PROPAGATION ANALYSIS OF A 900 MHZ SPREAD SPECTRUM CENTRALIZED TRAFFIC SIGNAL CONTROL SYSTEM

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The objective of this research is to investigate different propagation models to determine if specified models accurately predict received signal levels for short path 900 MHz spread spectrum radio systems. The City of Denton, Texas provided data and physical facilities used in the course of this study. The literature review indicates that propagation models have not been studied specifically for short path spread spectrum radio systems. This work should provide guidelines and be a useful example for planning and implementing such radio systems. The propagation model involves the following considerations: analysis of intervening terrain, path length, and fixed system gains and losses.

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CHAPTER 1

INTRODUCTION

The City of Denton Traffic Department is using dial-up connections to communicate with various traffic control signals throughout the city. The dial-up connections have several problems, one of which is speed. It can take up to five minutes to download information from a single controller. In order to improve communications with signal controllers at various intersections, the City of Denton Traffic Department has committed to implementing centralized control of traffic signals using microwave point-to-point spread spectrum digital radio links.

Impact of Traffic Signal Control

Traffic control signal timing has significant impact on the lives of North Texans. Reports by local media have detailed how the North Texas air quality suffers from excessive automobile exhaust emissions. The longer a vehicle is on the road, the more emissions are released into the air. [1] Traffic control signals not properly timed and synchronized contribute to longer drive times. It is common knowledge among traffic engineers that if a traffic light stays red for too long, motorists will proceed through the red signal. Conversely, if the signal does not stay green long enough, motorists tend to continue through the intersection after the signal has turned red. Both situations reduce motorist safety at intersections, defeating the signal purpose. [1]

The City of Denton plans to install a master signal controller to improve traffic signal control that will be linked via radio from a central location to a signal controller at each designated intersection. This master controller is currently linked to remote sites using leased telephone lines. [2] Timing of signals at local intersections is contained within the local controller. Several timing plans are typically programmed in each controller; each timing plan is triggered by a time of day schedule. Local controllers, if properly equipped, can gather and report traffic statistics. The master controller is used to monitor local intersection controllers and provide coordination between controllers at different intersections to promote traffic flow. [2] This capability is especially useful when unusual circumstances, such as an event that draws hundreds of people into an area (e.g. Denton State Fair), require signal-timing changes outside the normal time of day schedules. [2]

Proposed Centralized Signal Control System

The system, as described in the traffic study documents furnished by the City of Denton Traffic Department, consists of three zones. [3] Each zone, designated A, B, and C in the study, consists of a central radio repeater and a maximum of twelve individual radios, one radio located at each local traffic signal control. [3] The central repeater for each zone will communicate with the central traffic controller located at the Traffic Department office, 901 Texas Street, Denton, Texas. Traffic signal controllers at each designated intersection will communicate with the zone central repeater. [3] See Figure 1.

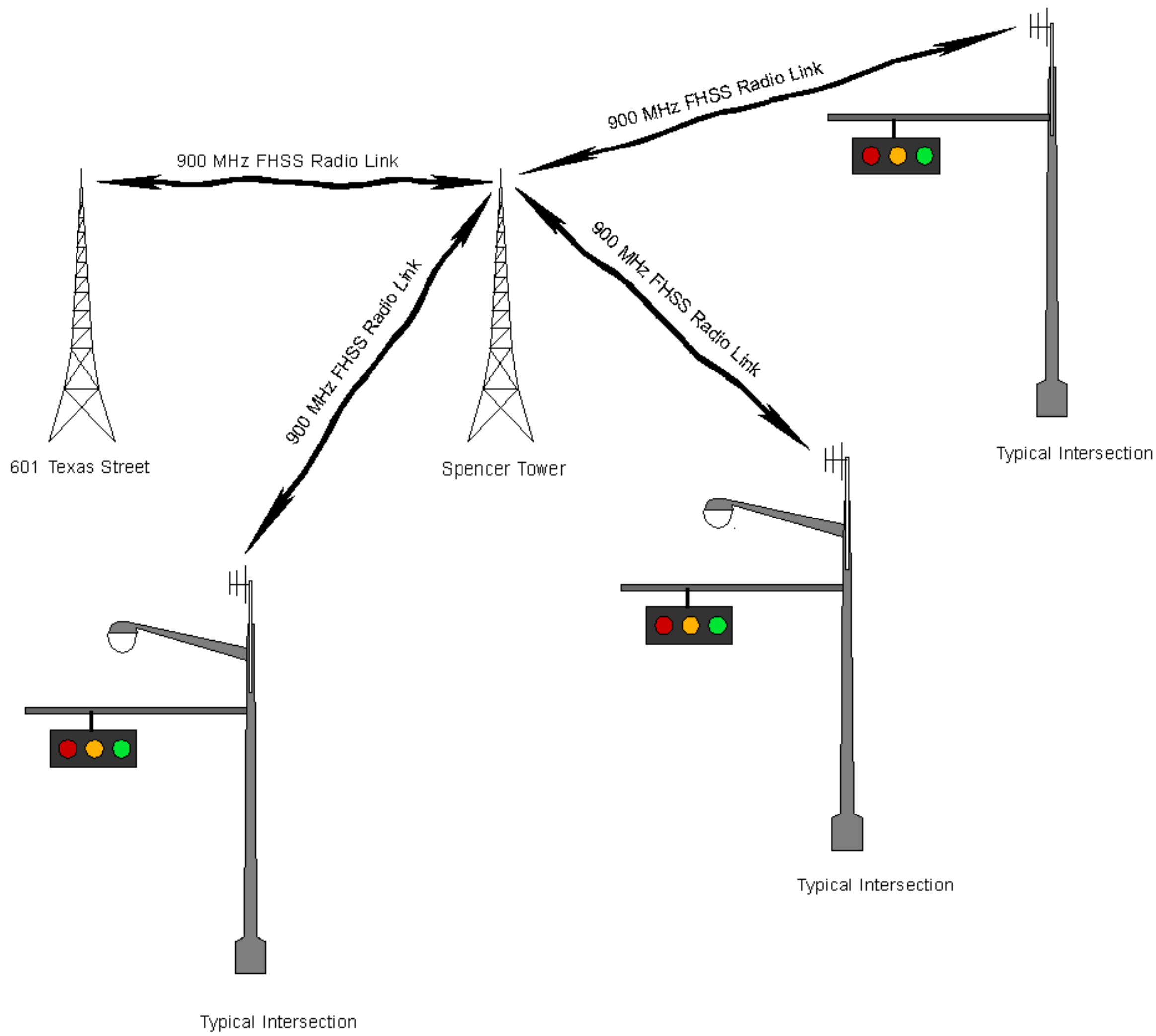


Figure 1. System Diagram

The entire system will operate using frequency hopping spread spectrum (FHSS) radios under Part 15 of the Federal Communications Commission (FCC) regulations in the 902 MHz to 928 MHz (herein after referred to as 900 MHz) frequency band. [3] Operation in this frequency band under Part 15 of the FCC rules exempts the radio system from licensing requirements, resulting in reduced paperwork requirements and the ability to quickly implement the system. Polling is the process of sending a request from a central controller to each station in the network. Each controller radio will have a unique identifier assigned, and will be polled by the zone repeater. [3] Only the polled station has authority to transmit over the network. Thus, only one radio will be transmitting at any given time. The system is configured to operate in half duplex mode; that is the master station transmits a query to a remote site and listens while the remote site transmits a response. A single "channel" is used for two-way communication. [3]

The system, as described in the traffic study, will transmit from the Texas Street facility to a tower repeater located at the power plant on Spencer Road (Spencer Tower). Spencer Tower will transmit to the individual controllers at "A" designated intersections. Other relay sites will be constructed as the system is expanded. The "A" intersections are: [3]

IH35E & Lillian Miller

Teasley & Hickory Creek

Teasley & Ryan

Lillian Miller & Teasley

Lillian Miller & Southridge

Lillian Miller & Southridge Village

Loop 288 & Mall Entrance

Loop 288 & Colorado

Loop 288 & Brinker

Loop 288 & Spencer

Loop 288 & Morse

Loop 288 & McKinney

Figure 2 presents a map showing the "A" sites.

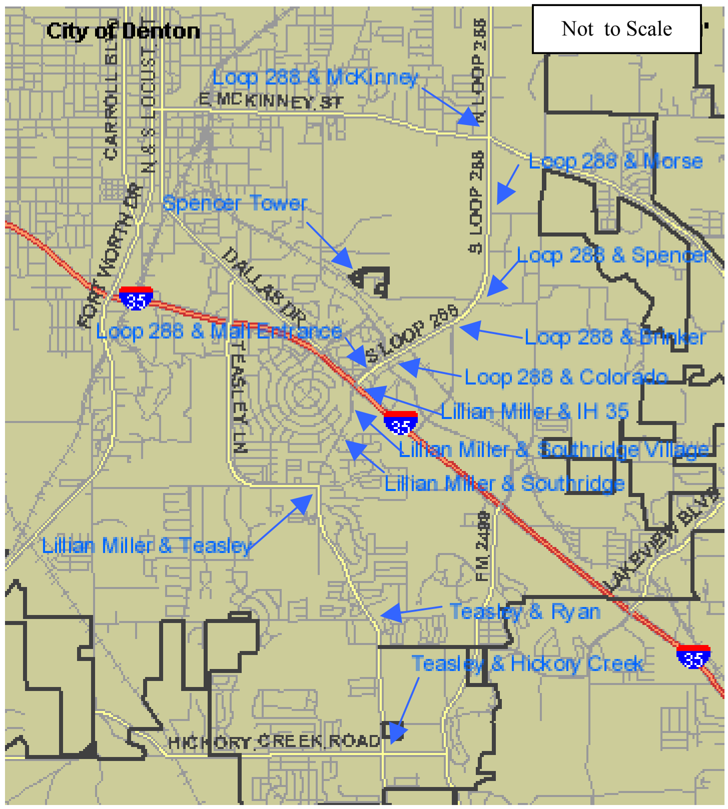


Figure 2. Map Showing "A" Sites

Object of the Research

The object of the research is to determine if the Hata radio propagation model is suitable for predicting the RF link performance of a 900 MHz spread spectrum radio system.

Statement of the Problem

The problem addressed in this thesis is the quality of service of the 900 MHz spread spectrum radio system. RF strength of the radio signal must be maintained above a radio manufacturer specified level for proper reception of the data carried by the signal.

Research Question

The research question in this study is presented in terms of null (H_o) and alternative (H_a) hypotheses for signal strength prediction.

$$H_o : \mu_{Hata} = \mu_{RF}$$
$$H_a : \mu_{Hata} \neq \mu_{RF} \qquad (1.1)$$

where

μ_{Hata} is the RF signal strength predicted by the Hata model,

μ_{RF} is the measured RF signal strength.

Hypotheses

Null Hypothesis

There is no difference between the received field strength values predicted by the Hata model and measured received field strength values.

Alternative Hypothesis

There is a difference between the received field strength values predicted by the Hata model and measured received field strength values.

Significance of the Research

Most point-to-point microwave link propagation analysis is performed using Longley-Rice modeling. Links modeled using Longley-Rice usually traverse open (rural) terrain and are longer than the links to be used by the City of Denton. This study proposes to investigate other propagation models in an effort to determine if another model is better suited for use in digital radio applications where link distances are short, less than 8 km (5 miles), and over developed (urban or suburban) terrain. Specifically, the Hata propagation model will be studied to determine if it accurately predicts received signal strength in 900 MHz spread spectrum radio applications.

Assumptions

The following assumptions are made for purposes of this study:

- Terrain data obtained from 7.5-minute United States Geological Survey topographic maps is accurate.
- Frequency hopping Spread Spectrum (FHSS) can be modeled as if it were a conventional single channel radio system.
- Site dimension data given in the CES traffic study is accurate.
- The MDS 9810 radio system has built-in metering functions for signal integrity and quality. These metering functions provide sufficient accuracy to determine link performance.
- The accuracy of the Magellan GPS 300 receiver is given as 49 feet (15 meters) RMS without selective availability.
- Earth curvature is not considered to be a significant factor.

Limitations

The following limitations are placed on this study:

- Only the intersections designated as “A” will be examined.
- Data is limited to initial readings taken when sites were constructed
- Resources are limited to those materials available through the University of North Texas libraries, credible Internet sources (e.g. FCC) and the author’s personal library.

Definitions

Frequency Hopping Spread Spectrum (FHSS). A transmission method in which a modulated signal is subjected to pseudorandom frequency shifts.

dB. Logarithmic measure of power. Mathematically $10 \log_{10} (power_2/power_1)$

Expected Outcomes

Propagation modeling will provide valuable information in predicting the operating parameters of the RF segment of the 900 MHz spread spectrum radio system. It is expected that the information gathered in this study will assist in determining suitable propagation models for spread spectrum radio systems.

Summary

This study focuses on problems associated with configuring and monitoring traffic signal controls at intersections in the City of Denton, Texas. The City currently employs leased telephone lines to communicate with traffic signal controllers. Ongoing expense and slow data transfer have been cited as reasons for seeking alternative communications strategies. The City has committed to communicating with traffic signal controllers at various intersections using 900 MHz unlicensed spread spectrum radios. The City is searching for a way to predict radio link performance prior to constructing a specific link. This study is undertaken to provide the City of Denton with a method of predicting link performance using computer methods that have proven to be accurate when compared to measured data.

CHAPTER 2

RADIO FREQUENCY PROPAGATION MODELS AND METHODS

A review of literature reveals there are at least eleven different models used in propagation analysis of radio waves. Models examined for this study are the Okumura, Carey, Damelin, Bullington, Epstein-Peterson, Joint Radio Committed, Allsbrook, Lee, COST-231 Longeley-Rice, and Hata. Radio wave propagation is analogous to light propagation, i.e. subject to diffraction, reflection, diffusion, and reflection. [4] Scattering occurs when radio waves encounter objects, which are small compared to the wavelength being studied, and when the number of objects per unit volume is large. [4]

A significant issue in planning and implementing a radio system is signal strength and its fluctuations at each system receive point. Accurate prediction of the propagation environment on the signal is essential in the development and design of a communications system. [5] Current methods of propagation prediction, while relatively simple, do not adequately address all propagation prediction factors. [5] Signal levels can be obtained by direct field measurement, usually at great cost. [4] Computer modeling is used to predict signal strength, coverage area, and potential interference problems. Propagation prediction algorithms usually return an average signal strength value at a given distance from the transmitter. [4]

There are two basic methods of modeling: statistical analysis, and direct analytical resolution of direct signal paths through ray tracing methods. Theoretical, empirical, and semi-empirical models are used in propagation prediction. [4] Empirical models are based on mean values and simple relationships between attenuation factors and distance from the transmitter to receiver. Empirical models usually include all factors that affect propagation. The model must be calibrated and validated for each environment in which it is used. [4] Theoretical models do not take into account all factors affecting propagation and require the use of complex terrain databases. Semi-empirical models combine approaches from both methods. [4]

Some models, such as the Okumura or Hata, take terrain roughness and structural type and density into account. Other models, Carey being one, use terrain averaging and statistical methods to predict areas covered by a signal. [4] Typically, statistical models use the antenna Height Above Average Terrain (HAAT) and the transmitter Effective Radiated Power (ERP). Terrain averages are determined over 3 to 16-kilometer radial segments projecting from the transmitter site. Consideration is not given to local terrain, which may block a line of site path between the transmitter and a given receiver location. [4]

Work by Qin Zhou proposed propagation prediction using neural network models to overcome the disadvantages of both theoretical and empirical models. Zhou's model uses multilayer feed forward neural networks and counter propagation networks with learning algorithms to model radio propagation in both indoor and outdoor environments. [6] Casciato proposed that electromagnetic wave theory would result in propagation models, which are both accurate and more generally applicable than existing models, especially Longley-Rice or Okumura. [7]

Analytical models such as Longley-Rice take into account scattering effects such as terrain roughness or individual obstructions in the path. Man made structures, street and building layout and environmental conditions are also addressed in some models. A list of models investigated for this study consists of models contained in Parts 22 and 73 of the FCC rules (Carey and Damelin et. al. respectively), Bullington, Okumura, Longley-Rice, Hata, Epstein-Peterson, Joint Radio Committed, Allsbrook, Lee, and COST-231.

Basic Propagation Theory

All radio propagation models studied are based on free space propagation principles. Received signal strength, *s*, in free space from an isotropic radiator at a given distance *r* is: [8]

$$s = \frac{P_T}{4\pi r^2} \text{ Watts Per Square Meter} \qquad (2.1)$$

where

$s =$ received signal strength
$P_T =$ transmitter power
$r =$ distance from antenna to measurement point

An isotropic radiator is a theoretical antenna, or point source, that radiates equally in all directions as shown in Figure 3. [4] A signal referenced to an isotropic radiator is given in dBi.

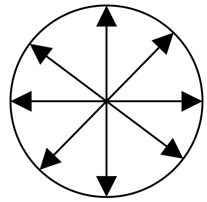


Figure 3. Depiction of an Isotropic Radiator

A receiving antenna placed at distance *r* with an effective aperture or receiving area of A_R (square meters) would intercept a signal at a level defined as: [8]

$$P_R = \frac{P_T A_R}{4\pi r^2} \text{ Watts} \tag{2.2}$$

where

$P_R =$ received power
$A_R =$ effective aperture of receiving antenna

Thus the received power is proportional to the receiving antenna area and transmitted power, and inversely proportional to the square of the distance between the respective antennas. [8] Practical antennas and particularly the antennas used in this application, have a characteristic gain over an isotropic radiator. An antenna that is highly directional radiates a strong signal in one direction and reduced signals in all other directions. The design of the antenna re-directs the energy in the desired direction. When the antenna gain over an isotropic radiator is factored into the signal strength equation, it takes the form: [8]

$$P_R = \frac{P_T G_T A_R}{4\pi r^2} \text{ Watts} \tag{2.3}$$

where

$P_T =$ transmitter power
$G_T =$ transmitting antenna gain

The gain of the non-isotropic receiving antenna is related to its aperture by

$$G = \frac{4\pi A}{\lambda^2} \quad (2.4)$$

where

$G =$ antenna gain
$A =$ antenna aperture
$\lambda =$ wavelength

and thus received power for non-isotropic systems becomes

$$P_R = \frac{P_T G_T G_R \lambda^2}{16\pi^2 r^2} \quad (2.5)$$

where

$P_R =$ received power
$G_R =$ receiving antenna gain

A is defined as the effective aperture of the receiving antenna and λ is the wavelength being studied. [8]

Radio Path Signal Strength Budgets

When designing a radio system, a link budget must be prepared which contains all RF system gains and losses. System gains are transmitter output power, transmit antenna gain, and receiving antenna gain. [4] Antenna gain is typically specified in dB relative to an isotropic radiator (dBi) or to a half-wave ($\lambda/2$) dipole (dBd). Transmitter power is usually given in watts, which for a link budget calculation, must be converted to dB by the equation: [4]

$$dB = 10\log\frac{P_2}{P_1} \tag{2.6}$$

where

$P_1 =$ reference power level
$P_2 =$ device power level

P_1 may be expressed in watts, in which case the transmitter gain is dBw, or milliwatts, expressed as dBm.

