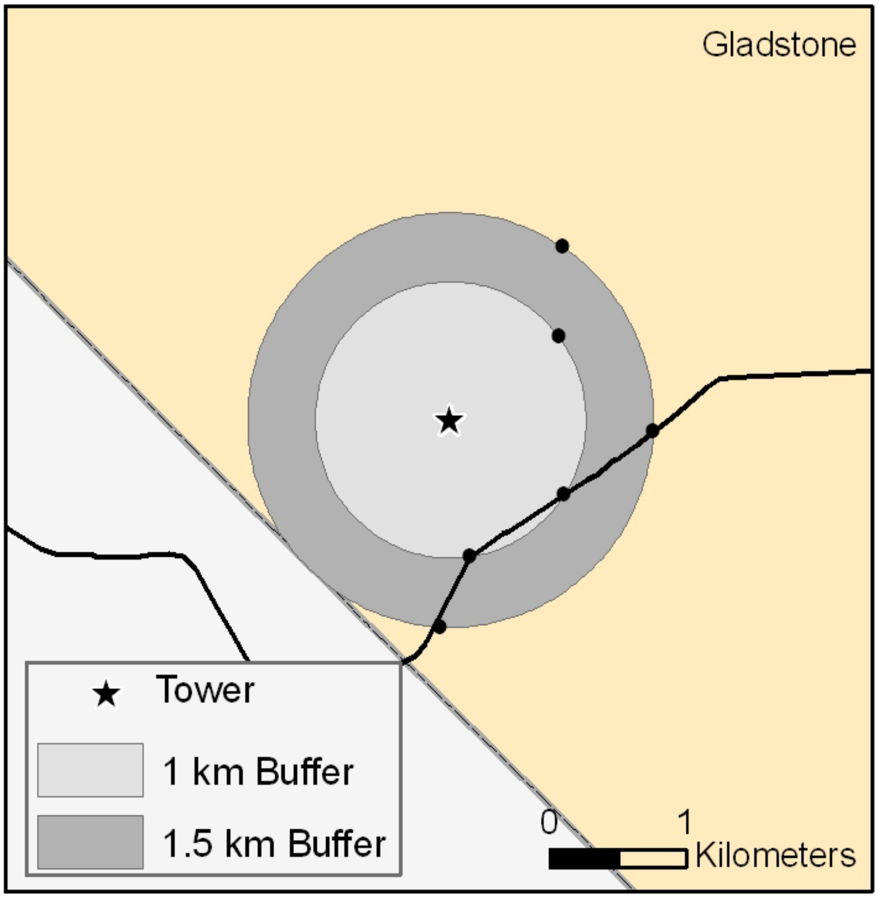

Figure 3.9b Reference Sampling Sites for the Tower near Gladstone

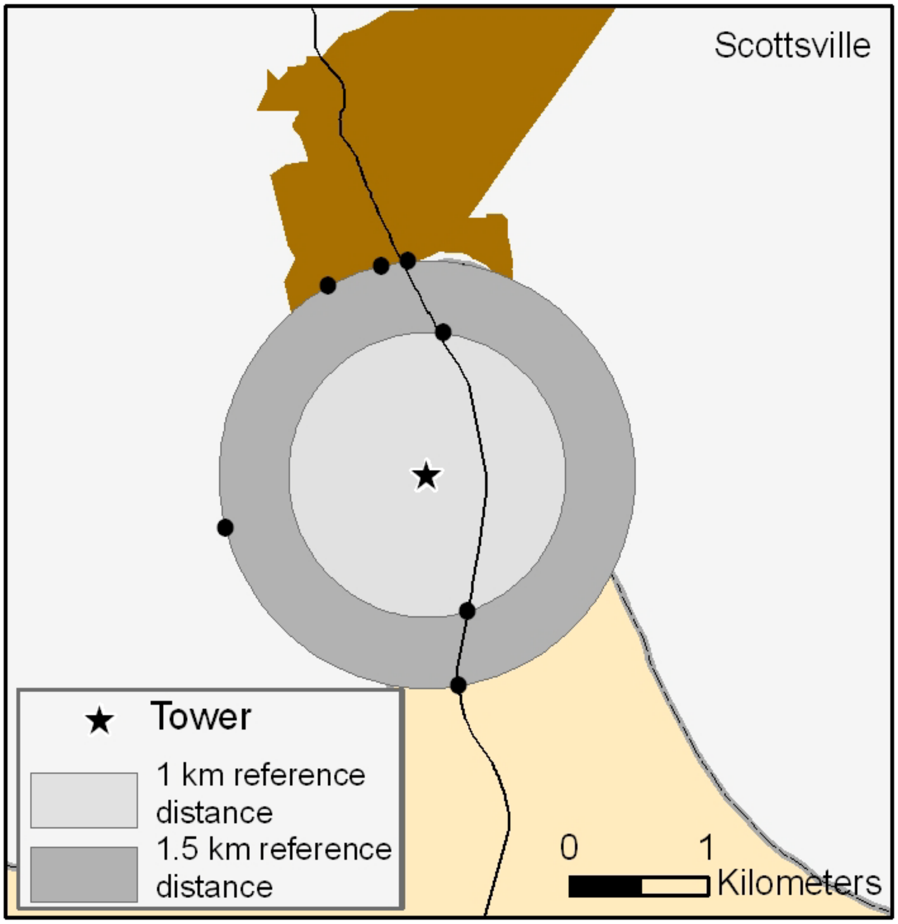

Figure 3.9c Reference Sampling Sites for the Tower near Scottsville

Once the reference points and subsequent reference powers were determined, it was necessary to determine the land cover class for each sample point based upon the NLCD classes. To do so, a comparison of the sampling sites to the land cover was made using the NLCD 2001. According to the NLCD, a deciduous forest is “areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change” (Homer (pg. 836), 2004). An Evergreen forest is defined as “areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage (p. 836).” Shrub/scrub is defined as “areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions (p. 836).” Lastly, Grassland/Herbaceous and Pasture/Hay are defined as “areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing (p. 836)” and “areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation” respectively (Homer, 2004, p.836).

After a preliminary examination of the sample locations compared to the NLCD data, there were a large number of samples classified as Developed - Open. This class refers predominantly to the road network in the county, and given that the samples were taken along the roads, this makes sense. However, the radio wave does not travel perpendicular to the earth’s surface and openness directly above the sample location was not the same as openness in the direction of the transmitting tower. To correct this, any point that was classified as Developed - Open was examined individually to determine whether or not it was appropriate to have that classification and if not, the appropriate classification was given to the point. Using GIS, a polyline shapefile containing lines digitized between the transmitting tower and each of the sample points was created. The transmitting tower which was the closest to the sample point was used in creating the polyline shapefile. A 100 meter buffer was then placed around the sample point. Using the NLCD layer, the point was assigned the class which made up the majority of the path along the line between the tower and sample point within the 100 meter buffer. The buffer distance was chosen as an estimation of typical opening in the county based upon field experience.

Because a distance of 1.5 km from the tower is used as the reference point, any samples which were closer to a tower than 1.5 km were not used in the subsequent analyses. In addition, only the sampling sites within the viewshed of a tower and within line-of-sight were included in the analysis (Figure 3.10). To determine whether or not a location is within the line-of-sight, a viewshed analysis was conducted using the heights of the transmitting antenna and receiving antenna, as well as a terrain model such as a digital elevation model (DEM). This process identified those locations where the receiving antenna could be "seen" from the transmitting antenna. The result produced a raster layer with values ranging from zero to the three (if all transmitting antennas could "see" a given location). Those raster cells which had a value greater than or equal to one existed within the viewshed. The viewshed analysis uses line-of-sight and eliminates the need to determine the effects of diffraction.

There were 164 samples taken within the viewshed and further than 1.5 kilometers from a tower. Of those, only the samples which were within NLCD classifications 41, 42, 52, 71 or 81 were selected. The NLCD classification 41 refers to areas which are classified as deciduous. Class 52, shrub/scrub was included in the analysis because in the field it was obvious that those samples were no longer small unknown plants, but instead were evergreen trees of significant height to impact the radio wave propagation. For the analysis classes 42 and 52 were combined to represent the overall evergreen distribution. Classes 71 and 81 were used to represent open areas in the study, thus creating a control group of samples which reduces the influence of vegetation. The areas classified as Deciduous & Evergreen in the county were shown on Figure 3.11 in green and brown respectively. Several other land cover classes such as developed, open areas, and water represent the remaining areas within the county. It appeared that the deciduous and evergreen trees are throughout the county; however, in the field the distribution of evergreen trees was more clustered while deciduous trees were evenly distributed throughout the county. The locations of sample points were mapped by land cover class to show the overall distribution (Figure 3.12). Initially, the distribution of the three land cover classes appeared evenly distributed. But after further review, the evergreen clustering was apparent and the vast majority of the open areas were located further south and east. The distribution of sample locations closely follows the land cover distribution seen in Figure 3.11.

