INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

MEASUREMENT AND CHARACTERIZATION OF RADIO CHANNELS IN FIXED WIRELESS ACCESS AT 2 GHZ

by

Deborah Mary Rockwood, B.A.Sc., P.Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Masters of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University

May 11, 1998

© copyright

1998, Deborah Mary Rockwood

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-32406-0

The undersigned hereby recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis,

"Measurements and Characterization on Radio
Channels in Fixed Wireless Access at 2 GHz",

submitted by Deborah Mary Rockwood in partial fulfilment of the requirements
for the degree of Masters of Engineering.

Dr. Samy A. Mahmoud
Thesis Co- supervisor

Dr. Mohamed Samy El-Hennawey
Thesis Co-supervisor

Dr. R. A. Goubran
Chair,
Department of Systems
and Computer Engineering

Department of Systems and Computer Engineering
Faculty of Engineering
Carleton University
May 11, 1998

ABSTRACT

Fixed Wireless Access is emerging as an alternative to conventional telephone services in which subscriber loops are based on wired connections. Fixed wireless telephony is emerging in developing countries as a favoured approach due to its low installation costs and short deployment time. In developed countries, it is gaining momentum as the technology of choice for new entrants in local phone access markets. In addition to cost savings, wireless telephony provides the advantage of portability. However, to compete with wired telephony, Fixed Wireless Access must provide a higher quality of service.

To facilitate the installation of subscriber phone stations, avoiding the need for an outside antenna system is highly desirable. An indoor antenna has the advantage of low installation cost and it avoids the need for the mounting structure associated with roof antennas. An outdoor base station transmit antenna and an indoor user receive antenna installation are examined in this thesis. To mitigate multipath fading, space diversity is incorporated. The performance of the outdoor/ indoor link is measured and analyzed.

The measurement results are analyzed to determine the envelope fading statistics and diversity performance. The average diversity gain for a 99% availability is 5.1 dB. Significant variations in single channel fade statistics are mitigated by space diversity. Variations in the envelope cross-correlation adversely affect the diversity gain. The outdoor/ indoor communications large-scale fade statistics are a path loss exponent of 1.96 and a shadow margin of 7.33 dB. The path loss exponent is lower than for indoor communications and the shadow margin experiences less obstruction than in the indoor case. The results are useful for predicting communication reliability and quality of service for outdoor/ indoor communication in similar buildings.

ACKNOWLEDGEMENTS

I am grateful to my supervisors, Dr. Samy Mahmoud for his vision and insightful guidance throughout this research project and Dr. Mohamed Samy El-Hennawey for his assistance during the later measurements and his critical review of my material. The support from the technicians at Carleton University, specifically Dave Sword and Danny Lemay, and their quick response to my requests was of great assistance. Csilla Ladanowski's administrative support was much appreciated, especially her expertise in WordPerfect and Corel Draw. I would like to express my appreciation for Selina Bishop's proofreading of this thesis and the suggestions she offered. Finally, I would like to thank my spouse and mentor Brian R. Smith (VE3 DHS) whose enthusiasm for amateur radio never ceases to inspire me.

TABLE OF CONTENTS

Abstract	iii
Acknowledgments	iv
List of Figure	ix
List of Tables	x
List of Acronyms	xii

CHAPTER 1

INTRODUCTION: FIXED WIRELESS ACCESS SYSTEM	1
1.1 Related Research	4
1.2 Thesis Motivation	5
1.3 Thesis Objective	6
1.4 Empirical Approach	6
1.5 Thesis Contributions	7
1.6 Context of this Study	8
1.7 Thesis Organization	9

CHAPTER 2

BACKGROUND ON FIXED WIRELESS ACCESS, RF PROPAGATION AND DIVERSITY TECHNIQUES	11
2.1 Fixed Wireless Access Radio Systems	11
2.2 RF Propagation	14
2.2.1 Large-scale Fading	14
2.2.2 Small-scale Fading	16
2.3 Diversity Techniques	17
2.3.1 Correlation Coefficient	18
2.4 Diversity Combining Techniques	19
2.4.1 Selection Combining	20

CHAPTER 3

CURRENT RESEARCH AND THESIS MOTIVATION	25
3.1 Current Research - Outdoor/ Indoor Communication	25
3.2 Diversity Performance	27
3.3 Analysis of Current Research	28
3.4 Problem Statement	28
3.4.1 Information Required to Incorporate Diversity into a System Design	29
3.4.2 Problem Definition	29
3.4.3 Approach to a Solution	30
3.4.4 Benefits of Proposed Research	31

CHAPTER 4

OUTDOOR / INDOOR EXPERIMENT	32
4.1 Experiment Scope	32
4.2 Experiment Purpose	33
4.2.1 Location	33
4.2.2 Antennas	34
4.2.3 Environmental Conditions	34
4.2.4 Operating Frequency	35
4.3 Transmitter Architecture	35
4.4 Antenna Design	37
4.4.1 Omni-directional Antenna Design	38
4.4.2 Transmit Directional Antenna	39
4.4.3 Receive Directional Antenna Design	44
4.4.4 Matching Network Design	46
4.5 Receiver Architecture	47
4.5.1 Receiver Front End - RF Stage	47
4.5.2 Mixer Stage	50
4.5.3 IF Stage	53

4.5.4	Logarithmic Detector Stage	54
4.6	Calibration Procedure	55
4.6.1	Transmitter Calibration	55
4.6.2	Receiver Calibration	56
4.7	Experimental Setup	58
4.7.1	Experimental Data Interpretation	58
4.7.2	Data Acquisition	59

CHAPTER 5

RESULTS AND ANALYSIS	60
5.1 Small Scale Fading	60
5.1.1 Data Collection	60
5.1.2 Data Reduction Procedure	61
5.2 Envelope Cross Correlation	62
5.3 Selection Combining	63
5.4 CDF of Envelope Fading	66
5.5 Global Envelope Statistics	71
5.5.1 Average CDF Statistic	71
5.5.2 Rayleigh Fading CDF	72
5.5.3 Diversity Performance	74
5.6 Large Scale Fading	81
5.7 Indoor Communication and Outdoor/ Indoor Communication Comparison	86
5.7.1 Small Scale Fading Results	89
5.7.2 Large Scale Fading Results Comparison	90
5.8 Summary of Analysis	90

CHAPTER 6

APPLICATION OF DIVERSITY RESULTS TO A LINK BUDGET	92
6.1 Fixed Wireless Access	93

6.2	Sensitivity	94
6.3	Noise Figure	95
6.4	Total Link Gain	96
6.5	Total Link Attenuation	97
6.6	Large Scale Path Loss or Penetration Loss	97
6.6.1	Free Space Loss	97
6.7	Shadow Margin	98
6.8	Fading Margin	98
6.9	Discussion	99
6.9.1	Comparison to Indoor Cordless System Link Budget	99
6.10	Summary	103

CHAPTER 7

CONCLUSIONS AND THESIS SUMMARY	104
7.1 Choice of Space Diversity Parameters	104
7.2 Variation in Diversity Performance	105
7.2.1 Comparison Between Indoor and Outdoor/ Indoor Communication Links	105
7.3 Application to Fixed Wireless Access	106
7.4 Recommendations	106
7.4.1 Further Measurements	106
Bibliography	108
Appendix A Receiver Calibration	113
Appendix B Measurements' Locations	117
Appendix C Data Reduction and Analysis Software	119

List of Figures

Figure 2.1	Selection Combining Block Diagram	20
Figure 2.2	Rayleigh CDF for Selection Combining, $M = 1, 2, 3, 4$	23
Figure 4.1	Transmitter Circuit Diagram for Experiment	36
Figure 4.2	Omni-directional Ground Plane Antenna	39
Figure 4.3	Transmit Directional 12 - Element Yagi Antenna	41
Figure 4.4	Receive Directional 3 - Element Yagi Antenna	44
Figure 4.5	Typical Single Frequency Conversion Receiver Architecture	48
Figure 4.6	Receiver Circuit Diagram for Experiment	49
Figure 4.7	Receiver Calibration Setup	57
Figure 4.8	Logarithmic Amplifier Calibration Setup	58
Figure 5.1	Cross Correlation Coefficients Histogram	64
Figure 5.2	Normalized Channel 1 and 2 and Selection Combined Signal	65
Figure 5.3	CDF of Channel 1	68
Figure 5.4	CDF of Channel 2	69
Figure 5.5	CDF of Combined Channel 1 & 2	70
Figure 5.6	Mean of Single Channel and Two-Branch Space Diversity Empirical and Theoretical CDFs	73
Figure 5.7	Worst Case Statistics, Average Statistics and Theoretical	78
Figure 5.8	CDFs at 99% Availability for Single and Two-Branch Space Diversity	80
Figure 5.9	Propagation Loss vs. Distance	84

List of Tables

Table 2.1	PCS Air Interface Attributes	13
Table 3.1	Path Loss Exponent for Different Environments	26
Table 4.1	Frequency Doubler Parameters	35
Table 4.2	High-Power Amplifier Parameters	37
Table 4.3	Ground Plane Antenna Dimensions	38
Table 4.4	Transmit Yagi Antenna Design Parameters	42
Table 4.5	Transmit Yagi Antenna Dimensions	43
Table 4.6	Receive Yagi Antenna Design Parameters	45
Table 4.7	Receive Yagi Antenna Dimensions	45
Table 4.8	Gamma Match Design Objectives	46
Table 4.9	Gamma Match Design Parameters	46
Table 4.10	RF Low Noise Amplifier	50
Table 4.11	Mixer Parameters	51
Table 4.12	XCO Parameters	52
Table 4.13	IF Amplifier Parameters	53
Table 4.14	Logarithmic IF Amplifier Parameters	54
Table 5.1	Measurement Locations	67
Table 5.2	Fading Statistics for 90% Availability	75
Table 5.3	Fading Statistics for 99% Availability	75
Table 5.4	Fading Statistics for 99.9% Availability	75
Table 5.5	Comparison of Average, Best and Worst Case Fading Statistics for 90%, 99% and 99.9% Availability	76
Table 5.6	Fading Statistics for Rayleigh Fading	77
Table 5.7	Large Scale Fading Statistics	82
Table 5.8	Comparison of Indoor and Outdoor/ Indoor Fading Statistics	87
Table 6.1	Noise Figure Calculation	95
Table 6.2	Sensitivity Calculation	96

Table 6.3	Link Budget for Outdoor/ Indoor Fixed Wireless Access System Using Measured Diversity Results	100
Table 6.4	Link Budget for Cordless Telephone System Using Measured Diversity Results	101

LIST OF ACRONYMS

ADC	Analog to Digital Convertor
BER	Bit Error Rate
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CO	Central Office
CW	Continuous Wave
dB	decibel
dBc	decibel referenced to the carrier
dBd	decibel referenced to a dipole
dB _i	decibel referenced to an isotropic antenna
dBm	decibel referenced to a milliwatt
DC	Direct Current
DQPSK	Differential Quadrature Phase Shift Keying
DCS	Digital Communication Standard
EIA	Electronics Industry Association
ETSI	European Telecommunications Standards Institute
FDD	Frequency-Division Duplex
FDMA	Frequency Division Multiple Access
FSL	Free Space Loss
FWA	Fixed Wireless Access
GHz	GigaHertz

GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile Communications
IM	InterModulation
IMT-2000	International Mobile Telecommunications by the year 2000
Hz	Hertz
kHz	kiloHertz
LSB	Least Significant Bit
MAHO	Manual Handover
MHz	MegaHertz
mm	millimeter
MMSE	Minimum Mean Square Error
MSB	Most Significant Bit
nsec	nanosecond
OMC	Operation and Maintenance Center
PBX	Private Branch Exchange
PC	Personal Computer
PCS	Personal Communications Service
pdf	probability distribution function
pF	picoFarads
POTS	Plain Old Telephone System
QoS	Quality of Service

SNR	Signal-to-Noise Ratio
SSB	Single SideBand
SWR	Standing Wave Ratio
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Association
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
VHF	Very High Frequency
WAM	Wireless Access Manager
WLL	Wireless Local Loops
WSC	Wireless System Controller
XCO	Crystal-Controlled Oscillator
Z_0	Characteristic Impedance in ohms

CHAPTER 1

INTRODUCTION: FIXED WIRELESS ACCESS SYSTEM

The telephone service industry is growing at an unprecedented rate. The International Telecommunication Union projects 150 million new telephone lines will need to be installed in developing countries by the year 2000 [1]. With this projected growth, telecommunication operators are looking to wireless technology to replace part of the hard-wire infrastructure. The part of the infrastructure being considered for this wireless technology is the individual drops for the residential homes called the local loop. The cost of the infrastructure is dominated by this portion, which is often termed the expensive "last mile" service.

A Wireless Local Loop (WLL) system uses radio technology to provide reliable, flexible and economical local telephone service. Wireless technologies' inherent cost structure presents less dependence on economies of scale than alternative wireline networks. A wireless solution makes possible fast infrastructure deployment for new entrants, allowing them to compete against entrenched wireline carriers. The process of building a WLL system does not require precise knowledge of the user's location, adding flexibility to planning and deployment of the system. WLL networks can function as core communication systems in times of disaster. WLL systems can also be used as redundant backup systems for existing wireline networks. WLL technology is gaining popularity in the Asian and Latin American countries for providing telephone services in sparsely populated rural areas [2].

The WLL systems are typically based on one of three technologies:

- Cellular systems provide large power, large range, medium subscriber density and medium circuit quality WLL services. Cellular WLL technologies are primarily used to expand the basic telephony services.
- Cordless or microcellular systems provide low power, small range, high subscriber density and high circuit quality WLL services. Cordless technologies can provide rapid market entry and expand the capacity of the existing infrastructure.
- Fixed Wireless Access (FWA) systems that are proprietary radio systems designed specifically for fixed wireless applications. The systems for zonal areas are designed to cover the local telephone area directly from the public switched telephone network switches. The systems for rural areas provide connections at the remote ends of rural links to the end users. The systems usually replace part of the loop distribution and part of a very long drop.

The wireless communication medium provides many advantages to implementing a Fixed Wireless Access WLL system rather than the cellular or cordless mobile WLL systems:

- In an FWA system, the frequency reuse distance can be reduced. The FWA fixed-to-fixed link may use directional antennas on both ends, so the interference area becomes small. A reduction in frequency reuse distance provides an increase in the capacity.
- In an FWA system, no handoffs occur because of its fixed-to-fixed link. The air link from each building to the cell site can be customarily

installed to reduce the interference. Since the link remains unchanged (provided growth and/or cell splitting is moderate) after installation, the design of the FWA system is much simpler than that of a mobile system.

In the conventional Fixed Wireless Access system, the user antenna is mounted on the highest spot possible on the exterior of the building, usually the roof. This configuration has major disadvantages limiting its viability to become a contender to provide local telephone services. The primary disadvantage is the expensive installation cost of the Fixed Wireless Access system for the user. Mounting an antenna on the roof requires installer expertise, is time consuming, and dangerous for the installer. Tuning could require a two-man installation. The installation costs would not eliminate Fixed Wireless Access as a candidate for rural settings where "last mile" service may have an exorbitant installation cost for poles, trenching and cabling. As a competitor for local telephone service in urban or suburban settings, the installation expense may be higher than that charged by the local telephone carrier deterring subscribers from buying into FWA.

An alternative to installing the user antenna outdoors is to install the user antenna indoors with the transceiver. The exact antenna position could be determined at the time of the installation of the Fixed Wireless Access system at the user site. This concept of an indoor user antenna in a Fixed Wireless Access system is the primary concern of this thesis.

The most important consideration in the competitiveness of Fixed Wireless Access as an alternative to local loops is the Quality of Service (QoS) that can be offered. Many RF propagation conditions degrade the received signal level. The major propagation loss comes from distance separating the transmit site and receive sites, or the Free Space Loss. Multipath fading also severely impairs the signal quality. The movement of vehicles or people around the user antenna can have a shadowing effect from time

to time. The shadowing by walls, floors or other objects will affect the received signal.

In this FWA scenario, macro-diversity is not a factor in improving the large scale variations in signal and will not be considered as part of the QoS equation. Instead, it is assumed that the user antenna and equipment setup is tuned for the most favourable reception during the user station installation.

The small-scale variations, short term and temporal changes of the channel can be improved by micro-diversity. This alleviates the need to increase the transmit power of the user station, which would increase the probability of interference with other users. The use of a directional antenna adds some gain and allows some increase in power since the narrow beamwidth of the antenna pattern reduces the possibility of interference. The micro-diversity technique investigated in this thesis is space diversity.

1.1 Related Research

To predict the large-scale propagation conditions of a radio channel, measurements have been taken and propagation models have been presented based on the environment. A free space propagation model where the radio channel is line-of-sight, based on frequency and distance between transmit and receive antennas, is the simplest case. Okumura [3] measured outdoor radio channels in urban, suburban and open areas and derived a prediction method using graphical information produced from the measurements based on frequency, distance, environment and the antennas' heights. Hata[4] proposed empirical formulas to simplify Okumura's process. Keenan and Motley [5] measured indoor radio channels and derived an empirical formula based on frequency, distance, and obstruction loss due to the number of floors and walls blocking the path. Moldkar [6] measured outdoor/ indoor radio channels to assess possible impacts on frequency reuse for indoor radio channels from leakage through

outside walls. Many textbooks such as Gibson [7] summarize the large-scale propagation characteristics for various environments by assigning an exponent to modify the distance relationship in the Free Space Loss (FSL) equation. An exponent for the outdoor/ indoor radio channel has not been established.

The benefit of micro-diversity to improve the fade margin of small-scale propagation has been well researched. Jakes [8] deduced that the receive antennas would have to be separated one-half wavelength or more to have uncorrelated envelopes assuming a Rayleigh model of the radio channel. Jakes [9] classified space diversity reception methods into four categories, selection combining being the simplest. Jefford [10] has taken extensive field measurements at 1800 MHz and derived empirical formulas relating loss of diversity gain to branch correlation and unequal branch powers for selection, equal gain and maximal ratio combining.

Several candidate WLL systems have been compared to evaluate the best system for the application. Garg [2] compared the Fixed Wireless Access with mobile cellular technology using capacity as the main criterion for the WLL application. Capacity is calculated and comparisons are made based on an assumed worst case large-scale propagation exponent of 4, typical of urban mobile cellular systems. To compare the merits of candidates for FWA applications, accurate knowledge of the propagation characteristics of these candidate systems is needed. These propagation characteristics can be known precisely only if they are derived from propagation measurements.

1.2 Thesis Motivation

The Wireless Local Loop is being proposed as a cost-effective means of addressing the increasing demand for local telephone services in developing countries. One candidate for this application is the outdoor/ indoor Fixed Wireless Access system. The effectiveness of this proposed WLL candidate, the outdoor/ indoor radio channel, is best achieved through field measurements to establish its propagation characteristics.

A comparison to other candidate WLL systems further establishes FWA as a contender for WLL. The propagation characteristics derived from the measurements are useful in designing Fixed Wireless Access radio systems. The outdoor/ indoor radio channel has not been previously characterized and this is the primary motivation for this thesis.

1.3 Thesis Objective

The objective of this thesis is to establish the propagation characteristics and diversity performance for a radio channel between an outdoor transmitter and indoor space diversity receiver in the 2 GHz frequency band. This objective is achieved through empirical measurements and numerical analysis of the results. The remainder of this thesis presents the experimental setup, and the analysis of the measurement data obtained using this setup.