Losses in the link budget are transmission line loss in dB per foot, connector losses and any losses associated with filters, diplexers, attenuators or other devices that may be present in the system. Propagation path loss is also in the link budget, and this is the one parameter over which the system designer has the least control, as path loss is dependant on various terrain factors. A link budget calculation sums the gains and losses in dB such that: [4]

$$P_R = P_T - L_T + G_T - A_P + G_R - L_R \tag{2.7}$$

where

P_R = Received power
P_T = Transmitter output power
L_T = Losses between transmitter and antenna
G_T = Transmit antenna gain
G_R = Receive antenna gain
L_R = Losses between receive antenna and receiver
A_P = Propagation path loss

This study focuses on A_P and its effects on the system being implemented by the City of Denton Traffic Department.

Signal Strength Losses in RF Propagation

System losses are typically classified in three major categories: path loss or distance loss, attenuation from shadowing by objects in the propagation path, and fading caused by multipath propagation. [4] Other factors that can affect signal quality are co-channel, or adjacent channel interference, and ambient noise. [4] There are also effects introduced into propagation analysis by five major environmental factors: terrain morphology, vegetation density, building height and density, open areas, and water surfaces. [8] Four environmental classes, shown in Table1 below, have been defined based on the five environmental factors. [4]

Environment Type	Description
Dense Urban	A central business area that consists of many high, close buildings, made of concrete, glass, or iron. They are usually more than 12 floors high and composed of structures such as financial institution offices, public administrations, and private accommodation
Urban	Business and residential area consisting of several very close, concrete buildings. They are about 10 to 15 floors high
Suburban	Decentralized business area with residential housing and buildings of 2 to 5 floors made of brick, iron , and concrete
Rural	Business and residential population spread over open areas with significant vegetation and man-made structures.

Table 1. Propagation Environments

A ground occupation rate (GOR) can be derived from the above five environmental classifications. The GOR defines the ratio between the area covered by buildings, and the total land area. GOR ratios are GOR > 1 for urban environments, 0.4 for suburban environments, and GOR < 1 for rural environments. [4]

Most signal attenuation losses are due to shadowing effects caused by human made or natural obstacles. Path attenuation increases as the number of obstacles also increases. [4] There are no obstacles in the direct ray path between the transmitting and receiving antennas in line-of-sight (LOS) paths, as shown in Figure 4. Non-line-of-sight (NLOS) paths have at least one obstacle that blocks the direct ray path (Figure 5).

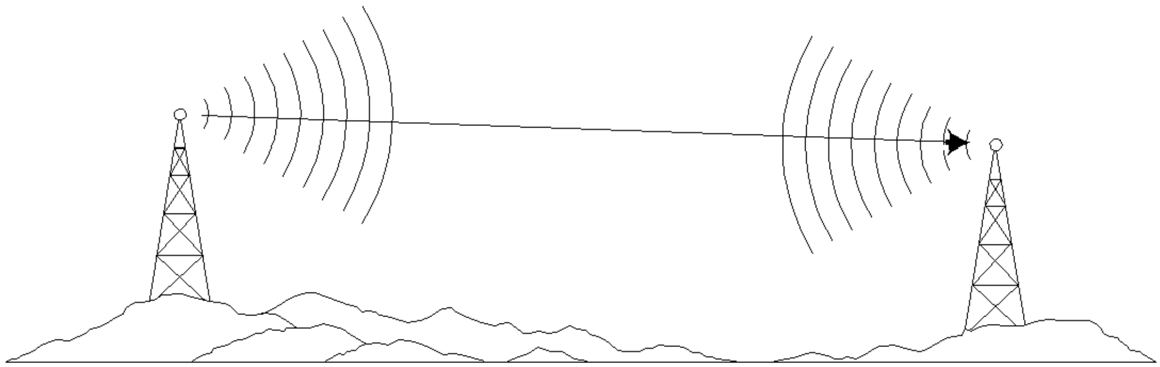


Figure 4. Line of Sight Path

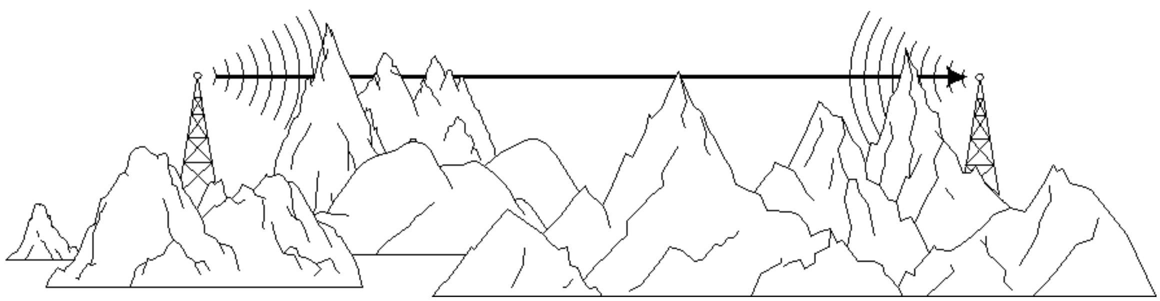


Figure 5. Non Line of Sight Path

Masking or shadowing can lead to slow fading due to time, space, and environmental variations. Shadowing is modeled using a lognormal law whose values, when expressed in dB, become normal law values. [4] Thus the probability (P) that the attenuation, A_s dB, will be greater than or equal to x dB is given by

$$P(A_s \geq x) = \frac{1}{\sigma\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{\mu^2}{2\sigma^2}} \tag{2.8}$$

where

$P =$ probability
$A_s =$ attenuation
$\mu =$ mean value of data
$\sigma =$ standard deviation

σ is usually assumed to be 6 dB for urban environments. [8]

Vegetation, especially trees, is a significant source of attenuation in rural environments. In urban environments where the number of trees is usually low, their effect is negligible. Height, shape, mass, time of year, and ambient humidity are factors in determining attenuation caused by trees. Many authors have studied these effects. The formula for vegetative attenuation proposed by Weissberger is given (without citation) as: [4]

$$L = 1.33 F^{0.284} d_f^{.0598} \text{ for } 14 \le d_f 400\text{m} \tag{2.9}$$

Or

$$L = 10.45 F^{.0248} d_f \text{ for } 0 \le d_f 14\text{m} \tag{2.10}$$

$L =$ calculated loss in dB
$F =$ frequency in GHz
$d_f =$ path length through vegetation (meters)

A factor of 10 dB is usually added to the loss to account for the difference in trees with leaves and trees without leaves. Weissberger's formula is valid for frequencies from 230 MHz to 95 GHz. [4]

Fresnel Zones Effects on Signal Strength

Fresnel zones are defined as a series of ellipsoids whose foci are transmit and receive antennas. [5] Within each Fresnel zone, all rays of RF radiation propagate with the same phase. The phase between adjacent Fresnel zones is reversed; thus, a ray propagated from the second Fresnel zone arriving at the antenna will cancel a ray propagated from the first Fresnel zone. [5] The size of each Fresnel zone is dependant upon the distance from each antenna; they are largest at the path midpoint and smallest at the ends of the path. Path length through each zone is $n\frac{\lambda}{2}$ longer than the direct path where n takes on an integer value = 2,3,4 . . . Fresnel zone clearance heights are calculated using the equation

$$h_{n=}\sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \tag{2.11}$$

h_n = height of Fresnel zone n
n = Fresnel zone number(2, 3, 4, . . .)
d_1 = distance from antenna 1 to measurement point
d_2 = distance from antenna 2 to measurement point

d_1 and d_2 are the respective distances between antenna 1, antenna 2 and the point of interest as shown in Figure 6. [5]

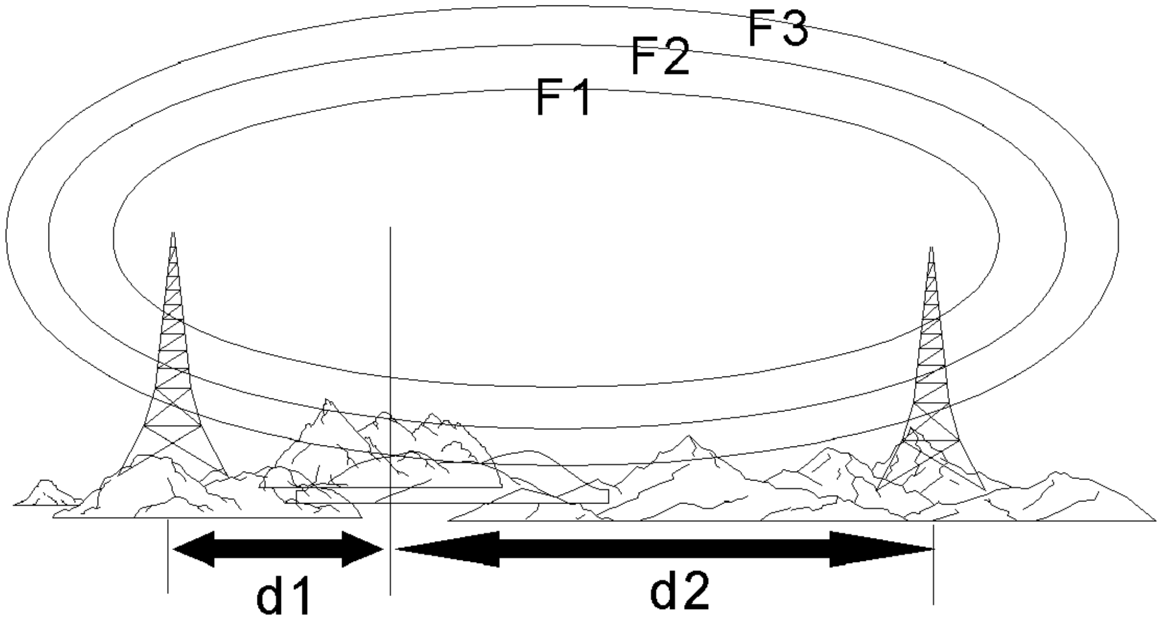


Figure 6. Fresnel Zone Calculation

The first Fresnel zone, in practice, must be kept substantially clear of obstructions if free space propagation conditions are to be met. If an obstruction extends into the second or third Fresnel zones, the received signal strength will tend to oscillate, as the reflected signal from the obstacle is out of phase between adjacent Fresnel zones. A value of 60% clearance in the first Fresnel zone is acceptable for point-to point-links. [5]

Radio waves will be reflected or absorbed by obstacles in their paths. In an urban area, reflected waves are more numerous than in largely rural areas due to the larger number of reflecting surfaces (buildings) in the urban area. [4] Reflected waves lead to multipath. Multipath can allow non-line-of-sight propagation or can impair reception of the signal through Rayleigh (fast) fading, or random frequency modulation due to Doppler shift. [4] Rayleigh fading and Doppler shift effects are more noticeable in mobile applications and usually are not significant in point-to-point service.

Okumura's Radio Propagation Prediction Model

Okamura developed a fully empirical model from a series of measurements made in and around Tokyo at frequencies up to 1920 MHz. Curves were generated from the measurements with factors such as terrain irregularities, antenna height and environment taken into considerations. Thus, the model contains a series of correction factors, which make it possible to associate the model to the propagation environment of the actual path under study. [9] Okumura's original equation is: [9]

$$L_{50} = L_{FS} + A_{RU}(f,d) + H_{Tu}(h_T,d) + H_{Ru}(h_R,d) \tag{2.12}$$

where

$L_{FS} =$ free space loss

$A_{Ru}(f,d) =$ average attenuation relative to free space over quasi-smooth terrian in an urban environment

$h_T =$ transmit antenna height (200 m reference)

$h_R =$ receive antenna height (3 m reference)

$H_{Tu} =$ transmit antenna gain

$H_{Ru} =$ receive antenna gain

Correction factors, which may be positive or negative, are used when the antenna heights are varied from the reference values given in the equation. Corrections such as terrain, vegetation, and mixed land-sea paths, are included in supplemental equations in the Okumura model. The result of these calculations is a series of curves, as shown in Figure 7, which are used to predict coverage. The Okumura model was not chosen for this study, as a series of curves that must be interpreted is not suited for computer analysis. [9]

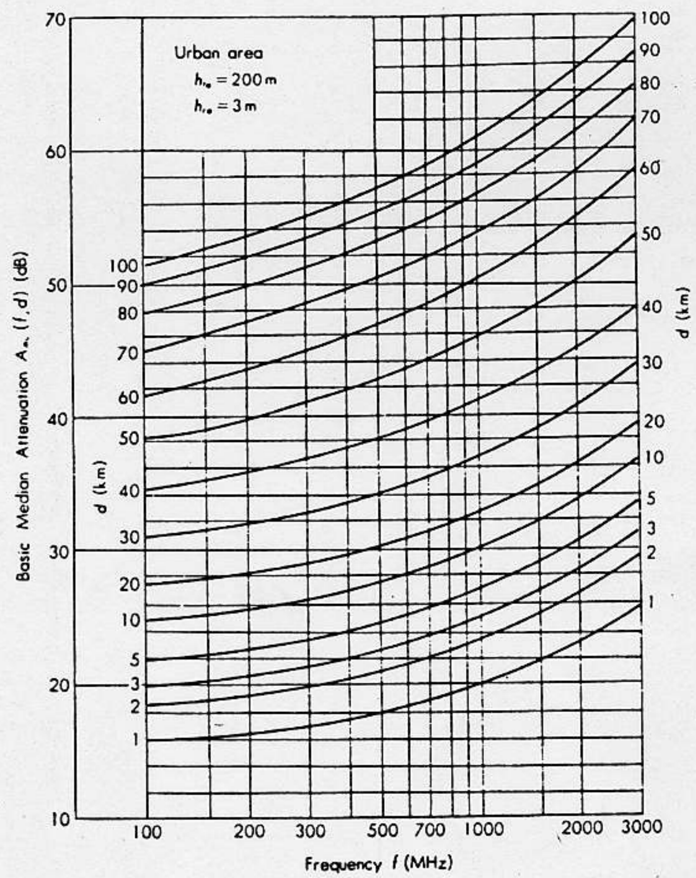


Figure 1. Prediction curve for basic median attenuation relative to free space in urban area over quasi-smooth terrain, referred to h_{te} = 200 m, h_{re} = 3 m. From Okumura et al. (1968).

Figure 7. Okumura Propagation Prediction Graph

Carey's Radio Propagation Prediction Model

Section 22 of the FCC Rules define the Carey model of propagation prediction. This model uses antenna height above average terrain (HAAT) to determine the limits of propagation. The FCC requires that average terrain elevation be calculated by computer using elevations from a 30-second point or better topographic data file. In cases of dispute, average terrain elevation determinations can also be done manually, if the results differ significantly from the computer-derived averages. [10] Radial average terrain elevation is calculated as the average of the elevation along a straight-line path from 3 to 16 kilometers (2 to 10 miles) extending radially from the antenna site. Average terrain elevation is the average of the eight radial average terrain elevations (for the eight cardinal radials). [10]

Once HAAT has been determined, various propagation prediction methods are used, depending on the specific radio service being studied.

Section 22.537 details the model for paging transmitters, both as an equation, and as a set of tables. Equations are used to predict VHF propagation, while tables are used for services operating at 931 MHz.

For base stations transmitting on VHF channels, the radial distance from the transmitting antenna to the service contour along each cardinal radial is calculated as follows:

$$d = 1.243 h^{0.40} p^{0.20} \tag{2.13}$$

where

d = radial distance in kilometers
h = radial antenna HAAT in meters d is the radial distance in kilometers
p = radial ERP in watts

(1) Whenever the actual HAAT is less than 30 meters (98 feet), 30 must be used as the value for h in the above formula.

(2) The value used for p in the above formula must not be less than 27 dB less than the maximum ERP in any direction, or 0.1 Watt, whichever is more.

The distance from the transmitting antenna to the service contour along any radial other than the eight cardinal radials is routinely calculated by linear interpolation of distance as a function of angle. [11]

Cellular services are addressed in Section 22.911. The predicted service contour is defined as follows: The distance to the Service Area Boundary (SAB) is calculated as a function of effective radiated power (ERP) and antenna center of radiation height above average terrain (HAAT), height above sea level (HASL) or height above mean sea level (HAMSL). The distance from a cell transmitting antenna to its SAB along each cardinal radial is calculated as follows: [12]

$$d = 2.53h^{0.34}p^{0.17} \tag{2.14}$$

where:

d = radial distance in kilometers
h = radial antenna HAAT in meters
p = radial ERP in watts

Carey's model, as outlined in Section 22 of the FCC rules, uses the height above average terrain over a three to 16 kilometer segment of the eight cardinal radials to predict received field strength. For point-to-point paths, especially short paths such as those contained in this study, the Carey model is not suitable as terrain averaging is used over a 3 to 16 kilometer segment.

Damelin's Radio Propagation Prediction Model

Damelin's propagation prediction model, like Carey's, uses the eight cardinal radials over a three to sixteen kilometer segment to determine antenna height above average terrain (HAAT). Terrain data is to be extracted from topographic maps or other means such as United States Geological Survey Topographic Quadrangle Maps, United States Army Corps of Engineers Maps or Tennessee Valley Authority maps, whichever is the latest, for all areas for which such maps are available. If such maps are not published for the area in question, the next best topographic information should be used. [13] A digital terrain database may also be used to obtain antenna height above average terrain. The height above mean sea level of the antenna site must be obtained manually using appropriate topographic maps. [13]

Once the HAAT has been determined, coverage predictions are made using the F(50,50) field strength chart, Figure 1 of § 73.333. Average terrain elevation is determined by drawing profile graphs for the eight cardinal radials over the 3 to 16 kilometer segment from the transmitter site. [14] Figure 1 of section 73.333 referred to in the above paragraph is reproduced as Figure 8 below.