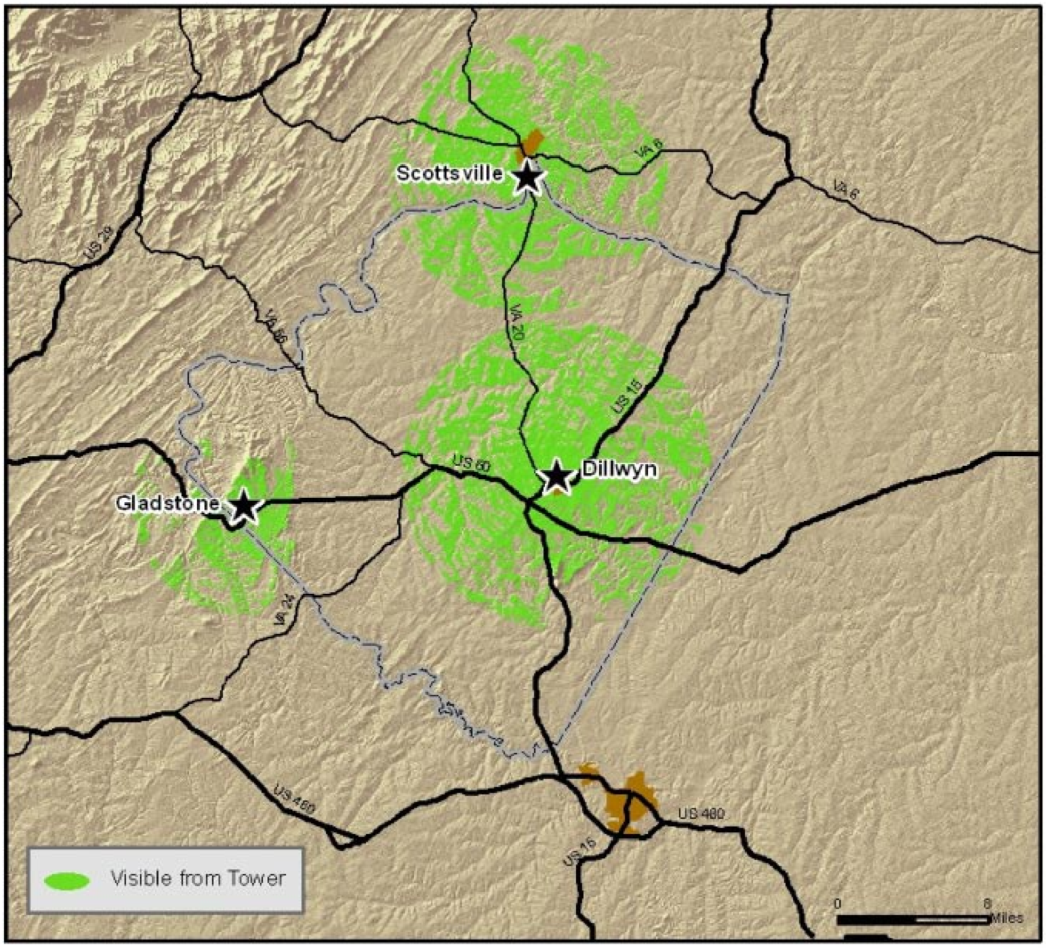

Figure 3.10 Viewsheds from Study Towers

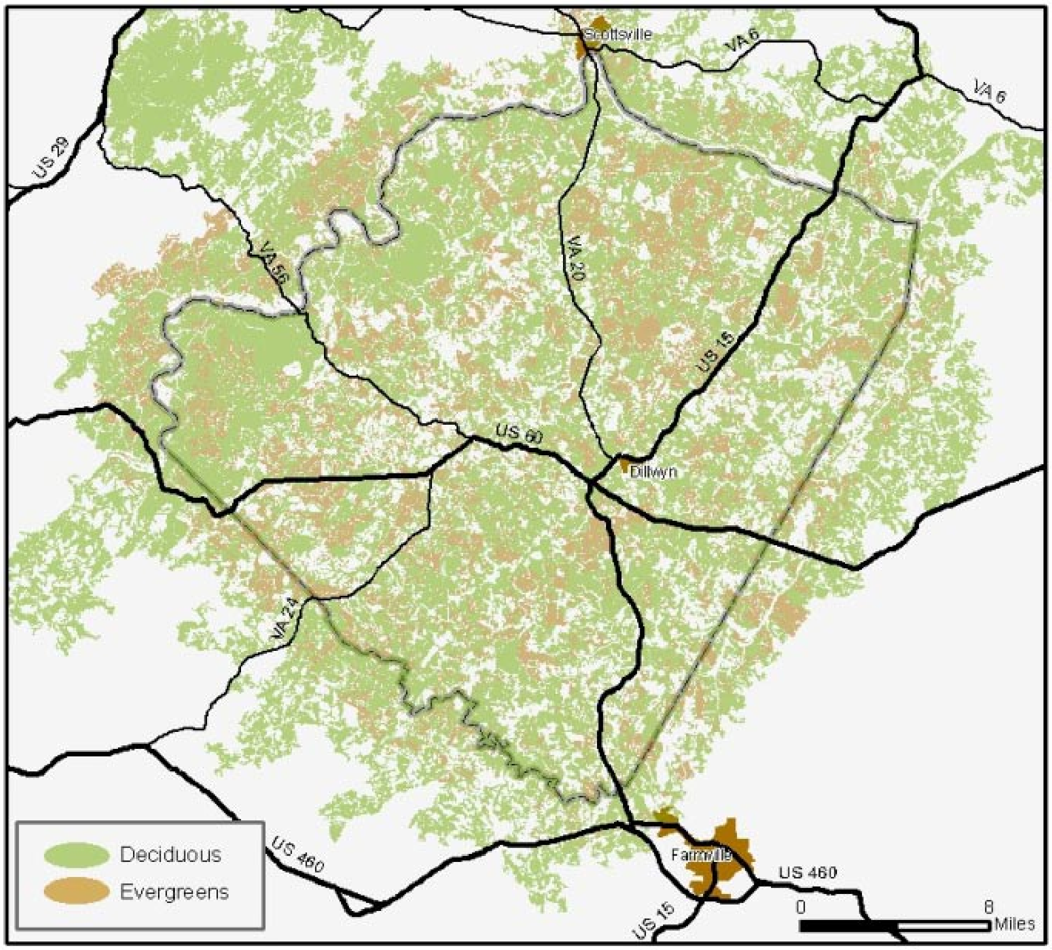

Figure 3.11 Distribution of Deciduous & Evergreen Trees

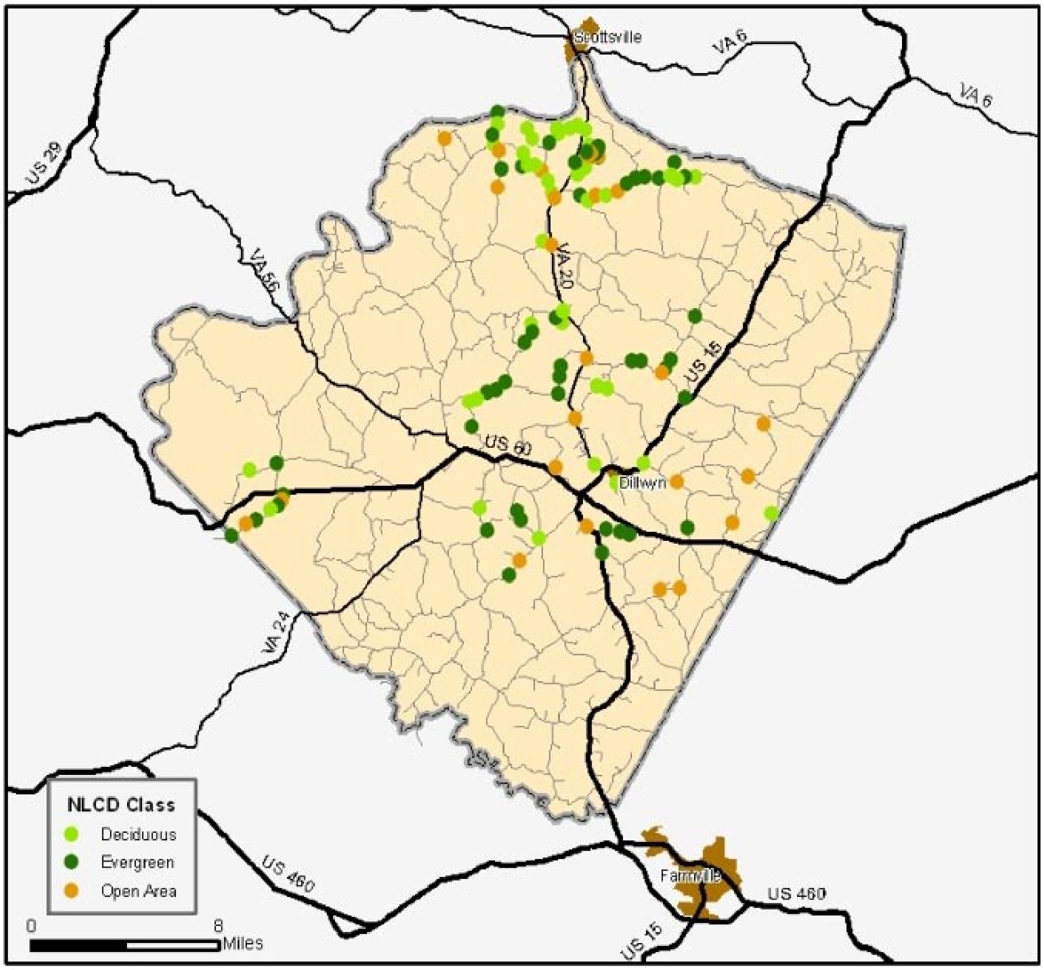

Figure 3.12 Land Cover Types for Sample Locations

CHAPTER IV

ANALYSIS

Data

There were two sets of data collected in this study. The first set consists of samples collected during the fall of 2008 and winter of 2009. The second set consists of data collected during the spring of 2009.

The data collected in September 2008 and January 2009 were actual signal strength readings and are not included in the main analysis in order to remove the possibility of seasonal differences in signal strength. These data were used to directly compare the signal strength between leaf-on and leaf-off observations. This is possible since the 61 actual signal strength samples taken in January 2009 were taken in the same 61 locations as the samples in September 2008. Twenty-one of the sixty one samples had adequate signal strength to be received by the spectrum analyzer in both fall and winter. The mean received signal strengths for the September and January samples were -99.9 dBm and -96.7 dBm, respectively (Table 4.1).

Table 4.1 Descriptive Statistics of Signal Strength (dBm) by Time Period

Time Period	Number of Samples	Mean	Median	Standard Deviation	Minimum	Maximum
Sept. 2008	21	-99.9	-103.2	9.3	-108	-73.2
Jan. 2009	21	-96.7	-98.4	8.5	-106	-76.8

Fifteen of the sixty one samples are located within an area classified as deciduous while three are located within an area classified as evergreen in the NLCD 2000 (Table 4.2). The sample mean for the evergreen class is greater than the sample mean for the deciduous class, however; after more thought this is expected. Since the two sets of samples were taken in different seasons (fall and winter), the deciduous trees had leaves for one set of samples and did not for the other. On the other hand, the evergreen trees always had their leaves. The range of signal strength differences between fall and winter deciduous samples is much greater than the comparable range for the evergreen samples. This is expected for the same reason as the sample mean for the evergreen class being greater than the mean for deciduous.

Table 4.2 Descriptive Statistics of Original Signal Strength Differences (dBm) between Fall and Winter by Land Cover

Land Cover Class	Number of Samples	Mean	Median	Standard Deviation	Minimum	Maximum
Deciduous	15	-5.0	-6.0	3.1	-11.2	0.8
Evergreen	3	-4.5	-4.0	1.3	-6.0	-3.6

The actual signal strength was recorded at 236 locations in the field during late May 2009, according to the second sampling scheme explained in the preceding chapter. Signal strength readings were all negative because as the power in milliwatts decreases, the dBms become negative in the conversion between the two units. One reading was taken at each location resulting in 236 observations of signal strength (see methodology section). The model in Equation 4 was then used to generate predicted values at the same 236 locations using the 1.5 kilometer signal strength averages found in Table 3.4. The differences between field-observed and model-predicted signal strength values are used in the subsequent data analysis. Since no field data were collected while the trees were without leaves, the predicted values from the model served as the leaf-off values. Given that the purpose of the study was to determine the effects of deciduous and evergreen trees on the signal strength, only samples located in one of the three land cover categories (deciduous, evergreen, and open areas) were used in the analysis. Specifically, there were 38 samples for deciduous trees, 52 for evergreens, and 27 for open areas with a total of 117 samples used in the analysis. Among these samples, 50 were located within range of the Dillwyn tower, 58 in the range of the Scottsville tower, and 9 in the range of the Gladstone tower. The data were examined several different ways to ensure that a complete and thorough assessment was obtained and variations in the data could be explained. Lastly, the possible effect of the third tower located in Gladstone with the smallest number of samples was examined to determine whether the tower may have changed the overall results.

Tables 4.3 and 4.4 show the descriptive statistics of the signal strength differences in dBm for land cover types and three towers.

Table 4.3 Descriptive Statistics of Signal Strength Differences by Land Cover Class

Land Cover Class	Number of Samples	Mean	Median	Standard Deviation	Minimum	Maximum
Deciduous	38	-1.184	-1.928	6.0549	-9.1	18.1
Evergreen	52	-1.404	-1.359	6.4706	-12	18.5
Open Areas	27	0.3222	0.345	5.5855	-10.9	12.4

Table 4.4 Descriptive Statistics of Signal Strength Differences by Tower

Tower	Number of Samples	Mean	Median	Standard Deviation	Minimum	Maximum
Dillwyn	50	0.474	-0.251	5.120	-7.741	13.347
Scottsville	58	-3.197	-3.655	5.957	-11.976	18.084
Gladstone	9	1.727	1.353	8.938	-10.945	18.479

It was apparent the data had a large range for each of the classes which spanned both positive and negative values (Table 4.3). The positive differences represented instances where the observed signal strength was stronger than the predicted signal strength, whereas the negative differences signified cases where the observed signal strength was weaker than the predicted signal strength. The mean signal strength differences for deciduous and evergreens, -1.184 and -1.404 respectively, were not as large as expected from the literature and given the model, did not include any clutter loss values, the resulting difference values should have all been negative. The unexpected results could possibly be explained by a closer examination of the variables accounted for by the model and perhaps more importantly, those variables which were not.

The literature shows that terrain is a significant variable in the path loss calculations. It also shows that the effects of diffraction could positively impact the path loss calculations. The effects of diffraction were reduced by using only those samples within the viewshed of the towers because of issues concerning the accuracy of the diffraction models. However, diffraction could have occurred in the field especially in the more rugged terrain in the western region of the county. If diffraction did occur, it would have positively contributed to the observed signal strength and consequently made the signal strength difference become positive. Many of the positive signal strength differences shown in Figure 4.1 are on the edge of the viewshed and further away from the towers increasing the probability that diffraction impacts the signal strength. The effects of reflection were not included in the model used to predict the signal strength at the sample locations. However, reflection could have occurred between the tower and the sample locations potentially producing stronger signal strength than the model predicted. In this case, the signal strength difference could have become positive or at a minimum, could have become less negative. One last variable which could account for a small positive effect on the signal strength differences was scattering. As noted in the literature, scattering usually results in signal strength attenuation and could add to signal strength in some cases. In this study, it is quite possible that scattering contributed additional signal strength, but its effect would rank among the smallest of all three variables.

