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Achieving Cochannel Interference Objectives Over Selected Topologies in the Portland, Oregon Cellular Network

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THESIS APPROVAL

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Department of Electrical Engineering

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ABSTRACT

An abstract of the thesis of David A. Wand for the Master of Science degree in Electrical Engineering presented June 5, 1997.

Title: Achieving Cochannel Interference Objectives Over Selected Topologies in the Portland Oregon Cellular Network

Wireless cellular mobile communications is a rapidly growing global technology which places increasing demands on a limited electromagnetic radio frequency spectrum. However, in North America only a 25 MHz block of spectrum has been allocated to each of two service providers. This must be utilized for all services offered within their assigned market.

The wireless cellular link from the mobile or portable phone to terrestrial base stations utilize this limited frequency spectrum. This is divided into 416 two-way channels, each 30 kHz in width, a subset of which is assigned to each base station. As more base stations are constructed, these channels are reused on a spatial basis causing increased intra-system interference in the service area. This interference can deteriorate voice service quality if it is not contained within industry accepted limits.

The 3 sector per cell, 7 cell per cluster cellular system design is utilized in many domestic markets. It is based on an early system model in which the random

characteristics of the interfering signals are simulated using a log-normal distribution. However, interference measurements in the Portland, Oregon cellular network, which also utilizes this design, confirms that the receive signal strength from combined interferers more closely follows a Rayleigh distribution. As a direct result, the mean interference level must be from 0.3 to 2.2 dB higher than previously thought to achieve acceptable network performance. This thesis shows that interference objectives for good voice quality cannot be met by a rigorous application of this design because it does not provide adequate spatial separation between base stations which have been constructed in an environment with relatively flat topology.

Measurements are made in various cellular network configurations and terrain topologies to help identify the primary contributors to poor interference. Cell sectoring, a method of isolating a portion of the interfering sources from the desired service area, is evaluated and does reduce interference. The severe terrain obstructions associated with hilly environments contribute additional interfering radio signal path loss. These are shown to have a profound impact on interference results in the cellular system.

ACHIEVING COCHANNEL INTERFERENCE OBJECTIVES OVER SELECTED TOPOLOGIES IN THE PORTLAND OREGON CELLULAR NETWORK

by
DAVID A. WAND

A thesis submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING

Portland State University
1997

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I am grateful to the many authors who have shared their work through writings in the wireless communications industry. This field is rich with new creative ideas, applications and advancements in theory, of which I have drawn only a small portion. The staff at the Electrical Engineering Department has provided a fine wireless communications curriculum which has formed a basis for my understanding of wireless communications. Especially notable are Dr. Fu Li's comprehensive two term Communication Design series and my advisor Dr. Y. C. Jenq's excellent two term course on Mobile Radio Communications. I further thank the secretarial staff for their all-around administrative assistance.

My thanks to the Portland RF Engineering team at AT&T Wireless Services whose invaluable technical support has allowed access to a working cellular network which I have used as a virtual field laboratory. They have generously provided the time and resources necessary for this research.

And a special thanks to my family, especially my wife Bobbie, who have supported me during the many hours in research, field testing, data analysis and word processing.

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CHAPTER I

INTRODUCTION

Cellular mobile communications was introduced in 1983 to provide high density wireless service. A limited portion of the 800 MHz electromagnetic radio frequency spectrum was assigned to each of two service providers in each of 51 Metropolitan Statistical Areas (MSA) in the United States. Each provider uses the "cellular" design which divides the coverage area into small "cells". With this concept, a subset of the available radio frequency (RF) channels are assigned to each cell where a cluster of cells use all the channels. These clusters are repeated throughout the serving area to increase voice channel capacity. As a result, mobile cellular communications has been an exploding industry, experiencing upwards of 40% annual growth.

A disadvantage of this reuse method is the creation of interference from within the system. A mobile unit may receive a "foreign" RF channel from a neighboring cell in addition to the RF channel from a serving cell. This causes intra-system interference which contributes to high noise levels in analog cellular service and Intersymbol Interference (ISI) in digital service. Controlling interference is crucial to providing quality mobile cellular service.

Cellular networks are designed to contain this interference within industry accepted limits. In practice, however, the cellular networks are constructed in non-ideal geographic environments and can actually experience interference levels which cause poor service quality. This thesis will demonstrate that these limits are not achievable in a high density working cellular network with the current design philosophy. Analysis of field measurements will be used to determine that the industry standard cellular network design meets expectations only in hilly rural topologies.

Chapter II will first explain several basic components and how the radio frequency spectrum is utilized within the North American Cellular System (NACS). Then the definition and causes of interference will be discussed as well as identifying interference as it will be addressed in this thesis. The practice of sectoring the cellular system is also discussed. In Chapter III a procedure for making interference field measurements in the cellular network based on the mobile radio transmission model is developed and validated.

A mobile radio signal path loss model is discussed in Chapter IV and how it's parameters affect interference. This also includes a method for calculating interference from measured data. Chapter V contains a description of the tests that were performed, the reasoning used in selecting the test routes and their characteristics. In this chapter, a sectored cellular system is field simulated. Measured data is used to show that interference is not meeting industry standards for good quality voice service in 3 out of the 4 tests conducted.

Sectoring and the affects of severe terrain obstructions on interference are examined in Chapter VI. By simulating an omnidirectional system, cellular network sectoring was found to be effective and meets industry expectations, especially in urban settings. In rural hilly environments, the major contributor to meeting industry standards is the increased path loss due to severe terrain obstructions. Chapter VI will conclude and suggest related topics of further study.

CHAPTER II

A BRIEF OVERVIEW OF THE NORTH AMERICAN CELLULAR NETWORK

A. PRIMARY BASE STATION COMPONENTS

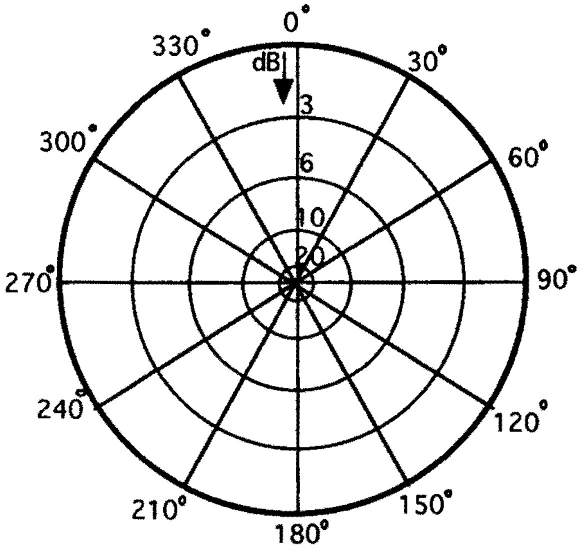
The wireless interface for the portable and mobile phone is to/from a transmitter/receiver housed in a terrestrial base station. Base stations are constructed by the cellular service provider in various locations throughout the serving area with one base station serving one cell. The direction of transmission from the portable to the base station is the up-link and the direction from the base station to the portable is the down-link. The base station contains the antenna systems, the antenna support structure and a building which houses radio transceivers, electronic control and multiplex equipment. Cable facilities or microwave systems are used to transport the voice conversations from the base station to the Public Switched Telephone Network (PSTN).

The size and shape of the area served in each cell is affected by the type of base station antenna deployed, either omnidirectional or directional. The omnidirectional antenna (sometimes abbreviated as "omni") radiates equal power in all azimuths (directions) in the H-plane, measured horizontally as if viewed from above. The directional antenna on the other hand has a dominant front lobe, which radiates with much greater power than in other directions. These exhibit a radiation pattern in the

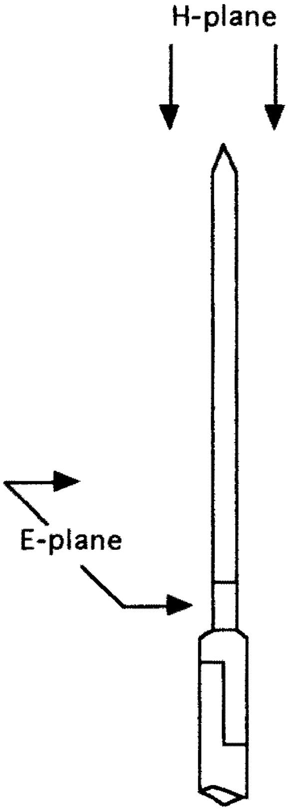
H-plane that has up to 30 dB more power emitted at the front of the antenna than at the back. This difference is called the front-to-back ratio. A second characteristic unique to the directional antenna is it's H-plane beam width. This is the width, in degrees, of the front lobe at the points where the radiated power is 3 dB lower than at the center of the main lobe. Typical 3 dB beam widths are 60°, 90°, 105° and 120°. Figure 1 illustrates a typical omnidirectional antenna and it's radiation pattern characteristics. Figure 2 illustrates a typical directional panel antenna and it's radiation pattern characteristics.

The gain of an antenna is the amount of radiation emitted over that of a $\lambda/2$ dipole antenna and can be expressed in dBd (decibels over dipole). The gain of a directional antenna is measured at the front lobe whereas the gain of an omnidirectional antenna is the same at all azimuths. Typical gains are 3, 6, 7.5, 10 and 12 dBd. Antenna gain and it's radiation pattern will affect the amount of power which is radiated in any given azimuth from the antenna and is referred to as the Transmit Effective Radiated Power (TXERP).

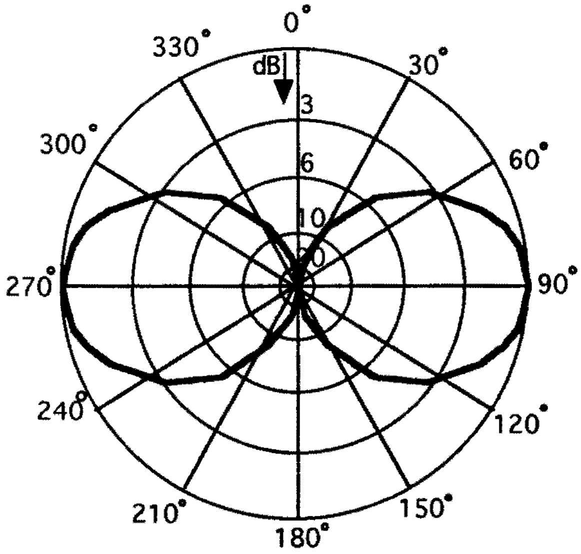
At the azimuth of the main lobe the TXERP will be maximum. At any other azimuth, it will be attenuated by the amount shown on the antenna radiation pattern (far-field radiation assumed).



H-plane
Horizontal pattern, V-polarization
Omnidirectional Antenna
Figure 1a

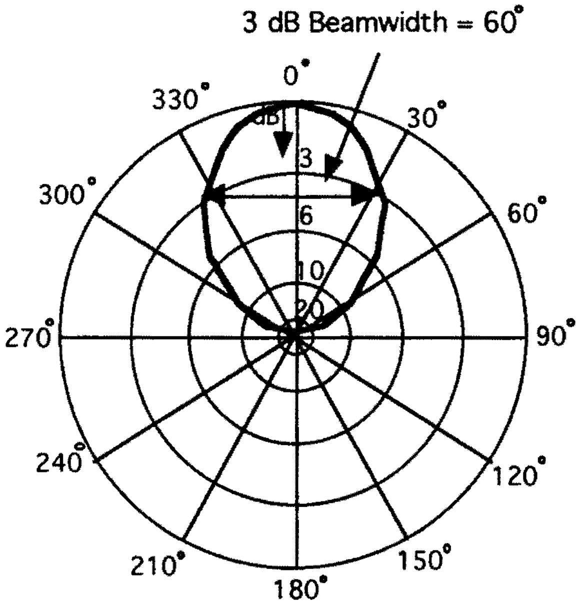


Omnidirectional Antenna
Figure 1c

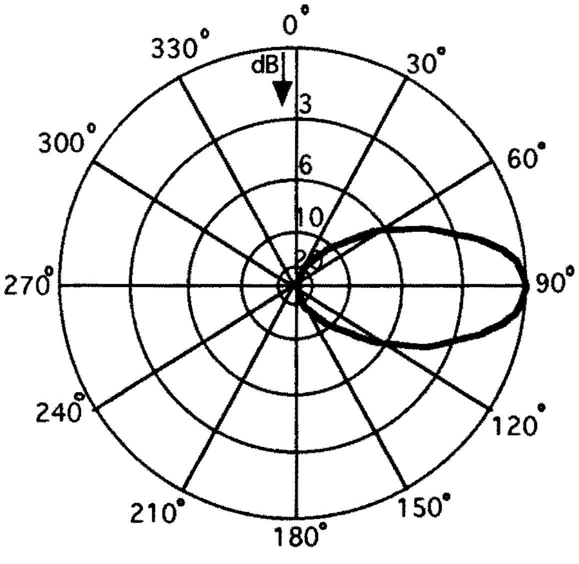


E-plane
Vertical pattern, V-polarization
Omnidirectional Antenna
Figure 1b

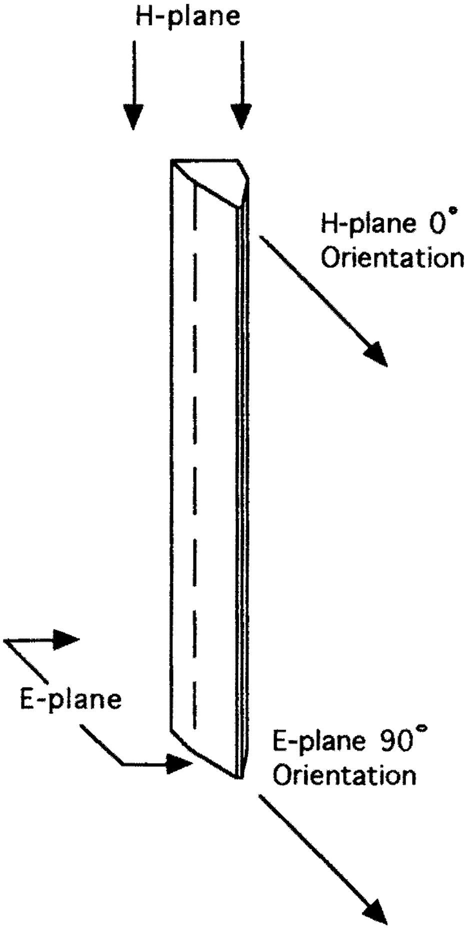
Figure 1: Omnidirectional Antenna and Radiation Patterns



H-plane
Horizontal pattern, V-polarization
Directional Panel Antenna
Figure 2a



E-plane
Vertical pattern, V-polarization
Directional Panel Antenna
Figure 2b



Directional Panel Antenna
Figure 2c

Figure 2: Directional Panel Antenna and Radiation Patterns

B. FREQUENCY ALLOCATION AND REUSE

The North American cellular Analog Mobile Phone Service (AMPS) standard allocates 25 MHz in the 800 - 900 MHz radio spectrum to each of two service providers. Each of these is divided into 832 30 kHz channels, which are matched into 416 frequency pairs for two-way wireless communications [8]. AMPS uses Frequency Modulation. A North American Digital Cellular (NADC) standard was established using Time Division Multiple Access (TDMA) such that each 30 kHz channel can transport 3 digitized compressed voice conversations using Vectored Sum Excited Linear Predictive (VSELP) coding and $\pi/4$ Differential Quadrature Phase Shift Key ($\pi/4$ DQPSK) modulation [9]. AMPS and TDMA digital service operate side by side in the 800 - 900 MHz frequency spectrum.

Each cellular service provider utilizes their assigned spectrum within a Metropolitan Statistical Area (MSA) to offer mobile phone service to multiple customers. Because this spectrum is limited, the cellular concept was established. With this philosophy, multiple base stations are deployed in the MSA each utilizing a fixed set of channels serving an area called a "cell". Collectively, the cells form a more or less honeycomb pattern. A predetermined number of cells are grouped together (typically 7) to form a cluster, which utilizes all the 416 channel pairs. These clusters are then repeated throughout the service area, allowing the radio frequency channels to be reused over the MSA. This cellular concept is illustrated in Figure 3. The number in each cell represents a frequency set used in that cell. Notice the reuse of frequency set 1 in the center cell of each 7 cell cluster. These cells utilize omnidirectional antennas and one frequency set consisting of 59 or 60 RF channels (416 RF channels per cluster divided by 7 cells per cluster = 59.4 channels per cell).

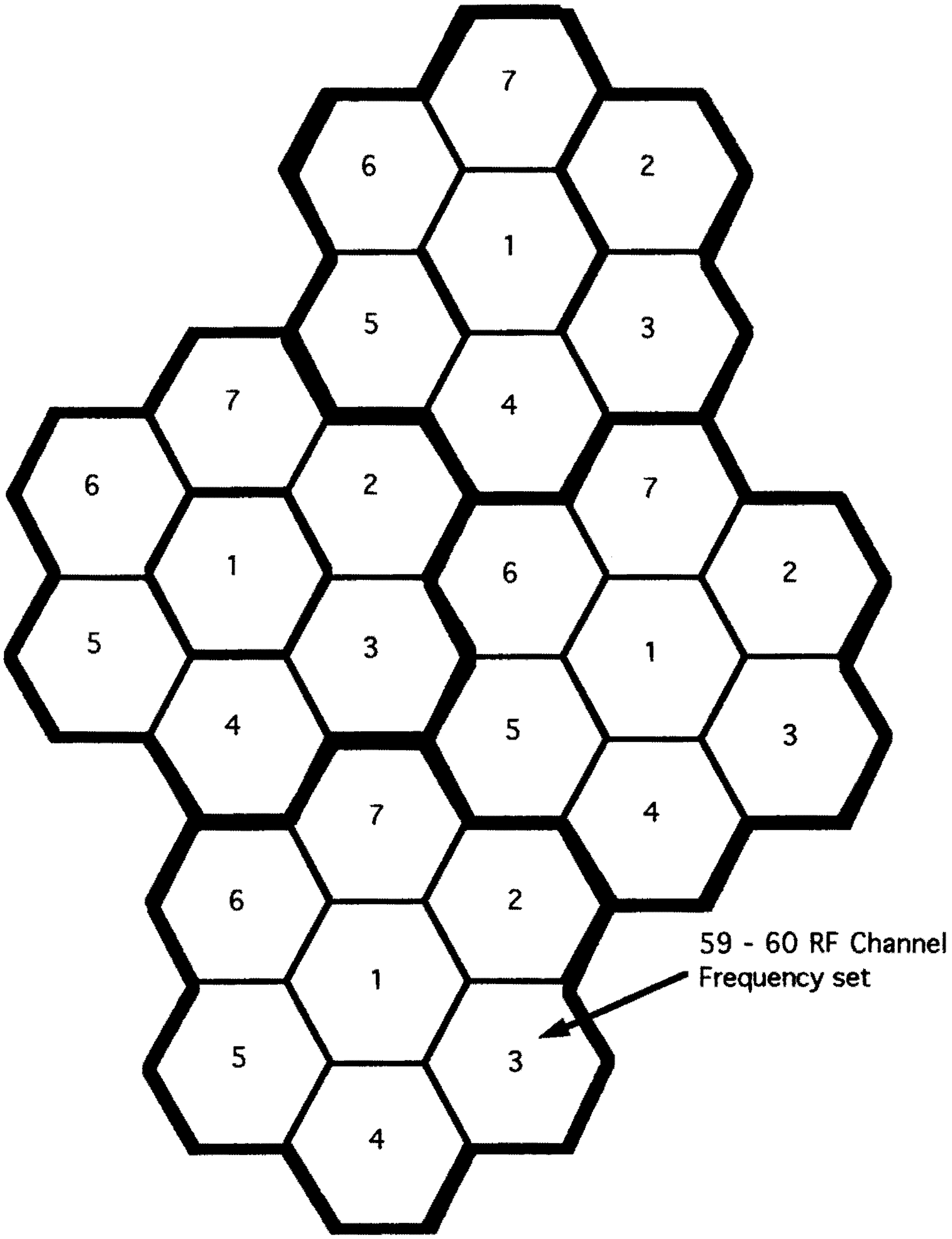


Figure 3: The Cellular Frequency Reuse Concept, Omnidirectional Antennas

Cells can be divided into sectors, typically 3 or 6 per cell, by utilizing directional antennas. This is done to reduce interference and is explained in the next section. Sectoring at 3 sectors per cell increases the number of frequency sets to 21, where each sector is assigned 19 or 20 channels (416 RF channels per cluster divided by 21 sectors per cluster = 19.8 channels per sector). This is illustrated in Figure 4 [4].