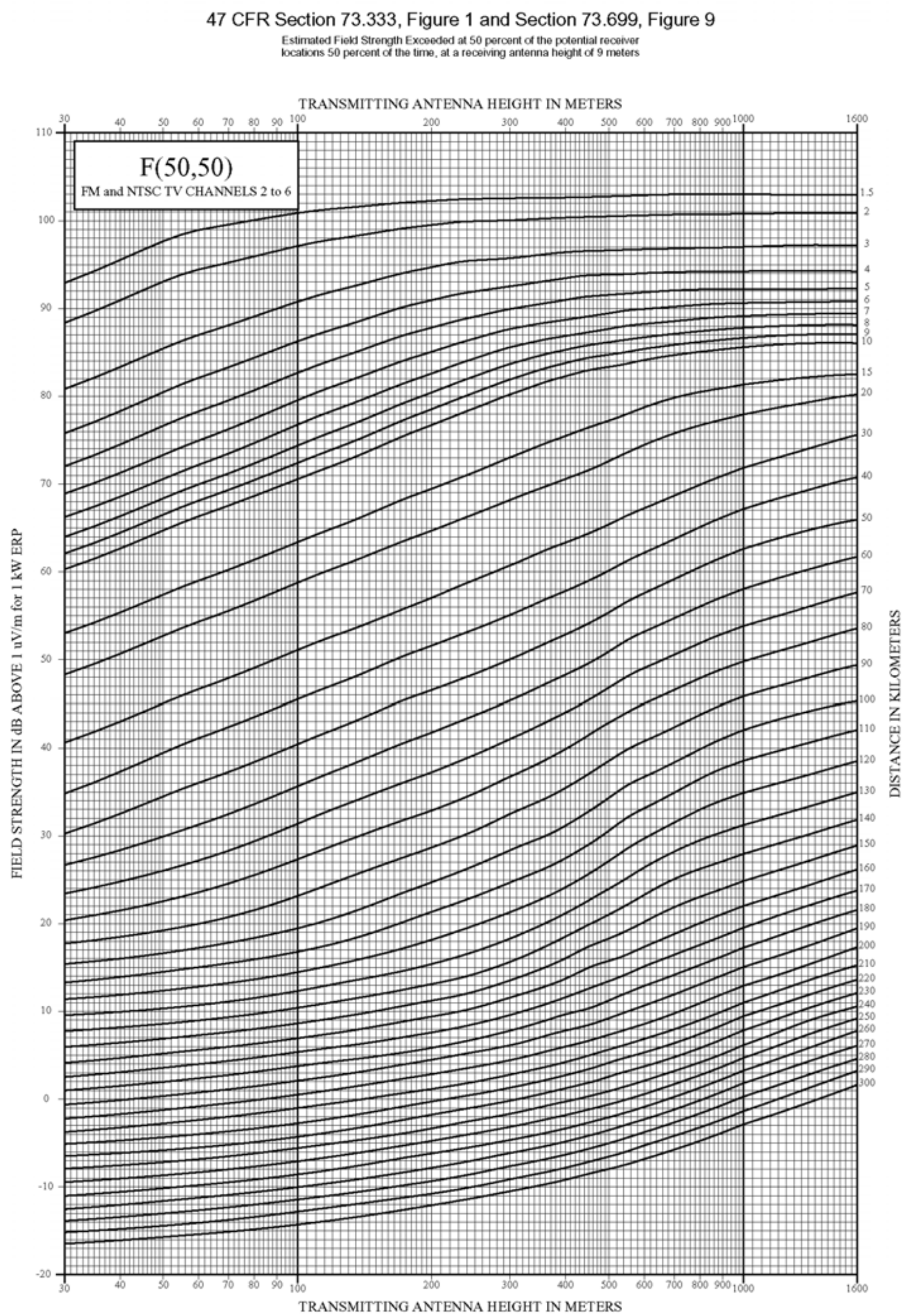


Figure 8. FCC Engineering Graph Used to Predict Received Signal Strength

As in the Carey model, Damelin uses HAAT as a predictor of received signal strength. The FCC uses the Damelin model for frequencies between 88 MHz and 108 MHz (FM broadcast band). Average terrain elevation is calculated over a three to sixteen kilometer segment. The Damelin model is not suitable for use in this study as it covers a narrow frequency band located 800 MHz in frequency from the band of interest and is designed for predicting coverage over a wide area.

Bullington's Radio Propagation Prediction Model

Bullington's model, in its original form, is a series of nomograms for solving VHF propagation problems. In addition to the smooth earth theory of propagation, an approximation method is included for estimating the effects of hills and other obstructions in the radio path. [15] Atmospheric effects such as ducting and absorption are discussed, but the principal purpose of the model is to provide simplified charts for predicting radio wave propagation under average weather conditions. [15] Bullington states that propagation over plane earth is given by

$$E = E_0[1 + \mathrm{Re}^{j\Delta} + (1-R)Ae^{j\Delta} + \ldots] \qquad (2.15)$$

where:
$1+$ = direct wave
$\mathrm{Re}^{j\Delta}$ = reflected wave
$(1-R)Ae^{j\Delta}$ = surface wave
$\ldots$ = unspecified induction field and secondary ground effects

Thus ground wave propagation is considered to be the sum of three principal waves; ground wave, reflected wave, and surface wave. [15] Surface wave importance is limited to one wavelength above ground over land, since for greater heights, direct and reflected waves predominate. [15]

Diffraction around earth curvature allows transmission beyond line of sight, but at the cost of additional loss. The amount of loss increases with frequency and/or distance. Bullington's Figures 5 and 6 provide nomographs for calculating loss over the horizon. The line of sight loss is 21 *db* down from the free space value, and decreases at a rate of approximately 0.8 *db* per mile beyond line of sight. [15]

Atmosphere adds another loss factor to the model. The dielectric constant of atmosphere is slightly greater than 1, and varies with pressure, temperature, and humidity. Changes in the dielectric constant can have significant effect on radio propagation. As the dielectric constant varies over the entire radio path, a series of assumptions is necessary to obtain an engineering solution. [15]

Loss due to knife-edge diffraction is given as 6 *db* at grazing incidence and increases as the obstruction protrudes further into the path. [15] This grazing factor evolves into Fresnel zone effects, requiring a clearance of 120 feet at the center of a 40 mile path at a frequency of 3000 MHz. [15] Effective clearance will vary with weather conditions on any given path. Adding a second knife-edge would add an additional 2 to 3 *db* of loss. [15]

Built up areas tend to increase attenuation as frequency increases. Most buildings are opaque to radio frequencies above 30 MHz, with losses as great as 40 *dB* observed. [15] At frequencies above 100 MHz, trees and other vegetation thick enough to block vision tend to completely block radio waves. [15]

Bullington addresses many factors discussed in basic propagation theory. These factors include atmosphere effects, obstructions in the propagation path, Fresnel zone clearance, building density and construction, and vegetation. As originally published, the model is a series of nomographs that are not suited to modern computer methods. In addition, Parsons and Gardiner state that because some intervening obstacles may be omitted from the calculations, Bullington's model tends to oversimplify the propagation path which can cause large errors. [16] Therefore, Bullington's model was not selected for investigation in this study.

Epstein-Peterson Diffraction Method

This model is briefly discussed in some sources. Epstein-Peterson calculates the propagation loss of multiple obstacles in the propagation path by adding the attenuation of each knife-edge in a series in succession. Analysis suggests that large errors can occur when two obstacles are closely spaced. [16] Epstein-Peterson was not considered for this study due to the potential for large errors.

Other knife-edge diffraction models include the Japanese Atlas method, Piquenard's method, and the Deygout method. Each of the above knife-edge diffraction models is useful over a specific region and under specific conditions. For example, Deygout gives good results over highly irregular terrain at the cost of high complexity of calculations. [16] These models were not examined due to the specific nature of, and complexity in using each model.

Joint Radio Committee Model

This model uses a computerized topographical database, which provides height reference points at 0.5 km intervals. [16] A computer program then constructs a path profile between the transmitter and receiver. A test is made for a line of sight path and Fresnel zone clearance. If the line of sight path and Fresnel zones are clear, the program calculates free space and plane earth losses and selects the higher loss value. [16] If the path is not true line of sight, or does not meet Fresnel zone clearance, path loss is calculated by evaluation losses caused by obstructions, separating them into single or multiple diffraction edges. [16] The JRC method does not take into account effects of buildings, and thus produces errors in built up areas. [16] This model was not selected for this study due to the complexity of providing a digital terrain database.

Allsebrooks Model

This model proposes a flat city prediction based on the formula for VHF: [16]

$$\text{Path Loss} = L_p + L_B \tag{2.16}$$

where

L_p = plane earth path loss
L_B = diffraction loss caused by buildings near receiver

For UHF frequencies, a correction factor, γ, is added to the formula. Allsebrook states that if the city is considered hilly, a modified version of the Blomquist and Ladell model should be used as given by: [16]

$$\text{Path Loss} = L_F + \left[\left(L_p - L_F\right)^2 + L_D^2\right]^{1/2} + \gamma \text{ dB} \tag{2.17}$$

where

L_F = free space path loss
L_p = plane earth path loss
L_D = diffraction loss over terrain obstacles

In other studies, there is a fourth order law range dependence of the path loss, which Allsebrook states is the excess loss above the plane earth loss caused by urban clutter factor, β. [16]

Lee's Model

Lee's model is based on a series of measurements made at 900 MHz. Lee states that the mean power measured at distance d is expressed as: [17]

$$P_d = P_0 \left(\frac{d}{d_0}\right)^{-\gamma} \left(\frac{f}{f_0}\right)^{-n} F_0 \tag{2.18}$$

or in logarithmic scale

$$P(d)_{dB} = (P_0)_{dB} - \gamma \log\left(\frac{d}{d_0}\right) - n \log\left(\frac{f}{f_0}\right) + (F_0)_{dB} \tag{2.19}$$

where

P_0 = reference median power at 1 km
F_0 = correction factors selected by

$$F_0 = \prod_{i=1}^{5} F_i \tag{2.20}$$

F_i are described as

$$F_2 = \left(\frac{\text{actual receive antenna height [m]}}{30.5\ \text{[m]}} \right)^v \tag{2.21}$$

$$F_1 = \left(\frac{\text{actual transmit antenna height [m]}}{30.5\ \text{[m]}} \right)^2 \tag{2.22}$$

where
$v = 1$ for antenna heights less than 3 meters
$v = 2$ for antenna heights greater than 10 meters

$$F_3 = \frac{\text{actual power}}{10\ \text{W}} \tag{2.23}$$

$$F_5 = \frac{\text{transmit anntenna gain with respect to } \tfrac{1}{2}\lambda \text{ dipole}}{4} \tag{2.24}$$

$$F_5 = \text{receive antenna gain with respect to } \tfrac{1}{2}\lambda \text{ dipole} \tag{2.25}$$

The factors P_0 and γ are selected experimentally based on performed measurements.

Examples of values for some characteristic environments are given in Table 2. [17]

Environment	P_0	$\gamma\left[dB/decade\right]$
Free space	-41	20
Open (rural area)	-40	43.5
Suburban, small city	-54	38.4
Philadelphia	-62.5	36.8
Newark	-55	43.1
Tokyo	-78	30.5

Table 2. Values of P_0 and γ for Selected Environments

The mean power loss is a function of frequency, modeled as factor $\left(f / f_o \right)^{-n}$.

n ranges between 2 and 3 for frequencies between 30 MHz and 2 Ghz and path lengths of 2 to 30 kilometers. [17] Factoring in topography n is set to 2 for suburban and rural areas at frequencies below 450 MHz, and $n = 3$ for urban environments at frequencies above 450 MHz. [17] Lee's model was not selected for this study due to the difficulty in determining proper environmental variables.

COST 231-Hata Model

The COST 231 model is an extension of the Okumura and Hata models optimized for frequencies from 1.5 GHz to 2 GHZ, transmit antenna heights between 30 m and 300 m, receive antenna heights of 1 m to 10 m, and distances from 1 kilometer to 20 kilometers. This model was developed as the Okumura and Hata models underestimate signal attenuation in the defined conditions. [17] The model is expressed as:

$$\begin{aligned} L_{(50)dB} &= 46.3 + 33.9 \log f - 13.82 \log\left(h_{BS,eff}\right) + \\ &- a\left(h_{MS}\right) + \left(44.9 - 6.55 \log\left(h_{bs,eff}\right)\right) \log d + C \end{aligned} \tag{2.26}$$

where

$C = 0$ for medium cities and suburban areas
$C = 3$ for large city centers

The model has several variations, restrictions and limitations. For example, the COST 231-Hata model is not suitable for estimating path loss for distances less that one kilometer as attenuation strongly depends on terrain topography over the path. [17] A variation of COST 231, the COST 231-Walfish-Ikegami model, is used when the transmit antenna is placed either above or below the roofline in an urban area. [17] COST 231 models were not selected for study due to frequency, height, and distance restrictions.

Longley-Rice Model

Longley-Rice is a computer-based model that was originally developed for use with low antennas in irregular terrain. [18] The model is based on propagation theory and has been compared to measured data for a wide range of frequencies, antenna heights, terrain types, and distances. The model adequately predicts the median attenuation for moderately large cities in rather smooth terrain as a function of distance. [18] If the terrain is not homogeneous, the computer model calculates attenuation from point to point for a large number of points along radials from the transmitter. A digitized terrain database is used to generate a radial profile. [18] As currently implemented, the Longley-Rice model has two modes: point to point and area prediction. [19] The point-to-point mode must provide details of the terrain profile that the area prediction mode will estimate using empirical medians. [19] Some parameters used in the model include: [19]

$d =$ distance between terminals
$h_{g1}, h_{g2} =$ antenna structure heights
$k =$ wave number of carrier, $k = 2\pi/\lambda = f/f_0, f_0 = 47.7 MHz \cdot m$
$\Delta h =$ terrain irregularity parameter
$N_s =$ mean surface refractivity
$\gamma_e =$ earth effective curvature
$Z_g =$ surface transfer impedance of ground
radio climate = qualitative number from a descrete type of climate

The area prediction and point-to-point modes have different input requirements, but both modes use the same general set of equations. Output can be user selected and range from a simple reference attenuation, A_{ref}, to two or three-dimensional cumulative distribution of attenuation, $A\left(q_T, q_L, q_s\right)$, with time, location and situation variability accounted for. [19]

Although Fortran source code for the Longley-Rice model is available from the United States Department of Commerce, it was not selected for this study due to complexity of implementation and the requirement of a digital terrain database.

Hata Model

The Hata model is an empirical formulation of the graphical path loss data provided by Okumura. The model is valid from 150MHz to 1500 MHz. Hata presented the urban area propagation loss as a standard formula and supplied correction equations for application to other situations. [20] The model first predicts the free space path loss and then adds various attenuation factors. For an urban center, path loss is given by: [4]

$$\begin{aligned} L_u(dB) = 69.55 + 26.16\log_{10} f - 13.82\log_{10} h_b - A(h_m) \\ +(44.9 - 6.55\log_{10} h_b)\log_{10} d(dB) \end{aligned} \tag{2.27}$$

where

$L_u =$ loss (dB) for urban areas
$f =$ frequency in MHz $(150 < f < 1{,}500)$
$h_b =$ transmit (base station) antenna height in meters $(30 < h_b < 300)$
$h_r =$ receive antenna height in meters $(1 < h_m < 10)$
$d =$ path distance in kilometers $(1 < d < 20)$
$A(h_m) =$ propagation environment correction factor

The term $A(h_m)$ is a correction factor whose value depends on the type of propagation environment. In medium or small cities: [4]

$$A(h_m) = [1.1\log_{10}(f) - 0.7]h_r - [1.56\log_{10}(f) - 0.8]db \tag{2.28}$$

where

$1m \le h_r \le 20m$

For large cities: [5]

$$A(h_m) = 8.29\log_{10}(1.54h_r) - 1.1dB \text{ for } f \le 200 \text{ MHz},$$
$$\text{A}(\text{h}_\text{m}) = 3.2\log_{10}(11.75h_r) - 4.97dB \text{ for } f > 200 \text{ MHz} \quad (2.29)$$

The generalized formula for suburban areas is: [4]

$$L_{su}(dB) = L_u - 2\left[\log_{10}\frac{f}{28}\right]^2 - 5.4\sqrt{a^2+b^2} \quad (2.30)$$
$A(h_m)$ determined by equation 2.29

where

$L_{su} =$ loss (dB) in suburban areas

Quasi-open rural area (built up areas that have widely spaced single story buildings and significant vegetation) path loss is calculated by: [4]

$$L_{rqo}(db) = L_u - 4.78\left[\log_{10}(f)\right]^2 + 18.33\log_{10}(f) - 35.94 \quad (2.31)$$
$A(h_m)$ determined by equation 2.28

where

$L_{rqo} =$ loss (dB) in semi rural areas

In rural areas, that is areas that are largely open with few obstacles, the path loss is given by: [4]

$$L_{ru}(db) = L_u - 4.78\left[\log_{10}(f)\right]^2 + 18.33\log_{10}(f) - 40.94 \quad (2.32)$$
$A(h_m)$ determined by equation 2.28

where
$L_{ru} =$ loss (dB) in rural areas

Although the Hata model does not have any of the path specific corrections, which are available in the Okumura model, the predictions compare very closely with the original Okumura model. [20] Since the model should give a reasonably accurate prediction of path propagation, and its ease of implementation in modern computer spreadsheets, the Hata model is the subject of this study.

Conclusion

. Propagation loss prediction is critical in designing radio systems. There are numerous propagation models that can be used to predict path loss in virtually any circumstance. Some models use statistical methods, while other models use empirical methods. Terrain databases are used by some models in an effort to obtain greater path loss prediction accuracy. Computer based methods have become the industry norm due to the power, speed and relatively low cost of desktop computers.