1.4 Empirical Approach

The empirical approach has three distinct phases: the experiment setup and calibration, the data measurements and the data analysis.

The experimental setup consists of a transmitter and two receivers. The transmitter produces a Continuous Wave (CW) signal at a frequency of 2.37 GHz. This coincides with the frequencies assigned the third-generation wide-area personal communication systems (Universal Mobile Telecommunication System, or UMTS) [11]. Frequencies are also available in this region of the 2 GHz band for Fixed Wireless Access. The receivers measure the faded signal using two separate antennas.

Measurements are conducted in three buildings on the Carleton University campus, on different floors, with typical levels of personnel activity for each area under conditions approximating the Fixed Wireless Access user station environment. Many measurements are made at each location for redundancy and for consistency.

Data analysis process evaluates the validity of the data collected to be further processed statistically. Many software programs are written to aid in the evaluation and statistical characterization process. The space diversity measurements are combined with selection combining software and the results are applied to a system link budget.

1.5 Thesis Contributions

This thesis presents an empirical study of space micro-diversity performance for the outdoor/indoor radio channel at 2.37 GHz with applications to Fixed Wireless Access. Experiment equipment has been configured to measure space diversity envelope fading. Analysis software has been developed to evaluate diversity performance. Based on the literature review in Chapter 3, no similar investigation has been conducted previously. General contributions from our analysis are as follows:

- Space diversity at 2.37 GHz to alleviate narrowband envelope fading is evaluated empirically. The antenna spacing is verified to give good diversity performance.
- Variations in envelope cross correlation, fading statistics and diversity performance are studied. The results allow more accurate prediction of communication reliability.

A detailed summary of contributions is presented in Chapter 7.

1.6 Context of this Study

The context and specific parameters of this study are:

- Measurements are taken in buildings constructed of concrete, concrete block, gyprock, and steel reinforced walls and rebar enforced floors and roofs.
- Antennas are directional Yagi's: 12 element, 12 dB for transmit and 3 element, 2 dB for receive. Omni-directional quarter-wave, vertically-polarized, ground plane antennas are used for the large-scale propagation characterization measurements and for the transmitter and the receiver calibration.
- Antenna spacing is 1 wavelength to ensure the radio channels fades are uncorrelated and independent. This is a requirement for effective selection combining.
- Statistics of the envelope fading are computed based on a 30-second measurement period.

The study is restricted to CW envelope measurements for the following reasons:

- For narrowband communication, the dominant effect on the channel is envelope fading.
- Selection combining systems are based on the received signal strength or envelope power.

- Phase variations significant for coherent demodulation schemes are less significant for differential detection.
- CW measurements provide a great deal of relevant information without a complicated experimental setup.

1.7 Thesis Organization

The thesis is organized to describe the process of the experiment and data analysis in chronological order. First, the relevant background information is explored in Chapter 2. The Fixed Wireless Access approach is described. The nature of the RF propagation channel and various terminology are defined and the diversity and combining techniques used in this thesis are also described.

In Chapter 3, a review of current literature that relates to the areas explored in this thesis is provided. The literature review includes those on Fixed Wireless Access, outdoor/indoor propagation, and penetration loss with special emphasis on results for the 2 GHz frequency band. This leads to the thesis problem statement and the objective of the research done for this thesis.

In Chapter 4, the experimental setup is described. The experiment equipment includes the transmitter, the identical receivers, the antennas and the data acquisition system. The components for the transmitter and the receiver are described in detail. The design of the transmit and receive directional antennas is described. The computer system and the data acquisition card used to collect the data are also discussed.

In Chapter 5, the data analysis and results are described. The process for converting the data from the data acquisition format to power in dB, and the preprocessing required for combining is described. The statistics calculated for the data characterization include the cross correlation, coefficients and cumulative distribution

functions. The outdoor/ indoor FWA system statistics are compared with the indoor cordless system statistics.

In Chapter 6, the link budget for a Fixed Wireless Access system is calculated. Each line in the link budget is described in detail including the receiver sensitivity, noise bandwidth, Noise Figure, propagation loss and fade margin. The outdoor/ indoor FWA system link budget is compared with an indoor cordless system link budget.

In Chapter 7, the conclusions of the research are presented. The main results and contributions are summarized and further research based on the findings of this thesis is recommended.

Appendix A provides the spectrum analyzer outputs taken during the receiver calibration for each receiver component.

Appendix B provides plan views of the engineering buildings and the Carleton University campus where the propagation measurements are taken.

Appendix C provides a commented listing of the source programs written to analyze the data measured.

CHAPTER 2

BACKGROUND ON FIXED WIRELESS ACCESS, RF PROPAGATION AND DIVERSITY TECHNIQUES

This chapter provides background information on the Fixed Wireless Access (FWA) radio system, RF propagation channel characteristics and terminology as well as diversity and combining techniques used in this thesis.

2.1 Fixed Wireless Access Radio Systems

This section presents the radio system that forms the context for the measurements and analysis performed in this thesis. That radio system is the Fixed Wireless Access (FWA) system. The background information on FWA provided in this section describes the architecture of the FWA system and the standards being proposed for Fixed Wireless Access.

Fixed Wireless Access is an innovation to the present Plain Old Telephone System (POTS) as it currently exists. The FWA system architecture has two general approaches [2]: a direct connection to the Central Office (CO) switch or if there is room to accommodate it, through a base station connected to a Private Branch Exchange (PBX) which is connected to the CO.

The channel access method used affects the operational requirements of the FWA radio system. For example, a narrowband Time Division Multiple Access (TDMA) Wireless Local Loop (WLL) would include a subscriber database and an Operation and Maintenance Center (OMC) for network maintenance. Whereas a wideband WLL using, for example, Code Division Multiple Access (CDMA), would require a Wireless Access Manager (WAM) along with the OMC. The WAM would include a

Subscriber Access Manager (SAM) similar to that of the TDMA system. The WAM would also include a transcoder to communicate between the base site and CO and a Wireless System Controller (WSC) to control radio channel functions and monitor cell performance [2].

This thesis is concerned with the narrowband channel characteristics because the outdoor/ indoor radio channel has no line-of-sight path and experiences no significant frequency spreading. This is more fully described later in this chapter in the RF Propagation section. The narrowband channel access method used as an example in this thesis is TDMA. Two of the standards used for TDMA systems are: North American Telecommunications/ Electronics Industry Association (TIA/ EIA) IS-136, and European Telecommunications Standards Institute (ETSI) Global System for Mobile Communications (GSM).

There are a number of differences between the two standards. The IS-136 and the GSM standards have different channel bandwidths (30 kHz for IS-136 and 200 kHz for GSM). The two standards use different modulation techniques (i.e., $\pi/4$ -Differential Quadrature Phase Shift Keying, ($\pi/4$ -DQPSK) for IS-136 and Gaussian Minimum Shift Keying (GMSK) for GSM). IS-136 and GSM have air interfaces for the 900 MHz band and the 2 GHz band. This thesis is concerned with the 2 GHz frequency band. Table 2.1 lists the attributes for 2 GHz air interfaces based on the IS-136 and GSM standards. This thesis is concerned primarily with the North American standard IS-136. The IS-136 standard is an enhanced version of the existing IS-54 North American standard for 900 MHz cellular systems.

The range of the high-tier or macro-cell Wireless Local Loops (WLL) depends on location of the CO or base station. The highest location in the centre of the cell is the traditional for the base station. The range can be further extended using point-to-

Table 2.1 PCS Air Interface Attributes [12,13]

Item	Units	GSM (PCS-1900)	IS-136 (PCS-2000)
High/low mobility support		Both	High
Frequency band: uplink/downlink	MHz	1930 to 1970 2180 to 2200	1850 to 1970 2130 to 2200
Duplex method		FDD	FDD
RF channel spacing	kHz	200	30
Number of two-way voice channels		8	3
Equivalent Bandwidth per voice channel	kHz	25	10
Baseband modulation technique forward or reverse		GMSK	$\pi/4$ -DQPSK
Access technology		TDMA/ FDMA	TDMA/ FDMA
Voice encoding rate	kbps	8, 16, 24	6.3, 13, 14.5
Voice channels per RF carrier per sector		8-16	3
Channel bit rate	kbps	270.833	97.2
Base Station Transmit Power	W	20	63
Terminal Transmit Power	W	0.6	1.0/ 0.25
Maximum user bit rate	kbps	9.6, 13	24
Receiver threshold (mobile/ base)	dBm	-105/ -110	-100/ -104
Handover		Yes	Yes, MAHO
Related system technology or standards		DCS 1800 T1.602/607	G.728

point microwave hops to some hilltop locations. Also, for the user site, the antenna is located at a high spot on the building to provide the best possible signal. This thesis proposes an indoor location for the user antenna.

2.2 RF Propagation

The RF propagation conditions experienced by a Fixed Wireless Access radio channel come from the FWA configuration. With an outdoor base station and indoor user station, no line-of-sight path normally exists between the transmit and receive sites. The normal personnel and road traffic about the user station produce variations in the received signal over time.

In general, a transmission received from multiple reflective paths experiences a condition called multipath fading. The non line-of-site paths lead to a propagation category called large-scale fading. The time-variations in the received signal are called small-scale fading. Large and small-scale fading characteristics are described in the following subsections.

2.2.1 Large-scale Fading

Large-scale fading attenuates the received signal so that the average signal power is constantly lower than a channel governed by the idealized propagation characterized by the Free Space Loss (FSL). The indoor receiver is 'shadowed' by the blockage in the path. Instead of a square law relationship to distance experienced by FSL, an n -power law governs the large-scale fading. The log-normal deviation from the mean described by the exponent γ is the shadow margin for the link.

The Lee model [14] for large-scale fading L is a log distance path loss model and is shown in the following equation:

$$L = L_0 + \gamma 10 \log D \quad (1)$$

where L_0 is FSL computed for a distance of 1 m for indoors, 100 m for micro-cells and 1 km for macro-cells and γ is the power law that fits empirical measurements of propagation loss versus distance, D . The following equations are used to calculate FSL for distance in kilometers:

$$A = 32.44 + 20 \log (D_{km}) + 20 \log (F_{MHz}) \quad (2)$$

where A represents FSL, D_{km} is distance in kilometers and F_{MHz} is frequency in MHz. Linear regression for a Minimum Mean Square Error (MMSE) estimate of L versus distance on a log-log scale is a straight line with a slope of $\gamma * 10$ dB/decade. Equation 1 describes only the average large-scale fading and is sometimes called the local average or path loss exponent. The path loss exponent is determined from propagation measurements.

Equation 1 does not consider the effects of surrounding clutter that leads to measured signals vastly different from the average value for the same transmit-receive separation. The measurements' variations from the average value are modelled by lognormal model for path loss as defined by:

$$L = L_0 + \gamma 10 \log D + X_\sigma \quad (3)$$

where X_σ is a zero-mean Gaussian-distributed random variable (in dB) with a standard deviation σ (also in dB). The worst case variations about the mean path loss are typically 6 to 10 dB and are called a large-scale fading or shadow margin [15].

2.2.2 Small-scale Fading

The time variant fading or small-scale fading for the outdoor/ indoor link has no line-of-sight component and has many reflective paths. The envelope of the received signal follows a Rayleigh probability distribution function (pdf) [15]. This type of small-scale multipath fading is termed Rayleigh fading whose pdf is defined by:

$$\begin{aligned}
 p(r) &= \frac{r}{\sigma^2} \exp\left[-\frac{r^2}{2\sigma^2}\right] \quad \text{for } r \geq 0 \\
 p(r) &= 0 \quad \text{otherwise}
 \end{aligned} \tag{4}$$

where r is the envelope of the received signal and $2\sigma^2$ is the predetection mean power of the multipath signal. The worst case variation due to Rayleigh fading that can be tolerated in an RF channel is typically 20 to 30 dB and is called the small-scale fading margin [15].

The small-scale fading relevant to the outdoor/ indoor radio channel does not exhibit significant time spreading [15]. This is called frequency non-selective fading or flat fading. Flat fading occurs when the coherence bandwidth is greater than the signal bandwidth, as defined by:

$$f_0 > W = \frac{1}{T_s} \tag{5}$$

where W is the signal bandwidth, T_s is the symbol period, and f_0 is the coherence bandwidth of the receiver, the reciprocal of channel coherence time, T_0 . The symbol period, T_s is the reciprocal of the signal bandwidth, W .

A substantial reduction in the average Signal-to-Noise Ratio (SNR) results from this type of fading. The receiver cannot resolve the phase components of the received signal because they reside within one symbol interval [15]. Two very efficient ways to improve the SNR are: error correction coding and signal diversity.

The outdoor / indoor channel's signal is correlated for a time shorter than the symbol period [15]. This condition is termed fast fading and is defined by:

$$T_0 < T_s \quad (6)$$

where T_0 is the channel coherence time, the reciprocal of the coherence bandwidth, f_0 . Fast fading can cause the baseband pulse to be distorted, resulting in a loss of SNR that often yields an irreducible Bit Error Rate (BER).

2.3 Diversity Techniques

Diversity techniques are useful in combatting reductions in the signal-to-noise ratio of received signals due to small-scale fading. A diversity technique requires a number of signal transmission paths called diversity branches. Each independent diversity branch carries the same information but the multipath fades experienced on each individual branch are uncorrelated with multipath fades experienced on the other branches.

Diversity techniques include a mechanism to combine the received signals or select one of them. In general, the resulting combined signal experiences much less severe fading than either of the individual signals alone.

2.3.1 Correlation Coefficient

In practice, the diversity branches may not be fully independent and the signal fades may not be completely uncorrelated. The envelope cross correlation that measures the independence of signals is defined by [7]:

$$\rho = \frac{E[(r_1 - \bar{r}_1)(r_2 - \bar{r}_2)]}{\sqrt{E[r_1 - \bar{r}_1]^2 E[r_2 - \bar{r}_2]^2}} \quad (7)$$

where r_1 and r_2 are instantaneous values of the signal envelope for two receivers and $\bar{r}_1$ and $\bar{r}_2$ are their corresponding means. The correlation coefficient varies between 1 and -1 with uncorrelated signals having a coefficient of 0.

To achieve independent diversity branches, the branches must be sufficiently separated on its diversity dimension. The diversity dimension depends on the type of diversity implemented. Diversity techniques include space diversity, angle/ direction diversity, polarization diversity, frequency diversity, or time diversity. The space diversity dimension is coherence distance. To have independent space diversity branches, the antenna must be spaced greater than the coherence distance. For frequency diversity, the diversity branches must be receiving on frequencies separated by more than the coherence bandwidth. In time diversity, the channel reuse must occur less often than the coherence time.

Space diversity has been historically the most common form of diversity.

Implementing it is easy. It requires no additional frequency spectrum like frequency diversity [7]. This thesis is concerned with space diversity.

2.4 Diversity Combining Techniques

The three main diversity combining methods are: maximal ratio, equal gain and selection. In maximal ratio combining, the M diversity branches are first cophased and then weighted proportional to their signal level before summing. Maximal ratio combining is optimum yielding the best statistical reduction of fading of any linear diversity combiner. Estimating the amplitudes accurately may be difficult. If the combining gains are set to unity (i.e., the weighting omitted), the resulting combining method is called equal gain combining. This is slightly inferior to maximal-ratio combining since interference and noise corrupted signals may be combined with an information signal. Selection combining chooses the one of the two diversity branches with the best SNR and connects it to the output.

For UHF and microwave wireless radio applications, with their rapidly changing, random-phase, multipath fading environments, maximum ratio and equal gain combining's cophasing circuit cannot produce precise and stable tracking performance [12]. Selection combining is the simplest and has stable operation even in fast multipath fading environments. Selection combining is the most frequently used form of diversity combining and is used exclusively in this thesis.

2.4.1 Selection Combining

Figure 2.1 shows a block diagram for selection combining. The block diagram has two diversity antennas each connected to a receiver. A signal from the output of each receiver is fed to a comparator circuit. This circuit determines which receiver output will be switched to the final output yielding the best SNR of the two receivers.

Figure 2.1 Selection Combining Block Diagram

The performance improvement of selection combining can be seen by considering its effect on Rayleigh fading channels. The Rayleigh Cumulative Distribution Function (CDF) calculates the probability that the instantaneous SNR, γ_i , is less than or equal to a SNR threshold, γ as defined by:

$$P[\gamma_i \leq \gamma] = 1 - e^{-\frac{\gamma}{\bar{\gamma}}} \quad (8)$$

where Γ is the mean SNR of the diversity branch signals as defined by [16]:

$$\Gamma = \frac{E_0}{N_0} \bar{\alpha}^2 \quad (9)$$

where E_0/N_0 is the signal-to-noise ratio SNR of the RF carrier and α is the diversity branch signal envelope. The Rayleigh CDF for M independent diversity branches' received signal simultaneously below a SNR threshold is termed outage and is defined by:

$$P[\gamma_1 \dots \gamma_M \leq \gamma] = (1 - e^{-\frac{\gamma}{\Gamma}})^M \quad (10)$$

The probability of exceeding a threshold γ using selection combining is termed availability and is defined by:

$$P[\gamma_i > \gamma] = 1 - (1 - e^{-\frac{\gamma}{\Gamma}})^M \quad (11)$$

The outage versus the threshold for M Rayleigh fading channels where M is 1, 2, 3 and 4 are plotted in Figure 2.2. The mean of the output γ_0 from selection combining is defined by:

$$\text{mean} (\gamma_o) = \Gamma \sum_{k=1}^M \frac{1}{k} \quad (12)$$

Using Equation 11, for an availability of 99% (i.e., an outage of 1% on Figure 2.2), the signal with respect to the mean (i.e., $10 \log (\gamma/\Gamma)$) for one diversity branch is -19.9 dB. The two-branch diversity signal with respect to the mean is -9.8 dB using selection combining. The diversity gain for selection combining at 99% availability is 10.1 dB.

Figure 2.2 Rayleigh CDF for Selection Combining, $M = 1, 2, 3, 4$

In summary, Chapter 2 described the relevant background information for the main concerns of this thesis. The main concerns of this thesis are Fixed Wireless Access systems, small and large-scale propagation, space diversity and selection combining. The next chapter describes the current research concerning Fixed Wireless Access, outdoor/ indoor radio channel propagation characteristics and diversity performance.

CHAPTER 3

CURRENT RESEARCH AND THESIS MOTIVATION

This chapter reviews the current literature concerning on Fixed Wireless Access, outdoor/indoor radio channel propagation characteristics, diversity performance and penetration loss with special emphasis on results for the 2 GHz frequency band. This leads to the thesis problem statement and the objective of the research done for this thesis.

3.1 Current Research - Outdoor/ Indoor Communication

The radio channel is influenced by large-scale and small-scale propagation conditions. Research to predict both large-scale and small-scale propagation for wireless communication involves collecting field strength measurements. A number of wireless topologies have been investigated including those for outdoor, indoor and outdoor/ indoor communication.

For large-scale propagation, both theoretical and measurement-based propagation models show the average received signal power decreases with distance raised to some exponent. The exponent of the path loss is related to the radio channel's environment. Table 3.1 lists a number of environments and the path loss exponents established from field strength measurements.

The path loss power distance law is an estimate of the local average of the received signal relative to the transmitted power rather than the instantaneous value. The amount that instantaneous values of the received signal vary from the local average is measured by a standard deviation or shadow margin.