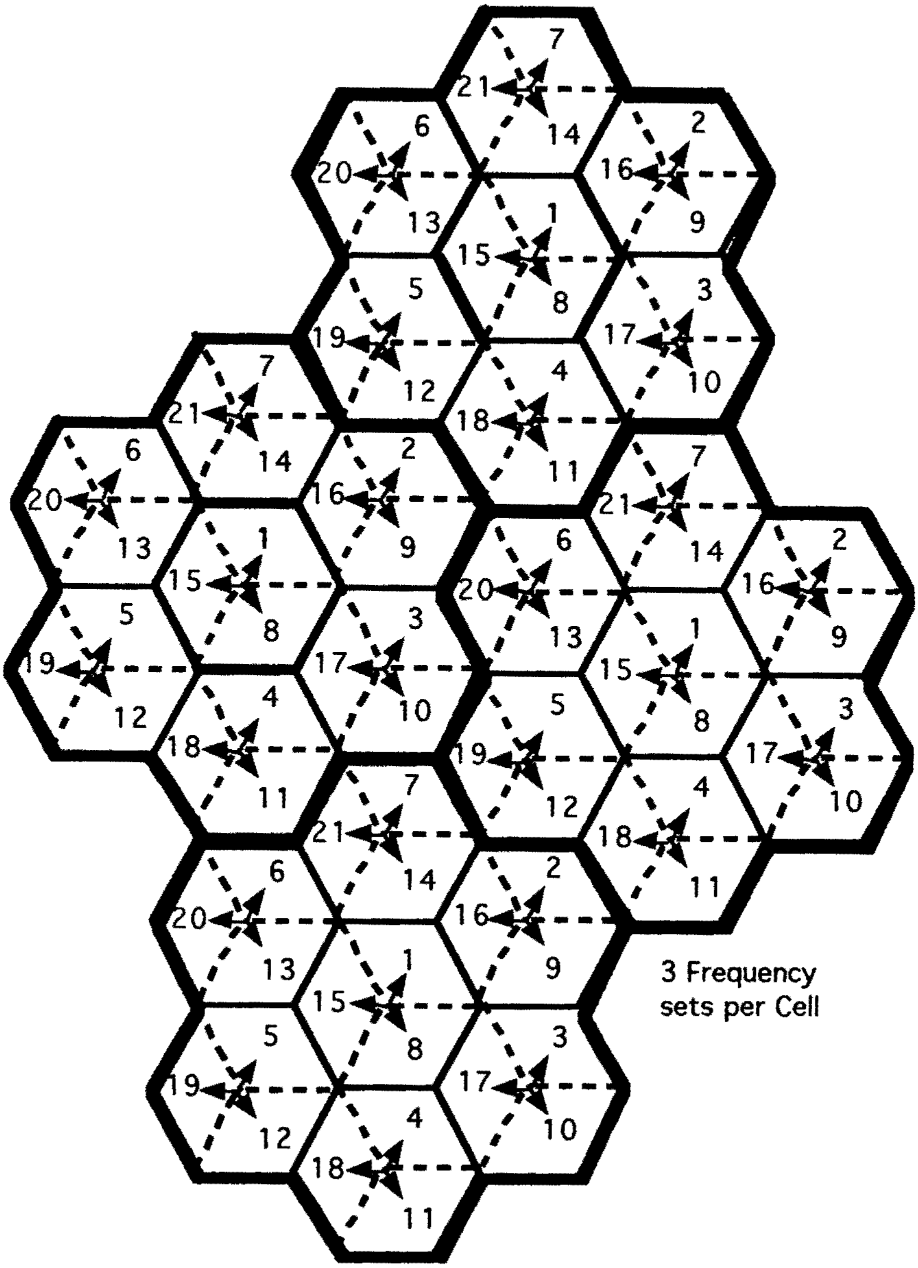


Figure 4: The Cellular Frequency Reuse Concept, Sectored Network

As mobile cellular traffic requirements increase, new base stations are constructed within the existing cluster and typically at lower elevations and/or with shorter towers. Frequencies are reassigned to these new stations such that the area once served by one cluster is now served by multiple clusters, forming a spatial frequency reuse pattern.

C. INTERFERENCE AND SECTORING

The frequency reuse scheme provides for increased traffic needs of the MSA at the expense of increased interference. Interference is unavoidable because multiple RF channels are typically present in the average cellular network. Unacceptable interference occurs when the portable phone receives one or more foreign RF channels at too high of a signal power relative to the desired channel signal power.

In an analog receiver, interference has the same effect on voice quality as does noise. An increase in interference power, relative to the carrier signal power, causes the audible noise level to increase. In a digital receiver, multiple relatively high power signals cause Intersymbol Interference (ISI). This distorts the speech decoding, causing warble, loss of synchronization and loss of syllables, words or larger portions of speech.

The serving cell provides a dominant RF channel called the carrier. The interfering channels are collectively called the interferers. When the surrounding clusters' interfering channels are the same frequency as the carrier channel, the interference is called cochannel. When the surrounding clusters' interfering channel is a frequency above or below the carrier channel, the interference is called adjacent channel. As more base stations are constructed the possibility of interference becomes more likely.

Interference may occur at any receiver, and can be seen on the up-link (at the base station receiver) and on the down-link (at the portable phone receiver). This thesis will investigate only the cochannel carrier to interference experienced at the portable receiver, on the down-link.

In the typical omnidirectional (non sectored) network, each channel will experience interference from the cochannel frequencies of the surrounding clusters, as illustrated in Figure 5. The cochannel interferers are the six surrounding cells designated with frequency set 1. In the hexagonal shaped cell, 6 interfering cells form the first, or closest, tier. Additional interfering cells exist in a second tier, third tier and so on but pose a negligible affect on overall interference [4]. Interference in a sectored network is analogous.

The signal power received by the portable phone is Received Signal Strength (RSS) and is typically expressed in dBm, decibels above one milliWatt. The ratio of the dominant carrier RSS and the combined RSS of the interferers is called Cochannel Carrier to Interference (CC/I). Notice in Figure 5, that the portable phone is illustrated near the edge of the carrier cell. This is the location where the carrier RSS is the weakest and the CC/I is the smallest.

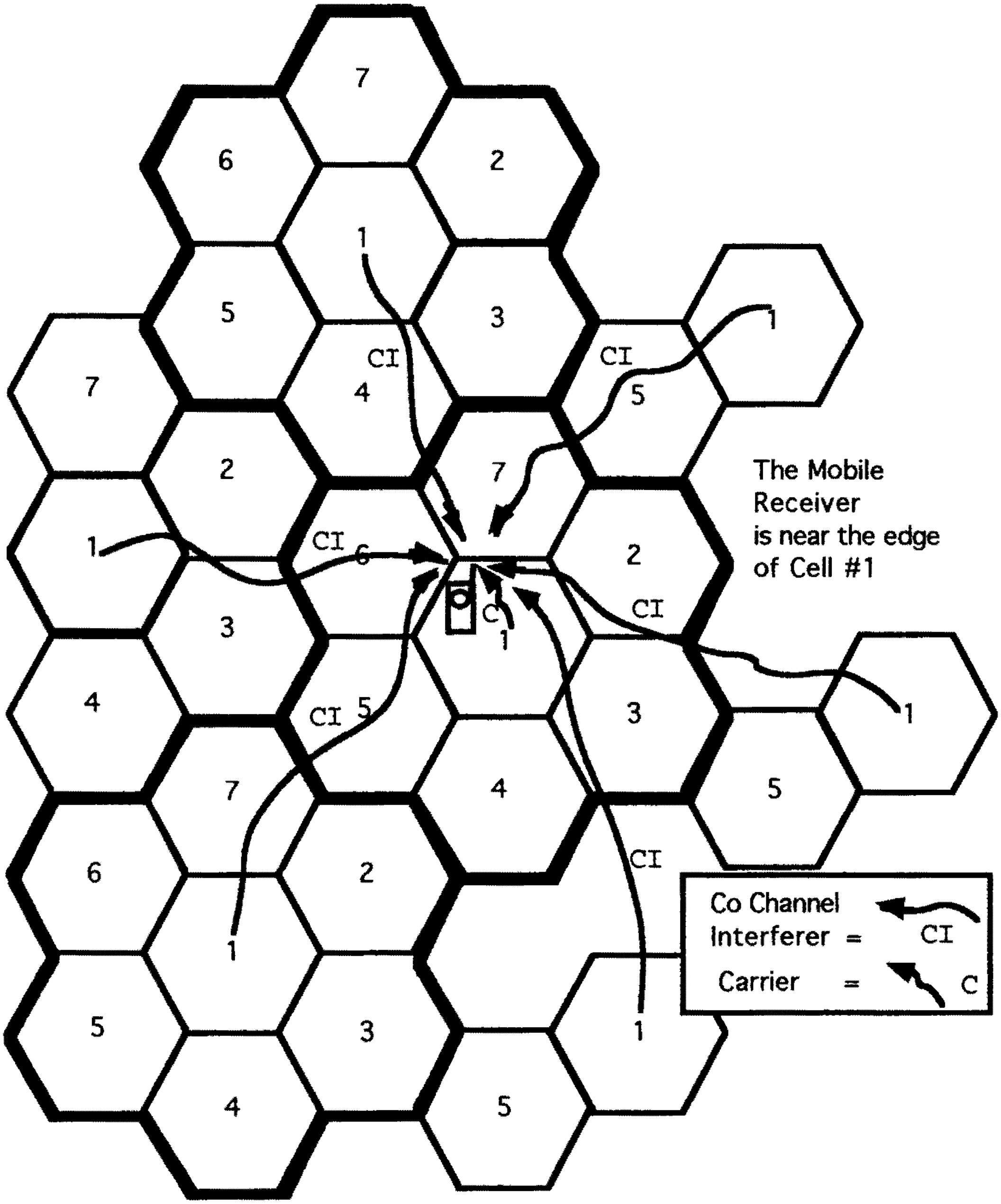


Figure 5: Down-Link Cochannel Interference

Acceptable audio quality can be achieved with a CC/I_{dB} of 18 dB or more based on subjective testing. 18 dB CC/I_{dB} is an industry objective for AMPS and is discussed further in Chapter V. The objective for TDMA digital varies with the type of interference, either digital or analog, and whether the receiver is operating on the up-link or down-link [4]. This thesis deals only with analog channels so the 18 dB CC/I_{dB} objective is used.

The 7 cell per cluster design was chosen when cellular networks were first constructed because this was intended to position the first tier cochannel cell interferers far enough from the mobile such that when it is operating near the radius of the carrier cell the 18 dB CC/I_{dB} is achieved [4]. Let;

K = 7 (number of cells per cluster)
R = radius of cell
D = distance of center of carrier cell to center of first tier cochannel interfering cell

By geometry (illustrated in Figure 6),

$$\begin{aligned} D/R &= (3K)^{1/2} \\ &= 4.58 \end{aligned} \tag{1}$$

Given all transmit TXERP's are equal and the terrain is homogeneous throughout the network, the received signal strength of the carrier and the interferers will be distance dependent where path loss is a function of 40 dB/dec. The smallest CC/I will occur at R;

$$CC/I = \frac{(D/R)^4}{6}$$

after substitution,

$$CC/I \;=\; 73.5 \Rightarrow 18.66\ \text{dB} \qquad (2)$$

Therefore, the 7 cell per cluster philosophy with omnidirectional antennas will meet the 18 dB standard in theory. However, this is not the case when CC/I_{dB} is degraded to 14 dB allowing for imperfect site locations, path fading anomalies and rolling terrain [4].

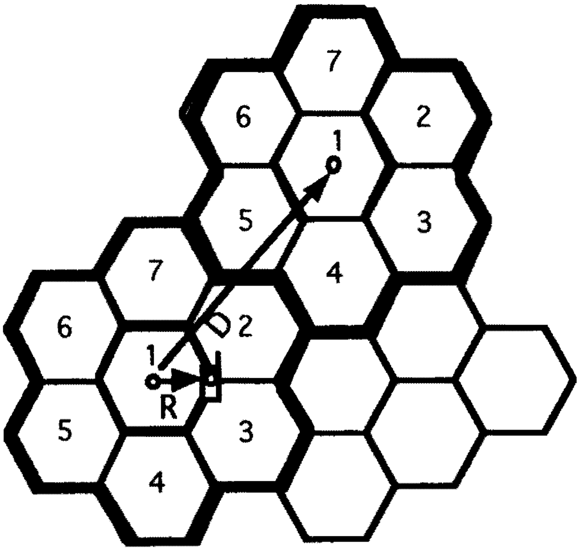


Figure 6: The Distance D and Radius R in a 7 Cell per Cluster Network

To improve CC/I_{dB}, the cellular network is sectored using directional antennas at each base station. The Portland MSA uses the 7 cell per cluster 3 sectors per cell approach where three sets of antennas are oriented at three different and equally spaced azimuths, ideally 120° apart. Directional antennas with a front-to-back ratio of 25 dB or more are utilized. This increases the CC/I_{dB} by reducing the number of interfering cells. Antenna azimuths at 4 of the 6 first tier base stations are directed away from the carrier cell, see Figure 7. The theoretical CC/I_{dB} is increased to 24.5 dB with 120° antennas for a mobile customer at the outer radii edges of the cell serving area [4]. However, because the serving antenna is directional, the weakest carrier RSS_{dB} occurs not only at the outer edge of the cell but also near the sector 3 dB beam edge boundary. This causes an additional reduction in carrier RSS_{dB}. Per Lee [4], the CC/I_{dB} is now reduced by 6 dB allowing for imperfect site locations, path fading anomalies, rolling terrain and the carrier transmit antenna pattern, therefore the design still meets the 18 dB objective.

Cellular network performance is influenced by both interference and noise, expressed as Carrier to Interference (C/I) and Carrier to Noise (C/N). C/I is the dominant and most challenging of the two in a mature cellular network because the carrier channel RSS is well above the noise floor [3]. The Cellular RF Engineer utilizes the industry standard 7 cell per cluster and 3 sector per cell frequency plan on the assumption that the CC/I_{dB} objective of 18 dB is achievable.

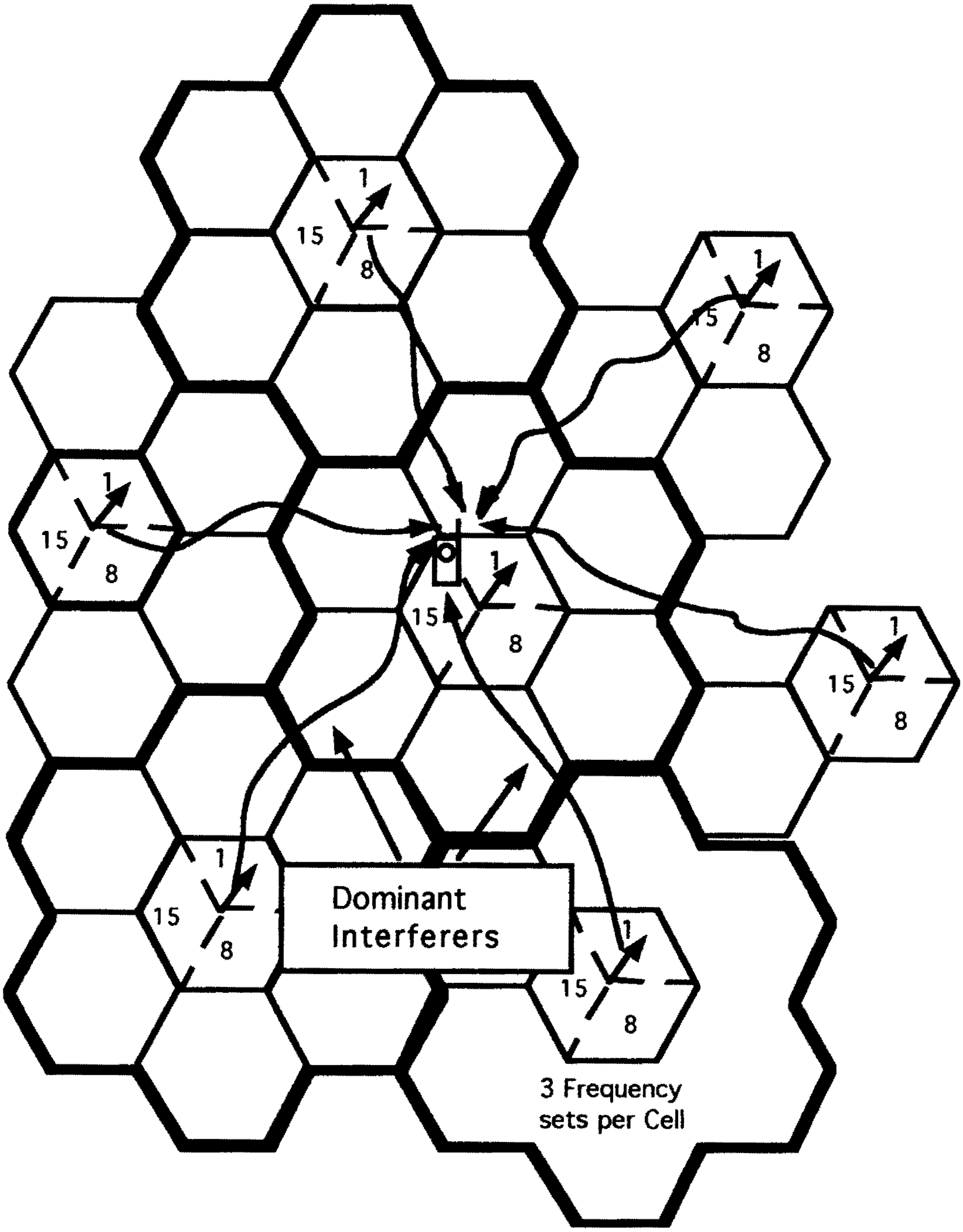


Figure 7: The 7 Cell per Cluster, 3 Sector per Cell Pattern and Associated Interference

CHAPTER III

MEASUREMENT OF RECEIVE SIGNAL STRENGTH

A. THE MOBILE RADIO TRANSMISSION MEDIUM

The theory surrounding the transmission of a radio frequency electromagnetic energy source to a receiver has been studied by Lee, Clarke, Jake and others since the mid-1960's. A radio signal, $S(x)$, received at a mobile antenna can be characterized by two components. The relationship is as follows;

$$S(x) = m(x)r(x)$$

where x is typically a spatial rather than a time variable. The first component, $m(x)$, is long-term slow fading which is variations in received power due to natural terrain and foliage and will vary slowly over a distance of many wavelengths. The Probability Density Function (PDF) of this long-term data is log-normal. The second term, $r(x)$, is short-term fast fading and is defined as rapidly occurring variations in received power over a fraction of a wavelength. It is caused by multiple reflections off man-made obstructions and moving objects. The PDF of short-term data is either Rayleigh or Ricean. When the mobile is line-of-sight, one direct ray dominates and the distribution is Ricean. When the mobile is non-line-of-sight (most typical) a

Rayleigh distribution is used [1]. In this environment the waves propagate along multiple reflective paths and are received at the mobile omnidirectional antenna with uniformly distributed phases and independent magnitudes [2].

A plot of typical received radio signal data, expressed in terms of Receive Signal Strength in dBm (RSS_{dBm}) is illustrated in Figure 8. This shows the measured RSS_{dBm} for radio channel #330 transmitting from the A sector of a base station at Southeast (SE) 39th & Powell Boulevard. A line representing path loss due to distance is included, where the 40 dB/dec slope contributes 4.2 dB loss across the test. The short peaks and sharp valleys are characteristics of Rayleigh fading. The long-term fading component is the "smooth" curve.

The route traveled is north on SE 39th Street from SE Woodward to SE Clinton Streets and is away from the transmitting antenna which has an azimuth of 15° (directed northerly along 39th Street). As illustrated in Figure 9, SE 39th Street rises gradually along the beginning of the test route then falls off in elevation near SE Clinton Street. The long-term component shows the effects of shadowing between SE Taggart and Clinton Streets.