CHAPTER 3

USING THE HATA MODEL IN PREDICTING RADIO FREQUENCY PROPAGATION

The Hata model for predicting radio frequency propagation is relatively easy to implement using a computer spreadsheet. When used by its self, the model does not require a digital terrain database. The lack of a terrain database requirement is both an asset and a fault of the Hata model. Without examining terrain, it could be possible to analyze a propagation path that is obstructed and the analyses show the path viable, when in fact, the path is partially or completely blocked. Terrain data or topographic maps typically do not provide information on buildings that may lie in the propagation path. Therefore, it is recommended that, in addition to terrain data analysis, someone familiar with the general area physically examine the propagation path. Thus, the author examined terrain data in this study to ensure that clear propagation paths exist.

The following parameters were considered in designing the research for this study: data necessary to complete the study, data collection, and data analysis. Necessary data included, but were not limited to, required received signal strength, transmitter power out, antenna gain, transmission line losses, path distance, path terrain, and Fresnel zone clearance considerations. Data collection was performed using software supplied by the radio manufacturer. This software is capable of querying the radio at each site and recording current operating parameters such as transmitter power out and received signal strength. Data is recorded in an Excel spreadsheet compatible format, and is easily imported to Excel for analysis.

Data analysis is performed using standard statistical methods. Dr. Robert Getty of the University of North Texas College of Business Administration, an expert in statistical methods, was consulted prior to determining sample rates and analysis methods. Dr. Getty's recommendations were followed in performing the data analysis.

Research Method

The research method is experimental. Terrain data was extracted from topographic maps and used to determine Fresnel zone clearance over each path. Terrain usage was examined to determine which propagation environment (urban, suburban, rural) was suitable for use in the selected model. [1] Analysis was performed for the large city, urban, small city, semi-rural, and rural forms of the Hata model in order to determine which provided the best fit to the measured data. Eleven sites along Loop 288 were constructed and one set of received signal strength data recorded for each site. Figure 9 presents a map of the selected sites.

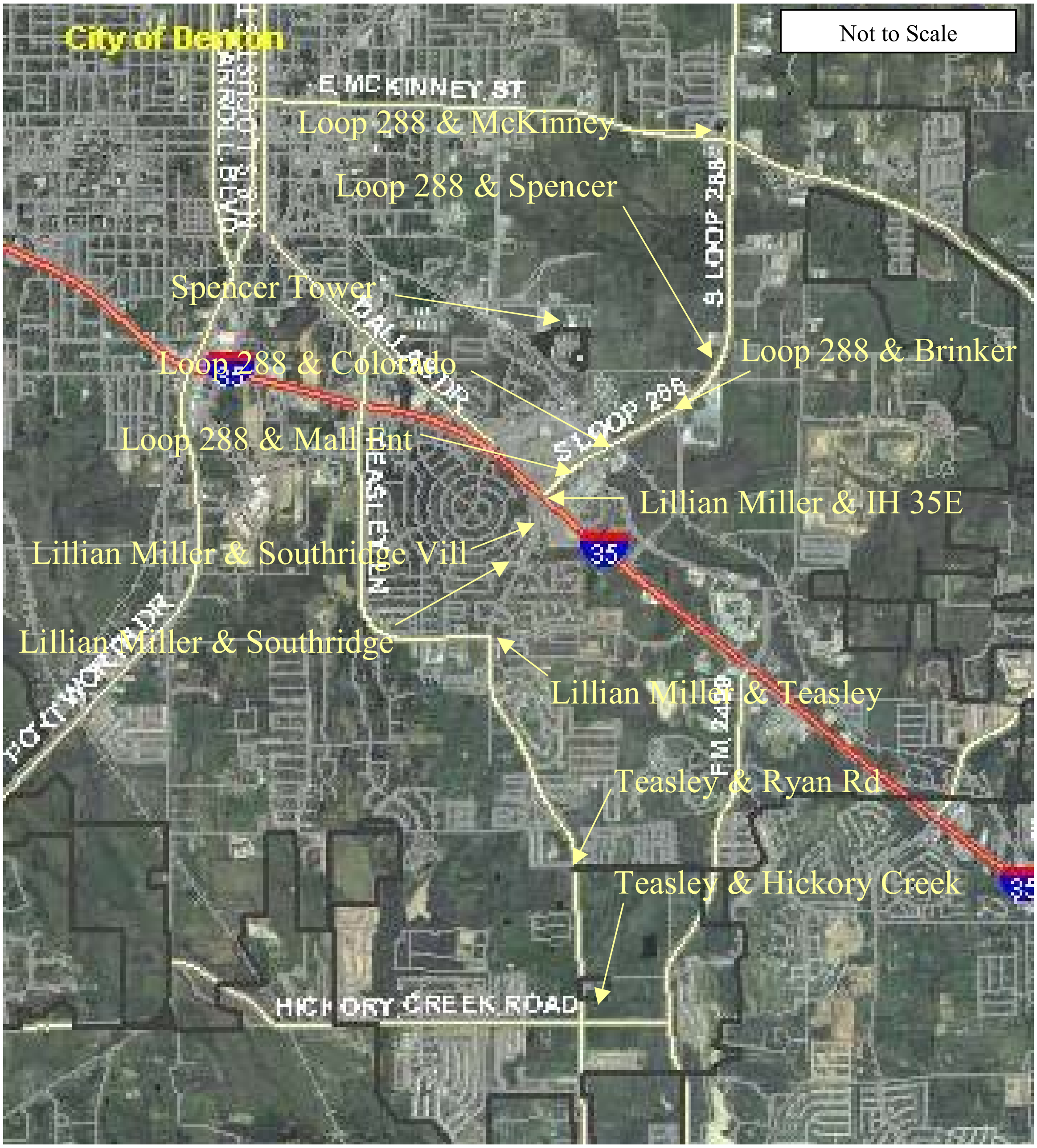


Figure 9. Photomap of Study Sites

Sites Selected for Study

The path from McKinney at Loop 288 to Spencer Tower is over a creek and largely wooded area that would be considered a rural area in the Hata model. Path length is 2.168 km (7114 ft, 1.347 mi.). The antenna support at this intersection is a 9.14 m (30 ft) aluminum pole. The antenna is mounted so that the height above ground of the antenna centerline is 9.14 meters (30 ft) above ground. [3]

. The antenna is a 9.15 *dBi* gain directional, with 18.3 m (60 ft) of LMR 600 transmission line. [3] Thus, the site will be in compliance with the limitations of the Hata model specifications of $1<d<10$ and $1<h_r<10$.

Lillian Miller at Teasley Lane to Spencer Tower meets the definition of suburban as defined in the Okumura model and used in the Hata model. Numerous buildings of various heights, from single story homes to multi-story office buildings, characterize the path. Path length is 2.593 km (8506 ft, 1.611 mi.). The antenna support at this intersection is a 9.14 m (30 ft) aluminum pole. The antenna is mounted so the height above ground of the antenna centerline is 9.1 meters (30 ft) above ground. [3] Antenna gain is 9.15 *dBi*; transmission line length is given as 12.2 m (40 ft) of LMR 600. [3] The height and distance parameters are within the minimum and maximum values specified in the Hata model.

IH 35 at Lillian Miller is 1.3 km (4277 ft) from Spencer Tower. [3] There is clear line of site to Spencer; the tower is easily visible from the intersection over the Golden Triangle Mall complex. This path is characterized by buildings of one to five stories in height, qualifying as an urban environment in terms of the Hata model. Antenna support is provided by a 9.1 m (30 ft) aluminum pole, with the antenna centerline 9.1 m (30 ft) above ground. [3] The antenna is a directional type with a gain of 9.15 *dBi*, and is connected to the radio with 30.5 m (100 ft) of LMR 600 coaxial cable. [3] This meets the Hata model requirements of path length between 1 and 10 km and antenna height less than 10 meters above ground.

Spencer Tower to Teasley Lane and Ryan Road is over varying terrain and may have significant Fresnel zone obstruction. There are numerous buildings, mostly single story homes and a few multi-story buildings near Spencer Tower. The path is classified as suburban in the Hata model. It is the second longest path in the study at 4.0 km (13253 ft). The antenna is mounted at 7.6 m (25 ft) above ground on a 7.6 m (25 ft) wood pole. Antenna gain is 9.15 *dBi*; transmission line length is given as 12.2 m (40 ft) of LMR 600. [3] The distance and height requirements for the Hata model are met at this site.

Lillian Miller and Southridge has a 6.1 m (20 ft) aluminum pole with the antenna centerline at 6.1 m (20 ft) above ground. The antenna is a 9.15 *dBi* directional with 15.2 m (50 ft) of LMR 600 transmission line. [3] The path length is 1.9 km (6178 ft). Terrain is suburban, with line of site to Spencer Tower over the Golden Triangle Mall. This site is on the upslope of a significant ridge that may pose Fresnel zone clearance problems for sites further south (Hickory Creek, Ryan Road, etc.). There are no terrain obstructions; the site parameters meet the Hata model requirements.

The intersection of Lillian Miller and Southridge Village is 1.5 km (4910 ft) from Spencer Tower. A 9.1 m (30 ft) aluminum pole provides antenna support; antenna centerline is 7.6 m (25 ft) above ground. A 9.15 *dBi* directional antenna is utilized with 13.7 m (45 ft) of LMR 600 coax. [3] There is line of site to Spencer tower; terrain is suburban as defined in the model parameters. Minimum Hata model requirements are satisfied.

The traffic signal system at Loop 288 and the entrance to Golden Triangle Mall has a 6.1 m (20 ft) aluminum pole with the antenna mounted 6.1 m (20 ft) above ground.

[3] The antenna is a 9.15 *dBi* Yagi type directional antenna. It is connected to the radio with 10.7 m (35 ft) of LMR 600 coax. [3] Spencer Tower is visible over the mall buildings 1.1 km (3590 ft) away; the path would be considered suburban according to Hata model definitions. All height and distance requirements of the model are met.

Loop 288 at Colorado has a 9.1 m (30 ft) aluminum pole for antenna support. The 9.15 *dBi* gain antenna is mounted 9.1 m (30 ft) above ground. Coax cable length is given as 10.7 m (35 ft) of type LMR 600. It is 1.0 km (3326 ft) from Spencer Tower. [3] The area has recently experienced considerable development, with a new strip type shopping center constructed. The path would be considered suburban in the Hata model; all model parameters are satisfied.

A 9.1 m (30 ft) aluminum pole supports the 9.15 *dBi* directional antenna at Loop 288 and Brinker. The antenna center line is 9.1 meters (30 ft) above ground. [3] Coax length is 18.3 meters (60 ft) of LMR 600. Path length is 1.2 km (3907 ft). [3] The propagation path would most likely be considered suburban, as there are numerous single story buildings along the path. Hata model minimum parameters are met.

The last site studied is the link from Teasley Lane and Hickory Creek Road to Tower. It is the longest path in the initial study group of "A" sites. Terrain analysis shows that there may be significant intrusion into the required Fresnel zone clearance. The path to Spencer Tower passes over terrain that is rough, contains many trees, and has buildings of varying heights, ranging from single story residences to low-rise office complexes. These factors make this the link most likely to limit system performance. [1] The path length is 5.7 km (18706 ft). The signal support at this site is a 7.6 m (25 ft) wood pole. The antenna centerline is 8.5 m (28 ft) above ground. [3] Antenna gain is

9.15 *dBi*; transmission line length is given as 12.2m (40 ft) of LMR 600. [3] Approximately one half of the path distance is over open terrain with only a few houses. The other half of the path is over terrain similar to the Lillian Miller and Teasley Lane path. [1] The height and distance parameters are within the limits specified in the Hata model. Table 3 summarizes all parameters for each study site.

Spencer Tower to	Terrain	Path Length	Antenna Support	Antenna Centerline	Antenna Gain	Transmission Line Length
Spencer Tower			Steel Tower	33.53 m	12.15 dBi	36.58 m (LMR1200)
Loop 288 at McKinney	Rural	2.168 km	Aluminum Pole	9.14	9.15 dBi	18.3 m (LMR 600)
Lillian Miller at Teasley Lane	Suburban	2.593 km	Aluminum Pole	9.1 m	9.15 dBi	12.2 m (LMR 600)
IH 35 at Lillian Miller	Urban	1.3 km	Aluminum Pole	9.1 m	9.15 dBi	30.5 m (LMR 600)
Teasley Lane at Ryan Road	Suburban	4.0 km	Wood Pole	7.6 m	9.15 dBi	7.6 m (LMR 600)
Lillian Miller at Southridge	Suburban	1.9 km	Aluminum Pole	6.1 m	9.15 dBi	15.2 m (LMR 600)
Lillian Miller at Southridge Village	Suburban	1.5 km	Aluminum Pole	7.6 m	9.15 dBi	13.7 m (LMR 600)
Loop 288 at Mall Entrance	Suburban	1.1 km	Aluminum Pole	6.1 m	9.15 dBi	10.7 m (LMR 600)
Loop 288 at Colorado	Suburban	1.0 km	Aluminum Pole	9.1 m	9.15 dBi	10.7 m (LMR 600)
Loop 288 at Brinker	Suburban	1.2 km	Aluminum Pole	9.1 m	9.15 dBi	18.3 m (LMR 600)
Teasley Lane at Hickory Creek	Suburban/ Rural	5.7 km	Wood Pole	8.5 m	9.15 dBi	12.2 m (LMR 600)
Loop 288 at Spencer	Suburban	1.3 km	Wood Pole	9.1 m	9.15 dBi	12.2 m (LMR 600)

Table 3. Site Parameter Summary

Data Collection Methodology

Signal strengths from the various study sites were monitored using InSite 6i™ Radio Management Software provided by the radio manufacturer, MDS. This software has specific provisions for monitoring signal quality parameters from remote sites at a central location. [21] Logging of parameters with output to disk is provided in the software. Monitoring features of the MDS 9810 radio, as recorded by the InSite™ software, were used to test system performance. [21] A single set of measured data was taken when the system was constructed. The data consists of one reading per site for the twelve sites. Shortly after the system was constructed, lightening destroyed the radio at Spencer Tower. This radio serves as a sub-master for the entire system constructed to date. Without the Spencer radio, additional data collection is not possible. Existing measured data was analyzed using statistical methods to determine if the appropriate confidence level was met. Dr. Robert Getty, an expert in statistical analysis has been consulted and recommended that data analysis be done in the following manner. [22] Data from the initial eleven site readings was averaged together to develop mean and standard deviation values for received signal strength. Model data for the same eleven sites was also averaged to arrive at mean and standard deviation values. Standard t tests were used to compare the mean of measured data and model data. [22] Once the mean and standard deviation values were known, full analysis of received signal strength data was performed. [22] Using equations provided by Dr. Getty, the sample mean, $\bar{x}$, and sample variance, s, were calculated using equations 3.1 and 3.2. [22]

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{3.1}$$

$$s_p = \sqrt{s_p{}^2} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \tag{3.2}$$

where
$n =$ number of samples
$n_1 =$ number of samples in the model
$n_2 =$ number of measured data samples
$s_p =$ pooled standard deviation

The t test equation was given by Dr. Getty as: [22]

$$t = \frac{\bar{x} - \mu}{\frac{s}{\sqrt{n}}} \tag{3.3}$$

For a confidence level of $\alpha = 0.05$, 95%, and 20 degrees of freedom, t was found to be 2.086
This value was determined by

$$t\left(\frac{\alpha}{2}, 20\right) \tag{3.4}$$

or

$$t\left(\frac{0.05}{2}, 20\right) \tag{3.5}$$

and using a t test look up table.[23]

Adjusting to Received Signal Data Values

Propagation prediction models calculate the free space path loss, and usually do not contain system fixed gains and losses. The Hata model is no exception. Received signal values obtained from Insite 6™ do include fixed system gains and losses as well as the free space path loss. Therefore, the model must be adjusted to accommodate system fixed gains and losses.

Fixed gains in this system are transmitter output power, and transmit and receiving antenna gain. Fixed losses are antenna feed line loss and connector loss. All gains and losses are calculated in dB so as to facilitate calculating overall system performance. As stated in Chapter 2, gain and loss values in dB may be algebraically summed to arrive at a final system signal level. Antenna gains are given in manufacturer's data sheets and specific site data provided by CES Network Services. Transmission line losses are calculated from manufacturer's data where the loss is given as dB per unit length, usually 100 feet. Transmission line loss is frequency dependent; therefore, care must be taken in reading the data sheet to obtain the correct loss value. In addition, none of the transmission lines used in this study are in 100 foot increments, thus the length must be calculated as a ratio of the actual transmission line length to the given loss per 100 feet to obtain a correct loss value. Connector losses are assumed to be 1 dB per connector; this value is given in the CES Network Services data. [3] All values for transmission line length, antenna gain, connector loss, and transmitter output power were extracted from CES Network Services documents.

As an example, the transmission line at Teasley Lane and Hickory Creek is 40 feet of LMR 600 coax. [3] Loss for this coax is 2.50dB per 100 feet. [3] The calculated transmission line loss is then calculated as

$$Attenuation_{dB} = \frac{(2.50db)(ft)}{100} \tag{3.6}$$

or $Attenuation_{dB} = \frac{(2.50)(40)}{100} = 1.0dB$

There are 2 connectors with a loss of 1*dB* each for a total of 2 *dB*, and an antenna gain of 7.0 *dBd*. The net gain for the system at Teasley Lane and Hickory Creek is 4 *dB*. This value is added to the Hata model predicted propagation loss, as is the gain from the Spencer Tower system. Note that the gain value for Spencer Tower also includes transmitter output power in *dB*. All gain/loss calculations were performed using standard Excel spreadsheet functions.