Table 3.1 Path Loss Exponent for Different Environments [7]

Environment	Path Loss Exponent
Free Space	2
Urban area cellular radio	2.7-4
Shadowed urban cellular radio	5-6
In building line of sight	1.6-1.8
Obstructed in building	4-6
Obstructed in factories	2-3

The shadow margin for indoor propagation is related to the material composition of walls and floors. Indoor mobile wireless communication has transmission paths that will traverse a varying number of walls and floor. The number of walls and floors traversed depends on the position of the receiver with respect to the transmitter location. The material composition of walls often differs from the material composition of floors. Cox [17], Rappaport [18] and Violette [19] have measured the average signal loss for radio paths obstructed by common building materials.

The measure of penetration loss into buildings is seen in the literature to be important for determining frequency reuse. Few measurements have been made with an outdoor/indoor configuration, but some generalizations have been made. Penetration loss decreases with increasing frequency. Turkmani [20] measured penetration loss values of 16.4, 11.6 and 7.6 dB for frequencies 441, 896.5 and 1400 MHz, respectively. Turkmani [21] also measured 14.2, 13.4 and 12.8 dB for 900, 1800 and 2300 MHz, respectively.

The received signal strength within a building generally increases as the receiver's height above ground increases. At lower floors, urban clutter induces greater attenuation and less penetration. At higher floors, a line-of-sight path may exist and

therefore, a stronger signal may be incident at the exterior wall. Walker [22] measured the signal strength in an office building. From ground level to the fifteenth floor, the penetration loss decreased by 1.9 dB per floor. Above the fifteenth floor, an increase in penetration loss is attributed to shadowing from adjacent buildings. Turkmani [20] measured similar results. From ground level to the ninth floor, the penetration loss decreased by 2 dB per floor. Above the ninth floor, the penetration loss increased. Durante [23] results also agree.

The number and type of windows in a building affect penetration loss. Measurements in front of windows experienced penetration losses 6 dB less than those in parts of buildings without windows. Tinted metal windows can have a huge impact on penetration loss. A metallized window can provide attenuation of 3 to 30 dB per single pane of glass [16].

Small-scale fading for indoor communication has been observed to be different from outdoor communication. The spatial fading rate is much lower indoors because the motion indoors is much slower [6].

3.2 Diversity Performance

The diversity techniques described in Chapter 2 assume uncorrelated diversity branches and equal powers. In practice, a cross correlation coefficient of 0.7 is considered acceptable [7] and equal mean power in the diversity branches is rare. As a result the diversity performance will suffer a worse-than-predicted diversity gain.

Space and polarization diversity are used in field strength measurements made by Jefford [10] in the 1800 MHz frequency band. From the measurements, a formula to predict diversity gain is derived. The selection combining diversity gain for an availability of 90% is defined by:

$$G = 5.71 e^{(-0.87 \rho - 0.16 \Delta)} \quad (13)$$

where ρ is the correlation coefficient and Δ is the difference between the two signals' means. Results at 1.75 GHz for space, frequency and hybrid diversity by Todd [24] also attributed the loss of diversity gain to non-ideal cross correlation coefficients.

3.3 Analysis of Current Research

Analysis of the current research shows little attention has been devoted toward characterizing the outdoor/ indoor channel. The outdoor/ indoor field strength measurements are prompted by neighbour interference and frequency reuse issues. The diversity performance of an outdoor/ indoor channel has yet to be investigated. The principle of diversity was first explored in 1927 when the first experiments in space diversity were reported. The measurements to date do not address the issue of appropriate diversity parameters to use for outdoor/ indoor channel in the 2 GHz frequency band. The issue of fading variability with and without diversity techniques is also not addressed. For large-scale fading, an appropriate exponent to use in the distance power law has not been derived for the outdoor/ indoor communication scenario. The appropriate magnitude has not yet been established for the related standard deviation.

3.4 Problem Statement

This section includes the basis for the problem statement. The information required to incorporate diversity into a system design for an outdoor/ indoor wireless communication system is described. The problem definition describes the current status regarding deficiencies in the information. The approach to a solution describes the measurements required to derive the missing information. This is concluded by the benefits of the proposed research.

3.4.1 Information Required to Incorporate Diversity into a System Design

The following information is required to design an outdoor/ indoor wireless communication system employing diversity:

- An estimate of average diversity performance with fading statistics over durations of interest: 30 seconds. Details of the measurement parameters and data acquisition settings are described in Chapter 4.
- The parameters to obtain this performance.
- Variations of diversity performance.
- An estimate of the path loss exponent for urban outdoor/ indoor communication.
- An estimate of the shadow margin for outdoor/ indoor communication.

3.4.2 Problem Definition

In this thesis, the problem of estimating realistic diversity performance for portable indoor radio communication in the 2 GHz frequency band is addressed. Realistic estimates of diversity performance can most reliably be obtained from measurements employing diversity. The problem encompasses the design of the radio channel measuring equipment, the collection of channel fading data and the data analysis to extract relevant information on diversity performance.

3.4.3 Approach to a Solution

Three steps are followed to solve the problem:

- **Experimental setup:**
This setup comprises design and testing of radio measurement equipment; design of calibration software and data file storage method and the development of the experimental procedure to measure fading.
- **Measurements:**
This involves data collection using a transmitter and diversity receiver in various locations around the Carleton University campus. Measurements are made during typical activity under conditions that approximate the use of a Fixed Wireless Access system.
- **Data analysis:**
Software is developed to analyze data from similar groups of measurements. Simple selection combining is executed in software after data collection. Envelope cross-correlations are calculated and envelope fading of diversity is measured. Correlation, diversity gain and fading statistics are also investigated. The results of the analysis are used to calculate a link budget which is an important tool in any system design.

3.4.4 Benefits of Proposed Research

Solving the above described problem is important for the following reasons:

- The 2 GHz frequency band is important to next generation wireless systems [25], in general, and to Fixed Wireless Access systems [26], in particular.
- The worst-case performance must be known, not just the average, to design highly reliable and quality communication systems (equivalent to wireline telephones).
- The outdoor/ indoor communication large-scale propagation parameters are important for future Fixed Wireless Access system design, which represents the main concern in this thesis.

The following secondary benefits are also achieved by solving this problem:

- Considering practical combining techniques that have low complexity and require a manageable amount of processing is important.
- Knowing the impact of employing diversity on the system link budget is very useful in the system design of future Fixed Wireless Access systems.

CHAPTER 4

OUTDOOR / INDOOR EXPERIMENT

This chapter describes the experiment purpose, the operating procedure, experimental setup and the calibration procedure. The experiment equipment includes the transmitter, the identical receivers, the antennas and the data acquisition system. The components for the transmitter and the receiver are described in detail. The design of the transmit directional antenna and the receive directional antenna are described. The computer system and the data acquisition card used to collect the data are also described in this chapter.

4.1 Experiment Scope

The experiment measures the CW signal transmitted from an outdoor antenna on the Minto Case building by moving a two-branch spaced diversity receivers to various indoor locations about the Carleton university campus. The application for these measurements is the characterize the Fixed Wireless Access for an indoor/ outdoor radio channel at 2.37 GHz.

Eight small scale propagation measurements with the receivers located in various levels in MacKenzie and Loeb buildings were taken. Eight measurements provide the deep fades, reflecting the movement of people within the campus buildings, needed to characterize small-scale fading. Twenty large scale measurements on the same level in the MacKenzie, Loeb, Grenville and Stormont-Dundas buildings were taken. Twenty measurements ranging from 50 to 500 m spacing between the transmitter and receivers provided the data to perform a linear regression and calculate the large scale fading path loss exponent and shadow margin.

The two-branch spaced diversity receivers measure and collect data simultaneously for both branches for 30 seconds at a sampling rate of 800 samples per second. The 30-second measurements use a sampling rate of 800 samples per second providing 24,000 samples of data for each channel. The sampling rate is chosen large enough for adequate resolution to capture deep fades but not so large as to cause prolonged data reduction. With the 20 large-scale propagation measurements and 8 small-scale measurements each having two channels of 24,000 data samples, this amounted to a total of $(20 + 8) * 2 * 24,000 = 1,344,000$ samples of data. The eight, two channels of small scale measurements by themselves take 3 days to reduce and extract statistics.

The data collected is 12 bits representing a voltage ranging from 0 - 2 volts. This voltage represents a signal at the logarithmic amplifier input ranging from 5 to -65 dB providing a dynamic range of 70 dB for the receiver.

4.2 Experiment Purpose

This experiment acquires data for analysis of propagation characteristics such as multipath effects at 2.37 GHz. Specifically, the data for an RF channel with an outdoor transmitter and indoor receiver is acquired.

4.2.1 Location

The receiver is moved to a number of locations about the Carleton University campus and throughout the MacKenzie and Minto Centre Engineering Buildings. Appendix B contains a plan view of the university campus as well as the engineering buildings.

The transmit antenna is located outdoors on the roof of the Minto Centre Engineering building. It is fed by a collocated transmitter that transmits a low power CW signal. There is no line-of-sight path between the transmit and receive antennas. The transmit

directional antenna pointing direction is set in azimuth and elevation to give acceptable signal quality for all the receive locations.

4.2.2 Antennas

The experiment uses directional antennas for both transmit and receive sites as would be expected for an operational Fixed Wireless Access system. Directional antennas provide better immunity from potential neighbouring interferers due to their narrow beamwidth and stronger signal reception due to their increased antenna gain.

The directional antennas are designed and built specifically for this experiment. The receive antennas are designed for moderate antenna gain and small size to maintain a compact receive unit. The receive directional antennas are 3-element Yagis. The transmit antenna is designed for maximum gain, with no size restrictions. The transmit directional antenna is a 12-element Yagi.

During the calibration phase of the experiment and for the large-scale propagation characterization measurements, omni-directional antennas are used for both transmit and receive. These omni-directional antennas are identical for both transmit and receive. These omni-directional antennas are monopoles antennas with ground planes.

4.2.3 Environmental Conditions

The atmosphere has non-uniform characteristics of temperature, pressure and relative humidity, which determine the dielectric constant and velocity of propagation of microwaves. The atmosphere is a refracting medium, which makes the radio horizon appear closer or further away and affects path clearances.

The effects of relative humidity, rain, snow and other precipitation are not examined in this thesis. The experiment's measurements are taken on clear days. Further research

must be undertaken to examine these various environmental effects on the 2 GHz band propagation characteristics.

4.2.4 Operating Frequency

The operating frequency of 2.37 GHz is chosen for the experiment. This coincides with the frequencies assigned the third-generation wide-area personal communication systems (Universal Mobile Telecommunication System, or UMTS). Frequencies are also available in this region of the 2 GHz band for Fixed Wireless Access. The signal transmitted in the experiment is an unmodulated carrier. (i.e., a CW signal)

4.3 Transmitter Architecture

The transmitter consists of a frequency synthesizer, two cascaded frequency doublers, a low-noise amplifier and a high-power amplifier to provide a carrier (CW signal). The circuit diagram for the transmitter used in the experiment is shown in Figure 4.1.

The frequency synthesizer's operating range is 0 to 1 GHz. The frequency synthesizer produces a 592.5 MHz signal. This is fed to two cascaded frequency doublers [27] to provide an RF frequency of 2.37 GHz. The parameters for the frequency doublers are listed in Table 4.1.

Table 4.1 Frequency Doubler Parameters

Input Freq Range (MHz)	Output Freq Range (MHz)	Conversion Loss @ 20-1800 MHz (dB)	Conversion loss @ input power 10 dBm (dB)	Max. Input Power (W)
30-2100	60 - 4200	11	14	1

Figure 4.1 Transmitter Circuit Diagram for Experiment

Note:

Spurious referenced to output F2 level:

F1	30-500 MHz	-25 dB
F3	90-1500 MHz	-30 dB

The cascaded doublers attenuate the signal while doubling the frequency. To boost the signal, the output of the frequency doublers is fed to two cascaded amplifiers. The first amplifier is a low-noise amplifier described in the receiver architecture section, later in this chapter. The second and final amplifier before the transmit antenna is a high-power amplifier [28]. The parameters for the high-power amplifier are listed in Table 4.2.

Table 4.2 High-Power Amplifier Parameters

Freq range (MHz)	Gain (dB)	Maximum Power (Output 1 dB Compression) (dBm)	Dynamic Range NF dB Typ	Max. Input Power (dBm) (no damage)
700-4200	30	+28	10	+5

Note:

1. Gain Flatness: ± 1.0 dB Max measured at 25°C
2. Intercept Point: + 38 dB Typ

4.4 Antenna Design

This section describes the antennas used in the propagation characterization measurements and during the calibration. The omni-directional antennas used during the calibration of the transmitter and receiver and for the large-scale propagation characterization measurements are described first. This is followed by the description of the directional antennas used in the small-scale propagation characterization

measurements. The directional antennas' description includes the design objectives as well as the dimensions used to build the antennas.

4.4.1 Omni-directional Antenna Design

Vertically-polarized omni-directional antennas are used during the calibration of the transmitter and receiver and for the large-scale propagation characterization measurements. Vertical antennas are widely used in the wireless communications. The omni-directional antennas used are $1/4$ wavelength (λ) monopole with a ground plane. A grounded $1/4$ wave vertical resonates at the same frequency as an ungrounded $1/2$ wave antenna. The ground plane antenna is physically short, end fed and easily mounted with a 50 ohm impedance requiring no special matching network to connect to coaxial cable [29]. Table 4.3 lists the dimensions of the $1/4$ wave ground plane vertical antenna.

Table 4.3 Ground Plane Antenna Dimensions

Elements	Length (mm)
Vertical	$1/4 \text{ wavelength} = 126.49 / 4 = 31.6$
Ground radials	$\geq 1/4 \text{ wavelength} + 5\%$

The ground plane antenna has the ground radials mounted to a 2 cm x 2 cm sheet of brass. The brass sheet has a 45 degree bend 0.5 cm from the tip of each corner. The angle of the ground radials with respect to the vertical element determines the impedance of the antenna. A $1/2$ wave dipole has an impedance of 72.3 ohms. A $1/4$ wave vertical with ground radials perpendicular to the vertical element has an impedance of 30 ohms. The vertical with 45 degree ground radials has an impedance of 50 ohms.

Figure 4.2 shows the construction of the ground plane antenna. A hole is drilled in the brass sheet's center and an SMA connector mounted, the threaded part facing down. The vertical radial is soldered to the center pin of the connector. All the radials are made from brass rods. The ground plane radials are soldered to the four bent corners of the plate. The ground plane antenna has a measure gain of 1.8 dBi [24].

Figure 4.2 Omni-directional Ground Plane Antenna

4.4.2 Transmit Directional Antenna

Antenna gain is increased by concentrating the power radiated into a sharper beam. Antenna gain is measured with respect to an isotropic antenna that has an ideally omni-directional antenna pattern in all planes. The ground plane is omni-directional in the azimuth plane but has less gain in the elevation plane [24]. (ergo the 1.8 dBi antenna gain)

The transmit directional antenna used in the experiment is a 12-element Yagi antenna. The gain and beamwidth of depends on the number of director elements on the Yagi antenna. For a 12-element antenna the gain is 12.8 dBd and the beamwidth at the 3 dB points is 30 degrees. The transmit Yagi is designed using a procedure written by Günter Hoch [30]. The procedure involves selecting design values from a series of

graphs, starting with a desired gain to select boom length. Then the placement of the reflector, driven element and directors is chosen from a table with spacing in wavelengths. Finally, the length for the elements is selected for a desired element diameter. For a metallic boom and for elements not insulated from the metallic boom, a shortening effect must be accounted for also.

The design procedure has been programmed by several other radio amateurs. Figure 4.3 shows the construction of the transmit Yagi antenna. Table 4.4 describes the transmit Yagi antenna design parameters. Table 4.5 lists the dimensions used to build the transmit Yagi antenna.

Figure 4.3 Transmit Directional 12 - Element Yagi Antenna

Table 4.4 Transmit Yagi Antenna Design Parameters

Parameter	Value
CENTER FREQUENCY	2370 MHz
GAIN	12.8 dBd
DRIVE IMPEDANCE	200 OHMS (APPROX). WITH FOLDED DIPOLE D.E.
BOOM LENGTH: REFLECTOR TO LAST DIRECTOR	1.19 FT = 14.3 IN. = 36.3 CM
BOOM DIAMETER	0.157 IN. = 0.40 CM
TOTAL NUMBER OF ELEMENTS	12
ELEMENT DIAMETERS: DRIVEN PARASITIC	ANY DIAMETER 0.063 IN. = 0.16 CM

NOTE: Elements pass through and are NOT insulated from a metal boom

Table 4.5 Transmit Yagi Antenna Dimensions

ELEMENTS	CUMULATIVE SPACING		ELEMENT LENGTH	
	CM	IN.	CM	IN.
REFLECTOR	Ref	Ref	6.27	2.47
DRIVEN ELEMENT	2.73	1.08	5.97	2.35
DIRECTOR 1	3.76	1.48	5.58	2.19
DIRECTOR 2	5.86	2.31	5.50	2.17
DIRECTOR 3	8.58	3.38	5.42	2.13
DIRECTOR 4	11.75	4.63	5.35	2.10
DIRECTOR 5	15.26	6.01	5.28	2.08
DIRECTOR 6	19.05	7.50	5.23	2.06
DIRECTOR 7	23.08	9.09	5.18	2.04
DIRECTOR 8	27.31	10.75	5.14	2.02
DIRECTOR 9	31.73	12.49	5.10	2.01
DIRECTOR 10	36.30	14.29	5.07	1.99

4.4.3 Receive Directional Antenna Design

Figure 4.4 shows the construction of the receive 3-element Yagi antennas. Table 4.6 describes the design parameters for the receive 3-element Yagi antennas. Table 4.7 lists the dimensions used to build the receive 3-element Yagi antennas.

Figure 4.4 Receive Directional 3 - Element Yagi Antenna

Table 4.6 Receive Yagi Antenna Design Parameters

Parameter	Value
DESIGN FREQUENCY	2370.00 MHz
LAMBDA (Wavelength)	126.49 mm = 4.980 in
GAIN (With -15 dB side lobes)	4.70 dBd
DRIVE IMPEDANCE	200 OHMS (APPROX), WITH FOLDED DIPOLE D.E.
NUMBER OF ELEMENTS	3
DIAMETER OF ELEMENTS	1.60 mm = 0.063 in
DIAMETER OF BOOM (O.D.)	4.00 mm = 0.157 in
BOOM LENGTH	33.39 mm = 1.315 in

- NOTE:
1. Design with tapered spacing to optimize gain
 2. Elements are NOT INSULATED from the Boom

Table 4.7 Receive Yagi Antenna Dimensions

ELEMENTS	CUMULATIVE SPACING		ELEMENT LENGTH	
	CM	IN.	CM	IN.
REFLECTOR	Ref	Ref	6.43	2.53
DRIVEN ELEMENT	2.34	0.92	5.98	2.36
DIRECTOR 1	3.34	1.31	5.60	2.21

These antennas are constructed from materials purchased from a hobby shop. The boom is brass box tubing and the elements are made from solid brass rods. The measuring is accurate to 0.01 cm using a set of calipers. A wooden jig is made to hold the boom and elements in place while soldering.