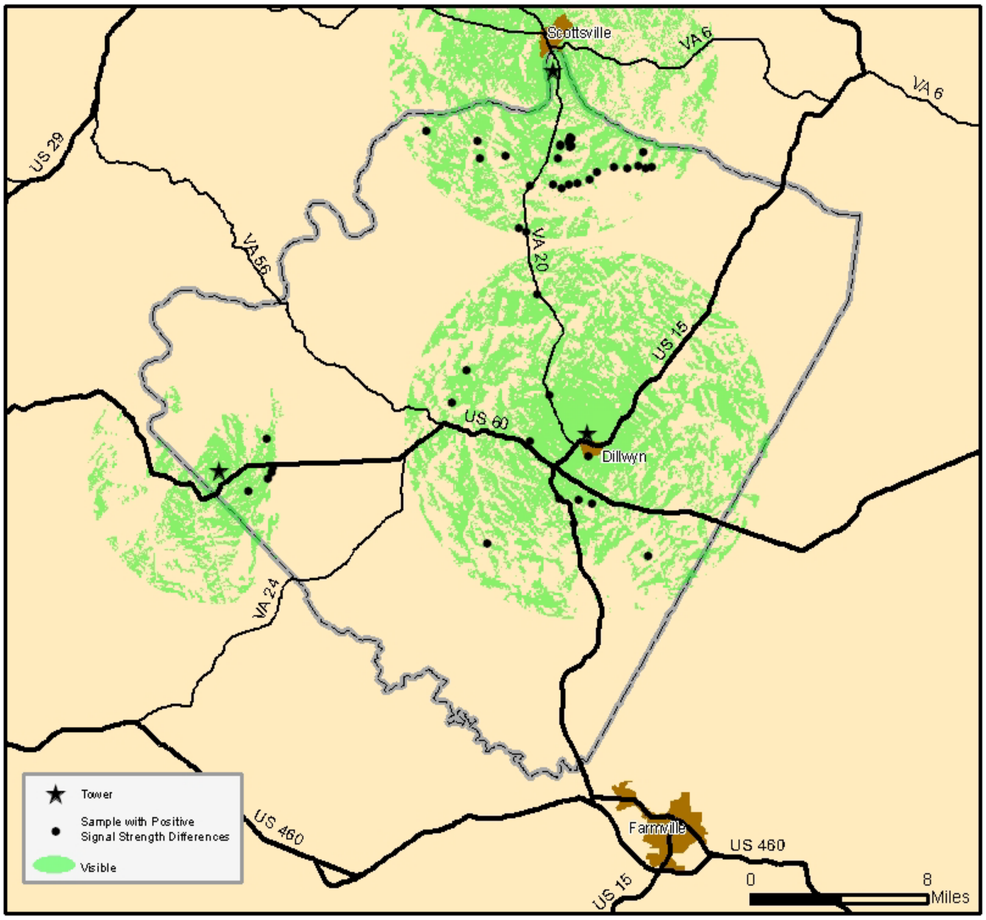

Figure 4.1 Positive Signal Strength Differences with Viewsheds

The descriptive statistics of signal strength differences between the towers revealed that the Gladstone tower appeared to be different from the Dillwyn and Scottsville towers (Table 4.4). The mean was higher (1.727) than the other two tower means. Additionally, the median (1.353) was the only positive median suggesting there were more positive signal strength differences from samples around the Gladstone tower than the other two towers. Lastly, the standard deviation was significantly higher than the other two indicating the differences were more variable. As a result, analysis was conducted using all three towers as well as using only the Dillwyn and Scottsville towers to determine if there were any significant differences between the two sets of data or whether it was most likely the small sample size which made the Gladstone tower appear different.

Comparison between Fall and Winter Observations

The date collected in September 2008 and January 2009 are used to compare the fall and winter samples directly to determine whether there is a statistically significant difference between the September and January samples. The resulting p-value is 0.000 indicating the two sets of data are statistically different from one another at the 0.05 significance level. Both sets of data had relatively high standard deviations, which would be expected given the varying terrain and other variables affecting propagation. It is clear from examining the two sample means that they are similar, but a t-test using the 15 samples identified as deciduous and the 3 samples identified as evergreen is used to confirm that the two data sets are not statistically significant from one another. The p-value is 0.765 (alpha = 0.05) which means there is not a statistical difference between the deciduous and evergreen samples.

The spatial distribution of the eighteen samples classified as either deciduous or evergreen is given in Figure 4.2. Given the small sample size, it was difficult to infer any patterns from the distribution, however; the evergreen samples did follow the trend of being located in a tree farm while the deciduous samples were located throughout the study area.

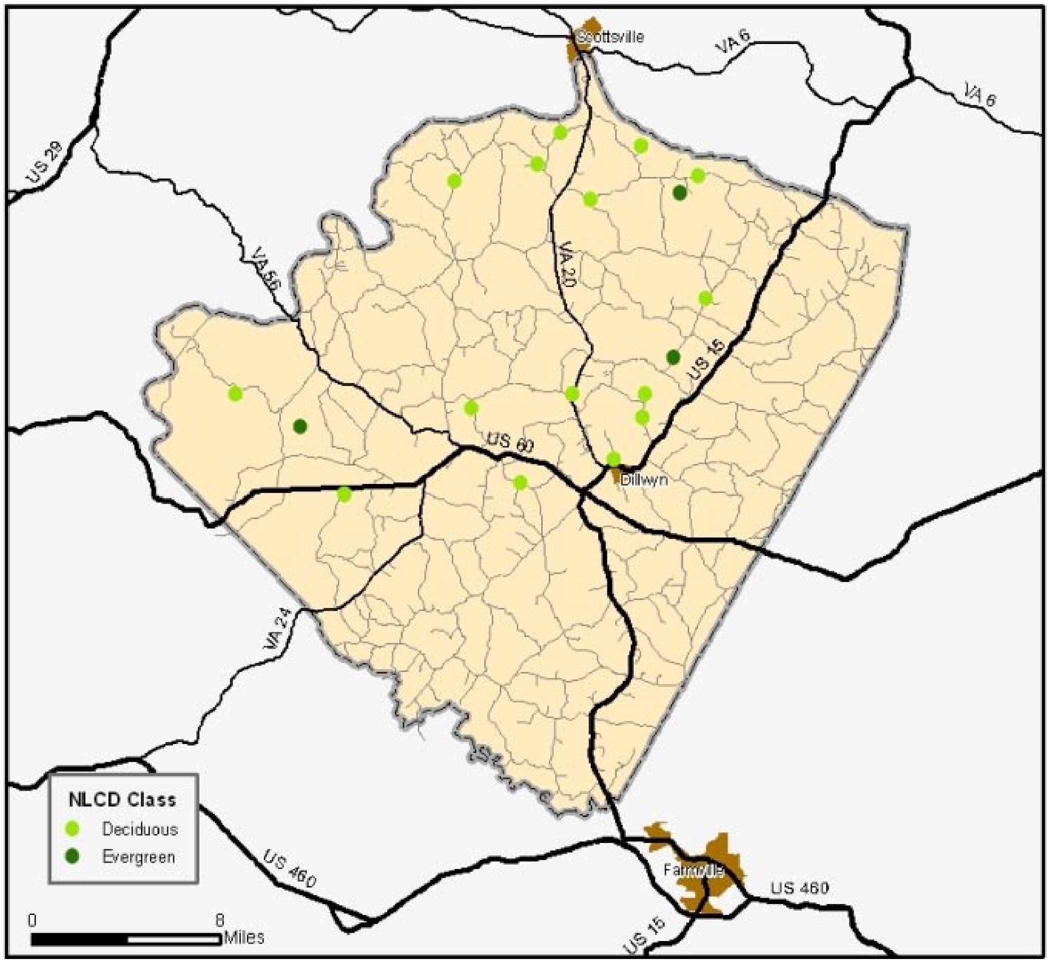

Figure 4.2 Land Cover Distributions for Fall & Winter Observations

It is clear that there is a difference in signal strength between fall and winter observations because of the lack of leaves during the winter. However, this knowledge does not provide much assistance in propagation modeling because many places have leaves on trees at least for the majority if not all of the year. To obtain more appropriate and useful data to assist in propagation modeling, the samples collected in May 2009 are used in a comparative analysis between the observed and predicted signal strength.

Model Verification

The accuracy of the model, Rappaport's received power reference formula (Equation 4), was verified using the signal difference data for the open areas. Since the signal strength measured in the open areas was supposedly not influenced by vegetation, the sample mean of the differences between measured and predicted signal strength should be near zero if the model predictions are accurate. The frequency distribution of differences between observed and predicted signal strength for the open areas is approximately symmetrical and centered around zero providing a visual clue indicating no difference in signal strengths (the sample mean is 0.32) (Table 4.3 and Figure 4.3). A t-test using the same data further confirmed that on average there is no statistically significant difference between the measured and predicted signal strength for the open areas (p-value=0.77, alpha = 0.05). As such, the overall model predictions can be considered to be accurate.

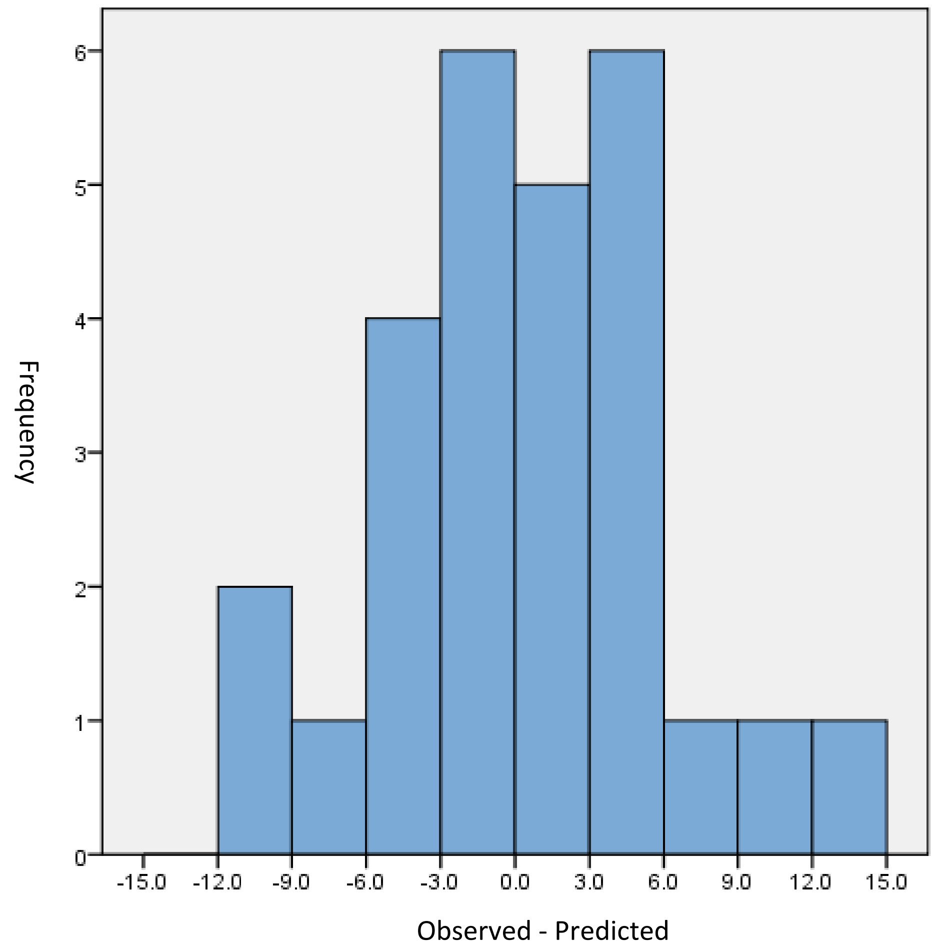

Figure 4.3 Frequency Distribution of Differences (dBm) between Observed and Predicted Signal Strength for the Open Areas.