Data Analysis

Based on the calculations above, the mean and sample variance were calculated for the eleven locations and a standard two sided t test was used to determine if the pooled means of the calculated and measured values were equal. t tests can be used to determine if the means of two small (n<30) groups of data are equal when the parent population is approximately normal. [23] To use the t test, the sample mean, $\overline{y}$, and sample variance, $\overline{s^2}$, are calculated. [23] The test statistic is then calculated using Equation 3.3. For pooled data, s^2 is calculated using equation 3.2. [22] Using a t distribution with $v = n - 2$ degrees of freedom, the area in the tail of the curve beyond t_0 is evaluated. [22]

If the t statistic value calculated from the model data is less than or equal to the reference t statistic value determined by Equations 3.4 or 3.5, then one must fail to reject the null hypothesis. Otherwise, reject the null hypothesis and accept the alternative hypothesis for values of t greater than the reference value. [22]

Tables 4 and 5 contain the sample data taken by Insite 6i™ software when the radio system was first tested. Adding the sample values together and dividing by the number of samples calculated the mean value of the samples as shown by Equation 3.1.

The sample mean was found to be 68.36dB. Sample variance calculations were performed using Equation 3.2. Variance was calculated to be 44.85. Calculating t using Equation 3.4 resulted in a value of 2.086.

DATA FIELDS	SPENCER SITE		801 ST. HQ	REMOTE SITES								
	MASTER (OMNI ANTENNA)	REMOTE MASTER (YAGI ANTENNA)	TRAFFIC CONTROL CENTER	I-35 & LILLIAN MILLER	TEASLEY & HICKORY	TEASLEY & RYAN	LILLIAN MILLER & TEASLEY	LILLIAN MILLER & SOUTHRIDGE	LILLIAN MILLER & SOUTHRIDGE VILLAGE	LOOP 288 & MALL ENTRANCE	LOOP 288 & COLORADO	LOOP 288 & BRINKER
TX FREQ												
RX FRE												
UNIT ADDRESS	7946	7987	0530	11561	16710	53500	1690	55600	16750	17160	10536	10537
TIME OUT TIMER												
SOFTCARRIER DELAY												
NETWORK ADDRESS	17946	2002	2002	17946	17946	17946	17946	17946	17946	17946	17946	17946
CTS DELAY	0	0	0	0	0	0	0	0	0	0	0	0
POWER CONTROL	30	30	30	30	30	30	30	30	30	30	30	30
HOP PATTERN	A	NA	A	NA	NA	NA	NA	NA	NA	NA	NA	NA
SQUELCH TAIL												
SIMPLEX MODE	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
BUFFER MODE	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
MASTER/REMOTE MODE	MASTER	REMOTE	MASTER	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE
OWNER'S NAME	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON
OWNER'S MESSAGE	SPENCER MASTER	SPENCER R/M	801 HQ	I35	HICKORY	RYAN	TEASLEY	SOUTHRIDGE	SOUTHRIDGE MALL	MALL	COLORADO	BRINKER
DATA RATE	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600
DATA FORMAT	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1
DEVICE TYPE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE
HOP TIME	NA	NA	NORMAL	NA	NA	NA	NA	NA	NA	NA	NA	NA
SKIP ZONE												
RX AUDIO LEVEL												
RSSI				-73	-75	-72	-74	-72	-74	-60	-60	-60
SNR				24	34	29	21	32	32	33	33	33
ZONE BLOCK OUT												2 & 4
SITE DESIGNATION				A	A	A	A	A	A	A	A	A

Table 4. Insite 6i™ Received Signal Strength Data

LOOP 288 & SPENCER	LOOP 288 & McKINNEY	WOODROW & SHADY OAKS	DALLAS & TEASLEY	TEASLEY & FASTLANE	TEASLEY & LONDONDERRY	LONDONDERRY & JASON	I35 & TEASLEY	UNIVERSITY & CARROLL	CARROLL & CRESCENT	CARROLL & CONGRESS	CARROLL & PARKWAY	CARROLL & OAK	CARROLL & HICKORY
0723	11570	11566											
17946	17946	17946	17946	17946	17946	17946	17946						
0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	30	30	30	30	30	30	30	30	30	30	30	30	30
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE	REMOTE
CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTON	CITY OF DENTO
SPENCER	McKINNEY	WOODROW											
9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600
8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1	8N1
DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE	DCE
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-60	-72	-68											
33	28	32											
		2											
A	A	B	B	B	B	B	B	C	C	C	C	C	C

Table 5. Insite 6i™ Received Signal Strength Data

Fresnel Zone Considerations

As outlined in Chapter 2, a line of sight path must exist between the two end points of the propagation path. An examination of Fresnel zone clearance was undertaken to determine if such a line of sight path exists. A terrain profile was generated, and Fresnel zone clearances calculated. Only the Spencer Tower to Lillian Miller and Teasley path showed potential Fresnel zone problems, with an estimated obstruction of 40%. As stated in Chapter 2, a Fresnel zone clearance of at least 60% is necessary to provide a propagation path free from terrain obstructions.

Terrain profiles can be obtained from several sources, from digital terrain databases to printed topographic maps. Digital terrain databases are commonly available in 30 arc second and 3 arc second resolutions. At least one company, V-Soft, has released a digital terrain database with a resolution of 30 meters. [24] The 30 meter resolution database is particularly suited for microwave and Longley-Rice path analysis. [24] Figure 10 presents a path plotted using the NGDC 30 arc second terrain database.

[24]

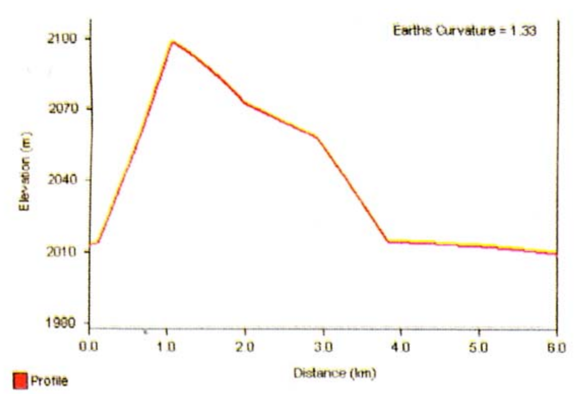


Figure 10. 30 Arc Second Terrain Profile Data

Figure 11 shows the same terrain profile using the USGS 3 arc second terrain database, while Figure 12 depicts the terrain profile extracted from the V-Soft NED 30 meter terrain database. [24]

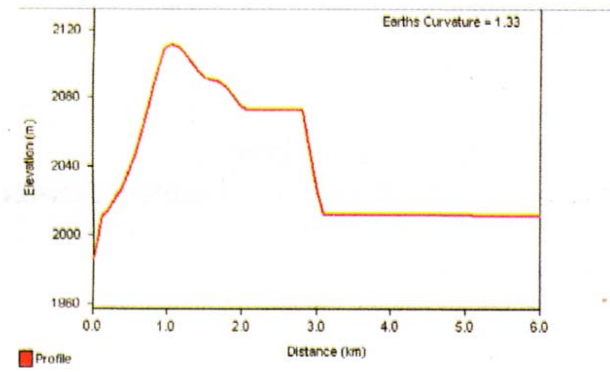


Figure 11. 3 Arc Second Terrain Profile Data

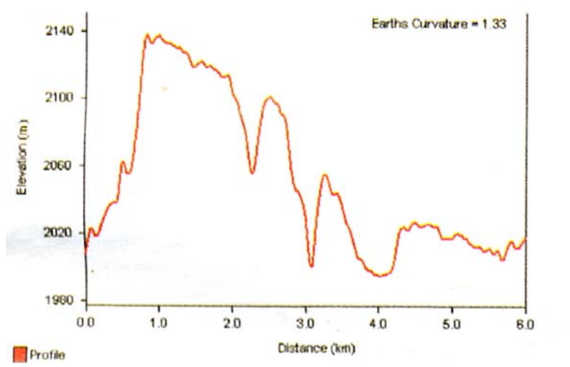


Figure 12. 30 Meter Terrain Profile Data

As shown in Figures 10, 11, and 12, it can be difficult to accurately determine the actual terrain profile when using digital terrain databases with large (30 arc second) point spacing. This difficulty in determining the actual terrain profile would be even more pronounced when short paths are involved, as is the case in this study. Thus, terrain data was extracted from USGS 7.5 minute topographic maps for the propagation paths examined in this study.

Terrain Data Extraction and Analysis

Terrain data was extracted from the Denton East quadrangle map as supplied by the United States Geological Survey. The map legend shows the map was originally issued in 1960, photo inspected in 1978 and photo revised in 1968 and 1973. The Spencer Tower site and the various intersections were plotted on the map; a line drawn between each end point, and the terrain extracted along each line in accordance with a method demonstrated by Mr. Stephen Kramer, P.E. [25] Coordinates and base elevation for Spencer Tower were extracted from the FCC Universal License System (ULS). Coordinates for each receiver location (street intersection) were determined using a Magellan GPS 300 (serial number 0132773) hand held GPS receiver. Base elevations for each receiver location were estimated from the topographic map. Figure 13 presents a portion of the Denton East topographic map with the sites and path lines plotted.

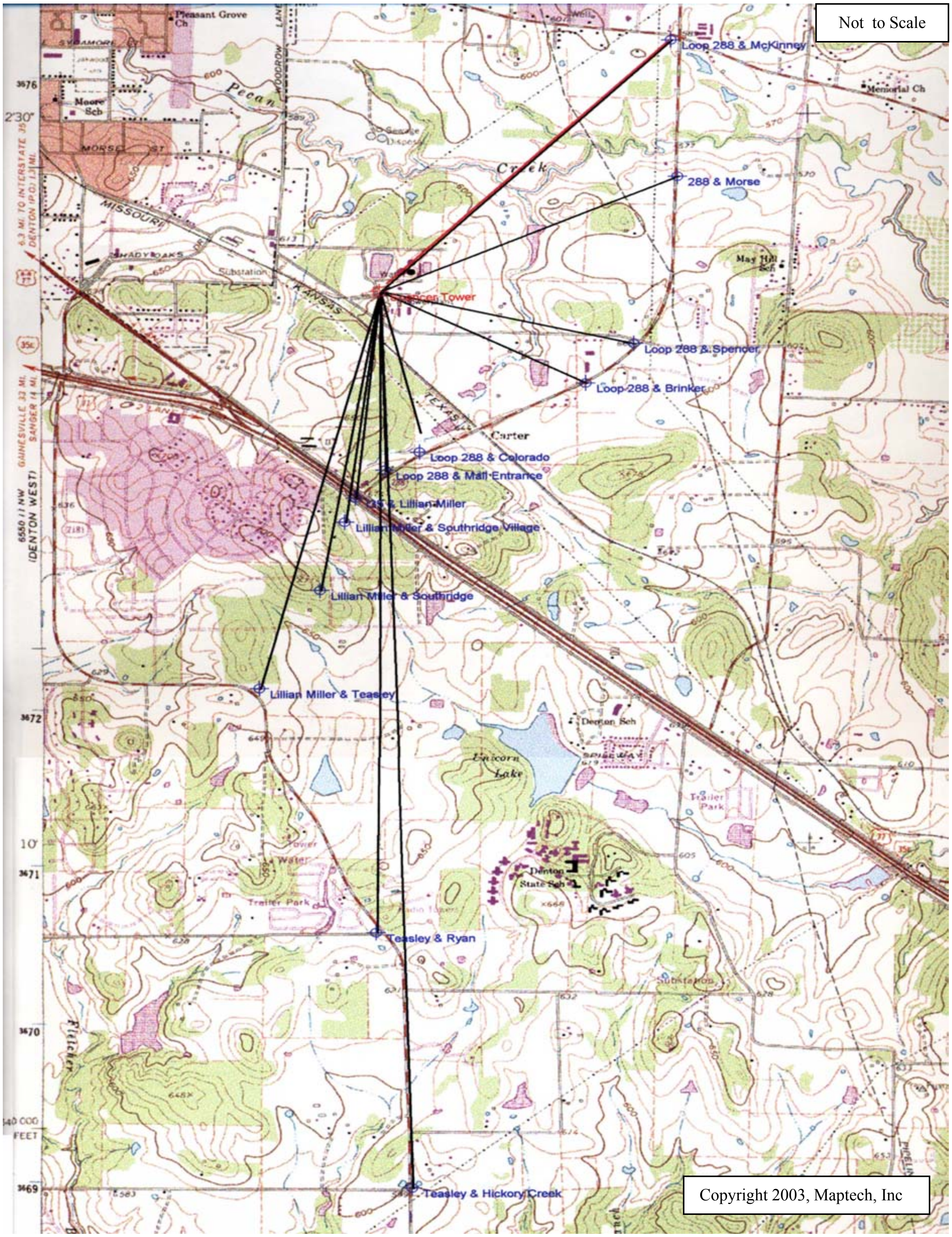


Figure 13. Topographic Map Depicting Propagation Paths

Starting at Spencer tower, the distance to the nearest contour interval line along each path line was scaled off using dividers. The distance from Spencer Tower and elevation were entered into an Excel spreadsheet for each successive contour interval. Uniform changes in elevation were assumed between contour intervals. [25] Excel plotted the resulting terrain profile. Using Equation 2.11, the Fresnel clearances were calculated and plotted by Excel. Figure 14 presents the Spencer Tower to McKinney and 288 terrain profile and Fresnel zone, Figure 15 depicts the Spencer Tower to Lillian Miller and Teasley Lane terrain profile and Fresnel zone, while Figure 16 shows the Spencer Tower to Teasley Lane and Hickory Creek profile and Fresnel zone.

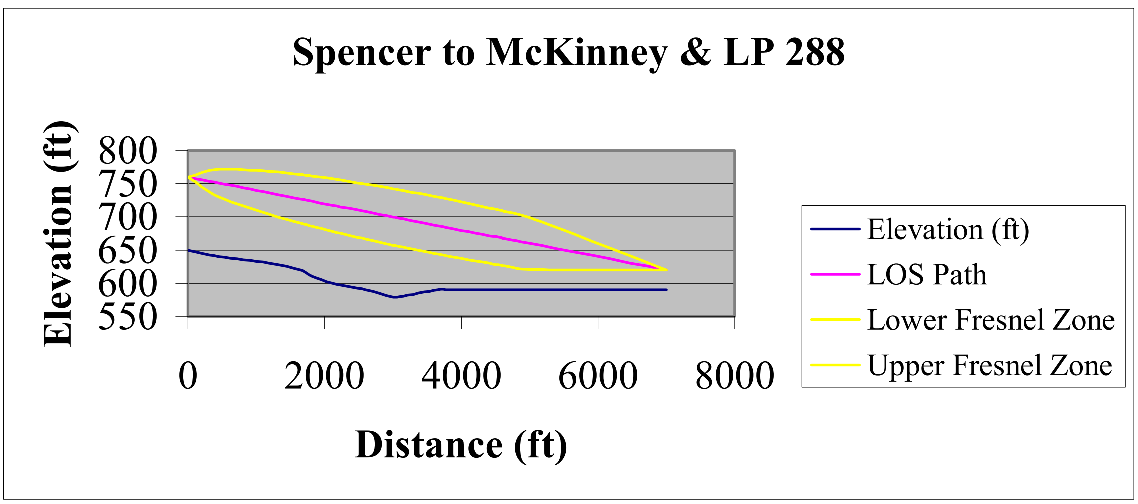


Figure 14. Spencer Tower to McKinney & Loop 288 Terrain Profile and Fresnel Zone

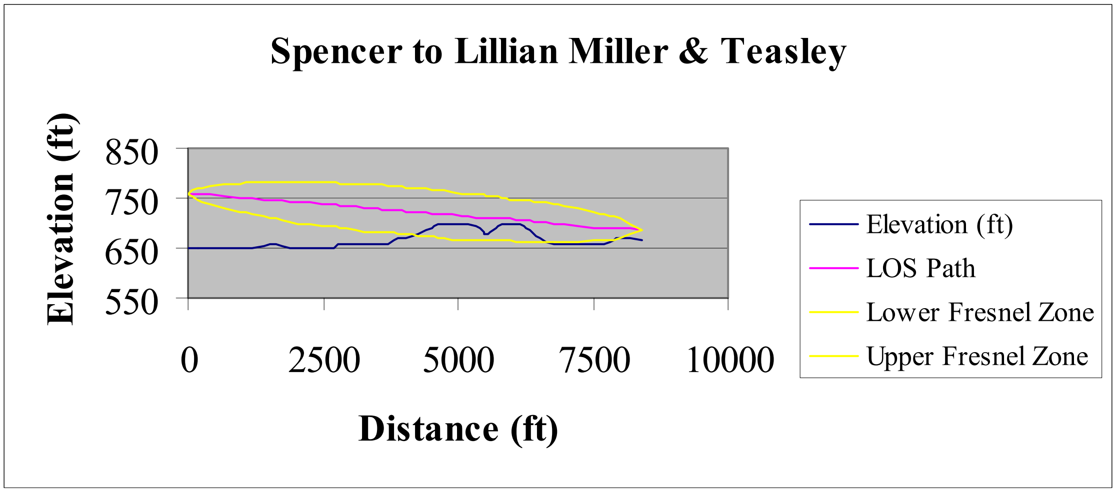


Figure 15. Spencer Tower to Lillian Miller & Teasley Terrain Profile and Fresnel Zone

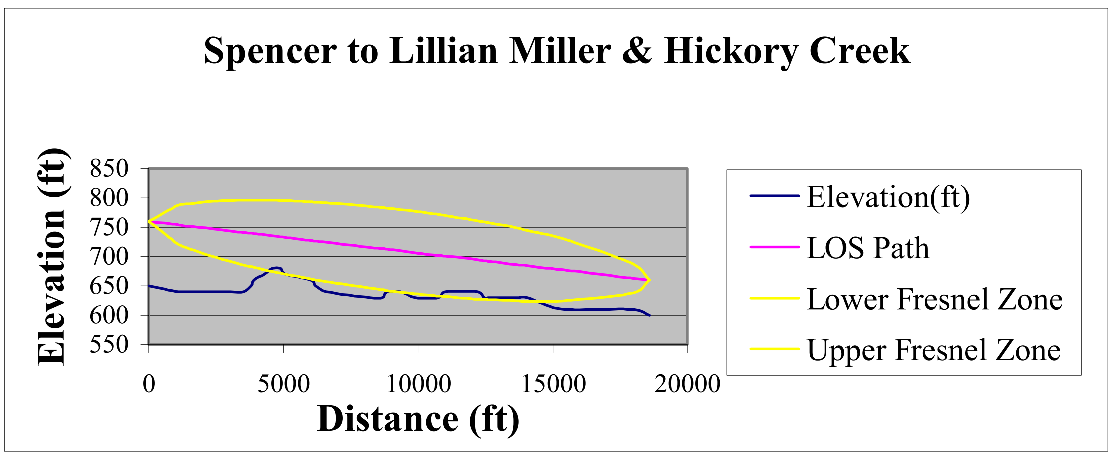


Figure 16. Spencer to Lillian Miller & Hickory Creek Terrain Profile and Fresnel Zone

Additional terrain profiles were extracted for the remaining paths. All terrain data is shown in Appendix A.