4.4.4 Matching Network Design

In the previous Yagi designs, the driven element impedance is listed as 200 ohms. This has to be matched to 50 ohm coaxial cable to connect to the transmitter or receiver equipment. Several baluns designs are available for this purpose, the gamma match being a good design for the Yagi antenna [29] as is evident from its design, which is detailed later in this section. Table 4.8 describes the design objectives for the matching network. Table 4.9 lists the characteristic impedance and capacitance and dimensions used to build the gamma match.

Table 4.8 Gamma Match Design Objectives

Parameter	Value
Desired Frequency (MHz)	
Enter Driven Element Diameter (cm.)	0.160 cm.
Enter GAMMA Rod Diameter (cm.)	0.160 cm.
Enter center to center spacing between Rods (cm.)	0.200 cm.
Resistance at 2370.000 MHz - (ohms)	50.00 ohms
Reactance (+/-) at 2370.000 MHz - (ohms)	50.00 ohms
Characteristic impedance of coaxial cable, Z_0 (ohms)	50.00 ohms

Table 4.9 Gamma Match Design Parameters

Parameter	Value
Transformed Impedance at GAMMA Rod	50.00 + j153.29 ohms
GAMMA Rod Length	1.4 cm.
GAMMA Capacitor	0.4 pF

The gamma match is constructed from 2 cm of 0.2 cm diameter brass tubing. This tubing is placed parallel and 0.1 cm from the driven element and soldered to the

driven element in two places. A coaxial cable with an SMA connector at one end is stripped 2 cm at the other end. The shield braid is soldered to the gamma match tubing and the dielectric and the center conductor is fed into the tubing. The impedance and Standing Wave Ratio (SWR) are measured and the dielectric and center conductor are trimmed to match the impedance and minimize the SWR.

4.5 Receiver Architecture

The receiver is a superheterodyne type in its basic form - a single frequency convertor. Figure 4.5 shows a typical receiver architecture for single frequency conversion. The circuit diagram for a receiver used in the experiment is shown in Figure 4.6.

4.5.1 Receiver Front End - RF Stage

Resonant networks before and after the RF stage that would normally provide front end selectivity are absent from this design. Selectivity provided by resonant networks is required where many other signals are competing for the same spectrum. During the calibration of the receiver, a spectrum analyzer is used to monitor a 5-MHz bandwidth about the experiment's transmit frequency of 2.37 GHz at random times of the day. No interfering signals are measured. Therefore, absence of resonant networks in the receiver front end does not impair the quality of the signal received for the experiment.

The RF stage comprises three RF low-noise amplifiers [28]. The parameters for the RF low-noise amplifiers are listed in Table 4.10.

Figure 4.5 *Typical Single Frequency Conversion Receiver Architecture*

Figure 4.6 Receiver Circuit Diagram for Experiment

Table 4.10 RF Low Noise Amplifier Parameters

Freq range (MHz)	Gain (dB)	Max. Power (Output 1 dB Compression) (dBm)	Dynamic Range NF dB Typ	Max Input Power (dBm) (no damage)
1700-4200	20	+26	1.5	+10

Note:

1. Gain Flatness: ± 1.0 dB Max measured at 25°C
2. Intercept Point: + 36 dB Typ

The RF amplifier used in the experiment has a Noise Figure (NF) of 1.5 dB. The Noise Figure of the first amplifier in the RF stage is the most significant component of the receiver Noise Figure. A low Noise Figure of the first amplifier in the RF stage translates to a low Noise Figure for the receiver overall. The receiver's Noise Figure is used to determine the receiver's sensitivity. A low Noise Figure for the receiver provides a high sensitivity. The RF stage amplifies the signal from the antenna before it reaches the mixer by 60 dB. A modicum of pre-selectivity is provided by the RF amplifier's operating frequency band of 1700 - 2400 MHz.

The RF amplifier is also used as an extra low power amplification stage in the transmitter.

4.5.2 Mixer Stage

The output signal from the RF amplifier stage is mixed with the local oscillator frequency to establish an IF (Intermediate Frequency). The mixer output provides an IF frequency of 70 MHz.

The Local Oscillator (LO) frequency is provided by a Crystal-Controlled Oscillator (XCO). This frequency source includes a crystal oven and is very stable but requires some time to reach its steady state RF frequency value. Although categorized as a 2.3 GHz frequency source, the actual measured steady state frequency is 2.2999897 GHz. Measuring the local oscillator frequency is important because it is used to specify the required transmitter RF frequency. Both these frequencies must be known accurately to convert the frequency to the required 70 MHz IF frequency.

Excessive LO noise will seriously degrade receiver performance. LO noise should be 80 dB or more below the peak level of the desired LO frequency. Excessive noise will appear as noise sidebands in the receiver output.

The mixer stage includes a double-balanced mixer [27]. The parameters for the mixer are listed in Table 4.11.

Table 4.11 Mixer Parameters

Freq Range of all ports (MHz)	Conversion Loss (dB)	Maximum Input Power (mW)
10-3000	7.5	600 (24 dBm)

Note:

1. Isolation

LO to RF	(1000-3000 MHz)	25 dB Min
LO to IF	(10-500 MHz)	20 dB Min
RF to IF	(10-500 MHz)	20 dB Min

2. SSB Noise Figure within 1 dB of Conversion Loss Max

3. Typical Two-Tone IM Ratio (with -10 dBm input, each input, 25 MHz and 35 MHz IF)

$$100 - 2000 \text{ MHz} \geq 56 \text{ dB}$$

4. RF Input

1 dB Compression + 7 dBm Typical

1 dB Desensitization + 5 dBm Typical

The local oscillator used in the mixer stage (a Crystal-Controlled Oscillator (XCO) [31]) has the parameters given by Table 4.12.

Table 4.12 XCO Parameters

Freq Range of all ports (MHz)	Minimum Power Output (mW)	Maximum Input Current (mA)
2000-2320	150	250

Note:

1. Frequency Stability Over Operating Temperature Range

-30°C to +60°C, 0 to 80% RH, 0 to 10,000 ft. $\pm 0.05 \%$

2. Output Power Stability

Over Operating Temperature Range +1.0, -1.5 dB Max

Over Frequency Range 3 dB Typ

3. Spurious Rejection

In Band -75 dBc Min

Out of Band - 20 dB

4.5.3 IF Stage

The IF crystal filter is used after the mixer to set the overall receiver selectivity. This receiver is designed for CW signal reception. The crystal filter 25 kHz bandwidth is adequate to receive the CW signal bandwidth of between 200 and 500 Hz.

The output of the IF filter is increased by one amplifier stage with an overall gain of 30 dB. This IF gain of 30 dB is sufficient to increase the signal strength to the detector without increasing the noise floor or reducing the dynamic range. These tradeoffs are made during the receiver calibration, which is described later in this chapter. The parameters for the IF Amplifier [27] are listed in Table 4.13.

Table 4.13 IF Amplifier Parameters

Freq Range of all ports (MHz)	Gain (+25°C) @ 10 MHz (dB)	Output Power (1 dB Compression) (dBm Max)	Noise Figure (dB)
0.5 - 100	29.7	+ 21	5.5

Note:

- Frequency Response

0.5-100 MHz	± 0.5 dB Max
1-60 MHz	± 0.3 dB Max
- Reverse Transmission

- 35 dB Max
- 37 dB Typ
- Intermodulation Intercept Point (for two-tone output power up to -10 dBm, 25 MHz and 35 MHz IF)

Second Order (0.5-100 MHz)	+ 33 dB Min
----------------------------	-------------

Second Order (1-60 MHz)	+ 42 dB Min
Third Order	+ 33 dB Min
4. Input Power	+18 dBm Max

4.5.4 Logarithmic Detector Stage

The output of the receiver is made proportional to the logarithm of the input envelope using a logarithmic amplifier. The log amp is ideally suited to this application where multipath effects may induce large variations in input signals. It helps prevent receiver saturation and reduces the effects of unwanted noise signals [32].

The log IF amplifier detects IF input signals and provides video proportional to the logarithm of the IF input power. They are widely used in applications where compressing a wide input dynamic range of signals for processing is necessary. The dynamic range for the log amp's linear region is 70 dB compared with 30 dB for a typical envelope detector [33]. The log amps with dc-coupled output are ideally used in CW or pulsed signal reception.

The parameters for the detector stage's logarithmic IF amplifier [34] are listed in Table 4.14. The log amp converts signals ranging from 5 to -65 dBm to voltages of 2 to 0 volts.

Table 4.14 Logarithmic IF Amplifier Parameters

Center Freq (MHz)	Bandwidth (MHz)	Input Dynamic Range (dB)	Rise Time (nsec)	Fall Time (nsec)
70	10	70	100	200

Notes:

1. Dynamic Range from +5 to -65 dBm.
2. Video Output: 2.0 v (Typical) into 93 Ohms. Units are direct coupled.
3. Log transfer slope < 10 % average change.
4. Linearity: within ± 1 dB of best straight line.

An ideal amplifier has a constant slope and a straight line logarithmic input power/ output voltage transfer function. In practical design, the log amp is realized by piecewise approximation. The output voltage of the log amp is measured for a number of input powers and compared with the best fit straight line with a slope of 0.024 v/dB. The experiment's propagation measurements are taken at distances to ensure the log amp use is confined to its linear region only.

4.6 Calibration Procedure

The calibration procedure for the outdoor / indoor Fixed Wireless Access system involves calibrating both the receiver and transmitter.

4.6.1 Transmitter Calibration

The frequency of the transmitter is tuned to 2.3699897 GHz. This frequency is selected based on the receiver characteristics, as outlined earlier. The receiver Local Oscillator frequency is measured to be 2.2999897 GHz. When these two frequencies are mixed, an exact IF frequency of 70 MHz results.

When transmit frequency of 2.37 GHz is generated by a frequency synthesizer operating from 0 to 1 GHz, two cascaded frequency doublers are required. The cascaded doublers attenuate the signal while doubling the frequency. To boost the signal, the output of the cascaded frequency doublers is fed to two cascaded

amplifiers. The first amplifier is a 20 dB low-noise amplifier. The second and final amplifier before the transmit antenna is a 30 dB high-powered amplifier. The output level of the frequency synthesizer is set to 12.5 dBm resulting in a transmit power of 29.7 dBm or 933 mW.

4.6.2 Receiver Calibration

Calibration of the Outdoor / Indoor Wireless receiver is important for evaluating the performance of the receiver and for interpreting the data acquired during the experiment. Figure 4.7 shows the calibration circuit setup for the receiver identifying calibration points and the power in dBm at each point. The transmitter is shown on the top portion of the diagram. For the calibration, the antennas are not used and the output of the transmitter is connected via a coaxial cable to the input of the receiver. The power out of the transmitter is attenuated by two 20 dB attenuators to prevent saturation of the receiver front end.

Appendix A contains the plots of the measurements made with the spectrum analyzer at each calibration point in the receiver. Figure A.7 and A.8 are two graphs of the Calibration Point G. Figure A.7 has its reference level set to 10 dB and the marker positioned on the carrier. Figure A.8 has its reference level set to -40 dB and the marker positioned on the noise floor. In the right top corner is the power level at the marker which is 8.84 dB for the signal and -68.79 dB for the noise. This shows the S/N ratio at the RF stage Calibration Point G is 77.5 dB.

The log amp is characterized using a special setup shown in Figure 4.8. The log amp is isolated from the receiver circuit. A frequency synthesizer provides the power input in dBm. A precise measurement of this power input is made by a spectrum analyzer also connected to the input using a power splitter. A multimeter and an oscilloscope are connected via BNC T-connector to the output of the log amp to measure its output in volts dc. The transfer function remains within ± 1 dB for the operating dynamic range of the log amp.

Figure 4.8 Logarithmic Amplifier Calibration Setup

4.7 Experimental Setup

A spectrum analyzer is used to monitor the received power level in dBm at the receiver's IF stage. The data acquisition screw terminal board connects the receiver to the data acquisition board.

4.7.1 Experimental Data Interpretation

The experiment's goal is to collect data in the 2 GHz frequency band for outdoor / indoor Fixed Wireless Access and analyze multipath effects observed in the data. The data is transmitted from an outdoor antenna and received indoors with a receiver and an automated data acquisition PC. The data format and the interpretation of the results in terms of multipath effects, depends on the receiver architecture and the data acquisition configuration.

4.7.2 Data Acquisition

The receiver output is connected to a PC with a resident data acquisition card [35]. This setup is used to record the measurement results on the hard drive of the PC. The data from the data acquisition card is a voltage expressed as a 12 bit binary word. The voltage range that the data acquisition card can accept is 0 to 10 volts or 0 to 4096 binary. The lowest gain expected in the dynamic range will be binary 1. The largest gain expected in the dynamic range will be binary 4096 (2^{12}).

The 30-second measurements use a sampling rate of 800 samples per second providing 24,000 samples of data for each channel. The sampling rate is chosen large enough for adequate resolution to capture deep fades but not so large as to cause prolonged data reduction. With the 20 large-scale propagation measurements and 8 small-scale measurements each having two channels of 24,000 data samples, this amounted to a total of $(20 + 8) * 2 * 24,000 = 1,344,000$ samples of data. The eight, two channels of small scale measurements by themselves take 3 days to reduce and extract statistics.

The logarithmic amplifier output feeds the data acquisition board with a voltage ranging from 0 - 2 volts. The logarithmic amplifiers input ranges from 5 to -65 dB providing a dynamic range of 70 dB.

In summary, this chapter describes the experiment purpose, the operating procedure, experimental setup and the calibration procedure. The experimental setup is used in a series of signal strength measurements. Results and analysis of the various measurements are presented in the following chapter.

CHAPTER 5

RESULTS AND ANALYSIS

This chapter presents the small and large scale fading analysis and a comparison between outdoor/ indoor and outdoor propagation statistics. The emphasis is on the small scale fading analysis, which includes sections on envelope statistics, envelope cross correlation, selection combining, cumulative distribution functions and global envelope statistics. The small scale fading analysis of this chapter describes the data reduction procedure required to extract the statistics.

5.1 Small Scale Fading

The time variations in the received signal are called small-scale fading. A description of the small-scale fading is presented in Chapter 2. The small-scale fading analysis begins with this section on the procedure for data collection and the procedure for data reduction. The data is reduced to a suitable format to extract the envelope fading statistics.

5.1.1 Data Collection

Data collection is required to analyze the outcomes of the measurements. A data acquisition system, connected to the receiver output, is used. The receiver output is a voltage representing the received power in dB. The data acquisition system comprises a data acquisition card installed in a PC and a data acquisition software program. This program reads data from one or more Analog to Digital Converter (ADC) channels on an A/D converter card and stores the data in a file. The program uses the internal clock on the A/D card. The maximum aggregate sampling rate cannot go above 65535 samples/sec. The aggregate sampling rate equals the Channel Sample

Rate * the Number of Channels. The minimum per channel rate is 20 samples/sec (max sample and hold time is 50 msec). The program can collect data on one or more channels. Channel 0 is always used and the user can specify which of the other channels (i.e., 1, 2 or 3), if any, are also needed.

The output file contains a 1024-byte header. The sampled channel data follows the header. Each sample contains 16 bits. Only 12 bits are significant and they are the Least Significant Bits (LSB) of the word. (The bits are stored in the file with first 8 bits being the LSB and then next 8 bits being the Most Significant Bits (MSB)).

The data acquisition program prompts for user input for the filename to save the data; the data format whether it is binary or offset binary; the duration of the data collection in seconds; the number of channels to be collected; the sampling rate for data collection and the delay in seconds before the data collection starts. If the binary format is chosen, then the data translation card saves the voltage as a binary 16-bit word.

Signal variability measurements are made at eight locations around the Carleton University campus. Eight measurements are collected showing deep fades representing the movement of people within the campus buildings. The voltage values are captured for 30 seconds. The signal is measured in two-channel space diversity configured receivers as described in Chapter 4.

5.1.2 Data Reduction Procedure

To analyze results using MATLAB, a program is used to convert the data to a MATLAB compatible .mat file. The mat file translates the header information and the sampled channel data into separate variables. The variables for the header information are DataFile, BoardType, NumOfChannels, ChSamplesPerSec, ExternalClock,

CollectForSeconds, CollectionDate, and CollectionTime. The sampled channel data variable is Ch.

The voltage values are then processed using various MATLAB programs. The MATLAB m files scripts used in the analysis are listed in Appendix A. The measured data is converted from binary format to decimal format representing the voltage value. The mean (μ) and standard deviation (σ) calculated for each diversity channel are used to normalize each channel's voltage values. The resulting normalized voltage values have a normal distribution with a mean of zero and a standard deviation of one as shown by:

$$\begin{aligned}\mu &= 0 \\ \sigma &= 1\end{aligned}\tag{14}$$

To eliminate any possible differences in the two channels' statistics, the means and standard deviations of the two channels are averaged and reapplied to the normalized voltage values for each channel. These aligned voltage values are then converted to dB using the logarithmic amplifier transfer function characteristic.

5.2 Envelope Cross Correlation

The envelope cross correlation is very important in combining two signals at the micro-diversity receiver [36]. The efficiency of the combining technique is directly related to the envelope cross correlation coefficient. Correlation coefficients range from -1 to 1. Envelope cross correlation coefficients close to 0 characterize independent channels. Dependent channels have values close to either 1 or -1. Channels can be combined legitimately only if they exhibit some independence. In this analysis, ideal selection combining is used to combine the two channels. A description of selection combining and other combining techniques are presented in Chapter 2.

To understand the cross correlation of two channels, it is useful to know its relationship with variance σ^2 and cross correlation matrix K . Cross correlation matrix K is obtained from the two channels' observation vectors A_1 A_2 as defined by [37]:

$$\begin{aligned} K &= A_1 A_2^T \\ K &= \sigma^2 \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix} \end{aligned} \quad (15)$$

where the cross correlation coefficient is denoted by ρ and the variance is denoted by σ^2 . The correlation coefficient of the measurements is plotted on a histogram. The histogram plots the cross correlation incidence versus 100 bins between -1 and 1. Figure 5.1 shows the correlation coefficients for the indoor/ outdoor space diversity measurements. The spread of correlation coefficients is closely grouped around zero showing the independence of the receiver channels. The mean cross correlation for the two-branch diversity measurements is 0.04 with a standard deviation of 0.15.

5.3 Selection Combining

Ideal selection combining is computed using a MATLAB program as a post processing function. The normalized power in dB for channel 1 is compared with that of channel 2 and the largest signal of the two is output as the combined signal. The normalized channel 1 and 2 inputs and the selection combined output are plotted in Figure 5.2. Channel 1 shows several deep fades around 3 seconds and one deep fade at 10 seconds. Channel 2 shows several deep fades around 22 and 23 seconds. The fact that fades of channel 1 and 2 do not occur simultaneously suggests that the fades are uncorrelated. The selection combined signal shows the deep fades evident in channel 1 and 2 have been eliminated in the combined signal.

Figure 5.1 Cross Correlation Coefficients Histogram

Figure 5.2 *Normalized Channel 1 and 2 and Selection Combined Signal*

5.4 CDF of Envelope Fading

The cumulative probability distribution function (CDF) is calculated using each channel's normalized power determined in the data reduction process. The CDF for empirical data is defined by [37]:

$$F(x) = \frac{\text{number of outcomes less than } x}{\text{total number of outcomes}}, \quad -\infty < x < \infty. \quad (16)$$

The total number of outcomes for the sampled channel data is equal to the sampling rate multiplied by the time duration over which the data is collected. The number of outcomes less than x is calculated by comparing each data sample a fade threshold value (x). Every time the sample is below the threshold the count is incremented. This is calculated for 91 threshold values from -70 to +20 dB. The number of occurrences of a fade is divided by the total Number of Samples measured to calculate the CDF for each channel.