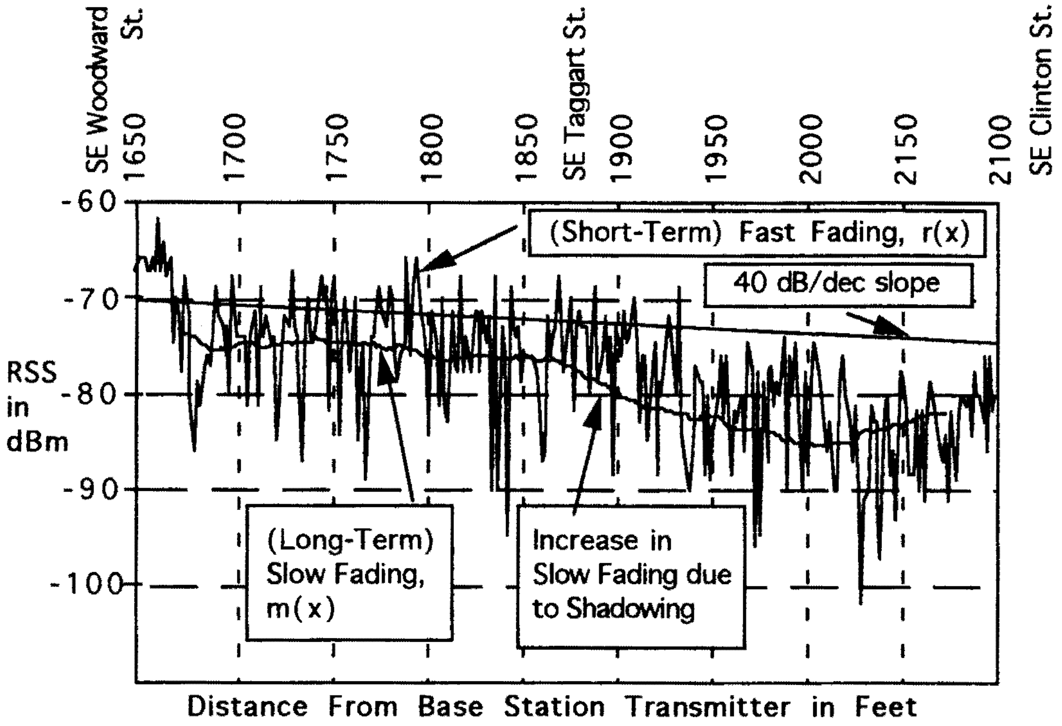


Figure 8: RSS From Channel # 330 SE 39th St. & Powell Blvd. A Sector

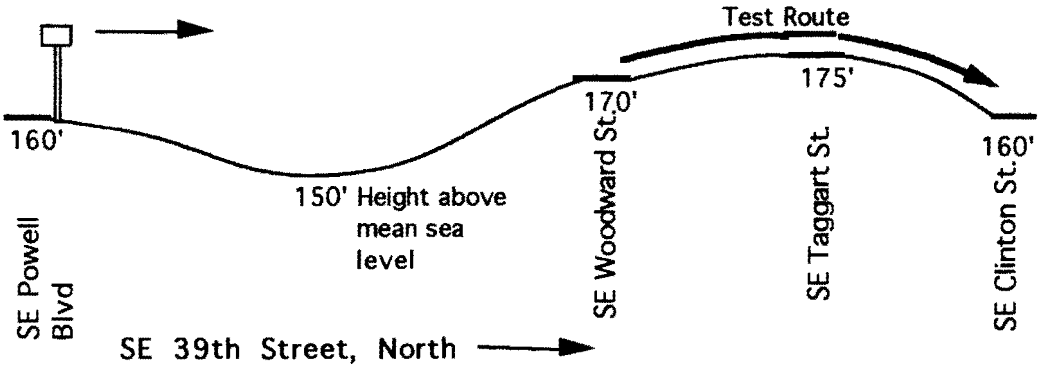


Figure 9: Topology North Along SE 39th Street

B. RSS MEASUREMENT CONSIDERATIONS

The next chapter will discuss how CC/I data is generated from RSS_{dBm} measurements. The closer these measurements match the theoretical characteristics discussed in the previous section, the more confidence can be placed on CC/I data. Therefore, RSS_{dBm} should be measured in such a way that both long-term and short-term information is represented. To assure short-term (Rayleigh) characteristics, the successive measurements should be loosely correlated. A separation between adjacent measurements, called records, of 0.8λ or more is required for a correlation coefficient below 0.2 [1] [2].

The long-term fading characteristics are determined by taking running averages of these records. Ideally, 50 RSS_{dBm} records are averaged over a 40λ window which covers a distance of 47 feet at 850 MHz, or roughly one record per foot [1]. The long-term component averages the extreme excursions in amplitude so is not expected to adversely impact CC/I.

Short-term fading represents the rapid RSS_{dBm} excursions experienced by the mobile receiver, has the most dramatic affect on CC/I and is therefore the critical component. One objective of this chapter is to verify that a valid short-term component is included in RSS_{dBm} measurements. The short-term component is obtained by subtracting the original raw RSS_{dBm} records by the long-term data.

C. GATHERING RSS DATA WITH THE LCC MSAT-2000

The LCC Mobile System Analysis Tool (MSAT-2000) is a portable battery powered cellular band scanning receiver, programmed to measure RSS_{dBm} on preselected frequency channels. It continually scans these channels every 1.2 seconds at a rate of 6075 samples per second. Sixteen consecutive RSS_{dBm} samples of each channel are averaged, forming one record. Data files of these records are created and reported directly on a DOS compatible Personal Computer (PC) containing a time stamp, the channel numbers and their associated RSS_{dBm} record (sample average). More detailed MSAT-2000 product specifications are listed in Appendix E.

A hand cart is used to transport the MSAT-2000, a 0 dBd gain antenna and a laptop PC. Figure 10 illustrates the test cart. A counter is attached to one wheel so that the speed of the tests can be synchronized with the MSAT-2000 scanning rate.

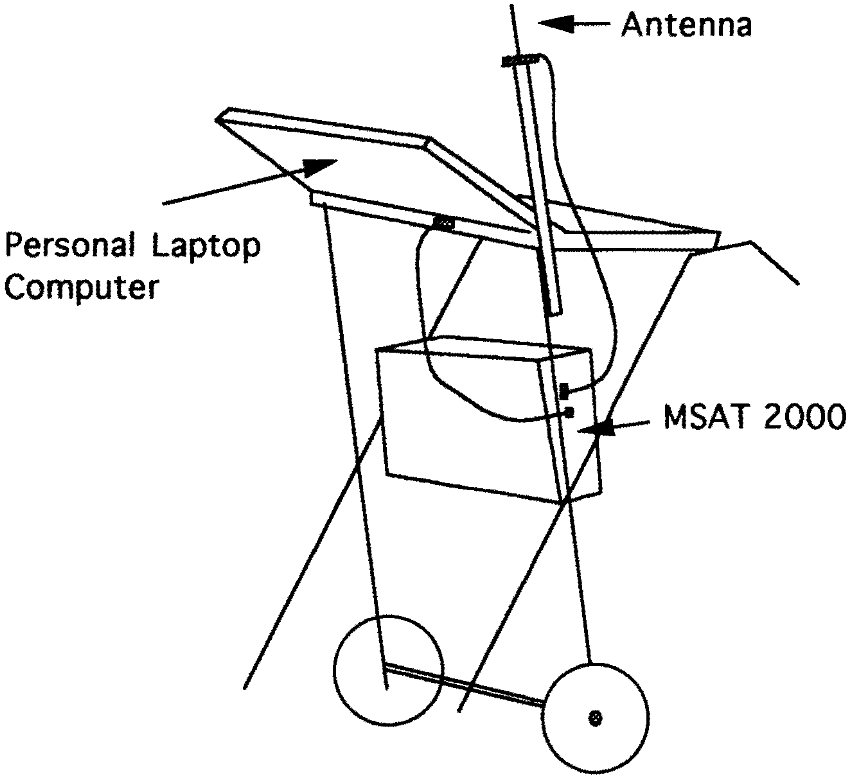


Figure 10: Test Cart for Data Gathering

D. DETERMINING MEASUREMENT SPEED

The speed at which the MSAT-2000 is transported during RSS measurements is critical to achieving valid data. An optimum speed can be determined by finding the minimum and maximum. The MSAT-2000 sampling sequence is illustrated in Figure 11, is based on MSAT-2000 specifications and is used to help determine the transportation speed.

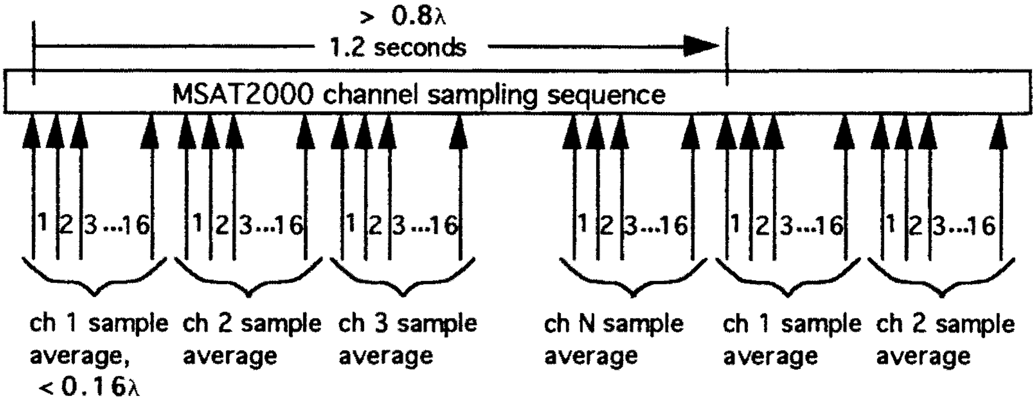


Figure 11: The MSAT-2000 Scanning Sequence

As stated in Section B, the distance between adjacent RSS records for each channel should be greater than 0.8λ. The minimum speed is determined by the distance traveled and time interval between records. The time interval would be the time it takes to measure the samples of the channel in question, scan the other N channels and return for the next set of records. This will occur while traveling 0.8λ or more in a time interval of 1.2 seconds.

$$\text{Minimum speed} = (0.8\lambda \;/\; 1.2 \text{ seconds}) \times 1.2 \text{ feet}/\lambda$$
$$= 0.8 \text{ feet/second} \tag{3}$$

The MSAT-2000 should be transported fast enough so that the successive 16 samples provide an accurate sample average. An envelope correlation between two Rayleigh signals, at the same transmit frequency, is greater than 0.7 when the sample window is 0.16λ or less [2]. The maximum speed is then limited by the distance and time required to measure each 16 sample set over a 0.16λ distance or less. At very high transportation speeds, this time interval could represent hundreds of wavelengths.

$$\begin{aligned}\text{Maximum speed} &= 0.16\lambda \text{ x } 6075 \text{ samples/second x } 1/(16 \text{ samples}) \text{ x } 1.2 \text{ feet}/\lambda \\ &= 4.55 \text{ feet/second} \qquad (4)\end{aligned}$$

However, at this speed the unit will travel over 4λ between records, placing them too far apart to accurately represent local long-term characteristics. Therefore, the test cart will be transported at a speed of 1 foot per second.

E. VALIDATING RSS DATA

In this section, data gathered with the MSAT-2000 instrumentation is analyzed to see how closely it matches long-term log-normal and short-term Rayleigh distributions. The MSAT-2000 system measures the RSS_{dBm} for 12 RF channels and reports them to a data file. These data files are exported to EXCEL worksheets where custom Macros are used for data manipulation and analysis.

A MSAT-2000 measurement data file was gathered from the C sector of the Erroll Heights base station transmitter which is near the intersection of SE 57th and Bybee Streets. The test walk starts along SE Brookside Drive, west 480' to and along SE Johnson Creek Boulevard, then to SE 42nd Street. The distance traveled was 1265' along a test route at an approximate constant radius from the base station and located within the 3 dB beam width of the transmitting antenna. The base station transmitter antenna is non line-of-sight (obstructed by foliage and man made structures) but is not obstructed by terrain contour. Figure 12 is a plot of 1252 RSS_{dBm} records against the distance traveled in feet. This contains and displays both long-term and short-term data, which are to be separated and analyzed individually.

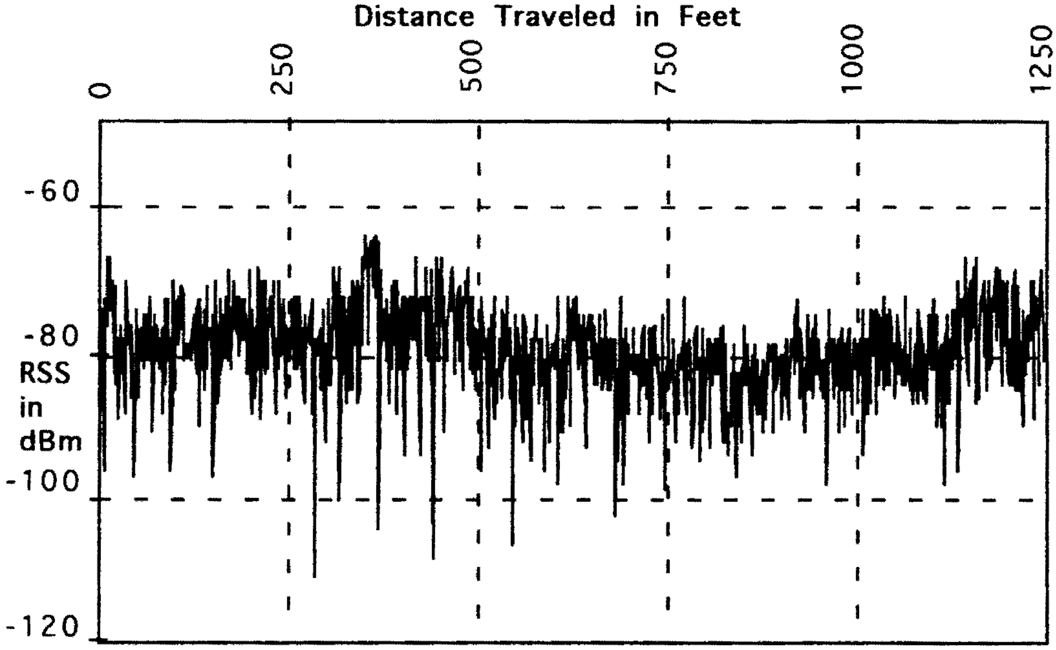


Figure 12: RF Channel #107 RSS_{dBm} Records, Erroll Heights C Sector

To separate the two components, first determine the long-term local mean over a 40λ window of 50 samples. A new data set is generated by taking a 50 sample running average, consisting of 25 samples on either side of each RSS_{dBm} MSAT-2000 record. This contains 50 less data points since the first 25 and last 25 are averaged into the first and last local mean data point, respectively. Figure 13 illustrates this new set of sample averages. This contains only the local mean long-term RSS_{dBm} data. The short-term component, with it's erratic characteristics, has been removed by averaging.

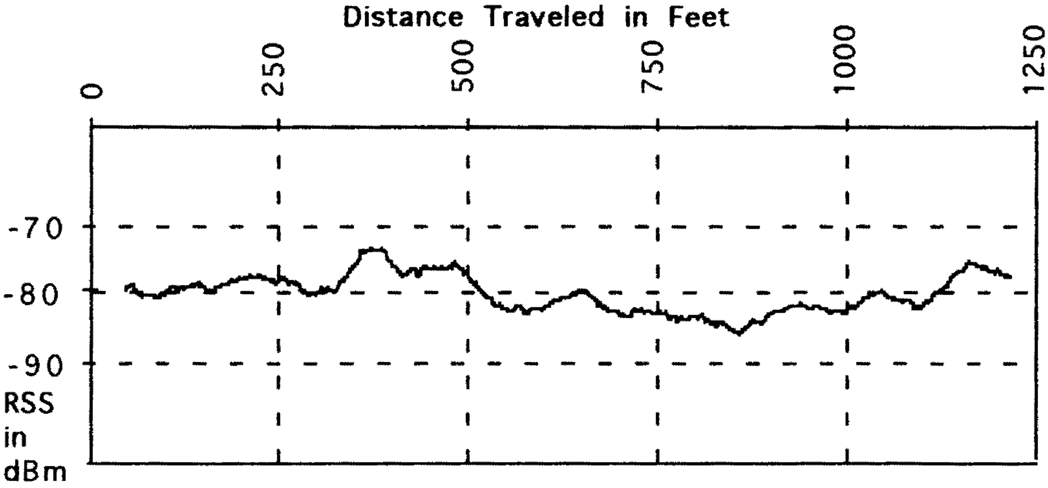


Figure 13: RF Channel #107 Long-Term RSS_{dBm} Component, Erroll Heights C Sector

This long-term slow fading data is listed in an EXCEL data file where the Probability Density Function (PDF) is generated. The correlation between it and an ideal log-normal PDF is a very close 0.918, as illustrated in Figure 14. See Appendix D for the equation used for the log-normal PDF.

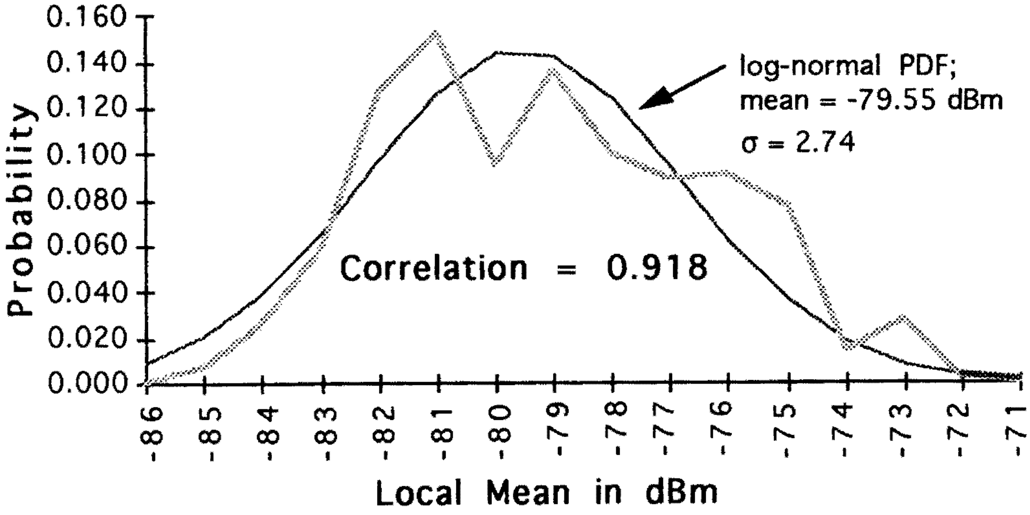


Figure 14: PDF of Channel #107 Long-Term RSS_{dBm} Component, Erroll Heights C Sector

To obtain the fast fading short-term data, the long-term averages of Figure 13 are subtracted from the RSS_{dBm} data of Figure 12 at each record point. This eliminates the long-term component and leaves only the variation in RSS due to fast fading, illustrated in Figure 15.

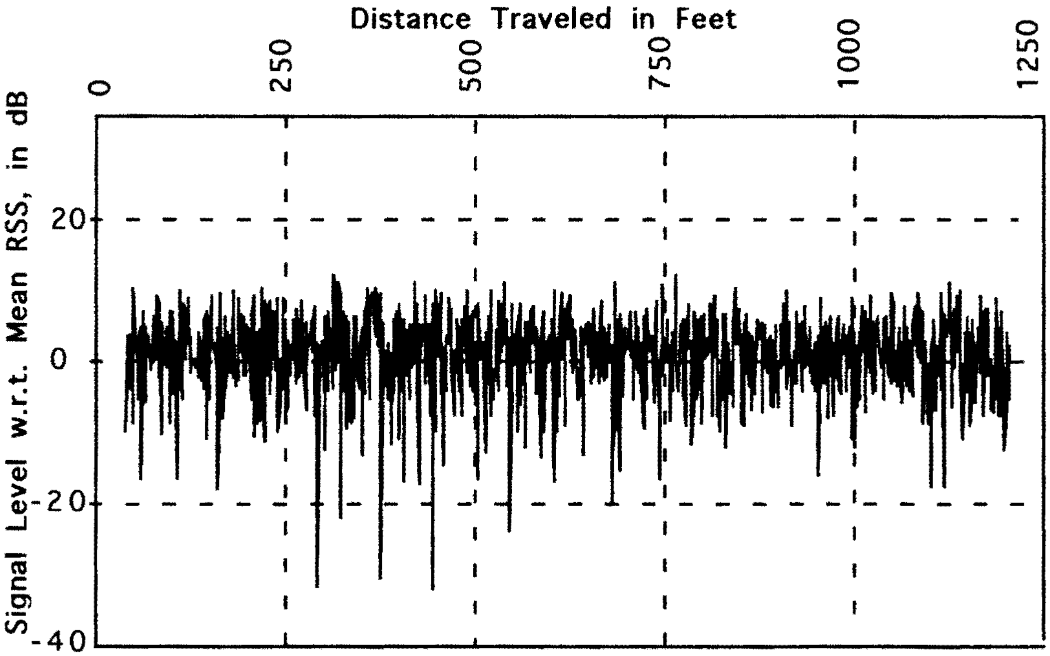


Figure 15: RF Channel #107 Short-Term RSS_{dBm} Component, Erroll Heights C Sector

Now this short-term fast fading data can be compared to a Rayleigh distribution. The Cumulative Distribution Function (CDF) is generated in the EXCEL file and is plotted on Rayleigh paper, Figure 16, along with the ideal Rayleigh CDF. See Appendix D for the equation used for the Rayleigh CDF. The cross correlation between these two CDF's is a surprisingly close 0.988.

The preceding analysis shows that the data gathering technique provides RSS_{dBm} data which correlates closely to the mobile radio transmission medium characteristics. The slow fading long-term data is log-normal distributed and the fast fading short-term data is Rayleigh distributed.