Conclusion

When proper methods are used, propagation modeling can easily predict if a particular propagation path is viable strictly from a received signal level view. However, terrain between the transmitter and receiver may contain obstructions that preclude viable propagation paths due to lack of Fresnel Zone clearance. Thus it can be concluded that propagation models alone are not sufficient to determine if a particular radio link will perform satisfactorily. Terrain databases using large arc second data points are shown to be unsuitable for short path analysis as covered in this study. Topographic maps are a viable alternative to expensive digital terrain databases.

CHAPTER 4

DATA ANALYSIS OF THE HATA MODEL OF PATH PROPAGATION PREDICTION

Details pertaining to the methodology of numerical data analysis for this project are explained. Data is depicted in spreadsheet form and results of analysis are detailed. The null and alternative hypotheses are presented for acceptance or rejection as appropriate. Based on the results of analysis, conclusions will be drawn and recommendations as to the validity of using the Hata model for spread spectrum propagation will be presented in Chapter 5.

Analysis Methodology

As detailed in Chapter 3, data from eleven sites was collected when the spread spectrum traffic signal control system was initially installed. Received signal strength levels for each site were averaged together and compared to calculated propagation loss. Since the number of data points available was small, a two-sample analysis of the mean of measured and calculated data was used. Dr. Robert Getty, an expert in statistical analysis methods, assisted in performing the data analysis by providing exact methods and equations for the analysis. In addition, Kiemele's statistical analysis text was used to obtain values from standard probability distribution tables. Several variations of the Hata model were examined to determine which, if any, gave the best prediction of received signal strength. Microsoft Excel was used to perform calculations using built-in functions. Measured data was first averaged to obtain the mean value. Once the mean was known, the variance and standard deviation were found.

Calculated propagation path loss values for Hata's Large City model were treated in the same manner as measured data. The mean value, variance and standard deviation were found using Excel functions. Pooled variance, s_p^2, and pooled deviation, s_p, were calculated using Equation 3.2. Using these calculated values, the t statistic was determined using standard lookup tables extracted from Kiemele's statistics textbook. For the Large City model, the mean is –88.40 dBm, pooled variance, s_p^2, is 112.60, deviation, s_p, is 10.61, and t, using Equation 3.3, was found to be -4.43.

The Large City model was also tested using the Large City $A(h_m)$ variation of the Hata model. Using this variation, the calculated mean received signal strength is –97.97 dBm, pooled variance, s_p^2, is 100.82, pooled deviation, s_p, is 10.4, and t is –6.92.

Using the method described above, the Urban Area variation of the Hata model was examined. For this variation, mean was found to be –85.36 dBm, s_p^2 is 67.99, s_p is 8.25, t is -4.83. The mean for the Suburban Area variation was calculated to be –75.33 dBm, s_p^2, 67.99, s_p 8.25, t -1.98. The Semi-Rural variation produced values of mean –61.72 dBm, s_p^2 67.99, s_p 8.25, t 1.89. Rural variation of the Hata model, the last variation examined resulted in mean received signal strength of –56.72 dBm, s_p^2 67.99, s_p 8.25, t 3.31. All statistical data is presented in Table 6.

	Measured RX Signal Strength (X_0)	Large City Received Power (X_{LM})	Large City Received Power (large city A_{hre}) (X_{LMLA})	Urban Area Calculated Received Power (X_{UM})	Suburban Calculated Received Power (X_{SBM})	Semi-Rural Calculated Received Power (X_{SRM})	Rural Calculated Received Power (X_{RM})
Average Value	-68.36	-88.40	-97.97	-85.36	-75.33	-61.72	-56.72
Variance (s^2)	44.85	180.34	156.78	91.12	91.12	91.12	91.12
Standard Deviation (s)	6.70	13.43	12.52	9.55	9.55	9.55	9.55
Pooled Variance (s_p^2)		112.60	100.82	67.99	67.99	67.99	67.99
Pooled Deviation (s_p)		10.61	10.04	8.25	8.25	8.25	8.25
t value		-4.43	-6.92	-4.83	-1.98	1.89	3.31

Table 6. Data Values for Hata Model Variations

Hypothesis Testing

As stated in Chapter 1, the research question is formulated into a null hypothesis and alternative hypothesis. Statistical analysis methods are used to determine if we can fail to reject the null hypothesis or accept the alternative hypothesis. Each variation of the Hata model is tested against the null and alternative hypotheses. The hypotheses are:

Null Hypothesis (H_0)

There is no difference between the received field strength values predicted by the Hata model and measured received field strength values

Alternative Hypothesis (H_1)

There is a difference between the received field strength values predicted by the Hata model and measured received field strength values

Testing at a standard confidence level of 95%, the calculated t value (from Chapter 3) is 2.086.

The large city Hata model, designated X_{LM}, calculated t value was found to be 4.02. This value is greater than the calculated 95% value of t. Therefore, reject H_0 and conclude that the Hata Large City model does not predict received signal strength. Mathematically

$$\begin{aligned}&t_{\bar{X}_o} < t_{\bar{X}_{LM}}\\&2.086 < 4.43\\&\text{Therefore,}\\&\text{ Reject } H_0,\ \text{Accept } H_1\\&\bar{X}_0 \neq \bar{X}_{LM}\end{aligned} \tag{4.1}$$

The large city Hata model using large city $A(h_m)$ designated X_{LMLA}, calculated t value was found to be 6.92. This value is greater than the calculated 95% value of t. Therefore, reject H_0 and conclude that the Hata Large City, model using large city $A(h_m)$ does not predict received signal strength. Mathematically

$$\begin{aligned}&t_{\bar{X}_o} < t_{\bar{X}_{LM}}\\&2.086 < 6.92\\&\text{Therefore,}\\&\text{ Reject } H_0,\ \text{Accept } H_1\\&\bar{X}_0 \neq \bar{X}_{LMLA}\end{aligned} \tag{4.2}$$

Urban Area variation of the Hata model, X_{UM}, t value was found to be 4.83. This is larger than the 95% confidence t value of 2.086. Thus, reject H_0 and accept H_1. The Urban Area Hata model does not accurately predict received signal strength.

$$\begin{aligned}&t_{X_0} < t_{X_{UM}}\\&2.086 < 4.83\\&\text{Therefore,}\\&\text{Reject } H_0, \text{Accept } H_1\\&\bar{X}_0 \neq \bar{X}_{UM}\end{aligned} \tag{4.3}$$

Suburban model, X_{SBM}, t value is 1.98 which is smaller than the stated confidence level t value of 2.086. H_0 is accepted and the alternative hypothesis, H_1 is rejected. The Suburban model is suitable for predicting propagation loss for this study.

$$\begin{aligned} & t_{X_0} > t_{X_{SBM}} \\ & 2.086 > 1.98 \\ & \text{Therefore:} \\ & \text{Accept } H_1 \\ & \bar{X}_0 = \bar{X}_{SBM} \end{aligned} \tag{4.4}$$

For the Semi-Rural variation of the Hata model, X_{SRM}, t is 1.89. This is less than 2.086. Therefore, H_0 is accepted. The Semi-Rural model does accurately predict received signal strength

$$\begin{aligned} & t_{X_0} > t_{X_{SRM}} \\ & 2.086 > 1.89 \\ & \text{Therefore:} \\ & \text{Accept } H_1 \\ & \bar{X}_0 = \bar{X}_{SRM} \end{aligned} \tag{4.5}$$

Rural model calculations resulted in an X_{RM} t value of 3.31. The 95% confidence level t value of 2.086 is smaller. H_0 is rejected and the alternative hypothesis, H_1 is accepted. As used in this study, the Hata rural model does not provide accurate prediction of propagation loss.

$$\begin{aligned} & t_{X_0} < t_{X_{RM}} \\ & 2.086 < 3.31 \\ & \text{Therefore:} \\ & \text{Reject } H_0\text{, Accept } H_1 \\ & \bar{X}_0 \neq \bar{X}_{RM} \end{aligned} \tag{4.6}$$

Conclusion

Using the limited data set available for this study, analysis shows that the Hata model can be successfully used to predict propagation for 900 MHz spread spectrum radio systems. The scope of this project is narrow and results are only valid in that narrow scope. Specifically, the propagation paths in this study are short, varying from approximately 1 kilometer to 4 kilometers in length. Terrain varied from virtually flat to large hills. Building density and height ranged from none through United States standard residential to business districts. Terrain variation and building density tend to create difficult propagation paths, while short paths tend to make propagation easily predictable.

Data analysis showed that using the Suburban or Semi-rural variations of the Hata model, prediction of spread spectrum propagation was fairly simple and statistically accurate. All other variations of the Hata model, (Rural, Large City, Large City with Large City $A(h_m)$ and Urban) failed to properly predict propagation losses.

The results of this study clearly show that Hata's Suburban and Semi-rural models, implemented in a simple spreadsheet form, can be used to predict signal strength for the City of Denton's 900 MHz spread spectrum traffic signal control system.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Analysis of the data in this study reveal that Hata's models vary widely in accuracy when used as a means to predict propagation for short path 900 MHz spread spectrum radio systems. The Hata model is particularly appropriate for this application, as it does not require a terrain database to predict propagation. Other models, particularly any of the Longley-Rice models, require a terrain database in order to predict propagation losses. The Hata model can be implemented using a simple spreadsheet program to obtain accurate path prediction results provided the proper variation of the model is chosen. For the City of Denton application addressed in this study, Hata's Semi-rural model provides the most statistically accurate prediction of received signal strength.

Recommendations

Recommendations for further research

1. A study should be undertaken using individual propagation paths for data collection.
2. Data for the above-recommended study should be taken over the course of several weeks and/or months.
3. Similar studies should be undertaken in other cities.

APPENDIX A

TERRAIN DATA

Table 7. Lillian Miller at Hickory Creek Terrain Data

	Distance (ft)	Elevation(ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	18590	0	1.064	0.0
	1070	640	754.2	721.5	787.0	17520	1070	1.064	32.8
	1270	640	753.2	717.7	788.7	17320	1270	1.064	35.5
	1850	640	750.0	707.9	792.1	16740	1850	1.064	42.1
	2400	640	747.1	699.9	794.2	16190	2400	1.064	47.2
	3020	640	743.8	691.9	795.6	15570	3020	1.064	51.9
	3530	640	741.0	685.9	796.2	15060	3530	1.064	55.2
	3800	650	739.6	682.8	796.3	14790	3800	1.064	56.7
	3900	660	739.0	681.8	796.3	14690	3900	1.064	57.3
	4300	670	736.9	677.6	796.2	14290	4300	1.064	59.3
	4590	680	735.3	674.7	796.0	14000	4590	1.064	60.6
	4900	680	733.6	671.7	795.6	13690	4900	1.064	62.0
	5070	670	732.7	670.1	795.4	13520	5070	1.064	62.6
	6010	660	727.7	661.9	793.5	12580	6010	1.064	65.8
	6190	650	726.7	660.4	793.0	12400	6190	1.064	66.3
	6600	640	724.5	657.2	791.8	11990	6600	1.064	67.3
	8220	630	715.8	645.9	785.6	10370	8220	1.064	69.8
	8670	630	713.4	643.2	783.5	9920	8670	1.064	70.2
	8850	640	712.4	642.2	782.6	9740	8850	1.064	70.2
	9350	640	709.7	639.4	780.0	9240	9350	1.064	70.3
	9910	630	706.7	636.5	776.9	8680	9910	1.064	70.2
	10750	630	702.2	632.7	771.6	7840	10750	1.064	69.5
	11000	640	700.8	631.7	770.0	7590	11000	1.064	69.1
	12220	640	694.3	627.5	761.0	6370	12220	1.064	66.7
	12450	630	693.0	626.9	759.2	6140	12450	1.064	66.1
	12670	630	691.8	626.3	757.4	5920	12670	1.064	65.5
	13150	630	689.3	625.3	753.3	5440	13150	1.064	64.0
	13650	630	686.6	624.4	748.7	4940	13650	1.064	62.1
	14050	630	684.4	624.0	744.8	4540	14050	1.064	60.4
	14620	620	681.4	623.7	739.0	3970	14620	1.064	57.6
	15420	610	677.1	624.2	729.9	3170	15420	1.064	52.9
	18005	610	663.1	638.6	687.7	585	18005	1.064	24.6
LM&Hick Cr	18590	600	660.0	660.0	660.0	0	18590	1.064	0.0

Table 8. Lillian Miller at Teasley Lane Terrain Data

LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
760.0	760.0	760.0	8410	0	1.064	0.0
758.5	745.2	771.8	8240	170	1.064	13.3
749.4	716.4	782.4	7220	1190	1.064	33.0
746.6	710.4	782.8	6910	1500	1.064	36.2
745.5	708.1	782.9	6780	1630	1.064	37.4
743.1	703.5	782.6	6510	1900	1.064	39.6
736.5	692.7	780.4	5780	2630	1.064	43.9
735.0	690.5	779.6	5610	2800	1.064	44.6
729.6	683.1	776.0	5000	3410	1.064	46.4
727.0	680.0	774.0	4710	3700	1.064	47.0
725.2	678.0	772.4	4510	3900	1.064	47.2
723.9	676.6	771.1	4360	4050	1.064	47.3
721.9	674.6	769.2	4140	4270	1.064	47.3
719.9	672.7	767.1	3910	4500	1.064	47.2
718.8	671.7	765.9	3790	4620	1.064	47.1
713.9	667.9	759.9	3240	5170	1.064	46.0
711.9	666.6	757.3	3020	5390	1.064	45.4
711.0	666.0	756.0	2910	5500	1.064	45.0
709.0	664.9	753.1	2690	5720	1.064	44.1
708.1	664.4	751.8	2590	5820	1.064	43.7
705.2	663.2	747.1	2260	6150	1.064	41.9
704.3	662.9	745.6	2160	6250	1.064	41.3
702.7	662.5	743.0	1990	6420	1.064	40.2
702.0	662.4	741.7	1910	6500	1.064	39.6
699.6	662.1	737.1	1640	6770	1.064	37.5
691.3	665.0	717.6	710	7700	1.064	26.3
688.6	668.4	708.7	400	8010	1.064	20.1
685.0	685.0	685.0	0	8410	1.064	0.0

Table 9. McKinney at Loop 288 Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760	760.00	760.00	7000	0	1.064	0.00
	450	640	751	729.83	772.17	6550	450	1.064	21.17
	1175	630	736.5	704.25	768.75	5825	1175	1.064	32.25
	1650	620	727	690.37	763.63	5350	1650	1.064	36.63
	1820	610	723.6	685.75	761.45	5180	1820	1.064	37.85
	2125	600	717.5	677.82	757.18	4875	2125	1.064	39.68
	2600	590	708	666.30	749.70	4400	2600	1.064	41.70
	2975	580	700.5	657.84	743.16	4025	2975	1.064	42.66
	3100	580	698	655.13	740.87	3900	3100	1.064	42.87
	3650	590	687	643.89	730.11	3350	3650	1.064	43.11
	3810	590	683.8	640.82	726.78	3190	3810	1.064	42.98
	4210	590	675.8	633.55	718.05	2790	4210	1.064	42.25
	4570	590	668.6	627.52	709.68	2430	4570	1.064	41.08
	4620	590	667.6	626.72	708.48	2380	4620	1.064	40.88
	5010	590	659.8	620.87	698.73	1990	5010	1.064	38.93
Mc & 288	7000	590	620	620.00	620.00	0	7000	1.064	0.00

Table 10. Lillian Miller at IH35E Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.00	760.00	4190	0	1.064	0.00
	175	650	756.4	743.09	769.81	4015	175	1.064	13.36
	1100	650	737.7	708.31	767.06	3090	1100	1.064	29.38
	1610	650	727.3	694.86	759.82	2580	1610	1.064	32.48
	1950	640	720.4	687.14	753.75	2240	1950	1.064	33.30
	2390	640	711.5	678.46	744.57	1800	2390	1.064	33.05
	2575	650	707.8	675.27	740.26	1615	2575	1.064	32.50
	3010	650	698.9	668.91	728.97	1180	3010	1.064	30.03
	3450	640	690.0	664.55	715.47	740	3450	1.064	25.46
	3750	640	683.9	663.46	704.40	440	3750	1.064	20.47
	4000	650	678.9	664.96	692.75	190	4000	1.064	13.89
LM & 35	4190	645	675.0	675.00	675.00	0	4190	1.064	0.00

Table 11. Lillian Miller at Southridge Village Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.00	760.00	4710	0	1.064	0.00
	190	650	757.4	743.45	771.31	4520	190	1.064	13.93
	1075	650	745.2	715.45	774.88	3635	1075	1.064	29.71
	1650	650	737.2	703.46	771.00	3060	1650	1.064	33.77
	2020	640	732.1	697.09	767.16	2690	2020	1.064	35.04
	2380	640	727.2	691.76	762.55	2330	2380	1.064	35.39
	2500	650	725.5	690.17	760.83	2210	2500	1.064	35.33
	3075	650	717.6	683.86	751.26	1635	3075	1.064	33.70
	3450	640	712.4	681.05	743.73	1260	3450	1.064	31.34
	3920	650	705.9	679.45	732.35	790	3920	1.064	26.45
	4210	660	701.9	680.09	723.71	500	4210	1.064	21.81
	4580	670	696.8	685.20	708.39	130	4580	1.064	11.60
LM & SR Vill	4710	670	695.0	695.00	695.00	0	4710	1.064	0.00