The CDF is also calculated with space diversity where the selection combined signal is used. The CDF is calculated for eight measurements. All of the eight measurements have correlation coefficients less than 0.5 suggesting that the two channels are to the most degree of independent of each other.

Table 5.1 shows the measurements' locations. Refer to Appendix B for the layout of the university campus and a detailed plan of the engineering buildings. The measurements are taken in two buildings on a number of different floors. Rooms in the interior of buildings and near the exterior walls are included in the measurement locations.

The Loeb building is the furthest building on campus from the Minto Case building. The plan view of the campus in Appendix B shows that the Minto Case and

MacKenzie Engineering buildings and the Loeb building are located in two valleys separated by a hill. Several buildings are on the hill including the University Centre, the Dunton Tower, the MacOdrum Library and Southam Hall. A straight line from the transmit site on the Minto Case to the receive site in the Loeb building is blocked. The line-of-sight path maybe blocked by the hill, or one of these buildings as well as the walls of the Loeb building itself depending on the floor and location the measurement is taken.

Table 5.1 Measurement Locations

Measurement Number	Building	Level	Distance
1	MacKenzie	4	49.5
2		4	111
3		1	130
4		2	120
5	Loeb	2	500
6		4	500
7		4	500
8		6	500

The eight measurements are graphed on a semilog plot. Figure 5.3, 5.4 and 5.5 are the CDF of channel 1, the CDF of channel 2 and the CDF of the selection combined signal, respectively. The plot of CDF for each measurement is marked with its own distinctive line type. A legend is presented beneath each figure matching the line

Figure 5.3 CDF of Channel 1

Measurement #	Line Style
1	X
2	O
3	+
4	*
5	#
6	&
7	?
8	S

Figure 5.4 CDF of Channel 2

Measurement #	Line Style
1	X
2	O
3	+
4	*
5	#
6	&
7	?
8	S

Figure 5.5 CDF of Combined Channel 1 & 2

Measurement #	Line Style
1	X
2	O
3	+
4	*
5	#
6	&
7	?
8	\$

type with the measurement number given in Table 5.1. Signal values of channel 1 and channel 2 in Figures 5.3 and 5.4 for the outage of 0.01 % (the outage at the abscissa) range from less than - 40 dB to 0 dB. The selection combined signal values for the outage of 0.01 % , range from a little less than - 20 dB to 0 dB.

5.5 Global Envelope Statistics

Some global envelope statistics can provide insight into the fading characteristics of a receiver channel. Of particular interest are the average CDF and the spread from the average, namely the worst and best case CDFs.

5.5.1 Average CDF Statistic

To calculate the average CDF, a new CDF must be generated by interpolating between CDF calculated from each measured channel for the 91 threshold values. This new CDF is calculated for 500 probability values from 0.01% to 100% (shown in the figure as 10^{-2} to 10^{+2}). The signal level with respect to the mean value is interpolated from the CDF calculated from the 91 threshold values. A linear interpolation is calculated using the following equation [38]:

$$y = y_0 + \frac{(x - x_0)}{(x_1 - x_0)} (y_1 - y_0) \quad (17)$$

where x is the probability value for the new CDF; x_0 is the probability of the measurement below x ; x_1 is the probability of the measurement above x ; and y , y_0 , and y_1 are the threshold values corresponding to the probabilities x , x_0 , and x_1 , respectively. The average CDF is calculated from the signal level below mean. For each probability value, the signal level for the eight measurements is added. The result is divided by the number of measurements (i.e., 8).

5.5.2 Rayleigh Fading CDF

Small scale fading experienced by non line-of-sight wireless channels is characterized by a Rayleigh CDF as shown by:

$$\begin{aligned}
 P(y) &= 1 - e^{-y^2}, \\
 \text{where } y &= \frac{x}{\sqrt{2b_0}} \\
 \sqrt{b_0} &= \text{mean voltage} \\
 \sqrt{2b_0} &= \text{rms voltage}
 \end{aligned} \tag{18}$$

where y^2 is the antilog of the threshold value on the abscissa of Figure 5.6 and can also be calculated from the observed voltage value x normalized by the rms voltage $\sqrt{2b_0}$. Figure 5.6 plots the global average for single channel and two-branch diversity (annotated Avg1 and Avg2, respectively) along with single and joint Rayleigh CDFs [36] (annotated Rayleigh1 and Rayleigh2, respectively). The single channel average is taken from channel 1 only. The improvement afforded by two-branch space diversity over no diversity is evident from this figure.

Note that the global average CDF for the single channel measurements shows that it does not experience fades as deep as a theoretical Rayleigh signal. The outdoor/ indoor radio channel fades are caused by the ambient movement of people about the building. The outdoor/ indoor FWA system is fixed and has no time variations in the signal propagation due to the movement of the antennas. Therefore, the deep fades experienced by the Rayleigh signal are not expected in the outdoor/ indoor FWA system.

The slighter fades in the measured single-channel CDF are commuted to the two-branch space diversity results. At the 99% availability, the theoretical diversity

Figure 5.6 *Mean of Single Channel and Two-Branch Space Diversity Empirical and Theoretical CDFs*

improvement is 10 dB whereas the measurements show a diversity improvement of 5.1 dB. Even with the lower diversity performance, the measured two-branch diversity CDF is better than the joint Rayleigh CDF because of the lower fading in the single measured channel.

5.5.3 Diversity Performance

Figures 5.3, 5.4, 5.5 and 5.6 show the probability that the amplitude of the signal received will be less than a set threshold level. This is also called the outage of the signal. Tables 5.2, 5.3 and 5.4 show statistics for outage = 10%, 1% and 0.1 %. It is common practice to present CDF results in terms of availability, the probability that the amplitude of the signal received will be greater or equal to a set threshold level. Availability is related to outage according to the following equation:

$$Availability(\%) = 100\% - Outage(\%) \quad (19)$$

Tables 5.2, 5.3 and 5.4 show CDF statistics for 3 availability values: 90 %, 99 % and 99.9%. The statistics include the average fade, the minimum fade or best case, the maximum fade or worst case and the spread between the minimum and maximum fades. These tables show the statistics for each channel and for the selection combined output. The gain is the measure of improvement from the single receiver channel to the selection combined space diversity receiver channel.

For the 99% availability shown in Table 5.3, the average fade for Channel 1 of -13.3 is slightly higher than Channel 2's average fade of 13.4. The Combined signal has an average fade of 8.2, which is an improvement or gain of 5.1 over the best average signal from either of the two channels. The difference between the minimum fade and maximum fade for channel 1 is 16.1 dB. the difference for channel 2 is higher at 19.9 dB. The combined signal's difference of 10 dB shows an improvement of 6 dB

Table 5.2 Fading Statistics for 90% Availability

@90% availability	Channel 1	Channel 2	Combined	Gain (dB)
Average fade (dB)	-5.6	-5.5	-3.8	1.7
Minimum fade (dB)	-1.0	-0.9	-0.9	
Maximum fade (dB)	-8.1	-8.4	-6.0	
Spread (dB)	7.1	7.5	5.1	

Table 5.3 Fading Statistics for 99% Availability

@99% availability	Channel 1	Channel 2	Combined	Gain (dB)
Average fade (dB)	-13.3	-13.4	-8.2	5.1
Minimum fade (dB)	-2.0	-1.9	-1.7	
Maximum fade (dB)	-18.1	-21.8	-11.7	
Spread (dB)	16.1	19.9	10.0	

Table 5.4 Fading Statistics for 99.9% Availability

@99.9% availability	Channel 1	Channel 2	Combined	Gain (dB)
Average fade (dB)	-19.1	-19.4	-12.2	6.9
Minimum fade (dB)	-2.9	-2.0	-2.0	
Maximum fade (dB)	-27.8	-26.8	-18.4	
Spread (dB)	24.9	24.8	16.4	

over the best of the two channels, which is even more than what is calculated for the average fade.

Similar results are shown in Tables 5.2 and 5.4 for availabilities of 90 and 99.9% respectively. The combined signal offers an improvement over the best of the two channels. Table 5.2 for the 90% availability shows an improvement of 1.7 dB for the average fade and Table 5.4 for the 99.9% availability shows an improvement of 7.1 dB for the average fade.

Table 5.5 shows a comparison of average, best and worst case fading statistics for 90%, 99% and 99.9% availability. As expected for CDFs following a Rayleigh distribution, the lower availability, the lower the improvement. Also, the reverse is true, the higher the availability, the higher the diversity improvement. The improvement or gain for both average fade and spread, summarized in Table 5.5, shows it is lowest for the availability of 90% and highest for the 99.9% availability.

Table 5.5 Comparison of Average, Best and Worst Case Fading Statistics for 90%, 99% and 99.9% Availability

Availability	90%	99%	99.9%
Average Fade Gain (dB)	1.7	5.1	7
Combined Signal Min - Max Fade Spread (dB)	5.1	10	16.5
Min-Max Fade Spread Gain (dB)	2.0	6.1	8.4

Table 5.6 shows the single and joint Rayleigh fade statistic for three availabilities. The values presented in this table are calculated using equations described in Rayleigh Fading section of Chapter 2. The diversity gain for the Rayleigh fading case is also calculated for each availability. For the 99 % availability, Rayleigh diversity gain is 10.2 dB and for the measurement average fade, the diversity gain is 5.1 dB. This is a

discrepancy of 5 dB. The diversity improvement differs from theory because the fading of the measured results does not fade as severely as theory. Comparing the measured and theoretical single channel average fade, the Channel 2 measurement is 6.6 dB better than theory. Also the difference between the measured and theoretical gain may be attributed to the effects of non-ideal selection combining of channels that have some small degree of dependence. Note that the two-branch Rayleigh model performance is achieved assuming that the correlation coefficient of the diversity receiver is zero (i.e., the two branches are independent).

Table 5.6 Fading Statistics for Rayleigh Fading

Average fade (dB)	Channel 1	Combined	Gain (dB)
@90% availability	-6.8	-1.2	5.6
@99% availability	-20.0	-9.8	10.2
@99.9% availability	-30.0	-14.9	15.1

Figure 5.1 shows that the correlation coefficients of the measurements vary from +0.3 to -0.2. This variance from a cross correlation of 0, which is the value for purely independent diversity channels can be partly responsible for discrepancies between predicted and measured results. Chapter 2 describes the cross correlation coefficient and its significance to diversity envelope statistics.

Figure 5.7 shows the average fade, maximum fade and Rayleigh fade for single and joint CDFs. This is a visual representation of what is presented numerically in Tables 5.2, 5.3, 5.4, 5.5 and 5.6. The improvement for two-branch space diversity over no diversity is evident in the maximum and average fade for single and joint CDFs. The worst case CDFs are the maximum fade CDFs annotated by Max1 and Max2. The spread between the minimum and maximum CDF for the combined channel is also

Figure 5.7 *Worst Case Statistics, Average Statistics and Theoretical*

influenced by the spread of the diversity branches' CDFs and the spread in the cross correlation coefficients.

Figure 5.8 shows a histogram of the single and joint CDFs for the measurements at a 99% availability. This is a visual representation of the numerical data presented in Table 5.3. The single channel histogram includes the data for both channel 1 and channel 2 and therefore has twice as many measurements total graphed as in the two-branch diversity histogram. The improvement in the spread between the single and two-branch diversity measurements at 99% availability is evident in the minimum and maximum values shown in the histogram. At 99% availability, the spread for the two-branch space diversity channel is 10 dB. Considering that the spread in the single channel CDFs is between 16.1 and 19.9 dB, the spread in the output CDFs is not as surprising. Variations in the combined CDF can also be attributed to the variations from ideal selection combining of independent channels that have correlation coefficient equal to zero. The spread in CDF can be attributed to the spread in correlation coefficients as shown in Figure 5.1.

In summary, the small-scale fading properties of an outdoor transmitter and indoor receiver radio follow a Rayleigh CDF. Cross correlation values must be close to zero to provide independent, uncorrelated diversity channels required for successful selection combining. Global statistics such as worst case, average fade and maximum fade for single and joint CDFs show the diversity improvement and the spread. The spread and the dependence of two channels will contribute to spread in the combined signal. This section covered the time variations characteristics of the outdoor/ indoor radio channel. The next section will describe the shadowing experienced by the outdoor/ indoor radio channel called large-scale fading.

Figure 5.8 *CDFs at 99% Availability for Single and Two-Branch Space Diversity*

5.6 Large Scale Fading

The general nature of large-scale fading is described in Chapter 2. The large scale fading for outdoor/ indoor Fixed Wireless Access communication can be characterized by the log normal path loss model shown by:

$$L = L_0 + \gamma 10 \log D + X_\sigma \quad (20)$$

where the Free Space Loss (FSL) L_0 is computed for a distance of 1 m for indoors, 100 m for micro-cells and 1 km for macro-cells [16]; γ is the power law that fits empirical measurements of propagation loss versus distance, D ; and X_σ is the variation from the average value due to the differing clutter environments for signals with the same transmit-receive separations and is a zero-mean Gaussian-distributed random variable (in dB) with a standard deviation σ (also in dB).

Twenty measurements, taken at various locations on the Carleton University campus, are used to determine the exponent. The mean (μ) received channel power in dB taken at the output of the receive is used to calculate the propagation loss. The mean is calculated exactly as was described for the small-scale measurements using the same Matlab routines.. The propagation loss is the difference between the power output of the transmit antenna and the power input to the receive antenna. The signal received at the antenna input is determined by subtracting the gains and losses through the receiver and the receive antenna from the signal received at the log amp output. The transmit signal power at the antenna output is the accumulated gains and losses through the transmitter components and transmit antenna. The values for these gains and losses for the receiver and transmitter including the antenna gains are annotated on Figures 4.1 and 4.6 respectively. The calculated propagation loss is listed in Table 5.7

Table 5.7 Large Scale Fading Statistics

Distance (m)	Propagation Loss (dB)	Fit to Propagation Loss (dB)	Minimum Error (dB)
49.5	-131.95	-135.06	-3.11
60	-143.60	-136.70	6.90
70	-145.65	-138.01	7.64
80	-136.68	-139.14	-2.46
90	-129.26	-140.15	-10.89
100	-148.58	-141.04	7.54
120	-146.39	-142.59	3.80
135	-149.70	-143.59	6.10
220	-132.39	-147.74	-15.35
240	-132.64	-148.48	-15.84
270	-154.27	-149.48	4.78
300	-145.54	-150.38	-4.83
340	-150.55	-151.44	-0.89
350	-149.01	-151.69	-2.68
380	-156.23	-152.39	3.84
400	-152.12	-152.82	-0.71
500	-165.10	-154.72	10.38
500	-162.10	-154.72	7.38
500	-156.10	-154.72	1.38
500	-152.46	-154.72	-2.26

This propagation loss is used to determine the exponent for large scale fading and the standard deviation used for the shadow margin. A regression curve to fit to the propagation loss versus distance is calculated using the method of least squares [38]. If the regression curve is given by $y = a + b x$, then Equations 21 and 23 calculate the slope and y intercept.

$$b = \frac{n \sum_{j=1}^n x_j y_j - \sum_{j=1}^n x_j \sum_{j=1}^n y_j}{n(n-1) s_1^2} \quad (21)$$

$$\text{where } s_1^2 = \frac{1}{n-1} \left[\sum_{j=1}^n x_j^2 - \frac{1}{n} \left(\sum_{j=1}^n x_j \right)^2 \right] \quad (22)$$

$$a = \frac{1}{n} \sum_{j=1}^n y_j - b \frac{1}{n} \sum_{j=1}^n x_j \quad (23)$$

The exponent γ is represented by b , L_0 is represented by a , $10 \log D$ is represented by x_j and L is represented by y_j . Figure 5.9 shows the regression curve plotted with the propagation loss measurements versus distance.

Table 5.7 contains twenty measurements taken at distances ranging from 49.5 m to 500 m. The propagation loss calculated from the signal received at these distances ranges from -131.95 dB to -165.10 dB. The line fit to the measured propagation loss is calculated from the equation shown in Figure 5.9 and by:

$$L = -101.9 - 1.957 * 10 \log D$$

Figure 5.9 *Propagation Loss vs. Distance*

The exponent γ that gives the least square error is calculated to be 1.957. The outdoor/ indoor radio channel exponent of 1.96 is better than the exponent for Free Space Loss (FSL), which is 2. An exponent value better than FSL suggests the signal is being reinforced in some respect. The measurements were taken in corridors known to channel signal energy much like a waveguide [6].

The Minimum Mean Square Error (MMSE) estimate is calculated from the error between the points on the regression curve and measured propagation loss for a given distance. The calculation sum of the squared errors is shown by [16]:

$$J(n) = \sum_{j=1}^n (L_j - \hat{L}_j)^2 \quad (24)$$

where L_j represents the measured propagation loss and $\hat{L}_j$ is the regression curve estimate. The minimum error $(L_j - \hat{L}_j)$ in the last column of Table 5.7 is the difference between the linear regression fit and the measured propagation loss. Figure 5.9 shows visually the match between the linear regression curve and the scatter plot of the measured propagation loss measurements. The minimum error ranges from 10.38 dB to -15.84 dB. Three errors are smaller than -10 dB and one is larger than 10 dB. The other sixteen measurements have minimum errors ranging from -4.83 dB to 7.38 dB. The anomalies are measurements taken in hallways with a window at the end of it. The signals measured at two locations in this corridor are higher by 15 to 20 dB than measurements taken further down the hallway blocked by a steel door. The minimum error of 10.38 dB occurred in the Loeb building's second floor, which is below ground level with respect to the transmit site atop the Minto Case building resulting in greater than average propagation loss.

The variance σ^2 for the twenty measurements is equal to:

$$\sigma^2 = J(n)/20 = 53.70$$

The standard deviation or shadow margin when using the log normal path loss model is calculated to be:

$$\sigma = 7.33 \text{ dB}$$

In summary, the large-scale fading for the outdoor/ indoor radio channel is calculated by curve fitting to measurement data. The propagation exponent calculated is 1.957 for the outdoor/ indoor radio channel. From the research outlined in Chapter 3, this exponent of 1.957 is within the exponent range of 2 to 3 established by measurements taken by other researchers. The shadow margin is calculated to be 7.33 dB. This margin and results from the small-scale fading analysis are compared with the fading characteristics of the indoor radio channel in the following section.

5.7 Indoor Communication and Outdoor/ Indoor Communication Comparison

In order to better understand the small and large scale fading characteristics of the outdoor transmitter and indoor receiver radio channel, this section presents a comparison of the outdoor/ indoor results and the indoor radio channel propagation statistics. The indoor fading statistics used in this comparison are taken from research done by Todd [24, 39]. Table 5.8 summarizes the fading statistics for indoor and outdoor/ indoor wireless communication.