Analysis of All Samples from Three Towers

The frequency distributions in Figures 4.4 and 4.5 are different from that in Figure 4.3. Both Figure 4.4 and 4.5 show distributions skewed to the right indicating that there are more negative values than positive values. The sample means for the deciduous samples and evergreen samples are -1.184 and -1.404, respectively (Table 4.3). These sample means contrast to the positive sample mean of 0.32 found from the open area samples. T-tests using the same data confirmed that on average there is not a statistically significant difference between the measured and predicted signal strength for the areas under deciduous and evergreen (p-value = 0.24, alpha = 0.05). The skewness may have been the cause of the non-significant results. Although the sample means of deciduous and evergreen appeared to be different from that of open areas, the results of the t-test indicate that there is not a statistical difference between them. Both deciduous and evergreen samples have negative medians whereas the Open Areas have a positive median (Table 4.3). Since the median is not affected by extreme values, it could again be inferred that the deciduous and evergreen samples are different from the Open Area samples. However, the results found from the Kruskal-Wallis test of medians show a Chi-Square of 2.602 and a significance value of 0.272 (alpha = 0.05). This result further confirms the t-test results that the deciduous, evergreen, and open area signal strength differences are not statistically significantly different from zero.

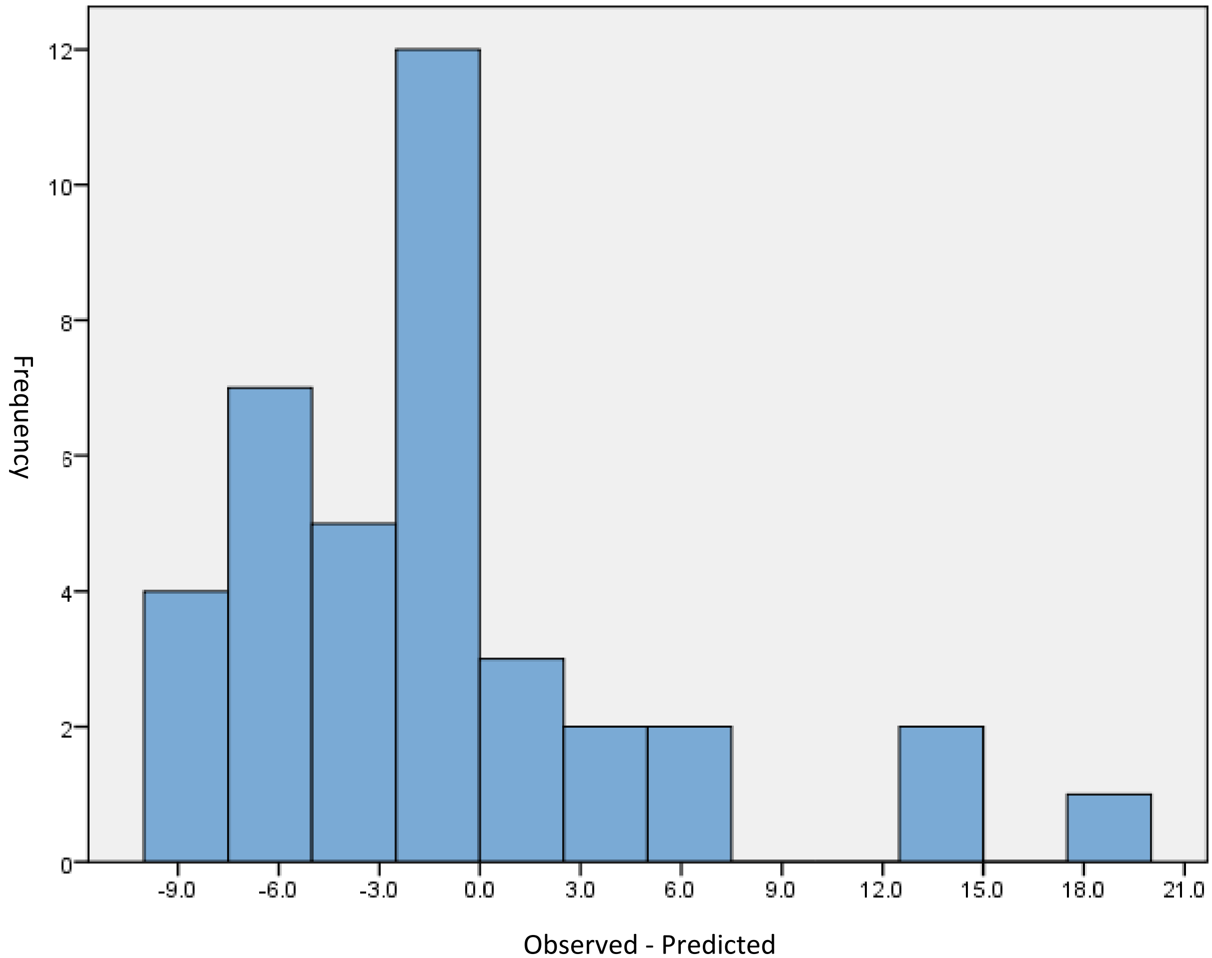

Figure 4.4 Frequency Distribution of Differences (dBm) between Observed and Predicted Signal Strength for the Areas under Deciduous Trees

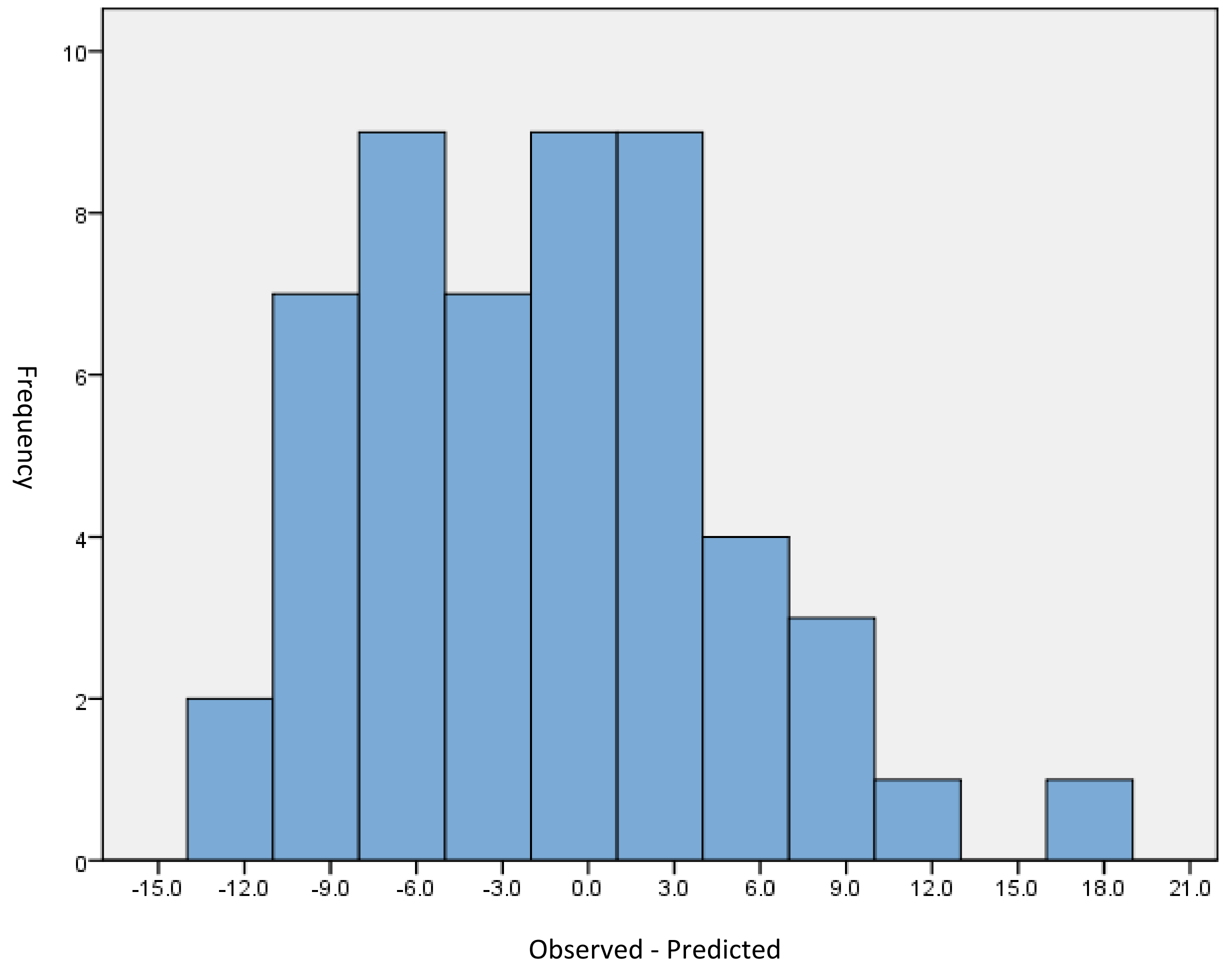

Figure 4.5 Frequency Distribution of Differences (dBm) between Observed and Predicted Signal Strength for the Areas under Evergreen Trees.

Analysis of Only Negative Difference Values from Three Towers

Since the signal strength differences should have all been negative, it was obvious that there were additional factors which impacted the results. The positive signal strength differences could have been erroneous or could have been impacted by variables not included in the prediction equation. The rationale behind examining only the negative values was developed based upon the knowledge from the literature that variables, such as diffraction, reflection and scattering could positively affect the observed values. If the analysis of the negative signal strength differences shows that there is not a statistically significant difference between the deciduous and evergreen classes and zero, then it could be said that the method used in this study is flawed. However, if a statistically significant difference is found, it will provide evidence that the method has validity.

The results of the Analysis of Variance (ANOVA) test are significant with a p-value of 0.0122. This indicates that different types of land cover have an impact on radio wave attenuation. A post hoc range of means test (Least Significant Difference (LSD)) is also conducted to determine any differences between land cover classes. The results of this test are displayed in Table 4.5. The range of means test for signal strength measurements indicates no significant difference between the deciduous and open areas, but evergreen is significantly different than both deciduous and open area categories. The ANOVA shows that there is not a statistically significant difference in signal strength between the open areas and the areas covered by deciduous trees. There is, however, a significant difference between the evergreen trees and the other two land cover classes.

Table 4.5 Comparison of Signal Strength (Observed-Predicted) among Land Cover Classes using the Least Significant Difference (LSD) Test for Data from All Three Towers. Different letters indicate significant differences at the level of 0.05.

Land Cover Class	Class Mean
Deciduous	-3.9500[a]
Evergreen	-6.2464[b]
Open Areas	-4.2692[a]

Analysis of Samples from Two Towers

Similar to the t-test used for samples collected around all three towers, a t-test is used for samples collected from only the two towers near Dillwyn and Scottsville. The rationale for excluding the Gladstone tower is due to the limited number of observations and fewer received power reference points. The limited number of observations in both cases was a result of time and accessibility. The average received power reference value for the excluded Gladstone tower was the highest of the three, which raised skepticism about measurement validity. The topography surrounding the Gladstone tower is mostly characterized by rugged mountains and the James River, thus, the terrain varied greatly within the region of the tower location. Several of the samples taken around the Gladstone tower were completely unobstructed which produced strong signal strengths. Although all the reference power samples were taken within the viewshed and with no obstructions, the signal strengths were not as strong as what was expected. This could have been caused by directional bias of transmitting power on the tower, but without the specific tower information, it would be impossible to know for sure.

The frequency distributions shown in Figures 4.6 and 4.7 are both skewed to the right indicating there are more negative values than positive values. The skewed distribution would be greatly enhanced if there were not such a large number of observations between zero and positive three. The sample means from both deciduous and evergreen are negative whereas the sample mean for the open areas is positive (Table 4.6). Two t-tests were performed on all samples from the deciduous and evergreen land cover classes. The results showed no statistically significant difference from zero for the deciduous samples, while they showed a statistical difference from zero for the evergreen samples with p-values of 0.2518 (alpha = 0.05) and 0.0070 (alpha = 0.05) respectively (Table 4.6). Unlike the t-test results from the three tower analysis, there was a statistical difference for the evergreen signal strength differences from zero and there was a difference between the deciduous and evergreen signal strength differences.

Table 4.6 Results from Two Tower T-test

Land Cover Class	Group Mean (dBm)	P-value
Deciduous	-1.208	0.2518
Evergreen	-2.300	0.0070
Open Areas	0.676	0.5304

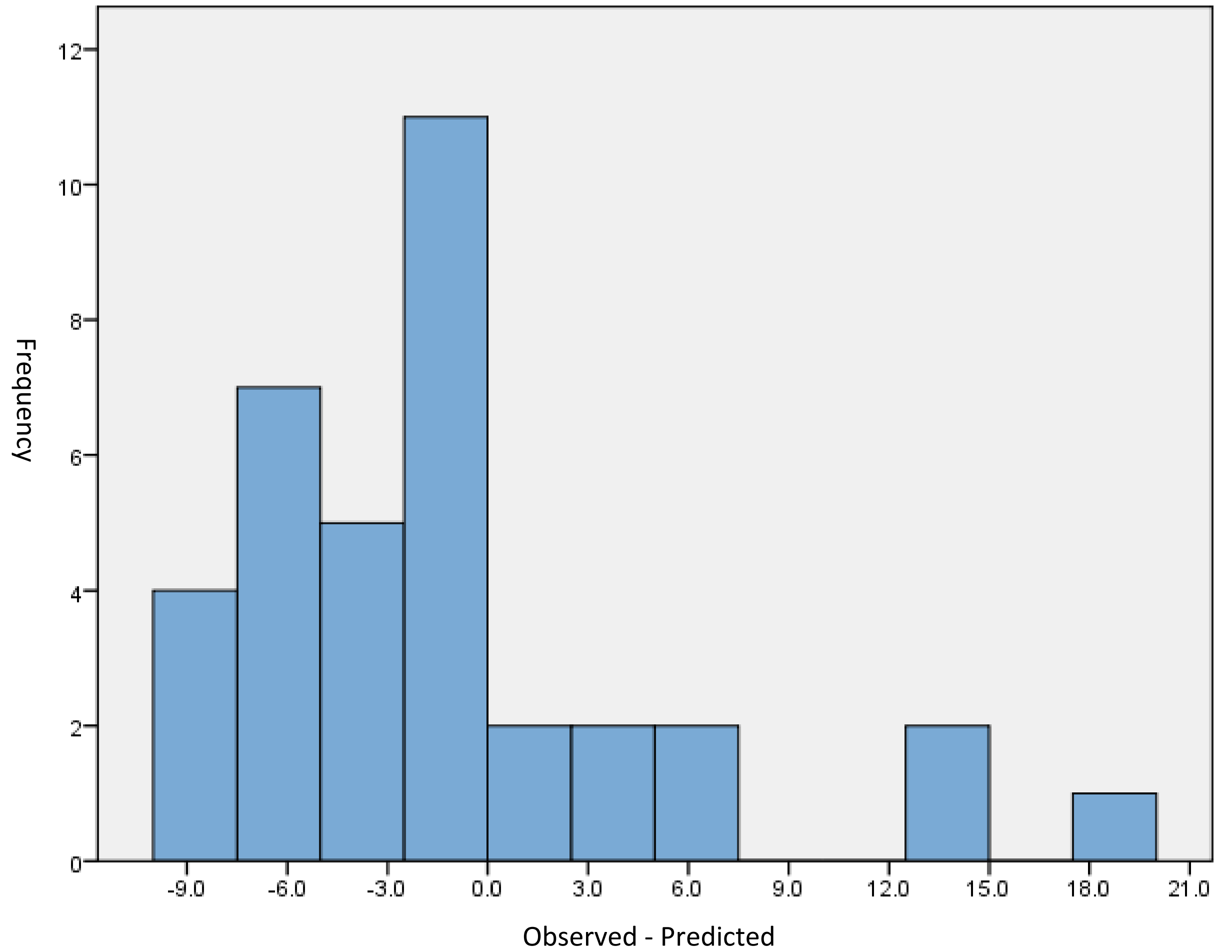

Figure 4.6 Frequency Distribution of Differences (dBm) between Observed and Predicted Signal Strength for Areas under Deciduous Trees (Dillwyn and Scottsville Towers Only).

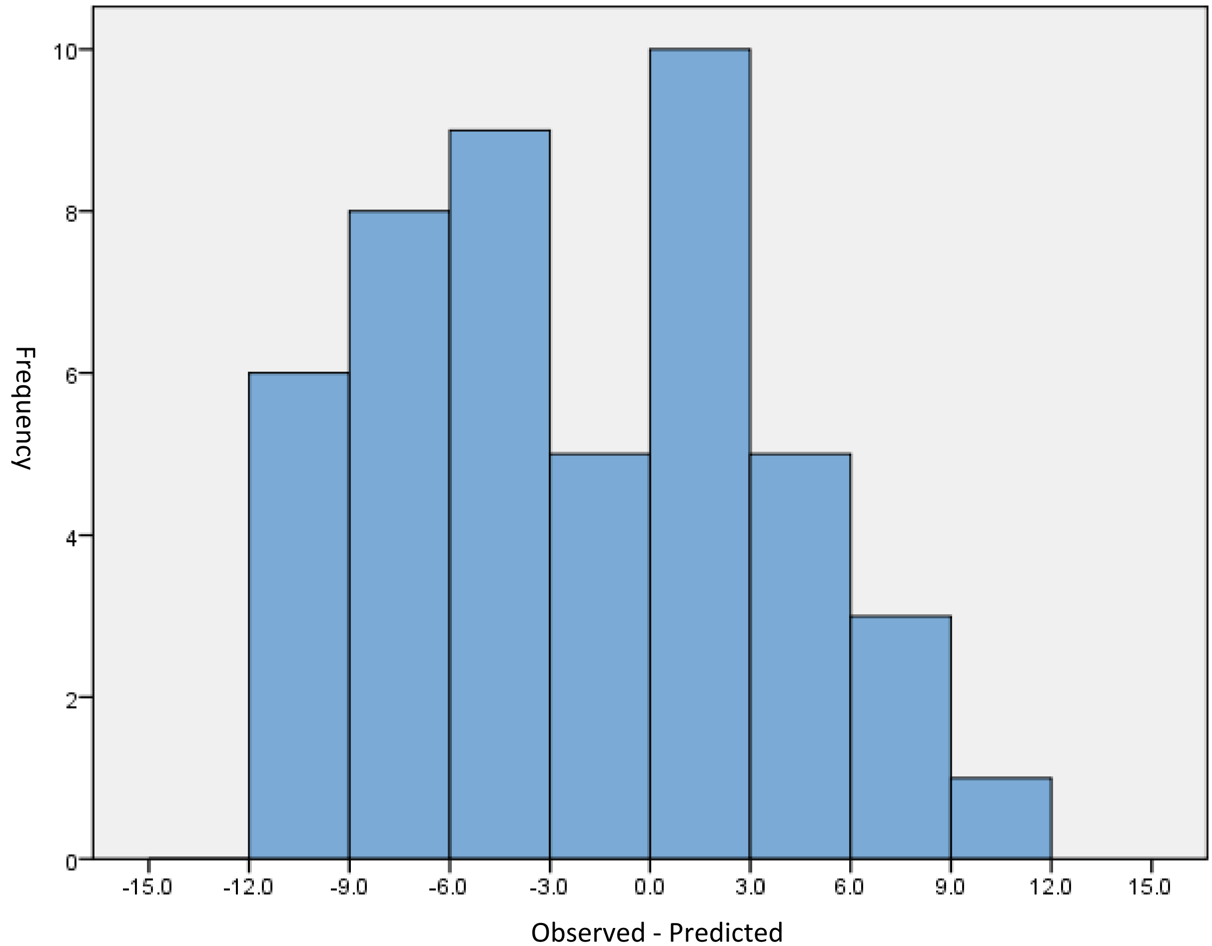

Figure 4.7 Frequency Distribution of Differences (dBm) between Observed and Predicted Signal Strength for Areas under Evergreen Trees (Dillwyn and Scottsville Towers Only).

Analysis of Only Negative Difference Values from Two Towers

An ANOVA procedure was performed on the negative signal strength differences from deciduous and evergreen areas. Unlike in the three tower analysis, the statistical model was significant with a p-value of 0.0059 (alpha = 0.05). A hoc range of means test (LSD) was used to determine the difference among classes and their signal strength (Table 4.7). The results show that the deciduous and open areas were grouped together leaving the evergreen in its own group. Given that the resulting p-value from the ANOVA is half of the equivalent p-value from the three towers analysis it was clear that the Gladstone tower did show a different effect of the trees from the other two towers.

Table 4.7 Comparison of Signal Strength (Observed – Predicted) among Land Cover Classes using the Least Significant Difference (LSD) Test for Data from Only the Dillwyn and Scottsville Towers. Different letters indicate significant differences at the level of 0.05.

Land Cover Class	Class Mean
Deciduous	-4.0407[a]
Evergreen	-6.3111[b]
Open Areas	-3.7167[a]

Relationship between Distance and Signal Strength Differences

The path-loss formula shown in Equation 4 used in the study considered only the distance between the transmitting and receiving antennas, therefore, those distances should be examined to see if any patterns exist. For each land cover type, the differences between measured and model-predicted signal strength were plotted against the distances of sampled sites from the tower (Figure 4.8 to Figure 4.10).

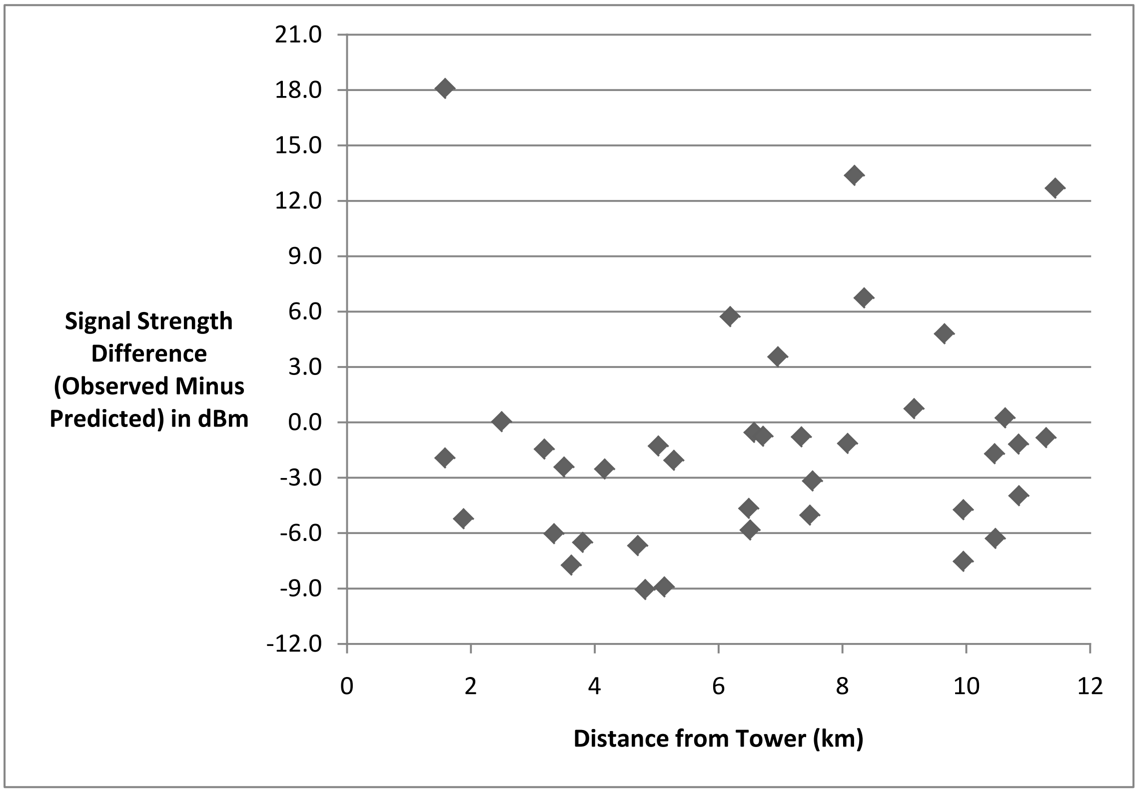

Figure 4.8 Changes in Signal Strength Difference with increasing distance from the tower (Deciduous Trees)

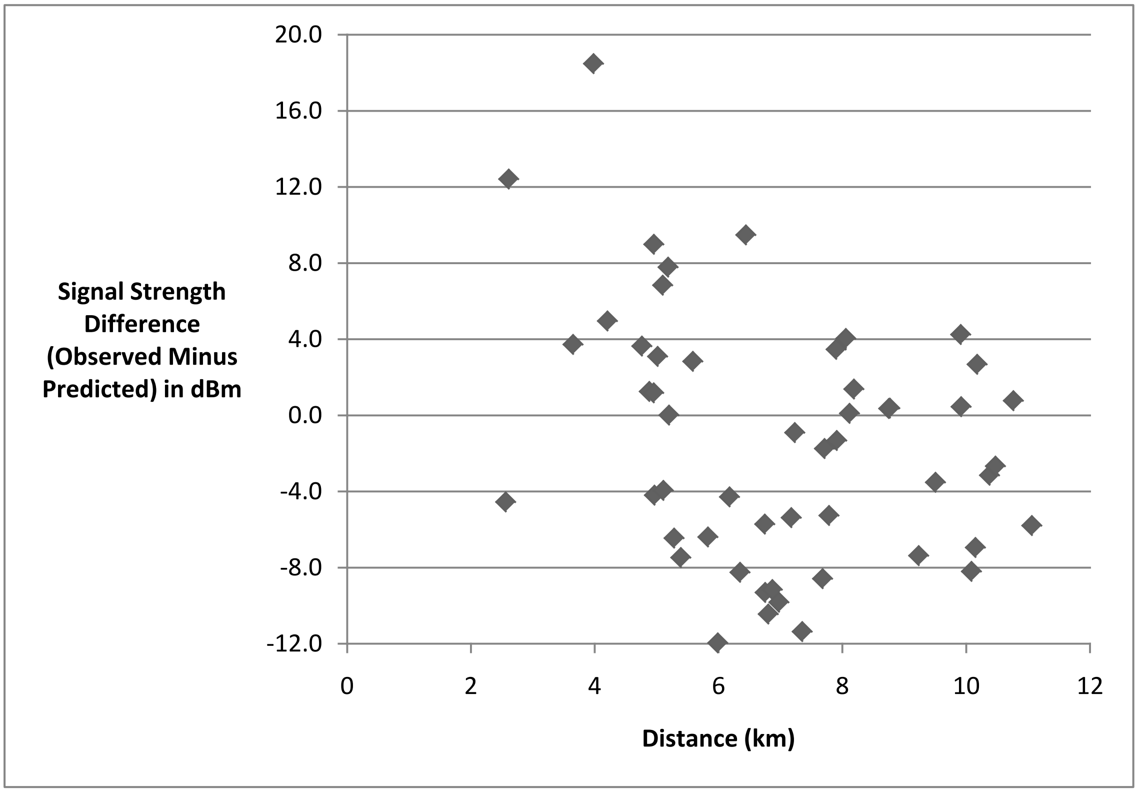

Figure 4.9 Changes in Signal Strength Difference with increasing distance from the tower (Evergreen Trees)

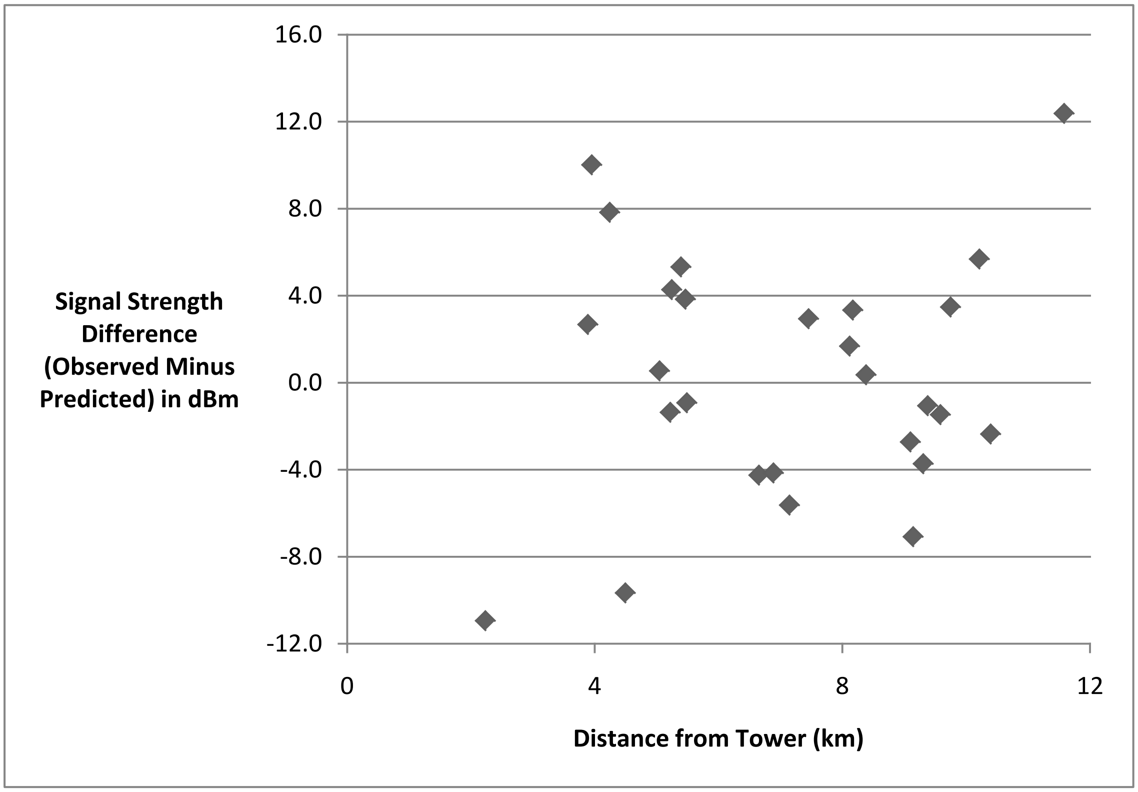

Figure 4.10 Changes in Signal Strength Difference with increasing distance from the tower (Open Areas)

The signal strength differences for the deciduous samples are mostly negative with a few positive differences. There is no increasing or decreasing trend over distance indicating that the observed differences between the observed signal strength and predicted signal strength are not a function of distance. The evergreen signal strength differences are more evenly split between positive and negative differences. Similar to the deciduous samples, there does not appear to be an increasing or decreasing trend over distance. The open area signal strength differences are similar to the evergreen due to them being more or less evenly distributed between both positive and negative. Again, there is no increasing or decreasing trend over distance. The Pearson Correlation test is used to check for any correlation between the signal strength differences and distance for all three land cover classes (Table 4.8). There is no correlation between signal strength differences and distance from tower for the deciduous and open area classes at a significance level of 0.05. However, there is a weak negative correlation between signal strength difference and distance from the towers for the evergreen class.

Table 4.8 Results of Pearson Correlation Test for Land Cover Classes and Distance from Tower

Land Cover Class	Correlation Coefficient	P-value
Deciduous	0.116	0.489
Evergreen	-0.301	0.030
Open Areas	0.126	0.530

The signal strength differences shown in the three graphs were mapped by land cover class with graduated circles representing the magnitude of difference to demonstrate the spatial distribution of the collected samples (Figure 4.11 to Figure 4.13). The smallest circles represented the most negative differences while the largest circles represented the most positive differences. The distribution of the deciduous samples was mainly in those areas surrounding Dillwyn and Scottsville with the vast majority just south of Scottsville. With the one exception near Dillwyn, the most positive observations were further away from the towers. It would be in such areas where the other factors such as diffraction, reflection, and scattering could potentially strengthen the signal strength.

Although the distribution of the evergreen samples was more evenly spread throughout the study area, the observations tended to be clustered into small groups. This was not surprising given that most of the evergreen samples were taken in tree stands. Unlike the deciduous sample distribution, there did not appear to be a pattern to the distribution of the magnitude of differences. Similar to the deciduous sample distribution, the open area samples were primarily found in those areas surrounding the Dillwyn and Scottsville towers. There did not appear to be a pattern to the distribution of the magnitude of differences for the open area samples as both large negative and positive observations were found at all distances from the towers. This probably contributed to the open area samples being good control groups as the samples were taken from a wide variety of distances.

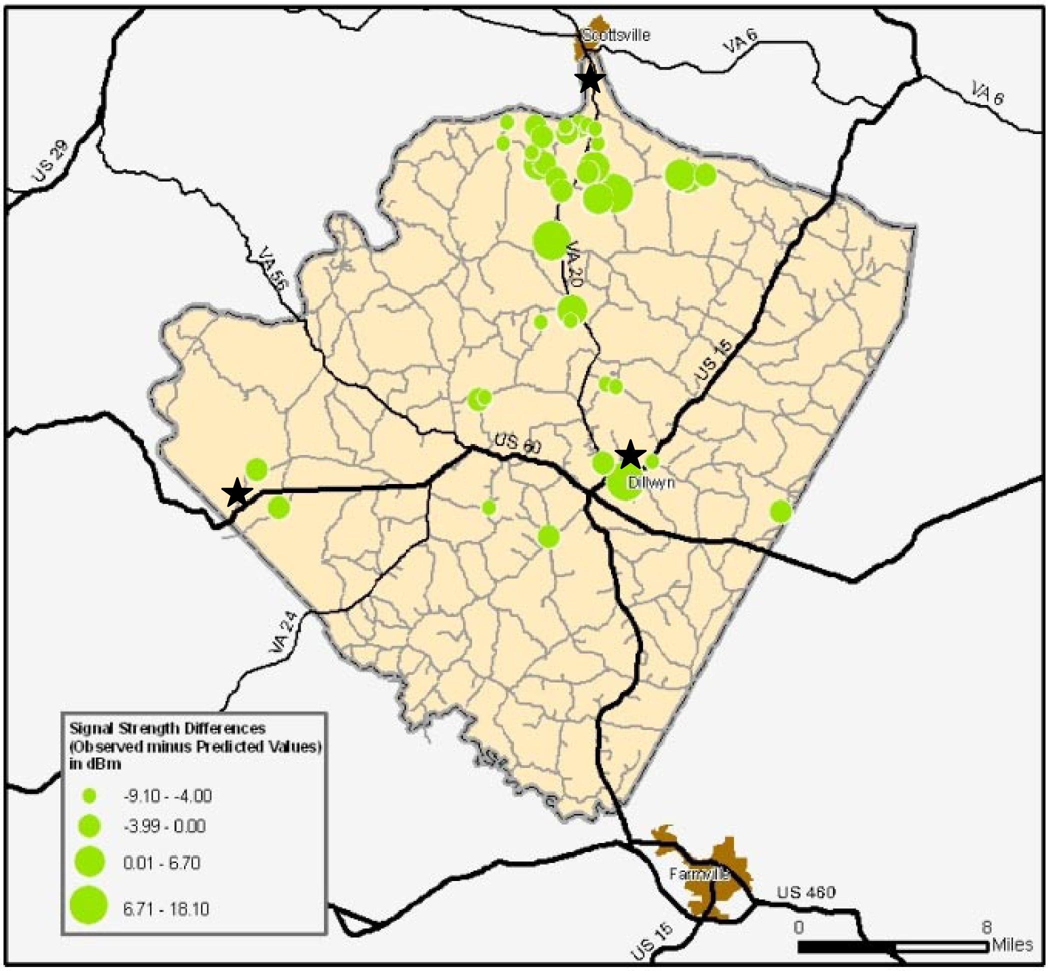

Figure 4.11 Signal Strength Differences for Deciduous Samples. Stars represent tower locations.

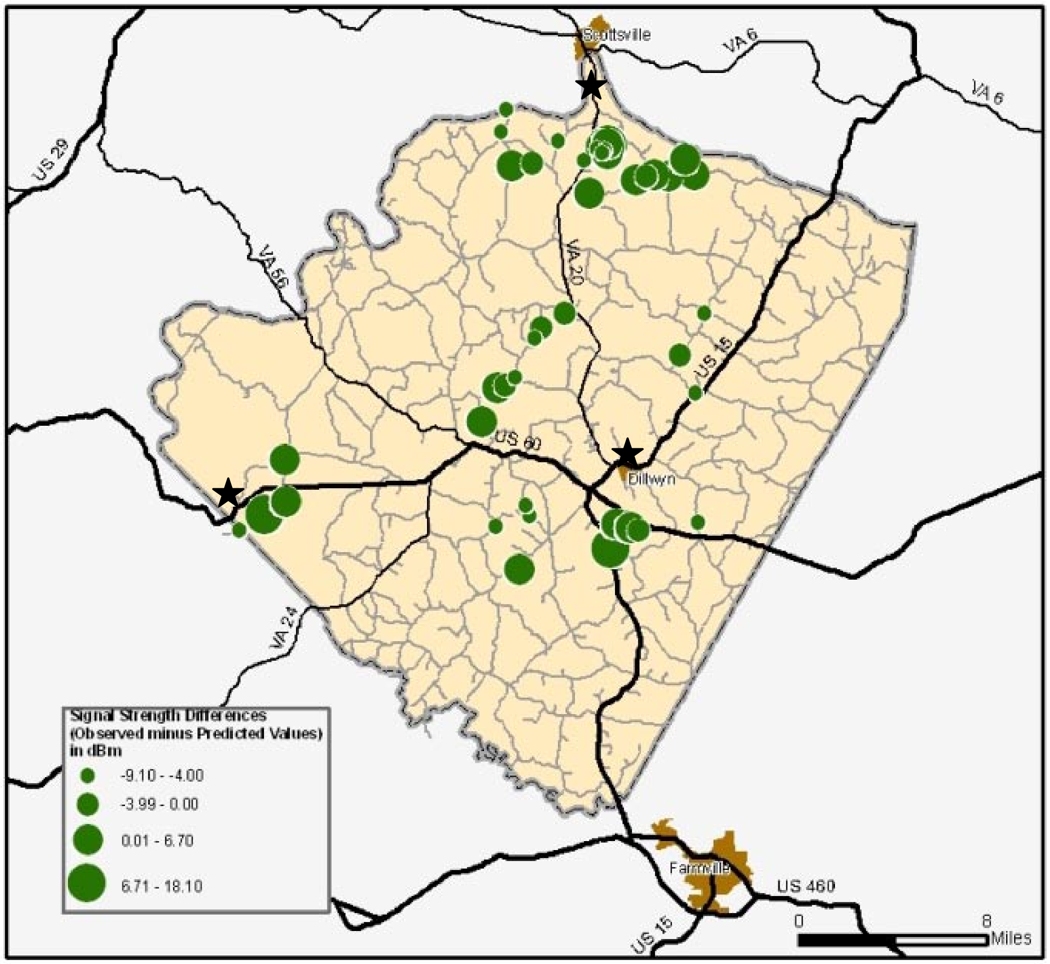

Figure 4.12 Signal Strength Differences for Evergreen Samples. Stars represent tower locations.

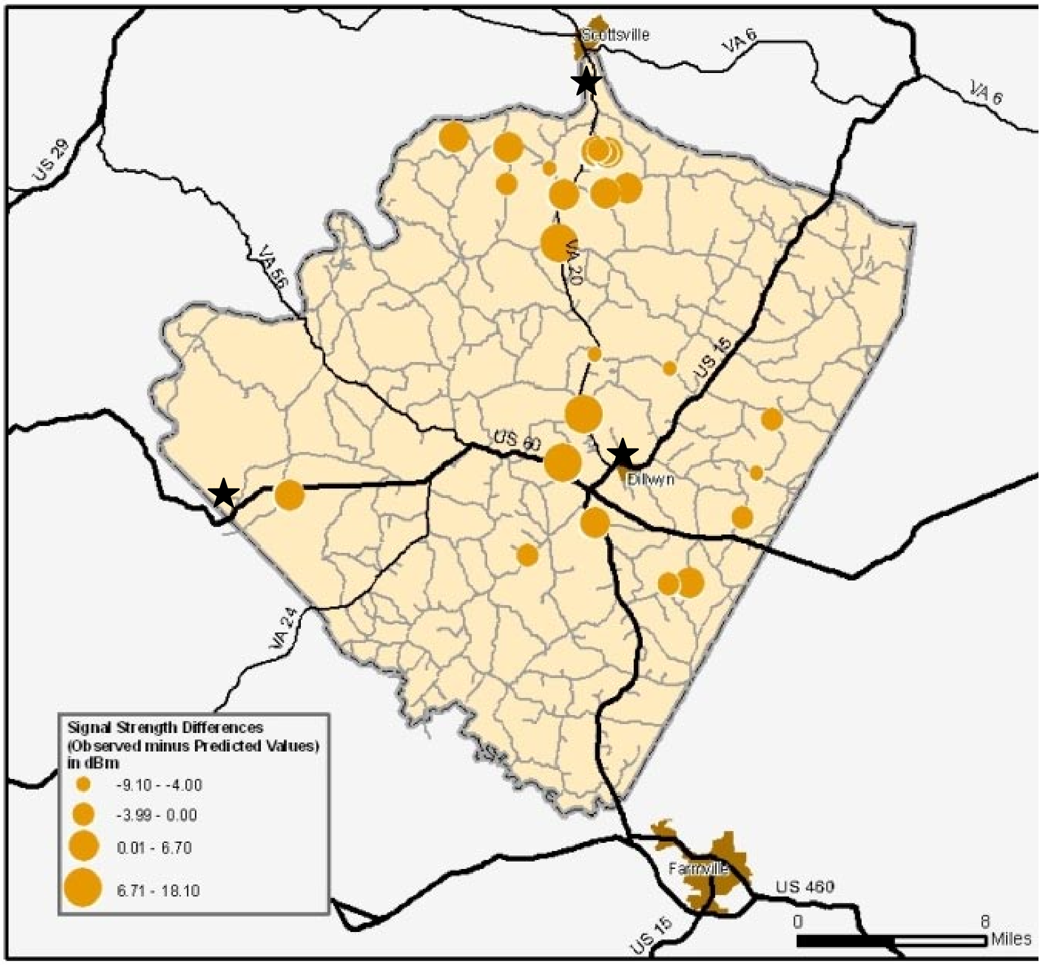

Figure 4.13 Signal Strength Differences for Open Area Samples. Stars represent tower locations.

Spatial Distribution of Signal Strength

Using the collected actual signal strength readings throughout the county, a signal strength distribution was developed by interpolating from the observed points (Figure 4.14). The interpolation was done using GIS software with the Inverse Distance Weighting (IDW) method. The IDW method was chosen because the predicted values calculated in the study were calculated using only distance from the tower as a variable.

In addition, the resulting interpolations, especially the distribution of signal strength, fit the perception of the signal strength distribution received from the field work. The darker shades of blue represent the areas with weaker signal strength than -100 dBm.

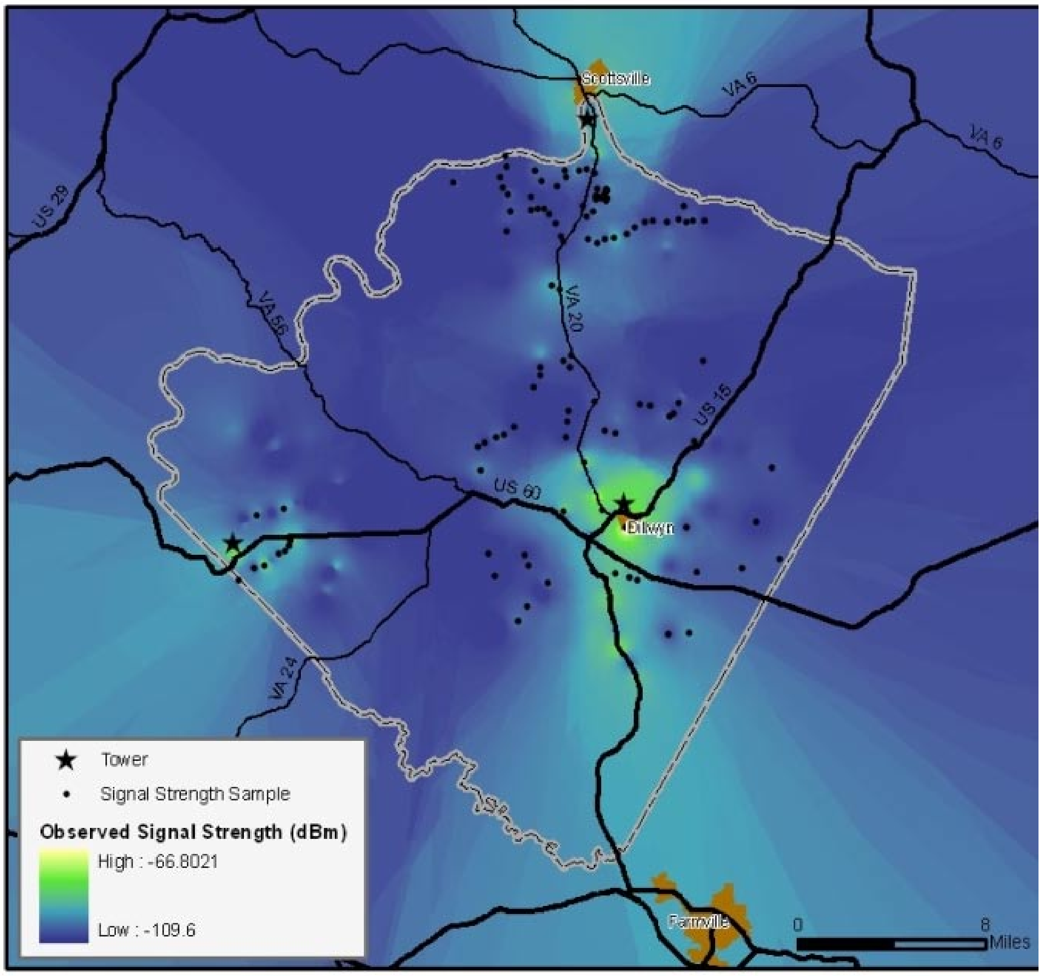

Figure 4.14 Interpolated Spatial Distribution of Observed Signal Strength

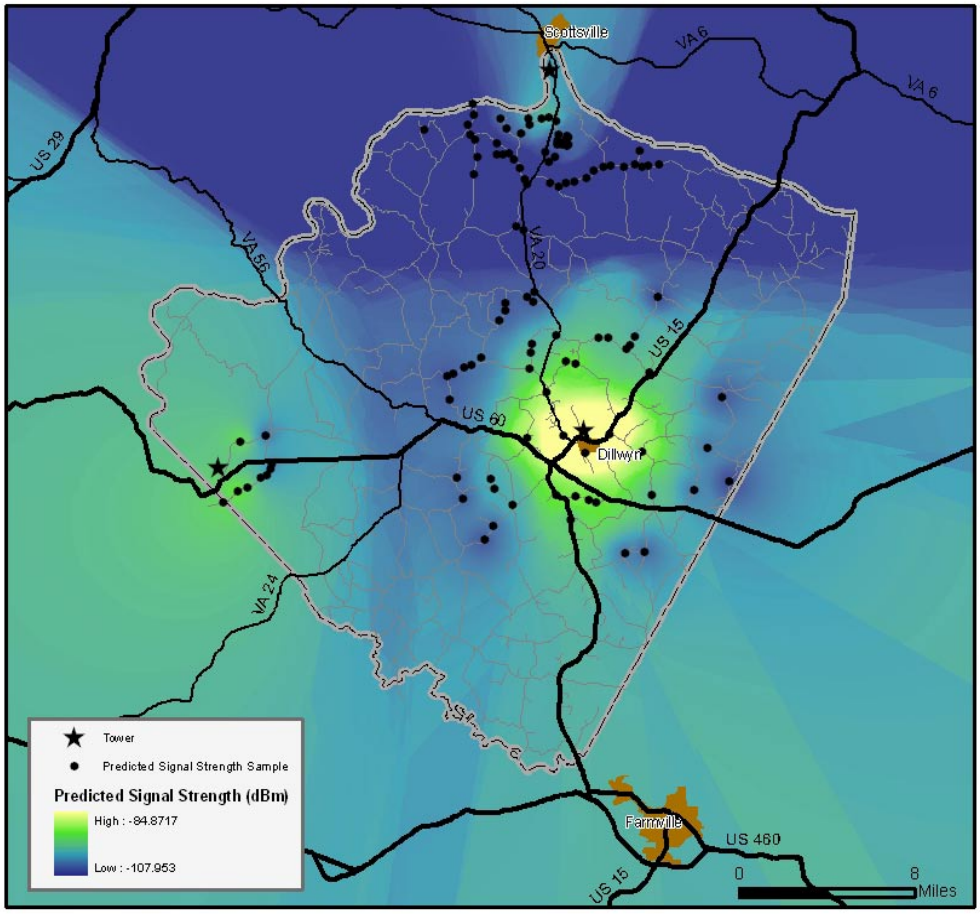

Figure 4.15 Interpolated Spatial Distribution of Predicted Signal Strength

Several observations were clear from the signal strength interpolation. The first was that there were "hotspots" located directly around the Dillwyn and Gladstone towers, but not around the Scottsville tower. While all three towers sat at relatively high elevations, the Scottsville tower had considerable areas with no signal due to terrain. Additionally, the Dillwyn tower not only sat at a high elevation, but it was also the tallest of the three towers examined in the study. The second noticeable observation was with the exception of the "hotspots", the majority of the county had limited signal strength.

Signal strengths of -100 dBm or worse (areas shown in darker shades of blue) were considered to have difficulty making or receiving calls, therefore, a large portion of the county would have had this difficulty. This conclusion can be easily verified by examining the large number of readings which were not included in the study because the only signal received was atmospheric noise. This type of reading was prevalent in the majority of the county and was caused by both terrain interference as well as the being located outside of the coverage zones. It was very apparent after a short duration of time conducting field work that the chosen provider's coverage in the county was limited to the towns and along the two U.S. highways. Given there were no samples taken in the southern part of the county, it was deceiving to see relatively strong signal strengths. This was a result of the interpolation process forcing all areas to have an interpolated value.

The spatial distribution of the predicted signal strength was obtained using the same IDW method as the observed signal strength (Figure 4.15). Again, the darker shades of blue are representative of the areas with weaker signal strength than -100 dBm. Right away it is clear that there are more areas with stronger signal strength in the observed distribution. This is counterintuitive. It would be expected to see weaker signal strength in the observed distribution than in the predicted distribution. However, given that there were a considerable amount of positive signal strength differences, it makes sense to have an overall weaker signal strength distribution. In both distributions, the areas with stronger signal strengths are the same which is expected if the prediction is not severely inaccurate.

Signal Strength Loss Distribution

Similar to the map of actual signal strength distribution, the signal strength differences were mapped using IDW interpolation (Figure 4.16). The signal strength difference between observed and predicted values distribution showed several patterns which can be attributed to the distribution of NLCD classes.

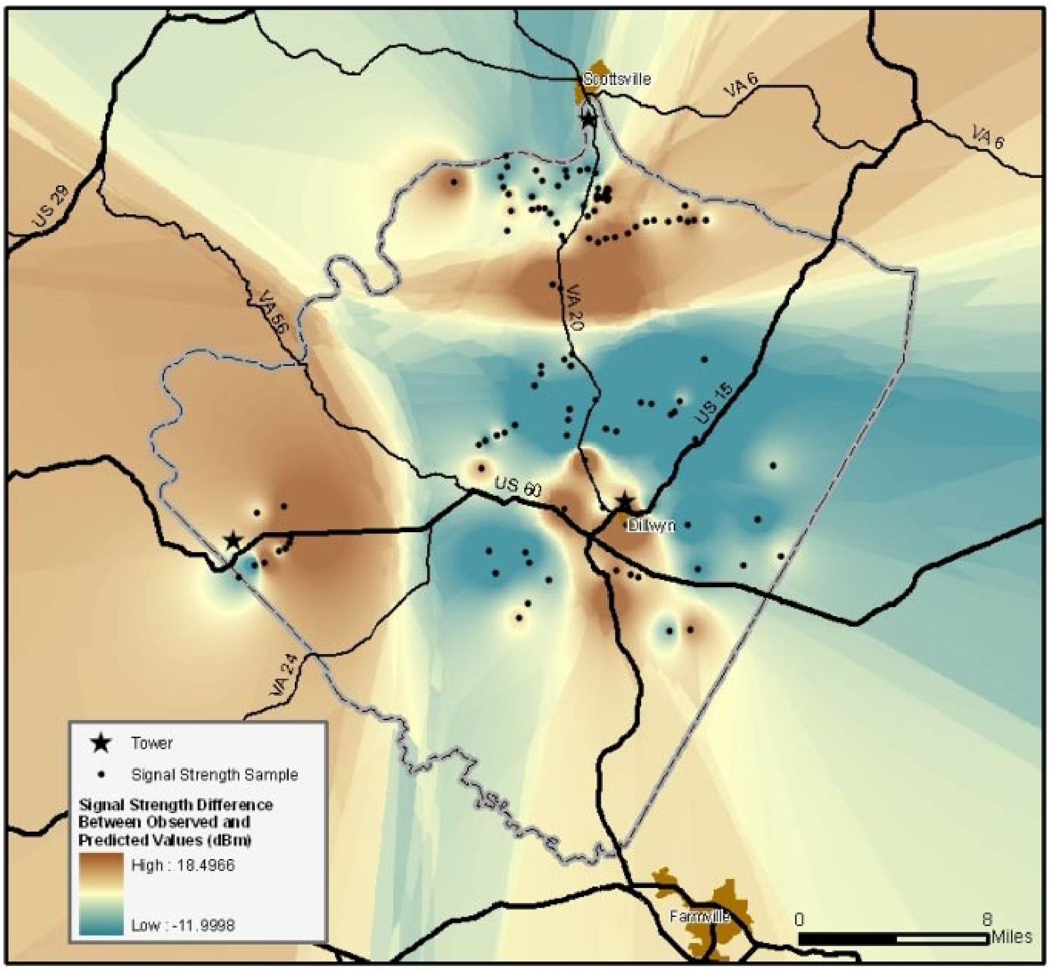

Figure 4.16 Interpolated Spatial Distribution of Signal Strength Loss

To the north of Dillwyn, there was a large area which showed the greatest signal strength loss in the county. From knowledge of the county, it was known that the area of interest north of Dillwyn had a significant tree farm consisting of mainly evergreen trees. Overall, the patterns found in Figure 4.15 also appeared in Figure 4.16 with one considerable difference. The area which showed the greatest improvement in signal strength from the predicted strength, south of Scottsville, was not one of the areas with the strongest signal strengths. This could have been a result of the distribution of reference signal strength points around the Scottsville tower being mostly towards the north. North of the tower was the James River valley and the town of Scottsville. Several of the reference samples were taken in or around Scottsville where buildings and other manmade objects could have negatively interfered with the signal.

Determination of Clutter Values

The goal of the study was to develop clutter loss values for deciduous and evergreen trees which could be applied to propagation modeling using the NLCD. Each clutter loss value was negative indicating that the model over-predicted the signal strength at the location and therefore the signal strength needed to be weakened to better represent the actual signal strength found at the location (Table 4.9). Two sets of values were given. The first set of values were calculated using both positive and negative signal strength differences, while the second set of values were calculated using only the negative differences. For instance, the average loss using all values for the evergreen land cover was -1.40 dBm, which meant that on average the model over-predicted the received signal strength at a location by 1.40 dBm. If the model calculated signal strength was decreased by 1.40 dBm, then on average the predicted signal strength would equal the observed signal strength in the field.

Table 4.9 Clutter Loss Values for Deciduous and Evergreen Land Covers

Land Cover	Average Loss (dBm) using All Values	Average Loss (dBm) using Only Negative Values
Deciduous	-1.18	-3.95
Evergreen	-1.40	-6.25

CHAPTER V

DISCUSSION

Results

This study showed that there is a statistically significant difference between fall and winter with respect to the magnitude of attenuation. More specifically, the study showed that the difference for deciduous trees is more pronounced than the difference of evergreens since evergreen trees do not lose their leaves during the winter. It was determined there is no distinguishable pattern between the distance from the tower and the magnitude of attenuation of open areas and deciduous trees. There is, however, a weak negative correlation between the magnitude of attenuation of evergreen trees and distance. When considering all three towers, there is no statistically significant difference between the land cover classes when all values (positive and negative) are used. When only negative signal strength differences are used, there is a statistically significant difference between evergreens and the other two classes. The tower in Gladstone was determined to have different results with respect to the magnitude of attenuation than the Dillwyn and Scottsville towers. This was evident as there was a statistically significant difference found for the evergreen samples whereas with all three towers there was no statistically significant difference. Lastly, clutter loss values for deciduous and evergreens were determined based upon the average difference between the observed and predicted signal strength values.

Conclusions

In the end, this empirical study showed that the prior literature can be applied to this type of research, but this technique had its limitations which need to be considered at the beginning. The work completed in this study was not designed to be the end, but rather the start of a more intense study which takes the lessons learned from this study, making the necessary changes, and putting them into affect. Prior work has underscored the difficulty in producing correction factors for vegetation, and this study only supports the need for further research in this area. The clutter values determined in this study can be used to make corrections to the existing models to account for attenuation due to vegetation, specifically deciduous and evergreen trees.

The propagation models used today are better than those used in the past; however, all models depend on accurate representations of reality. Studies conducted on the effects of vegetation and man-made objects like this study will continue to be important to provide more accurate corrections for the models. These models with their corrections will be used to predict the signal strength attenuation in cities, towns, and rural areas. An entire industry and its large customer base rely on such improvements to aid in critical decision making with respect to locations for new towers or adjustments to existing infrastructure. Cellular telecommunications is ever changing and there will always be research which leads to improvements in the infrastructure, placement of towers, and transmitting equipment.

Implications for Future Research

The data obtained from the FCC was not in a format which could easily be used for the study. Although there were methods which would allow the data to be used in the study after conversion, the data were deemed to be inaccurate or outdated, because all attempts to verify the origin of the data were unsuccessful. Given that the foundation for the original methodology was based upon the FCC data, changes had to be made to successfully complete the study. What was once believed to be a small oversight, actually resulted in a complete change in methodology and additional field work. For any additional work, specific data about the towers to include height, number, and direction of antennas, antenna gain, type of wiring used on the tower, and the transmitting power would need to be determined with a high level of confidence in the accuracy. Although there have been estimation methods developed, those methods would always fall short of the actual specifications of the towers. Gathering this data would be difficult because the cellular providers consider the information proprietary. Possible coordination with the FCC and Federal Aviation Administration (FAA) may provide a way to obtain the data.

Any empirical study requires large numbers of samples to provide accurate results, therefore; future studies should develop the sampling methodology with both quality and quantity in mind. Additional towers on or near the study area boundary should also be examined as they could impact the study area. The more towers included in the study allows for larger study areas which can accommodate larger sample sizes, and therefore better and more accurate studies will occur. Sampling distributions stopped at the county line unlike radio waves. Future work should have sampling methodologies which span the entire study area that covers all network antennas independent of political borders.

A possible approach for future research could follow the methodology used in the rainforests of India by Tewari et al. (1990). This research utilized a transmitting tower which was put into place exclusively for the purposes of the study. The advantage of this approach allows the investigators to obtain all the pertinent information about the transmitting antennas and their surrounding vegetation, which increases the accuracy of prediction. The limitations presented by using existing infrastructure would be eliminated using this method; however, an additional limitation is produced. The results will not be as realistic as those produced using the existing infrastructure because there will not necessarily been any consideration of coverage for wireless telecommunication customers. The purpose of such studies is to make the propagation modeling more accurate so that wireless coverage can be improved. This is why the research should consider realistic situations as best as possible.

Future research needs to be done to incorporate additional NLCD classes beyond the deciduous and evergreen classifications. The vegetation classes will need to be studied in areas which have large continuous areas of each type of vegetation to allow for a large sample size in each. Additionally, the study areas need to be distributed throughout the entire study area as to provide a variety of distances from the towers to account for the radio waves travelling through vegetation at differing angles and consequently different lengths through the vegetation. The developed classes will need the same level of attention as the vegetation classes. It is important to note that a study area which contains multiple land classes may not be the best area for this type of study. For instance, if an area possesses a considerable amount of buildings and deciduous forests another study area should be selected. This would remove the opportunity for the buildings to impact the attenuation due to deciduous trees and vice versa.

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