Table 12. Lillian Miller at Southridge Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	6220	0	1.064	0.0
	650	650	754.8	710.0	799.5	5570	2840	1.064	44.7
	1500	660	747.9	701.0	794.9	4720	3690	1.064	46.9
	1650	660	746.7	699.6	793.9	4570	3840	1.064	47.1
	1900	650	744.7	697.4	792.0	4320	4090	1.064	47.3
	1900	640	744.7	697.4	792.0	4320	4090	1.064	47.3
	2390	650	740.8	693.7	787.9	3830	4580	1.064	47.1
	2610	650	739.0	692.2	785.8	3610	4800	1.064	46.8
	3400	660	732.7	688.0	777.3	2820	5590	1.064	44.7
	4200	670	726.2	685.8	766.6	2020	6390	1.064	40.4
	4400	680	724.6	685.7	763.6	1820	6590	1.064	39.0
	4800	690	721.4	686.0	756.9	1420	6990	1.064	35.4
	5175	680	718.4	687.2	749.6	1045	7365	1.064	31.2
	5280	670	717.6	687.8	747.4	940	7470	1.064	29.8
	5550	670	715.4	689.8	741.0	670	7740	1.064	25.6
	5750	680	713.8	692.0	735.5	470	7940	1.064	21.7
	6000	690	711.8	696.7	726.9	220	8190	1.064	15.1
LM & SR	6220	680	710.0	710.0	710.0	0	8410	1.064	0.0

Table 13. Loop 288 at Spencer Road Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	4390	0	1.064	0.0
	400	650	749.2	729.6	768.9	3990	400	1.064	19.7
	725	640	740.5	715.1	765.9	3665	725	1.064	25.4
	1350	630	723.7	692.2	755.3	3040	1350	1.064	31.5
	2000	620	706.2	672.2	740.3	2390	2000	1.064	34.0
	2350	610	696.8	662.7	730.9	2040	2350	1.064	34.1
	2500	600	692.8	659.0	726.6	1890	2500	1.064	33.8
	2650	610	688.8	655.3	722.2	1740	2650	1.064	33.4
	2820	620	684.2	651.4	717.0	1570	2820	1.064	32.8
	3475	620	666.6	638.8	694.4	915	3475	1.064	27.8
	3800	610	657.9	634.5	681.2	590	3800	1.064	23.3
288 & Spencer	4390	612	642.0	642.0	642.0	0	4390	1.064	0.0

Table 14. Loop 288 at Brinker Road Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	3850	0	1.064	0.0
	400	650	749.2	729.7	768.7	3450	400	1.064	19.5
	750	640	739.7	714.4	765.1	3100	750	1.064	25.3
	1010	630	732.7	704.6	760.9	2840	1010	1.064	28.2
	1400	620	722.2	691.4	753.0	2450	1400	1.064	30.8
	2000	610	706.0	674.0	738.0	1850	2000	1.064	32.0
	2750	600	685.7	656.8	714.6	1100	2750	1.064	28.9
	3125	610	675.6	650.6	700.6	725	3125	1.064	25.0
	3500	620	665.5	647.1	683.9	350	3500	1.064	18.4
288 & Brinker	3850	626	656.0	656.0	656.0	0	3850	1.064	0.0

Table 15. Loop 288 at Colorado Street Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	3400	0	1.064	0.0
	250	650	754.1	738.4	769.8	3150	250	1.064	15.7
	800	640	741.2	715.7	766.7	2600	800	1.064	25.5
	1410	630	726.8	697.2	756.5	1990	1410	1.064	29.6
	2600	630	698.8	673.3	724.3	800	2600	1.064	25.5
288 & Colorado	3400	650	680.0	680.0	680.0	0	3400	1.064	0.0

Table 16. Loop 288 at Mall Entrance Terrain Data

	Distance (ft)	Elevation (ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	3650	0	1.064	0.0
	1070	640	732.2	703.8	760.5	2580	1070	1.064	28.4
	1270	640	726.9	697.3	756.6	2380	1270	1.064	29.7
	1850	640	711.8	680.7	743.0	1800	1850	1.064	31.2
	2400	640	697.5	668.0	727.1	1250	2400	1.064	29.6
	3020	640	681.4	657.8	704.9	630	3020	1.064	23.6
	3530	640	668.1	657.0	679.2	120	3530	1.064	11.1
288 & Mall Ent	3650	645	665.0	665.0	665.0	0	3650	1.064	0.0

Table 17. Lillian Miller at Ryan Road Terrain Data

	Distance (ft)	Elevation(ft)	LOS Path	Lower Fresnel Zone	Upper Fresnel Zone	D1	D2	λ (ft @925 MHz)	Fresnel Zone Radius (ft)
Spencer	0	650	760.0	760.0	760.0	13275	0	1.064	0.0
	100	650	759.3	749.0	769.6	13175	100	1.064	10.3
	1000	640	752.8	721.5	784.2	12275	1000	1.064	31.4
	1800	640	747.1	706.4	787.8	11475	1800	1.064	40.7
	2350	640	743.2	697.8	788.5	10925	2350	1.064	45.4
	2500	650	742.1	695.6	788.6	10775	2500	1.064	46.5
	2750	650	740.3	692.2	788.5	10525	2750	1.064	48.2
	2975	640	738.7	689.2	788.3	10300	2975	1.064	49.6
	3420	640	735.5	683.6	787.5	9855	3420	1.064	52.0
	5010	630	724.1	666.5	781.8	8265	5010	1.064	57.6
	5900	640	717.8	658.7	776.8	7375	5900	1.064	59.1
	6250	650	715.3	656.0	774.6	7025	6250	1.064	59.3
	7420	640	706.9	647.9	765.9	5855	7420	1.064	59.0
	8650	630	698.1	641.5	754.7	4625	8650	1.064	56.6
	9030	640	695.4	639.9	750.8	4245	9030	1.064	55.4
	9420	640	692.6	638.6	746.5	3855	9420	1.064	53.9
	9850	630	689.5	637.5	741.5	3425	9850	1.064	52.0
	11500	630	677.7	637.3	718.2	1775	11500	1.064	40.4
	11775	640	675.7	638.1	713.4	1500	11775	1.064	37.6
	11925	650	674.7	638.7	710.6	1350	11925	1.064	35.9
	12075	640	673.6	639.5	707.7	1200	12075	1.064	34.1
	12380	630	671.4	641.6	701.2	895	12380	1.064	29.8
	12990	630	667.0	649.8	684.3	285	12990	1.064	17.2
LM & Ryan	13275	640	665.0	665.0	665.0	0	13275	1.064	0.0