Similar to the outdoor/ indoor wireless measurements, the indoor wireless measurements generating these statistics are also made at the MacKenzie building on the Carleton University campus. The environment where signals are measured is important. Signal fading characteristics are affected by the building construction

Table 5.8 Comparison of Indoor and Outdoor/ Indoor Fading Statistics

Parameters @ 99 % Availability	Indoor [24, 39]	Outdoor/ Indoor	Difference (%)
Small Scale Fading			
Single Channel			
Average Fade (dB)	-15.1	-13.3	11.9
Two-Branch Space Diversity			
Average fade (dB)	-10.0	-8.2	18
Diversity Gain (dB)	5.1	5.1	0
Minimum fade (dB)	-1.9	-1.7	10.5
Maximum fade (dB)	-15	-11.7	22
Spread or Fading Margin (dB)	13.1	10.0	23.7
Large Scale Fading			
Number of Paths	34	20	
Exponent	2.85	1.96	31.3
Shadow Margin (dB)	37	7.33	80.2

materials. Depending on the building, the signal may be reflected or absorbed to different degrees. The fading characteristic differences between the indoor and outdoor/ indoor measurements should be independent of the building construction materials because they are both taken at the same building. The indoor wireless measurements were made at 1.75 GHz, which is within the 2 GHz frequency band where the outdoor/ indoor measurements were also taken.

Some difference should be noted in the measurement setup that could contribute to any discrepancies found in results between the two scenarios. The first difference is the indoor fading statistics include obstructed and line-of-sight paths while the outdoor/ indoor scenario is obstructed by definition. The second difference is the indoor measurements' duration is one minute each whereas the outdoor/ indoor measurements last only 30 seconds. The indoor measurement duration is chosen to capture typical variations in the channel due to the movement of people. The one minute duration is used to approximate the average telephone call duration. The outdoor/ indoor measurement duration is also chosen to capture the typical variations in the channel due to the movement of people in the building. Early in the calibration stage, measurement durations of 4 and 10 seconds are noticed at times to exhibit no variation. The thirty-second measurement shows deep fades even in off peak times and has the advantage of being less bulky to post process. The number of fades is prorated over the measurement duration and therefore the impact of this experiment setup difference is not expected to be large. Further research to explore this issue is required.

The third difference is that the receive antennas are moved during the indoor measurements but the outdoor/ indoor measurements have both stationary transmit and receive antennas. In the indoor wireless communication research, the application is the growing cordless phone industry. Measurements are taken with the receive antenna being moved to simulate the motion of the portable phone. The application of this outdoor transmitter and indoor receiver wireless communication, however, is

Fixed Wireless Access. The transmit and receive antennas are kept stationary to simulate the Fixed Wireless Access scenario.

Table 5.8 includes the percent difference between the two fading statistic values. The percent difference is calculated with respect to the indoor communication results using the following equation:

$$\% \text{ difference} = \frac{\text{indoor} - \text{outdoor/indoor}}{\text{indoor}} \times 100 \% \quad (25)$$

5.7.1 Small Scale Fading Results

All the small scale fading statistics for outdoor wireless communication with respect to the indoor wireless communication results vary within 24 %. All the absolute values for the indoor measurements are larger than the outdoor/ indoor measurements. The larger magnitude of the fade statistics can be directly related to the movement of the receive antennas during the indoor measurements. The small-scale fading is a measure of the variations in time. The magnitude of fades due to the normal movement of personnel about the equipment is less than those due to movement of the antennas.

The space diversity gain is identical for indoor and outdoor/ indoor communication. This is not unexpected because both indoor and outdoor/ indoor wireless communications follow the same Rayleigh distribution for both single and joint CDFs. Space diversity is equally effective in mitigating the effects of multipath fading for both indoor and outdoor/ indoor wireless communication.

5.7.2 Large Scale Fading Results Comparison

The indoor shadow margin is 80.2% larger than the outdoor/ indoor shadow margin. This may be attributed to the number of walls and floors that the path traverses. The outdoor/ indoor scenario, with its outdoor antenna, traverses fewer barriers and has only severe fading in the tunnels or the basements of buildings.

The difference in the path loss exponents can be seen as a genuine effect of the environment in which the measurements are taken, indoor versus outdoor/ indoor. The indoor path experiences FSL for only a few meters. The outdoor transmit signal can have FSL for hundreds of meters before being obstructed by the building walls housing the receive antenna.

5.8 Summary of Analysis

In this chapter, the results for envelope cross-correlation are presented. The mean values for the two channel cross correlation is 0.04. Cross correlation coefficients vary significantly with as many positive as negative coefficients. The maximum correlation performs the worst using diversity. Jefford [10] substantiated this finding and formulated a relationship between diversity gain and correlation formulated as detailed in Chapter 3. Chapter 5 also shows the benefits of selection combining to mitigate multipath fading. This is followed by a section on envelope fading results. The CDFs for the individual channel and the selection combined results are plotted. This shows graphically the significant improvement made by space diversity on the average and worst case CDFs. Next, a graphical comparison of the average CDFs shows that the results follow the Rayleigh distribution. The diversity results show a trend not only to reduce fading but to reduce variability as well. The average fade is 13.3 and -8.2, the maximum fade is -19.5 and -11.7 and the spread is 18 and 10 for single channel and two-branch diversity respectively for 99% availability.

This is followed by an examination of the large scale fading statistics. The path loss exponent for the outdoor/ indoor radio channel is 1.96 and the shadow margin is 7.33 dB. Lastly, the small-scale and large-scale fading statistics for a set of indoor measurements is compared with the outdoor/ indoor measurements. The indoor measurements receive antenna movement decreased the magnitude of all the small-scale statistics. The path loss exponent of the indoor scenario is 2.85 for obstructed paths is greater than the outdoor/ indoor scenario's of 1.96. The significantly larger shadow margin of 37 dB for the indoor scenario is attributed to the degree of obstruction inherent in an indoor scenario compared with the outdoor/ indoor shadow margin of 7.33 dB.

CHAPTER 6

APPLICATION OF DIVERSITY RESULTS TO A LINK BUDGET

In this chapter, the diversity results are applied to a link budget for a Fixed Wireless Access system. The link budget is used to establish a radio coverage area for the Fixed Wireless Access application. Small scale fading can complicate the determination of radio coverage areas. The multipath propagation resulting from reflections and scattering from walls and the movement of people in the building, manifests itself as large variations in signal level over short time intervals. Antenna diversity at the receive end of the radio link can reduce the small scale multipath effects. Antenna diversity takes advantage of the fact that two antennas separated at least a half wavelength are not likely to be in signal nulls simultaneously. Chapter 2 describes in more detail the advantages of diversity and Chapter 5 shows the results of measurements using space diversity.

A link budget is used to determine whether Fixed Wireless Access would be a candidate for an outdoor/ indoor wireless application. Fixed Wireless Access is currently configured as an outdoor/ outdoor wireless application. The cost saving in installing the user antenna indoors could not only make this a replacement of copper in last mile scenarios but it also competes with the POTS monopoly for local distance telephone services. Wireless is being positioned for more than traditional mobile applications. Fixed Wireless Access is an emerging market for the 'last mile' to replace expensive POTS using copper or fiber optic cable.

The link budget calculation follows the approach taken by Todd [24]. Using the same approach facilitates the comparison of the link budget results for the outdoor/ indoor Fixed Wireless Access application with the link budget results for the indoor cordless telephone application. The total link gain in dB should exceed the total link

attenuation for the required SNR, the difference being the link implementation margin.

6.1 Fixed Wireless Access

For this Fixed Wireless Access configuration, the base station would be positioned as in a traditional macro-cell, atop a high-rise building in the 2-km cell. The environment is assumed to be urban or suburban in nature. The path is assumed to be blocked primarily by the building walls and floors housing the user station.

The Fixed Wireless Access system specification is from the IS-136 standard. The PCS-2000 air interface operates in the 2 GHz frequency band. The maximum transmit power of a base station is 20 W (43 dBm). The maximum power of a mobile station is 1 W (30 dBm).

Macrocells are typically 2 to 20 km in diameter with the base station antenna radiating 0.6 to 10 W of power from the top of a building [40]. The cell size chosen for this link budget, 2 km, is at the low end of the typical macrocell size. Therefore, a power at the low end of the typical antenna radiating power is chosen (i.e., 1 W). The typical handset used for mobile communications transmit 250 mW or less. For the Fixed Wireless Access application, the user site transmitter will be positioned with the antenna near an outside wall if possible and at as high a point in the building as possible. The signal will be relayed to the user using cordless technology. The system is designed to keep the user at least a meter from the transmitter and its antenna. With this design, the user site transmit power is also chosen to be 1 W.

6.2 Sensitivity

Sensitivity is the ability of the receiver to respond to weak incoming signals. The sensitivity of a receiver may be defined as the input signal required to give a signal-plus-noise output of some ratio (usually 15 dB for $\pi/4$ -DQPSK) above the noise output of the receiver. Sensitivity is measured with respect to the noise generated within the receiver, originating from the RF and mixer stages. A key to achieving high sensitivity in a receiver is a low-noise front end.

The following describes how to calculate Sensitivity of a receiver. Table 6.1 shows the calculation of Noise Figure for the experiment's receiver. The IS-136 standards specify a channel separation of 30 kHz. This value is used to calculate the noise bandwidth of the receiver. PCS-2000 uses $\pi/4$ -Differential Quadrature Phase Shift Keying ($\pi/4$ -DQPSK) modulation that has a Carrier to Noise Ratio threshold approximately equal to 15 dB for a BER of 10^{-2} [12].

$$\text{Sensitivity} = \text{Noise at input} + 15 \text{ dB} \quad (26)$$

where the 15 dB is the SNR threshold and noise at input is calculated by the following equation:

$$\text{Noise at input} = k T B NF \quad (27)$$

where noise level is in mW, k is Boltzmann's constant $= 1.38 \times 10^{-23}$, T is temperature, which in this case is room temperature $= 290$ °K, B is the channel bandwidth, which for $\pi/4$ -DQPSK is 30 kHz and NF is the receiver Noise Figure calculated using equation 30 and shown in Table 6.1. Equation 27 expressed in dBm is shown by:

$$N \text{ (dBm)} = -114 \left(\frac{\text{dBm}}{\text{MHz}} \right) + 10 \log_{10} B_{ch} \text{ (MHz)} + NF \text{ (dB)} \quad (28)$$

where N is the noise level in dBm, -114 dBm/MHz is the $10\log(kT)$, B_{ch} is channel bandwidth in MHz and NF is the receiver Noise Figure.

Table 6.1 Noise Figure Calculation

Receiver Stage	Gain (dB)	Noise Figure (dB)
RF Amp 1	20	1.5
RF Amp 2	20	1.5
RF Amp 3	20	1.5
Mixer	-8	7.5
IF Amp	30	5.5
Receiver Total		1.5

6.3 Noise Figure

The degree to which a "perfect" receiver is approached by a practical receiver having the same bandwidth is called the Noise Figure of the receiver. Noise Figure is the ratio of the total output noise power to the input noise power at the standard temperature of 290 °K. Equations 29 and 30 are used to calculate Noise Figure. Table 6.2 shows the calculation of the Noise Figure for the experiment's receiver.

$$NF = 10 \log_{10} \frac{S/N \text{ at input}}{S/N \text{ at output}} \quad (29)$$

$$NF = 10 \log_{10} \left\{ NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} \right\} \quad (30)$$

where NF_1 is the Noise Figure for the RF Amplifier Stage, NF_2 is the Noise Figure for the Mixer stage, G_1 is the gain for the RF amplifier stage, NF_3 is the Noise Figure for the IF amplifier stage, and G_2 is the gain for the Mixer stage. From equation 30, the importance of a low Noise Figure for the first stage of a receiver becomes apparent. The first stage Noise Figure is the largest contributor to the receiver Noise Figure with the subsequent stage contribution attenuated by the gain of the previous stage.

Table 6.2 Sensitivity Calculation

Parameters	Units	Value
Boltzmann's Constant k	J/deg	1.38×10^{-23}
Room Temperature	°K	290
Effective Antenna Noise	dBm/Hz	-174
S/N (required)	dB	15
Channel Bandwidth	Hz	30000
Channel Bandwidth	dB-Hz	44.8
Receiver Noise Figure + S/N	dB	16.5
Noise Level	dBm	-112.7

6.4 Total Link Gain

Antenna used at the user site would be a directional antenna with a gain of 6 dB. The signal-to-interference ratio benefits of directional antennas are well known [41, 42]. The base station for the Fixed Wireless Access application is an array of directional antennas to optimize pattern shape with a nominal gain of 8 dB. The user wireless radio has a transmit power of between 250 mW and 1 W variable depending on where

in the 2-km radius the user is positioned. At installation, this is tuned for maximum reception and signal quality and minimum interference to other stations. For this link budget calculation the maximum setting is assumed

6.5 Total Link Attenuation

The total link attenuation comprises four components including Free Space Loss, penetration loss, antenna diversity multipath margin, and base station large-scale variation margin.

6.6 Large Scale Path Loss or Penetration Loss

This scenario assumes a base station site with an outdoor antenna and a user site with an indoor antenna separated by a distance D , between 2 and 10 km in an urban and suburban setting. The Lee model [14] is described by:

$$L_{50} = L_0 + \gamma 10 \log D \quad (31)$$

where L_0 is FSL at 1 km and γ is a coefficient representing the environment and the degree of obstruction in the path. A coefficient of 1.96 is used for outdoor/ indoor wireless communication derived from measurements in Chapter 5.

6.6.1 Free Space Loss

When no ground influences, obstructions blocking, refraction, diffraction or absorption exist, there is still a loss between two isotropic antennas in free space. The loss of radio energy occurs in the spreading in the wavefront as it travels through space. If free space attenuation between isotropic antennas in dB is represented by the letters FSL, F is frequency in MHz and D is path distance in kilometers, there are related by [43]:

$$FSL = 32.4 + 20 \log (D_{km}) + 20 \log (F_{MHz}) \quad (32)$$

The worst case Free Space Loss is experienced by the highest frequency of the duplex pair. For example, a distance of 1 km and a frequency of 2200 MHz has an FSL is equal to 99.3 dB.

6.7 Shadow Margin

The shadow margin is a large-scale fading characteristic. A simplified model of large scale fading characterizes the local mean propagation loss proportional to a power of the path distance. Variations about the local average are modelled statistically with a lognormal distribution for shadow fading and a Rayleigh distribution for fast fading [15]. Large-scale fading characteristics are described in more detail in Chapter 2. In Chapter 5, the standard deviation or shadow fading is found from the outdoor/ indoor empirical data to be 7.33 dB.

6.8 Fading Margin

The fade margin is the spread between the minimum and maximum CDFs at a set availability. The fade margin for this link budget assumes the user station will set up antenna diversity with a spacing of one wavelength. Ideal selection combining is used to select the "best" signal present. With reference to Chapter 5, the CDFs at a 99% availability of the outdoor/ indoor two-branch space diversity measurements show a maximum fade of -11.7 dB and a minimum fade of -1.7 dB. The spread or the fade margin is 10 dB.

6.9 Discussion

The total path calculation is shown in Table 6.3 for the longest distance of 2 kilometers. An implementation margin is calculated to be 27.5 dB, which allows for reliable and quality service. Without the micro-diversity improvement of multipath fading, this value could be as much as 10 dB worse than calculated.

6.9.1 Comparison to Indoor Cordless System Link Budget

To understand the significance of the link budget results for the outdoor/ indoor Fixed Wireless Access system in Table 6.3, this section compares the results with those obtained for indoor cordless systems by Todd [24]. The link budget for the indoor cordless telephone system is reprinted below in Table 6.4.

Comparing the two link budgets, a number of the outdoor/ indoor Fixed Wireless Access system link parameters have less loss than the indoor cordless telephone system:

- The indoor cordless DECT standard specification uses a channel bandwidth of 1728 kHz. This translates to a noise bandwidth of 62.4 dB-Hz. The IS-136 standard channel separation is 30 kHz translates to a noise bandwidth of 44.8 dB-Hz. The FWA's smaller channel bandwidth translates to a lower noise bandwidth and contributes 17.6 dB to the implementation margin of the FWA system.
- The indoor wireless receive antenna is a 1/4 wave vertical with a ground plane with a gain of -4 dB. The cordless handset has a vertical antenna mounted above the earpiece so as not to be blocked by the user's head. The omni-directional pattern requires no specific orientation to receive. A vertical antenna has a slim profile and does

Table 6.3 Link Budget for Outdoor/ Indoor Fixed Wireless Access System Using Measured Diversity Results

Link Parameters	Gains	Losses	Units
Thermal noise at 25 Celsius (kT_{amb})		174	dBm/Hz
Noise Bandwidth for 30 kHz channel spacing	44.8		dB-Hz
Noise Figure of Receiver	1.5		dBm
SNR Threshold for BER = 0.01	15		dB
Receiver Sensitivity (Sub Total)		112.7	dBm
Receiver Sensitivity (subtract)	112.7		dBm
Transmit Antenna Gain	8		dBi
Receive Antenna Gain	6		dBi
Peak Transmit Power	30		dBm
Transmit EIRP	38		dBm
Total Link Gain (Sub Total)	156.7		
Large Scale Pathloss ($F=2.37$ GHz, $N=1.96$, $D=2$ km)		111.8	dB
Fading Margin (2-branch diversity for 99% availability of 30 second calls)		10	dB
Shadowing Margin (1-branch macrodiversity at 99 % availability)		7.33	dB
Total Attenuation (Sub Total)		129.2	
Implementation Margin	27.5		

**Table 6.4 Link Budget for Cordless Telephone System
Using Measured Diversity Results**

Link Parameters	Gains	Losses	Units
Thermal noise at 25 Celsius (kT_{amb})		174	dBm/Hz
Noise Bandwidth for 1728 kHz channel spacing (DECT standard)	62		dB-Hz
Noise Figure of Receiver	3		dBm
SNR Threshold for BER = 0.001	11		dB
Receiver Sensitivity (Sub Total)		98	dBm
Receiver Sensitivity (subtract)	98		dBm
Transmit Antenna Gain	8		dBi
Receive Antenna Gain	-4		dBi
Peak Transmit Power	24		dBm
Transmit EIRP	32		dBm
Total Link Gain (Sub Total)	126		
Large Scale Pathloss ($F=1.75$ GHz, $N=2.85$, $D=200$ m)		102.9	dB
Fading Margin (4-branch diversity for 99% availability in 95% of 1 minute calls)		10	dB
Shadowing Margin (4-branch macrodiversity at 99 % availability)		10	dB
Total Attenuation (Sub Total)		122	
Implementation Margin	4		

not detract from the appearance of the handset. The outdoor/ indoor wireless receive directional 3-element Yagi antenna has a gain of 6 dB. The Yagi is mounted on a unit and does not require the aesthetics required of the handset. The fixed nature of FWA allows a directional antenna to be used, which contributes 10 dB to the FWA system implementation margin.

- The indoor cordless telephone system peak transmit power is 24 dBm. The proximity to the transmitter to the user's head limits the peak transmit power of the handset. The outdoor/ indoor Fixed Wireless Access system has a peak transmit power of 30 dBm. The user FWA system is designed and installed so that the transmitter is always at least one meter away from the user. The less restricted peak transmit power contributes 6 dB to the FWA system implementation margin.
- The shadow margin for the cordless system is 10 dB for 4-branch macrodiversity at 99% availability. Even without macrodiversity, the outdoor/ indoor Fixed Wireless Access system has a lower shadow margin of 7.33 dB. The degree of obstruction inherent in an indoor scenario compared with the outdoor/ indoor case is improved using macrodiversity but the FWA system still contributes 2.67 dB to its implementation margin.