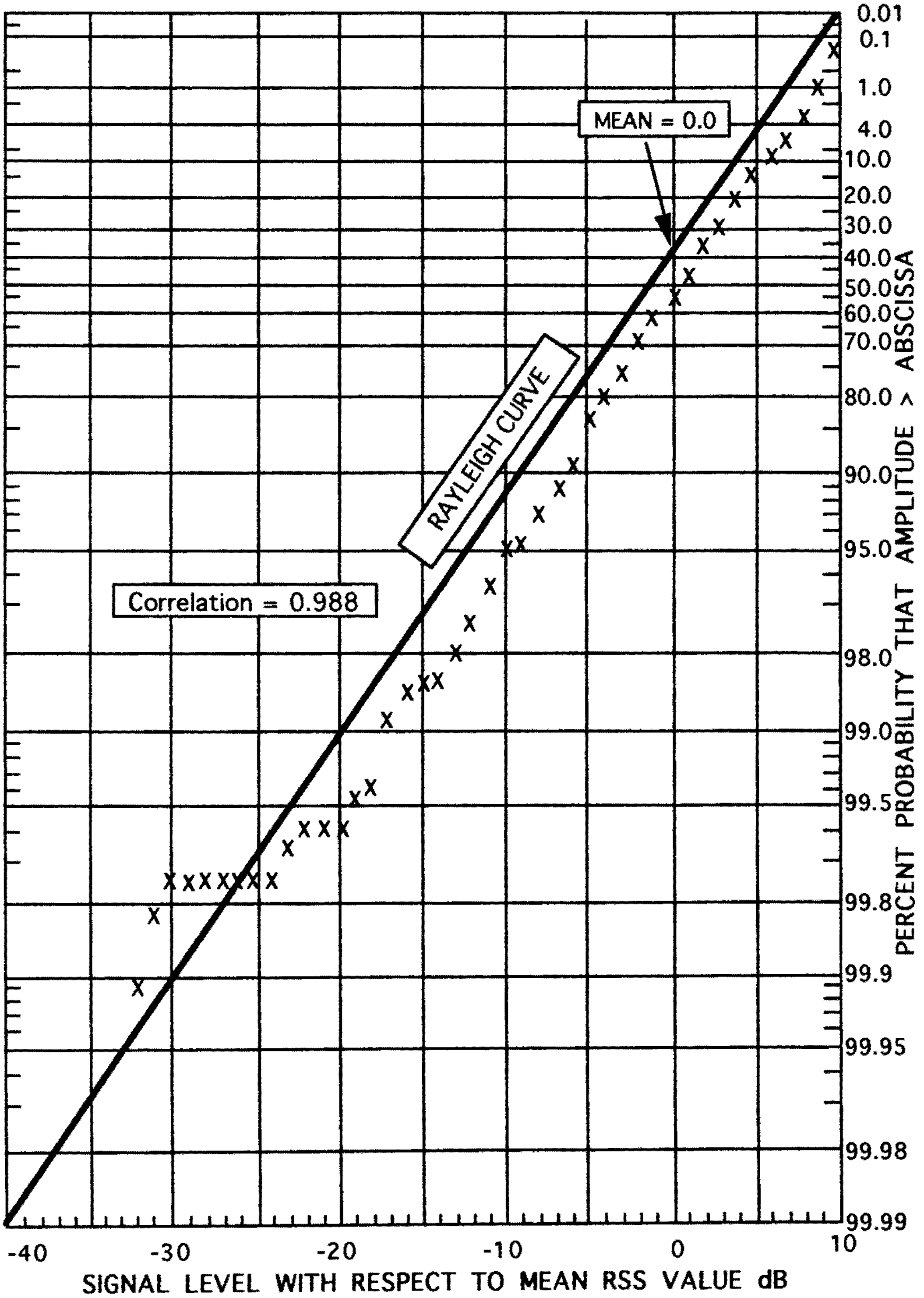


Figure 16: CDF of Channel #107 Short-Term RSS_{dBm} Component on Rayleigh Paper, Erroll Heights C Sector

CHAPTER IV

DETERMINING CC/I FROM RSS DATA

In Chapter II, Cochannel Carrier to Interference CC/I was defined as the ratio of the dominant carrier RSS and the combined RSS of the interferers. The CC/I is expressed (in dB) as;

$$CC/I_{dB} = RSS_{dBmC} - RSS_{dBmI} \qquad (5)$$

where,

RSS_{dBmC} = RSS_{dBm} of the carrier

RSS_{dBmI} = combined RSS_{dBm} of the 6 interferers.

In this chapter, a general expression for RSS_{dBm} will be used to isolate the path and network parameters which affect CC/I. Per Lee [4] a general form for mobile radio path loss prediction in an environment unobstructed by terrain contour can be used within an expression for RSS as follows;

$$RSS_{dBm} = P_{TdBm} - L_{AP} - \gamma * 10\log r + \alpha * 10\log h_T + \beta * 10\log h_M + G_M + P_O \qquad (6)$$

Where the last 5 terms are Lee's path loss formula and;

RSS_{dBm} = Receive Signal Strength in dBm

P_{TdBm} = on-beam Effective Radiating Power of the base station transmit antenna in dBm

L_{AP} = loss due to transmitting directional antenna discrimination pattern when the azimuth to the receiver is not the same as the antenna azimuth

γ = distance constant, usually 4.0

r = distance from base station to mobile receiver

α = base station transmit antenna height constant, usually 2.0

h_T = height of base station antenna above ground level

β = mobile receive antenna height constant, usually 1.0

h_M = height of mobile antenna above ground level

G_M = gain of the receive antenna

P_O = constant

These parameters affect CC/I in a variety of ways. Those that have a common impact on RSS_{dBmC} and RSS_{dBmI} will be used for normalizing. This will be accomplished either by applying a normalizing factor to the CC/I calculations or by selecting a measurement procedure which in effect will cancel their impact on all RSS_{dBm} values. Those that are not constant across the sectors tested will be identified but will remain a "random" network characteristic. These may also serve as a basis for determining the test routes to minimize their overall affect on CC/I.

In the following discussion, the subscript C will be used to identify a parameter associated with the carrier signal, subscript I will be used to identify a parameter associated with the combined interferers signal and the subscript i will be used to identify a parameter associated with an individual interferer signal.

P_{TdBm} will vary from base station to base station because not all emit the same on-beam TXERP. The TXERP at each base station is a known quantity and therefore RSS_{dBmI} will be normalized to simulate equal TXERP's, see the following section for details.

The test routes are chosen such that the azimuth from the carrier sector to the mobile receiver is within the 3 dB beam width of the transmitting antenna. This limits the range of L_{APC} at 0 to 3 dB. L_{APi} will vary from 6 dB to possibly 15 dB or more. This loss is the theoretical advantage to sectorization and is expected to be a major parameter for improving CC/I, as discussed in Chapter II and VI. Both L_{APC} and L_{APi} are intrinsic to a worst case analysis of a sectored cellular network so neither will be specifically identified nor will adjustments to CC/I be made for them.

A γ of 4.0 is used because most path loss prediction models use the classic 40log(distance) in the mobile environment which gives a 40 dB/dec path loss distance dependency.

Distance r_i is the distance between the first tier i"th interfering cell and the carrier cell, which is treated constant across i. In Chapter V, these values are equalized as much as possible by carefully selecting the first tier interferers. The RSS_{dBmC} dependency on distance r_C is minimized by selecting test routes that are along a constant radius of the serving carrier cell, thus r_C is kept nearly constant.

The typical h_T is between 40' and 140' but the effective height of the transmitting antenna relative to the mobile antenna can vary over hundreds of feet for hilly terrain and tens of feet in a flat or gently sloping terrain. The affect that this and the associated constant α has on CC/I are outside the scope of this thesis.

The parameters $\beta^*10\log h_M$ and G_M have no impact on CC/I because the RSS of the carrier channel and the 6 first tier interfering channels will be measured from a single omnidirectional mobile antenna. P_O, used for units conversion, is common to all RSS values.

Real-time CC/I_{dB} measurements are difficult to achieve in practice primarily because it is difficult to distinguish between the carrier and the interferers. We can, however, select and measure RSS_{dBm} in a separate channel from each interfering sector to obtain down link CC/I. The RSS from all channels transmitted from a base station will occur equally in a given area [4], therefore any channel can be selected.

To determine CC/I_{dB}, one analog channel in the serving sector is selected and it's RSS_{dBmC} is measured. This is the Carrier. The RSS_{dBm} of a unique analog channel in each of the 6 interfering cochannel sectors in the first tier will be measured and the combined RSS_{dBmI} is the Interferer. Therefore, the RSS_{dBm} for each of 7 RF analog channels are measured for CC/I_{dB}. The composite RSS_{dBmI} of all interferers is calculated then subtracted from the carrier RSS_{dBmc} to obtain CC/I_{dB}.

Let the following expression represent the combined RSS of the 6 interferers, note that values are linear and not in dB;

$$RSS_I = \Sigma_{i=1}^{6} (RSS_i * n_i) \tag{7}$$

Where,

$$n_i = P_{TC} / P_{Ti} \tag{8}$$

normalizes all the RSS measurements to the carrier TXERP.

Expressing the normalizing factor in dB;

$$N_i = P_{TdBmC} - P_{TdBmi} \tag{9}$$

Then, in dB;

$$RSS_{dBmI} = 10\log\left[\Sigma_{i=1}^{6} 10^{\left(\frac{RSS_{dBmi} + N_i}{10}\right)}\right] \tag{10}$$

CHAPTER V

REAL TIME CC/I MEASUREMENT IN A SECTORED CELLULAR NETWORK

A. ESTABLISHING THE TEST SECTORS AND ROUTES

A carrier base station which has 6 surrounding base stations of near equal distance is chosen for each field test. This minimizes the individual impact of each r_i on CC/I, as discussed in the previous chapter. The distance from the carrier base station to each neighboring station is determined and the average of all six becomes the frequency reuse distance D. The radius R of the carrier cell is determined by dividing this average D by 4.58, the D/R ratio for 7 cell per cluster. All measurements for the 7 cell per cluster design can then be made at a radius R from the base station. Table I lists the carrier base station sectors which were tested, the average distance D to the first tier interfering sector transmitters, the standard deviation of these distances and the radius R at which the tests were made. The interfering sectors all contain the same letter designation as the carrier sector tested and nearly the same transmitting antenna azimuth. This guarantees simulation of a 3 sectored design. If any of the other two sectors in the interfering cells were used, then the advantages of the 3 sectored design could be compromised.

Table I
D And R in Carrier and First Tier Interfering Sectors
(in miles)

Carrier Sector	Average Distance to First Tier Interferers	Standard Deviation of these Distances	Carrier Sector R,For Test
Orbanco B	0.765	0.22	0.17
Lloyd Center B	2.21	0.40	0.48
Erroll Heights C	4.65	0.62	1.01
Stafford A	6.86	0.67	1.5

A labeling convention is illustrated in Figure 17. The designations DL (Direct Left) and DR (Direct Right) are for the two sectors with antenna azimuths directed towards the Carrier Test Sector and to the Left and Right , respectively. The two interferers off to the side are FL (Flanking Left) and FR (Flanking Right). These two interferers' antenna azimuths are not directed towards the test sector, which is out of it's 3 dB beam width. The two sectors directed away from the test sector are IL (Indirect Left) and IR (Indirect Right) which have only the back lobe towards the test sector. More detailed test route parameters are listed in Appendix A which includes the test route, date tested, radius R, distances D, sector names, designation of each sector, RF channel used, transmit antenna ERP's, normalizing factor N_i, antenna azimuths, azimuths to test routes, antenna 3 dB beam widths, base station antenna height above ground level h_T, average RSS_{dBm}, RSS_{dBm} standard deviation, CC/I_{dB} average, CC/I_{dB} standard deviation and a portion of the recorded data.

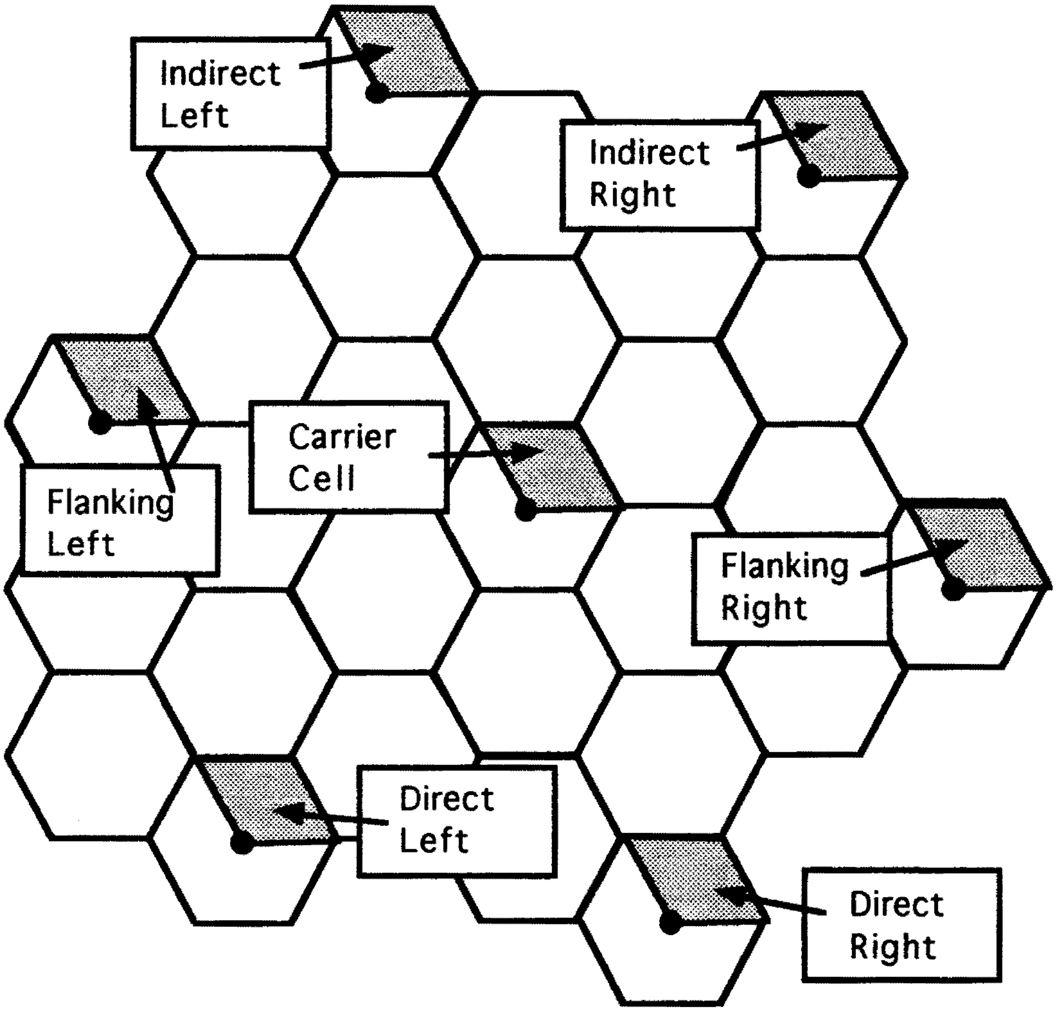


Figure 17: Labeling Convention for Carrier and Interfering Sectors

Test routes are selected along the radii perimeter of the serving sector and near a 3 dB boundary of the on-beam azimuth to establish the worst case condition. This is illustrated in Figure 18. The preselected radio channels at all 7 sectors are "keyed" by accessing the Mobile Switching Center (MSC) computer to guarantee that they are transmitting at their maximum TXERP. This simulates the network at busy hour traffic conditions. All other cochannel transmitters in the network out to the third tier are turned off or "blocked" to guarantee that the measured RSS_{dBm} is from only the desired sectors.

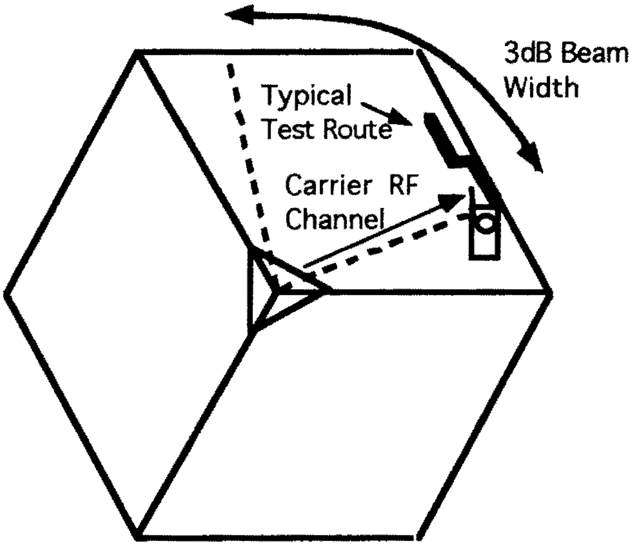


Figure 18: Worst Case CC/I Test Route in a Sector

B. GATHERING RSS AND DETERMINING CC/I

Seven channels are programmed into the MSAT-2000, using the LCC Toolbox software, for recording the RSS_{dBm} necessary for CC/I_{dB}. As stated earlier, the MSAT-2000 will measure and record the RSS_{dBm} for twelve channels. The remaining 5 channels will be utilized in Chapter VI.

RSS_{dBm} data for the carrier channel and the 6 interfering channels is stored in the PC as records and later down loaded to an EXCEL file. A collection of CC/I_{dB} data points are calculated from these records using equations 5 and 10.

These seven collections of RSS_{dBm} data are uncorrelated because their associated waves travel over much different routes in time and space and, as discussed in Chapter III, they are Rayleigh distributed [6]. Due to the Central Limit Theory of equally distributed random signals, the combination of CC/I_{dB} data is expected to be log-normal distributed. However, Hagerman [7] concludes from a Monte-Carlo computer simulation model that the total interference is dominated by one strong interferer and a log-normal distribution is a poor choice for simulating total interference.

Because RSS_{dBm} data contains both log-normal and Rayleigh characteristics, which more closely describes the CC/I_{dB} data? To determine which distribution best fits the CC/I_{dB} data gathered here in the Portland MSA, a CDF and PDF for each CC/I_{dB} file is generated. Then an ideal Rayleigh CDF and log-normal PDF are calculated from the mean and standard deviation CC/I_{dB}. The best fit will have the highest correlation between ideal Rayleigh CDF and CC/I_{dB} CDF or between log-normal PDF and CC/I_{dB} PDF. A Rayleigh CDF is used rather than a PDF because it can be easily viewed on Rayleigh paper. Table II summarizes these results for walk tests in the Portland MSA sectors tested. The actual distributions are plotted in Appendix D, which also contains the equations used for calculating ideal distributions. The CC/I_{dB} distributions more closely match the ideal Rayleigh distributions, which reinforces Hagerman's simulations.

Table II
Correlation Coefficients for Eastside Portland MSA Walk Tests, Sectored Network

Carrier	Cross-Correlation Coefficient	
Sector	CC/I CDF vs. Rayleigh CDF	CC/I PDF vs. log-normal PDF
Orbanco B	0.991	0.967
Lloyd Center A	0.988	0.969
Erroll Heights C	0.991	0.961
Stafford A	0.989	0.963

C. MEETING THE 18 dB CC/I OBJECTIVE

Service quality is said to be acceptable if 75 percent of the listeners subjectively view service as "good" or "excellent" in 90 percent of the covered area [4]. The 18 dB objective is based on this criterion. If 90 percent of the CC/I_{dB} at the worst case field test routes, which are at maximum distance R, meet the objective then it will be met in the entire sector. Therefore, 90% of the CC/I along these 4 test routes should be greater than 18 dB.

For a log-normal distribution 90% of the CC/I measurements will be above 18 dB when the mean CC/I$_{dB}$ is 1.27σ higher than 18 dB. In the Portland MSA, σ was found to vary from 6.0 to 7.5 (Appendix A) so 1.27σ can range from 7.6 to 9.5 dB. On the other hand, for a Rayleigh distribution, 90% of the CC/I measurements will be above 18 dB when the mean CC/I$_{dB}$ is 27.8 dB. Therefore, the Rayleigh distributed CC/I requires a greater margin (9.8 dB) between the 18 dB objective and the mean CC/I than does log-normal distributed CC/I (7.6 to 9.5 dB), illustrated in Figure 19 (σ = 6.0 dB).

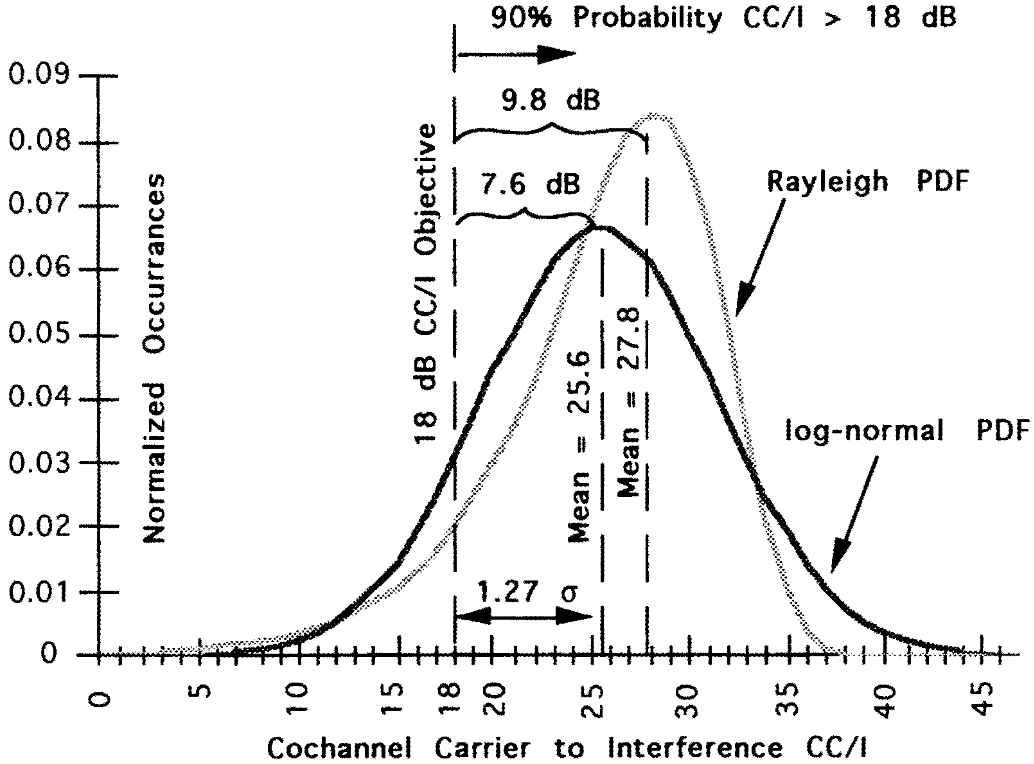


Figure 19: Rayleigh and Log-normal CC/I PDF's

For a Rayleigh PDF [1],

$$P[CC/I_{dB} > 18\text{ dB}] = \text{Probability that } CC/I_{dB} \text{ is greater than 18 dB}$$

$$= e^{-10\wedge[0.1(18_{dB}-\text{Mean } CC/I_{dB})]} \qquad (11)$$

The mean CC/I_{dB} and $P[CC/I_{dB} > 18\text{ dB}]$ for each carrier sector is summarized in Table III. The urban setting produced a very poor mean CC/I_{dB} of 5.7 dB but the mean CC/I for the other 3 carrier sector tests appear favorable because they exceed 18 dB. However, when the restrictions of equation 11 is applied, we see that only the Stafford A test meets the requirement that 90% CC/I_{dB} exceed the 18 dB objective. The other hilly sector, Erroll Heights C, very nearly does with 84% CC/I above 18 dB.

Table III
Meeting the 18 dB CC/I Objective for Portland MSA Walk Tests, Sectored Network

Carrier Sector	Topology	Mean CC/I_{dB}	**P[CC/I > 18 dB]**
Orbanco B	Urban, 5° Slope	5.7	0
Lloyd Center B	Suburban, Sloping	21.1	0.613
Erroll Heights C	Suburban, Hilly	25.6	0.840
Stafford A	Rural Hilly	39.8	0.993

CHAPTER VI

EVALUATING CELL SECTORING AND TERRAIN VARIATIONS

A. CC/I IMPROVEMENT DUE TO SECTORING

A network with omnidirectional interferers was also simulated. CC/I_{dB} data was collected from this and compared to the sectored tests to determine the actual improvement in CC/I that sectoring provides. The Portland MSA Network is almost exclusively sectored but by careful selection of interfering sectors, an omnidirectional (non sectored) network can be simulated. To accomplish this, the RSS_{dBmi} for one channel in each of 6 first tier sectors with azimuths towards the mobile receiver was programmed, measured and used for CC/I_{dB} calculations. Figure 20 illustrates how the omnidirectional interferers are chosen.

The same base stations are used here as in the sectored tests. In fact, data for both networks was gathered simultaneously and some base stations had a channel in two sectors keyed and measured (one for the sectored test and one for the non-sectored test). The 5 unused channels in the MSAT-2000 (12 minus the 7 needed for the sectored network) were utilized for the additional sectors needed. The actual sectors tested are listed in Appendix B, which contains data in a similar format as Appendix A, with the addition of directional antenna discrimination loss (L_D).

L_D is typical in a cellular network and occurs at a receiver when it is not in-line with the on-beam azimuth of the sector transmit antenna. Therefore, the TXERP towards the test route is less than the on-beam power by an amount shown on the discrimination pattern of the transmit antenna, see Figure 2. To accurately simulate an omnidirectional network, CC/I calculations will require RSS data which has been normalized to on-beam antenna TXERP by adding the antenna discrimination loss L_{Di}. This is shown by the following equation where L_{Di} is the pattern loss toward the test route for each individual interferer;

$$RSS_{dBmI} = 10\log\left[\sum_{i=1}^{6} 10^{\left(\frac{RSS_{dBmi} + N_i + L_{Di}}{10}\right)}\right] \qquad (12)$$

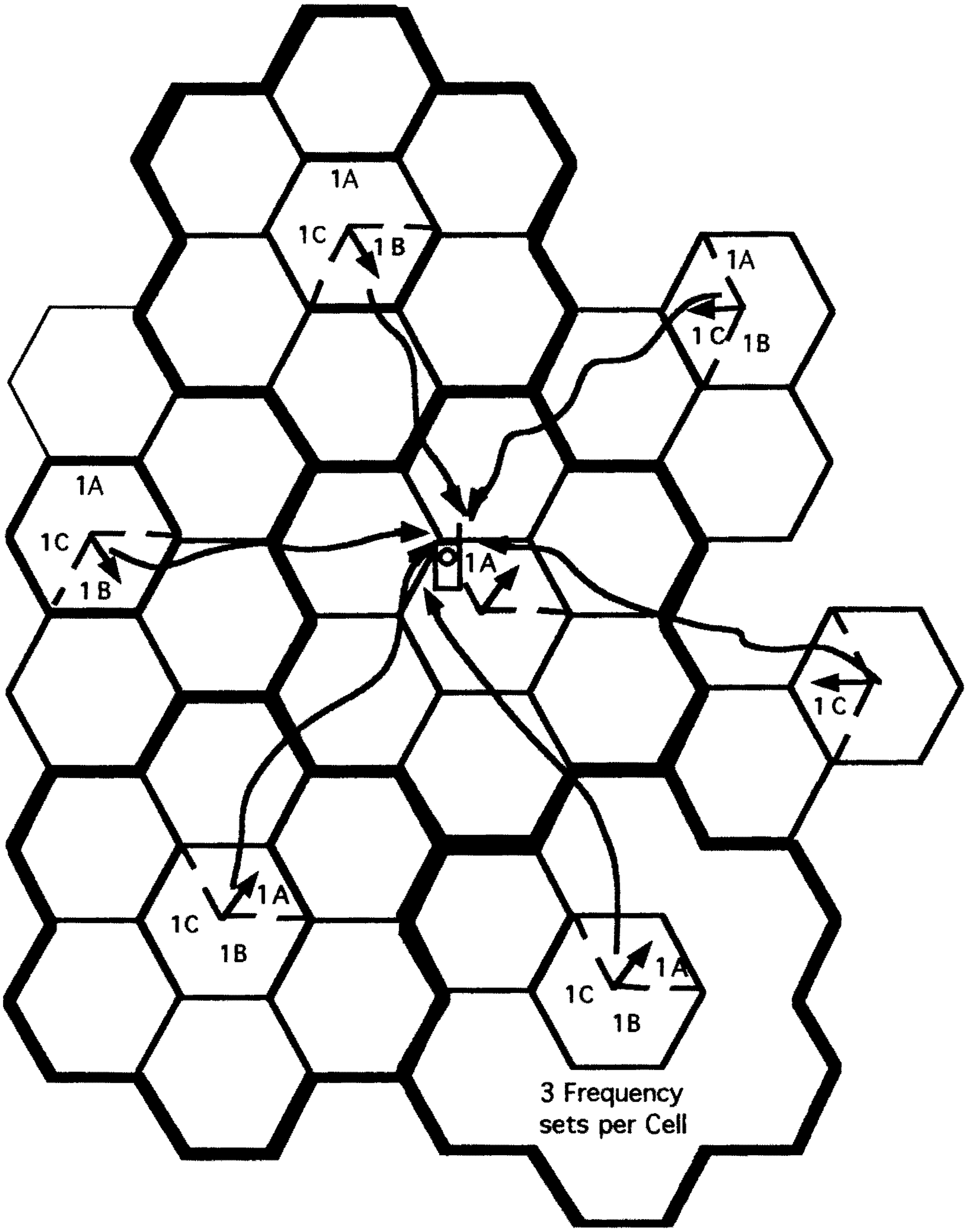


Figure 20: Simulating an Omnidirectional Cellular Network

The RSS_{dBm} data for these 7 channels was recorded, stored in the PC and downloaded to EXCEL files similar to the procedure used in the sectored simulation in Chapter V. The collection of CC/I_{dB} data points are calculated from these records using equations 5 and 12.

As was anticipated, the mean CC/I for the omnidirectional network is lower than for the sectored network. Per Lee, the theoretical improvement for sectored over omnidirectional is 6.5 dB [4]. Sectoring meets expectations (or nearly so) in three test routes where the improvement in mean CC/I_{dB} is greater than 6.0 dB, see Table IV. Note the exception here is for the Stafford A Sector which is in a rolling forested terrain where all paths from the interferers to the MSAT-2000 are severely obstructed. This will be discussed in more detail in the next section.

Table IV
Meeting the 18 dB CC/I Objective for Portland MSA Walk Tests, Omni Network

Carrier Sector	Topology	(Omni) Mean CC/I_{dB}	(Sectored) *Mean CC/I_{dB}	**Improvement in Mean CC/I_{dB} due to Sectorizing**
Orbanco B	Urban, Flat	-5.6	5.7	**11.3**
Lloyd Center B	Suburban, Flat	14.8	21.1	**6.3**
Erroll Heights C	Suburban, Hilly	19.5	25.6	**6.1**
Stafford A	Rural, Hilly	38.9	39.8	**0.9**

* From Table III

B. IMPROVED CC/I IN HILLY TOPOLOGIES

As shown in the previous chapter, CC/I in the sectored network simulation did not meet the 18 dB objective for service quality in 3 of the 4 test routes. To determine if terrain has an affect, the average RSS_{dBm} for each sector is compared across the test routes. This data is charted in Figure 21, where test routes are arranged in order of progressively hilly topology. Orbanco B, the most urban environment, is on the left and Stafford A, the most rural hilly, is on the right. All RSS_{dBm} data is normalized to 100 watt base station antenna TXERP. The most significant trend is the decrease in RSS_{dBmi} as the sector topology becomes more hilly.

In rural hilly environments, interferers tend to be further from the carrier mobile so are more apt to be influenced by natural obstructions. This attenuates their RSS_{dBmi} more severely than in flatter suburban and urban environments.

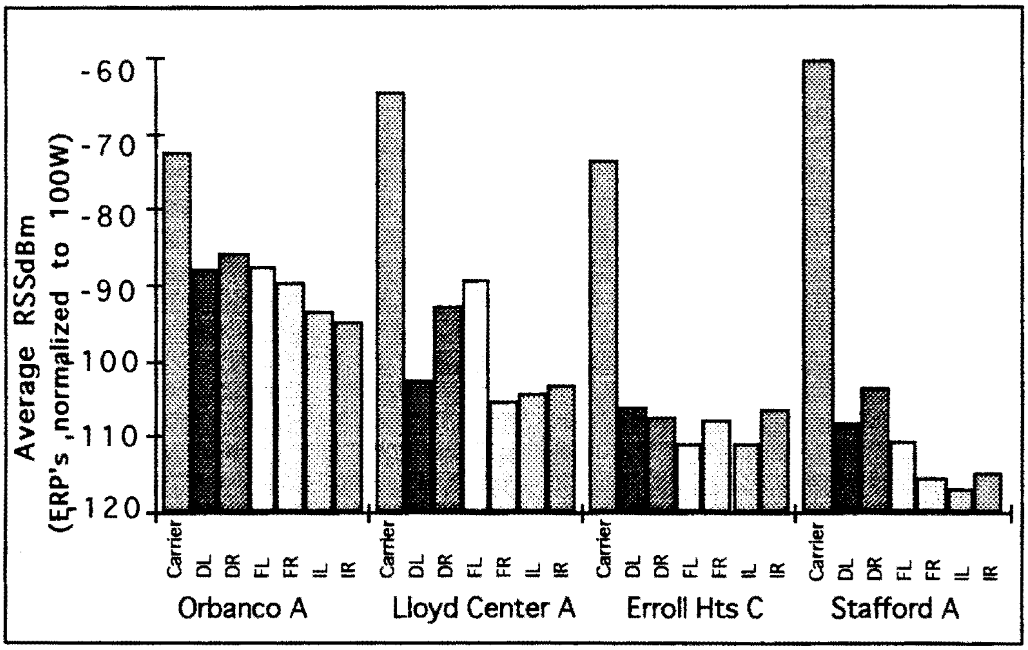


Figure 21: Average RSS_{dBm} by Sector

C. ADDITIONAL PATH LOSS DUE TO OBSTRUCTIONS

The path loss model discussed in Chapter IV applies to paths which are unobstructed by terrain contour where, generally, only foliage and man made objects block the direct RF wave from reaching the mobile receiver. An additional path loss component due to terrain obstructions will be identified in this section.

An obstructed path is one that does not have at least 0.6 x first Fresnel clearance ($0.6F_1$) [4]. The first Fresnel zone is an ellipsoid with the mobile antenna and the base station antenna at the foci. The sum of the distances from any surface on the ellipsoid to both foci is equal to one half wavelength more than the path length (shortest distance between foci). The first Fresnel zone distance is the orthogonal distance from path line-of-sight to the ellipsoid surface and the equation at any point d_1 along the path is,

$$F_1 = 2280\sqrt{\frac{d_1 + d_2}{F\,d}} \tag{13}$$

where,

F_1 = first Fresnel zone distance in feet

d_1 = distance measured in miles

d = total path length in miles

$d_2 = d - d_1$

F = frequency in MHz

Three actual path profiles are shown in Figure 22 - 25. Each represents the terrain contour from the mobile receiver at the approximate midway point in the test route, on the left, to a sector transmitting antenna on the right. Figure 22 illustrates an unobstructed path and the ellipsoid formed by plotting the first Fresnel zone. The frequency is 860 MHz.

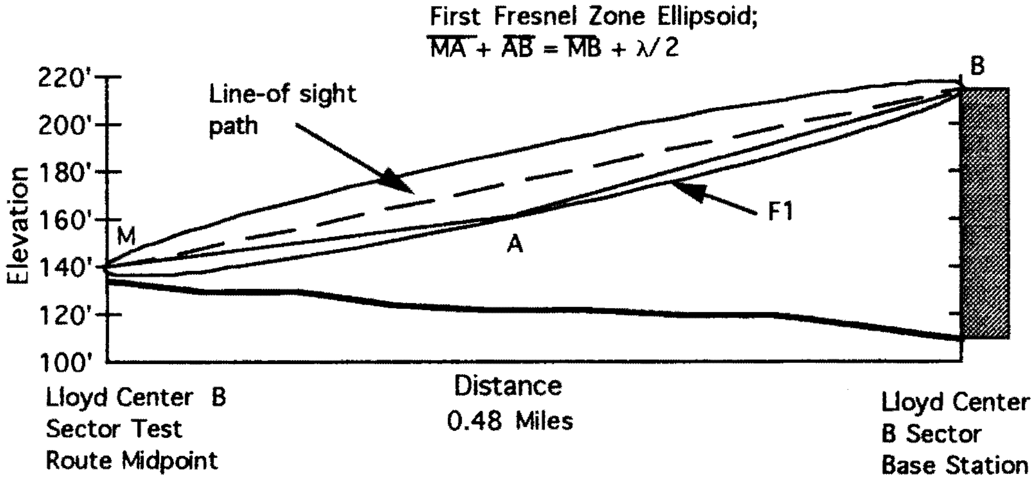


Figure 22: An Unobstructed Path Profile Illustrating The First Fresnel Zone

A path can be obstructed by terrain contour in two ways, grazing and knife-edge. A grazing path has line-of-sight but terrain obstructs 0.6 of the first Fresnel Zone somewhere along the path. A knife-edge path has one or more obstructions that completely blocks line-of-sight. A grazing path is illustrated in Figure 23 along with the distance parameters h_p, r_1 and r_2, where h_p is negative feet and r_1 and r_2 are measured in miles. Figure 24 illustrates an obstructed path with one knife-edge, where h_p, r_1 and r_2 are measured similar to Figure 23 except h_p is positive.

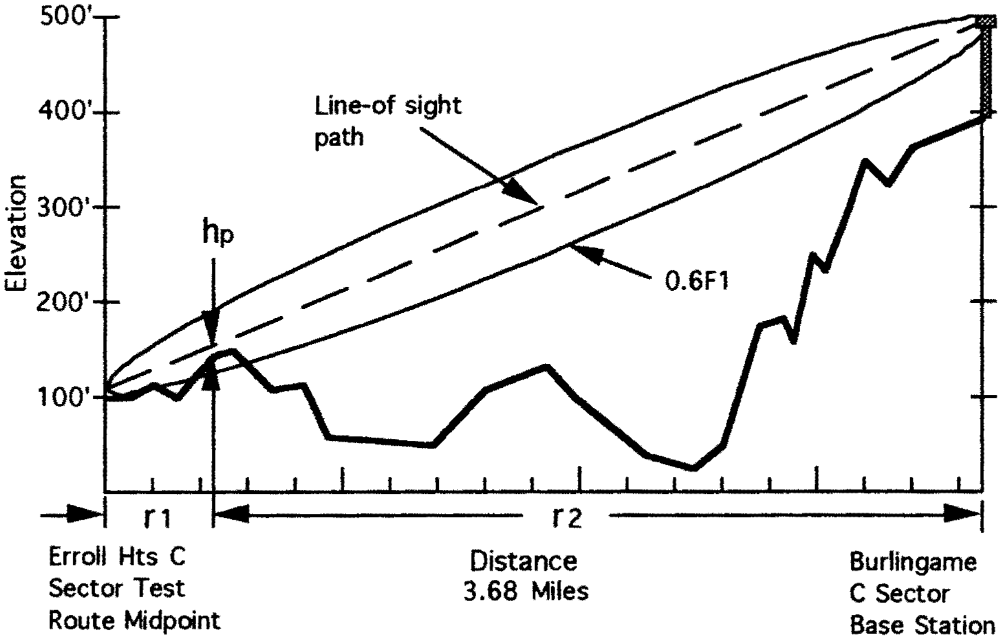


Figure 23: A Grazing Obstructed Path Profile Illustrating 0.6 First Fresnel Zone Blockage

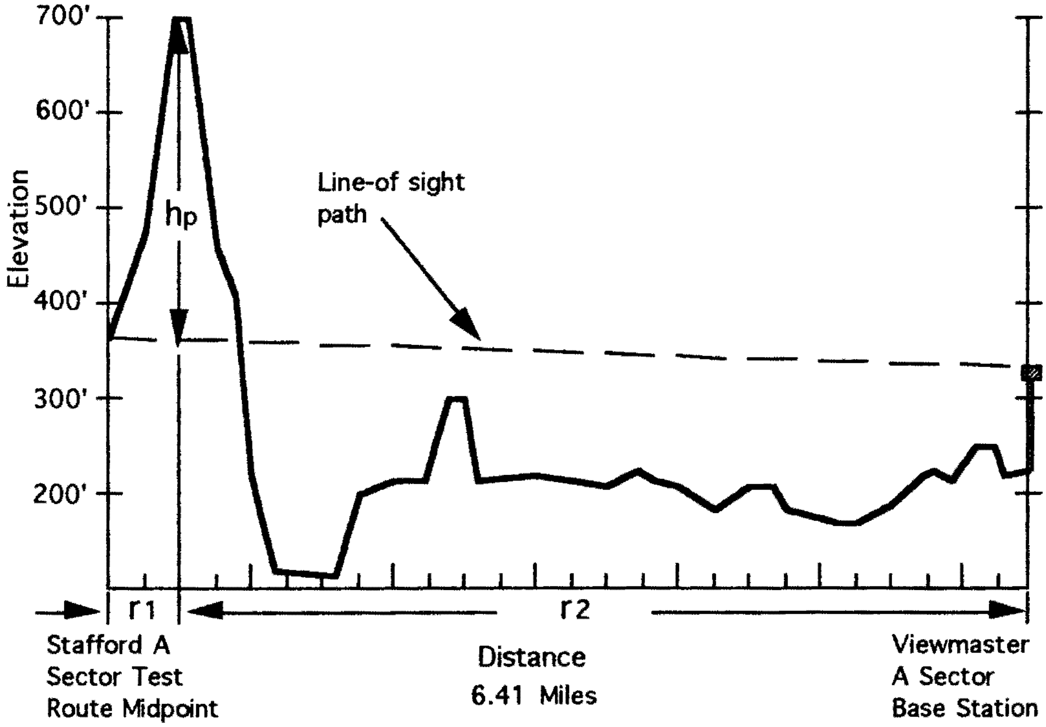


Figure 24: A Single Knife-Edge Obstructed Path Profile

Some paths actually experience more than one knife-edge obstruction, called double or triple knife-edge. These are evaluated similarly by breaking the path into tandem single knife-edge sections. Figure 25 illustrates a typical double knife-edge path profile.

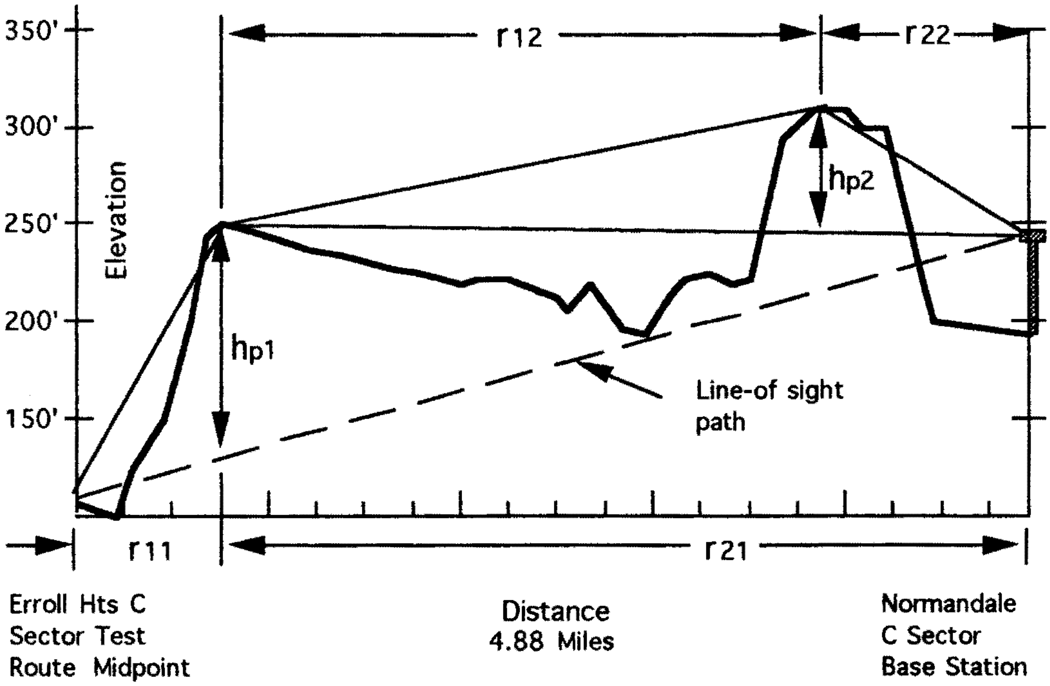


Figure 25: A Double Knife-Edge Obstructed Path Profile

The obstructed paths contribute an additional loss to the overall path loss. This is called diffraction loss, L_{diff} [4]. To quantify L_{diff} , Lee defines the parameter v, which is derived by using a different expression for the first Freznel zone distance formula (13).

$$v = -h_p \sqrt{\frac{2}{\lambda}\left(\frac{1}{r1}+\frac{1}{r2}\right)} \tag{14}$$

After h_p, r_1 and r_2 are measured on a path profile plot, L_{diff} is determined using the approximate formula,

$$\begin{array}{rl} 0.8 \le v & L_{diff} = 0 \text{ dB} \\ 0 \le v < 0.8 & L_{diff} = 20 \log(0.5 + 0.62v) \\ -1 \le v < 0.0 & L_{diff} = 20 \log (0.5e^{0.95v}) \\ -2.4 \le v < -1 & L_{diff} = 20 \log (0.4 - \sqrt{0.1184 - (0.1v + 0.38)^2}) \\ v < -2.4 & L_{diff} = 20 \log\left(- \frac{0.225}{v}\right) \end{array} \qquad (15)$$

Equation 15 is modified slightly from Lee's. Here an upper bound for v of 0.8 is used, this identifies where the path clearance is $0.6F_1$ or more and L_{diff} is 0 dB [4].

C. APPROXIMATING L_{diff}

The objective of this section is to determine if L_{diff} improves CC/I in hilly environments. Large L_{diff} will contribute to higher path loss. If the interfering RSS are attenuated more than the carrier RSS, then CC/I will be higher.

The path profiles for all test routes (similar to Figures 22 - 25 and choosing the approximate midway point in each mobile receiver test route) to it's test carrier sector transmitting antenna and to the 6 interfering sector transmitting antenna were created from a USGS terrain data base. The distance parameters h_p, r_1 and r_2 are scaled directly from these. The parameters v and L_{diff} are calculated in an EXCEL file and the results are shown in Appendix C.

Figure 26 charts average RSS_{dBm} normalized to base station TXERP's of 100 watts with L_{diff} added. L_{diff} is expressed in dB so it can be added to the mean RSS_{dBm} of each carrier and interfering channel to eliminate the effects of obstruction on path loss and RSS. This creates a hypothetical "flat" terrain environment free of path obstruction loss which reduces CC/I in hilly topologies. Notice when comparing Figures 21 and 26 that CC/I is reduced in the Erroll Heights C and Stafford A tests, suggesting that obstruction loss is a significant factor.

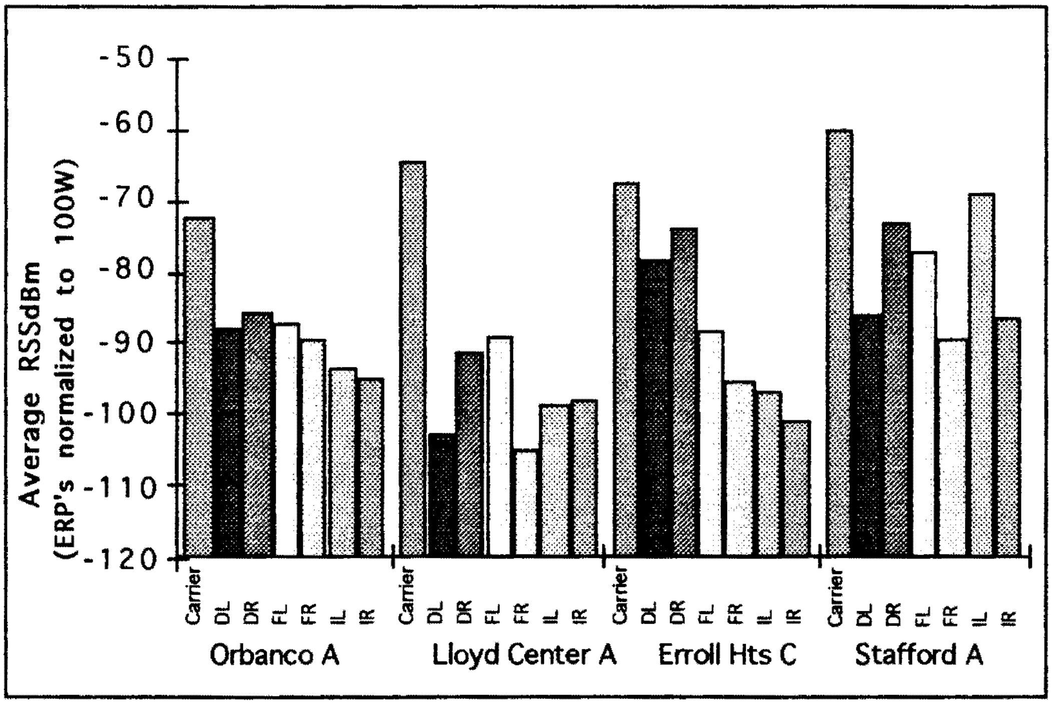


Figure 26: Average RSS_{dBm} With L_{diff} Added

D. MEETING THE 18 dB CC/I OBJECTIVE

Obstruction loss was shown in the previous section to have a significant impact on C/I. A more quantitative approach is needed to determine if CC/I in the hilly topologies meets the 18 dB objective when the effects of obstruction loss is removed. Diffraction loss L_{diffi} calculated in the previous section is first assumed constant across each test route. Then when determining the CC/I for each record, L_{diffi} is added to each RSS along with Ni. This "flattens" all interfering signal paths, eliminating terrain obstruction loss. The new expression for RSS_{dBmI} is;

$$RSS_{dBmI} = 10\log\left[\sum_{i=1}^{6} 10^{\left(\frac{RSS_{dBmi} + N_i + L_{Diffi}}{10}\right)}\right] \tag{16}$$

This tends to increase RSS_{dBmi} where paths were severely obstructed by terrain contour and creates a new listing of CC/I and a new mean, shown in Table V. In this non-obstructed environment, all tests fall far short of meeting requirements. This shows that a cellular network constructed in flat and sloping terrain environments using the 7 cell per cluster, 3 sector per cell design with a rigorous application of the associated frequency plan cannot meet the 18 dB objective required for quality service.

Table V
Meeting the 18 dB CC/I Objective for Portland MSA Walk Tests, Sectored Network Without Terrain Obstructions

Carrier Sector	Mean CC/I_{dB} w/Ldiff	**P[CC/I > 18 dB]**	* Mean CC/I_{dB}	**Change in Mean CC/I_{dB} with Ldiff added**
Orbanco B	5.7	**0**	5.7	**0.0**
Lloyd Center B	20.0	**0.532**	21.1	**-1.1**
Erroll Heights C	4.5	**0**	25.6	**-21.1**
Stafford A	6.2	**0**	39.8	**-33.6**

* Mean CC/I_{dB} from Table III

CHAPTER VII

CONCLUSION

A readily available cellular system test set, the LCC MSAT-2000, was used to gather RSS data that was shown to be valid for down-link CC/I evaluation. A procedure for simulating a near ideal sectored cellular system at busy hour traffic load was accomplished by using existing base stations in the Portland MSA.

CC/I at 4 sectors in the Portland MSA were measured, one urban with sloping terrain, one suburban with sloping terrain, one suburban with hilly terrain and one rural with hilly terrain. The associated CC/I distributions are Rayleigh distributed rather than log-normal, the latter of which is the commonly used random distribution for computer simulation of interfering signals. The significance of this is that Rayleigh distributions require a higher mean than log-normal distributions, for 0.9 percentile probability. Therefore, the criterion for meeting the 18 dB CC/I objective requires a mean CC/I value that is as much as 2.2 dB higher than previously thought.

As a direct result, two of the four sectors tested failed to meet the CC/I industry standard 18 dB objective by a substantial margin. These are sectors in urban and suburban topologies where the environments are essentially flat terrain with only small variations in elevation. Only the two tests conducted in hilly environments provided CC/I at or near acceptable levels for good voice quality. The 3 sector per cell, 7 cell per cluster cellular system design, utilized in this and many domestic markets, does not provide adequate spatial separation between base stations in flat terrain. In practice, it is common for the Cellular RF Engineer to make modifications to the frequency plan to accommodate this.

A non-sectored omnidirectional network was also simulated using existing base stations. CC/I measurements from this was used to substantiate that sectoring is meeting expectations, by providing 6.0 dB or more improvement in CC/I in all but very hilly topologies where interferers are already attenuated by severely obstructed paths. A substantial improvement , over 11 dB, was seen in the urban flat topology test.

The RF signal path characteristics which contribute to diffraction loss were analyzed. It was found that severe terrain obstructions account for the ability of rural very hilly sectors to meet the 18 dB CC/I objective, due to severely obstructed interference signal paths.

Clearly, a modified cellular network design is needed. Future work could consist of identifying a network design which has a larger D/R but that will serve the same geographic area with the same traffic efficiency as the present 21 sector per cluster system. This can be simulated using a similar approach as used here and field tested for it's ability to meet the 18 dB CC/I objective. Also, the effect of modifying the existing network using down tilted antennas, variations in transmitter antenna heights, variations in antenna support structures and "smart" antennas could be field tested.

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APPENDIX A

Table AI

Network Data and Some Results for ORBANCO A Sector, Sectored Simulation

SW 3rd & Clay, north on 3rd to Columbia, east to 2nd, north to 100' n/o Madison. 1 ft traveled per record.								
11/16/96	21 sector per cluster simulation. 0.16 miles from base station.						1002 records	
R and D in miles =	R = 0.16	D = 0.73	D = 0.49	D = 0.94	D = 0.44	D = 0.94	D = 0.98	
Sector=	Orbanco B	Honeyman B	Stadium B	E Burnside B	PSU B	Marquam B	Hawthorne B	
Designation =	C	DL	DR	FL	FR	IR	IL	
RF Channel =	158	694	132	152	156	136	70	
TX ERPw =	11 Watts	25 Watts	15 Watts	30 Watts	15 Watts	50 Watts	20 Watts	
Ni =	0	-3.6 dB	-1.3 dB	-4.4 dB	-1.3 dB	-6.6 dB	-2.6 dB	
Antenna Azimuth =	135.0 °	135.0 °	135.0 °	135.0 °	135.0 °	135.0 °	135.0 °	
Azimuth to Test Rt =	100.0 °	170.0 °	130.0 °	220.0 °	90.0 °	0.0 °	270.0 °	
Tx Antenna BeamW =	60.0 °	60.0 °	60.0 °	60.0 °	105.0 °	60.0 °	60.0 °	
Tx Antenna hT =	125 ft	105 ft	110 ft	110 ft	100 ft	140 ft	100 ft	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average=	-82.1	-94.1	-94.0	-92.8	-97.8	-97.8	-100.8	5.7
Standard Deviation =	6.5	7.8	6.1	6.5	6.2	6.0	7.8	6.2
Time								
17:16:38:07	-75	-86	-88	-95	-88	-96	-110	9.4
17:16:39:20	-75	-86	-88	-95	-90	-104	-111	10.0
17:16:40:36	-74	-87	-88	-95	-87	-108	-108	10.4
17:16:41:48	-74	-83	-85	-112	-97	-94	-105	9.2
17:16:42:63	-78	-79	-93	-98	-91	-93	-101	3.8
17:16:43:77	-81	-81	-85	-96	-82	-96	-110	-1.3
17:16:44:92	-75	-81	-97	-102	-90	-95	-109	8.5
17:16:46:05	-73	-82	-89	-97	-90	-95	-105	10.4
17:16:47:21	-75	-82	-84	-96	-92	-109	-101	7.0
17:16:48:33	-84	-81	-90	-94	-93	-94	-112	-0.8

Table AII
Network Data and Some Results for Lloyd Center B Sector, Sectored Simulation

South on NE19th from Weidler to Multnomah				1 ft traveled per record			612 records	
12/7/96	21 sector per cluster simulation							
R and D in miles =	R = 0.49	D = 1.41	D = 2.5	D = 2.17	D = 2.17	D = 2.31	D = 2.7	
Sector =	Lloyd B	Piedmont B	Monty Pk B	Killingswth B	PSU B	39/Hawthne B	Normandale B	
Designation =	C	FL	DR	DL	FR	IR	IL	
RF Channel =	93	263	136	175	156	113	124	
TX ERPw =	14 Watts	40 Watts	16 Watts	42 Watts	15 Watts	19 Watts	25 Watts	
Ni =	0.0 dB	-4.6 dB	-0.6 dB	-4.8 dB	-0.3 dB	-1.3 dB	-2.5 dB	
Antenna Azimuth =	135 °	135 °	135 °	135 °	135 °	135 °	135 °	
Azimuth to Test Rt =	113 °	182 °	96 °	139 °	55 °	322 °	275 °	
TX Antenna BeamW =	60 °	60 °	60 °	60 °	105 °	92 °	80 °	
TX Antenna hT =	115 ft	130 ft	120 ft	110 ft	100 ft	45 ft	100 ft	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average =	-72.3	-93.4	-93.6	-106.6	-113.7	-109.6	-112.7	21.1
Standard Deviation =	6.4	5.6	6.5	5.5	1.5	5.1	4.6	7.5
Time								
17:50:51:95	-73	-90	-101	-102	-113	-112	-114	20.5
17:51:05:03	-75	-92	-91	-106	-114	-106	-113	15.2
17:51:06:65	-73	-89	-95	-106	-113	-106	-113	18.3
17:51:07:55	-72	-92	-95	-103	-114	-105	-113	20.7
17:51:08:86	-68	-96	-90	-103	-114	-106	-112	22.0
17:51:09:79	-68	-102	-86	-114	-112	-108	-113	18.5
17:51:11:22	-71	-92	-85	-104	-112	-109	-110	14.2
17:51:12:12	-77	-93	-85	-106	-116	-104	-113	8.3
17:51:13:12	-62	-97	-86	-100	-112	-114	-116	24.4
17:51:14:30	-65	-90	-100	-110	-113	-111	-116	28.5
17:51:15:45	-81	-92	-95	-112	-114	-112	-110	11.9

Table AIII
Network Data and Some Results for Erroll Heights C Sector, Sectored Simulation

Brookside Dr, 480' from Johnson Ck Blvd, west to JC Blvd, then to 42nd.						1252 records		
11/23/96	21 sector per cluster simulation			1 ft traveled per record			1 mile from BS	
R and D miles =	R = 1.0	D = 4.78	D = 4.01	D = 4.27	D = 5.88	D = 4.18	D = 4.76	
Sector =	Erroll Hts C	Clackamas C	Normandale C	Burlingame C	Division C	Oak Grv C	Orbanco C	
Designation =	C	FL	DR	IR	DL	IL	FR	
RF Channel =	107	149	129	176	81	707	235	
TX ERPw =	25 Watts	50 Watts	10 Watts	100 Watts	25 Watts	50 Watts	22 Watts	
Ni =	0.0 dB	-3.0 dB	4.0 dB	-6.0 dB	0.0 dB	-3.0 dB	0.6 dB	
Antenna Azimuth =	255 °	255 °	255 °	200 °	250 °	255 °	255 °	
Azimuth to Test Rt =	218 °	327 °	189 °	99 °	242 °	25 °	142 °	
TX Antenna Beamw =	90 °	60 °	80 °	105 °	90 °	120 °	60 °	
TX Antenna hT =	110 ft	100 ft	100 ft	65 ft	125 ft	120 ft	125 ft	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average =	-79.5	-114.4	-117.4	-106.5	-111.9	-114.2	-113.9	25.6
Standard Deviation =	6.0	3.4	2.1	5.0	4.0	3.3	1.2	6.0
Time								
15:08:45:48	-83	-108	-115	-106	-109	-111	-114	20.7
15:08:46:53	-86	-108	-105	-106	-109	-111	-114	13.4
15:08:47:67	-83	-113	-116	-110	-109	-111	-112	21.7
15:08:48:52	-79	-110	-113	-103	-114	-113	-108	23.8
15:08:49:93	-79	-110	-113	-111	-108	-110	-110	24.0
15:08:51:31	-74	-111	-116	-109	-114	-114	-111	31.6
15:08:52:47	-96	-109	-111	-104	-109	-113	-109	5.9
15:08:53:28	-88	-110	-112	-106	-111	-112	-113	15.6
15:08:54:54	-73	-105	-114	-104	-111	-113	-112	29.8
15:08:55:61	-76	-110	-114	-100	-114	-114	-116	27.1

Table AIV
Network Data and Some Results for Stafford A Sector, Sectored Simulation

Southwest on Childs Rd, starting at Stafford Rd, 1070'				1 ft traveled per record		1002 records		
11/24/96	21 sector per cluster simulation			1.5 miles from BS				
R and D in miles =	R = 1.48	D = 6.66	D = 6.65	D = 7.41	D = 6.18	D = 6.22	D = 8.06	
Sector =	Stafford A	Viewmstr A	Burlingame A	Clackamas A	Sherwood A	Wilsnvlle A	Canby A	
Designation =	C	FL	IL	IR	DL	DR	FR	
RF Channel =	141	139	186	122	704	161	62	
TX ERPw =	25 Watts	20 Watts	75 Watts	50 Watts	50 Watts	50 Watts	125 Watts	
Ni =	0.0 dB	1.0 dB	-4.8 dB	-3.0 dB	-3.0 dB	-3.0 dB	-7.0 dB	
Antenna Azimuth =	90.0 °	15.0 °	345.0 °	15.0 °	omni	15.0 °	omni	
Azimuth to Test Rt =	42.0 °	136.0 °	181.0 °	258.0 °	81.0 °	42.0 °	352.0 °	
TX Antenna BeamW	120.0 °	92.0 °	60.0 °	105.0 °	omni	105.0 °	omni	
TX Antenna hT =	140 ft	80 ft	65 ft	100 ft	180 ft	100 ft	170 ft	
	RSSdBmC	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	CC/I
Average =	-66.3	-117.6	-117.8	-118.3	-111.0	-106.7	-114.6	39.8
Standard deviation =	6.4	2.0	1.9	2.9	4.9	5.6	2.6	6.6
Time								
17:01:04:10	-67	-117	-118	-118	-120	-105	-116	39.8
17:01:04:93	-76	-119	-118	-119	-112	-108	-113	32.3
17:01:06:26	-64	-119	-118	-119	-118	-108	-114	45.1
17:01:07:34	-65	-117	-116	-118	-119	-112	-115	45.7
17:01:08:42	-68	-117	-116	-117	-114	-104	-112	37.6
17:01:09:29	-61	-117	-117	-118	-114	-108	-112	47.2
17:01:10:65	-66	-118	-117	-119	-113	-108	-112	42.2
17:01:11:94	-62	-117	-116	-117	-118	-104	-116	43.9
17:01:12:89	-60	-116	-116	-115	-113	-103	-116	44.7
17:01:13:91	-61	-115	-115	-117	-109	-103	-116	43.2

APPENDIX B
Table BI
Network Data and Some Results for ORBANCO A Sector, Omni Simulation

SW 3rd & Clay, north on 3rd to Columbia, east to 2nd, north to 100' n/o Madison. 1 ft traveled per record.								
11/16/96	omindirectional simulation. 0.16 miles from base station.					1002 records		
Sector=	Orbanco B	Honeymn B	Stadium B	E Burnside C	PSU B	Marquam A	Hawthorne C	
RF Channel =	158	694	132	103	156	122	707	
TX ERPw =	11 Watts	25 Watts	15 Watts	15 Watts	15 Watts	16 Watts	16 Watts	
Ni =	0	-3.6 dB	-1.3 dB	-1.3 dB	-1.3 dB	-1.6 dB	-1.6 dB	
Antenna Azimuth =	135.0 °	135.0 °	135.0 °	255.0 °	135.0 °	15.0 °	255.0 °	
Azimuth to Test Rt =	100.0 °	170.0 °	130.0 °	220.0 °	90.0 °	0.0 °	270.0 °	
Tx Antenna BeamW =	60.0 °	60.0 °	60.0 °	60.0 °	105.0 °	60.0 °	60.0 °	
Discrimination Loss	4.0 dB	4.0 dB	0.0 dB	4.0 dB	6.0 dB	1.0 dB	1.0 dB	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average=	-82.1	-94.1	-94.0	-86.5	-97.8	-85.0	-75.2	-5.6
Standard Deviation =	6.5	7.8	6.1	5.8	6.2	6.3	9.1	8.5
Time								
17:16:38:07	-75	-86	-88	-89	-88	-81	-77	3.5
17:16:39:20	-75	-86	-88	-88	-90	-82	-77	3.9
17:16:40:36	-74	-87	-88	-91	-87	-82	-77	4.7
17:16:41:48	-74	-83	-85	-104	-97	-82	-81	6.8
17:16:42:63	-78	-79	-93	-89	-91	-81	-82	1.0
17:16:43:77	-81	-81	-85	-83	-82	-76	-81	-5.3
17:16:44:92	-75	-81	-97	-87	-90	-90	-84	6.0
17:16:46:05	-73	-82	-89	-90	-90	-82	-89	8.2
17:16:47:21	-75	-82	-84	-86	-92	-81	-96	5.3
17:16:48:33	-84	-81	-90	-84	-93	-80	-81	-5.3
17:16:49:48	-79	-82	-85	-85	-86	-84	-85	0.4

Table BII
Network Data and Some Results for Lloyd Center B Sector, Omni Simulation

South on NE19th from Weidler to Multnomah				1 ft traveled per record			612 records	
12/7/96	omnidirectional simulation			0.49 miles from base station				
Sector =	Lloyd B	Piedmont B	Monty Pk B	Killingswrth B	PSU A	39/Hawthrne A	Normandale C	
RF Channel =	93	263	136	175	142	79	129	
TX ERPw =	14 Watts	40 Watts	16 Watts	42 Watts	15 Watts	19 Watts	10 Watts	
Ni =	0.0 dB	-4.6 dB	-0.6 dB	-4.8 dB	-0.3 dB	-1.3 dB	1.5 dB	
Antenna Azimuth =	135 °	135 °	135 °	135 °	10 °	15 °	255 °	
Azimuth to Test Rt	113 °	182 °	96 °	139 °	55 °	322 °	275 °	
TX Antenna BeamW	60 °	60 °	60 °	60 °	60 °	92 °	80 °	
Discrimination Loss	1.0 dB	6.0 dB	4.0 dB	0.0 dB	5.0 dB	2.5 dB	1.0 dB	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average =	-70.7	-93.4	-92.3	-106.2	-113.3	-99.3	-98.4	14.8
Standard Deviation =	6.4	5.6	6.5	5.5	3.2	5.1	7.5	7.5
Time								
17:50:51:95	-73	-90	-101	-102	-112	-99	-105	15.4
17:51:05:03	-75	-92	-91	-106	-112	-93	-110	10.9
17:51:06:65	-73	-89	-95	-106	-112	-93	-110	13.1
17:51:07:55	-72	-92	-95	-103	-111	-96	-106	16.1
17:51:08:86	-68	-96	-90	-103	-112	-97	-106	18.4
17:51:09:79	-68	-102	-86	-114	-109	-94	-106	15.1
17:51:11:22	-71	-92	-85	-104	-104	-95	-106	10.8
17:51:12:12	-77	-93	-85	-106	-108	-94	-97	4.7
17:51:13:12	-62	-97	-86	-100	-107	-105	-99	21.1
17:51:14:30	-65	-90	-100	-110	-107	-107	-101	23.4
17:51:15:45	-81	-92	-95	-112	-106	-95	-96	6.1
17:51:16:60	-66	-96	-99	-102	-110	-96	-110	25.0

Table BIII
Network Data and Some Results for Erroll Heights C Sector, Omni Simulation

Brookside Dr, 480' from Johnson Ck Blvd, west to JC Blvd, then to 42nd.						1252 records		
11/23/96	omnidirectional simulation			1 ft traveled per record			1 mile from BS	
Sector =	Erroll Hts C	Clackamas A	Normandle C	Burlingme C	Division C	Oak Grve	Orbanco B	
RF Channel =	107	122	129	176	81	198	158	
TX ERPw =	25 Watts	50 Watts	10 Watts	100 Watts	25 Watts	25 Watts	11 Watts	
Ni =	0.0 dB	-3.0 dB	4.0 dB	-6.0 dB	0.0 dB	0.0 dB	3.6 dB	
Antenna Azimuth =	255 °	15 °	255 °	200 °	250 °	15 °	135 °	
Azimuth to Test Rt	218 °	327 °	189 °	99 °	242 °	25 °	142 °	
TX Antenna Beamw	90 °	105 °	80 °	100 °	90 °	105 °	60 °	
Discrimination Loss	4.0 dB	3.0 dB	6.0 dB	14.0 dB	0.0 dB	0.0 dB	0.0 dB	
	RSSdBmC	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	RSSdBmi	CC/I
Average =	-78.8	-103.3	-113.7	-106.5	-110.9	-103.4	-114.8	19.5
Standard Deviation =	6.0	5.7	2.1	5.0	4.0	5.3	5.7	6.2
Time								
15:08:45:48	-83	-98	-115	-106	-109	-104	-111	15.4
15:08:46:53	-86	-97	-105	-106	-109	-104	-109	9.6
15:08:47:67	-83	-102	-116	-110	-109	-105	-116	16.8
15:08:48:52	-79	-98	-113	-103	-114	-109	-113	19.7
15:08:49:93	-79	-98	-113	-111	-108	-103	-113	19.1
15:08:51:31	-74	-100	-116	-109	-114	-112	-117	26.6
15:08:52:47	-96	-96	-111	-104	-109	-108	-113	1.5
15:08:53:28	-88	-97	-112	-106	-111	-108	-113	10.4
15:08:54:54	-73	-102	-114	-104	-111	-96	-114	24.3
15:08:55:61	-76	-94	-114	-100	-114	-102	-114	18.4
15:08:56:47	-67	-111	-117	-99	-110	-100	-117	31.0
15:08:57:56	-70	-107	-116	-97	-117	-105	-116	25.5

Southwest on Childs Rd, starting at Stafford Rd, 1070'				1 ft traveled per record		1002 records		
11/24/96	omnidirectional simulation			1.5 miles from BS				
Sector =	Stafford A	Viewmastr B	Burlingme C	Clackamas C	Sherwood A	Wilsonvlle A	Canby A	
RF Channel =	141	53	92	233	704	161	62	
TX ERPw =	25 Watts	25 Watts	100 Watts	50 Watts	50 Watts	50 Watts	125 Watts	
Ni =	0.0 dB	0.0 dB	-6.0 dB	-3.0 dB	-3.0 dB	-3.0 dB	-7.0 dB	
Antenna Azimuth =	90.0 °	125.0 °	200.0 °	235.0 °	omni	15.0 °	omni	
Azimuth to Test Rt	42.0 °	136.0 °	181.0 °	258.0 °	81.0 °	42.0 °	352.0 °	
TX Antenna BeamW	120.0 °	92.0 °	100.0 °	60.0 °	omni	105.0 °	omni	
Discrimination Loss	2.0 dB	0.0 dB	0.0 dB	2.0 dB	0.0 dB	1.0 dB	0.0 dB	
	RSSdBmC	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	RSSdBmI	CC/I
Average =	-66.3	-110.5	-111.3	-112.3	-111.0	-106.7	-114.6	38.9
Standard deviation =	6.4	4.3	6.0	2.9	4.9	5.6	2.6	6.8
Time								
17:01:04:10	-67	-114	-114	-109	-120	-105	-116	39.4
17:01:04:93	-76	-112	-110	-109	-112	-108	-113	30.8
17:01:06:26	-64	-113	-114	-108	-118	-108	-114	43.2
17:01:07:34	-65	-116	-108	-108	-119	-112	-115	43.1
17:01:08:42	-68	-110	-106	-107	-114	-104	-112	36.2
17:01:09:29	-61	-119	-106	-108	-114	-108	-112	45.8
17:01:10:65	-66	-119	-106	-108	-113	-108	-112	40.7
17:01:11:94	-62	-113	-112	-105	-118	-104	-116	42.4
17:01:12:89	-60	-110	-109	-114	-113	-103	-116	44.9
17:01:13:91	-61	-110	-109	-114	-109	-103	-116	43.6
17:01:15:01	-59	-116	-114	-112	-105	-98	-114	42.0

Table BIV

Network Data and Some Results for Stafford A Sector, Omni Simulation

APPENDIX C

Table CI
Diffraction Loss on Obstructed Paths

Transmitting	Sect.	Path	For First Knife-Edge					For Second Knife-Edge					Total
Sector	Des.	Topology	r11	r21	hp1	v1	Ldiff	r21	r22	hp2	v2	Ldiff	Ldiff
Orbanco B	C	unobstr.					0.0					0.0	0.0
Honeyman B	DL	unobstr.					0.0					0.0	0.0
Stadium B	DR	unobstr.					0.0					0.0	0.0
E Burnside B	FL	unobstr.					0.0					0.0	0.0
PSU B	FR	unobstr.					0.0					0.0	0.0
Hawthorne B	IL	unobstr.					0.0					0.0	0.0
Marquam B	IR	unobstr.					0.0					0.0	0.0
Lloyd Ctr B	C	unobstr.					0.0					0.0	0.0
Killingsworth	DL	unobstr.					0.0					0.0	0.0
Monty Pk B	DR	grazing	0.12	2.83	-10.0	0.5	-1.6					0.0	-1.6
Piedmont B	FL	grazing	0.18	1.34	-25.0	1.1	0.0					0.0	0.0
PSU B	FR	grazing	0.13	2.25	-15.0	0.8	-0.2					0.0	-0.2
Normandale B	IL	grazing	0.70	1.53	0.0	0.0	-6.0					0.0	-6.0
39/Hawth B	IR	grazing	0.07	1.80	-1.0	0.1	-5.3					0.0	-5.3
Erroll Hts C	C	single KE	0.55	0.58	-1.0	0.0	-5.7					0.0	-5.7
Division C	DL	single KE	0.20	6.60	125.0	-5.2	-27.2					0.0	-27.2
Normandale C	DR	double KE	0.70	4.18	115.0	-2.7	-21.6	1.18	3.00	34.0	-0.7	-11.6	-33.2
Clackamas C	FL	double KE	1.34	3.00	47.0	-0.9	-13.4	1.04	0.30	11.0	-0.4	-9.4	-22.8
Orbanco C	FR	single KE	0.71	4.20	33.0	-0.8	-12.4					0.0	-12.4
Oak Grove C	IL	single KE	0.68	2.50	40.0	-1.0	-14.2					0.0	-14.2
Burlingame C	IR	grazing	0.43	3.25	-1.0	0.0	-5.7					0.0	-5.7
Stafford A	C	grazing	0.03	1.40	-7.0	0.7	-0.3					0.0	-0.3
Sherwood	DL	single KE	0.65	6.60	120.0	-2.8	-22.0					0.0	-22.0
Wilsonville	DR	double KE	3.74	3.90	125.0	-1.6	-17.6	2.41	0.34	25.0	-0.8	-12.9	-30.5
Viewmaster A	FL	single KE	0.40	6.00	350.0	-10.4	-33.3					0.0	-33.3
Canby	FR	single KE	3.60	5.30	365.0	-4.5	-26.1					0.0	-26.1
Burlingame A	IL	double KE	0.20	5.30	100.0	-4.1	-25.3	4.60	0.70	133	-3.1	-22.8	-48.1
Clackamas A	IR	single KE	1.70	4.50	350.0	-5.7	-28.1					0.0	-28.1

APPENDIX D

A. LOG-NORMAL PDF AND RAYLEIGH CDF EQUATIONS

Ideal log-normal Probability Density Functions PDF's and Rayleigh Cumulative Distribution Functions CDF's for both RSS and CC/I data are used for various purposes in this thesis. These are generated in the EXCEL files containing the RSS measurements and their corresponding CC/I calculations. The ideal log-normal PDF is calculated using the following equation [2];

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad \text{(D1)}$$

where;

all variables are expressed in decibels

x is the data type, either RSS_{dBm} or CC/I_{dB}

μ is the mean value of the x data

σ is the standard deviation of the x data

The ideal Rayleigh CDF is calculated using the following equation (this also serves as the derivation of equation 11, chapter V). All variables are in linear form. The probability that x exists between two values x_1 and x_2 is [5];

$$P[x_1 < x < x_2] = F_x(x_2) - F_x(x_1) \qquad \text{(D2)}$$

let $x_1 = X$ & $x_2 = \infty$;

$$P[X < x \leq \infty] = F_x(\infty) - F_x(X)$$

$$= 1 - F_x(X) \qquad \text{(D3)}$$

Since $F_x(x_0) = 1 - e\text{^}[-(x_0^2/2\sigma^2)]$, x_0 = amplitude, x_0^2 = power and $2\sigma^2$ = mean power [2], then substituting and restating the probability that x is greater than X;

$$P[x > X] = 1 - (1 - e\text{^}[-(X/\sigma)])$$

$$= e\text{^}[-(X/\sigma)] \tag{D4}$$

Expressing all variables in decibels;

$$P[x > X] = e^{-10\text{^}[0.1(X-\sigma)]} \tag{D5}$$

B. CC/I PDF AND CDF ANALYSIS

An EXCEL file for each test route contains it's cochannel carrier to interference calculations. One CC/I value has been generated from the corresponding RSS measurements for each time record, creating a new data series. A Probability Density Function (PDF) and a Cumulative Distribution Function (CDF) have been generated for this CC/I data. The PDF for each is plotted below in Figures D1 through D4 along with it's corresponding log-normal PDF to determine how closely the two are correlated. The ideal log-normal PDF is determined using equation D1.

In a similar fashion, the CDF plots for each test route are in Figures D5 through D8. These are plotted on Rayleigh paper to determine how closely they match the straight line "Rayleigh curve" of a Rayleigh CDF, calculated using equation D5.

The actual correlations take place in the EXCEL file. These plots are attached for illustrative purposes.

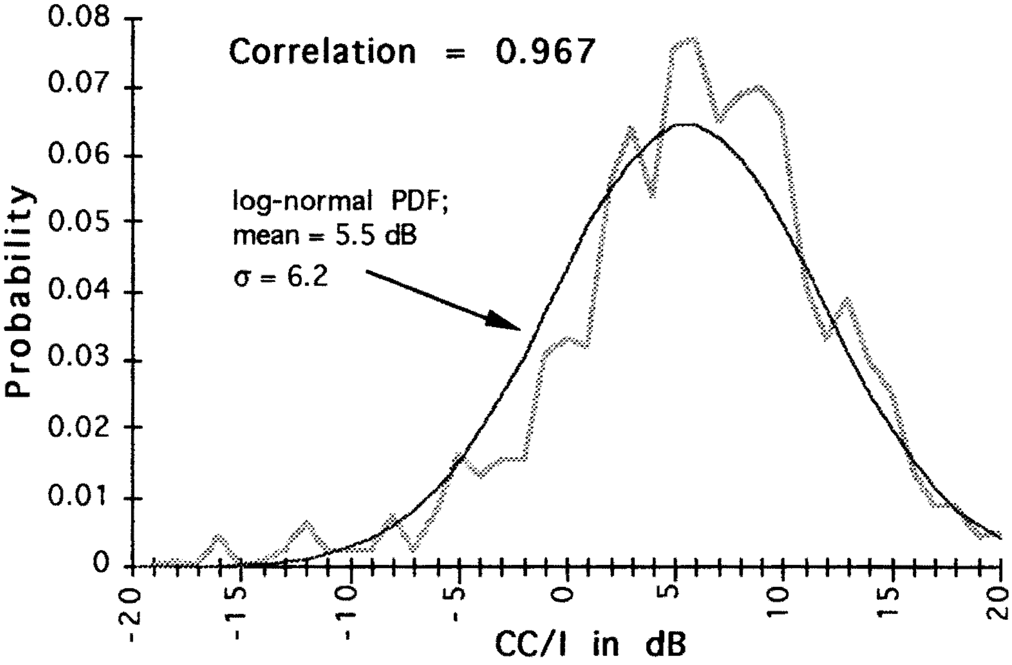

Figure D1: CC/I PDF For Test Route in The Orbanco B Sector

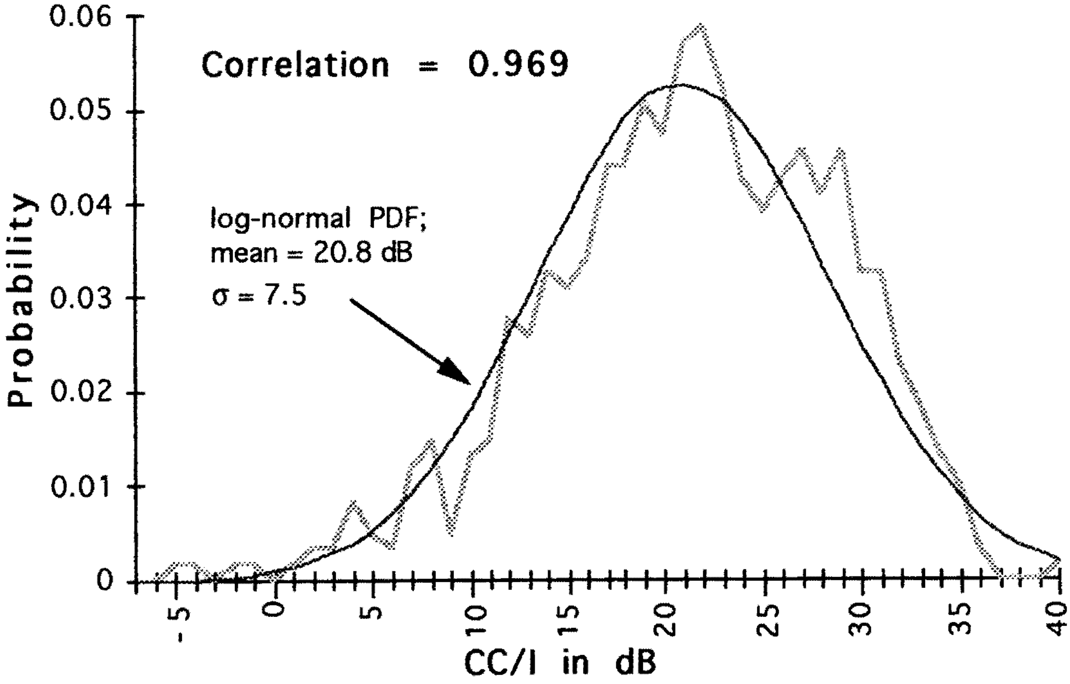

Figure D2: CC/I PDF For Test Route in The Lloyd Center B Sector

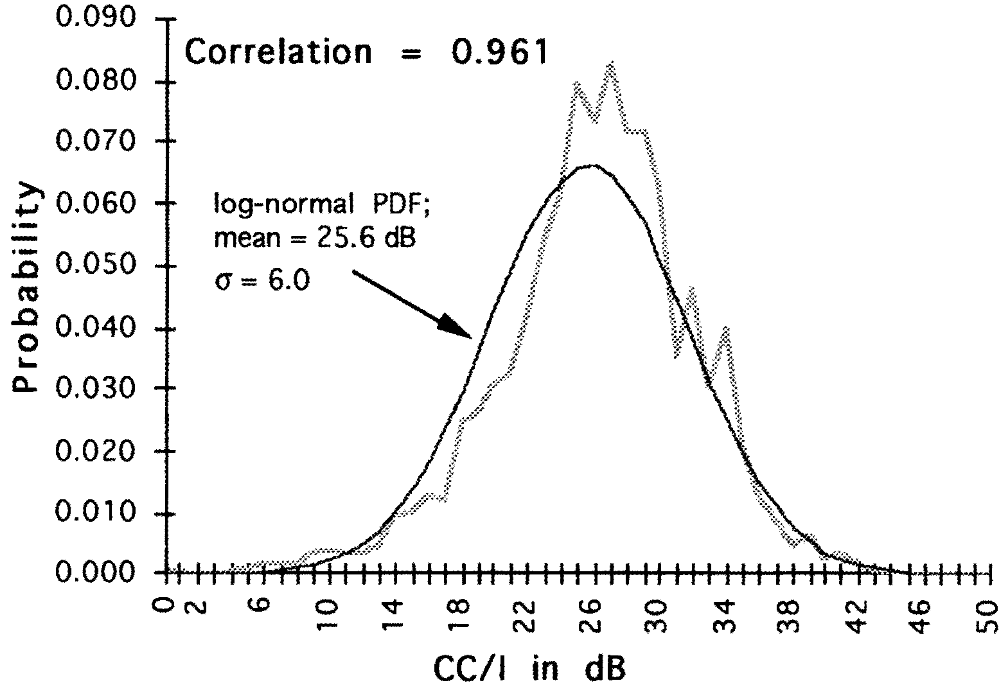

Figure D3: CC/I PDF For Test Route in The Erroll Heights C Sector

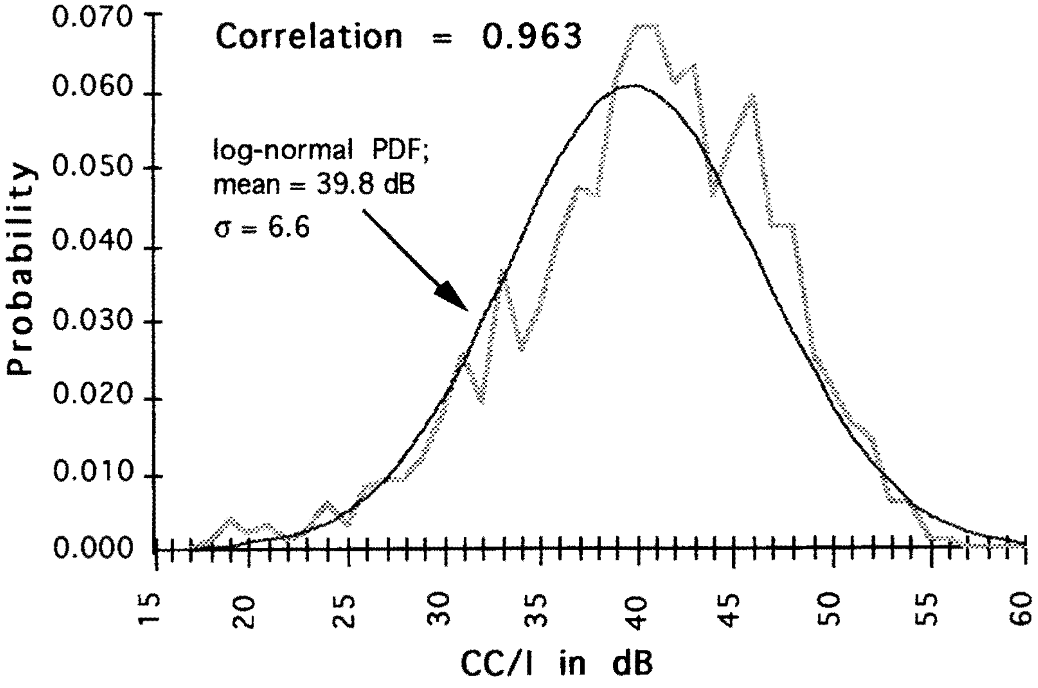

Figure D4: CC/I PDF For Test Route in The Stafford A Sector

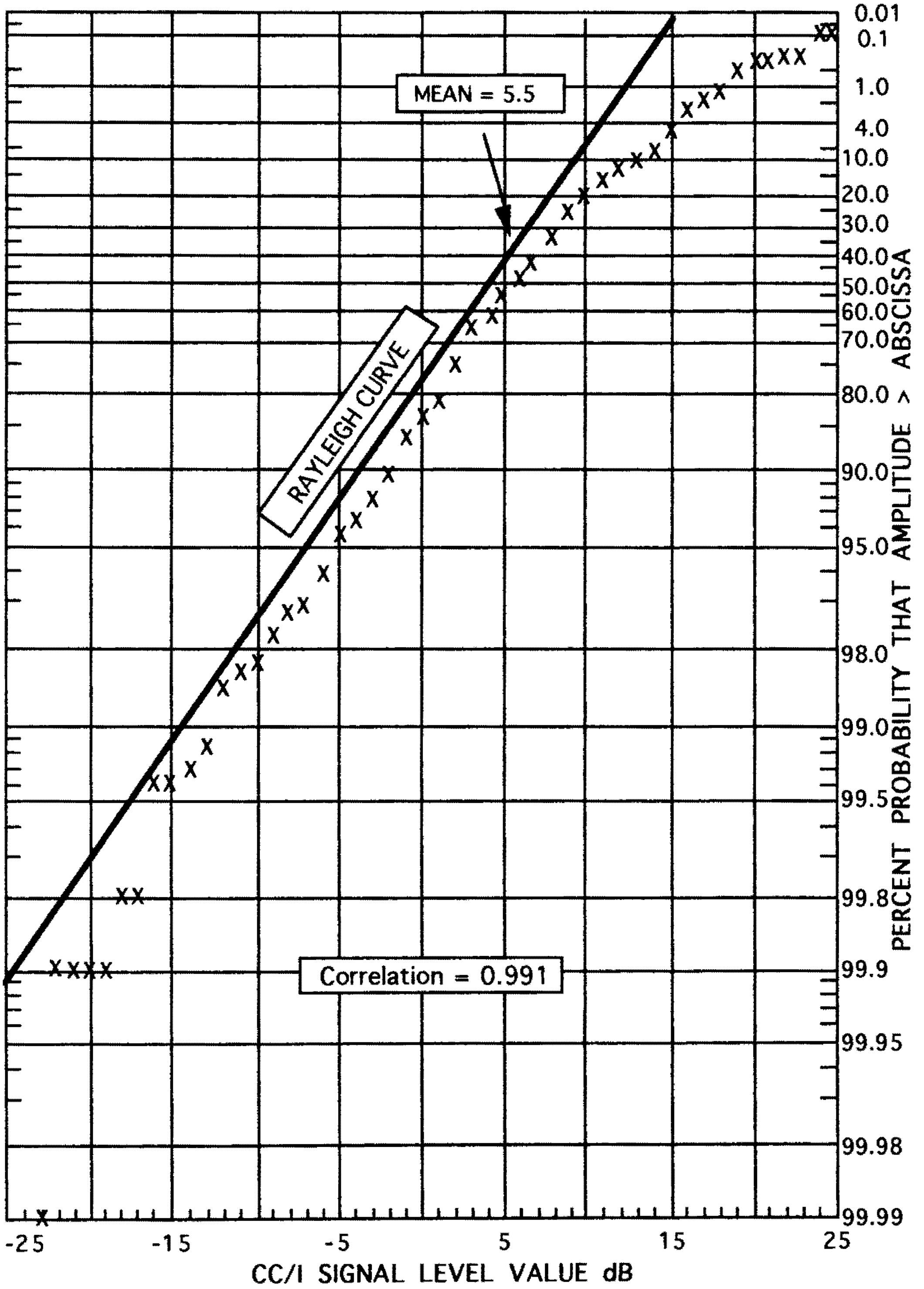

Figure D5: CC/I CDF For Test Route in The Orbanco B Sector

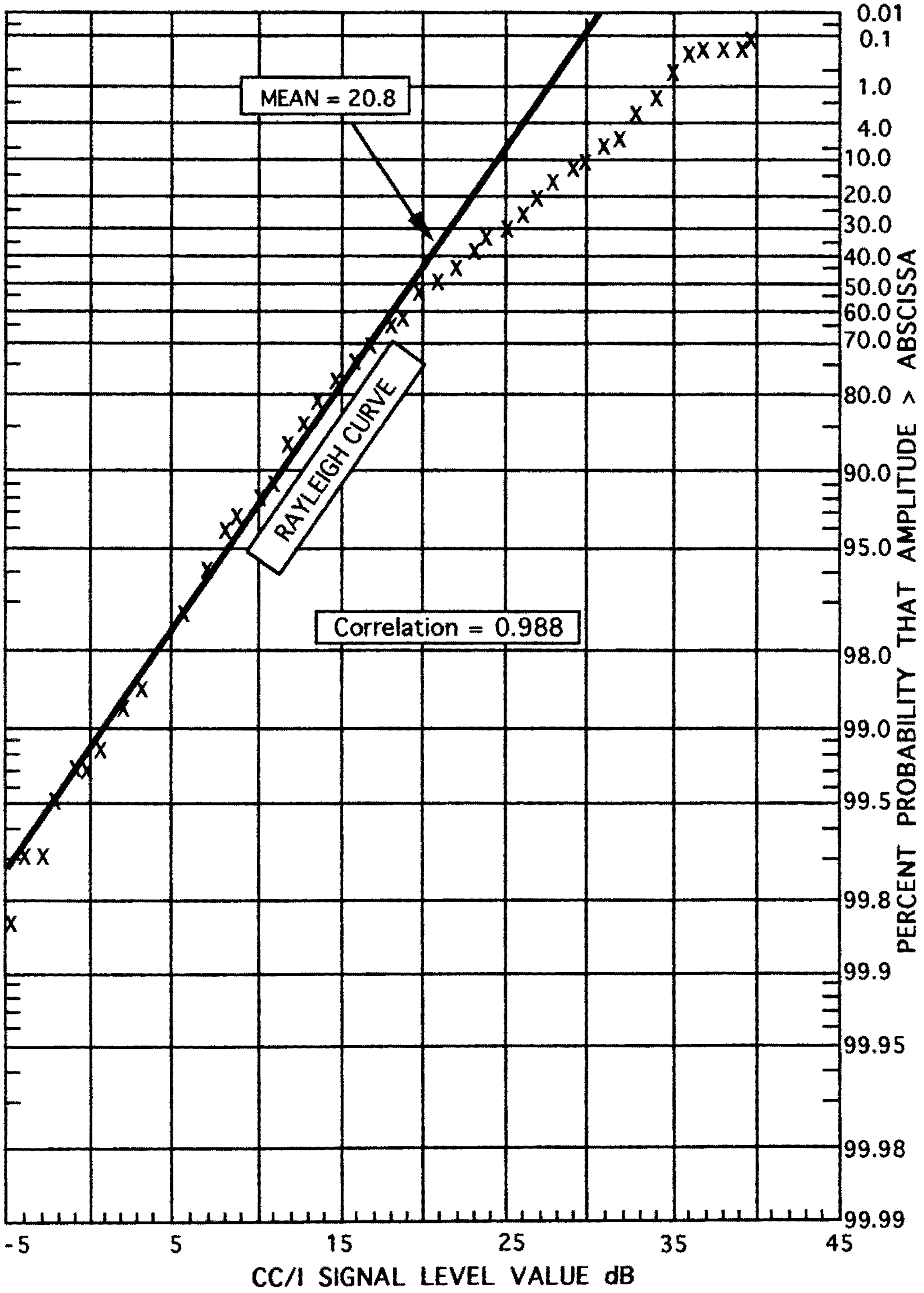

Figure D6: CC/I CDF For Test Route in The Lloyd Center B Sector

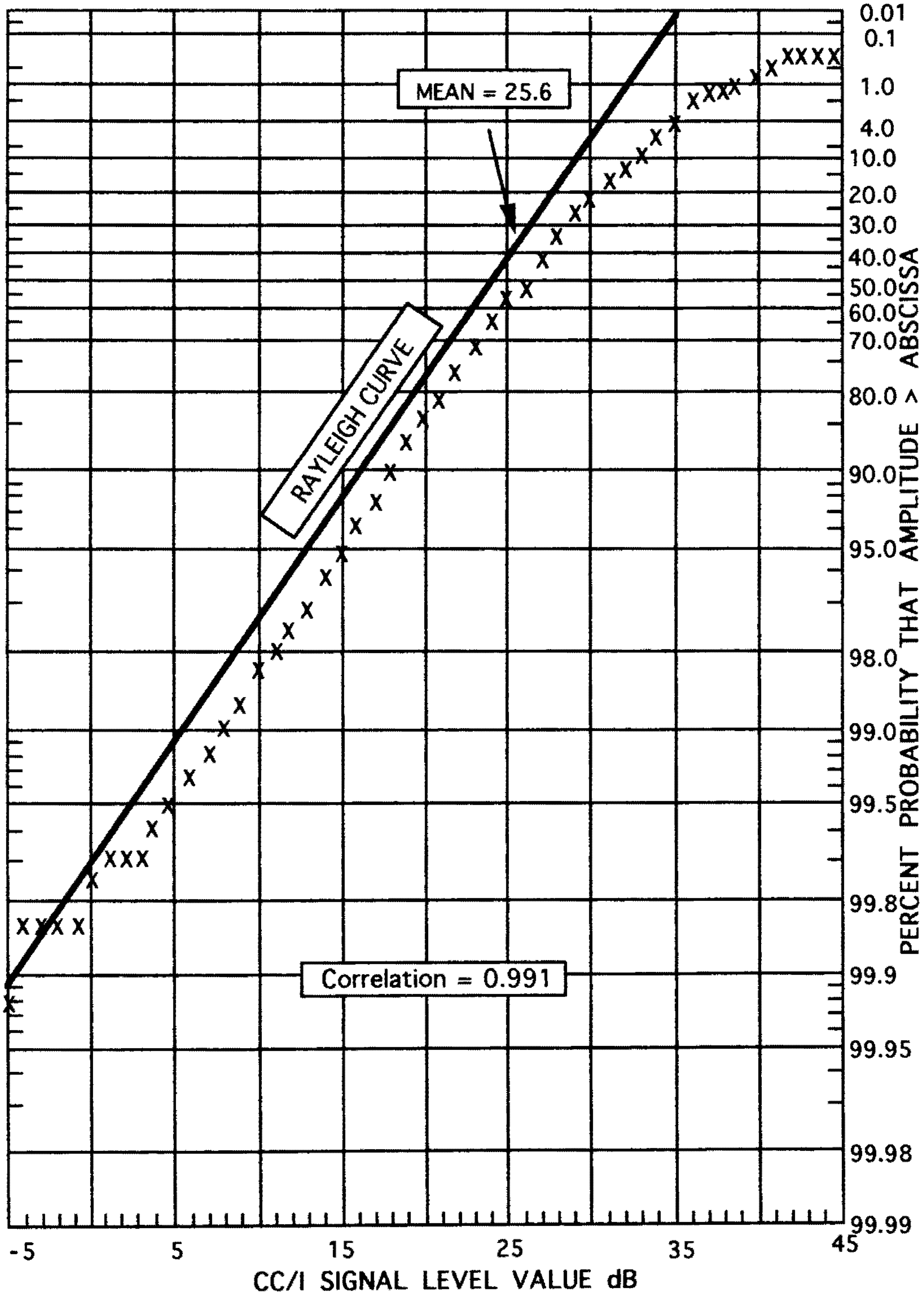

Figure D7: CC/I CDF For Test Route in The Erroll Heights C Sector

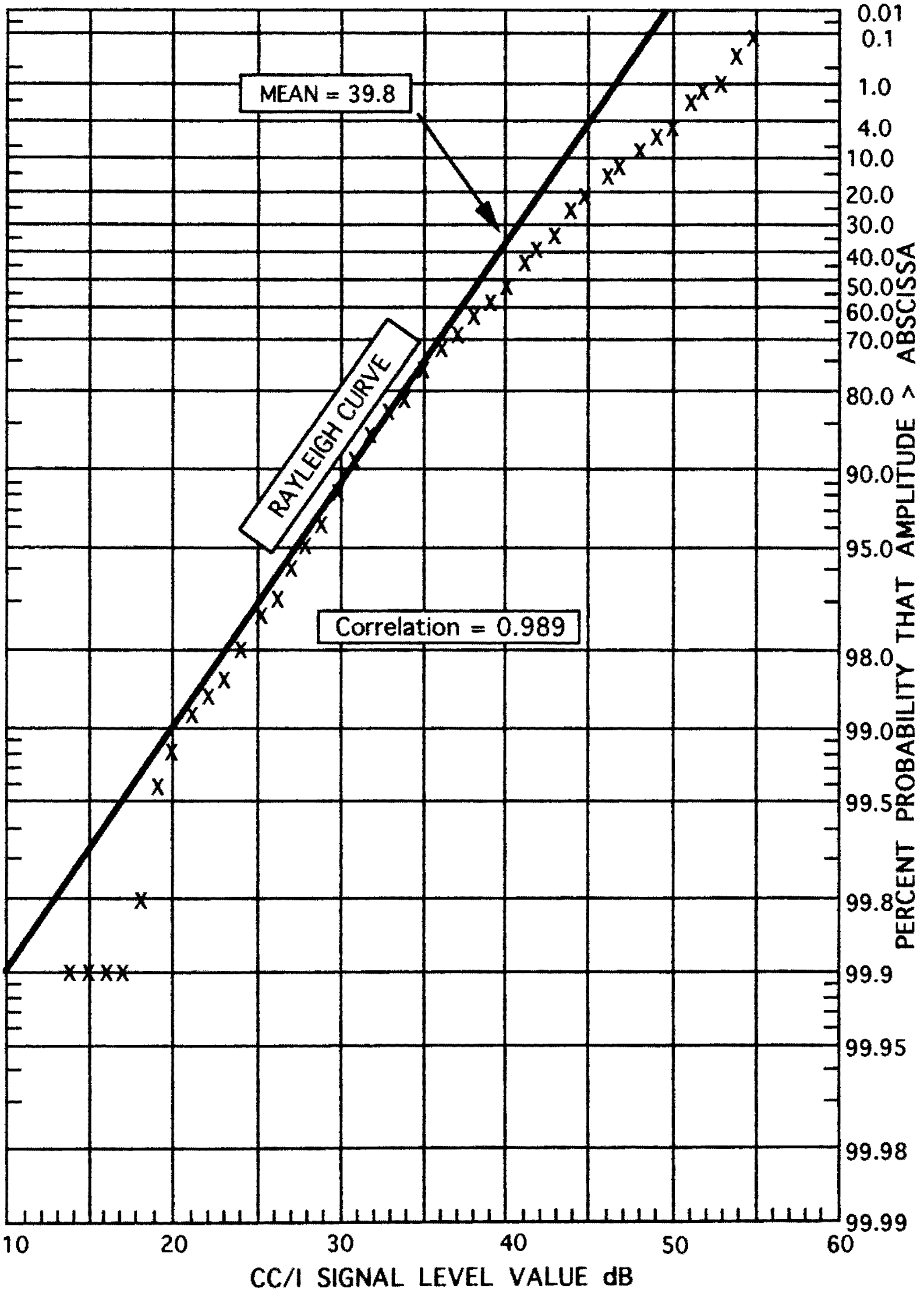

Figure D8: CC/I CDF For Test Route in The Stafford A Sector

APPENDIX E

MSAT-2000™ PRODUCT SPECIFICATIONS

Manufacturer:	LCC,L.L.C. Arlington Courthouse Plaza II 2300 Clarendon Blvd., Suite 800 Arlington, VA 22201
Size:	H; 11 inches, W; 18.5 inches, D; 12.3 inches.
Data Interface:	Printer/PC, RJ11 female (RS232C, 19.2 kbaud, full duplex)
Antenna input:	TNC female
Battery:	Six D size Ni-Cd cells, 7.2 VDC, 4 amp-hr
Power consumption:	1 amp max., 0.75 amps typical
Scanning Receiver:	Channels 1 to 799, 991 to 1023. 30 kHz channel spacing, 869.040 MHz to 893.970 MHz
RF Sensitivity:	≤ 16 dBm (12 dB SINAD)
Receive Level Range:	-35 to -120 dBm
RSS Accuracy:	± 1.5 dB RMS from -115 to -45 dBm
Frequency Stability:	+/- 2.5 ppm
Adjacent Ch Rejection:	≥ -45 dB at 30 kHz offset
Alternate Ch Rejection:	≥ -65 dB at 60 kHz offset
Spurious Rejection:	≥ 70 dB from 25 kHz to 25 MHz with -50 dBm input signal
Intermod Rejection:	≥ 70 dB with two tones 25 kHz apart
Operation Mode:	1 + 12, one channel programmed for in-service follow-call monitoring of RSS, MAHO data and BER + 12 channels programmed for RSS monitoring.
Scanning Rate:	Scans 1 + 12 channels at 1.2 second intervals
Sample Rate:	6075 samples/sec. 16 consecutive samples = 1 sample ave.

"MSAT-2000™ " is a trademark of LCC,L.L.C.