Figure 17. Spencer to Lillian Miller & Hickory Creek Fresnel Zone

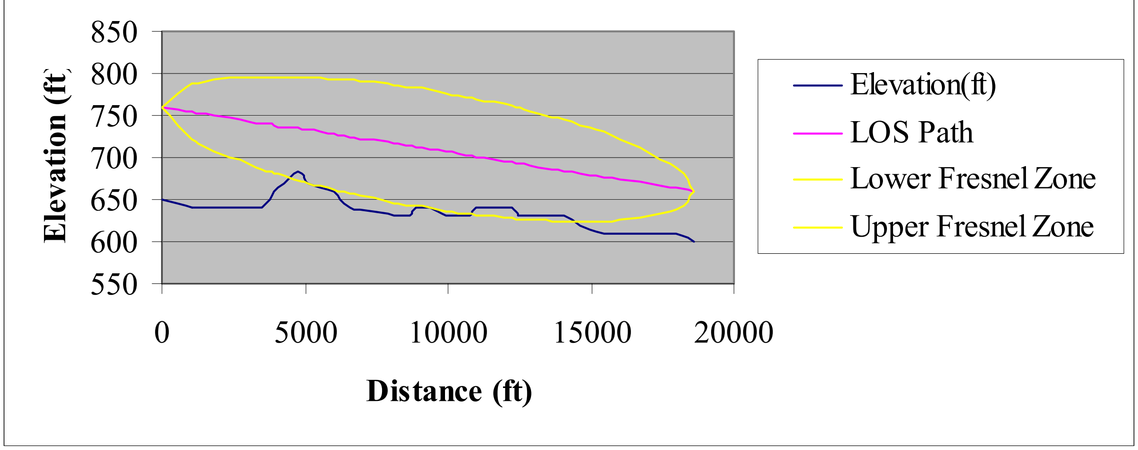


Figure 18. Spencer to Lillian Miller & Teasley Fresnel Zone

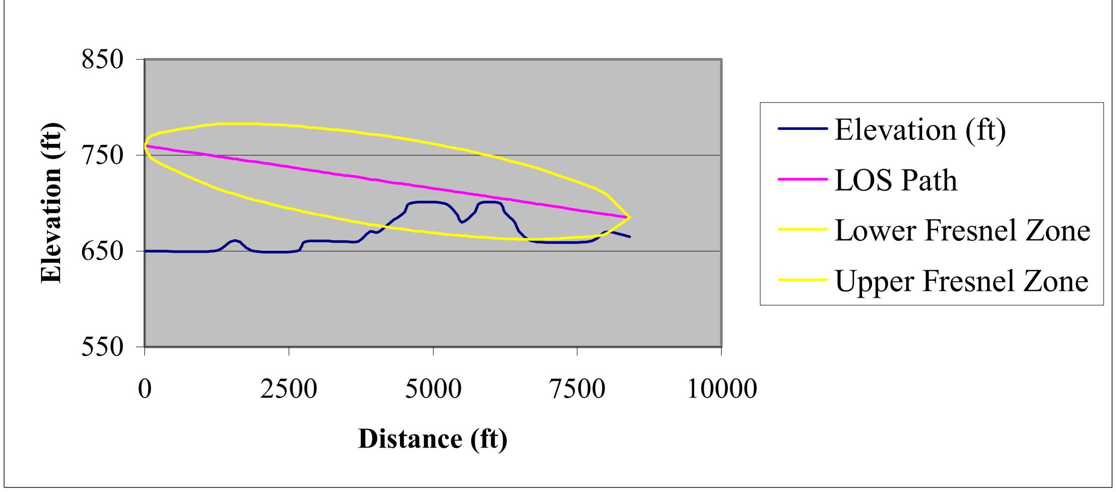


Figure 19. Spencer to McKinney & LP 288 Fresnel Zone

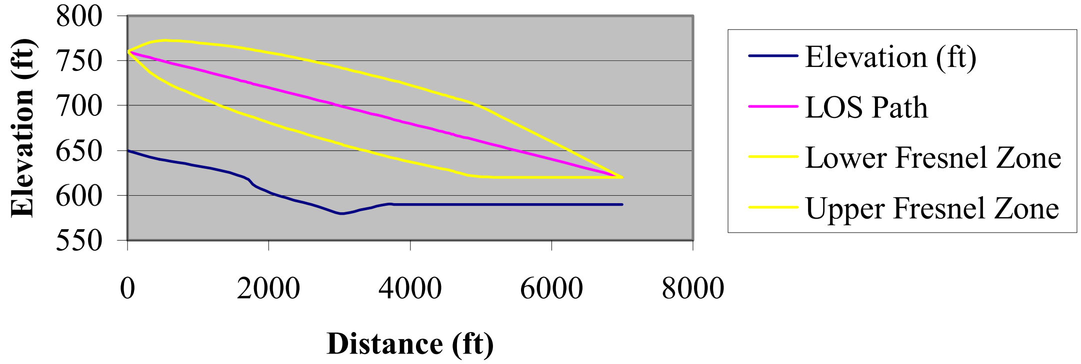


Figure 20. Spencer to Lillian Miller & IH35E Fresnel Zone

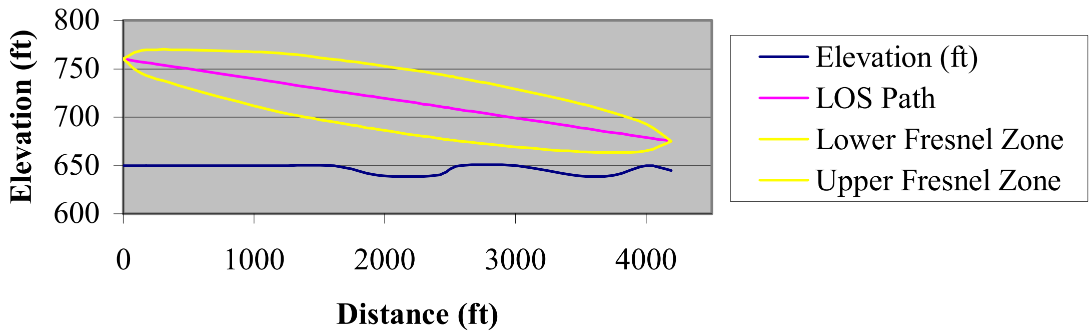


Figure 21. Spencer to Lillian Miller & Southridge Village Fresnel Zone

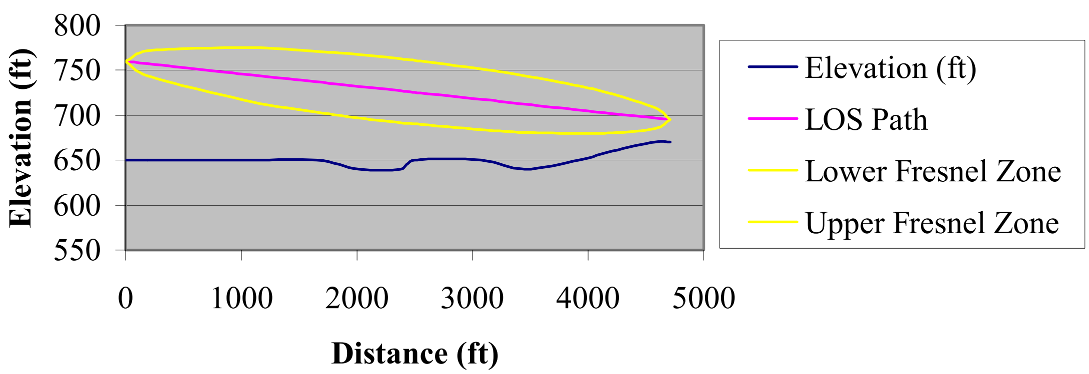


Figure 22. Spencer to Lillian Miller & Southridge Fresnel Zone

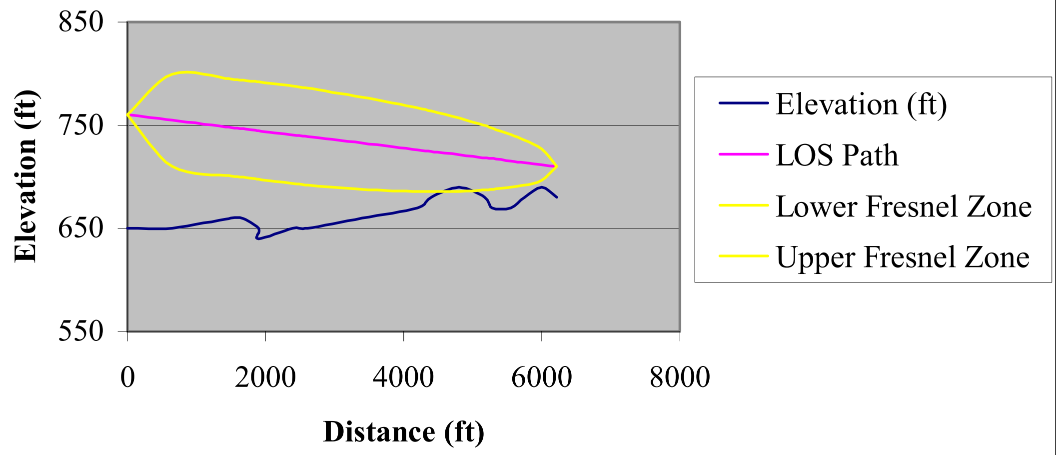


Figure 23. Spencer to 288 & Spencer Road Fresnel Zone

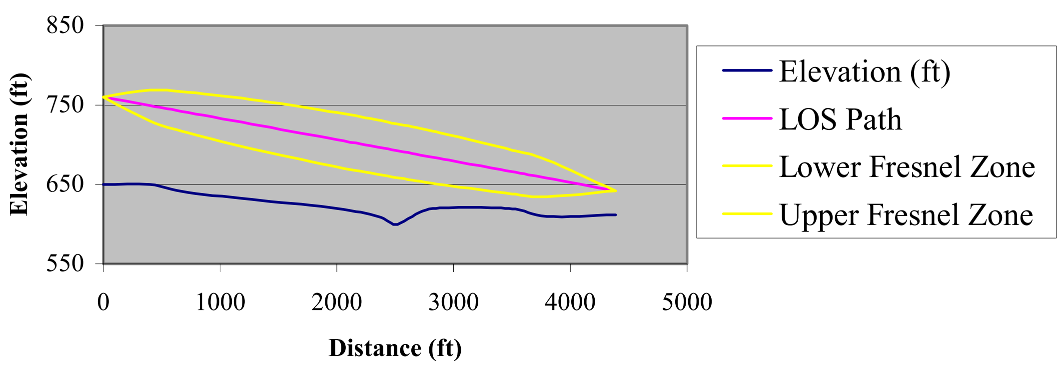


Figure 24. Spencer to 288 & Brinker Road Fresnel Zone

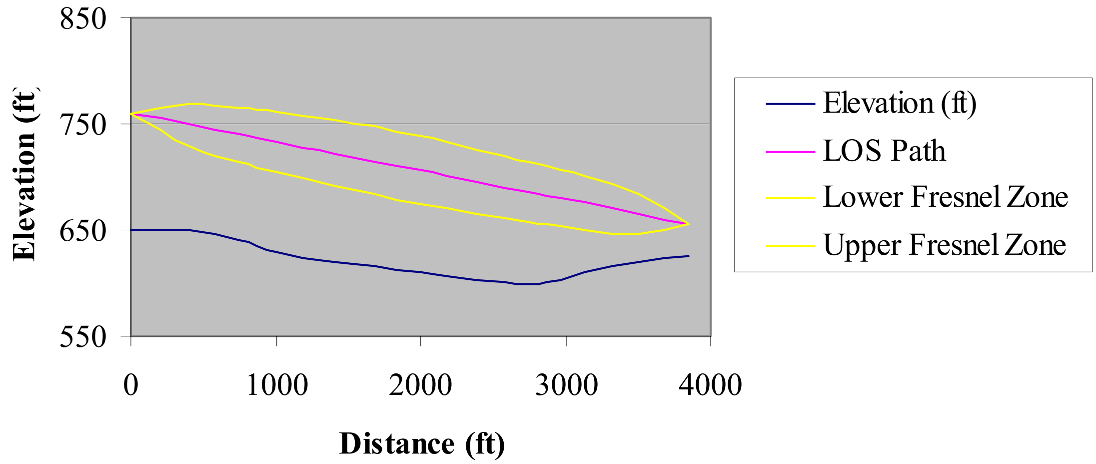


Figure 25. Spencer to 288 & Colorado Street Fresnel Zone

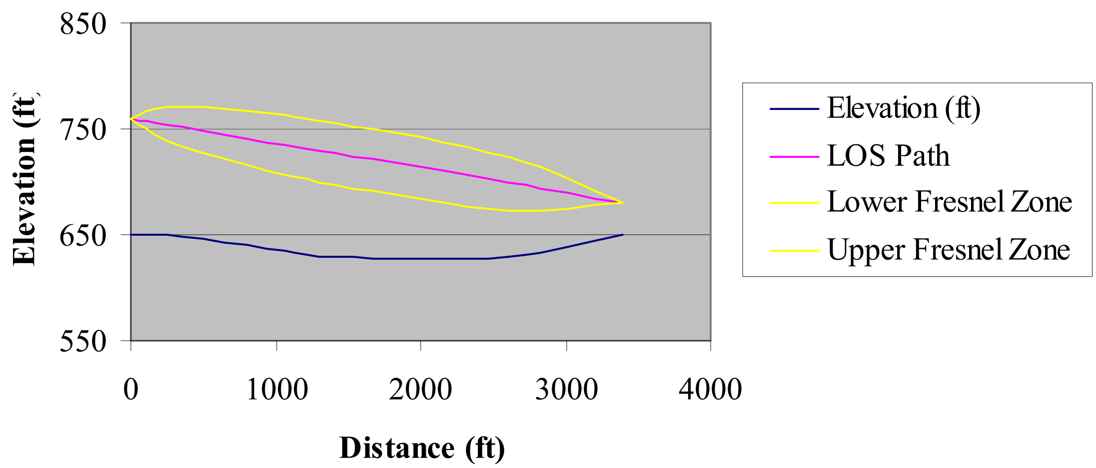


Figure 26. Spencer to 288 & Mall Entrance Fresnel Zone

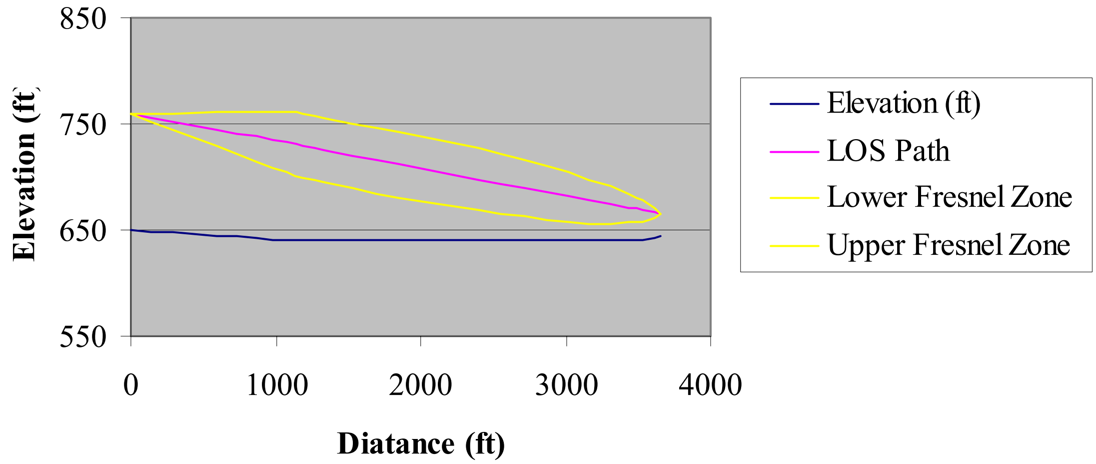
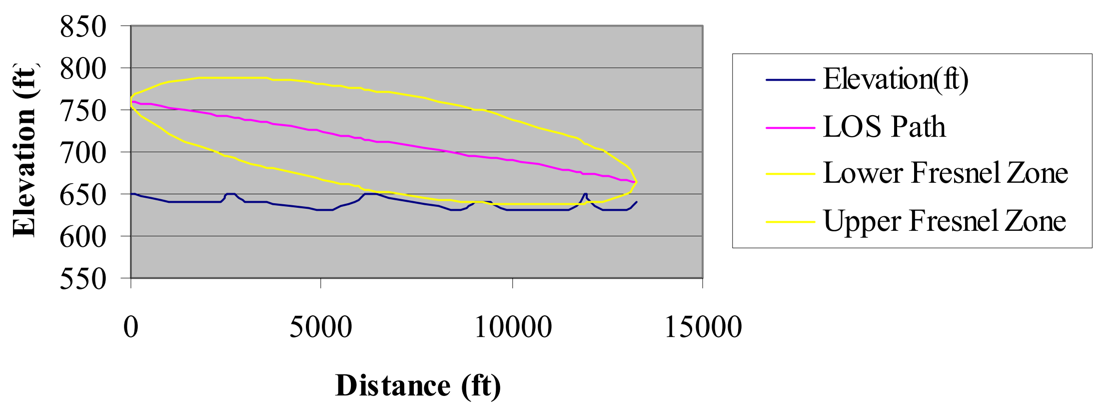


Figure 27. Spencer to Lillian Miller & Ryan Road Fresnel Zone



APPENDIX B

PATH LOSS CALCULATIONS

Table 18. Fixed Gain and Loss Calculations

Site	Transmitter Power (dBm)	Transmission Line Length (ft)	Transmission Line Length (m)	Line Loss Per 100 meters (dB)	Total Line Loss (db)	Connector Loss (dB per connector)	Number of Connectors	Total Connector Loss (dB)	Other Losses (db)	Antenna Gain (dBd)	Total Gain (db)	Transmit Antenna Height (ft) AGL	Transmit Antenna Height (m) AGL	Receive Antenna Height (ft) AGL	Receive Antenna Height (m) AGL
Spencer Tower	30	120	36.57	4.2	1.53	1	2	2	4	10	32.4	110	33.5	110	33.5
IH 35E & Loop 288	30	100	30.48	8.2	2.49	1	2	2	3	6.5	-0.99	110	33.5	30	9.14
Teasley & Hickory Creek	30	40	12.19	8.2	1.00	1	2	2	3	7	1.00	110	33.5	25	7.62
Teasley & Ryan Rd	30	40	12.19	8.2	1.00	1	2	2	3	6.5	0.50	110	33.5	25	7.62
Lillian Miller & Teasley	30	40	12.19	8.2	1.00	1	2	2	3	6.5	0.50	110	33.5	30	9.14
Lillian Miller & Southridge	30	50	15.24	8.2	1.25	1	2	2	3	6.5	0.25	110	33.5	20	6.09
Lillian Miller & Southridger Village	30	45	13.71	8.2	1.12	1	2	2	3	6.5	0.37	110	33.5	25	7.62
Loop 288 & Mall Entrance	30	35	10.66	8.2	0.87	1	2	2	3	6.5	0.62	110	33.5	20	6.09
Loop 288 & Colorado	30	45	13.71	8.2	1.12	1	2	2	3	6.5	0.37	110	33.5	30	9.14
Loop 288 & Brinker	30	30	9.14	8.2	0.75	1	2	2	3	6.5	0.75	110	33.5	30	9.14
Loop 288 & Spencer	30	30	9.14	8.2	0.75	1	2	2	3	6.5	0.75	110	33.5	30	9.14
Loop 288 & Morse	30	20	6.09	8.2	0.50	1	2	2	3	6.5	1.00	110	33.5	20	6.09
Loop 288 & McKinney	30	60	18.28	8.2	1.50	1	2	2	3	6.5	0.00	110	33.5	30	9.14

Table 19. Hata Model Calculations

Site	Frequency (MHz)	Loss (dBm) (urban area)	Loss (dBm) (suburban area)	Loss (dBm) (quasi rural area	Loss (dBm) (rural open area)	Small City A*hre*	Large City A*hre*	Loss (dBm) (urban area using Large City A*hre)*
IH 35E & Loop 288	902.220	110.468	100.519	86.951	81.951	19.515	8.232	121.751
	905.400	110.495	100.537	86.963	81.963	19.528	8.232	121.791
	908.600	110.522	100.555	86.975	81.975	19.541	8.232	121.831
	911.800	110.549	100.573	86.987	81.987	19.554	8.232	121.871
	915.800	110.583	100.595	87.001	82.001	19.570	8.232	121.921
	921.400	110.630	100.625	87.022	82.022	19.592	8.232	121.990
	924.600	110.656	100.643	87.033	82.033	19.605	8.232	122.029
	927.775	110.683	100.660	87.044	82.044	19.618	8.232	122.068
Teasley & Hickory Creek	902.220	136.543	126.594	113.026	108.026	15.627	7.223	144.947
	905.400	136.572	126.614	113.040	108.040	15.638	7.223	144.987
	908.600	136.602	126.634	113.054	108.054	15.648	7.223	145.027
	911.800	136.631	126.655	113.069	108.069	15.658	7.223	145.067
	915.800	136.668	126.680	113.086	108.086	15.671	7.223	145.117
	921.400	136.719	126.715	113.111	108.111	15.689	7.223	145.186
	924.600	136.748	126.735	113.125	108.125	15.700	7.223	145.225
	927.775	136.777	126.755	113.139	108.139	15.710	7.223	145.264
Teasley & Ryan Rd	902.220	131.461	121.512	107.944	102.944	15.627	7.223	139.865
	905.400	131.491	121.532	107.958	102.958	15.638	7.223	139.905
	908.600	131.520	121.553	107.973	102.973	15.648	7.223	139.945
	911.800	131.550	121.573	107.987	102.987	15.658	7.223	139.985
	915.800	131.587	121.598	108.005	103.005	15.671	7.223	140.035
	921.400	131.638	121.633	108.030	103.030	15.689	7.223	140.104
	924.600	131.667	121.653	108.044	103.044	15.700	7.223	140.144
	927.775	131.696	121.673	108.058	103.058	15.710	7.223	140.183
Lillian Miller & Teasley	902.220	120.710	110.761	97.193	92.193	19.515	8.232	131.993
	905.400	120.737	110.779	97.205	92.205	19.528	8.232	132.033
	908.600	120.764	110.797	97.217	92.217	19.541	8.232	132.073
	911.800	120.791	110.814	97.228	92.228	19.554	8.232	132.113
	915.800	120.825	110.836	97.243	92.243	19.570	8.232	132.162
	921.400	120.871	110.867	97.263	92.263	19.592	8.232	132.232
	924.600	120.898	110.885	97.275	92.275	19.605	8.232	132.271
	927.775	120.924	110.902	97.286	92.286	19.618	8.232	132.310

Site	Frequency (MHz)	Loss (dBm) (urban area)	Loss (dBm) (suburban area)	Loss (dBm) (quasi rural area	Loss (dBm) (rural open area)	Small City A*hre*	Large City A*hre*	Loss (dBm) (urban area using Large City A*hre)*
Lillian Miller & Southridge	902.220	123.970	114.021	100.453	95.453	11.740	6.042	129.668
	905.400	124.002	114.044	100.470	95.470	11.748	6.042	129.708
	908.600	124.034	114.067	100.487	95.487	11.755	6.042	129.748
	911.800	124.067	114.090	100.504	95.504	11.763	6.042	129.788
	915.800	124.107	114.118	100.525	95.525	11.773	6.042	129.837
	921.400	124.162	114.158	100.554	95.554	11.787	6.042	129.907
	924.600	124.194	114.180	100.571	95.571	11.794	6.042	129.946
	927.775	124.225	114.203	100.587	95.587	11.802	6.042	129.985
Lillian Miller & Southridger Village	902.220	116.082	106.133	92.565	87.565	15.627	7.223	124.486
	905.400	116.111	106.153	92.579	87.579	15.638	7.223	124.526
	908.600	116.141	106.173	92.594	87.594	15.648	7.223	124.566
	911.800	116.170	106.194	92.608	87.608	15.658	7.223	124.606
	915.800	116.207	106.219	92.626	87.626	15.671	7.223	124.656
	921.400	116.258	106.254	92.650	87.650	15.689	7.223	124.725
	924.600	116.288	106.274	92.664	87.664	15.700	7.223	124.764
	927.775	116.316	106.294	92.678	87.678	15.710	7.223	124.803
Loop 288 & Mall Entrance	902.220	115.994	106.044	92.477	87.477	11.740	6.042	121.691
	905.400	116.026	106.067	92.493	87.493	11.748	6.042	121.731
	908.600	116.058	106.090	92.510	87.510	11.755	6.042	121.771
	911.800	116.090	106.113	92.527	87.527	11.763	6.042	121.811
	915.800	116.130	106.142	92.548	87.548	11.773	6.042	121.861
	921.400	116.186	106.181	92.577	87.577	11.787	6.042	121.930
	924.600	116.217	106.204	92.594	87.594	11.794	6.042	121.969
	927.775	116.248	106.226	92.610	87.610	11.802	6.042	122.008
Loop 288 & Colorado	902.220	105.024	95.075	81.507	76.507	19.515	8.232	116.307
	905.400	105.051	95.093	81.519	76.519	19.528	8.232	116.347
	908.600	105.078	95.111	81.531	76.531	19.541	8.232	116.387
	911.800	105.105	95.129	81.543	76.543	19.554	8.232	116.427
	915.800	105.139	95.151	81.557	76.557	19.570	8.232	116.477
	921.400	105.186	95.181	81.578	76.578	19.592	8.232	116.546
	924.600	105.212	95.199	81.589	76.589	19.605	8.232	116.585
	927.775	105.239	95.216	81.600	76.600	19.618	8.232	116.624

Site	Frequency (MHz)	Loss (dBm) (urban area)	Loss (dBm) (suburban area)	Loss (dBm) (quasi rural area	Loss (dBm) (rural open area)	Small City A*hre*	Large City A*hre*	Loss (dBm) (urban area using Large City A*hre)*
Loop 288 & Brinker	902.220	108.902	98.953	85.385	80.385	19.515	8.232	120.184
	905.400	108.929	98.970	85.396	80.396	19.528	8.232	120.224
	908.600	108.956	98.988	85.408	80.408	19.541	8.232	120.264
	911.800	108.983	99.006	85.420	80.420	19.554	8.232	120.304
	915.800	109.016	99.028	85.435	80.435	19.570	8.232	120.354
	921.400	109.063	99.059	85.455	80.455	19.592	8.232	120.423
	924.600	109.090	99.076	85.466	80.466	19.605	8.232	120.463
	927.775	109.116	99.093	85.478	80.478	19.618	8.232	120.501
Loop 288 & Spencer	902.220	110.500	100.551	86.983	81.983	19.515	8.232	121.782
	905.400	110.527	100.568	86.995	81.995	19.528	8.232	121.822
	908.600	110.554	100.586	87.006	82.006	19.541	8.232	121.862
	911.800	110.581	100.604	87.018	82.018	19.554	8.232	121.902
	915.800	110.614	100.626	87.033	82.033	19.570	8.232	121.952
	921.400	110.661	100.657	87.053	82.053	19.592	8.232	122.021
	924.600	110.688	100.674	87.065	82.065	19.605	8.232	122.061
	927.775	110.714	100.691	87.076	82.076	19.618	8.232	122.100
Loop 288 & Morse	902.220	121.787	111.838	98.270	93.270	11.740	6.042	127.485
	905.400	121.819	111.861	98.287	93.287	11.748	6.042	127.525
	908.600	121.852	111.884	98.304	93.304	11.755	6.042	127.565
	911.800	121.884	111.907	98.321	93.321	11.763	6.042	127.605
	915.800	121.924	111.935	98.342	93.342	11.773	6.042	127.654
	921.400	121.979	111.975	98.371	93.371	11.787	6.042	127.724
	924.600	122.011	111.997	98.388	93.388	11.794	6.042	127.763
	927.775	122.042	112.020	98.404	93.404	11.802	6.042	127.802
Loop 288 & McKinney	902.220	117.999	108.050	94.482	89.482	19.515	8.232	129.281
	905.400	118.026	108.068	94.494	89.494	19.528	8.232	129.321
	908.600	118.053	108.086	94.506	89.506	19.541	8.232	129.362
	911.800	118.080	108.103	94.517	89.517	19.554	8.232	129.401
	915.800	118.114	108.125	94.532	89.532	19.570	8.232	129.451
	921.400	118.160	108.156	94.552	89.552	19.592	8.232	129.520
	924.600	118.187	108.173	94.564	89.564	19.605	8.232	129.560
	927.775	118.213	108.191	94.575	89.575	19.618	8.232	129.599

Table 20. Received Power Calculations

Spencer Tower to	Measured Received Power (dBm)	Large City Calculate Received Power (dBm)	Large City Calculated Received Power Large City Ahre (dBm)	Urban Calculated Received Power (dBm)	Suburban Calculated Received Power (dBm)	Semi-rural Calculated Received Power (dBm)	Rural Calculated Received Power (dBm)
Teasley & Hickory Creek	-75	-103.31	-111.80	-103.31	-93.29	-79.68	-74.68
Loop 288 & Mall Entrance	-60	-83.16	-88.92	-83.16	-73.14	-59.52	-54.52
Lillian Miller & Teasley	-74	-87.96	-99.35	-87.96	-77.94	-64.32	-59.32
Lillian Miller & Southridge Village	-74	-116.94	-125.43	-83.48	-73.45	-59.84	-54.84
Lillian Miller & Southridge	-72	-91.51	-97.27	-91.51	-81.49	-67.87	-62.87
Loop 288 & IH 35E	-73	-79.22	-90.60	-79.22	-69.20	-55.58	-50.58
Teasley & Ryan RD	-72	-98.73	-107.22	-98.73	-88.71	-75.09	-70.09
Loop 288 & Colorado	-60	-72.40	-83.79	-72.40	-62.38	-48.76	-43.76
Loop 288 & Brinker	-60	-75.90	-87.29	-75.90	-65.88	-52.26	-47.26
Loop 288 & Spencer	-60	-77.50	-88.89	-77.50	-67.48	-53.86	-48.86
Loop 288 & McKinney	-72	-85.75	-97.13	-85.75	-75.73	-62.11	-57.11

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