A number of link parameters counter the contributions to the FWA implementation margin stated above. This is where the indoor cordless telephone system has less loss than the outdoor/ indoor Fixed Wireless Access system:

- The SNR of the FWA system is based on the BER of the $\pi/4$ -DQPSK modulation scheme used in the IS-136 standard. The BER for $\pi/4$ -DQPSK is 10^{-2} which translates to a Carrier to Noise Ratio threshold of

15 dB. The cordless DECT standard uses GMSK with a BER of 10^{-3} for a SNR threshold of 11 dB. This provides 4 dB to the cordless system implementation margin.

- The large scale propagation loss of 102.9 dB for the indoor cordless telephone system is based on a transmit frequency of 1.75 GHz and a distance of 200 m. The outdoor/ indoor FWA system's loss of 111.8 dB is calculated for a higher frequency of 2.37 GHz and for a longer distance of 2 km. The FWA's lower path loss exponent of 1.96 compared to the cordless's exponent of 2.85 does not counter the distance and frequency contribution to the propagation loss. The resulting difference contributes 8.9 dB to the cordless system implementation margin.
- The fading margin for the cordless system is 9.1 dB. This is based on selecting the statistics for the best 95% of the measurements. The fading margin of 10 dB used for the FWA system is using all the measurements collected that has a cross correlation less than 0.5 to provide uncorrelated diversity channels for effective selection combining. The contribution to the cordless system implementation margin is 0.9 dB.

6.10 Summary

In this chapter, results obtained from the previous chapter are used to calculate the link budget for an outdoor/ indoor FWA system. The implementation margin of 27.5 dB provides a reliable and quality service for an outdoor/ indoor Fixed Wireless Access system. A comparison with a similar link budget calculated for an indoor cordless system is provided.

CHAPTER 7

CONCLUSIONS AND THESIS SUMMARY

This research is motivated by the need for a viable alternative to the local telephone service in the provision of "last mile" service in rural settings, and the introduction of communications technology into developing countries. Fixed Wireless Access has been proposed as a candidate Wireless Local Loop system. To be competitive, the quality of service of a wireless system must be as high as or higher than that provided by the local telephone service while maintaining low installation costs. An FWA system with an outdoor base station antenna and an indoor user antenna installation is examined in this thesis. To mitigate multipath fading, space diversity is incorporated. The performance of the outdoor/ indoor link is measured and analyzed.

A review of Fixed Wireless Access, multipath fading and diversity techniques is presented in Chapter 2. This is followed by a current research review in Chapter 3. Previously taken outdoor/ indoor propagation measurements were motivated by frequency reuse issues. Microdiversity techniques in outdoor/ indoor wireless communications have not been examined to estimate performance. In Chapter 4, the experimental setup for the outdoor/ indoor experiment is described. The results of a number of measurements are analyzed in Chapter 5. The outdoor/ indoor multipath fading statistics are applied to a link budget for a Fixed Wireless Access system and are presented in Chapter 6, along with a comparison with an indoor communications system.

7.1 Choice of Space Diversity Parameters

Diversity performance is based on measurements with a transmit antenna on the Minto Case building roof and an indoor space diversity receiver at various locations in

adjacent buildings. The measurements are taken on clear days with typical movement of people. Analysis includes extracting statistics such as envelope cross correlation, large-scale and small-scale fading and diversity gain for 99 % availability using ideal selection combining.

The mean envelope cross-correlation is 0.04 for a spacing of one wavelength λ between the receive antennas. The receiver is stationary during the measurements to simulate the conditions governing a user site in a Fixed Wireless Access system. The diversity gain for space diversity is 5.1 for 99% availability.

7.2 Variation in Diversity Performance

The average results of the measurements follow theory predicted by the Rayleigh distribution. Variations in the envelope correlations and the input single channel envelope fade statistics result in significant variation in the diversity performance.

The variations in the cross-correlation coefficients shown in a histogram range between -0.14 and 0.37. These variations have a direct effect on diversity gain. The input single channel envelope fading statistics between individual measurements vary considerably. The spread between maximum and minimum fade for the input CDFs is 18 dB for 99% availability. The worst case fade statistics are 4.3 dB worse than average. The selection combined statistics experience a spread of 10 dB. The worst case fade is 3.4 dB worse than the average. Diversity reduces the variation in fade statistics for the measurements.

7.2.1 Comparison Between Indoor and Outdoor/ Indoor Communication Links

Fade statistics from indoor measurements taken in previous research at the same university campus and buildings are compared with those of the outdoor/ indoor measurements taken for this research. Differences between two experiments' setups

lead to discrepancies in the fade statistics. The movement of the receive antennas in the indoor experiment produces larger overall small-scale fading statistics. The large-scale path loss exponent for the outdoor/ indoor environment is 1.96 compared with 2.85 for indoor obstructed communication. The shadow margin of 7.33 dB for outdoor/ indoor communication is significantly smaller than the 37 dB shadow margin reported for indoor communication. This is an indication of the degree of obstruction experienced by the blocked indoor path.

7.3 Application to Fixed Wireless Access

Diversity fade statistics are applied to a link budget for outdoor/ indoor Fixed Wireless Access. Parameters are based on PCS-2000 in a macrocell of 2 km. The large-scale path loss exponent, the shadow margin, and the fade margin derived from the empirical results are used to calculate the total attenuation. The implementation margin calculated is 27.5 dB, which would provide reliable and high-quality service for an outdoor/ indoor Fixed Wireless Access system.

7.4 Recommendations

Further research is warranted in a number of areas related to outdoor/ indoor communication.

7.4.1 Further Measurements

The context of this research limited the measurements to clear days. The effects of various environmental conditions could be investigated to identify the impact of rain, humidity, temperature, and snow on the outdoor/ indoor radio channel propagation characteristics.

It was assumed that the outdoor/ indoor FWA system narrowband characteristics are the most significant. The frequency spreading and other wideband propagation phenomenon could be investigated to establish their impact on channel performance.

It was noted that the global average statistics of the outdoor indoor channel were better than the theoretical Rayleigh CDF. A number of groups of measurements in the 2 GHz band could be taken for various levels of blockage (near windows, in the core of the building) and ambient motion of people varied. The results could be compared with the Rayleigh, Ricean, log-normal and other distribution.

It is noticed that the height of the receiver's location affects the received signal. This could be further investigated by moving the receiver to a number of different levels and quantifying the effect on the received signal.

The experiment's transmit antenna is not on the highest building on campus. To simulate conditions of a typical macrocell, the transmit antenna could be located on the Dunton Tower and the received signal measured at buildings around the campus.

The penetration loss investigated for the outdoor/ indoor radio channel in this thesis is confined to concrete and brick buildings in a university campus setting. Other settings could be investigated including a suburban, rural or industrial and heavy urban settings for the macrocell could be investigated. These settings would include various building constructions including wood, aluminum siding, and vinyl siding. Industrial setting would include equipment clutter.

BIBLIOGRAPHY

- [1] Y. -B. Lin, "The Wireless Local Loop: Hooking Up Homes Without Cable", *IEEE Potentials*, pp. 8-10, August/September 1997.
- [2] V. K. Garg and E.L. Sneed, "Digital Wireless Local Loop System", *IEEE Communications Magazine*, vol. 34, no. 10, pp. 112-115, October 1996.
- [3] Y. Okumura, E. Ohmori, T. Kawano and K. Fukuda, "Field Strength and its Variability in the VHF and UHF Land Mobile Radio Service", *Review Elec. Commun. Lab.*, vol. 16, no. 9-10, pp. 825-873, 1968.
- [4] M. Hata, "An Empirical Formula for Propagation Loss in Land Mobile Radio Service," *IEEE Trans. on Vehicular Tech.*, vol. VT-29, no. 3, pp. 317-325, 1980.
- [5] J. M. Keenan and A. J. Motley, "Radio Coverage in Buildings", *British Telecom. Technol. J.*, vol. 8, no. 1, pp. 19-24, January 1990.
- [6] D. Molkdar, "Review on Radio Propagation Into and Within Buildings", *IEE Proceedings-H*, vol. 138, no. 1, pp. 61-73, February 1991.
- [7] J. D. Gibson, *The Mobile Communications Handbook*, CRC Press/ IEEE Press, 1995.
- [8] W. C. Jakes, "New Techniques for Mobile Radio", *Bell Laboratory Rec.*, pp. 326-330, December 1970.

- [9] W. C. Jakes. "A Comparison of Specific Space Diversity Techniques for Reduction of Fast Fading in UHF Mobile Radio Systems". *IEEE Transactions on Vehicular Technology*, vol. VT-20, no. 4, pp. 81-93, November 1971.
- [10] P. A. Jefford, A. M. D. Turkmani, A. A. Arowojolu and C. J. Kellett. "An Experimental Evaluation of the Performance of the Two Branch Space and Polarization Schemes at 1800 MHz". *IEEE Trans. Veh. Tech.*, VT-44, no. 2, pp. 318-326.
- [11] F. Leite, R. Engelman, S. Kodama, H. Mennenga and S. Towaij, "Regulatory Considerations to IMT-2000". *IEEE Personal Communications*, vol. 4, no. 4, pp. 14-19, August 1997.
- [12] K. Feher, *Wireless Digital Communications: Modulation and Spread Spectrum Applications*, New Jersey: Prentice-Hall, 1995.
- [13] H. Salgado-Galicia, M. Sirbu and J.M. Peha, "A Narrowband Approach to Efficient PCS Spectrum Sharing Through Decentralized DCA Access Policies", *IEEE Personal Communications*, vol. 4, no. 1, pp. 24-34, February 1997.
- [14] J. D. Parsons. *The Mobile Radio Propagation Channel*, London: Pentech Press, 1992.
- [15] B. Sklar, "Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization", *IEEE Communications Magazine*, vol. 35, no.9, pp. 136-146, September 1997.
- [16] T. S. Rappaport, *Wireless Communications: Principles and Practice*, New Jersey: Prentice Hall, 1996.

- [17] D. C. Cox, R. R. Murray and A. W. Norris, "Measurements of 800 MHz Radio Transmission into Buildings with Metallic Walls", *Bell Systems Technical Journal*, vol. 62, no. 9, pp. 2695 - 2717, November 1983.
- [18] T. S. Rappaport, "The Wireless Revolution", *IEEE Communications Magazine*, pp. 52 - 71, November 1991.
- [19] E. J. Violette, R. H. Espeland and K. C. Allen, "Millimeter-Wave Propagation Characteristics and Channel Performance for Urban-Suburban Environments", *National Telecommunications and Information Administration*, NTIA Report 88-239, December 1988.
- [20] A. M. D. Turkmani, J. D. Parsons and D. G. Lewis, "Radio Propagation into Buildings at 441, 900 and 1400 MHz", *Proceedings of the 4th International Conference on Land Mobile Radio*, December 1987.
- [21] A. M. D. Turkmani and A. F. Toledo, "Propagation Into and Within Buildings at 900, 1800 and 2300 MHz", *IEEE Vehicular Technology Conference*, 1992.
- [22] E. H. Walker, "Penetration of Radio Signals into Buildings in Cellular Radio Environments", *Bell Systems Journal*, no. 62 (9), pp. 2719-2735, 1983.
- [23] J. M. Durante, "Building Penetration Loss at 900 MHz", *IEEE Vehicular Technology Conference*, 1973.
- [24] S. R. Todd, "Empirical Evaluation of Diversity Techniques for Indoor Digital Radio at 1.75 GHz", Master's Thesis, Department of Systems and Computer Engineering., Carleton University, December 1992.

- [25] J. Rapeli, "UMTS: Targets, System Concept and Standardization in a Global Framework", *IEEE Personal Communications*, February 1995.
- [26] M. H. Callendar, "Future Public Land Mobile Telecommunication Systems". *IEEE Personal Communications*, Fourth Quarter 1994.
- [27] Anzac/ RHG/ SDI, *RF & Microwave Signal Processing Components*, Massachusetts: Adams-Russell Co., Inc., 1989.
- [28] Mini-Circuits, *RF/ IF Designer's Handbook*, New York, 1992.
- [29] *The ARRL Antenna Book*, American Radio Relay League, 1994.
- [30] *The ARRL UHF/ Microwave Experimenter's Manual*, American Radio Relay League, 1990.
- [31] Loral Microwave-Narda West, *Catalog 300 Defense Electronics / Space/ Wireless*, California, 1994.
- [32] M. I. Skolnik, *Introduction to Radar Systems*, 2nd Edition, New York: MacGraw-Hill, 1980.
- [33] S. M. Sherman, *Monopulse Principles and Techniques*, Massachusetts: Artech House, 1984.
- [34] Miteq LIFD-7010-080
- [35] Data Translation, Inc., *UM-05073-H User Manual for DT2821 Series*, Massachusetts, 1990.

- [36] W. C. Jakes, *Microwave Mobile Communications*. New York: John Wiley & Sons, 1974.
- [37] A. Leon-Garcia, *Probability and Random Processes for Electrical Engineering*, Ontario: Addison-Wesley Publishing Co, 1989.
- [38] E. Kreyszig, *Advanced Engineering Mathematics. Third Edition*. Wiley, 1972.
- [39] S. R. Todd, M.S. El-Tanany and S.A. Mahmoud. "Space and Frequency Diversity Measurements of the 1.7 GHz Indoor Radio Channel Using Four Branch Receiver," *IEEE Trans. Veh. Technol.*, vol. 41, no. 3, pp. 312-320, August 1992.
- [40] R. Prasad., "Overview of Wireless Personal Communications: Microwave Perspectives", *IEEE Communications Magazine*, vol. 35, no. 4 pp. 104-108, April 1997.
- [41] R. D. Carsello et al., "IMT-2000 Standards: Radio Aspects", *IEEE Personal Communications*, vol. 4, no. 4, pp. 30-40, August 1997.
- [42] M. Madfors et al., "High Capacity with Limited Spectrum in Cellular Systems", *IEEE Communications Magazine*, vol. 35, no. 8, pp. 38-45, August 1997.
- [43] Lenkurt Electric Co., Inc., *Engineering Considerations for Microwave Communications Systems*, California, 1970.

ANNEX A RECEIVER CALIBRATION

Figure A.1 Calibration Point A

Figure A.2 Calibration Point B

Figure A.3 Calibration Point C

Figure A.4 Calibration Point D

Figure A.5 Calibration Point E

Figure A.6 Calibration Point F

Figure A.7 Calibration Point G

Figure A.8 Calibration Point G

Figure A.9 Calibration Point H

Figure A.10 Calibration Point I

Figure A.11 Calibration Point J

Figure A.12 Calibration Point K

Figure A.13 Calibration Point L

Figure A.14 Calibration Point M

APPENDIX B MEASUREMENTS' LOCATIONS

APPENDIX C DATA REDUCTION AND ANALYSIS SOFTWARE

```

%
% Filename:
%   fixdata.m
%
% Version:
%   09/22/97
%
% Purpose:
%   Implementation of the algorithm to align channel 1 data in column 1 and
%   channel 2 data in column 2 of the data file.
%
%   This Software Product is provided under the terms of a masters thesis.
%   This Software Product or any copies thereof may not be provided or
%   otherwise made available to any other person or organization.
%   No title to or ownership of this Software Product is hereby
%   transferred.
%   Copyright (c) 1997, Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ',i_pfile])
t=1/ChSamplesPerSec:1/ChSamplesPerSec:CollectForSeconds;
for i=1:length(Ch)
    if rem(i,2)==1
        Data(i,1)=Ch(i,1);
        Data(i+1,1)=Ch(i,2);
    else
        Data(i-1,2)=Ch(i,1);

```



```

        Data(i,2)=Ch(i,2);
    end
end
plot(t,Data);
o_pfile=input('Output file name', 's');
eval(['save ',o_pfile,' CollectForSeconds Data NumOfChannels t ChSamplesPerSec'])

%
% Filename:
%   corrcoef.m
%
% Version:
%   09/22/97
%
% Purpose:
%   Implementation of the algorithm to normalize the power in dB.
%
%   Copyright (c) 1997. Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ',i_pfile])
volt=(Data*(10-(-10))/4096)+(-10);
subplot(2,2,1), plot(t,volt);
e = ones(length(volt),1);
mvolt=mean(volt);
normvolt = volt - e*mvolt;
stdvolt=std(normvolt);
normvolt = normvolt ./ (e*stdvolt);
subplot(2,2,2), plot(t,normvolt);
avgvolt=mean(mvolt);

```

```

avgstd=mean(stdvolt);
samevolt=normvolt * avgstd + avgvolt;
db=41.666667*samevolt + (-83.41667);
mdb=mean(db)
normdb = db - e*mdb;
stddb=std(normdb)
subplot(2,2,3), plot(t,db);
o_pfile=input('Output file name', 's');
eval(['save ' .o_pfile,' CollectForSeconds volt samevolt db mdb stddb NumOfChannels
t ChSamplesPerSec'])

%
% Filename:
%   corrcoef.m
%
% Version:
%   09/22/97
%
% Purpose:
%   Implementation of Correlation Coefficient calculation.
%
%   Copyright (c) 1997, Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ' .i_pfile])
e = ones(length(db),1);
mdb=mean(db)
normdb = db - e*mdb;
stddb=std(normdb)
normdb = normdb ./ (e*stddb);

```

```

corcoef=mean(normdb(:,1).*normdb(:,2))
bin=-1:1/100:1;
%hist(corcoef,bin);
o_pfile=input('Output file name', 's');
eval(['save ',o_pfile,' bin mdb stddb normdb corcoef db'])

%c
%c Filename:
%c   histcc.m
%c
%c Version:
%c   09/22/97
%c
%c Purpose:
%c   Implementation of histogram of the correlation coefficient for space diversity.
%c
%c   Copyright (c) 1997, Deborah Rockwood
%c
eval(['load cc.dar'])
bin=-1:1/20:1;
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','linear','XScale','linear',...
'XLim',[-1 1],'YLim',[0 5],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
[x,y]=hist(cc(:,1),bin);
[v,u]=bar(y,x);
plot(v,u,'k').ylabel('# of Measurements','Color',[0 0 0]),...
xlabel('Correlation Coefficients','Color',[0 0 0]);
o_pfile=input('Output file name', 's');
eval(['save ',o_pfile,' bin mdb stddb normdb corcoef db'])

```

```

%
% Filename:
%   combine.m
%
% Version:
%   09/22/97
%
% Purpose:
%   Implementation of Selective Combining.
%
%   Copyright (c) 1997, Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ',i_pfile])
subplot(3,1,1), plot(t,db(:,1));
subplot(3,1,2), plot(t,db(:,2));
for i=1:CollectForSeconds*ChSamplesPerSec
    if db(i,1)>=db(i,2)
        combined(i,1)=db(i,1);
    else
        combined(i,1)=db(i,2);
    end
end
subplot(3,1,3), plot(t,combined);
o_pfile=input('Output file name', 's');
eval(['save ',o_pfile,' CollectForSeconds db combined NumOfChannels t
ChSamplesPerSec'])

```

```

%
% Filename:
%   plotcm.m
%
% Version:
%   11/02/97
%
% Purpose:
%   Implementation of plotting normalized power in dB and Selective Combining.
%
%   Copyright (c) 1997, Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ',i_pfile])
mdb=mean(db)
e = ones(length(db),1);
normmdb = db - e*mdb;
for i=1:CollectForSeconds*ChSamplesPerSec
    if normmdb(i,1)>=normmdb(i,2)
        combined(i,1)=normmdb(i,1);
    else
        combined(i,1)=normmdb(i,2);
    end
end
set(gcf,'Color',[1 1 1]);
axes('position',[.1 .7 .8 .2]);
set(gca,'Color',[1 1 1],'XLim', [0 30], 'YLim', [-40 10],...
'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
plot(t,normmdb(:,1),'k'), title(['filename= ',i_pfile,...

```

```

' mean= ',num2str(mdb(1))), 'Color',[0 0 0]), ylabel('Ch1'....
'Color',[0 0 0]);
axes('position',[.1 .4 .8 .2])
set(gca, 'Color',[1 1 1], 'XLim', [0 30], 'YLim', [-40 10],...
'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
plot(t,normdb(:,2),'k'), ylabel('Ch2 normalized dB','Color',[0 0 0]);
axes('position',[.1 .1 .8 .2])
set(gca,'Color',[1 1 1], 'XLim', [0 30], 'YLim', [-40 10],...
'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
plot(t,combined,'k'), xlabel('time (s)','Color',[0 0 0]), ...
ylabel('Combined','Color',[0 0 0]);

%
% Filename:
%   lcr2.m
%
% Version:
%   09/22/97
%
% Purpose:
%   Implementation of the Level Crossing Rate and Average Fade Duration
calculation.
%
%   Copyright (c) 1997, Deborah Rockwood
%
i_pfile=input('Input file name', 's');
eval(['load ',i_pfile])
e = ones(length(db),1);

```

```

mdb= mean(db);
normmdb = db - e*mdb;
mcombine= mean(combined);
normcomb = combined - e*mcombine;
slope(:,1) = (diff(normmdb(:,1))) ./ (diff(t));
slope(:,2) = (diff(normmdb(:,2))) ./ (diff(t));
slope(:,3) = (diff(normcomb)) ./ (diff(t));
threshold=input('Input Crossing Level');
lcrcount=[0 0 0];
timefade=[1/ChSamplesPerSec 1/ChSamplesPerSec 1/ChSamplesPerSec];
for i=1:CollectForSeconds*ChSamplesPerSec-1
    if normmdb(i,1)>threshold & normmdb(i+1,1)<=threshold & slope(i,1)<0
        lcrcount(1)=lcrcount(1)+1;
        fadedur(lcrcount(1),1)=t(i+1)-timefade(1);
        timefade(1)=t(i+1);
    end
    if normmdb(i,2)>threshold & normmdb(i+1,2)<=threshold & slope(i,2)<0
        lcrcount(2)=lcrcount(2)+1;
        fadedur(lcrcount(2),2)=t(i+1)-timefade(2);
        timefade(2)=t(i+1);
    end
    if normcomb(i)>threshold & normcomb(i+1)<=threshold & slope(i,3)<0
        lcrcount(3)=lcrcount(3)+1;
        fadedur(lcrcount(3),3)=t(i+1)-timefade(3);
        timefade(3)=t(i+1);
    end
end
lcrcount
if lcrcount(1) == 0
    avgfadedet(1)=CollectForSeconds

```

```

else
    avgfadet(1)=mean(fadedur(1:lrcount(1),1)')
end
if lrcount(2) == 0
    avgfadet(2)=CollectForSeconds
else
    avgfadet(2)=mean(fadedur(1:lrcount(2),2)')
end
if lrcount(3) == 0
    avgfadet(3)=CollectForSeconds
else
    avgfadet(3)=mean(fadedur(1:lrcount(3),3)')
end
abscissa=-70:1:20;
for j=1:length(abscissa)
    occurrence(j,1)=0;
    for i=1:length(normmdb)
        if normmdb(i,1)<abscissa(j)
            occurrence(j,1)=occurrence(j,1)+1;
        end
    end
    occurrence(j,2)=0;
    for i=1:length(normmdb)
        if normmdb(i,2)<abscissa(j)
            occurrence(j,2)=occurrence(j,2)+1;
        end
    end
    occurrence(j,3)=0;
    for i=1:length(normcomb)
        if normcomb(i)<abscissa(j)

```



```

        occurrence(j,3)=occurrence(j,3)+1;
    end
end
probability(j,1)=occurrence(j,1)/(CollectForSeconds*ChSamplesPerSec)*100;
probability(j,2)=occurrence(j,2)/(CollectForSeconds*ChSamplesPerSec)*100;
probability(j,3)=occurrence(j,3)/(CollectForSeconds*ChSamplesPerSec)*100;
end
figure(1)
plot(abscissa,probability(:,1)), ...
ylabel('Probability that amplitude < abscissa (%)'), ...
xlabel('Signal level (dB), with respect to mean value');
hold on
figure(2)
plot(abscissa,probability(:,2)), ...
ylabel('Probability that amplitude < abscissa (%)'), ...
xlabel('Signal level (dB), with respect to mean value');
hold on
figure(3)
plot(abscissa,probability(:,3)), ...
ylabel('Probability that amplitude < abscissa (%)'), ...
xlabel('Signal level (dB), with respect to mean value');
hold on
%subplot(3,1,1), plot(t,db(:,1)), title(['filename= 'i_pfile,' lcr= '....
%num2str(lcrcount(1)),' fadeduration= ',num2str(avgfadet(1))]), ...
%ylabel('dB Ch1');
%subplot(3,1,2), plot(t,db(:,2)), title(['lcr= ',num2str(lcrcount(2))....
%' fade duration= ',num2str(avgfadet(2))]), ylabel('dB Ch2');
%subplot(3,1,3), plot(t,combined), title(['lcr= ',num2str(lcrcount(3))....
%' fade duration= ',num2str(avgfadet(3))]), xlabel('time (s)'), ...
%ylabel('dB Combined');

```

```

o_pfile=input('Output file name', 's');
eval(['save ',o_pfile,' CollectForSeconds normdb db slope normcomb combined
lcrcount avgfadet abscissa probability NumOfChannels t ChSamplesPerSec'])

%
% Filename:
%   grpplot.m
%
% Version:
%   10/26/97
%
% Purpose:
%   Implementation of the plotting the Channel 1, 2 and combined for a group of
%   measurements.
%
%   Copyright (c) 1997. Deborah Rockwood
%
figure
figure
figure
figure
filename = 'lcr';
fname = 'prob';
sumcdf=zeros(91,3);
for i=1:8
    eval(['load ',filename,int2str(i)])
    plotcdf
    sumcdf = sumcdf + probability;
    eval(['save ',fname,int2str(i),' probability -ascii'])
end

```

```

meancdf = sumcdf ./ 8;
save meancdf.dat meancdf -ascii
for i=1:8
    eval(['load ',filename,int2str(i)])
    normcdf = probability - meancdf;
    stdcdf = std(normcdf);
    save stdcdf.dat stdcdf -ascii
end
for j=1:length(abscissa)
    rayleigh(j,1) = (1-exp(-(10^(abscissa(j)/10))/2))*100;
    rayleigh(j,2) = ((rayleigh(j,1)/100)^2)*100;
end
figure(4)
set(gca,'YScale','log','XScale','linear','XLim',[-40 10],'YLim',[0.01 100]);
hold on
semilogy(abscissa,meancdf(:,1),abscissa,meancdf(:,3),...
abscissa,rayleigh(:,1),abscissa,rayleigh(:,2)), ...
ylabel('Probability that amplitude < abscissa (%)'), ...
xlabel('Signal level (dB), with respect to mean value');
hold on

%
% Filename:
%   plotcdf.m
%
% Version:
%   10/25/97
%
% Purpose:
%   Plotting of CDF on Semilog y graph scale.

```

```

%
% Copyright (c) 1997, Deborah Rockwood
%
figure(1)
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','log','XScale','linear',...
'XLim',[-40 10],'YLim',[0.01 100],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(abscissa,probability(:,1),'k'), ...
ylabel('Probability that amplitude < abscissa (%)','Color',[0 0 0]),...
xlabel('Signal level (dB), with respect to mean value','Color',[0 0 0]);
text(-37,.02,'2','Color',[0 0 0])
text(-33,.02,'4','Color',[0 0 0])
text(-28,.02,'5','Color',[0 0 0])
text(-24,.02,'8','Color',[0 0 0])
text(-23,.07,'7','Color',[0 0 0])
text(-20,.02,'3','Color',[0 0 0])
text(-10,.02,'6','Color',[0 0 0])
text(-2,.02,'1','Color',[0 0 0])
hold on
figure(2)
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','log','XScale','linear',...
'XLim',[-40 10],'YLim',[0.01 100],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(abscissa,probability(:,2),'k'), ...
ylabel('Probability that amplitude < abscissa (%)','Color',[0 0 0]),...
xlabel('Signal level (dB), with respect to mean value','Color',[0 0 0]);
text(-35,.2,'8','Color',[0 0 0])
text(-32,.02,'2','Color',[0 0 0])

```

```

text(-26,.02,'4','Color',[0 0 0])
text(-23,.03,'5','Color',[0 0 0])
text(-20,.04,'7','Color',[0 0 0])
text(-18,.02,'3','Color',[0 0 0])
text(-12,.02,'6','Color',[0 0 0])
text(0,.2,'1','Color',[0 0 0])
hold on
figure(3)
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','log','XScale','linear',...
'XLim',[-40 10],'YLim',[0.01 100],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(abscissa,probability(:,3),'k'). ...
ylabel('Probability that amplitude < abscissa (%)','Color',[0 0 0]),...
xlabel('Signal level (dB), with respect to mean value','Color',[0 0 0]);
text(-22,.02,'8','Color',[0 0 0])
text(-19,.02,'5','Color',[0 0 0])
text(-17,.02,'7','Color',[0 0 0])
text(-15,.05,'3','Color',[0 0 0])
text(-15,.02,'2','Color',[0 0 0])
text(-11,.03,'4','Color',[0 0 0])
text(-8,.04,'6','Color',[0 0 0])
text(-1,.1,'1','Color',[0 0 0])
hold on

```

```

%
% Filename:
%   mnplot3.m
%
% Version:
%   11/16/97
%
% Purpose:
%   Implementation of the Average CDF Statistic Calculation for a Group of
%Measurements.
%
%   Copyright (c) 1997, Deborah Rockwood
%
figure
fname = 'lcr';
filename = 'dblk';
summdb=zeros(500,3);
cdfy = logspace(-2,2,500);
for i=1:8
    eval(['load ',fname,int2str(i)])
    for l=1:3
        for k=1:length(cdfy)
            for j=1:length(abscissa)
                if cdfy(k) > probability(j,l)
                    m=j;
                end
            end
        end
        if m==length(abscissa)
            dblk(k,l)=abscissa(m);
        else

```

```

        dblk(k,l)=abscissa(m)+(abscissa(m+1)-abscissa(m))*...
                (cdfy(k)-probability(m,l))/...
                (probability(m+1,l)-probability(m,l));
    end
end
end
eval(['save ',filename,int2str(i),'.mat dblk' ])
end
for i=1:8
    eval(['load ',filename,int2str(i)])
    sumdb = sumdb + dblk;
end
meandb = sumdb ./ 8;
for i=1:8
    eval(['load ',filename,int2str(i)])
    normdb= dblk-meandb;
    stddb = std(normdb);
    save stddb.dat stddb -ascii
end
for j=1:length(abscissa)
    rayleigh(j,1) = (1-exp(-(10^(abscissa(j)/10))))*100;
    rayleigh(j,2) = ((rayleigh(j,1)/100)^2)*100;
end
figure(4)
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','log','XScale','linear',...
'XLim',[-40 10],'YLim',[0.01 100],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(meandb(:,1),cdfy,'k-',meandb(:,3),cdfy,'k-',...
abscissa,rayleigh(:,1),'k-.',abscissa,rayleigh(:,2),'k-.'),...

```

```

ylabel('Probability that amplitude < abscissa (%)','Color',[0 0 0]),...
xlabel('Signal level (dB), with respect to mean value','Color',[0 0 0]):
%eval(['load dblk8.mat']):
%semilogy(dblk(:,2),cdfy,'k.'):
%eval(['load dblk7.mat']):
%semilogy(dblk(:,3),cdfy,'k.'):
text(-40,.05,'Rayleigh1','Color',[0 0 0])
text(-27,.05,'Avg1','Color',[0 0 0])
%text(-40,.5,'Max1','Color',[0 0 0])
text(-10,1,'Rayleigh2','Color',[0 0 0])
text(-11,.05,'Avg2','Color',[0 0 0])
%text(-21,.05,'Max2','Color',[0 0 0])

%
% Filename:
%   ninety9.m
%
% Version:
%   10/28/97
%
% Purpose:
%   Implementation of the Global Statistic Calculation for a Specified Availability.
%
%   Copyright (c) 1997, Deborah Rockwood
%
filename = 'dblk';
cdfy = logspace(-2,2,500);
cdf99=0.10;
for i=1:8
    eval(['load ',filename,int2str(i),'.mat'])

```



```

for l=1:3
    for k=1:length(cdfy)
        if cdf99 > cdfy(k)
            m=k;
        end
    end
    dblk99(i,l)=dblk(m,l)+(dblk(m+1,l)-dblk(m,l))*...
        (cdf99-cdfy(m))/...
        (cdfy(m+1)-cdfy(m));
    end
end
for l=1:3
    avgdb99(l) = mean(dblk99(:,l));
    maxdb99(l) = max(dblk99(:,l));
    mindb99(l) = min(dblk99(:,l))
end;
eval(['save dblk99.dat dblk99 -ascii'])
eval(['save avgdb99.dat avgdb99 -ascii'])
eval(['save maxdb99.dat maxdb99 -ascii'])
eval(['save mindb99.dat mindb99 -ascii'])

%
% Filename:
%   histcdf.m
%
% Version:
%   11/04/97
%
% Purpose:
%   Implementation of histogram of the cumulative distribution function for space

```

```

%    diversity.
%
%    Copyright (c) 1997, Deborah Rockwood
%
eval(['load dblk991.dat'])
bin=-40:1:10;
set(gcf,'Color',[1 1 1]);
axes('position',[.1 .625 .8 .3]);
set(gca,'Color',[1 1 1],'YScale','linear','XScale','linear',...
'XLim',[-40 10],'YLim',[0 5],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
[x1,y1]=hist(dblk991,bin);
[v1,u1]=bar(y1,x1);
plot(v1,u1,'k'),ylabel('# of Measurements','Color',[0 0 0]),...
title('Single Branch','Color',[0 0 0]),...
xlabel('CDFs at 99% avail.','Color',[0 0 0]);
eval(['load dblk992.dat'])
axes('position',[.1 .125 .8 .3]);
set(gca,'Color',[1 1 1],'YScale','linear','XScale','linear',...
'XLim',[-40 10],'YLim',[0 5],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
[x2,y2]=hist(dblk992,bin);
[v2,u2]=bar(y2,x2);
plot(v2,u2,'k'),ylabel('# of Measurements','Color',[0 0 0]),...
title('2-Branch Space Diversity','Color',[0 0 0]),...
xlabel('CDFs at 99% avail.','Color',[0 0 0]);

```

```

%
% Filename:
%   rayleigh.m
%
% Version:
%   11/16/97
%
% Purpose:
%   Implementation of Rayleigh Statistics Calculation for a Specified Availability.
%
%   Copyright (c) 1997, Deborah Rockwood
%
abscissa=-70:1:20;
for j=1:length(abscissa)
    rayleigh(j,1) = (1-exp(-(10^(abscissa(j)/10))))*100;
    rayleigh(j,2) = ((rayleigh(j,1)/100)^2)*100;
    rayleigh(j,3) = ((rayleigh(j,1)/100)^3)*100;
    rayleigh(j,4) = ((rayleigh(j,1)/100)^4)*100;
end
set(gcf,'Color',[1 1 1]);
set(gca,'Color',[1 1 1],'YScale','log','XScale','linear',...
'XLim',[-40 10],'YLim',[0.01 100],'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(abscissa,rayleigh(:,1),'k-'.abscissa,rayleigh(:,2),'k-'.,...
abscissa,rayleigh(:,3),'k-'.abscissa,rayleigh(:,4),'k-'.),...
ylabel('Probability that amplitude < abscissa (%)','Color',[0 0 0]),...
xlabel('Signal level (dB), with respect to mean value','Color',[0 0 0]);
text(-31,.05,'1','Color',[0 0 0])
text(-15,.05,'2','Color',[0 0 0])
text(-10,.05,'3','Color',[0 0 0])

```

```

text(-7.05,'4','Color',[0 0 0])
eval(['save rayleigh.dat rayleigh -ascii'])
filename = 'rayleigh';
cdfy = logspace(-2,2,500);
cdf99=10.0;
eval(['load ',filename,int2str(i),'.dat'])
for l=1:2
    for k=1:length(cdfy)
        for j=1:length(abscissa)
            if cdfy(k) > rayleigh(j,l)
                m=j;
            end
        end
        if m==length(abscissa)
            raylk(k,l)=abscissa(m);
        else
            raylk(k,l)=abscissa(m)+(abscissa(m+1)-abscissa(m))*...
                (cdfy(k)-rayleigh(m,l))/...
                (rayleigh(m+1,l)-rayleigh(m,l));
        end
    end
end
eval(['save raylk.mat raylk'])
for l=1:2
    for k=1:length(cdfy)
        if cdf99 > cdfy(k)
            m=k;
        end
    end
    ray99(l)=raylk(m,l)+(raylk(m+1,l)-raylk(m,l))*...

```

```

        (cdf99-cdfy(m))/...
        (cdfy(m+1)-cdfy(m))
    end
end
eval(['save ray99.dat ray99 -ascii'])

%
% Filename:
%   proploss.m
%
% Version:
%   10/19/97
%
% Purpose:
%   Implementation of plot of the propagation loss for outdoor/indoor.
%
%   Copyright (c) 1997, Deborah Rockwood
%
eval(['load distance.dat']);
eval(['load proploss.dat']);
%regression coefficient
logdist=10*log10(distance);
n=length(distance);
s1_2=(1/(n-1))*(sum(logdist.^2)-(1/n)*(sum(logdist)^2));
sxy=n*sum(logdist.*proploss)-(sum(logdist)*sum(proploss));
b=sxy/(n*(n-1)*s1_2)
a=sum(proploss)/n-(b*sum(logdist))/n
fitprop=b*logdist+a
stddev=proploss-fitprop
set(gcf,'Color',[1 1 1]);

```

```

set(gca,'Color',[1 1 1],'XScale','log','YScale','linear',...
'XColor',[0 0 0], 'YColor',[0 0 0]);
hold on
semilogy(distance,proploss,'kx',distance,fitprop,'k'),...
ylabel('Propagation loss (dB)','Color',[0 0 0]),...
xlabel('distance (m)','Color',[0 0 0]);
text(15,-140,'L =','Color',[0 0 0])
text(20,-140,num2str(b),'Color',[0 0 0])
text(30,-140,'*10 log (d)','Color',[0 0 0])
text(60,-140,num2str(a),'Color',[0 0 0])
eval(['save fitprop.dat fitprop -ascii'])
eval(['save stddev.dat stddev -ascii'])

```

IMAGE EVALUATION TEST TARGET (QA-3)

APPLIED IMAGE, Inc.
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved