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Radio Coverage of Millimetre-Wave Broadband Wireless Access Systems in Suburban Areas

by

Jean-Paul DeCruyenaere, B.Sc. (Eng.), M.Eng.

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

Doctor of Philosophy

Ottawa-Carleton Institute for Electrical and Computer Engineering

Department of Systems and Computer Engineering

Carleton University

Ottawa, Ontario

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and Research acceptance of the thesis

**“Radio Coverage of Millimetre-Wave Broadband Wireless
Access Systems in Suburban Areas”**

submitted by Jean-Paul DeCruyenaere, B.Sc., M.Eng.
in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

Chair, Department of Systems and Computer Engineering

Professor D. D. Falconer, Thesis Supervisor

External Examiner

Carleton University

April 2000

Abstract

The possibility of providing broadband services to residential subscribers has generated a great deal of activity in recent years, with terrestrial broadband wireless access (BWA) systems being an important contender amongst competing “last mile” technologies. Of the possible BWA schemes, the use of millimetre-wave bands has generated interest due in part to the very large bandwidths which are available. The term LMDS (Local Multipoint Distribution Service, and in Canada LMCS) has been used to denote such systems which operate at carrier frequencies in the vicinity of 28 GHz and 40 GHz, and with system bandwidths on the order of 1 GHz or more.

The wide acceptance of millimetre-wave BWA systems is limited in large part by the difficult propagation conditions which occur in residential areas. Shadowing by obstructing buildings and trees, as well as rain attenuation can result in radio coverage values between 40% and 60% when conventional present-day systems are deployed without special measures being taken.

A quantitative study of several coverage enhancing methods (CEMs) has been completed for the purpose of illustrating the effectiveness of various strategies for achieving arbitrarily high coverage values in this context. These strategies have been evaluated for two different cases, namely Line-of-Sight (LOS) operation, where an unobstructed LOS is required between transmitting and receiving antennas, and Non-Line-of-Sight (NLOS) operation, with emphasis being placed on the latter.

To this end, a propagation model has been developed which predicts shadowing. The model is neither purely deterministic nor purely empirical, being based on ray tracing but including a number of empirically determined parameters. Comparisons with field measurements indicate that the model is sufficiently accurate for the comparative evaluation of CEMs.

Predicted coverage values are presented for a typical suburban area that is characterized by flat terrain, one- and two-story residential buildings and the predominance of a mature tree canopy. Coverage is presented as a function of both

maximum tolerable path loss (MTPL), which is based on the system's link budget, and specific rain attenuation, which is related to the service availability.

The predicted coverage values result from a number of simulated scenarios, each one demonstrating the effectiveness of one of the following CEMs; alternatively, the results can be seen as revealing the relative importance of the associated factors in determining coverage:

- increasing MTPL using any combination of methods, such as an increase in receiver sensitivity, or an increase in EIRP (Effective Isotropic Radiated Power) resulting from increases in transmit power or antenna gains,
- selectively increasing subscriber antenna heights,
- globally increasing base station antenna heights,
- reducing base station spacing, i.e. cell radius,
- using a microcell architecture, which involves the mounting of base station antennas on existing man-made structures such as lamp posts and with spacings on the order of a few hundred metres,
- using on-channel, broadband nonregenerative repeaters to fill in coverage in heavily shadowed areas,
- using naturally occurring reflections for link establishment, either singly or in combination,
- using a simple form of macrodiversity which results from the selection of a neighbouring base station during subscriber antenna installation,
- optimization of the subscriber antenna rooftop location.

In particular, the degree to which each CEM must be applied, if possible, to reach a coverage of 90% or more is tabulated. Based on these results, it is recommended that the use of NLOS operation receive serious consideration, in spite of the additional channel impairments which are associated with this mode. Otherwise, no single CEM stands out as being the best in all circumstances, due largely to the undetermined implementation costs associated with each. Nevertheless, the use of combinations of CEMs is evidently a promising approach which could be addressed by extending the approach presented here.

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List of Acronyms

ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
CDMA	Code Division Multiple Access
CEM	Coverage Enhancement Method
CPE	Customer Premise Equipment
CPM	Continuous Phase Modulation
CRC	Communications Research Centre
CRP	Candidate Repeater
CST	Candidate Subscriber Terminal
DL	Downlink (base station to subscriber terminal)
DSL	Digital Subscriber Line
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
FDMA	Frequency Division Multiple Access
FSPL	Free Space Path Loss
GSM	Global System for Mobile communication; also Groupe Special Mobile

HAG	Height Above Ground
HAR	Height Above Rooftop
ISI	Inter-Symbol Interference
LAN	Local Area Network
LMCS	Local Multipoint Communication System
LMDS	Local Multipoint Distribution Service
LOS	Line-Of-Sight
MMW-BWA	Millimetre-Wave Broadband Wireless Access
MTPL	Maximum Tolerable Path Loss
NLOS	Non-Line-Of-Sight
NTIA	National Telecommunications and Information Administration
PCS	Personal Communication Services
QPSK	Quadrature Phase Shift Keying
RCS	Radar Cross Section
RF	Radio Frequency
Rx	Receive
SA	Simulation Area
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
ST	Subscriber Terminal

TCP/IP	Transmission Control Protocol / Internet Protocol
TDMA	Time Division Multiple Access
Tx	Transmit
UL	Uplink (subscriber terminal to base station)
ULOS	Unobstructed Line-Of-Sight
XPB	Cross-Polarization Discrimination

List of Symbols

Primary Symbols

α	tree diffraction scaling factor; arbitrary angle; specific rain attenuation
β	multiple diffraction weighting factor
γ	path loss offset scaling factor; Signal-to-Noise Ratio (SNR)
$\gamma_{min}, \gamma_{thresh}$	SNR threshold
Γ	specific rain attenuation
δ	path loss offset
ε	small quantity
θ	arbitrary angle
λ	wavelength
μ	mean
v	Fresnel-Kirchoff diffraction parameter
π	pi (3.14159...)
ρ	reflection coefficient; correlation
σ	standard deviation
φ	arbitrary angle
Ω_A	antenna beam solid angle
a, b, c	arbitrary constant
A	amplifier gain; antenna aperture width; arbitrary point in space
B	channel bandwidth; antenna aperture height; arbitrary point in space
C	suburb construction date; arbitrary constant; coverage
d	distance

<i>D</i>	diameter; directivity; diffraction loss
<i>E</i>	electric field; excess path loss error
<i>EPL</i>	excess path loss
<i>e_r</i>	radiation efficiency
<i>f</i>	frequency
<i>F</i>	noise figure
<i>G</i>	antenna gain; base station grid spacing
<i>h, H</i>	height
<i>HP</i>	half-power beamwidth
<i>i</i>	arbitrary index
<i>I</i>	SNR improvement; length of <i>interspan</i>
<i>j</i>	$\sqrt{-1}$
<i>k</i>	Boltzman's constant = 1.38×10^{-23} J/K
<i>K</i>	arbitrary constant
<i>L</i>	path loss
<i>L_{MAX}</i>	Maximum Tolerable Path Loss (MTPL)
<i>M</i>	measurement date; cost metric; arbitrary integer
<i>n</i>	arbitrary index
<i>N</i>	arbitrary integer; noise power; database creation date
<i>P</i>	transmitted power; aerial photo date
<i>R</i>	rainfall rate; distance; cell radius
<i>S</i>	symbol rate
<i>t</i>	time
<i>T</i>	symbol period; foliage ground clearance (trunk height)

T_0	standard temperature = 290 K
x, y, z	spatial coordinate
Z	vector in parameter space

Subscripts and Superscripts

0	donor link; incident
I	distribution link
a	additional (excess)
adj	adjusted
BD	building diffraction
$bldg$	building
BS	base station
C	calibration
cov	covered
$d, diff$	diffracted
D, DL	downlink
E	electric field; error; empirical
eff	effective
EP	excess path
$...est$	estimate
FB	feedback
FS	free space
GD	ground diffraction
H	magnetic field

<i>KE</i>	knife-edge
<i>M</i>	measured
<i>MD</i>	multiple diffraction
<i>nom</i>	nominal
<i>o</i>	origin; nominal; output
<i>obstr</i>	obstruction
<i>P</i>	predicted
<i>PD</i>	partial diffraction
<i>R, rep</i>	repeater
<i>r, R</i>	received
<i>ref, refl</i>	reflected
<i>SL</i>	sidelobe
<i>ST</i>	subscriber terminal
<i>t, T</i>	transmitted
<i>T</i>	theoretical
<i>TD</i>	tree diffraction
<i>trans</i>	transmitted
<i>U, UL</i>	uplink
<i>WC</i>	worst-case

Glossary

availability: $100\% \times (1 - p)$, where p is the probability that the RF link will be subject to an outage at any given instant. This is the percentage of time for which the BWA service is “up” as perceived by the subscriber.

base station: a network node radio (air) interface unit, also called a “hub”. A base station provides radio coverage to service subscribers in a cell. Typically, a base station will contain several antennas arranged in a sector pattern, with a radio transceiver dedicated to each sector.

broadband wireless access (BWA) system: in the present context, an outdoor terrestrial radio communication system which provides bi-directional broadband services to fixed subscribers over a covered area. LMDS is an example of a present-day BWA system which operates at MMW frequencies.

clear-sky: referring to a total lack of precipitation.

convex hull: the convex hull of a set of points is the smallest convex set that includes the points; in two dimensions it is a convex polygon.

convex set: a set of points S is a convex set if the line segment joining any pair of points in S is wholly contained in S . [88]

coverage: the ratio the number of (potential) subscriber sites in an area which are “covered” to the total number of (potential) subscriber sites in the area; refer to Section 6.2.2. A site is covered if the availability of the service at the site is above a pre-determined threshold. This definition is in contrast to the area-based definitions of coverage which are typically applied to mobile communication systems.

coverage enhancing method (CEM): any change to a radio system design which leads to an increase in coverage; for example, globally increasing antenna heights. In contrast, there are several factors which influence coverage which may not correspond to CEMs, for example tree height statistics.

excess path loss: $(L - L_{FS})$, where L is the path loss (see below) and L_{FS} is the free space path loss as given by Eqn. (3.3).

fading: Refer to Section 5.1.3 for a discussion of path loss, shadowing and fading. In the present context, fading refers to a time-varying and frequency-dependent attenuation which is in addition to the predicted path loss, and which is attributed to the motion of ground clutter objects only, as opposed to rain. Fading is not modelled explicitly, instead its effect is accounted for through the application of a fading margin during link budget computations.

ground clutter: the set of all potential obstructions, in particular the buildings and trees in an area.

LMDS/LMCS: any BWA system operating at carrier frequencies in the neighbourhood of 30 GHz or 40 GHz.

LOS: the straight line segment which extends between two points in space, in particular between two antennas.

LOS operation: involving or requiring an unobstructed LOS between two antennas for proper operation. A LOS is unobstructed if (roughly) 55% of the first Fresnel zone surrounding the LOS is clear of obstructions [63].

maximum tolerable path loss (MTPL): the path loss value which results in an SNR value which is at the threshold required for proper operation; this threshold is determined by the modulation scheme and required BER, or more generally by the overall signalling scheme and quality requirements. Refer to Section 2.1.1.

NLOS: involving an obstructed LOS between two antennas.

NLOS operation: where link establishment is based on a set of one or more propagation paths which involve interactions with ground clutter, such as reflections or diffractions, and which does not include the LOS path.

obstruction: a solid object which impedes EM propagation at millimetre wavelengths, in particular trees, buildings and other man-made objects, but not including rain or other forms of precipitation.

outage: An RF link is subject to an outage if the subscriber perceives that the service is “down” or of unacceptable quality due to RF channel impairments. This results when frame errors occur at a sufficiently high rate over a sufficiently long period of time. Individual fades may or may not lead to outages depending on a) the fading characteristics (rate, duration, etc), b) details of the frame structure and error control coding, and c) quality of service requirements.

path: a single, non-divisible route through space along which EM propagation occurs, and having an associated path loss.

path loss: Refer to Section 5.1.3 for a discussion of path loss, shadowing and fading.

shadowing: Refer to Section 5.1.3 for a discussion of path loss, shadowing and fading. In the present context, shadowing is due to obstruction by ground clutter, and is fixed in time and frequency by definition, other than for very long term changes such as due to tree growth or seasonal variations.

suburban area, typical: a geographical area which characterized by flat terrain, one- and two-story residential buildings and the predominance of a mature tree canopy. An example of a typical suburban area is given in Section 4.1.1.

subscriber site: In the present context, each and every building is a potential subscriber site, having a single subscriber terminal. In practice, a subscriber may involve a cluster of buildings (as in the case of a large enterprise), or a single building may have several subscribers, each with a subscriber terminal, as in the case of an apartment block.

subscriber terminal: the subscriber radio (air) interface unit, which is a component of the Customer Premise Equipment (CPE). In general, it includes a single antenna and a single radio transceiver.

system, conventional: a typical, present-day, commercially available LMDS (or more generally MMW-BWA) system, which is characterized in Section 1.1.

Chapter 1: Introduction

1.1 Millimetre-Wave Broadband Wireless Access Systems

Regulatory agencies from many nations around the world are currently licensing or allocating significant blocks of spectrum for use by terrestrial wireless broadband access systems [70]. These nations include, but are not limited to the United States, Canada, the United Kingdom, France, Argentina, Australia, Japan and Russia. These blocks are being allocated in the millimetre-wave region of the spectrum, at frequencies that are roughly between 24 GHz and 32 GHz, and between 40 GHz and 42 GHz. This licensing activity provides an opportunity for the deployment of systems capable of providing wireless bi-directional broadband services over extended regions.

The bandwidth of the allocated blocks is unprecedented. Industry Canada [35] has released two 500 MHz wide blocks and plans to release another 2 GHz of bandwidth as the demand increases as illustrated in Figure 1. In addition, Industry Canada is allocating further bandwidth near 23 GHz and 38 GHz for both point-to-point and point-to-multipoint communication systems [36]. In the United States, the Federal Communications Commission [20,21] has allocated two blocks: one of 1150 MHz, and another of 150 MHz, also illustrated in Figure 1. Systems that operate within these bands are named LMDS (Local Multipoint Distribution Service) in the United States and LMCS (Local Multipoint Communication System) in Canada (hereon the term LMDS will be used to denote either one). Similar allocations are being made in other nations.

The current industry trend is towards the development of LMDS systems that are point-to-multipoint with fixed (non-mobile) subscribers. It has been proposed that these systems provide many different services, both broadcast and bi-directional, to both residential and business subscribers. Some of these services are listed below [20,34].

- video program distribution
- two-way interactive video
- teleconferencing
- telemedicine
- telecommuting

- high speed data services
- interactive games
- broadband internet access

These services are not specific to LMDS; in principle all forms of broadband traffic can be delivered by any physical medium that is bidirectional, and that has sufficient bandwidth and suitable bit error and latency characteristics, such as coaxial cable, optical fibre or DSL (Digital Subscriber Line).

In addition to these services, a survey of existing commercial LMDS systems indicates the ability to provide high-rate data links in general to business subscribers, such as leased lines (T1, E1), links for microcell networking (such as GSM or PCS), or Local Area Network (LAN) interconnect.

Together with the very wide bandwidth available, a further advantage of LMDS is its relative ease and speed of deployment when compared with the currently competing broadband access systems [34].

Existing commercial LMDS systems can generally be summarized as having the following features; for example, see [47]. A typical system is illustrated in Figure 2.

- cellular architecture with cell radii on the order of 1-5 km,
- LOS (Line-Of-Sight) operation, which is the requirement for an unobstructed LOS between the subscriber terminal and base station,
- sector antennas at the base station with gains in the range of 12-20 dBi and beamwidths in the range of 15°-90°, mounted on tall masts or buildings (on the order of 15 metres or more above ground),
- small (30-60 cm) dish antennas at the subscriber terminal with gains in the range of 35-40 dBi and beamwidths in the range of 1°-5°, mounted on rooftops,
- linear polarization, either H and V, selectable per sector,
- downlink (base station to subscriber terminal) frequency channels on the order of 30-40 MHz,
- uplink (subscriber terminal to base station) frequency channels on the order of 2 MHz, or the same width as downlink channels,

- transmit power values of 1 W and 0.1 W for the base station and subscriber terminals respectively,
- Quadrature Phase Shift Keying (QPSK) modulation, with larger constellations available,
- Forward error correction consisting of Reed Solomon and convolutional codes such as trellis or turbo codes,
- packetized data, such as ATM (Asynchronous Transfer Mode) or TCP/IP (Transmission Control Protocol / Internet Protocol),
- various multiple access schemes, such as FDMA (Frequency Division Multiple Access) or TDMA (Time Division Multiple Access).

In general, downlink channels are divided into broadcast (common) channels (data transmitted by all base stations to all subscribers) and dedicated channels (data transmitted by a single base station to a single subscriber). In contrast, uplink channels are always dedicated.

Figure 1: LMCS and LMDS frequency allocation

Figure 2: LMDS system

1.2 Radio System Coverage in Suburban Areas

In spite of the advantages associated with an LMDS system, the requirement for LOS operation (or “near” LOS [47, p.365]) proves to be very restrictive in certain situations. In the case of typical suburban environments, the LOS between base station and subscriber sites is often obstructed, usually by tall trees, as illustrated in Figure 3. It is evident from this photograph that, at distances greater than a few hundred metres, most building roofs are not visible. From this observation it can be deduced that most subscribers at these distances would have an obstructed LOS, assuming that subscribers antennas are mounted directly on rooftops. As a consequence, the deployment of a conventional LMDS system in a suburban area, without taking special measures, can lead to poor coverage. Furthermore, poor coverage values have been found in a number of field trials, with values ranging from 100% down to 50% or less, and commonly between 60% and 70%, as described in Section 2.4.

The stated requirement for LOS operation is largely a result of the path losses caused by obstructions at these frequencies. For example, in a recent propagation study of LMDS in suburban sites [59], it was concluded that signal attenuation is the most serious propagation impairment. Nevertheless, other forms of channel impairment that

are associated with obstructed paths may also play a part in the requirement, such as depolarization or delay spread.

In addition to path losses resulting from obstructions, the attenuation due to rain at these frequencies also plays a role in limiting radio coverage, as discussed in Section 2.5.2.1. Rain creates additional path loss on a random, time-varying basis, resulting in service outages with durations on the order of minutes or more; consequently, to determine the effect of rain attenuation on coverage, the required availability of the service must be considered.

For LMDS to become a viable alternative for providing broadband access to the residential market, systems deployed in suburban areas must meet target values for radio coverage and availability in a cost-effective manner. In turn, the selection of these target values requires the consideration of customer expectations as well as the costs involved in reaching these targets.

Figure 3: Typical Ottawa suburb, view from 40 metres

1.3 Coverage Enhancement Methods

In principle, coverage and availability values can be made to approach 100% simultaneously if extreme design changes to the conventional system are allowed, such as by using very tall subscriber antenna masts for example. In practice, such simplistic solutions are not currently cost-effective or are infeasible for other reasons such as safety considerations or public acceptance.

Nevertheless, there are several methods which can be used to increase coverage and/or availability as listed below; hereon referred to as Coverage Enhancement Methods (CEM). In general, CEMs can be used in combination, thereby reducing the degree to which individual associated changes must be applied. The strategy of combining CEMs can result in significant improvements in cost and/or feasibility, due to the typically nonlinear way in which these are related to any one system parameter, such as cell radius, antenna height or transmit power for example. In summary, the problem of cost-effective coverage enhancement can be viewed as requiring the evaluation of CEMs, both alone and in combination.

CEMs can be roughly divided into two categories, both of which are detailed below: those which are compatible with LOS operation, and those which are additionally compatible with NLOS operation.

All CEMs which are compatible with LOS operation (denoted LOS-CEMs) involve an increase in the number (or percentage) of unobstructed direct paths between subscribers and base stations. This set includes but is not necessarily limited to:

- a) increasing base station antenna height, either globally or as needed,
- b) increasing subscriber antenna height, either globally or as needed,
- c) decreasing base station spacing (i.e. cell radius),
- d) ensuring that subscribers can choose from multiple base stations (i.e. providing macrodiversity),
- e) the addition of repeaters or artificial reflectors for the purpose of providing alternate paths which bypass obstructions.

Those CEMs which are only compatible with NLOS operation (NLOS-CEMs) include, but are not necessarily limited to:

- f) the use of naturally occurring reflections, possibly in combination, and
- g) increasing the system's maximum tolerable path loss (MTPL).

The use of NLOS-CEMs implies that additional channel impairments which are associated with NLOS links, such as increased delay spread and fading for example, can be tolerated by the system. It should be noted that the LOS-CEMs are also of use in the case of NLOS operation, since each one decreases the average path loss of obstructed paths in addition to increasing the number of unobstructed paths.

Additionally, coverage can be increased by:

- h) providing alternative links as needed, such as at a greatly reduced carrier frequency, or using a wireline connection.

This method is listed for completeness only and is not considered in the remainder of the thesis; it represents a possible method of providing service to subscribers when all other options fail.

In addition to these, the manner in which both subscriber and base station antennas are positioned and pointed has a bearing on the coverage; this aspect will be examined but not treated as an additional CEM, being considered as a normal measure taken.

All of the methods listed above counteract shadowing due to obstructions. In contrast, shadowing due to rain attenuation can be counteracted only by reducing link length, or by providing alternate paths with reduced rain shadowing, or by increasing the amount of shadowing that can be tolerated by the system. Of the methods listed above, those that can counteract rain attenuation include (c), (d), (f) and (g).

An examination of Eqn. (2.7) indicates design changes that can lead to increases in a link's MTPL:

- i) increasing transmitted power,
- j) increasing transmit antenna gain,
- k) increasing receive antenna gain,

- l) decreasing receiver noise figure,
- m) decreasing the RF bandwidth allocated to the link.
- n) decreasing the receiver's minimum required Signal-to-Noise Ratio (SNR).

It must be stressed that the use of an increase in MTPL to increase coverage directly contradicts the often-stated notion that LOS operation is necessary for LMDS. For example, [34] states the following: "Millimetre-wave radio signals do not penetrate trees. Thus, line-of-sight propagation paths are required". Statements such as these are correct only given certain assumptions on system design limitations. In contrast, to allow for a thorough evaluation of the options available for increasing coverage, the path losses resulting from obstructions will be treated as finite (albeit often large) quantities in the remainder of this thesis.

All coverage enhancing methods listed here, (a) through (n), are discussed further in Section 2.1

1.4 Thesis Objectives and Scope

The main objective of this thesis is to evaluate the coverage enhancing methods listed in Section 1.3 when applied to millimetre-wave broadband wireless access (MMW-BWA) systems in a typical suburban environment. This evaluation will consist of a quantitative comparison of estimated coverage values, both for cases of LOS operation and NLOS operation, with emphasis being placed on NLOS operation. The resulting information is intended to aid in the design and specification of next generation systems when used alongside other sources of information that deal with further requirements on the physical layer, such as mitigation of co-channel interference [24], inter-symbol interference, and fading.

As a prerequisite for such an evaluation, a propagation model is required that can account for the effects of the proposed coverage enhancing methods. No previous suitable model was identified as discussed in Section 2.2, and for this reason the development of such a model proves to be a secondary objective. The accuracy of the model need be no greater than that which is required for the prediction of coverage.

Ideally, the thesis would result in a general coverage model, i.e. an expression of coverage as a function of all system parameters and options mentioned in Section 1.3, such as antenna height or the availability of macrodiversity. This goal proves to be infeasible, due to the complexity involved in an analytical approach, and similarly due to the excessive computing time required to derive such an expression from simulation results. Consequently, the objective will be to illustrate the relative importance of the various coverage enhancing methods by way of the presentation of selected scenarios. This will be done by defining a baseline system, and providing coverage estimates for systems that differ from the baseline by one or more parameters. From this point on, all system designs considered can be thought of as being defined by a parameter vector, this vector being composed of both continuous and Boolean variables. As such, the problem will be to choose “points” that sample the system design “space” in a meaningful manner.

Nevertheless, it is intended that the results be as general as possible. To this end, the results will be applicable to a full range of target values for coverage, availability, and MTPL.

The coverage estimates given throughout this thesis will represent the satisfaction of a condition that is necessary, but not sufficient, for establishment of service to the subscribers in question, namely that the (long term) signal-to-noise ratios on both uplink and downlink are sufficient to maintain an arbitrary target BER (Bit Error Rate) for a percentage of time specified by an accompanying availability criterion. Consequently, the coverage estimates given represent an upper limit on the percentage of subscribers for which service can be provided. Other factors that generally degrade link performance include interference, fading, ISI (Inter-Symbol Interference), and Doppler spread; these impairments will only be briefly discussed.

1.5 Thesis Contributions

The major contributions of this thesis include:

- a review of pertinent literature describing existing propagation and coverage models, both theoretical and empirical, as well as empirical coverage studies, and empirical studies of the propagation effects of trees, buildings and rain,

- the development of a quasi-empirical propagation model for the prediction of shadowing on terrestrial paths in suburban areas that are characterized by flat terrain and a mature tree canopy,
- the quantitative evaluation of a number of methods for (and factors involving) enhancing coverage in MMW-BWA systems, given either LOS or NLOS operation. The evaluation is presented by way of coverage predictions for a range of MTPL and specific rain attenuation values. The methods (factors) include:
 - changing the link budget by way of any of a number of factors, such as increasing antenna gains, reducing receiver noise figure, changing modulation and corresponding SNR threshold, etc.,
 - globally increasing base station antenna heights,
 - selectively increasing subscriber antenna heights,
 - decreasing cell radius,
 - the use of naturally occurring reflections,
 - the use of macrodiversity,
 - the selection of optimal rooftop subscriber antenna sites,
 - the use of broadband, bi-directional, non-regenerative repeaters,
 - the use of a microcellular architecture.
- the enumeration of several ways in which a coverage value of 90% can be reached in a representative scenario, given either LOS or NLOS operation,
- recommendations for further usage and development of the propagation and coverage models presented here.

1.6 Thesis Summary

1.6.1 Objective

The objective of the thesis is to evaluate, by way of quantitative comparisons, a number of methods to counteract shadowing and thereby increase the coverage of MMW-BWA systems in typical suburban environments, including the use of simple repeaters.

1.6.2 Propagation Model

As a prerequisite for such an evaluation, a propagation model is required that can account for the effects of coverage enhancing methods. Such a model has been developed and is presented here.

The model is quasi-empirical, being largely based on ray tracing, but also involving a number of empirical parameters. Furthermore, the model is site-specific, requiring a detailed terrain database of the area in question.

Fading is not modelled explicitly, but only indirectly through the use of assumed fading margins.

1.6.2.1 Input and Output

The propagation model input consists of:

- a detailed 3D terrain database of the area in question, including representations of the ground elevation, buildings and trees,
- the arbitrary 3D coordinates of two antenna positions *A* and *B*,
- the carrier frequency.

The propagation model output is a set of predicted propagation paths between *A* and *B*, consisting of one and only one direct path (having no reflections) and zero or more first-order reflection paths. Each path consists of an arbitrary number of straight line path segments separated by diffraction points or reflection points. In addition, the path segments may include an arbitrary number of partial diffractions as well as intervals that intersect bodies of foliage.

Each predicted path has an associated predicted scalar path loss value that represents shadowing and that applies equally to transmissions in either direction along the path. The predicted path set, as well as the paths themselves are approximations that represent the most significant (i.e. least loss) paths that exist between *A* and *B*.

1.6.2.2 Algorithm

The prediction of first-order reflection paths is based on the method of images [43,53]. Only building walls are treated as potential reflectors; furthermore only a subset of all buildings in the terrain database are tested for reflection, consisting of those buildings that are either taller than the surrounding ground clutter, or sufficiently near to the shorter of the two antenna positions. The possible occurrence of obstructions between either antenna position (A or B) and the reflection point R is initially ignored.

In the general case, both the direct path AB and the reflection paths AR and RB are obstructed by ground objects. In practice, a high number of propagation paths may exist between the two end points, generally involving multiple diffraction by ground objects as well as transmission through foliage. A partially “greedy” algorithm [57] is used to determine the least loss path only between the end points in each case. This algorithm is iterative, involving only currently obstructing ground objects, and making use of heuristics to prune what is effectively a search through all possible propagation paths that extend between the end points.

The final form of a predicted path generally includes diffraction points, reflection points, intervals that intersect bodies of foliage and partial diffractions that result from the close proximity of ground objects to the path. A corresponding scalar path loss value is computed, consisting of a clear-sky path loss component and a rain attenuation component. The clear-sky component consists of the predicted free space loss and a predicted excess path loss. The excess path loss consists of the combined reflection, diffraction and transmission loss to which is applied a linear transformation involving the empirical parameters γ and δ . The components of the excess path loss are computed as follows:

- The reflection loss is set to 0 dB, with this value being based on field measurements.
- The diffraction loss due to single diffractions (including partial diffractions) by buildings or trees is determined by the knife-edge diffraction model; furthermore, the predicted loss due to diffraction by trees is further reduced by a third empirical parameter α . The loss due to multiple diffraction is found using a form of weighted summation, using a fourth empirical parameter β to determine the degree to which each individual diffraction loss affects the net multiple diffraction loss.

- The transmission loss is computed as a nonlinear function of the total depth of penetration through foliage, using an existing empirical model [73].

Rain attenuation is modelled as being spatially uniform and linearly dependent on the total path length; consequently, the computed value is found by multiplying Γ , the specific rain attenuation value of interest, by the total length of all path segments.

1.6.2.3 Evaluation of Empirical Parameters

Values for the four empirical parameters (α , β , γ , δ) have been derived by way of a procedure that optimizes the agreement between a set of predicted and measured excess path loss values.

The measured excess path loss set corresponds to direct path measurements taken at roughly 80 sites within a typical suburban residential area in the Ottawa region, which is characterized by flat terrain, closely spaced one and two-story houses and a mature tree canopy which extends past the average roofline.

Corresponding predicted excess path loss values were found using the propagation model presented here, applied to a terrain database that corresponded to the measurement area.

The optimization procedure involved an ad-hoc cost metric, and was completed by way of several manually executed iterations.

1.6.2.4 Validation

The propagation model was validated through the use of several metrics which quantified the agreement between predictions and measurements. In summary, the comparisons involved:

- the direct path excess loss,
- the existence and power of specular reflections,
- the resulting coverage at all receiver sites.

The error between predicted and measured excess path loss on the direct path was found to have a mean of 3.2 dB (effectively represented by the empirical parameter δ) and a standard deviation of 9 dB.

Only the very strongest reflections were found to be in good agreement. In contrast, poor agreement was found in the case of all weaker reflections, both on a one-by-one basis, and in terms of the numbers of reflections that exist in any given range of power values.

Finally, clear-sky coverage values were computed for the entire set of measurement sites as a function of MTPL, based on both measured and predicted values. Three cases were considered: (A) with coverage being based on the direct path only, (B) with coverage being based on the single strongest received signal, whether via direct or reflected paths, and (C) with coverage being based on the optimal combining of all received signals, both direct and reflected. It was found that the error in predicted coverage increased with the degree to which reflections played a role in determining coverage; the coverage error ranged from roughly 2% in Case (A) to roughly 5% in Case (C).

The completed validation process indicates that the propagation model is sufficiently accurate for the purpose of comparing coverage enhancing methods in the present context, in spite of all known errors and approximations.

1.6.3 Simulations

A number of coverage enhancing methods were evaluated by way of simulations based on the propagation model presented here. In each scenario, coverage was computed for a range of values of two parameters: i) L_{MAX} , the maximum tolerable path loss of the system, and ii) Γ , the specific rain attenuation in dB/km. For the purpose of illustration, two sets of parameter values were selected, one corresponding to the capabilities of a conventional LMDS system and a required availability of 99.99%, and the other corresponding to the addition of a 20 dB fade margin, representing the worst case effect of unmodelled temporal variation in path loss. All coverage enhancing methods were evaluated for the case of NLOS operation, and a subset of these were repeated for the case of LOS operation.

The simulations made use of a 6 km x 6 km terrain database that was created by joining together copies of the terrain database of the measurement area.

Coverage was estimated by random and uniform selection of 500 subscriber buildings within a square simulation area that corresponded to an integral number of quarter cells. A square cell pattern was used throughout. In the most general case, a building was deemed to be covered if a bidirectional link could be established between any of a number of potential subscriber antenna rooftop sites and any one of the four nearest base stations. Link establishment between any given pair of base station and subscriber antenna positions was evaluated by comparing the effective path loss between the two locations against the MTPL of the system. The effective path loss was computed as a function of the predicted path set and the specific rain attenuation in a manner that depended on the way in which reflections were assumed to be used in the scenario, i.e. the effective path loss corresponded to:

- the direct path loss, or
- the minimum path loss of all predicted paths in the set, or
- an effective path loss value that results from the optimal combining of all signals received via all predicted paths.

1.6.3.1 Repeaters

The effect of repeaters was evaluated by the additional prediction of propagation paths (a) between all base stations and a set of candidate repeater positions, and (b) between all candidate repeater positions and all subscriber rooftop antenna sites within range of the repeater. Coverage of subscriber buildings was determined as before, with the additional possibility of link establishment via a repeater. In a manner roughly analogous to that of a direct link, the effective path loss of a repeater link was computed and compared to the MTPL of the system. Using this method, it was possible to evaluate the increase in coverage that results from the optimal placement of N repeaters in the simulation area for a wide range of N values.

1.6.3.2 Baseline Simulation

A baseline scenario was first simulated to act as a reference against which all further simulations could be compared. This baseline corresponded to a conventional system that involves no special coverage enhancing methods other than those of little cost, including:

- the use of simple macrodiversity, involving assignment of the subscriber to one of the four neighbouring base stations at installation time,
- the selection of optimal rooftop subscriber antenna sites, and
- the possibility of link establishment by way of a single specular reflection.

1.6.3.3 Simulation of Coverage Enhancement Methods

Subsequent simulations evaluated the change in coverage, relative to the baseline, which results from the following changes to system design or usage:

- removal of any or all of the three “low cost” methods that were included in the baseline and listed above,
- the maximal ratio combining of all received signals,
- variation in base station antenna height above ground,
- variation in subscriber antenna height above rooftop,
- variation in cell radius,
- the use of a microcellular architecture, in which case a) base station antenna heights are fixed at 10 metres HAG (Height Above Ground), representing possible mounting onto existing light posts or utility poles, and b) cell radii are reduced accordingly,
- the use of N optimally located repeaters per square kilometre, and
- the combined effect of the addition of repeaters and the reduction of cell radius.

Finally, the effectiveness of each of these methods for increasing coverage to 90% was summarized for two sets of conditions: a) nominal conditions, where the MTPL corresponds to that of a conventional system and the specific rain attenuation corresponds to an availability of 99.99%, and b) difficult conditions, in which case the MTPL is

reduced by 20 dB from its nominal value to represent the effect of severe, unmitigated fading.

1.6.3.4 Simulations Involving LOS Operation

A number of simulations were repeated, with all aspects of these simulations remaining unchanged except for the consideration of LOS operation. In this case, all NLOS paths (either reflections or obstructed direct paths) were simply excluded from the simulations. The baseline simulation was repeated in this case, as well as those involving the following subset of coverage enhancement methods:

- variation in base station antenna height above ground,
- variation in subscriber antenna height above rooftop,
- variation in cell radius,
- the use of a microcellular architecture, and
- the use of N optimally located repeaters per square kilometre.

1.6.4 Conclusions and Recommendations

A number of coverage enhancing methods have been evaluated, with a summary given in Section 7.3. No single method stands out as being the best in all circumstances, due largely to the variable implementation costs associated with each. It is recommended that the results be used in conjunction with supplementary cost information to arrive at system design recommendations. Furthermore, it is recommended that the use of CEMs in combination be investigated with further simulations.

Chapter 2: Background

2.1 Costs and Limitations of Coverage Enhancement Methods

Each of the possible design changes listed in Section 1.3 has an associated cost or additional limitations. While several of these are obvious, others require clarification.

2.1.1 Increasing Maximum Tolerable Path Loss

Several methods, listed in Section 1.3, can be used to increase the degree of path loss that can be tolerated by the system. Some of these methods require additional clarification.

An expression for the MTPL can be derived for a unidirectional wireless digital link as follows:

The power at the receive antenna terminals is given by [62, p.317]

$$P_R = \frac{P_T G_T G_R}{L} \quad (2.1)$$

where P_T is the power applied to the transmit antenna terminals, G_T is the transmit antenna gain, G_R is the receive antenna gain, and L is the total path loss between transmit and receive antennas, given by

$$L = L_{FS} L_a \quad (2.2)$$

where L_{FS} is the free space path loss and L_a is an additional (excess) path loss due to obstructions, atmospheric attenuation, etc. The free space path loss is given by

$$L_{FS} = \left(\frac{4\pi d}{\lambda} \right)^2 \quad (2.3)$$

where d is the distance between antennas and λ is the carrier wavelength.

The internally generated receiver noise power, referenced to the receive antenna terminals is given by [30, p.625 and 89, p.570]

$$N = (F - 1)kT_0B \quad (2.4)$$

where F is the noise figure of the receiver, $k = 1.38 \times 10^{-23}$ J/K is Boltzman's constant, $T_0 = 290$ K is a standard temperature, and B is the system bandwidth.

The signal to noise ratio referenced to the receive antenna terminals is then

$$\gamma = \frac{P_R}{N} = \frac{P_T G_T G_R}{L(F - 1)kT_0B} \quad (2.5)$$

In general, the link BER decreases monotonically with the SNR γ , regardless of modulation, coding or the presence of channel impairments in addition to AWGN, such as fading. For this reason, the link BER will not exceed a pre-determined maximum value if the SNR exceeds a corresponding minimum $\gamma_{\min}$. In other words, the link will have an acceptable BER if the SNR satisfies the following:

$$\gamma = \frac{P_T G_T G_R}{L(F - 1)kT_0B} > \gamma_{\min} \quad (2.6)$$

This can be rewritten as:

$$L_{MAX} = \frac{P_T G_T G_R}{\gamma_{\min} (F - 1)kT_0B} > L \quad (2.7)$$

where L_{MAX} is the maximum tolerable path loss (MTPL).

An increase in coverage that results from an increase in MTPL (by any method) must necessarily result from the establishment of NLOS (Non-Line-Of-Sight) links, assuming that the unobstructed path loss* to the cell edge is less than the MTPL. In other words, the increase in coverage is entirely due to subscribers that have some degree of obstruction on all available signal paths. In general, NLOS paths possess impairments in

* the FSPL plus the rain attenuation loss associated with a target availability rate

addition to shadowing as described in Sections 2.5.1.2 and 2.5.4.5, so that the use of associated corrective measures is an additional requirement above and beyond the cost of a simple increase in MTPL. For example, flat fading could be mitigated using spatial diversity and error correction coding, depolarization could be mitigated using polarization diversity, and ISI could be mitigated using equalization.

A similar argument applies when an increase in MTPL is used to counteract rain attenuation, since rain also entails additional channel impairments as discussed in Section 2.5.2.5.

2.1.1.1 Maximum Transmitted Power Levels

An increase in the maximum transmitted power at either base station or subscriber antenna is limited, amongst other things, by safety considerations. For example, the maximum power density at millimetre wave frequencies to which the general public may be exposed is 10 watts per square metre according to Canadian safety standards [31]. For example, a worst-case interpretation of this rule would limit the power transmitted by a 30x30 cm subscriber antenna to 900 mW, assuming that the power is uniformly distributed over the antenna aperture. More stringent power limitations are proposed in [69].

2.1.1.2 Antenna Gains

Another approach for increasing MTPL is to increase the gain of the antennas at either the subscriber terminal or base station or both. Both the gain and beamwidth of reflector and horn antennas are functions of aperture as shown below. Increases in antenna gain are ultimately capped by EIRP limits such as given in [69].

The gain and half-power beamwidth for a typical circular parabolic reflector antenna of diameter D are given below [77]. This is an example of an antenna type that would be suitable for use at the subscriber terminal. The results of varying the antenna diameter are illustrated in Table 1.

$$G = 5.43 \frac{D^2}{\lambda^2} \quad (\text{dBi}) \quad (2.8)$$

$$HP = 58.4 \frac{\lambda}{D} \quad (\text{degrees}) \quad (2.9)$$

diameter	gain	half-power beamwidth
5 cm	20.7 dBi	12.5°
10 cm	26.8 dBi	6.2°
20 cm	32.8 dBi	3.1°
30 cm	36.3 dBi	2.1°
50 cm	40.7 dBi	1.2°

Table 1: Parabolic Reflector Antenna Gain and Beamwidth at 28 GHz

In the case of subscriber antennas, very high gains can be achieved using moderate sizes, although it is evident that arbitrary increases to size will eventually lead to problems with public acceptance. Furthermore, an increase in gain implies a necessary decrease in beamwidth, which can lead to pointing error problems. For example, a 50 cm wide dish will undergo a considerable amount of wind loading, so that it would require solid construction and mounting to maintain a pointing error under $\frac{1}{2}^\circ$ as required in this case.

The gain and half-power beamwidths for a vertically polarized pyramidal horn antenna with an aperture of width A and height B are given below [77]. This is an example of an antenna type that would be suitable for use as a base station sector antenna. Table 2 lists the gain corresponding to a number of different sector arrangements, assuming that the antenna has a vertical beamwidth of 45° .

$$G = 0.51 \frac{4\pi}{\lambda^2} AB \quad (\text{dBi}) \quad (2.10)$$

$$HP_E = 54 \frac{\lambda}{A} \quad (\text{degrees in elevation}) \quad (2.11)$$

$$HP_H = 78 \frac{\lambda}{B} \quad (\text{degrees in azimuth}) \quad (2.12)$$

sector width	gain
180°	5.2 dBi
120°	7.0 dBi
90°	8.2 dBi
60°	10.0 dBi
45°	11.2 dBi
30°	13.0 dBi
15°	16.0 dBi
10°	17.8 dBi
5°	20.8 dBi

Table 2: Sector Antenna Gains at 28 GHz, Assuming Pyramidal Horn and 45° Beamwidth in Elevation

In the case of base station antennas, assuming that sector antennas are used to provide coverage over an entire fixed geographical area, the gain in MTPL achieved by the use of narrow sectors results in a corresponding increase in system cost. This is because a change in gain is inversely proportional to the change in the solid angle contained in the main beam for antennas in general [77] as shown below:

$$D = \frac{4\pi}{\Omega_A} \quad (2.13)$$

where D is the directivity of the antenna, and Ω_A is the beam solid angle, which is an idealized version of the true solid angle contained in the main beam. The directivity is approximately equal to the antenna gain in this case, since

$$G = e_r D \quad (2.14)$$

and the radiation efficiency e_r is approximately equal to 1 for most aperture antennas. As a consequence of the relationship between gain and beam solid angle, an approximate expression that applies to high-gain antennas in general is [77]

$$G = \frac{26,000}{HP_E HP_H} \quad (2.15)$$

where the half-power beamwidths are expressed in degrees.

For example, halving the sector size in azimuth will double the gain of each antenna, but since the number of sectors has been doubled, twice as many power amplifiers are required to drive them. The net effect, which is to double the EIRP, can be achieved instead by doubling the power of the transmitters.

Nevertheless, it is not strictly necessary for the base station to radiate uniformly throughout the coverage region; instead, the pattern could in principle be modified so that more power is transmitted towards individual subscribers, and less power is wasted elsewhere are illustrated in Figure 4. In this case, a true benefit would be achieved by using narrow beams, whether implemented by an electrically-steerable antenna array, or a cluster of individually pointed narrow-beam antennas, or by a number of narrow sector antennas that provide coverage over selected portions only of the full region. This approach would be effective only so long as the subscribers could be spatially isolated given the angular resolution of the beam pattern, and so long as the ratio of the areas requiring coverage to the total area in the cell is significantly less than 1. Neither of these conditions is likely to apply in the case of a mature deployment with significant service penetration.

Figure 4: Increasing MTPL via Selective Coverage

2.1.1.3 Decreasing Bandwidth via Pulse Broadening

An examination of Eqn. (2.7) reveals that the MTPL can be increased by decreasing the channel bandwidth B , with all else being equal. The channel bandwidth B is a function of the symbol rate S :

$$B = \alpha S \quad (2.16)$$

where α is a constant that depends on the symbol waveform (pulse shaping), and $S = 1/T$ where T is the symbol period. To decrease the bandwidth without change to the symbol rate, it is necessary to spread the symbol waveform out in time, thereby introducing controlled ISI (and subsequently changing α), such as occurs when using modulation with memory [62]. This method requires additional complexity at the receiver; for example, the optimal receiver for a CPM (Continuous Phase Modulation) signal (which has memory) is a maximum likelihood sequence detector.

This option has been presented for completeness only. In practice, for a given receiver complexity, the gain achieved by this method is less than the gain that can be achieved by modern error correction coding schemes (for example [62]).

2.1.1.4 Decreasing Bandwidth by Decreasing Statistical Multiplexing Gain

Wideband multi-user systems generally involve the allocation of several users to each frequency channel, with each user occupying the entire bandwidth, for example by using TDMA or CDMA (Code Division Multiple Access) to separate the users within the frequency channel. Such a scheme has two important advantages: i) flexibility in the distribution of the frequency channel capacity (bit rate) between the users, and ii) an overall increase in system capacity due to the statistical multiplexing gain associated with bursty user traffic.

In principle, the system bandwidth can be partitioned into smaller frequency channels, which reduces the thermal noise and thereby increases the MTPL on the channel as shown by Eqn. (2.7). This increase in MTPL comes at the cost of reducing the peak bit rate that is available to any one user, as well as reducing the overall system capacity due to a reduction in statistical multiplexing gain.

2.1.1.5 Adaptive Modulation and Coding

Further examination of Eqn. (2.7) reveals that the MTPL can be increased by decreasing the SNR threshold γ_{thresh} . One approach is to increase the channel bandwidth in conjunction with a proportional increase in transmitted power, as illustrated in Figure 5. This can be viewed as providing a nonuniform distribution of the system resources, with a larger portion of the system resources being allocated to those subscribers that have a greater path loss and vice versa. This increase in bandwidth and power allows the data to be transmitted with a reduced SNR threshold by applying changes to modulation [54] or error control coding. Such a scheme can be time varying in response to changing conditions of load, path loss and interference.

Figure 5: Adaptive Modulation

2.1.1.6 Reduction of Bit Rate

As a final option, the MTPL can be increased by decreasing the code rate and therefore decreasing the bit rate while keeping the bandwidth constant. This method could be used to implement graceful degradation of service on a temporary basis, such as during the occurrence of severe fading.

2.1.2 Repeaters

The installation of broadband, bi-directional on-channel repeaters represents a technique for providing coverage in heavily shadowed areas, or for extending coverage outside of the nominal cell radius.

Bi-directional on-channel repeaters are devices that receive, amplify, and re-transmit RF signals in two directions as illustrated in Figure 6. Re-transmission is done without change to the carrier frequency. Repeaters can be either regenerative or non-regenerative.

Non-regenerative repeaters are essentially analog RF amplifiers that boost both signal and noise; regenerative repeaters demodulate, detect and re-modulate the signal, thereby regenerating a signal that is noise-free but with the possible introduction of bit errors. The performance of regenerative repeaters in a digital communication system is greater than that of non-regenerative repeaters [62, p.314], but at the cost of greater complexity.

Repeaters of either type increase coverage in two ways as illustrated in Figure 7: by providing alternate paths with reduced obstruction and by increasing the MTPL. Furthermore, repeaters can be thought of as providing additional macrodiversity, with the consequential possibility of combining the signals received from multiple repeaters, both direct and reflected, in addition to the direct and reflected signals from multiple base stations as discussed in Sections 2.1.4 and 2.1.5.

Figure 6: Broadband On-Channel Repeater

Figure 7: Coverage Increase Using Repeaters

2.1.2.1 Analysis of Links Including Repeaters

Expressions for the uplink and downlink SNR values which result from the inclusion of an on-channel, bi-directional non-regenerative repeater are derived below. Refer to Figure 8 for an accompanying illustration. All quantities listed in the figure are assumed to have the same value in either direction where appropriate; in particular, all path losses are assumed to be reciprocal.

The SNR at point (ST) on the downlink is found as follows:

The noise power at point (1), internally generated by the repeater, is given by [30.89]

$$N_1 = A(F_R - 1)kT_0B_{DL} \quad (2.17)$$

where A is the bi-directional repeater amplifier gain, F_R is the bi-directional repeater noise figure, k and T_0 are given in Section 2.1.1, and B_{DL} is the bandwidth of the downlink channel.

The signal power at point (1), P_1 , is given by:

$$P_1 = \frac{P_{BS}G_{BS}G_0A}{L_0} \quad (2.18)$$

where P_{BS} is the power transmitted by the base station, G_{BS} is the base station antenna gain, G_0 is the repeater donor antenna gain, and L_0 is the donor link path loss.

The SNR at point (1), γ_1 , is given by:

$$\gamma_1 = \frac{P_1}{N} = \frac{P_{BS}G_{BS}G_0}{L_0(F_R - 1)kT_0B_{DL}} \quad (2.19)$$

where B_{DL} is the downlink channel bandwidth.

The signal power at point (ST), P_{ST} , is given by:

$$P_{ST} = \frac{P_{BS}G_{BS}G_0AG_1G_{ST}}{L_0L_1} \quad (2.20)$$

where P_{ST} is the power transmitted by the subscriber terminal, G_{ST} is the subscriber terminal antenna gain, G_1 is the repeater distribution antenna gain, and L_1 is the distribution link path loss.

The noise power at point (ST) that is due to the repeater, N_a , is:

$$N_a = \frac{P_{ST}}{\gamma_{ST}} = \frac{P_{ST}}{\gamma_1} = \frac{AG_1G_{ST}(F_R - 1)kT_0B_{DL}}{L_1} \quad (2.21)$$

The noise power at point (ST) that is internally generated by the subscriber terminal receiver, N_b , is given by:

$$N_b = (F_{ST} - 1)kT_0B_{DL} \quad (2.22)$$

where F_{ST} is the noise figure of the subscriber terminal.

The total noise power at point (ST), N_{ST} , is then

$$N_{ST} = N_a + N_b = [AG_1G_{ST}(F_R - 1) + L_1(F_{ST} - 1)] \frac{kT_0B_{DL}}{L_1} \quad (2.23)$$

The SNR at point (ST), γ_{ST} , is therefore

$$\gamma_{ST} = \frac{P_{ST}}{N_{ST}} = \frac{P_{BS}G_{BS}G_0AG_1G_{ST}}{L_0kT_0B_{DL}[AG_1G_{ST}(F_R - 1) + L_1(F_{ST} - 1)]} \quad (2.24)$$

Due to the symmetry that exists in this situation, the SNR at point (BS) on the uplink, γ_{BS} , can be found by exchanging the following subscripts in Eqn. (2.24):

$$\begin{aligned} BS &\Leftrightarrow ST \\ DL &\Leftrightarrow UL \\ 0 &\Leftrightarrow 1 \end{aligned} \quad (2.25)$$

The resulting equation becomes

$$\gamma_{BS} = \frac{P_{BS}}{N_{BS}} = \frac{P_{ST}G_{ST}G_1AG_0G_{BS}}{L_1kT_0B_{UL}[AG_0G_{BS}(F_R - 1) + L_0(F_{BS} - 1)]} \quad (2.26)$$

where F_{BS} is the noise figure of the base station and B_{UL} is the uplink channel bandwidth.

Figure 8: Repeater Link Budget

2.1.2.2 Increasing MTPL Using Repeaters

Regenerative repeaters effectively increase the MTPL by splitting the link into two (or more) shorter hops. For example, assuming an AWGN (Additive White Gaussian Noise) channel, placing a regenerative repeater at the midpoint of the path will decrease the free space path loss (and hence increase the SNR) by a factor of 4 (6 dB) for each hop. Assuming a low BER on each hop, the total end-to-end BER is approximately double the BER of a single hop. This doubling of BER is equivalent to an SNR decrease of only a fraction of a dB in general, so that the MTPL is increased by nearly 6 dB.

Non-regenerative repeaters are also capable of increasing the MTPL, but under certain conditions on the repeater amplifier gain and antenna gains that are nevertheless easily met in general as discussed below.

For the use of a repeater to result in an increase in MTPL, it is necessary that the SNRs be increased on both uplink and downlink relative to their values without the use of a repeater. On the downlink, this requirement can be written as

$$\gamma_{STw} > \gamma_{STwo} \quad (2.27)$$

where the subscripts *w* and *wo* denote cases “with” and “without” repeater respectively. Using Equations (2.5) and (2.24) this can be rewritten as

$$\frac{P_{BS} G_{BS} G_0 A G_1 G_{ST}}{L_0 k T_0 B_{DL} [A G_1 G_{ST} (F_R - 1) + L_1 (F_{ST} - 1)]} > \frac{P_{BS} G_{BS} G_{ST}}{L k T_0 B_{DL} (F_{ST} - 1)} \quad (2.28)$$

and assuming that $F_R = F_{ST}$, simplifies to

$$\frac{G_0 A G_1}{L_0 [A G_1 G_{ST} + L_1]} > \frac{1}{L} \quad (2.29)$$

Assuming that the repeater is at the midpoint between base station and subscriber, i.e. $d_0 = d_1 = \frac{1}{2}d$, and assuming a propagation exponent of 2 (corresponding to free space propagation, Eqn. (2.3)), the relationship between the donor and distribution link path losses can be written as $L_0 = L_1 = \frac{1}{4}L$, which leads to further simplification:

$$\frac{4G_0 A G_1}{A G_1 G_{ST} + L/4} > 1 \quad (2.30)$$

The condition noted above will be considered in three cases:

$$A G_1 G_{ST} \gg L/4 \quad (2.31)$$

$$A G_1 G_{ST} \ll L/4 \quad (2.32)$$

$$A G_1 G_{ST} \approx L/4 \quad (2.33)$$

If case (2.31) applies, then condition (2.30) simplifies to the following

$$G_0 > 1/4 G_{ST} \quad (2.34)$$

and the resulting improvement in SNR, I , is given below:

$$I = \frac{\gamma_{STw}}{\gamma_{STwo}} = \frac{4G_0}{G_{ST}} \quad (2.35)$$

This condition is easily met in principle. For example, assuming that the repeater donor antenna is identical to the subscriber antenna, the resulting gain in SNR is 6 dB, which is the same value as in the case of a regenerative repeater.

If case (2.32) applies, then condition (2.30) simplifies to the following

$$G_0 A G_1 > L/16 \quad (2.36)$$

and the resulting improvement in SNR becomes:

$$I = \frac{16G_0 A G_1}{L} \quad (2.37)$$

Furthermore, if conditions (2.32) and (2.36) are both true, then condition (2.34) applies as well.

Finally, if case (2.33) applies, then condition (2.30) can be expressed as either of the following:

$$G_0 > 1/2 G_{ST} \quad (2.38)$$

$$G_0 A G_1 > L/8 \quad (2.39)$$

Furthermore, the SNR improvement can be written in this case as

$$I \approx \frac{8G_0 A G_1}{L} \approx \frac{2G_0}{G_{ST}} \quad (2.40)$$

On the uplink, similar equations can be derived by noting the symmetry evident in Figure 8 and exchanging subscripts as shown in Eqn. (2.25).

In conclusion, assuming that a non-regenerative repeater is placed at the midpoint between base station and subscriber, the gain in overall SNR is at least 3 dB assuming that the repeater donor and distribution antennas are identical to the subscriber and base station antennas respectively, and that the end-to-end gain of the repeater is sufficiently large in comparison to the end-to-end path loss. Higher gains are possible, particularly if the repeater amplifier gain A as well as each of the repeater antenna gains is increased. This argument holds if the true path loss is dominated by the free space path loss component, which is generally true in the cases considered here.

2.1.2.3 Stability Limitations on Repeaters

The stability criterion for a repeater is discussed for example in [75.76]; the corresponding analysis has been reproduced and expanded here.

The overall gain of a repeater is limited by positive feedback as described by the following equation in decibels:

$$G_{loop} = G_{rep} + G_{FB} \leq 0 \quad (2.41)$$

where $G_{rep} = G_1 + G_A + G_2$ is the total gain of the repeater, including antenna gains G_1 and G_2 and amplifier gain G_A , and G_{FB} is the total feedback gain. These gains are related to the transmitted, received and feedback power levels as follows, and as illustrated in Figure 9:

$$P_i = (P_r + P_{FB}) G_{rep} \quad (2.42)$$

$$P_{FB} = P_i G_{FB} \quad (2.43)$$

The loop gain that results from a single reflection in the environment can be described by:

$$G_{loop} = G_1(\alpha_1) + G_A + G_2(\alpha_2) - L_{FS} - L_{ref} \quad (2.44)$$

where the antenna gains are shown to have a dependence on the relative angle of the reflection path, L_{FS} is the free space loss over the length of the entire reflection path, and L_{ref} is the loss associated with the reflection itself. If the relative angle of the reflection path is such that the mainlobe is avoided, the antenna gains are given by:

$$G_i(\alpha_i) = G_i - I_{SLi} \quad (2.45)$$

where I_{SLi} is the power level of the sidelobes relative to the mainlobe. Consequently, the feedback gain in this case is

$$G_{FB} = -L_{FS} - L_{ref} - I_{SL1} - I_{SL2} \quad (2.46)$$

The worst case feedback gain due to N identical reflections can be modelled by a simple addition of power levels, resulting in

$$G_{FB} = 10 \log_{10} N - L_{FS} - L_{ref} - I_{SL1} - I_{SL2} \quad (2.47)$$

The positive feedback that occurs for such a repeater can occur in several ways:

- Internal coupling occurs that does not involve the antennas, such as due to cable leakage. It is assumed that proper shielding can be designed so that this component is negligible.

- External coupling occurs along the direct path between antennas. It is assumed that the antennas are placed and oriented such that this path does not pass through either mainlobe, and furthermore that design techniques can be used to ensure that this component is negligible.
- External coupling occurs by way of reflections in the environment. This coupling can occur in each of the following manners: i) sidelobe to sidelobe, ii) sidelobe to mainlobe, and iii) mainlobe to mainlobe. Each is discussed in turn below.

Sidelobe to sidelobe coupling via external reflections is assumed to be negligible, assuming 30 dB sidelobe isolation per antenna. As a pathological example, assume that 100 perfect reflectors, all oriented so as to provide reflection, exist at a distance of 10 metres. The free space equation gives a path loss of -148 dB per reflection, so that the combined total power from all reflections can be viewed as resulting in an effective gain that is 128 dB below that of the repeater itself. The value of 100 is at least an order of magnitude larger than the typical number of reflections that has been observed in the field as described in Section 4.1.

Similarly, sidelobe to mainlobe coupling is assumed to be minor, with the above quantities being increased by 30 dB, for an effective isolation of 98 dB in a pathological case. In reality, the isolation is expected to be greater due to reflection losses, increased reflection path distances, foliage attenuation, and a reduced number of reflections.

Finally, assuming that the main lobes of both antennas do not overlap, a multiple reflection is required as illustrated in Figure 10 to result in mainlobe to mainlobe coupling. Assuming perfect reflection and a total path distance of only 50 metres in the worst case, the resulting feedback gain is 96 dB for a single reflection. It is assumed that few such paths occur in general, and that adjustments to antenna position and/or orientation can be made to avoid these.

Figure 9: Repeater Positive Feedback

Figure 10: Repeater Feedback via Reflections

2.1.3 Antenna Positioning

Antenna mast heights for both base stations and subscribers may be limited by zoning requirements, customer acceptance or community acceptance.

The precise placement of base stations, as well as the distance between base stations may be limited by the availability of potential sites.

2.1.4 Macrodiversity

All forms of macrodiversity require some degree of cell overlap, i.e. the MTPL must be, at the very least, greater than the FSPL (Free Space Path Loss) for a distance that is greater than the nominal cell radius. This requirement may not represent an actual cost if the MTPL is made to exceed this value for other reasons, such as to provide margin against path losses due to obstructions and/or rain. Given a sufficient MTPL, cell overlap is automatic except for cells that are located on the boundary of a coverage area. The degree of macrodiversity available to these boundary cells depends on the local cellular geometry as illustrated in Figure 11. Full macrodiversity to all cells can be provided by placing additional base stations along the perimeter of the coverage area, with partial sector coverage as required.

The full cost of providing macrodiversity depends in part on the manner in which macrodiversity is implemented. Two forms of macrodiversity, termed *simple* and *full*, are described below.

Simple macrodiversity involves *long-term* link establishment between a single subscriber terminal and a single base station as illustrated in Figure 12. Diversity arises from the choice of a base station for link establishment to each subscriber terminal. The choice of base station could be made upon subscriber antenna installation, and at any time as required by changes to the network plan, such as due to the installation of new base stations. This form of macrodiversity is essentially cost-free given cell overlap, and can be used with fixed directional subscriber antennas. Simple macrodiversity will counteract shadowing due to obstructions, but it will not counteract shadowing due to rain, since alternate (intercellular) links are always longer than the (intracellular) link to the nearest base station, and therefore will experience more rain attenuation on average. Assuming that the path loss on both uplink and downlink are similar, simple macrodiversity improves both uplink and downlink performance equally.

Full macrodiversity involves link establishment between a single subscriber terminal *A* and a set of base stations *B* as illustrated in Figure 13. Full macrodiversity can

be implemented on the uplink, downlink or both; for example, in certain cases it may be possible to reduce the cost of the subscriber terminals while increasing the cost of the remainder of the network by implementing full macrodiversity on the uplink only.

In addition to the benefit associated with simple macrodiversity, namely the counteracting of shadowing by obstructions, full macrodiversity will counteract temporal fading, whether due to motion of objects in the environment or due temporal variations in rain rate, assuming that there is some degree of independence in the fading on the paths to different base stations in B .

Full macrodiversity on the downlink involves the combining of signals transmitted from each base station in B at the subscriber terminal A . This requires the use of signal splitting/redirection facilities within the backbone network, as well as signal processing equipment to perform the combining at A . In addition, the antenna at A must be capable of receiving signals from all base stations in B , for example being either an omnidirectional antenna or a multiple antenna array. An antenna array, if chosen, could be as simple as multiple fixed directional antennas, each pointed at a different base station in B . On the other hand, the use of an omnidirectional antenna implies a degradation in performance due to the loss in antenna gain and spatial selectivity. In addition to the equipment costs, this scheme may result in a reduction in system capacity due to an increase in the amount of spectrum (i.e. the number of cell-channels) dedicated to the link at any instant in time. The degree of system capacity reduction depends on the nature of the transmitted information as well as the method of diversity combining. In the case of broadcast data, no additional spectrum is required, and this method is effectively a form of multicasting. In the case of private data, little additional spectrum is required assuming selection combining, and assuming that transmissions can be rapidly switched between base stations in accordance with the selection at A . In contrast, an increase in spectrum which is proportional to the order of diversity is required if (for example) maximal ratio combining is used to combine private data at A . In this case, all base stations in B must allocate a channel for simultaneous transmission of the private data which otherwise would be free for other uses by all but one of the base stations.

Full macrodiversity on the uplink involves the combining of signals that are received by each base station in B from the subscriber terminal A . The overall architecture of the system is symmetrical to the downlink case as illustrated in Figure 13;

in particular, either an omnidirectional antenna or an antenna array is required at A as well. Similarly, more spectrum (cell-channels) may be required depending on the form of diversity combining: little additional spectrum is required assuming selection combining, but a proportional increase in spectrum is required if (for example) maximal ratio combining is used. The requirement for additional spectrum occurs in this case for reasons which are directly analogous to the downlink case, namely each base station in B must allocate a channel for simultaneous reception of the private data which otherwise would be free for other uses by all but one of the base stations.

In summary, little additional cost is associated with the implementation of simple macrodiversity, assuming that a sufficient degree of cell overlap exists, and that fixed directional subscriber antennas are used. Full macrodiversity results in increased performance at additional cost, and with effects on system capacity.

Figure 11: Macrodiversity and cell overlap

Figure 12: Simple macrodiversity

Figure 13: Full macrodiversity

2.1.5 Naturally Occurring Reflections

The use of a single stable, naturally occurring reflection, such as might occur from a multistory office tower, for bi-directional link establishment is essentially cost-free. In contrast, the use of multiple reflections by way of diversity combining implies a

cost associated with multiple antennas. Assuming that reflections occur in a relatively narrow angular spread at the BS (Base Station) end, and assuming that the BS sectors are relatively wide, diversity combining using multiple antennas at the ST (Subscriber Terminal) only can be used on both UL (Uplink) and DL (Downlink) as illustrated in Figure 14(a). For example, gain and phase adjustments can be applied to the signals transmitted by the ST, resulting in constructive interference of all reflections at the receiving BS sector antenna, thereby implementing a type of “reverse” maximal ratio (or optimal) combining. Similarly, the ST could transmit along the single strongest reflection path, thereby implementing “reverse” selection combining. If base station sector antennas are narrow, or if reflections generally arrive at the BS over a wide angular spread, then it would be necessary to implement diversity combining at both ends to fully benefit from all available reflection paths as illustrated in Figure 14(b). In addition to a potential improvement in coverage, diversity combining of multiple reflections can be used to counteract fading, interference and multipath.

The use of reflections to provide coverage assumes that the reflected signals do not undergo impairments in addition to, or to a much greater degree than, those associated with the direct-path signals, or that these additional impairments can be mitigated by some means. For example, reflections from building walls with a periodic structure will generally have a degree of ripple in the frequency response [37, 49]. Furthermore, the use of reflections to provide coverage assumes that the reflections are stable, which is to say that the reflected signal will not undergo significant, long-term changes in power or angle-of-arrival for an indefinite amount of time. Reflections from buildings are evidently stable in general, while care must be taken to avoid selection of reflections from stationary vehicles or the like.

The amount of delay spread associated with a single reflection from a typical building is generally small, although not necessarily negligible, assuming that the spread is due to changes in the arrival time of reflected energy from different portions of the building. For example, assuming that a reflection is composed of two components with a 20 metre total difference in path length as illustrated in Figure 15, the corresponding delay spread is 67 nsec, which corresponds to a coherence bandwidth on the order of 15 MHz. In contrast, the delay spread associated with the combination of multiple reflections can be on the order of microseconds or more.

The number and strength of naturally occurring reflections depends in part on local terrain features, such as the number, size, distribution and composition of buildings. For this reason it can be assumed that the degree of coverage enhancement that can result from the use of reflections will vary from one location to the next. Further field trials would be required to characterize the availability of reflections in suburban areas in general.

Figure 14: Diversity combining of reflections (a) at subscriber end only, (b) both at subscriber and base station ends

Figure 15: Delay spread for single building reflection

2.1.6 Artificial Reflectors

The installation of artificial reflectors represents an alternative technique for providing coverage in heavily shadowed areas as illustrated in Figure 16. These can be used to increase coverage by providing alternate paths with reduced obstruction in the same manner as repeaters as discussed in Section 2.1.2. In contrast, reflectors are not suitable for increasing MTPL as is discussed below.

A simple reflector might consist of a flat metal plate with dimensions on the order of tens of centimetres or larger, mounted on an available high point such as a light post or building corner that has an unobstructed (or nearly unobstructed) LOS to a nearby base station. At millimetre wavelengths, the reflection coefficient of metal is near unity, and any surface that is large in both dimensions relative to the wavelength, as well as flat according to the Raleigh criterion for surface roughness will behave as a perfect reflector. In this case, the reflected beam can be modelled using geometrical optics.

Based on geometrical optics, it is evident that the reflected beam emanating from a flat artificial reflector of reasonable size will typically have a very narrow beamwidth, making it suitable for the coverage of a single subscriber at most, and with an inherent problem of extreme pointing sensitivity. For example, ray tracing predicts that a flat reflector that is 1 metre across and that is 1000 metres from a transmitter will have a reflected beamwidth on the order of 0.05° . The actual beamwidth will be wider due to the finite dimensions of the reflector, but will nevertheless be very small; for example, the null-to-null width of the main lobe predicted by the Radar Cross Section (RCS) model of a flat plate [44] is roughly 0.6° in this case. Regardless of the model used, it is evident that the reflector should be designed to provide a beam width of at least a few degrees so the pointing error inherent with installation or wind-induced motion will not cause a severe loss of power. Beam spreading, such as would result by using a curved reflector, can be used to reduce pointing error sensitivity, and in principle to provide coverage to multiple subscribers. In either case, the total reflected power is equal at most to the incident power, so that an additional loss results. This loss can be roughly estimated by comparing the ratios of the solid angles corresponding to the beams before and after spreading, since the relationship between power density and beamwidth is the same as that for an antenna, given in Eqn. (2.13). For example, a spread from 0.6° to 2° in both elevation and azimuth, which may be sufficient to solve the pointing sensitivity problem,

implies a power loss of approximately 10 dB, which may be acceptable assuming that the reflector has been placed so as to minimize obstruction on both legs. Similarly, a spread from 0.6° to a $5^\circ \times 20^\circ$ rectangular beam, as could be used to provide coverage to multiple subscribers within a limited area, implies a power loss of 25 dB, which places the usefulness of such an approach in question.

In contrast, the use of reflectors to increase MTPL implies a degree of beam concentration, which in turn implies a narrowing of beamwidth; this is in opposition to the need for beam spreading to avoid pointing problems stated above, and for this reason this mode of operation is not recommended.

Regardless of design, a reflector with dimensions on the order of a few metres at most, placed at least several hundred metres from a base station will require some degree of beam spreading, which in turn implies a power loss that limits the reflector's usefulness.

In conclusion, the brief analysis presented here indicates that properly designed and installed reflectors may be useful for providing coverage to single subscribers, or at most a small number of co-located subscribers.

Figure 16: Coverage Increase Using Artificial Reflectors

2.1.7 Summary

The design of a MMW-BWA system involves several methods to counteract shadowing that can be used either alone or in combination to increase radio coverage. These methods can be roughly divided into two categories: those that provide, or make use of, alternate paths with reduced shadowing, and those that increase the amount of shadowing that can be tolerated on a given path.

Each of these methods involves a cost, the determination of which depends on many factors that are beyond the scope of this thesis, such as the cost and performance of low-noise amplifiers for example. Furthermore, several of the methods have an effect on other aspects of system performance, in particular interference and system capacity, which ultimately bear on the cost and feasibility of any particular system design.

2.2 Existing Coverage Models

Three existing coverage models for MMW-BWA systems have been identified and are summarized below; the first being deterministic and the other two being statistical in nature.

2.2.1 Rutherford Appleton Laboratory – Deterministic Coverage Model (RAL-D)

A method for estimating coverage as a function of transmitter and receiver heights and cell radius is described in [4]. This method is based on ray tracing and the use of a detailed site-specific 3D terrain database that includes individual buildings and trees; in this manner it is very similar to the model developed here (Chapter 3, Chapter 5 and Chapter 6).

The application of the RAL-D model is discussed in the context of a Millimeterwave Video Distribution Service (MVDS) operating at 40 GHz in an area that is described as “urban”, but that corresponds roughly to the suburban area described in Section 4.1.1, due to the predominance of houses that are roughly 8 metres tall and the flat terrain.

The RAL-D model assumes that diffraction losses at these frequencies are so large that shadowing by buildings always results in a loss of coverage. Furthermore, the effect of trees, precipitation and reflections are entirely neglected. In summary, the coverage at a receiver antenna site simply depends on the occurrence of buildings that obstruct the LOS to the transmitter. The coverage status of each building in the cell is determined by evaluating coverage at several antenna sites on a 2 metre grid on each rooftop.

The RAL-D model is essentially a simpler form of the model developed here; furthermore it resembles an earlier, undocumented version of the model where building obstruction was similarly assumed to result in a loss of coverage.

It is clear that the RAL-D model is not sufficient for meeting the thesis objectives in its present form. The model developed here can be thought of as an extension of the RAL-D model in the following ways:

- The inclusion of a predicted finite building diffraction loss, which was motivated by the argument given in Appendix 1, as well as by the field measurements described in Section 4.1. In an undocumented procedure, it was observed that the measured power at sites that were obstructed by buildings only agreed well with the knife-edge diffraction loss model.
- The inclusion of tree losses, both diffraction and attenuation. This was motivated by the existence of a dense tree canopy in the area under study that typically extended above rooftops (Chapter 4), the strong attenuation that has been reported in several studies of trees (Section 2.5.4), and the conclusion that such a dense tree canopy is the dominant factor in determining coverage in suburban areas [59]. Furthermore, the inclusion of a predicted diffraction loss for trees was motivated by the results of an undocumented procedure whereby the measured power at sites that were obstructed by a single tree was examined in isolation.
- The inclusion of a precipitation loss model. This has been motivated by the need to consider arbitrary service availability values, coupled with the very high specific rain attenuation values that can occur at millimeter-wave frequencies as described in Section 2.5.2. Furthermore, in the results described in Chapter 7, it has been found that rain attenuation is the dominant factor in determining coverage in several scenarios of interest.

- The inclusion of predicted reflections from building walls, which was motivated by the strength and number of reflections that were observed in the field (Section 4.6), and the desire to evaluate the importance of these reflections as a possible means of link establishment.

2.2.2 Rutherford Appleton Laboratory – Statistical Coverage Model (RAL-S)

In contrast to the RAL-D model described in Section 2.2.1, the RAL-S model [37] [4] does not make use of a detailed terrain database directly; instead coverage is computed as a function of three parameters that describe the building height distribution, the ratio of land covered by buildings, and the mean number of buildings per unit area. Otherwise, the RAL-S model is similar to the RAL-D model, in that it predicts coverage as a function of transmitter and receiver heights and cell radius, and it assumes that obstruction by buildings results in a loss of coverage. It is recommended that RAL-S be combined with separate models for attenuation due to vegetation [38] and rain [39]

The RAL-S model has a number of limitations, the first three being mentioned in [37]:

- It assumes a flat earth, although clearly variations of even a few metres could have a significant effect.
- Building heights and densities vary greatly from one location to another, while the model assumes uniform building statistics throughout the cell.
- It assumes that the receivers are all at the same height, while in reality the receiver heights follow the same distribution as the building heights.
- Blockage by buildings does not generally result in a complete loss of signal. The diffracted power over the roof of a building can generally provide coverage over a significant portion of the shadowed region as shown in Appendix 1, so that a coverage prediction based on simple building blockage will be underestimated.

More importantly, tree attenuation is not treated in sufficient detail. It has been concluded in [59] that the most significant impairment is attenuation caused by the tree canopy which extends above roof height; furthermore, differences in tree canopy were concluded to cause significant differences in coverage. In contrast, the recommended

tree attenuation model [38] is simply a constant specific attenuation in decibels per metre of foliage through which the path travels. Nevertheless, it may be possible to augment this coverage model by treating trees in a manner similar to buildings, involving parameters describing the distribution of tree heights, the ratio of land covered, etc.

In any case, the statistical approach described here, if substantially extended, could in principle be used to satisfy the thesis objectives, namely to predict the effect of each of the coverage enhancing methods listed in Section 1.3. For example, reflections, variations in ground elevation, and spatial correlations could all be accounted for using appropriate statistical modelling techniques. Nevertheless, an initial investigation revealed that the complexity of this approach was not warranted, in light of the fact that a deterministic modelling approach, including a realistic terrain database, would implicitly and correctly represent spatial correlations, in addition to capturing the effect of building height distributions, terrain elevation and the like.

2.2.3 Carleton University

Another statistical model of coverage in MMW-BWA systems is found in [24]. This model predicts coverage separately for two classes of subscribers: LOS and NLOS. Coverage for each individual subscriber is determined by considering the SINR (Signal-to-Interference-plus-Noise Ratio) for both uplink and downlink simultaneously. Interference is assumed to occur on NLOS paths for both LOS and NLOS subscribers.

The loss on a LOS path is simply given by the free space equation (2.3). The loss on a NLOS path is modelled as a random variable with a lognormal distribution as shown below:

$$f(s) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(s-\mu)^2}{2\sigma^2}\right) \quad (2.48)$$

where s is a random variable describing the path loss in dB, σ is the standard deviation of the path loss about the mean, and μ is the mean path loss:

$$\mu = k + m \log_{10}(d) \quad (2.49)$$

where d is the distance in metres, m is the path loss exponent, and k is a constant. The constants σ and m are allowed to vary over a range of typical values:

$$\begin{aligned} 0 \leq \sigma \leq 10 \\ 2 \leq m \leq 4 \end{aligned} \tag{2.50}$$

The use of a lognormal distribution to model shadowing in MMW-BWA systems is supported by experimental findings. In [64], it was found that the distribution of received power was roughly lognormal in a trial conducted at 11 GHz in a suburban area that included tree-covered hills.

For this approach to be used to satisfy the thesis objectives, it would be necessary to expand the statistical path loss model described above into a form that has explicit dependence on Tx antenna height and Rx antenna height. This would be required for two reasons: firstly, the results of coverage surveys described in Section 2.4 reveal such a dependence, and secondly, it would be necessary to allow the evaluation of changes to antenna heights. Furthermore, the standard deviation of shadowing σ may itself be a function of distance d , thereby requiring further expansion of the model, although there is currently no evidence to either support or refute this. Finally, it would be necessary to include an expression for the ratio of LOS to NLOS subscribers as a function of distance and antenna heights.

To allow for a comparison between the different coverage enhancing methods, it would be desirable that the resulting model parameters be fixed to values that correspond to a typical suburban environment, otherwise it would be difficult to present a clear evaluation of the different methods. The estimation of these parameters would require a very large number of experimental measurements due to the high dimensionality of the model. Regardless of whether the model parameters are estimated, it would be necessary to validate such an augmented statistical model with appropriate measurements, although once again this validation would probably be partial in nature due to the large number of measurements required to test all combinations of antenna heights and distances.

As in the case of the RAL-S model, this model would require further extension to account for naturally occurring reflections.

2.2.4 Summary

The deterministic model discussed above (RAL-D) is essentially a simplified version of the model developed here. This simplified approach has been found to be insufficient for meeting the thesis objectives as discussed in Section 2.2.1.

Neither of the two statistical models discussed above is suitable for meeting the thesis objectives due in part to a lack of information pertaining to spatial correlations. For any wireless system, the received power and hence the resulting coverage at two points in space are generally correlated due in part to the continuous nature of RF fields, and due in part to the continuous nature of obstacles such as trees and buildings. This type of information is required to evaluate certain system design issues, such as the coverage increase that results when the ST antenna is placed at the optimal rooftop location as opposed to being placed in an arbitrary manner. More importantly, this type of information is required to characterize the size and spacing of coverage “holes”, which bears on the effectiveness of repeaters, the evaluation of which is an important goal of this thesis.

The extension of either statistical model to include information pertaining to spatial correlations would involve either a high degree of complexity and/or a large number of field measurements.

2.3 Existing RF Propagation Models for Path Loss Prediction

A very wide range of models have been developed for the prediction of path loss in outdoor environments in the last few decades. A number of them are examined here to determine their usefulness in satisfying the thesis objectives, either as-is, with modification, or as the basis for the development of a related model that is more suitable to the problem at hand.

Existing models are roughly classified here as being either site-general or site-specific according to the amount of information that they require regarding the site. Site-general models are further subdivided as being either empirical or theoretical based on the degree to which they are based on field measurements. In principle, site-specific

models can also be either theoretical or empirical, but in practice theoretical models are by far the most common.

2.3.1 Site-General Propagation Models

In the case of all site-general models examined, information pertaining to spatial correlations, as discussed in Section 2.2, is lacking. In part for this reason, all models examined in this class have been found to be insufficient for meeting the thesis objectives.

2.3.1.1 Empirical Propagation Models

A number of related empirical models have been developed for the prediction of mean (50th percentile) path loss as a function of frequency, distance, base station antenna height and mobile antenna height, such as the Okamura, Hata, and COST-231 models [58,29,18]. These models include a term for the free space path loss, in addition to a number of correction factors that account for the terrain classification (such as urban, suburban or open) and significant terrain features (such as mountains, lakes, etc.). These models are all limited in their applicability to distances greater than 1 km, and frequencies under 3 GHz or less; for these reasons the models are not sufficient for meeting the thesis objectives.

To date, very little work has been reported in available literature on the empirical modelling of outdoor path loss for frequencies in the millimetre-wave region. One example [11] predicts average path loss as a function of frequency and distance, and is intended for frequencies near 60 GHz. This model contains additional terms for losses due to atmospheric oxygen and rain. A path loss exponent of 2.2 is recommended, which strongly contradicts the much larger values reported in [59] and [87]. The reason for this contradiction appears to be the limited nature of the measurements on which the path loss exponent estimate is based. In conclusion, this model is not suitable for use in meeting the thesis objectives due in part to the lack of dependence on antenna heights and terrain classification, and due in part to the lack of proper experimental verification.

A rudimentary model of mean path loss for the millimetre-wave region is given in [59]. In this case, a linear least squares fit is applied to measured excess path loss values for a few combinations of location and transmitter height. This model has the advantages of being based on measurements in suburban areas in the frequency range of interest. Nevertheless, this model is not sufficient for the uses intended here since only two transmitter heights and one receiver height are included, which is not enough to allow for prediction given arbitrary antenna heights.

A similar approach has been taken in [87]. The model is given by

$$PL = K + N \log(d) \quad (2.51)$$

where PL is the mean path loss in dB, d is the distance in kilometres, K and N are experimentally derived constants with values $K = 147.5$, $N = 36.7$. This model has the additional benefit of including a standard deviation about the mean path loss, namely $\sigma = 13.9$ dB. Nevertheless, this model is not a function of antenna heights, and for this reason it is not sufficient as previously discussed.

Regardless of the lack of a suitable pre-existing empirical model, the possible creation of a new, largely empirical model that is sufficient to meet the thesis objectives is assumed to be infeasible. A very large number of measurements would be required so that a statistically significant sample is available for all combinations of distance and antenna heights over the ranges of interest. Furthermore, it would be necessary to expand the form of the model to include information pertaining to spatial correlations, which would require a significant increase in the number of measurements.

2.3.1.2 Theoretical Propagation Models

In contrast to models that are based largely on experimental data, there exist propagation models that are derived from the theory of EM wave propagation. One such case is the Walfish/Bertoni model [84], which represents the terrain as consisting of a flat earth with continuous rows of buildings, equally spaced and having uniform height. Mean path loss is predicted as a function of frequency, distance, base station antenna height and mobile antenna height as in the case of the empirical models described here, as well as two parameters that describe the building spacing and height. Propagation is

modelled as diffraction over rooftops. It has been tested at 922 MHz, in which case it was found to be in good agreement with measurements.

If used in a literal fashion, this model is likely to perform poorly for the problem at hand due to the omission of trees. Nevertheless, some success may be achieved if the diffracting edges in the model are re-interpreted as representing rows of trees instead of rows of buildings. In [59] it was concluded that diffraction was the primary mode of signal propagation through trees, and this idea is also supported by the degree to which diffraction over tree tops was found to play a role in the model presented in Chapter 3. Such an extended use of the model would require verification using field measurements.

This model has been expanded to explicitly include the effect of trees in suburban areas by Torrico, Bertoni and Lang [80]. In summary, the model is similar to the Walfish/Bertoni model, with the tree canopy (assumed to extend over the average rooftop level) being represented by partially absorbing phase screens, and being based on EM scattering theory. Unfortunately, this model has been developed for the 800 to 2000 MHz range, and for this reason a number of approximations were made during the development that do not apply to the millimetre wave region. In particular, the wavelength is assumed to be much greater than the leaf radius, and the tree width is assumed to be less than the skin depth, so that only the mean field is accounted for, the incoherent field being neglected. Regardless of the issue of applicable frequency, the reported model is not in closed form, requiring a significant amount of computation.

This approach could be extended to millimetre waves, in fact the modelling of millimetre wave propagation through trees by scattering theory has been reported at numerous occasions, for example [71] and [2]. Even if this approach were taken, it would be necessary to expand this model to include information pertaining to spatial correlations.

2.3.2 Site-Specific Propagation Models

The common feature of the models described in this section is that they all make use of a database to describe the terrain, i.e. they result in site-specific predictions. This is in contrast to the site-general models described above (empirical and theoretical), that result in the same prediction for all locations that fall within a broad class. In principle, a

site-specific model can result in better prediction accuracy than a general model, although this is not necessarily always the case, depending on the degree to which the RF fields are perturbed by local terrain variations, the correctness with which interactions with terrain is modelled, etc. In the extreme, a model that solves Maxwell's equations everywhere and that makes use of a terrain database that is accurate to within a fraction of a wavelength, including electrical characteristics, will result in an accurate prediction of the field strengths, although this approach is patently infeasible for the wavelengths and dimensions of interest here.

Site-specific models are generally deterministic by nature, although it is possible to interpret the predicted signals in a statistical manner as described for example in [9, Chapter 5] and [46].

Site-specific models have, in principle, an important advantage over site-general models in this case, namely the inherent ability to predict the relationship between the field at two different points, i.e. information pertaining to spatial correlations.

Many site-specific models have been reported in the literature, with only a few examples being described here. They generally make use of terrain databases of different resolutions, depending on the distances involved, and also use different propagation mechanisms to model the modes that dominate for the intended scales and environments.

2.3.2.1 Macrocellular Propagation Models – 2D

A number of two-dimensional models have been developed that make use of the terrain profile on the path between antennas, and that model propagation primarily as multiple diffraction over peaks in the profile. An early example is the Edwards and Durkin model [17], which predicts path loss based on terrain elevation only, and which is based on knife-edge diffraction. More recent models, such as [74] and [86], also make use of information pertaining to the terrain classification, such as urban, open, or forest, and model the edges in different manners, such as wedges or cylinders. A rigorous solution to the multiple diffraction problem has been developed [83], but the resulting expression requires more computation than is feasible for use in path loss prediction over large areas, such as is required for a site planning tool, or as required for the thesis

objectives. For this reason, two-dimensional propagation models generally involve approximate expressions for multiple diffraction.

Two-dimensional models of this sort ignore reflections and scattering from terrain that is to either side of the profile. In contrast, the field measurements described in Section 4.1 demonstrated that a significant number of strong reflections can occur, so that some form of three-dimensional modelling would be required to evaluate the importance of reflections in providing coverage.

Nevertheless, the use of 2D propagation models is not without merit for the problem at hand. This has been made evident by the nature of the predicted paths that have resulted from the verification process described in Chapter 4. A large percentage of predicted paths were modelled as involving only diffraction over the top of one or more obstacles, in spite of the fact that alternate paths, involving diffraction around the sides of obstacles, as well as transmission through foliage, were generally evaluated as well. The predominance of paths involving top diffraction only is likely related to the typical antenna placement geometry that occurred during the verification process, in particular the transmitter height being well above the tree canopy, and the receiver being placed at a significant distance. In contrast, the geometry of a microcell scenario, assuming base stations at light post height and cells on the order of a few hundred metres, may result in the predominance of other paths, such as around, under or through obstructing trees. Since the evaluation of microcells is one of the objectives of this thesis, a 3D modelling approach was taken to avoid the errors associated with the possible occurrence of these other paths.

2.3.2.2 Macrocellular Propagation Models – 3D

The 2D approach described above can be extended to a three dimensional model as shown for example by Kurner et al. [46] or by Tameh et al. [78,79]. This approach, as well as 3D propagation models in general, have the added advantage of providing more channel information, such as complex impulse response, Rician K factor, and angles of arrival.

In the Tameh model, propagation is modelled along the direct path between transmitter and receiver, and in addition off-axis contributions from scattering by

illuminated terrain pixels and building walls are represented. Terrain and rooftop diffraction are modelled on the direct path as well as the paths to and from the scatterers. Attenuation by foliage is modelled as a function of the total distance travelled through foliage. A variable resolution terrain database was used, covering 10 km x 10 km, with 10 m resolution in built-up areas, and 50 m resolution or more in other areas. The database includes ten terrain classifications based on surface roughness and electrical properties, and includes a coarse building representation. The resulting predictions have been validated using narrowband measurements at 1823 MHz.

The Tameh model is similar to the one presented in Chapter 3, with the most significant differences being the resolution of the database, and the use of scattering to model off-axis contributions. The use of scattering to model off-axis contributions is an option that was considered during model development but finally rejected for the reasons given below:

- The prediction of only the strongest rays was sufficient for accurate coverage prediction as shown in Section 4.7. It was assumed that these strongest rays would arise from re-radiation by tall or nearby buildings only (Section 3.3.4), and not foliage (Section 2.5.4.4) nor the ground (Section 3.2).
- The modelling of re-radiation from buildings using a scattering model instead of specular reflection was investigated without documentation. The scattering model was found to lead to no improvement over the specular reflection model in the prediction of measured reflections.

2.3.2.3 Microcellular Propagation Models

A large amount of literature is available on site-specific propagation modelling in urban microcells, for example [48]. These models generally make use of ray tracing, and are based on principles of geometrical optics and ray-based models of diffraction, such as the uniform theory of diffraction [45]. A typical microcell environment is modelled using flat facets to represent buildings and the ground. A “brute force” method of solving for the field is generally not used, as this requires an exceedingly large number of computations in most cases as shown in [9]; instead a number of acceleration techniques are applied. Acceleration techniques fall into two classes: those that result in no additional loss of accuracy, such as discussed in [9], and those that omit certain classes of

rays that are assumed to be negligible. Example of the latter are found in [66], which considers 2D propagation in the horizontal plane and assumes that buildings are infinitely tall, and [50], which limits propagation to a set of vertical planes, an approach that is valid since building walls are almost always vertical.

These models generally do not treat foliage due to the absence of significant numbers of trees in high rise urban areas. An exception is found in [65], where attenuation by trees is modelled as being proportional to the distance travelled through the foliage.

2.3.3 Summary

All site-general propagation models examined here, whether empirical or theoretical, have been found to be insufficient for meeting the thesis objectives due to the lack of information pertaining to spatial correlations. While in principle these models could be expanded to include such information, this option was rejected due to the large number of required measurements anticipated in the case of an empirical model, and due to the anticipated complexity of a theoretical model that would meet all requirements.

In contrast, site-specific propagation models that are based on ray tracing are generally capable of meeting all the thesis objectives. Nevertheless, none of the site-specific models examined here have been validated with field measurements in a suburban environment at millimetre-wave frequencies. The significant effect of trees in this case, as pointed out in [59], puts into doubt the suitability of the urban microcellular propagation models if used without modification. As well, the suitability of the macrocellular models that are based on terrain scattering is put into doubt by the quasi-optical behaviour of radio waves in the millimetre range, and by the very low backscattering levels that have been observed for trees as discussed in Section 2.5.4.4.

As a result of these findings, and due to the large number of required simulations anticipated for the study of all coverage enhancing methods listed in Section 1.3, the approach taken here has been to develop a relatively simple site-specific propagation model based on ray tracing, and to modify it as required, based on the results of a comparison with field measurements. The final model is described in Chapter 3 and its validation is described in Chapter 4.

2.4 Existing Coverage Studies

A number of surveys have been conducted to estimate the coverage rate that can be expected to occur in typical suburban areas. Selected results are summarized and discussed below. All were conducted at or very near to 28 GHz, and all are assumed to have used narrowband transmission unless otherwise noted. Trees are assumed to have been in leaf unless otherwise noted.

2.4.1 Bellcore

A comprehensive survey was conducted circa 1995 by Bellcore in Brighton Beach NY, which is an urban residential environment [72].

Experimental Set Up:

- mostly 2-3 story residences with clusters of apartment buildings, 6 stories or more
- minimal terrain variations
- 77 locations, range between 300 m and 5 km
- transmitter located on top of a 95 metre tall apartment building
- vertical polarization, 18 MHz bandwidth (i.e. wideband)
- 23 dBi Rx antenna gain, 12 dBi Tx antenna gain
- -5.0 dBW Tx power, -112 dBm receiver threshold
- at each location, the receiver antenna was rotated 360° to search for specular reflections, with the strongest signal being recorded
- two sets of measurements were taken with differing Rx antenna heights:
 - 1) heights fixed to 13.3 metres,
 - 2) heights varying from 3.4 to 11.3 metres above ground

Results (I):

- The received signal at a majority of locations suffered additional path loss (relative to free space loss) due to obstruction by buildings or foliage.
- A cluster of measurements over the entire distance range were at the noise floor, i.e. coverage voids existed.

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UMI

- tree heights equal to single family rooftops
- range 0.25 to 3 miles (0.5 to 5 km)
- Tx power: +20 dBm
- Tx gain: +23 dBi horn
- Rx gain: +35 dBi dish
- good signal criterion: $BER < 10E-9$
- hub height: 120 ft (35 metres)

Results:

no. of hubs (diversity)	comm. bldg rooftop	multi-family rooftop	single family rooftop
1	70 %	62 %	18 %
2	90 %	85 %	30 %
3	95 %	95 %	40 %
4	98 %	97 %	50 %

Table 4: Texas Instruments Coverage Rate versus Subscriber Antenna Height

Once again, a strong dependence on subscriber antenna height can be seen, as well as a poor coverage rate for single family dwellings. Additionally, a significant improvement resulting from the use of macrodiversity is evident, although it appears that macrodiversity is not sufficient to achieve high coverage rates.

2.4.3 Hewlett Packard

The approach taken by Hewlett Packard [25,26,27] is fundamentally different from the others noted here: a survey was taken, and a propagation model was derived from the results. This model was then used to predict the coverage results listed below.

Experimental Set Up:

- Measurements were taken in a typical California suburban environment.

- The model assumes multi-hub coverage.
- The model assumes rainfall region C (99.9%).

Results (I):

The excess loss exponent (above and beyond the free space loss) was found to vary from 2 to 4, with a value of 2 corresponding to areas with few trees, and a value of 4 being more typical and corresponding to areas with moderate tree density.

Coverage was found to increase with increasing MTPL, which refutes the often-held notion that LOS operation is required for LMDS, such as is stated in [34]. In the case of a 75 ft base station antenna, coverage ranged from 45% to 90% as the excess link margin increased from 0 to 30 dB.

Results (II):

cell radius	15 m hub	25 m hub	30 m hub
1 km	78 %	85 %	87 %
2 km	50 %	68 %	72 %
3 km	23 %	45 %	53 %
4 km	13 %	25 %	32 %
5 km	8 %	17 %	20 %

Table 5: Hewlett Packard Coverage Rate versus Base station Antenna Height

Table 5 indicates that the coverage rate depends on BS mast height, but with less sensitivity in comparison to the effect of changes to the subscriber mast height. The coverage rate for a 15 metre mast is seen to be relatively good for a 1 km cell, which suggests by extension that a microcellular architecture is feasible.

cell radius	low density	med. density	high density
0.5 km	93 %	90 %	90 %
1 km	85 %	78 %	64 %
2 km	80 %	68 %	45 %
3 km	72 %	43 %	20 %
4 km	67 %	32 %	16 %

Table 6: Hewlett Packard Coverage Rate versus Tree Density

Table 6 indicates that the attenuation due to trees is responsible for a large portion of outages, particularly in the case of large cells. This further suggests that it may be desirable to tailor the cell radius depending on the local tree density, in much the same way that cell radius could be adapted to the local rain rate.

hub height	0 dB	10 dB	20 dB	30 dB
50 ft	25 %	38 %	57 %	75 %
75 ft	45 %	55 %	75 %	90 %

Table 7: Hewlett Packard Coverage Rate versus Excess Link Margin

The data found in Table 7 is listed for a 1 km radius cell and moderate tree density. It displays an almost linear relationship between coverage and excess margin. This relationship implies that the majority of sites in the experimental survey were subject to attenuation as opposed to complete signal blockage. This assumption is further supported by an accompanying scatter plot (not included) of the experimental measurements. In conclusion, it appears that a significant coverage increase can be achieved with a global increase in MTPL.

2.4.4 Communications Research Centre

A similar coverage survey has been conducted by the CRC (Communications Research Centre) in 1996 in Parkwood Hills [6, 87], which is a typical suburban environment in Ottawa.

Experimental Set Up:

- +24 dBm Tx power
- 18 dBi Tx antenna gain, 23 dBi Rx antenna gain
- transmitter located on a tall multi-story apartment building
- range approximately 300 metres to 3 km
- approximately 70 sites were measured

Results:

- Received power levels were found to vary over the entire range from the free space loss value down to the receiver threshold. Unlike the results found in [72], no clustering was noticed at the noise floor.
- A path loss exponent of approximately 3.7 was determined.
- The distribution of the excess path loss around the mean was found to have a skewed, roughly Gaussian distribution with a standard deviation of roughly 14 dB. The mean is defined as the value predicted using the path loss exponent noted above.
- The path loss difference between measurements taken with and without leaves on the trees was found to vary roughly between -5 dB and 20 dB, where a negative value indicates that the loss of leaves resulted in an increase in attenuation.

2.4.5 National Telecommunications and Information Administration

An extensive coverage survey has been recently conducted by the National Telecommunications and Information Administration (NTIA) [59]. In contrast to the other surveys described in this section, this survey resulted in an estimate of coverage as a function of the maximum tolerable path loss (MTPL).

Experimental Set Up:

- two suburban areas in Northglenn, Colorado and San Jose, California were used
- both areas consisted mainly of 1 and 2 story single family residences
- both areas had flat terrain

- signal power time record collected at 1 kilosample/sec for 50 sec
- receiver sensitivity of -130 dBm and dynamic range of 70 dB
- 14 dBi vertically polarized Tx horn antenna, 90° beamwidth in azimuth, 20° beamwidth in elevation
- Tx EIRP of 51 dBm
- 2.5° dish Rx antenna, vertically polarized, (assumed to have a gain ≈ 35 dBi)
- the Rx antenna was mounted on a boom and placed at the local roof height, plus one metre
- the Rx antenna was positioned at each site so as to avoid obvious obstructions
- the Rx antenna was pointed by scanning in both azimuth and elevation
- the Tx antenna was placed at 40 ft and 80 ft heights
- the number of sites was chosen so as to result in an acceptable sampling error in theory

Results:

The following graphs are taken directly from [59], and are reproduced here to allow for comparison with the results presented in Chapter 7. The term “availability” refers to the percentage of time that the recorded signal power, and hence the path loss was above the threshold MTPL.

Figure 17: Coverage vs. MTPL (Papazian et al.); North Glenn, 40 ft Tx, cell 1, 0.5 km cell radius

Figure 18: Coverage vs. MTPL (Papazian et al.); North Glenn, 40 ft Tx, cells 1 and 2, 99% availability, 0.5 km cell radius

Figure 19: Coverage vs. MTPL (Papazian et al.); San Jose, 40 ft Tx, 0.5 km and 1.0 km cell radii, 99% availability

Figure 20: Coverage vs. MTPL (Papazian et al.); San Jose, 80 ft Tx, 0.5, 1.0 and 2.0 km cell radii, 99% availability

An examination of these graphs reveals the following:

- Increasing the MTPL over a range of at least 25 dB generally leads to an increase in coverage in all cases presented here.
- For a given region, coverage can vary by as much as 10% or more depending on the precise location of the cell within the region as indicated in Figure 18.
- Coverage decreases with increasing cell radius.
- Coverage increases with increasing base station height as seen by comparing Figure 19 and Figure 20.
- Coverage can vary by at least as much as 20% between regions as seen by comparing Figure 18 and Figure 19. This difference is assumed to be caused by the difference in tree canopy in each region.

2.4.6 Summary

The studies described above illustrate the relationship between coverage and the environment for a conventional MMW-BWA system deployment in a suburban area, and also illustrate the effect on coverage of changes to basic system parameters. Based on these studies, the following conclusions are made.

The deployment of a conventional system in a typical suburban area, without taking special measures, results in coverage that is typically in the range of 40% to 70%. Coverage values are very site-specific, depending on the region and the precise location within a region. This sensitivity to location is in accordance with the observation that local tree density has a significant effect on coverage, and that path loss is associated with obstruction by trees and buildings.

Seen as a whole, the path loss in a cell can be modelled as having an excess path loss exponent occurs in a range roughly between 2 and 4, with a distribution about the mean that is roughly gaussian.

Coverage is significantly affected by changes to the MTPL over a range of 30 dB or more, which is contrary to the often-held notion that LOS operation is required for LMDS, such as is stated in [34] for example.

Macrodiversity can lead to significant increases in coverage, but not in all cases.

Coverage increases significantly with an increase in either BS or ST antenna heights. It depends strongly on ST height changes of only a few metres. In the case of the BS antenna height, coverage can be poor in spite of heights on the order of 100 metres above ground.

Finally, coverage decreases significantly with an increase in cell radius as expected, although coverage can be poor in spite of small cell radii on the order of 1 km.

2.5 Existing Studies of Radio Channel Impairments

Several impairments can occur to a radio channel, including the following. These impairments all exist to some degree on any radio channel, including both LOS and NLOS links in the present context.

- shadowing, i.e. attenuation due to obstructions or rain,
- fading, i.e. time-varying attenuation and phase shift that may or may not be frequency-selective,
- depolarization, due primarily to scattering by ground clutter and rain,
- inter-symbol interference, due primarily to multipath propagation,
- Doppler spread, due to the time-varying nature of the channel, and
- external interference, caused by all other users and systems that share the same or adjacent frequency bands.

A number of studies are found in the literature, both empirical and theoretical, that are applicable to fixed terrestrial broadband millimetre-wave channels. These studies can be broadly categorized as i) those that deal with the general nature of impairments on MMW-BWA links in suburban areas, and ii) those that deal with the effects of isolated elements in the environment, namely trees, buildings, vehicles and precipitation. The results of these studies are summarized below.

2.5.1 General Impairments

The following summarizes the findings of studies that do not involve the isolation of elements in the environment, other than having been conducted under clear-sky conditions. In other words, the findings pertain to links that undergo the combined effect of trees, buildings and vehicles in the environment.

2.5.1.1 Fading

The following observations and conclusions have been reported concerning fading on LMDS channels [34]:

- Even if the Tx and Rx are located at fixed points, the influence of motion of traffic and foliage, even in a LOS location, creates a hostile fading environment.
- Temporal fades of over 40 dB at the rate of at most a few (<2) Hertz are frequently seen.

2.5.1.2 National Telecommunications and Information Administration

An extensive experimental study of the radiowave propagation impairments for LMDS systems in suburban areas is reported in [59]. This work included a coverage study that is described separately in Section 2.4.5, and findings on fading that are discussed in Section 2.5.4.5. The following is a summary of the remaining findings and conclusions.

A number of the conclusions pertain to the influence of trees, although no measures have been reported to have been taken to isolate the effect of trees from buildings or vehicles. Nevertheless, these conclusions are supported by the noted prevalence of obstructing trees.

General Observations and Conclusions

- The most serious propagation impairment was found to be signal attenuation.

- The major source of attenuation was obstruction of the radio path by buildings and vegetation.
- The measured signal impairments were all found to worsen with increasing attenuation: cross-polarization discrimination (XPD), variability (fading) and delay spread.

Multipath

- Multipath was observed with delay spread on the order of 1 to 2 nsec.
- Multiple scattering and not multiple specular reflections is presented as a possible explanation for multipath.

Depolarization

- Depolarization caused by vegetation and other scatterers was found to be an order of magnitude greater than rain-induced depolarization.

Influence of Trees

- Subscriber sites had a high probability of NLOS paths due to trees.
- Signal attenuation is caused by the tree canopy which extends above roof height.
- Trees cause signal attenuation and variability (fading) when wind is present.
- The primary mode of signal propagation through trees is thought to be diffraction.
- In many cases, when a tree was obstructing the radio path, it was within 10 to 20 metres of the receiver site.

2.5.2 Atmospheric Effects

2.5.2.1 Attenuation by Atmospheric Gases

For frequencies near 28 GHz, the attenuation due to molecular absorption by atmospheric gases (principally oxygen and water vapour) is between 0.05 and 0.1 dB/km, which is negligible in comparison to all other sources of attenuation considered here [5]. Nevertheless, this is not the case for all millimetric frequencies; in particular, there is an

oxygen absorption line near 60 GHz, with a peak absorption of approximately 15 dB/km, which makes this frequency particularly suitable for reducing interference .

2.5.2.2 Attenuation by Rain

The field of rain attenuation modelling is extensive; only a very brief outline is given below, with emphasis placed on the choice of a simple model that is suitable for the task at hand.

Rain attenuation models are generally of the form given below [41]:

$$\alpha = a R^b \quad (2.52)$$

where α is the attenuation in dB/km, R is the rainfall rate in mm/hr, and a and b are frequency dependent constants. An example of the application of this model to LMDS system design is given in [60]. Examples of related models can be found in [41].

The rainfall rate statistics for a given location are commonly determined on the basis of the rain climate regions given in the Crane global rain attenuation model [12]. An outline of the rain rate statistics for regions in North America has been reproduced below.

rain rate exceeded, percent of year	B	C	D1	D2	D3	E	F
1.0 %	1.8	1.9	2.2	3.0	4.0	4.0	1.7
0.1 %	6.8	7.2	11	15	22	35	5.5
0.01 %	19	28	37	49	63	98	23
0.001 %	54	80	90	102	127	164	66

Table 8: Rain Rates in mm/hr for Rain Regions of the Crane Model

The major urban centres in each region are tabulated below [25].

Region B	Region C	Region D1
Denver, CO Portland, ME Spokane, WA Calgary, AB	San Francisco, CA Sacramento, CA Seattle, WA Portland, OR Vancouver, BC	Dallas, Tx Minneapolis, MN Toronto, ON Montreal, PQ Ottawa, ON

Table 9: Major North American Cities in Rain Regions - Part I

Region D2	Region D3	Region E	Region F
New York, NY Philadelphia, PA Boston, MA Chicago, IL Washington, DC Cleveland, OH Austin, TX	Memphis, TN Atlanta, GA	Houston, TX New Orleans, LA Miami, FL	Los Angeles, CA San Diego, CA Phoenix, AZ Salt Lake City, UT

Table 10: Major North American Cities in Rain Regions - Part II

The rain model equation listed above has been applied to the rain rate data for various estimates of the constants a and b at 30 GHz to produce attenuation predictions. Two sets of constants have been used: one corresponding to a polarization-independent spherical rain drop model, the other corresponding to a polarization-dependent non-spherical rain drop model.

availability	B	C	D1	D2	D3	E	F
99 %	0.3	0.4	0.4	0.6	0.8	0.8	0.3
99.9 %	1.4	1.5	2.3	3.1	4.7	7.6	1.1
99.99 %	4.0	6.0	8.0	10.8	14.0	22.2	4.9
99.999 %	11.9	18.0	20.3	23.1	29.1	38.0	14.7

Table 11: Rain Attenuation at 30 GHz in dB/km, Spherical Drop Model ($a = 0.186$, $b = 1.043$)

availability	B	C	D1	D2	D3	E	F
99 %	0.3	0.4	0.4	0.6	0.8	0.8	0.3
99.9 %	1.3	1.4	2.2	3.0	4.4	7.1	1.1
99.99 %	3.8	5.6	7.5	9.9	12.9	20.2	4.6
99.999 %	11.0	16.4	18.5	21.0	26.3	34.1	13.5

Table 12: Rain Attenuation at 30 GHz in dB/km, Horizontal Polarization ($a = 0.187$, $b = 1.021$)

availability	B	C	D1	D2	D3	E	F
99 %	0.3	0.3	0.4	0.5	0.7	0.7	0.3
99.9 %	1.1	1.2	1.8	2.5	3.7	5.8	0.9
99.99 %	3.2	4.7	6.2	8.2	10.5	16.4	3.8
99.999 %	9.0	13.4	15.0	17.0	21.2	27.4	11.0

Table 13: Rain Attenuation at 30 GHz in dB/km, Vertical Polarization ($a = 0.167$, $b = 1.000$)

An additional set of rain attenuation estimates is found in [25], with the original source of the estimates being unspecified.

availability	B	C	D1	D2	D3	E	F
99.9 %	1.5	1.6	2.5	3.3	4.7	7.2	1.2
99.99 %	6.7	9.4	12.2	15.7	19.7	29.3	7.9

Table 14: Rainfall Attenuation at 28 GHz in dB/km, Hewlett Packard

An examination of these tables reveals the following:

- All tables are in rough agreement.
- Very high availability levels (99.99% and up) can only be achieved in all but the most arid regions at the cost of very large rain margins, or very small cells.
- Horizontally polarized signals experience more attenuation than do vertically polarized ones, but not so much so as to warrant significant design changes.

2.5.2.3 Attenuation By Fog

A worst case fog density of 0.4 g/m^3 results in an attenuation of approximately 0.5 dB/km as predicted by the cloud attenuation model found in [41], which is negligible in comparison to the expected rain attenuation values.

2.5.2.4 Attenuation By Snow

Attenuation by dry snow is similar to that for rain for comparable values of equivalent rain rate [5]. The equivalent rain rate of dry snow does not usually exceed 10 mm/hr, which corresponds to a moderate rainfall.

Attenuation by wet snow can be greater than for comparable values of equivalent rain rate. Nevertheless, rain remains as the most significant attenuation factor [5], which is likely due to the relative rarity of wet snow, as well as the limited equivalent rain rate of wet snow.

2.5.2.5 Depolarization by Rain

The depolarization that is associated with rain attenuation can be described by the following model [41]. This model has been found to closely agree with an experimentally derived scatter plot found in [33] for the case of a 20 GHz wideband signal over a 7 km terrestrial link using circular polarization, which lends further credence to the suitability of this model in the present situation.

$$D_{XP} = U - V \log A \quad (2.53)$$

where D_{XP} is the cross-polar discrimination in dB, A is the rain attenuation in dB, and U and V are empirically determined coefficients given below.

$$U = 30 \log f - 10 \log(0.5 - 0.4697 \cos(4\tau)) - 40 \log(\cos \theta) \quad (2.54)$$

where f is the frequency in GHz, τ is the tilt angle of the polarization with respect to the horizontal (for circular polarization, $\tau = 45^\circ$), and θ is the elevation angle of the path. $V = 23$ for f in the range between 15 GHz and 35 GHz.

Figure 21 displays the resultant cross-polarization discrimination (XPD) for the case of linear polarization (either H or V) at 28 GHz and an elevation angle of 0° . For comparison, the same function has been plotted for the case of circular polarization, all else being equal.

Figure 21: XPD versus Rain Attenuation at 28 GHz.

The plot shown above clearly indicates the superiority of linear over circular polarization in this respect. Additionally, it indicates that the depolarization of linearly polarized signals that occurs in a worst-case scenario is small but not negligible. For example, assuming a 2 km link, rain region D3 (East Coast), a 99.99% availability design criterion (approx. 50 minutes outage per year) and the attenuation values given in Table 14, the resulting XPD is 25 dB.

2.5.3 Effects of Buildings

2.5.3.1 Building Reflection and Depolarization

2.5.3.1.1 Rutherford Appleton Laboratory, UK

An experimental study of the reflections emanating from a single building [73] is summarized below.

Experimental Set Up:

- 38 GHz, narrowband
- A single two story brick building with several aluminum framed windows was used.
- 30 m separation between the transmitter and wall
- 0° angle of incidence
- The receiver was moved around an arc of radius 30 m.

Results:

- copolar specular reflection loss of approx. 15 dB
- crosspolar specular reflection loss of approx. 40 dB, i.e. the XPD was approx. 25 dB.
- the received power levels outside of the main beam were roughly uniform, i.e. isotropic
- copolar diffuse reflection loss of approx. 40 dB, i.e. 25 dB below the specular level
- crosspolar diffuse reflection loss was not measurable

2.5.3.1.2 U.S. Dept. of Commerce

A similar measurement survey conducted at 28.8 GHz for several buildings of varying type is described in [82]. The copolar specular reflection loss for brick or concrete buildings was found to vary between 7 dB and 15 dB, with an average of 11.25 dB. The same loss for metal buildings had an average value of only 3 dB.

2.5.3.1.3 University of Glamorgan, UK

Yet another building reflection survey is described in [15,1]. This study was conducted at 11.2 GHz, and using 4 buildings that were mainly single construction of brick, concrete or pebble-dash. The angle of incidence in each case was near to 35°. The resulting specular reflection losses were in the range of 10 dB to 15 dB, and the diffuse reflection losses were typically 20 dB relative to the specular levels.

2.5.3.2 Building Blockage and Diffraction

An experimental survey of the blockage provided by buildings is described in [82] and summarized below.

Experimental Set Up:

- 28.8 GHz, narrowband
- Four large multistory buildings were used.
- The transmit and receive terminals were placed on opposite sides of the building and set on a line perpendicular to the building walls.
- Various distances and receiver orientations were tested.

Results:

- An effective loss of 100 dB relative to free space was observed for the brick and concrete buildings.
- Similarly, a loss of 60 dB was observed for a building that was empty and that had predominantly glass walls, with the glass being metal-coated.
- In both cases noted above, the received levels included an indeterminate amount of diffracted energy, so that the true blockage losses are likely to be even higher.
- A significant amount of diffraction was observed. In one case, the effective loss dropped by 40 dB when the Tx-Rx separation was increased from 40 to 90 metres. In another case, the effective loss dropped by 50 dB when the receiver was pointed at the building roof edge; nevertheless, the effective loss was always 60 dB or more.

Additionally, diffraction by building edges is investigated in [81], where plots of received power versus diffraction angle are presented. The diffraction loss is shown to vary from roughly 5 dB to roughly 30 dB as the angle varies from 0° to 5°.

2.5.4 Effects of Trees

2.5.4.1 Diffraction By Trees

Very little has been published on the topic of diffraction by trees at millimetre wave frequencies, either theoretical or experimental; nevertheless, the following has been reported:

- The primary mode of signal propagation through trees is thought to be diffraction [59], based on field observations in suburban areas.
- In NLOS cases, propagation by diffraction from (especially) treetops is likely to account for most of the received signal [81]. This is supported by at least one observation of a 30 dB increase in signal power that was observed when the receiver antenna was rotated 10° upwards in elevation, roughly towards treetop level.
- An experimental survey is described in [64], where reasonable agreement was found between measured signal strength in areas shadowed by tree-covered hills on one hand and the signal strength predicted by the knife-edge diffraction model on the other.

2.5.4.2 Attenuation By Trees

A number of experimental studies have been completed that characterize the attenuation that results from LOS obstruction by one or more trees. As expected, these studies display a wide range of attenuation estimates due in large part to the natural variability of trees.

The studies described here fall roughly into two categories: studies of the effects of single, isolated trees, and studies of propagation into areas of thick vegetation, such as forests or orchards.

2.5.4.2.1 University of Essex, UK

The results of a study of the attenuation resulting from single trees of various types are summarized below [14]. The study was conducted at 38 GHz and vertical polarization, and is assumed to be narrowband.

- An average attenuation of 2 to 4 dB/m was observed for dry trees, all types.
- An average attenuation of 4 to 6 dB/m was observed for wet trees, all types.
- Fluctuations as high as ± 6 dB were observed on windy days, and it was concluded that these fluctuations were a result of the motion of the leaves and branches.

2.5.4.2.2 U.S. Army Research

An extensive study of the attenuation that results from penetration into forested areas is described in [71]; portions of interest are summarized below.

Experimental Set Up:

- 28.8 GHz narrowband
- 10° Tx antenna beamwidth, 1.2° Rx antenna beamwidth
- both horizontally and vertically polarized transmissions used
- both Tx and Rx antennas at a 6 m height so that the LOS passes through the thickest portion of the trees.

The measurements were taken in a pecan orchard, both with and without leaves:

- trees on a square grid with 13 m spacing
- tree heights 8 m - 10 m
- maximum tree span 10 m - 13 m, i.e. the trees were nearly touching at their thickest point

Results:

- Attenuation is not significantly dependent on polarization.
- Attenuations at 57.6 GHz were very close to those at 28.8 GHz; otherwise attenuation increases with frequency.
- Attenuations due to a single tree were approx. 32 dB with leaves, 16 dB when bare.
- For the first 30 m through foliage, the attenuation rate is nearly linear at 2.0 dB/m, while at greater depths the attenuation averages 0.05 dB/m, i.e. the attenuation is

nearly flat at 60 dB. An abrupt break occurs at the boundary between the two regions. The initial fast rate of attenuation is associated with a direct path propagation mode, while the later reduced rate is associated with a multiple scattering propagation mode.

- A similar attenuation profile occurs for bare trees, but with the breakpoint occurring after 8 trees (80 metres).
- Attenuation profiles are more gradual for LOS paths that do not pass through the thickest portion of the trees.

The results of this study suggest that an appropriate model for the attenuation due to several randomly-spaced trees would take into consideration the multiple scattering that occurs between nearby trees and the consequent reduction in attenuation. This has been the motivation behind the clustering algorithm described in Section 3.2.5.

2.5.4.2.3 Rutherford Appleton Laboratory, UK

A similar study conducted at 38 GHz is described in [73]. In this case, a natural deciduous forest was used. The resulting recommended attenuation model is shown in Eqn. (3.22). This model is assumed to be suitable for use at 28 GHz in spite of the frequency change due to the observed frequency insensitivity noted in [71]. Alternative values for the parameters are given that correspond to the case of a straight line of evenly spaced deciduous trees which lay by a roadside, namely $C = 45.1$ and $\beta = 8.8$.

2.5.4.3 Depolarization by Trees

The survey described in [14] included XPD measurements, however the results are largely inconclusive due to the poor XPD of the test equipment itself. Some degree of cross polarization is reported.

Similarly, the survey described in [71] touched upon the issue of depolarization by noting that the XPD after 8 trees was very poor, on the order of 10 dB or less. This is to be expected due to the dominant multiple scattering mode at this depth.

2.5.4.4 Scattering by Trees

Scattering models generally involve the prediction of energy emissions in all directions which result when an EM wave is incident on an object [44]. In this sense they are very general models which implicitly account for all other propagation mechanisms, including reflection, transmission and diffraction. The treatment of a tree as a scattering object thereby encompasses the other propagation effects mentioned here; for example a tree's attenuation can be viewed as the difference between the power incident on the tree and the power emitted by the tree in the same direction as the incident wave.

Individual trees scatter energy in a highly non-isotropic manner as indicated for example by the scattering diagram presented in [28]. Most energy is emitted in the general direction of the incident wave (forward scattering) while some energy is emitted in roughly the opposite direction (back scattering).

A brief examination of the backscattering observed at 25 m from the front edge of a copse of deciduous woodland is described in [73]. A peak signal level 50 dB below the equivalent LOS strength was observed in the backwards direction, with the signal strength decreasing gradually to 55 dB down in other directions between $\pm 40^\circ$ relative to the first, i.e. the backscattered power is nearly isotropic.

A similar study of the backscattering that results from an apple orchard at 11.2 GHz is described in [2]. Once again, the backscattering is found to be isotropic and approximately 50 dB down; as well, the backscattering is insensitive to polarization. The backscattering level from leafless trees was found to be approximately 5 dB higher. The backscattering level was found to be insensitive to distance from the vegetation 'interface'.

2.5.4.5 Fading by Trees

A number of experimental studies have involved the characterization of fading as summarized below, all involving CW power measurements on tree-obstructed paths. In the present context, the term fading refers to the temporal variation in received power which results from a corresponding temporal variation in attenuation.

Observed fading has been briefly reported as follows:

- Fades of over 40 dB at the rate of at most a few (<2) Hertz are frequently seen [34].
- Fluctuations of as much as ± 6 dB have been seen on windy days [14].
- Fluctuations in received power were observed to often be between 10 dB and 20 dB, and sometimes more over a period of a few seconds (Section 4.1).
- Frequent drop outs of up to 50 dB attenuation lasting for around 10 msec have been observed; frequent drop outs of up to 50 dB attenuation lasting for around 10 msec [37].

Fading is discussed in greater depth in [59] as summarized below. In this case, no mention is made of any measures being taken to isolate the effect of trees, in particular the results apparently include the sites with unobstructed LOS, nevertheless tree obstruction was reported to be predominant.

- The fading was found to not be Rician, with the fades being too shallow; a lognormal distribution was found to result in a better fit.
- Diffraction by the tree canopy combined with wind is presented as a possible explanation of signal variability.
- Alternatively, variability may be caused by wind-induced motion causing changes in the gaps in the foliage that occur within the Fresnel zone, with the gaps allowing some energy through

A thorough characterization of fading on severely tree- and traffic-obstructed paths is given in [56], with some results being summarized here:

- power variation over a ten minute interval ranged from 35 dB to 55 dB,
- average probability for fade depth of 15 dB or more below the mean of a 10 minute interval ranged from 0.6 % to 12 %,
- average probability for fade depth of 30 dB or more below the mean of a 10 minute interval ranged from 0.2 % to 0.8 %,
- average fade duration is 1 msec,
- the channel remains approximately time invariant for 0.01 sec to 0.05 sec, i.e. fading is slow.

2.5.5 Effects of Vehicles

The multipath that results from reflections off of moving vehicles is potentially significant in certain situations, such as when the LOS grazes over a major thoroughfare. Such multipath could contribute to fading as mentioned for example in [34].

The effect of moving vehicles has been studied in [56]; nevertheless this study involves the effect of obstructing vehicles, which are unlikely to occur if subscriber antennas are mounted on rooftops.

2.6 Summary

Rain

- Of all the possible forms of precipitation, rain results in the most significant amount of attenuation.
- Attenuation due to absorption by atmospheric gases is negligible in comparison with rain attenuation near 28 GHz, but becomes significant near 60 GHz.
- Rain attenuation on a link can be described as a random process with a corresponding probability density function. Consequently, the rain attenuation value to be considered during system design depends on the percentage of time for which the attenuation is allowed to exceed that value.
- Specific rain attenuation distributions depend heavily on geographical location.

Buildings

- The observed loss associated with specular reflection from buildings is roughly in the range of 3 dB to 15 dB, depending on construction.
- Scattering from buildings outside of the specular beam is roughly isotropic and has an associated loss of 30 dB to 40 dB.
- The loss associated with transmission through a building is at least in the range of 60 dB to 100 dB, and possibly higher.
- Diffraction was found to be the primary mode of propagation into building shadows.

Trees

- The power observed in the shadow of tree-covered hills was found to agree with values predicted using the knife-edge diffraction model.
- Significant treetop diffraction has been observed in the field.
- Attenuation by single trees ranges from 2 dB/m to 6 dB/m.
- Back scattering from trees has an associated loss of roughly 50 dB.
- Severe fading (15 dB or more) on tree-obstructed paths occurs due to wind-induced motion.
- Neither class of existing tree attenuation study (single tree or orchard) is entirely sufficient for the problem at hand. A path in the present context will typically traverse, at random intervals, a number of isolated trees as well as clusters of trees, so that the dominant form of propagation may vary along the length of the path.

Vehicles

- More study is required to determine the degree to which moving vehicles cause channel impairments.

Chapter 3: Propagation Simulator

3.1 Terrain Model

Terrain is modelled using data structures that correspond to the ground, buildings and foliage (trees) as described below. In all cases, the data is purely geometrical in nature; information pertaining to electrical properties and surface roughness are not included.

Buildings and trees are denoted as *ground clutter*. These are assumed to be the dominant objects that provide obstruction to antennas that are mounted on residential rooftops.

Throughout this section a right-handed co-ordinate system with arbitrary origin is assumed, with the Z axis being in the vertical direction and the XY plane being horizontal. The elevation of a point corresponds to its Z co-ordinate.

3.1.1 Ground Surface

The ground is modelled as a continuous surface composed of flat triangular facets as shown in Figure 22. Elevation information is stored as a square grid of points. In each square, an additional centre point is constructed, thereby dividing the square into four flat triangular facets. The elevation of the centre point is the average of the elevations of the four corner points.

Figure 22: Ground Surface Representation

Background

Little emphasis has been placed on the precise representation of the ground surface, due to the rarity of predicted interactions of the ground surface with predicted paths, and due to the omission of ground reflections from the model. In particular, ground diffraction has been rarely predicted in the simulations described in this thesis, which is likely due to the density and uniformity of the distribution of ground clutter found in the database used here.

3.1.2 Buildings

Individual buildings are modelled using solids that are termed *polyprisms* as illustrated in Figure 23. A polyprism consists of one or more vertically aligned *prisms*, with each prism sharing one or more vertical surfaces, in whole or in part, with other prisms in the polyprism. In the present context, a prism is a polyhedron with parallel, polygonal and congruent bases, and sides that are rectangles; vertical alignment infers that the bases are horizontal and that the sides are vertical as illustrated in Figure 24. For brevity, the upper base of a prism is referred to as the *roof*, the lower base as the *floor* and the sides as *walls*. In general, the roof and floor elevations of each prism differ from those of the other prisms in the polyprism. In the case of a building, the walls of each

prism extend downward past the ground level to an arbitrary depth, so that the floor surfaces do not play a role in the channel simulator.

Figure 23: Building Representation Using Polyprism

Figure 24: Vertically Aligned Prism

Background

The choice of a building representation has been based on the information found in an available database, in the form of a closed polygon outline of the building in addition to a set of one or more enclosed rooftop elevation markers.

3.1.3 Individual Trees

Individual trees are represented by an ellipsoid as shown in Figure 25. The surface of the ellipsoid is given by all points (x, y, z) that satisfy the following equation:

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{a^2} + \frac{(z - z_0)^2}{b^2} = 1 \quad (3.1)$$

where (x_0, y_0, z_0) is the centre of the ellipsoid, the z axis is in the vertical direction, and a and b are semiaxes. Consequently, the ellipsoids are vertically aligned and symmetrical in azimuth. Each tree is characterized by a different value of a and b in general. The ellipsoid is suspended above the ground by a fixed distance T . The tree trunk is not explicitly represented. The ellipsoid marks the boundary of a volume of *foliage*, a term that is used here to denote leaves, twigs and branches.

Background

The representation of a ground clearance T is intended to represent the fact that most trees in suburban areas are groomed, and to allow for the possible prediction of propagation paths that are diffracted under trees, which may be of importance in scenarios where base stations or repeaters are mounted at relatively low heights, such as on light posts for example. The use of an ellipsoid with two degrees of freedom was chosen based on the information found in an available database, namely a circular outline representing the horizontal extent of the tree, and a single treetop elevation marker.

Figure 25: Individual Trees Over Ground Surface

3.1.4 Tree Thickets

Suburban areas typically contain groups of trees that have little or no spacing between them, or that are intertwined. These groups, termed *thickets*, are presented by polyprisms in much the same way that individual buildings are as illustrated in Figure 26. Thickets do not extend to the ground; instead they are suspended over the ground by a distance approximately equal to T , which is the same fixed distance as is the case of individual trees. The floor elevations of the prisms are generally at different elevations. The polyprism defines a volume of foliage.

Background

The choice of thicket representation has been based on the information found in an available database, in the form of a closed polygon outline of the thicket in addition to a set of one or more enclosed treetop elevation markers. The variation in bottom surface elevations across a thicket is required due to the very large horizontal expanse of some thickets. An alternative thicket representation, based on a cluster of overlapping individual trees, was considered but rejected due in part to difficulties associated with the computation of diffracted paths involving multiple overlapping ellipsoids.

Figure 26: Tree Thicket Over Ground Surface

3.2 Propagation Model

The propagation model results in the prediction of a set of paths between two arbitrary points in space as illustrated in Figure 27. Paths consist of a series of one or more straight line segments that are connected at points of diffraction or points of reflection as illustrated in Figure 28. In addition, path segments may include *foliage intervals*, i.e. portions of the segment that intersect trees or tree thickets, and points of partial diffraction.

The set of predicted paths includes one and only one *direct* path, and zero or more *reflection* paths. These two path classes differ only in the number of reflections, with direct paths having no reflection points and reflection paths having one and only one reflection point. In contrast, both classes have an unlimited number of diffraction points, foliage intervals, and partial diffraction points.

Each path has an associated power loss value L_{path} , which is given in decibels by the following expression:

$$L_{path} = L_{FS} + L_{obstr} + L_{rain} \quad (\text{dB}) \quad (3.2)$$

where L_{FS} is the free space path loss, L_{obstr} is the path loss due to obstructions, and L_{rain} is the path loss due to rain. An interpretation of this equation is given in Section 5.1.4. In this context, the term “obstruction” is taken to mean buildings, trees, thickets or ground surface elements that interact with the path, regardless of whether or not they obstruct the LOS between transmitter and receiver.

The free space loss is derived from the Friis transmission formula [77] by assuming ideal isotropic antennas and defining the loss as the ratio of transmitted power to received power at the antenna terminals:

$$L_{FS} = 20 \log \left(\frac{4\pi R}{\lambda} \right) \quad (\text{dB}) \quad (3.3)$$

where λ is the carrier wavelength, and R is the combined length of all segments in the path.

The path loss due to obstructions is given in decibels by:

$$L_{obstr} = \gamma (L_{diff} + L_{refl} + L_{trans}) + \delta \quad (\text{dB}) \quad (3.4)$$

where L_{diff} is the net loss attributed to diffractions, L_{refl} is the net loss attributed to reflections, L_{trans} is the net loss due to transmission through foliage, and γ and δ are constants. For the remainder of the thesis, these constants are given the following values, the derivation of which is discussed in Section 4.4:

$$\gamma = 0.8 \quad (\text{unitless}) \quad (3.5)$$

$$\delta = 3.2 \quad (\text{dB}) \quad (3.6)$$

The evaluations of L_{diff} , L_{refl} , L_{trans} and L_{rain} are given in Sections 3.2.3, 3.2.4, 3.2.5 and 3.2.1 respectively.

The predicted path loss is assumed to be reciprocal. The phase and depolarization of the path are not predicted by the model.

The resulting set of predicted paths and associated path losses are independent of the communication system, depending instead only on the terrain database. The effect of

antenna beam patterns and antenna orientation can be accounted for with, as an additional step, the application of appropriate antenna gains to the path losses as has been done for example in Section 4.2.

Background

The predicted paths are intended to represent the most significant propagation paths that exist between the two points in question, i.e. those paths with the least path loss. The manner in which these paths are chosen out of all possible paths is discussed in Section 3.3. The limitation to paths with single reflections is an example of a heuristic used to reduce the number of relatively weak rays that are predicted. Similarly, the limitation to a single direct path is another heuristic used for the same purpose.

The choice of the two propagation modes associated with trees, namely diffraction and transmission, is based on the assumption that either of the two modes may dominate in different situations as illustrated in Figure 29.

The omission of modelled transmission paths through buildings is suggested by the observed path losses described in [82], which are on the order of 60 dB or more.

The omission of modelled ground reflections is based on the assumption that these paths will typically be blocked by ground clutter due to the shallow angles that are typically involved as illustrated in Figure 30, as well as the density and randomness of the ground clutter that is found in a typical suburb as illustrated in (ref. illustration of the real database). Similarly, roof reflections are omitted for the same reason as illustrated in Figure 30.

Figure 27: Predicted Propagation Path Set (plan view)

Figure 28: Propagation Path Example

Figure 29: Alternate Propagation Modes Involving Obstructing Trees (side view)

Figure 30: Obstruction of Ground Reflected and Roof Reflected Paths

3.2.1 Rain Attenuation

The path loss due to rain is given in decibels by:

$$L_{rain} = \Gamma R \quad (\text{dB}) \quad (3.7)$$

where Γ is the specific rain attenuation in dB/km, and R is the combined length of all segments in the path. The value of Γ is allowed to vary over a range during the analysis presented in Chapter 6 and Chapter 7. The relationship between Γ and geographical location, rain rate and availability is discussed in Section 2.5.2.2.

3.2.2 Single Diffraction

The loss associated with a single diffraction point is based on the knife-edge diffraction model as described in [63]. In this case the obstruction, regardless of type, is modelled as a perfectly absorbing half-plane. The diffraction loss L_{KE} is given in decibels by:

$$L_{KE} = 20 \log |F(v)| \quad (\text{dB}) \quad (3.8)$$

where $F(v)$ is the ratio of E_d , the electric field of the knife-edge diffracted wave, to E_0 , the electric field in free space in the absence of the knife edge and ground. $F(v)$ is given by the complex Fresnel integral:

$$F(v) = \frac{(1+j)}{2} \int_v^{\infty} \exp((-j\pi t^2)/2) dt \quad (\text{unitless}) \quad (3.9)$$

and v is the Fresnel-Kirchoff diffraction parameter given by

$$v = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (\text{unitless}) \quad (3.10)$$

where h is the relative height of the edge, and d_1 and d_2 are the distances between transmitter, receiver and knife edge as illustrated in Figure 31. A positive value of h denotes that the LOS intersects the half-plane, while a negative value denotes that the LOS does not intersect the half-plane.

The values of h , d_1 and d_2 are based on the geometry of the path segments that are joined at the diffraction point as illustrated in Figure 32, i.e. they do not depend on the obstruction itself once the diffraction point has been located. The procedure for determining the existence of one or more diffraction points and their location for each type of obstruction is described in Section 3.3.

The loss due to diffraction by building edges, L_{BD} , is modelled as knife-edge diffraction without modification, i.e.:

$$L_{BD} = L_{KE} \quad (\text{dB}) \quad (3.11)$$

In contrast, the loss L_{TD} due to diffraction by foliage, both individual trees and thickets, as well as the loss L_{GD} due to diffraction over the ground surface are modelled using a modified form of knife-edge diffraction. These losses are given in decibels by:

$$L_{TD} = \alpha L_{KE} \quad (\text{dB}) \quad (3.12)$$

$$L_{GD} = \alpha L_{KE} \quad (\text{dB}) \quad (3.13)$$

where L_{KE} is given by equations (3.8) through (3.10), and α is a constant. For the remainder of the thesis, α is given the following value, the derivation of which is discussed in Section 4.4:

$$\alpha = 0.8 \quad (\text{unitless}) \quad (3.14)$$

Figure 31: Knife-Edge Diffraction Geometry

Figure 32: Single Diffraction

3.2.2.1 Partial Diffraction

The loss L_{PD} associated with an obstacle that is near to, but not intersected by the path is similarly determined by the knife-edge diffraction model as described in Section 3.2.2. The partial diffraction loss L_{PD} is given in decibels by:

$$L_{PD} = L_{KE} \quad (\text{dB}) \quad (3.15)$$

where in this situation the knife edge height h is negative. All types of obstruction are treated equally, such that α (Equation (3.14)) is not applied, even if the obstruction is foliage or the ground. Partial diffraction points are limited to obstruction edges that fall within the first Fresnel zone [63] of the path segment as illustrated in Figure 33:

$$h < \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \quad (3.16)$$

Unlike “full” diffraction points which join two path segments, partial diffraction points occur at arbitrary locations on existing segments. The procedure for determining the existence of one or more partial diffraction points and their locations for each type of obstruction is described in Section 3.3.

Figure 33: Partial Diffraction

3.2.3 Multiple Diffraction

The net diffraction loss resulting from N single diffractions on a path is given in decibels by:

$$L_{diff} = \sum_{n=0}^{N-1} \beta^n D_n \quad (\text{dB}) \quad (3.17)$$

where D_i is the loss of the i^{th} single diffraction, and β is a constant. For the remainder of the thesis, β is given the following value, the derivation of which is discussed in Section 4.4:

$$\beta = 0.6 \quad (\text{unitless}) \quad (3.18)$$

The losses D_i are ordered from largest in magnitude to smallest, i.e.:

$$D_i \geq D_{i+1} \quad (\text{dB}) \quad (3.19)$$

All types of single diffraction are treated equally when computing the net multiple diffraction loss. The loss D_i may be any one of $(L_{BD}, L_{TD}, L_{GD}, L_{PD})$.

3.2.4 Building Wall Reflection

Building wall reflections are modelled as specular. The path loss due to a single reflection is given in decibels by:

$$L_{refl} = \rho \quad (\text{dB}) \quad (3.20)$$

where ρ is a constant. For the remainder of the thesis, ρ is given the following value, the derivation of which is discussed in Section 4.4:

$$\rho = 0.0 \quad (\text{dB}) \quad (3.21)$$

The procedure for determining the existence of a reflection point and its location is described in Section 3.3.

3.2.5 Foliage Attenuation

The net path loss L_{trans} associated with transmission through foliage (individual trees or thickets) is modelled as follows. The intersection of the path with a volume of foliage results in one or more non-disjoint intervals as illustrated in Figure 35; each is denoted as a *foliage interval*. Foliage intervals are divided into *foliage groups* by (full) diffraction points as illustrated in Figure 34. In contrast, reflection points and partial diffraction points do not divide groups. The total length d_i associated with the i th group is found as the sum of the lengths of the individual foliage intervals that make up the group. Overlapping foliage intervals that may arise due to the existence of overlapping volumes of foliage within the terrain database are treated as a single interval, i.e. foliage is assumed to be of uniform density. The path loss of the i th group $L_{group(i)}$ is determined as follows [73]:

$$L_{group(i)} = K_2 \left[1 - \exp\left(-\frac{K_1 d_i}{K_2}\right) \right] \quad (\text{dB}) \quad (3.22)$$

where K_1 and K_2 are constants with the following values:

$$K_1 = 3.2 \quad (\text{dB/metre}) \quad (3.23)$$

$$K_2 = 34.4 \quad (\text{dB}) \quad (3.24)$$

Background

The experimental and theoretical studies of transmission through trees to date, discussed in Section 2.5.4, fall into two categories: the study of attenuation by single, isolated trees, and the study of signal penetration into continuously tree covered areas, such as forests and orchards. Neither class of study is perfectly suited to the situation of a typical MMW-BWA link, in which case the LOS will often intersect several isolated trees as well as thickets, with variable spacing between all. The model shown here is similar to those based on transport theory in that it predicts an attenuation that increases sharply at first with penetration depth, and less so at greater depths. Nevertheless, these transport theory models predict a loss that increases with depth indefinitely, while reported measurements often show a loss that approaches a constant value, as is the case in the model shown here. This behaviour strongly suggests that treetop diffraction comes into play at greater depths.

In summary, the foliage attenuation model presented here is ad hoc, and is not fully supported by experimental evidence. It is based on a reported model of attenuation as a function of depth of penetration, which follows a form that is partially consistent with transport theory (i.e. scattering as the dominant mechanism) as well as likely being consistent with treetop diffraction as a dominant mechanism at greater depths. When applied to the present situation, further interpretation of the model is necessary; in particular, the effect of reflections, diffractions and spacing along the path must be accounted for. In this case, reflections and diffractions are treated in a manner consistent with scattering as the dominant mode. Reflecting surfaces are assumed to result in virtual scattering sources so that negligible effect results. Diffracting obstacles are assumed to block most scattering, effectively dividing the foliage into separate attenuators. Spacing is assumed to have no effect, largely by default due to the lack of information required to characterize any effects to the contrary. Nevertheless, it is evident that sufficient spacing between trees will cause these to appear as point sources to each other, thereby limiting any interaction between them and making an additive model of attenuation more plausible.

In spite of the ad hoc nature of the foliage attenuation model, any errors associated with this model have been found to be largely inconsequential for two reasons: i) the relative rarity with which foliage attenuation is predicted in contrast to predicted diffraction by foliage, and ii) of the predicted foliage attenuations, the majority involved a single isolated tree or small thicket, so that issues involving the interpretation of intervening diffractions, reflections and spacings are moot.

Consequently, the foliage attenuation model presented here should be thought of as a remnant from early development stages, and that a simpler model is likely to be sufficient.

Figure 34: Foliage Attenuation (plan view)

3.3 Ray Tracing Algorithm

The ray tracing algorithm results in the prediction of a set of paths between two arbitrary points in space *A* and *B*. This set consists of one and only one *direct path*, and zero or more *reflection paths* as described in Section 3.2. The ray tracing algorithm is specified in Appendix 2. Descriptions and illustrations of key aspects of the algorithm are given in the remainder of this section.

The ray tracing algorithm involves the intersection of path segments with the objects in the terrain database. An object may intersect a segment on one or more non-disjoint intervals as illustrated in Figure 35. For brevity, each such interval is denoted an *interspan*.

Figure 35: Intersections of Segment with Object (Interspans)

3.3.1 Path Initialization

The direct path between points *A* and *B* is initially modelled as a single straight line segment *AB*. Reflection paths between points *A* and *B* are initially modelled as consisting of a single reflection point *R*, and two straight line segments *AR* and *RB*. These initial segments generally intersect terrain objects, including buildings, trees, thickets, and the ground itself as illustrated in Figure 36. Intersected objects are termed as *obstructions*.

Figure 36: Path Initialization and Obstructions (plan view)

3.3.2 Segment Resolution

Each of the initial segments described above is tested for the presence of obstructions. Segments that have one or more obstructions undergo *segment resolution*. Segment resolution is a recursive process that generally involves the replacement of an obstructed segment PQ with a multi-segment path as illustrated in Figure 37. Segment resolution can be thought of as a search for the least loss path out of all possible paths that extend from P to Q and that involve diffraction by or transmission through one or more terrain objects.

During this process, all obstructions are initially classified as *blockers*. The process continues until all segments are unblocked, i.e. the segments are unobstructed, or have non-blocking obstructions only. An obstruction is classified as non-blocking if transmission through it is assumed to occur. Only foliage objects (trees or thickets) support transmission in the present model.

A single iteration of the segment resolution process is illustrated in Figure 38. The iteration begins with the identification of all blockers on the segment, followed by the selection of a single blocker for further analysis, based on a measure of its *degree of obstruction*. The blocker with the highest degree of obstruction is selected.

Subsequently, a number of alternative paths are evaluated, with each path corresponding to a different mode of interaction with the selected blocker. The alternative paths correspond to either transmission through the object, or diffraction at some point on the surface of the object. One of the alternative paths is selected based on estimated path loss, marking the end of the current process iteration.

In the case of the selection of the transmission path alternative, the segment PQ remains unchanged, and the selected blocker is classified as non-blocking. This step occurs only if the selected blocker is a foliage object. In the case of the selection of a diffraction path alternative, the segment PQ is replaced with two segments PD and DQ , where D is a diffraction point on the surface of the selected blocker.

Figure 37: Segment Resolution Process (plan view)

Figure 38: Segment Resolution Process, Single Iteration

Background

The segment resolution process can be thought of as an optimization procedure involving a search for (ideally) the single least-loss path out of all possible paths having interactions (diffractions or transmission) with obstructions in the environment. The true least-loss path can be found in principle using an exhaustive search of all possible paths which include an arbitrarily high number of interactions with all objects in the environment. In contrast, the approach taken here has been to conduct a limited search for a sub-optimal solution, resulting in a path which is an approximation of the true least-loss path.

Each iteration of the process can be thought of as a step through a search “tree”, with the root (initial) node of the tree being the initial straight-line segment, and all leaf (terminal) nodes of the tree being (generally) multi-segment paths where each segment is unblocked, i.e. the paths are fully resolved. The intermediate nodes are multi-segment paths where one or more segments are blocked, i.e. these paths remain unresolved. Each intermediate node of the tree branches to B child nodes, where B is given by:

$$B = \sum_{i=1}^N \left(\sum_{j=1}^{M_i} A_{ij} \right) \quad (3.25)$$

and where N is the number of blocked segments in the path, M_i is the number of blockers in the i^{th} blocked segment, and A_{ij} is the number of alternate paths associated with the j^{th} blocker of the i^{th} blocked segment. Furthermore, the intermediate nodes generally have multiple parent nodes, which results from the (essentially) arbitrary way in which a blocked segment can be selected for further processing.

The search method used here involves a number of heuristics to limit the search, the most important ones being listed below:

1. only those terrain objects which are currently blocking the candidate path are considered as resulting in possible interactions,
2. the choice of blocker is based on a local (as opposed to global) metric, namely the blocker's degree of obstruction, and
3. the choice of alternate paths around (or through) a blocker is based on another metric which is largely local, namely the path loss estimate, which involves the current blocker as well as some (but not all) of the obstructions in the immediate vicinity.

Consequently, the search method can be thought of as being partially “greedy” [57], since the branching decisions are based on near-local information, and the evaluation of alternate paths can be thought of as implementing a minor degree of backtracking.

The segment resolution process can also be thought of as a three-dimensional extension of a two-dimensional algorithm for finding the shortest path over a terrain profile, illustrated in Figure 39. In particular, the segment resolution procedure degenerates into the 2D algorithm shown below when changes to the path are limited to positive vertical displacements only and when transmission through foliage is forbidden.

The determination of the shortest path over a terrain profile is discussed in [17]. The algorithm can be specified by the following recursive procedure:

FindPath(A,B,T):

given a line segment AB and a set of terrain points T

find the set of points $S \subset T$ which are above AB

if S is not an empty set

select the point C in S which has

the greatest vertical displacement relative to AB

replace segment AB with two new segments: AC and CB

FindPath(A,C,T)

FindPath(C,B,T)

else stop

This 2D algorithm is essentially equivalent to finding the perimeter of the convex hull of a set of points which includes the transmitter and receiver locations as well as all terrain elevation points between these two locations. In contrast, given a single convex 3D obstruction, the segment resolution process results in a set of paths which are *contained* within the 2D perimeter (surface) of the corresponding 3D convex hull, barring transmission through foliage. In the case of multiple and/or non-convex obstructions, the segment resolution process results in paths which are contained within the corresponding convex hull but not necessarily limited to the hull's perimeter.

Figure 39: Finding the Shortest Path Over a Terrain Profile

3.3.3 Construction of Diffraction Points

The segment resolution process involves the creation of a set of diffraction points on the surface of each blocker. These diffraction points are used in the evaluation of the blocker's degree of obstruction, as well as in the creation of the alternative paths. In the most general case, four diffraction points are created, entitled *top*, *bottom*, *left* and *right*. Fewer diffraction points may be created depending on the type of obstruction as listed below:

thicket: *top, bottom, left, right*
 tree: *top, bottom, left, right*
 building: *top, left, right*
 ground square: *top*

These diffraction points are in all cases displaced from the segment in either a purely horizontal or purely vertical manner as illustrated in Figure 40.

Figure 40: Diffraction Points on Surface of Arbitrary Obstacle

3.3.3.1 Building and Thicket Diffraction Points

A general method for determining the diffraction points on the surface of an obstructing polyprism is used for buildings and thickets. For this purpose, each prism P that makes up the polyprism is divided into sections by a number of horizontal planes as illustrated in Figure 41 and Figure 42. Each section thus created is termed a *cell*, and the original prism P is subsequently termed a *stack*. The horizontal planes that divide the cells within a stack are constructed by extending the floors and roofs of all other prisms in the polyprism. Furthermore, all cells that are horizontally adjacent to one another form a *tier*. Note that cells, stacks and tiers are all vertically aligned prisms.

In general, four diffraction points (T,B,L,R) are associated with an obstructing polyprism; in the case of an obstructing building, the bottom diffraction point is omitted. The construction of these diffraction points involves the selection of various subsets of the cells that make up the polyprism:

- the set of cells that are intersected by the segment,
- the set of stacks that are intersected by the segment, and
- the set of tiers that are intersected by the segment.

The stack set is composed of all stacks in the polyprism that include one or more intersected cells. Similarly, the tier set is composed of all tiers in the polyprism that include one or more intersected cells.

The diffraction points occur only on those polyprism edges that support diffraction. These include all outside edges that form a convex corner as illustrated in Figure 43. In addition, building floor edges do not support diffraction.

The construction of the top diffraction point involves the temporary creation of a diffraction point on each roof edge in the set of intersected stacks as illustrated in Figure 44. The diffraction point coordinates are found by the intersection of the projections of the segment and edge in the XY plane. Edges that do not support diffraction, as well as edges that fall below the segment at the diffraction point are omitted. The diffraction point with the largest degree of obstruction is selected. In this case, the degree of

obstruction is equal to the vertical separation between segment and edge at the diffraction point.

The construction of the bottom diffraction point is similar to that of the top diffraction point, with floor edges replacing roof edges.

The construction of the left and right diffraction points involves the temporary creation of a diffraction point on each wall edge in the set of intersected tiers as illustrated in Figure 45. The diffraction point coordinates are found by constructing the shortest segment U that connects the edge E and path P segments. As a consequence of U having minimum length, it is perpendicular to both E and P , and since E is vertical in this case, U is horizontal. Edges that do not support diffraction are omitted. The diffraction point with the largest degree of obstruction of all diffraction points that fall on the left side of the segment is selected as the left diffraction point. In this case, the degree of obstruction is equal to the length of segment U . A similar process is used to find the right diffraction point. In certain situations, there are no diffraction points on either the left or right sides that satisfy all requirements as illustrated in Figure 46, in which case the number of diffraction points, and consequently the number of alternate paths associated with the obstructing polyprism, are both reduced by one.

Figure 41: Polyprism Composed of Cells

Figure 42: Cell with Associated Tier and Stack

Figure 43: Polyprism Edge Diffraction Support

Figure 44: Polyprism Diffraction Points, (T)op and (B)ottom

Figure 45: Polyprism Diffraction Points, (L)eft and (R)ight

Figure 46: Polyprism Without (R)ight Diffraction Point

3.3.3.2 Tree Diffraction Points

The construction of the four diffraction points associated with an obstructing tree involves finding the midpoint M of the interspan J , and the horizontal and vertical extension of M to a cylinder Y that circumscribes the tree ellipsoid E as illustrated in Figure 47. The degree of obstruction associated with each diffraction point is equal to the distance from point M to the diffraction point in question.

Figure 47: Tree Diffraction Points

3.3.3.3 Ground Square Diffraction Point

The construction of the single diffraction point T associated with an obstructing ground square involves finding the midpoint M of the interspan J , and the vertical extension of M to a horizontal plane W that has the same elevation as the highest ground square point. The interspan J is defined as the intersection of the segment and a rectangular prism Y that is found by extending the ground square vertically in both directions. This procedure is illustrated in Figure 48. The degree of obstruction associated with the diffraction point T is equal to the distance from point M to point T .

Figure 48: Ground Square Diffraction Point

3.3.4 Reflective Building Selection

A subset of all buildings in the terrain database is chosen prior to the determination of reflection paths between points *A* and *B*. This subset includes all buildings that will be tested for reflection, i.e. only those buildings in the subset will be tested for the possible occurrence of a reflection from any of its wall surfaces. The subset includes all buildings that are either *tall* or that are *near* to point *B*.

A building is *tall* if its height above ground *H* satisfies the following:

$$h > h_{tall} \quad (\text{metres}) \quad (3.26)$$

where h_{tall} is a constant whose value is selected by the user. Similarly, a building is *near* to point *B* if the distance *d* between building and point *B* satisfies:

$$d < d_{near} \quad (\text{metres}) \quad (3.27)$$

where d_{near} is a constant with user-selected value.

Throughout the remainder of this thesis, point B is taken to be the location of the subscriber terminal or repeater, which is assumed to be below the ground clutter canopy. This assumption is required for the reflective building selection process to be valid.

Background

In general, h_{tall} should be chosen to correspond to the height of the ground clutter canopy, and d_{near} should be chosen to correspond to the distance at which the LOS between two points, both below the clutter canopy, has a high probability of being obstructed by ground clutter. Furthermore, both of these constants should be chosen conservatively, since the selection process is a heuristic with an associated error. The process of reflective building selection is equivalent to rejecting those buildings that are not tall and that are distant from point B, which is assumed to be below the ground clutter canopy as illustrated in Figure 49. In principle, the selection process can be made even more exclusive if point A is known to be below the clutter canopy as well.

Figure 49: Reflective Building Selection

3.3.5 Computation and Testing of Building Wall Reflection Point

Reflections from building walls are modelled as specular reflections, which implies that the angles of incidence and reflection are equal as illustrated in Figure 50. This allows the use of the *method of images* [43,53] to compute the position of the point of reflection. In summary, for a flat surface, a virtual source is located at a point opposite to the true source relative to the plane defined by the surface, and the reflection point is found as the intersection of the virtual LOS and the plane. In the present model, building walls are always vertical and rectangular, which simplifies the required computations.

If the reflection point lies on the surface of the wall, the reflection is valid, otherwise the reflection is rejected.

Figure 50: Building Wall Reflection

3.3.6 Recomputation of Reflection Point

Following the resolution of the two segments AR and RB, the reflection point R is recomputed using the method of images once again, and the reflection is rejected if the new reflection point is found to fall off of the surface of the wall. In this case, the reflection is based on the geometry of the two path segments that are adjacent to R as illustrated in Figure 51.

Background

When following the principles of geometrical optics, the precise determination of all diffraction and reflection points on a path generally requires the simultaneous solution of all point coordinates. The method presented here involves the sequential solution of point coordinates, and is therefore approximate. The iterative recomputation of point coordinates, as is done here, results in successive refinement.

In cases where path resolution results in at most a few shallow diffractions, the original reflection point estimate tends to be a good approximation, and the probability of

the point remaining on the wall after recomputation is high. In contrast, when path resolution results in several possibly steep diffractions, the original point estimate tends to be poor, so that the probability of the point remaining on the wall after recomputation is relatively low. Furthermore, the path in question is likely to have a high path loss due to the diffractions. As such, the final recomputation and testing of the reflection point serves to reduce the number of predicted reflections that are both weak and fallacious.

Figure 51: Recomputation and Testing of Reflection Point (plan view)

3.3.7 Removal of Negative Diffraction Points

Diffractions can be classified as being either positive or negative, based on the relationship between the two path segments that meet at the diffraction point, and an outward pointing vector on the obstruction surface or edge as illustrated in Figure 52. Only positive diffractions are allowed in the ray tracing algorithm described here. The segment resolution process will occasionally result in negative diffractions, which are removed in a final phase of the path resolution process as illustrated in Figure 53. The new path thus created may intersect obstructions that have not been previously involved, so that the segment resolution process is repeated recursively. In addition, the removal of a negative diffraction point may cause other existing diffraction points to become negative, requiring a second degree of recursion.

Figure 52: Positive and Negative Diffraction

Figure 53: Removal of Negative Diffraction Point

Background

Negative diffractions occur as a result of the heuristic nature of the segment resolution process, in particular the manner in which the sequence of operations is determined. Paths with negative diffractions are assumed to have a higher overall loss than the equivalent path created by the removal of the diffraction point.

3.3.8 Blocker Evaluation

Once the set of blockers has been determined for a segment, each blocker is evaluated in terms of the *degree of obstruction* it provides. The worst blocker (providing the greatest degree of obstruction) is then selected for further processing.

The degree of obstruction of a blocker is equal to the least degree of obstruction associated with the diffraction points for that blocker. The process of blocker evaluation is illustrated in Figure 54.

Figure 54: Blocker Evaluation

3.3.9 Alternative Paths

The segment resolution process involves the creation of a set of alternative paths that are associated with a blocker as illustrated in Figure 55. Each path involves either diffraction at a point on the surface of the blocker, or transmission through the blocker. In the case of diffraction, the current segment PQ is replaced with two segments PD and DQ , where D is one of the diffraction points associated with the blocker as described in Section 3.3.3. The number and type of paths depends on the type of obstruction as listed below:

thicket: *top, bottom, left, right, through*
 tree: *top, bottom, left, right, through*
 building: *top, left, right*
 ground square: *top*

The paths are compared on the basis of the relative path loss estimate $L_{pathest}$ for each. The path with the lowest value of $L_{pathest}$ is selected for further processing, the others being discarded. The value of $L_{pathest}$ is given in decibels by the expression below. Note that $L_{pathest}$ involves the entire path and not merely the current segment and blocker.

$$L_{pathest} = L_{obstrest} \quad (\text{dB}) \quad (3.28)$$

where $L_{obstrest}$ is the estimated loss dues to obstructions, given in decibels by

$$L_{obstrest} = \gamma(L_{diffest} + L_{refl} + L_{trans}) + \delta \quad (\text{dB}) \quad (3.29)$$

and with all quantities as described in Section 3.2, with the exception of $L_{diffest}$, which is the estimated net loss due to diffractions, given by

$$L_{diffest} = \sum_{n=0}^{N-1} \beta^n D_n \quad (\text{dB}) \quad (3.30)$$

where each single diffraction loss D_i may be any one of (L_{BD} , L_{TD} , L_{GD} , L_{ID}), each of which is described in Section 3.2.2, with the exception of L_{ID} which is the diffraction loss associated with a blocker interspan:

$$L_{ID} = K_3 I \quad (\text{dB}) \quad (3.31)$$

where I is the length of the interspan in metres, and K_3 is a constant with the following value:

$$K_3 = 1.0 \quad (\text{dB/metre}) \quad (3.32)$$

In summary, the metric $L_{pathest}$ is similar to L_{path} , except for the following differences:

- the omission of free space loss

- the omission of rain loss
- the omission of partial diffractions
- the inclusion of an estimated diffraction loss for each blocker interspan

Figure 55: Alternative Paths

Background

The segment resolution algorithm can in principle be made either more or less greedy by changing the manner in which the path loss is estimated for the alternative paths, resulting in a trade-off between computation and accuracy. As an extreme example, the path loss estimate for a particular alternative path could involve full resolution of the segments involved, i.e. an entire sub-tree of the search would be evaluated.

The difference between alternative paths in the value of the omitted loss components is assumed to be negligible, due to the observation that alternative paths are generally very similar in length, and due to the observation that partially diffractions generally play a small role in the net path loss of a fully resolved path.

For the purpose of path loss estimation, a blocker is assumed to result in path interactions which are dominated by one or more diffractions when the path is fully

resolved, as opposed to being dominated by transmissions, even if the blocker is a tree or thicket. This is in accordance with the observation that, of all predicted path interactions with foliage objects, predicted diffractions are much more common than predicted transmissions.

The segment resolution algorithm has been found to be very insensitive to the value of K_3 . For example, values of 0.2 and 5 were found to result in little difference in predicted path loss.

3.3.10 Path Resolution Using General and Limited Methods

Each path between points A and B is resolved twice, whether a direct or reflection path, each time using a different method as illustrated in Figure 56: the general method that is described above, and the limited method. Of the two resulting path versions, the one with the lower path loss is retained while the other is rejected.

The limited method is identical to the general method, with the exception that one and only one candidate path is considered for each obstruction. This candidate path involves diffraction over the top of the obstruction only, i.e. candidate paths that involve diffraction around the sides or under the obstruction, as well as candidate paths that involve transmission through the obstruction are excluded.

Figure 56: Path Resolution using General and Limited Methods (plan view)

Background

This strategy can be thought of as expanding the segment resolution path search to include a special case path that has a relatively high probability of being the least-loss path. This approach reduces the overall error associated with the search heuristics.

Even without the inclusion of the limited method, predicted paths have shown a bias towards having only (or being dominated by) top-diffraction interactions. This bias can be explained in large part by the typical spatial distribution of ground clutter, being limited to a narrow range in the vertical direction, and consisting of closely-spaced obstructions. In contrast, it would be reasonable to expect an entirely different bias in different environments; for example, left- and right-diffractions may dominate in a situation where both transmitter and receiver are placed well below the average roof height in an urban high rise environment. Consequently, there is a general need to match simplified propagation models to the scenario at hand, as discussed for example in [3,67].

The process of segment resolution always results in quick convergence in the limited case, but not in the general case. The possibility of slow convergence in the general case, resulting in a final path with many segments, exists largely due to the heuristic nature of the candidate path loss estimation process.

The limited method results in a path that follows the convex hull of the 2D terrain profile between A and B as discussed in Section 3.3.2. As such, the ray tracing algorithm degenerates into a form that is more closely related to existing diffraction link loss models based on 2D terrain profiles such as found in [17,13,61].

3.3.11 Discussion

Energy scattered from trees, buildings or the ground is assumed to be negligible in comparison with all rays that are predicted by the model. In particular, field measurements indicate that backscattering by trees is very weak as shown in Section 2.5.4.4.

Gaseous absorption has not been included in the propagation model because this loss is negligible in comparison with rain loss at frequencies near 28 GHz as discussed in Section 2.5.2.

The rain loss model used here (Section 3.2.1) implies a uniform spatial distribution of rain. In practice, rain rate and hence specific attenuation varies significantly from location to location at any instant in time due to the existence of rain cells [12]. The associated error in predicted rain attenuation, as well as the possibility of providing an improved rain model are discussed in Section 9.3.3.1.

The simulator described here (including all component models and algorithms) contains several known approximations and other sources of error, with some of the more important ones being listed below. Furthermore, the implementation of the simulator may contain errors as is often the case with large bodies of software. Nevertheless, a comparison of simulator output with EPL values measured in the field (Chapter 4) indicates that the sum of all such errors is not sufficient (under tested conditions) to cause significant errors in predicted clear-sky coverage.

- Available terrain databases generally contain significant errors as shown for example in Section 4.3. In particular, the representation of trees and buildings at a scale on the order of a wavelength is highly impractical if not impossible.
- Diffractions models that are generally more accurate than the knife-edge model are available, such as the uniform theory of diffraction [45,51].
- The method of computing multiple diffraction loss used here is approximate in comparison to the known precise solution [83]. A comparison of multiple diffraction estimates is given in Section 8.1.6.
- The location of all diffraction points and reflection points on a path must be solved simultaneously when following the principles of ray-based optics; in comparison, the iterative method given here results in approximate locations.
- Diffraction points are found here using only vertical or horizontal displacements of the path, which is only approximately correct.
- Only those objects that are currently obstructing the path are tested for diffraction at any step of the iterative ray tracing algorithm. In principle, significant diffracted energy may result from any object in the vicinity.

- Of all possible direct paths (i.e. those without reflection), only a single one is included in the model output; in principle, a number of significant direct paths may exist.
- The ray tracing algorithm ignores all obstructions when determining the existence of a reflection. This leads to two types of errors, the end result being the significant underestimation of weak reflections: i) some predicted reflections do not occur when computed in a precise (non-approximate) manner, and ii) many fewer reflections are predicted than would be if an exhaustive, precise algorithm were used.
- Second order reflections and higher are omitted; this appears to have caused at least some errors in the prediction of significant reflections as shown in Section 4.6.2.

3.4 Implementation of Simulator

In contrast to the heuristic aspects and approximate nature of the ray tracing algorithm described in this chapter, the implementation of the algorithm in software has involved a number of acceleration techniques that do not result in any loss of precision. The more important techniques are discussed below.

3.4.1 Intersection Testing

Intersection calculations dominate the run time of canonical ray tracers [23]; similar domination occurs for the ray tracing algorithm described here. Consequently, significant run time improvements can be achieved by improvements to the intersection testing algorithm.

One such improvement involves the use of bounding volume hierarchies [23]. In summary, objects in the environment (or more specifically their constituent polygons) are organized into a tree data structure, where all objects within a subtree are spatially contained within an associated bounding volume. Intersection testing therefore proceeds in a manner which can be summarized by the following recursive specification. This can be thought of as a pruning technique, since all polygons which are contained in volumes which are *not* intersected are ignored.

```

# initialize the volume V to enclose the entire terrain database
FindIntersectingPolygonsInVolume(AB, V):
    given line segment AB and volume V
    for every sub-volume S contained in V
        TestVolumeIntersection(AB, S)
        if AB intersects S
            FindIntersectingPolygonsInVolume(AB, S)
    for every polygon P which is contained in V but not contained in a sub-volume
        TestPolygonIntersection(AB, P)

```

Due to the spatial distribution of objects in the terrain databases used in the present context, a specialized, essentially two-dimensional bounding volume hierarchy has been used here, namely a set of nested grid squares as illustrated in Figure 57. The number of levels as well as the sizes of the grid squares are user-definable. Three grid levels have been used throughout the simulations presented here, with the grid square sizes being 2000 metres, 400 metres and 80 metres respectively. In addition to the grid squares, individual buildings and thickets are further partitioned by bounding cylinders, both at the polyprism and prism levels as illustrated in Figure 58.

The smallest grid squares (80 metres on a side in this case) are represented by data structures which include pointers to all buildings, trees and thickets which are contained within the square, in whole or in part: in contrast, the included ground square elements are not listed since these exist as a separate square pattern and therefore can be readily identified. In addition, the data structures for all squares, regardless of size, include the maximum elevations for each class of obstruction within the square, thereby resulting in true bounding volumes.

Intersection testing involves the identification of those grid squares which are crossed by the two-dimensional projection of the line segment as illustrated in Figure 59. The algorithm for completing this task is closely related to existing methods for rendering pixelized images of oblique lines [22, "scan conversion of lines"]. Following this two-dimensional test, the possibility of intersection in the vertical dimension is then checked for each crossed square by comparing the minimum elevation of the portion of the line

segment which exists over the square to the maximum elevations for each class of obstruction.

When testing for intersection with prisms, the testing of prism walls (as opposed to prism roof and floor surfaces) is generally sufficient in the present context for all but pathological cases. Due to the fact that prism walls are vertical by definition, the testing can be efficiently completed by first testing for the intersection of the two-dimensional projections of the line segment and wall; this simplification is commonly reported in related literature.

Figure 57: Bounding Volume Hierarchy - Nested Grid Squares

Figure 58: Building with Bounding Cylinder

Figure 59: Grid Squares Crossed by Line Segment in 2D

3.4.2 Reflections

Various methods are used to reduce the number of reflections which must be computed, as well as to simplify the reflection computations themselves as described below.

Given that a building has been selected as a potential reflector, all building walls are first tested to determine whether or not they face the transmitter; in other words, they are tested for possible illumination by the transmitter, barring obstructions between transmitter and wall. In this manner, the number of reflection computations is roughly halved. This test involves the dot product of an outward-facing vector that is normal to the wall with a vector which represents the displacement of the transmitter relative to the wall. Similar methods are commonly reported in related literature.

Given a transmitter position and a facing (potentially illuminated) building wall, the problem becomes one of identifying those receiver locations of interest for which a valid reflection will occur. Instead of using the method of images to test every receiver position (of which there are generally many in the present context), a simplified version of the *method of regions* [43] is used. In summary, the region in which valid reflections can occur is first computed, at which point the problem becomes one of identifying which receiver locations are included in the region, which is generally a much easier problem.

The region of reflection is generally a semi-infinite volume defined by a truncated pyramid as illustrated in Figure 60.

In the present context, the computational savings afforded by this method are significant, due to the fact that the regions of reflection are generally smaller in area by several orders of magnitude than the overall region of interest. This size differential is due in turn to the small size of typical building walls relative to the typical distance to the transmitter, as well as being due to the fact that the transmitter is typically located above the average roof elevation in the present context, causing the regions of reflection to be limited by intersection with the ground. Furthermore, the regions of reflection are effectively truncated in most cases to a length of d_{near} as discussed in Section 3.3.4.

The task of identifying those receivers which are located within a region of reflection is accelerated using the bounding volume hierarchy described in Section 3.4.1; specifically:

- the boundaries of the region of reflection are computed as a two-dimensional closed polygon as illustrated in Figure 61,
- the set of smallest-size grid squares which are crossed by the line segments of the region boundary polygon is determined using the grid-square-crossing algorithm described in Section 3.4.1,
- all grid squares which are contained within the resulting outline are identified using an algorithm which is closely related to existing methods for rendering pixelized images of filled polygons [22, “filling polygons”]
- all receivers within the resulting set of grid squares are readily identified, given that the grid square data structures have been initialized to include a list of all contained receivers.

Given a transmitter position, a facing wall and a receiver position which is included in the resulting region of reflection, the task of determining the point of reflection is equivalent to an intersection problem involving a line segment which extends from the virtual (image) transmitter to the receiver. This task is efficiently completed using the wall intersection test described in Section 3.4.1.

Figure 60: Region of Reflection

Figure 61: Grid Squares Included in Region of Reflection

3.4.3 Miscellaneous

Further significant reductions in run time have been achieved using general, widely known programming techniques, with particular emphasis placed on the form of the numerical computations involved in intersection testing and reflection computation:

- The software has been written to achieve speed at the cost of additional storage wherever reasonably possible, such as through the storage of intermediate values, initialization, and the extensive use of tables of pointers or similar data organization techniques intended to reduce data access overhead time.
- Numerical computations have been formulated so as to avoid the need for explicit transcendental functions (square root, exponentiation, trigonometric, etc.) as well as to avoid floating point division wherever possible, due to the increased computing time required for these operations relative to addition, multiplication and look-up operations, even given commonly available floating point coprocessors. Most computations have been formulated to represent angles implicitly using the dot product operation.

For example, the test for intersection of a line segment with a vertical cylinder (such as a bounding volume for a building) need not involve the square root operation. The value of the cylinder radius squared (R^2) is pre-computed, stored and compared to the square of the length (L^2) of the shortest line which extends from the cylinder axis to the line segment. In turn, the coordinates of the endpoints of the shortest connecting line can be found by minimizing L^2 , a process which involves only two floating point divisions as well as additions and multiplications.

Chapter 4: Simulator Validation and Optimization

4.1 Field Measurements

A set of field measurements was used to derive optimal values for the empirical propagation model parameters (α , β , γ , δ) which are described in Section 3.2. Furthermore, the same set of measurements was used to validate the propagation simulator by way of comparisons with predicted signal power values.

4.1.1 Environment

The measurements were taken in Parkwood Hills, which is a typical residential suburban neighbourhood in Ottawa, Canada, over a period of several days from late September to early October 1996. Trees were in full foliage during this period of time. All measurements were taken during daylight hours. No significant precipitation occurred while measurements were being taken.

A view of Parkwood Hills taken from the top of a multi-story apartment tower is shown in Figure 3. This area has roughly 750 buildings per square kilometre, mostly one and two story residences with some clusters of tall buildings. Approximately 20% of the ground area is covered by trees, both deciduous and evergreen, most of which were mature and taller than the surrounding buildings. The terrain is gently sloping.

The area over which the measurements were taken is represented by the terrain database described in Section 4.3.

4.1.2 Equipment

The transmitter produced a vertically polarized continuous wave (CW) signal with a centre frequency of 28.7 GHz and a nominal output power of 24 dBm. The transmitter was of simple design and without temperature compensation, and for this reason the output power was free to drift over a range estimated to be on the order of 3 or 4 dB. The transmit antenna consisted of a vertically polarized rectangular horn with 18 dBi gain and

a 3 dB beamwidth of 23° in azimuth and 16° in elevation. The antenna was mounted on a 1.5 metre tripod on the roof of a multi-story apartment tower, near to the roof edge. The roof was in turn 40 metres above ground. The transmit antenna was pointed 5° down in elevation from horizontal.

The receiver was composed essentially of a frequency downconverter, amplifiers and a spectrum analyzer. The receive antenna consisted of a vertically polarized square horn with 23 dBi gain and a 3 dB beamwidth of 10° in both azimuth and elevation. The antenna was mounted on rotating platform at the top of a fixed mast mounted on the roof of a trailer as shown in Figure 62. The antenna was fixed in elevation with the boresight being horizontal, but free to rotate 360° in azimuth. The height of the antenna above ground was 4.4 metres throughout. The noise floor of the receiver was observed to be near -95 dBm. The link budget is given below.

Tx power	24 dBm
Tx antenna gain	18 dBi
Rx antenna gain	23 dBi
Rx line losses	2 dB
1st LNA gain	18 dB
Rotary joint loss	4 dB
2ND LNA gain	20 dB
Down converter loss	24 dB
Total system back/back Rx power	73 dBm
Noise floor	-95 dBm
Maximum measurable path loss	168 dB
Free space path loss at 2.5 km	130 dB
Max measurable EPL at 2.5 km	38 dB

Table 15: Measurement Equipment Link Budget

Figure 62: Receiver Equipment

4.1.3 Measurement Procedure

A number of receiver sites were selected, consisting of 74 *regular* sites in addition to 5 *calibration* sites. The regular sites were chosen so as to have a roughly uniform distribution within an area of approximately 6 square kilometres as illustrated in Figure 63. The distances from the transmitter site to the receiver sites ranged from approximately 250 metres to 2.5 kilometres. The receiver sites were generally located on road sides. A photograph was taken at each site which was later used for precise estimation of the trailer position and heading.

At each site, the rotating platform was levelled, the trailer heading was estimated using a magnetic compass, and the antenna was roughly aligned to the pre-computed transmitter bearing. A peak search was then performed, in which case the antenna was adjusted in azimuth within a range of a few degrees until the received signal power was maximized. A power reading was taken at this time. A 360° scan was then performed, in which case the antenna was slowly rotated in azimuth, stopping at angles where the

received power was significantly above the noise floor. A power reading was taken each time that a significant signal was observed; in this manner, specular reflections were observed, as well as broad regions in which the received power was found to be above the noise floor.

Each reading involved the visual observation of the received power level over a period of a few seconds, followed by the estimation of the maximum and minimum power levels observed during that time interval. These values were recorded manually.

Due to the limited beamwidth of the transmitter antenna, it was necessary to periodically change the transmitter antenna orientation in azimuth, as well as to change the rooftop location. This allowed the entire measurement area to be covered by the transmitter beam.

A calibration process was used to account for possible temperature-induced drift in the transmitter output power level, and is described in Section 4.4.1. This involved the selection of a number of calibration sites, with a new calibration site being selected every time the transmitter antenna was reoriented. An unobstructed LOS to the transmitter was visually confirmed at each calibration site. A single calibration site was assigned for each day during which measurements were conducted. Two power readings were taken at the assigned calibration site every day, immediately prior to and following all other measurements.

Additional readings were taken at some sites to determine the existence of a fixed spatial fading pattern as might result from strong multipath originating from fixed objects in the environment. This was accomplished by moving the receive antenna by a few wavelengths in an arbitrary horizontal direction and repeating the readings. No significant variation in signal level was observed as a result of the antenna displacement.

For the purpose of simulator validation and optimization, only those measurements that resulted from the 74 regular sites were used for comparison with predictions. In addition, only those reflections that were narrow in angular extent (relative to the receive antenna beamwidth) were retained; measured signals that occurred over a broad angular spread were omitted.

4.2 Simulation Procedure

A terrain database of the measurement area was acquired and modified as described in Section 4.3.

Precise locations for the transmitter and receiver sites, as well as estimates of the transmitter boresight angles were arrived at by comparing available notes, site photographs and video footage to the terrain database. The resulting horizontal position error is estimated to be under 2 metres in almost all cases, and under 1 metre in most cases. The antenna elevations used in simulation were based on the terrain database elevations found at those locations, with appropriate offsets to represent mast or tripod heights. The site locations are illustrated in Figure 63.

For each measurement site, a corresponding simulation was conducted using the propagation simulator described in Chapter 3. Each simulation resulted in a set of predicted paths and associated path losses between the transmitter and receiver sites. Each path set consisted of a single direct path and a set of zero or more reflection paths.

The true transmit antenna gain was estimated by noting the bearing of the receiver site relative to the transmit antenna. This bearing consists of an angular offset in azimuth and elevation relative to the transmit antenna boresight axis. The corresponding off-axis gain of the transmit antenna was estimated from existing antenna gain pattern measurements. This process was required due to the existence of several measurements that had been made with the receiver being outside of the nominal transmitter beam.

Figure 63: Measurement Sites (Circles) and Buildings (Grey)

4.3 Terrain Database

A terrain database of the measurement area was created that conforms to the terrain model described in Section 3.1. An illustration of a portion of the database is given in Figure 64.

Figure 64: Terrain Database Portion, Elevation Shading

4.3.1 Data Sources

A detailed terrain database of the measurement area was provided by the National Capital Commission, a portion of which is illustrated in Figure 65. This database is used primarily for city planning. Building outlines, thicket outlines, tree symbols, spot elevation markers and contour lines were retained, with all other information being discarded. Building and thicket outlines are represented in the database by polygons formed from multiple straight line segments with lengths of 2 metres or more, and trees are represented by circles with radii that range from 1 to 6 metres. The database has no fixed date of creation, being instead continuously updated. A brief survey of the area revealed that the database was largely correct, with occasional errors arising due to recent construction activity and tree removal. A comparison of the tree and thicket outlines with aerial photos revealed some growth, indicating that these outlines were created prior to 1989.

The NCC database is largely two dimensional, having limited elevation information. For this reason, a map making company was hired to provide comprehensive elevation data based on stereographic aerial photos dating from 1989. This data consisted of:

- a single point marking the crown of each individually represented tree,
- one or more points that characterized the height profile of each thicket,
- a single point marking the rooftop of most buildings, with multiple points being used for large, multi-level buildings,
- a single point marking the ground elevation at the base of each building,
- points marking the ground elevation along streets and in open areas with a spacing of approximately 100 metres.

The stated accuracy of the elevation data is ± 25 cm, although the tree top markers are anticipated to have a greater error due to the growth and pruning that occurred between the photograph date (1989) and the measurement date (1996).

Figure 65: NCC Terrain Database

4.3.2 Ground Elevation

A database of ground elevation points was created by combining the existing elevation points and contours from the NCC database with the new ground elevation points that were provided by the map making company. Triangulation was performed on the set of points, resulting in a ground surface model composed of an irregular grid of flat triangular facets as illustrated in Figure 66. This surface was then resampled on a square

grid of points with a spacing of 10 metres. The resulting ground surface model for the measurement area is illustrated in Figure 67.

Figure 66: Ground Surface Triangulation corresponding to Figure 65

Figure 67: Ground Elevation, Measurement Area

4.3.3 Trees and Thickets

Three refinements were applied to the contour and elevation data corresponding to the trees and thickets.

Firstly, all trees and thickets were expanded by 20% both in height and in radius. This was performed to compensate for the time that had elapsed between the moment at which the tree heights were determined (via aerial photos) and the moment at which the measurements were taken. The value of the growth factor was arrived at by assuming linear growth both in height and radius for all trees since the date of construction of the subdivision as shown below. All trees were assumed to have been planted on the construction date. The construction date used here is an average of the construction dates of the multiple subdivisions that make up the measurement area.

construction date (estimated)	$C = \text{Jan 1955}$
NCC database date (tree outlines)	$N = ? < 1989$
aerial photo date	$P = \text{May 1989}$
RF measurement date	$M = \text{Oct 1996}$

Table 16: Dates used for tree growth correction

$$\frac{(M - P)}{(P - C)} \approx 20\% \quad (4.1)$$

Thicket expansion in radius was accomplished by displacing each vertex horizontally by a distance D along a constructed outward-pointing vector, with D being 20% of R , the average thicket radius, defined as the mean distance from each vertex to the thicket centre point. The outward pointing vector was constructed so as to bisect the angle formed by the adjoining thicket segments.

Secondly, a correction was applied to the radius of selected trees and thickets to compensate in part for the growth that had occurred between the unknown time of tree outline creation N and the aerial photograph date P . This error was evident in cases where the tree or thicket height (dated P) was much greater than the diameter (dated N , prior to P), while the aerial photographs indicated otherwise. Tree diameters were

limited to being no smaller than 0.8 of the tree height, and the value of R used for thicket radii expansion was similarly limited to being no less than half the thicket height.

Thirdly, thickets outlines were partitioned based on the location of enclosed elevation markers as illustrated in Figure 68. Each partition and corresponding elevation marker were used to form a prism, with all prisms in the thicket forming a polyprism as discussed in 3.1.4. The partitioning algorithm is summarized as follows:

- a pixel-based image of the thicket outline is constructed,
- each enclosed elevation marker is assigned a unique colour number from 1 to N ,
- all pixels within the outline are assigned to the nearest elevation marker and coloured accordingly,
- all pixels outside the outline are assigned to colour 0,
- *new* vertices are constructed at all points where three colours meet,
- each non-disjoint single-colour region is identified as a partition,
- the outline of each partition is traversed, with straight line segments being constructed between all pairs of new vertices that are encountered.

Figure 68: Thicket partitioning

4.3.4 Buildings

Most building outlines enclosed a single elevation marker, in which case the resulting building polyprism consisted of a single prism. In cases where multiple

elevation markers were enclosed, the single marker that was closest to the outline centre was retained, the others being discarded.

In a few rare instances, large buildings were manually partitioned. This was necessary in the case of large multi-story buildings that were near to the transmitter sites, and that resulted in large false shadow zones when modelled as being composed of a single prism.

4.4 Empirical Parameter Optimization

The empirical parameters of the propagation model (α , β , γ , δ) described in Section 3.2 have been given values that optimize the agreement between predicted and measured *excess path loss* values (EPL) on direct (not reflection) paths.

4.4.1 Excess Path Loss (EPL)

Predicted excess path loss EPL_P in decibels is defined as

$$EPL_P = L_{path} - L_{FS} = L_{obstr} \quad (L_{rain} = 0) \quad (\text{dB}) \quad (4.2)$$

where L_{path} , L_{FS} and L_{obstr} are given by equations (3.2), (3.3) and (3.4).

Measured excess path loss EPL_M in decibels is defined as

$$EPL_M = L_M - L_{FS} \quad (\text{dB}) \quad (4.3)$$

where L_{FS} is given by Equation (3.3), where the distance R is given by

$$R = \sqrt{(A_x - B_x)^2 + (A_y - B_y)^2 + (A_z - B_z)^2} \quad (\text{metres}) \quad (4.4)$$

and A and B are the coordinates of the transmitter and receiver antenna positions as recorded in the simulation, described in Section 4.2.

The expression for the measured path loss L_M is derived as follows; an illustration of L_M versus distance R is given in Figure 69. The power at the receive antenna terminals is given by Eqn. (2.1), which can be expressed in decibels as

$$P_R = P_T + G_T(\phi, \theta) + G_R - L_M \quad (\text{dBm}) \quad (4.5)$$

The measured power P_M is related to the received power by

$$P_M = P_R + G_M \quad (\text{dBm}) \quad (4.6)$$

where G_M is the net gain of the receiver, including all amplifications and losses. Combining Equations (4.5) and (4.6) and rearranging terms results in

$$L_M = G_T(\phi, \theta) - P_M + K_C \quad (\text{dB}) \quad (4.7)$$

where K_C is a calibration factor, given in decibels by

$$K_C = P_T + G_R + G_M \quad (\text{dBm}) \quad (4.8)$$

The included calibration factor serves to account for long-term, unknown changes in the back-to-back gain of the measurement equipment, due largely to drifting in the transmitter output power (P_T) and changes in connector and cable losses (G_M). For each calibration measurement, the corresponding value of the calibration factor was estimated by solving Eqn. (4.7), with the path loss being assumed to consist of a free space path loss component only, i.e.

$$K_C = L_{FS} + P_M - G_T(\phi, \theta) \quad (\text{dBm}) \quad (4.9)$$

In summary, for each receiver site, EPL_M was calculated from the measured direct path power P_M as follows:

1. The measured power value P_M was taken to be the maximum power reading,
2. the calibration factor K_C from the most recent calibration measurement was used,
3. the effective transmitter antenna gain G_T was estimated by noting the bearing of the receiver site relative to the transmit antenna $\{\phi, \theta\}$ as discussed in Section 4.2,
4. the distance R between transmitter and receiver was computed and the corresponding free space loss L_{FS} was computed,

5. the measured path loss L_M and excess path loss EPL_M were found by solving Equations (4.7) and (4.3).

Figure 69: Measured Path Loss and Free Space Loss versus Distance

4.4.2 Parameter Optimization Process

The values of the empirical parameters of the propagation model $(\alpha, \beta, \gamma, \delta)$ were determined by minimizing an ad hoc cost metric M that is based on the degree of similarity between EPL_P and EPL_M . The cost metric M is given as a function of three of the four empirical parameters (α, β, γ) by

$$M(\alpha, \beta, \gamma) = c_1 \sigma_E + c_2 \frac{(1 - \rho_{PM})}{\rho_{PM}} + c_3 |\mu_E| \quad (\text{unitless}) \quad (4.11)$$

where (c_1, c_2, c_3) are constants that determine the relative weight of the cost metric components, and that have been given the following values:

$$\begin{aligned}
c_1 &= 1.0 \\
c_2 &= 0.5 \\
c_3 &= 0.2
\end{aligned}
\tag{unitless} \tag{4.12}$$

The mean μ_E of the EPL error is given by

$$\mu_E = \frac{1}{n} \sum_{i=1}^n E_i \tag{dB} \tag{4.13}$$

where the EPL error E_i is defined as

$$E_i = EPL_{P_i} - EPL_{M_i} \tag{dB} \tag{4.14}$$

The index i refers to the i th regular receiver site, and n is the number of regular receiver sites that have been included in the simulator validation and optimization process,

$$n = 74 \tag{4.15}$$

The standard deviation of the EPL error σ_E is given by the sample (non-biased) statistic

$$\sigma_E = \sqrt{\frac{n \sum_{i=1}^n E_i^2 - \left(\sum_{i=1}^n E_i \right)^2}{n(n-1)}} \tag{4.16}$$

and the correlation between predicted and measured EPL ρ_{PM} is given by

$$\rho_{PM} = \frac{\text{Cov}(EPL_P, EPL_M)}{\sigma_{EPL_P} \sigma_{EPL_M}} \tag{4.17}$$

$$\text{Cov}(X, Y) = \frac{1}{n} \sum_{i=1}^n (x_i - \mu_X)(y_i - \mu_Y) \tag{4.18}$$

$$\mu_X = \frac{1}{n} \sum_{i=1}^n x_i \tag{4.19}$$

$$\sigma_X = \sqrt{\frac{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2}{n^2}} \tag{4.20}$$

The value of the cost metric M was minimized using a manual iterative process. At each iteration, the values of the three parameters (α , β , γ) were changed by an incremental amount, the simulation was repeated and the cost metric was re-evaluated. This process continued until a change of 0.1 units in any number of parameters resulted in an increase in the cost metric, i.e.

$$\begin{aligned} M(Z_o + \Delta Z) &> M(Z_o) \\ Z_o &= \{\alpha_o, \beta_o, \gamma_o\} \\ \Delta Z &= \{a\varepsilon, b\varepsilon, c\varepsilon\} \quad a, b, c \in \{+1, -1\} \quad \varepsilon = 0.1 \end{aligned} \quad (4.21)$$

This process resulted in the following optimal values:

$$\begin{aligned} \alpha_o &= 0.8 \\ \beta_o &= 0.6 \\ \gamma_o &= 0.8 \end{aligned} \quad (4.22)$$

Finally, the value of δ was set to negate the remaining mean EPL error:

$$\delta_o = 3.2 = -\mu_{\varepsilon}|_{Z=Z_o} \quad (\text{dB}) \quad (4.23)$$

4.5 Comparison of Predicted and Measured Direct Path Loss

The following error metrics characterize the degree of agreement between the predicted and measured direct path loss values, following the optimization of the empirical model parameters. Note that the propagation model includes the path loss offset δ that has been adjusted to negate the mean EPL error, so that the true mean EPL error of the propagation has the same value. Also note that no value is given for the mean and standard deviation of the path loss error ($L_{path} - L_M$) since the path loss error is identical to the EPL error in all cases

mean EPL error = EPL offset (δ)	3.2 dB
standard deviation of EPL error (σ_E)	9.0 dB
correlation between EPL_P and EPL_M (ρ_{PM})	0.73
correlation between L_{path} and L_M	0.82

Table 17: Agreement Between Predicted and Measured Path Loss

The degree of agreement between predictions and measurements is also illustrated in Figure 70 through Figure 73, with interpretations given below:

- Figure 70 illustrates the distribution of E (μ_E , σ_E).
- Figure 71 indicates that there is no apparent trend relating the error in the predicted values (E) and the predicted values themselves (EPL_P). This is in contrast to the situation which existed during the early stages of propagation model development, in which case the predictions and prediction errors were strongly correlated, which implied that the predictions included a systematic error component.
- Figure 72 illustrates the correlation between predicted and measured EPL (ρ_{PM}).
- Figure 73 illustrates the correlation between predicted path loss (L_{path}) and measured path loss (L_M). Note that this figure is not merely a shifted version of the previous figure, since the free space loss varies from measurement to measurement.

Figure 70: Excess Path Loss Error Distribution

Figure 71: Excess Path Loss Error Trend

Figure 72: Predicted versus Measured Excess Path Loss

Figure 73: Predicted versus Measured Path Loss

4.6 Comparison of Predicted and Measured Specular Reflections

Predicted reflections were compared with measured reflections using two methods: i) a comparison of received reflected power distributions, and ii) a process of matching the strongest measured and predicted reflections, one by one. Both methods are described below.

In all cases, measured power values were adjusted to remove the effect of long term changes in the back-to-back gain of the measurement equipment, i.e. the measured power values were adjusted to reflect the measured values that would have been observed if K_C (Eqn. (4.8)) had been constant throughout the measurement period. A nominal value of K_C was selected that corresponded roughly to the average of the values that had resulted from the calibration process:

$$K_C^{(nom)} = 55 \quad (\text{dBm}) \quad (4.24)$$

The adjusted measured power value was subsequently determined as follows:

$$P_M^{(adj)} = P_M + K_C^{(nom)} - K_C \quad (\text{dBm}) \quad (4.25)$$

Similarly, the predicted power values were based on the predicted path losses in a manner that corresponded to an equivalent value of $K_C^{(nom)}$ as follows:

$$P_P = P_T + G_T(\phi, \theta) + G_R - L_{path} + G_M \quad (\text{dBm}) \quad (4.26)$$

$$P_P = K_C^{(nom)} + G_T(\phi, \theta) - L_{path} \quad (\text{dBm}) \quad (4.27)$$

$$K_C^{(nom)} = P_T + G_R + G_M \quad (\text{dBm}) \quad (4.28)$$

The previous equation indicates that the values of transmitted power P_T , receiver antenna gain G_R and net receiver gain G_M were given values during simulation that added up to 55 dBm, but that otherwise were arbitrary. Furthermore, the effective transmit antenna gain G_T was based on the bearing of the reflection point relative to the transmit antenna boresight axis, and not the bearing of the receiver antenna as was done for direct path loss comparisons.

Background

Alternatively, the comparison of predicted and measured reflections could have been based on some form of effective EPL, for example being relative to the free space loss of the direct path between Tx and Rx. This approach would have had the advantage of being consistent with the approach taken to compare the predicted and measured direct path loss used in Section 4.5. Nevertheless, the decision to base the comparison of reflections on received power was made so that the effect of the measurement noise floor at approximately -90 dBm would be evident as can be seen in Figure 74. In contrast, this measurement artefact is no longer evident when a histogram of EPL values is displayed, i.e. the effect of the noise floor is blurred in this case. The display of a clear noise floor allows for a better comparison of predicted and measured distributions.

Furthermore, if measured reflections had not been adjusted as shown in Equation (4.25), the power distribution would have been unnecessarily smeared since each measured power value includes a known measurement bias that is represented by K_C .

4.6.1 Distribution of Received Reflected Power

Two histograms were produced from the following data sets and are illustrated in Figure 74:

1. the adjusted measured power $P_M^{(adj)}$ for all measured specular (narrow) reflections arising from the regular receiver sites,
2. the predicted power P_P for all predicted specular reflections with power values greater than -120 dBm.

Figure 74: Received Power Histograms for Measured and Predicted Specular Reflections

4.6.2 One by One Comparison of Predicted and Measured Reflections

Predicted and measured specular reflections were compared one by one using a visual representation as shown for example in Figure 75. The comparison process consisted of two stages: i) the matching of predicted and measured reflections based primarily on the agreement in azimuth angle-of-arrival and to a lesser degree on the agreement in received power, and ii) the study of trends in the power prediction error. Furthermore, the reflection diagrams were studied for any clues to the causes of errors in the predicted reflections. These comparisons were carried out on a subset consisting of 45 receiver sites, the others being discarded due to an identified experimental error that resulted in random angle-of-arrival data.

The error in the measured angles-of-arrival is estimated to be on the order of $\pm 10^\circ$, and resulting from the error in pointing the receive antenna in azimuth, as well as from the error in the trailer heading estimate. The antenna pointing error results from the limitations of the equipment, including the finite beamwidth of the receive antenna, as well as human error. The trailer heading estimates were derived from site photographs and confirmed with the on-site magnetic compass readings.

The five measured reflections with the lowest value of measured excess path loss EPL_M are listed in Table 18 and illustrated in Figure 75 through Figure 79. The selection of reflections with the lowest measured EPL was done so as to identify relatively unobstructed reflection paths, and thereby to isolate (as much as possible) the reflection and its path loss from other path losses due to attenuation and diffraction.

Rx site number	EPL_M (dB)	measured power $P_M^{(adj)}$ (dBm)	matching reflection identified	predicted power P_P (dBm)	azimuth error (degrees)	power error (dBm)
#39	10.8	-65.7	yes	-72.6	-4°	-6.9
#13	7.9	-61.4	yes	-62.5	+6°	-1.1
#01	18.5	-59.4	no	NA	NA	NA
#19	14.3	-70.4	yes	-91.5	+4°	-21.1
#18	11.2	-71.4	uncertain	-73.6	+182°	-2.2

Table 18: Comparison of Five Reflections with Least Measured EPL

The illustrations in Figure 75 through Figure 79 show received signals, both predicted and measured, superimposed on an image of the neighbouring trees and buildings. Each signal is represented by an arrow, with the angle-of-arrival and strength (in decibels) of the signal being represented by the direction and length of the arrow respectively. Predicted signals are shown in grey, measured signals in black. All predicted and measured signals are shown, including the direct path signal, but of the reflections, only those that are listed in Table 18 are labelled with text. Predicted reflections are further illustrated with a cross-and-circle symbol marking the predicted reflection point, and a dashed line which shows the signal path immediately prior to reflection. In all cases, the transmitter is outside of the image, and lies in a direction indicated by the predicted direct path signal (grey arrow).

An examination of the table and figures in this section reveals that three of the five reflections were predicted (sites #39, #13 and #19), with an additional fourth reflection (site #18) possibly being predicted, assuming that a 180° error in azimuth occurred during the measurement. Of these reflections, the predicted and reflected power values are in good agreement with the exception of site #19, which was predicted to have strong attenuation due to a number of nearby trees, including the tree that is immediately in front of the predicted reflection point. An examination of the corresponding site

photograph reveals that the nearest tree had been cut down some time after the database creation date, which explains the power prediction error to a large degree.

The sole unpredicted reflection (site #01) appears to be due to a corner reflection as illustrated in Figure 77. The houses in this area were covered with metal siding, and the small projections on either side of the houses were rectangular chimney shafts that extended from ground to rooftop, thereby creating a two-dimensional corner reflector as illustrated in Figure 80. A three-dimensional corner reflector is formed by three mutually perpendicular flat reflective surfaces, and has the property that the reflected wave is exactly opposite in direction to the incident wave, regardless of the relative orientations of reflector and incident wave direction. A two-dimensional corner reflector is formed by two flat reflective surfaces that are perpendicular, and results in wavefront direction reversal in one plane only.

Further examination of Table 18 reveals that all predicted reflection power values were underestimated. Based on this observation, a value of 0 dB was chosen for the reflection coefficient Γ , corresponding to perfect reflection.

An extension of the comparison process to include reflections with greater values of measured EPL results in much poorer agreement. For example, of the 21 measured reflections with lowest EPL, four matched predictions with a high degree of confidence, six appeared to be just outside of predicted reflection beams, and two appeared to be the result of corner reflections, the other nine being unaccounted for.

Figure 75: Predicted and Measured Signals, Site #39

Figure 76: Predicted and Measured Signals, Site #13

Figure 77: Predicted and Measured Signals, Site #01

Figure 78: Predicted and Measured Signals, Site #19

Figure 79: Predicted and Measured Signals, Site #18

Figure 80: Two-Dimensional Corner Reflector, Three-View

4.6.3 Discussion

The agreement between predicted and measured reflections can be considered as two separate cases:

- 1) the degree to which measured reflections can be matched to corresponding predicted reflections, and
- 2) the degree to which predicted reflections can be matched to corresponding measured reflections.

In the first case, it was found that the strongest measured reflections generally have corresponding predicted reflections, but that weak measured reflections generally do not have corresponding predicted reflections. Overall, the numbers of predicted reflections are underestimated, especially weak ones. The significance of this underestimation of (generally) weak reflections is discussed in Section 4.8.

The underestimation of weak reflections is likely due in large part to the following limitations in the propagation model, ray tracing algorithm and terrain database:

- the limitation to first-order reflections,
- the limitation to building walls as the only possible reflectors,
- the simplified building surface representation,
- the strict adherence to the specular reflection model, without beam broadening due to finite wavelength or surface roughness, and
- the very limited search for paths that include a reflection and one or more diffractions.

The second case has not been examined here. Some disagreement is to be expected (i.e. “false positive” reflections) due the simplified building surface representation.

4.7 Comparison of Predicted and Measurement-Based Coverage

Two sets of coverage estimates were compared to each other, with one based on predicted path losses and the other based on measured path losses. The coverage estimates were computed for the entire set of measurement sites by treating the set as a simulated cell, i.e. with the transmitter site being treated as a single base station and the 74 regular receiver sites being treated as subscriber sites.

Coverage was evaluated for three separate cases as shown in Figure 81 through Figure 83, with each case corresponding to a different manner in which reflections were treated when determining the coverage status of each site:

Case (A) reflections were not used for link establishment,

Case (B) the strongest received signal was used for link establishment, whether it be from the direct path or due to a reflection,

Case (C) link establishment was based on the optimal combining of all received signal powers.

Case (A) corresponds to a situation where reflections are not suitable for link establishment for any reason, such as due to additional channel impairments for example. Case (B) corresponds to a situation where a highly directional subscriber antenna is assumed, and the antenna is pointed in a direction which results in the strongest received signal, both at the base station and subscriber ends. Case (C) corresponds to a situation where both the base station and subscriber are assumed to have a multi-antenna array and associated electronics that perform maximal ratio combining [63] of all incoming signals.

In all cases, coverage is computed as a function of the MTPL. It is assumed that the system parameters that determine the link budgets are chosen in a manner that results in identical values of MTPL on both the uplink and downlink.

More specifically, for predicted coverage, a subscriber site (corresponding to a regular receiver site) is covered if

$$L_p^{(eff)} < L_{MAX} \quad (\text{dB}) \quad (4.29)$$

where L_{MAX} is the MTPL, given by Eqn. (2.7), and $L_p^{(eff)}$ is the effective predicted path loss between the subscriber site and the base station (corresponding to the transmitter site), with a value that depends on the case in consideration:

$$\text{Case (A)} \quad L_p^{(eff)} = L_p^{(0)} \quad (\text{dB}) \quad (4.30)$$

$$\text{Case (B)} \quad L_p^{(eff)} = \min_{i=0}^N (L_p^{(i)}) \quad (\text{dB}) \quad (4.31)$$

$$\text{Case (C)} \quad L_p^{(eff)} = -\text{Dec} \left(\sum_{i=0}^N \frac{1}{\text{Dec}^{-1}(L_p^{(i)})} \right) \quad (\text{dB}) \quad (4.32)$$

where $\text{Dec}(\cdot)$ and $\text{Dec}^{-1}(\cdot)$ are functions for conversion from linear units to decibels and vice-versa:

$$\text{Dec}(x) = 10 \log_{10}(x) \quad (\text{dB}) \quad (4.33)$$

$$\text{Dec}^{-1}(x) = 10^{\frac{x}{10}} \quad (\text{unitless}) \quad (4.34)$$

and where $L_p^{(i)}$ is the loss associated with the i th predicted path, with $i=0$ for the predicted direct path and $i = \{1, \dots, N\}$ for the set of N predicted reflection paths.

Equation (4.31) can be derived as follows. It is known that the SNR of the output of a maximal ratio combiner γ_o is simply the sum of the SNRs of the M individual diversity branches γ_i [63, p.329]:

$$\gamma_o = \sum_{i=1}^M \gamma_i \quad (\text{unitless}) \quad (4.35)$$

In this case each diversity branch is assumed to correspond to a predicted path with associated path loss L_i , so that the SNR associated with the branch is given by Eqn (2.5), rewritten here as

$$\gamma_i = \frac{P_T G_T G_R}{(F-1)kT_0 B L_i} = C \frac{1}{L_i} \quad (\text{unitless}) \quad (4.36)$$

where C is a constant in this situation. Combining Equations (4.35) and (4.36) results in

$$\gamma_o = C \sum_{i=1}^M \frac{1}{L_i} \quad (\text{unitless}) \quad (4.37)$$

The effective path loss $L^{(eff)}$ is defined by

$$\gamma_o = C \frac{1}{L^{(eff)}} \quad (\text{unitless}) \quad (4.38)$$

and by combining Equations (4.37) and (4.38), the resultant expression for the effective path loss becomes

$$L^{(eff)} = \frac{1}{\sum_{i=1}^M \frac{1}{L_i}} \quad (\text{unitless}) \quad (4.40)$$

which is equivalent to Eqn. (4.32) when all path losses are expressed in decibels.

Similarly, for coverage based on measurements, a subscriber site is covered if

$$L_M^{(eff)} < L_{MAX} \quad (\text{dB}) \quad (4.41)$$

where $L_M^{(eff)}$ is the effective measured path loss between the subscriber site and the base station, with a value that depends on the case in consideration as before. Corresponding equations for $L_M^{(eff)}$ in each case can be derived by replacing the subscript P with M in Equations (4.30), (4.31) and (4.32). The value of $L_M^{(i)}$, the path loss for the i th measured path, is given by Eqn. (4.7).

Figure 81: Predicted and Measured Coverage, Case A (Direct Path Only)

Figure 82: Predicted and Measured Coverage, Case B (Strongest Signal Selection)

Figure 83: Predicted and Measured Coverage, Case C (Maximal Ratio Combining)

4.8 Discussion

When interpreting the results of the optimization and comparison procedures, a number of issues can be considered, each of which is elaborated below in turn:

- Does the use of the same set of measurements for optimization and comparison purposes nullify the validation?
- To what degree does the validation extend to conditions other than those that have been directly tested?
- Is the demonstrated agreement between predictions and measurements sufficient to meet the thesis objectives?
- Does the ad-hoc nature of the parameter optimization process, or any other known model approximation, nullify the validation?

It is common practice that empirical models be constructed with one set of empirical data (the *model data set*), and that the model output then be compared to the model data set as well as (at least) one other set of data (the *test data set(s)*). The relevant conditions under which the model set and test sets were generated (such as carrier

frequency, transmitter height, terrain features, etc.) form the *model conditions* and one or more sets of *test conditions* respectively. This comparison process can be divided into three cases:

- 1) the model output can be compared to the model data set itself,
- 2) the model output can be compared to a test data set that has been generated under the same conditions (the model conditions), but nevertheless representing a different experimental sample, and ideally being independently generated, and
- 3) the model output can be compared to one or more test data sets that were generated under test conditions that are significantly different from the model conditions.

The comparison in the first case listed above represents a partial validation of an empirical model. A negative result indicates that the model is invalid, while a positive result indicates that the model may be valid, but may suffer from overfitting. The comparison in the second case results in a validation of the model for the model conditions; in particular, this test will reveal overfitting. The comparison(s) in the third case validate the model for a range of conditions that extend beyond the model conditions, i.e. the generality of the model is validated.

Similarly, theoretical models can be validated by comparison to a test data set that is generated under conditions that are of interest but otherwise largely arbitrary, and the generalization of the model can be determined by comparison to test data sets that are each generated under different test conditions.

In the case of a quasi-empirical model, as is the case of the model developed here, the validation and test for generalization of the model should ideally be done as in the case of a purely empirical model. Due to a lack of available measurements, neither type of ideal comparison was completed, nevertheless some conclusions can be drawn as is discussed below.

The completed comparisons between the model output and the model data set can be thought of as presenting a *partial* validation of the model in this case. Furthermore, this test is more significant than it would be in the case of a purely empirical model, since it can be thought of as providing some confidence into the theoretical portion of the

model as well. In other words, the model has been shown to be consistent with the measurements, which is not entirely unexpected, nor entirely anticipated, since the model is *partially* based on the measurements.

Similarly, there is some confidence in the ability of the model to generalize to conditions outside of the model conditions, in spite of the lack of testing, due to the fact that the generalization of the model is in part governed by the theoretical portions of the model, and that these theoretical portions are in general well established. For example, given that a receiver is placed in the shadow of an obstructing building, and assuming that the dominant propagation mode is diffraction over the rooftop, both as modelled and in reality, then the model will correctly predict the effect of changes in either antenna height, antenna separation or carrier frequency, with an accuracy that depends on the correctness of the diffraction model itself.

Nevertheless, the extension of the model to untested conditions is not without risk. For example, most predicted paths under the model conditions involve diffraction over the top of a single tree, so that the predicted effect of a global increase in antenna heights is largely based on the (modified) knife-edge model. In reality, some entirely different propagation mechanism may be at play, such as transmission through the tree, or scattering by many neighbouring objects. Such a mismatch is possible if the model is based on too small of a measurement set, and/or if both modes lead coincidentally to similar behaviour under the model conditions. In summary, in such a worst-case scenario, the chosen model would have been found to agree with measurements largely by coincidence, with the failings becoming evident only in situations well outside of the model conditions.

The comparison of the model output (the predicted paths and associated path losses) and model data set requires some interpretation in light of the thesis objectives. The site-by-site comparison of predicted and measured direct path loss values (Section 4.5) reveals error statistics that are illustrative and useful for comparison to other propagation models, but that are by themselves not sufficient to determine the validity of the model. Similarly, the comparison of predicted and measured specular reflections (Section 4.6) reveals the existence of prediction errors, but does not indicate the relative importance of these errors. Finally, the comparison of coverage values that are based on both predicted and measured paths and associated path losses (Section 4.7) indicates that

the model and its implementation are, at least under model conditions, sufficiently accurate to meet the primary thesis objective, which is to provide a comparative evaluation of various coverage enhancing methods. In other words, the coverage comparisons reveal that the coverage prediction error is small when regarded as a percentage of the coverage values themselves within the range of interest (roughly 50% and above).

In particular, the coverage comparisons indicate that the errors associated with predicted specular reflections are not sufficient to invalidate the model in this case, although these reflection errors are shown to result in a coverage error that increases with the degree to which reflections are depended upon for link establishment. This insensitivity to reflection errors comes as a surprise in light of the fact that 31% of all sites had one or more measured reflections that were stronger than the measured direct path signal. Nonetheless, this effect can be largely explained by noting that two conditions must be met for the coverage status of a site to change when link establishment via single reflections is allowed: a) the direct path signal power must be insufficient for link establishment, and b) at least one reflection must have a power value that is sufficient for link establishment. The simultaneous meeting of these two conditions is made infrequent by the correlation between direct path and reflection power levels.

The ad-hoc nature of the parameter optimization process can be thought of as resulting in a model output error component, relative to the model output that would have resulted had the parameters been given “truly” optimal values, according to an arbitrary definition of optimality. Since it has been demonstrated that the net error in the model and its implementation is sufficiently small for the intended use of the model, then it can be concluded that the approximate nature of the parameter optimization process, as well as all other known approximations in the model, are not sufficient, individually or in combination, to invalidate the model under the model conditions.

In conclusion, the propagation model and its implementation (the propagation simulator) have been, in a strict sense, partially validated for the model conditions only. The validation was completed by demonstrating that *all* sources of error result in a coverage prediction error that is small when regarded as a percentage of the coverage values themselves within the range of interest. For this reason, it can be concluded that

the model is sufficiently accurate for the comparative evaluation of coverage enhancing methods, at least in those cases where the model conditions apply. In contrast, all predictions for other conditions involve an increased degree of uncertainty, so that these predictions should be thought of as guidelines that can be used to help identify the most promising methods.

Chapter 5: Broadband Wireless Access System Model

The remainder of this thesis concerns the prediction of coverage for a number of scenarios, and following from that, the evaluation and comparison of means of enhancing coverage. In all cases, the coverage values are based entirely on the status of bi-directional links between base stations and subscriber terminals. In this context, the status of a link refers to the possibility (true or false) of establishing the link between the terminals in question with a given SNR threshold. These links may be either direct, or may involve the use of a single repeater as discussed in Section 5.3. The manner in which coverage values are derived from link status information is described in Chapter 6.

5.1 Model Assumptions

The assumptions and simplifications listed here are implicit in the derivation of the expressions for link status and coverage. References to Case (A) through Case (C) indicate the manner in which reflections are combined at the receiver as described in Section 4.7.

5.1.1 Capacity and Interference

All forms of interference from other users are disregarded; coverage is based on the SNR at each receiver, not the SINR.

All forms of self- interference are disregarded, including intersymbol interference that results from multipath.

The capacity of the system is disregarded; consequently the number of sectors and the number of subscriber terminals per sector is not considered as a limiting factor.

5.1.2 Modulation and Multiple Access Schemes

The multiple access scheme is not represented directly, nevertheless the expression for MTPL (5.8) is most easily applied to FDMA, TDMA or some combination thereof. Similarly, the symbol modulation is not represented directly, instead the effect

of different modulation schemes can be accounted for by way of the SNR thresholds in (5.8).

5.1.3 Propagation

Predicted paths are assumed to be constant; similarly, predicted path loss values are assumed to be constant as discussed in Section 5.1.4.

All propagation paths are assumed to have reciprocal long-term path loss values. This implies that TDD is used, or that FDD is used with a carrier spacing that is small relative to the carrier frequencies themselves, or that any other form of duplexing is used that does not result in significant differences in long-term path loss.

The propagation model does not include polarization-dependent terms; nevertheless the model assumes vertical polarization by default since the measurement data set used during the model development process involved vertical polarization only.

Similarly, the propagation model does not include bandwidth-dependent terms. The model can be interpreted as being applicable to either narrowband or wideband systems, in spite of the fact that only narrowband measurements were used during the model development process. This interpretation is based on the assumption that the long-term minimum path loss is approximately independent of channel bandwidth. Nevertheless, the fading depth characteristics can be expected to change with bandwidth, so that this particular effect of bandwidth can be accounted for by the choice of an appropriate fading margin when interpreting the results in Chapter 7.

5.1.4 Path Loss

The treatment of path loss in this thesis is developed as follows:

The path loss on a fixed link is generally time-varying and frequency dependant and can be expressed as follows:

$$L(t, f) = L_{FS}(f) + \textit{shadow} + \textit{fade}(t, f) + \textit{rainatten}(t, f) \quad (\text{dB}) \quad (5.1)$$

where L is given in Eqn. (2.1), L_{FS} is the free space path loss given by Eqn. (3.3), *shadow* and *fade* are attenuations due to obstructions, and *rainatten* is the attenuation due to precipitation. By definition, *shadow* is constant in time and frequency over intervals of interest.

The FSPL is approximately constant given the carrier frequencies, bandwidths and distances under consideration here, so that the above equation can be simplified as follows:

$$L(t, f) = L_{FS} + \textit{shadow} + \textit{fade}(t, f) + \textit{rainatten}(t, f) \quad (\text{dB}) \quad (5.2)$$

The term *shadow* is loosely defined here as corresponding to the minimum excess path loss which occurs at any frequency in the band of interest over an extended, finite period of time and under clear-sky conditions, i.e.:

$$\textit{shadow} = \min_{t,f} [L(t, f)] - L_{FS} \quad (\text{dB}) \quad (5.3)$$

Consequently, *fade* is essentially non-negative in value as discussed in Section 8.1.3 and illustrated in Figure 84.

The path loss value predicted by the propagation model described in Section 3.2 under clear-sky conditions is arrived at by simply omitting the *fade* and *rainatten* terms, thereby resulting in what is effectively a path loss floor:

$$L_{\text{floor}} = L_{FS} + \textit{shadow} \quad (\text{dB}) \quad (5.4)$$

where it can be seen that *shadow* corresponds to L_{obstr} by examining Eqn. (3.2).

The time-variability and frequency-dependence of the rain attenuation can be accounted for by using a constant “worst case” value, which corresponds to the maximum rain attenuation which is expected to occur within a given percentage of time, so that the path loss equation becomes

$$L_{\text{floor},WC} = L_{FS} + \textit{shadow} + \textit{rainatten}_{WC} \quad (\text{dB}) \quad (5.5)$$

where the subscript *WC* denotes “worst case”, and $L_{\text{floor},WC}$ and $\textit{rainatten}_{WC}$ correspond to L_{path} and L_{rain} respectively in Eqn. (3.2). In other words, the path loss value predicted by

the propagation model presented here is the worst case (w.r.t. rain fading) floor (w.r.t. obstruction fading) value.

Finally, when coverage is computed (Section 6.2), the MTPL L_{MAX} is compared to the predicted path loss value, with the possible inclusion of a fixed fade margin as shown for example in Section 7.1.1.3:

$$L_{floor,WC} < L_{MAX} - M_{fade} \quad (\text{dB}) \quad (5.6)$$

In this case, M_{fade} does not represent a worst-case value of *fade*, instead it represents the ability of the communication system to tolerate fading. The two forms of fading (obstruction and rain) are treated differently because rain fades are assumed to typically be of long duration relative to the frame length, thereby resulting in outages, while obstruction fades are, at least in part, of short duration relative to the frame length, thereby being relatively transparent due to the effect of error correction.

Figure 84: Predicted Path Loss and Fading

5.1.5 Antennas

In Case (A) and Case (B), subscriber terminals are assumed to have an ideal highly directional antenna, which is described by a fixed gain G_{ST} on the main lobe,

negligible main lobe beamwidth, and infinite sidelobe isolation for all directions outside of the main lobe as illustrated in Figure 85. The antenna is assumed to be pointed with perfect accuracy in the direction of the path (either direct or reflection) upon which the link to the subscriber is established.

In Case (C), subscriber terminals are assumed to have an ideal antenna array that is capable of realizing an arbitrary number of main lobes, each with fixed gain G_{ST} and with negligible beamwidth as illustrated in Figure 85. The sidelobe isolation is infinite in all directions outside of the main lobes. The main lobes are assumed to be pointed with perfect accuracy in the direction of all paths (direct and all reflections) between the subscriber terminal and node (base station or repeater). For the purpose of illustration, such an antenna can be visualized as being composed of several individually pointed highly directional antennas.

In all cases, the base station is assumed to have a set of ideal sector antennas, each with a fixed gain G_{BS} that is uniform over the entire main lobe as illustrated in Figure 85. The sidelobe isolation is infinite in all directions outside of the main lobe. The sector antennas are assumed to be arranged so as to provide 360° coverage in azimuth, with no gaps or overlap; otherwise the number of antennas and their azimuthal beamwidth is arbitrary. The antennas are assumed to have sufficient beamwidth in elevation so as to provide coverage over the entire cell. Furthermore, it is assumed that some form of ideal multiple access is used to separate signals in both directions that are associated with different users but that fall in the same sector. In effect, the sectoring of the cell does not come into play other than as an explanation for the arbitrary value of G_{BS} .

Note that, in Cases (A) and (B), all paths between a base station and subscriber terminal other than the one selected for link establishment are nullified by the subscriber terminal antenna, i.e. zero signal is received by way of these paths in either direction due to the perfect spatial selectivity of the subscriber terminal antenna.

Repeater donor antennas are analogous to subscriber terminal antennas in all ways, and therefore depend on the mode by which reflections are combined. Similarly, repeater distribution antennas are analogous to base station antennas in all ways.

Figure 85: Antenna Patterns and Orientation

5.2 Direct Links (without Repeaters)

A direct bi-directional link can be established between a base station and subscriber terminal if

$$L < L_{MAX} \quad (\text{dB}) \quad (5.7)$$

where L is the effective path loss between base station and subscriber, and L_{MAX} is the MTPL of the system, defined by

$$L_{MAX} = \frac{P_{BS} G_{BS} G_{ST}}{\gamma_{ST(\min)} (F_{ST} - 1) k T_0 B_{DL}} = \frac{P_{ST} G_{BS} G_{ST}}{\gamma_{BS(\min)} (F_{BS} - 1) k T_0 B_{UL}} \quad (\text{dB}) \quad (5.8)$$

This equation is derived by applying Eqn. (2.7) to the uplink and downlink separately, and by assuming that the system is designed in such a way as to result in identical values of MTPL in both directions.

The effective path loss L is given by either Eqn. (4.30), (4.31) or (4.32), depending on the assumed manner in which reflections are combined at the receiver as discussed in Section 4.7. These equations are repeated here for convenience:

$$\text{Case (A)} \quad L = L^{(0)} \quad (\text{dB})$$

$$\text{Case (B)} \quad L = \min_{i=0}^N (L^{(i)}) \quad (\text{dB})$$

$$\text{Case (C)} \quad L = -\text{Dec} \left(\sum_{i=0}^N \frac{1}{\text{Dec}^{-1}(L^{(i)})} \right) \quad (\text{dB})$$

where $L^{(i)}$ is the loss associated with the i th path, with $i = 0$ denoting the direct path and $i = \{1, \dots, N\}$ denoting the set of N reflection paths.

5.3 Links with Repeaters

A bi-directional link can be established between a base station and subscriber terminal by way of a repeater if the following two conditions are met:

$$L_{DL}^{(rep)} < L_{MAX} \quad (\text{dB}) \quad (5.9)$$

$$L_{UL}^{(rep)} < L_{MAX} \quad (\text{dB}) \quad (5.10)$$

where $L_{DL}^{(rep)}$ and $L_{UL}^{(rep)}$ are the effective path losses on the downlink and uplink between base station and subscriber terminal when a repeater is included in the link, and L_{MAX} is the MTPL of the system, defined by Eqn. (5.8). Expressions for $L_{DL}^{(rep)}$ and $L_{UL}^{(rep)}$ are derived below.

The values for L_0 and L_I , the path losses on the donor and distribution links respectively, are given by either Eqn. (4.30), (4.31) or (4.32), depending on the manner in which reflections are combined at the receiver as discussed in Section 4.7.

5.3.1 Downlink Budget and Status

For the downlink to be established, it is necessary that

$$\gamma_{ST} > \gamma_{ST(\min)} \quad (5.11)$$

where $\gamma_{ST(\min)}$ is the minimum value of SNR that is required to result in a maximum acceptable downlink BER. Combining Equations (2.24) and (5.11) results in

$$1 < \frac{P_{BS} G_{BS} G_0 A G_1 G_{ST}}{\gamma_{ST(\min)} L_0 k T_0 B_{DL} [A G_1 G_{ST} (F_R - 1) + L_1 (F_{ST} - 1)]} \quad (5.12)$$

Substituting the left-hand expression for the MTPL L_{MAX} in Eqn (5.8) results in

$$1 < \frac{L_{MAX} G_0 A G_1}{L_0 [A G_1 G_{ST} (F_R - 1) / (F_{ST} - 1) + L_1]} \quad (5.13)$$

which can be rewritten as

$$L_{DL}^{(rep)} = \frac{L_0 [A G_1 G_{ST} (F_R - 1) / (F_{ST} - 1) + L_1]}{G_0 A G_1} < L_{MAX} \quad (5.14)$$

where $L_{DL}^{(rep)}$ is the effective path loss on the downlink between base station and subscriber terminal when a repeater is included in the link.

5.3.2 Uplink Budget and Status

Due to the symmetry which exists as discussed in Section 2.1.2.1, the expression for the effective path loss on the uplink can be found by a simple exchange of subscripts applied to Eqn.(5.14):

$$L_{UL}^{(rep)} = \frac{L_1 [A G_0 G_{BS} (F_R - 1) / (F_{BS} - 1) + L_0]}{G_0 A G_1} < L_{MAX} \quad (5.15)$$

Chapter 6: Coverage Simulation Procedure

The following is a description of the general method used to produce the coverage predictions given in Chapter 7. The following applies by default to all predictions, with individual exceptions listed in the following chapter.

6.1 Initialization of Simulation Area

A terrain database covering a square area of 6 km by 6 km was created by joining several copies of the Ottawa suburb terrain database that is described in Section 4.3. Individual copies were rotated and at times mirror-imaged as illustrated in Figure 86 and Figure 87 so as to achieve continuous ground elevation throughout, thereby avoiding erroneous shadowing caused by potentially large steps in elevation at the segment boundaries. This large database was created so that scenarios involving all cell radii of interest could be simulated in a consistent manner.

For each cell radius of interest, a square portion of the terrain database was selected as the simulation area (SA), possibly extending over the entire database, as illustrated in Figure 88. Base stations were placed on a square grid within the SA so as to coincide with the SA edges and corners, resulting in a square cell pattern. The simulation of areas covering several cells was done in general to help reduce any bias associated with the local terrain in particular cells, as well as the particular location of the base station within the cell. Furthermore, the required computing time was found to be largely insensitive to the size of the SA, instead being largely dependent on the number of simulated subscriber terminals. In all cases, the SA was chosen to coincide with an integral number of quarter cells, some times as few as one as shown in Figure 90; otherwise a bias in the results may occur if the SA area is chosen in an arbitrary manner.

Five hundred subscriber buildings were selected at random from all buildings in the SA, with each subscriber building being the site of a single subscriber terminal. The selection process, which resulted in a nearly uniform distribution of subscriber buildings within the SA, can be summarized as follows:

repeat until 500 buildings are selected

```

# P is a 2D point representing a surface location
P.x = SA.left_edge + UniformRV(SA.size)
P.y = SA.bottom_edge + UniformRV(SA.size)
select the building nearest to P that has not been previously selected

```

X = UniformRV(R):

```

# return a random variable X that is uniformly distributed in the range [0,R]
# generate X in a manner that is independent of previously generated values

```

For each subscriber building, a number of candidate subscriber terminal antenna sites were chosen as illustrated in Figure 89. These sites were located at a fixed elevation above the rooftop, representing the use of a rooftop-mounted antenna mast. The candidate rooftop sites were selected using the following algorithm:

```

add rooftop centre point to set of candidate sites C
arbitrarily select a rooftop edge vertex V
repeat until all rooftop edge vertices have been processed
    if V is at least 6.0 metres distant from all points in set C
        add point V to set C
    select next rooftop edge vertex V by following rooftop outline in CCW direction

```

All following computations of coverage involve the implicit selection of a single subscriber terminal antenna site from all candidate sites belonging to a given subscriber building as described in Section 6.2. The manner in which the building rooftop centre point is defined has been omitted for brevity.

In those scenarios that included the use of repeaters, a number of candidate repeater sites were placed on a square grid that covered the SA as illustrated in Figure 90. A grid spacing of 100 metres was used throughout. The possibility of an additional increase in coverage that might result from the evaluation of additional candidate repeater sites was not investigated, due in part to the limitation on site availability that is likely to occur in practice. Repeater antenna heights, both donor and distribution, were set at 10 metres above ground; this height value was selected to represent the mounting of repeaters on light posts and utility poles.

All following computations of coverage in scenarios that include repeaters involve the selection of a number of repeater sites from all candidate repeater sites in the SA as described in Section 6.2.

Background

The redundancy and symmetry inherent in the terrain database (TD) may result in coverage prediction errors, and the potential magnitude of these errors has not been determined. Nevertheless, there are reasons to believe that the approach taken is rational given the existing limitations.

Given only one “tile” (a single rectangular copy of the original TD), the simulation of a cell with radius greater than the dimensions of the tile requires that the base station be placed outside of the tile, i.e. in the “void” region. In this case, it is necessary to determine the ground elevation at the BS, as well as to model the possibility of obstruction and reflection by terrain objects in the void region. With regards to the ground elevation at the BS, it is rational to assume that the terrain elevation statistics are the same in the void region as in the tile, given no information to the contrary, and this is guaranteed by replication of the tile in the void region. Similarly, it is rational to assume that the distributions for obstruction density and height are similarly universal given no other information, and these statistics are similarly guaranteed by tile replication.

In addition, the role played by the void region in this situation is a relatively minor one, since simulations involving large cells also involve BS masts which are much taller than the ground clutter level by necessity. Consequently, obstruction of any of the predicted paths tends to occur at points which are near to the subscriber, and thereby which generally fall within the original tile. In addition, reflections from tall buildings in the void region tend to be relatively weak due to the larger distances involved, and therefore are of relatively minor importance.

Subscribers are always placed randomly and uniformly throughout the simulation area, so that the subscribers placed in any one tile are generally in different locations relative to those in any other tile. Similarly, the base stations are in different locations in each tile, even though they are placed on a uniform grid; the differences in location result from the difference between tile dimensions and grid spacing, as well as being due to the

rotation and/or mirror-imaging of the tiles. Consequently, the simulation over the entire TD can be thought of as being equivalent to several simulations involving a single tile, i.e. the overall simulation is equivalent to multiple runs of a Monte Carlo technique.

The tile duplication method used here will admittedly result in substantial errors if the tiles are sufficiently small and numerous, since the tile will no longer represent a statistically significant sample. In the current situation, the tile dimensions are on the order of several kilometres, and only a small number are used. The original tile is sufficiently large to capture the statistical nature of the terrain on dimensions of a few kilometres or less. An examination of the terrain which surrounds the tile in reality reveals a high degree of uniformity in all aspects of the terrain, such as building heights and spacings for example.

Where possible, the joints between tiles have been chosen to correspond to an actual boulevard which is wide and straight. The effect of the duplication in this case is to replace the terrain on one side of the boulevard with a mirror-image copy of the terrain on the other side. This approach is in agreement with the observation that the terrain is similar on both sides in reality.

Figure 86: Terrain Database, 6 km by 6 km (buildings)

Figure 87: Terrain Database, 6 km by 6 km (ground elevation, 0 to 40 metres)

Figure 88: Simulation Area

Figure 89: Candidate Subscriber Terminal Antenna Sites on Building Rooftop

Figure 90: Candidate Repeater Positions

6.2 Coverage Prediction: NLOS Operation

For each scenario involving NLOS operation, coverage was computed in a two-step process, each step being described in further detail below.

- 1) Propagation paths and associated path losses were computed for all links of interest, and

- 2) coverage was computed for a range of values of both MTPL L_{MAX} and specific rain attenuation Γ based on the predicted paths and losses.

6.2.1 Path Prediction

A set of propagation paths consisting of a single direct path and zero or more first-order reflection paths were predicted using the propagation simulator described in Chapter 3 between pairs of base stations and candidate subscriber terminal (CST) antenna sites in the simulation area. In cases where the SA was smaller in width than the base station spacing as illustrated for example in Figure 90, additional base stations were placed outside of the SA to allow for the simulation of macrodiversity.

A path set was predicted for every BS-CST pair for which the distance between BS and CST was less than or equal to the base station grid spacing G , where the distance metric in this case is the 2D L_∞ norm:

$$D_\infty(A, B) = \max(|B_x - A_x|, |B_y - A_y|) \quad (6.1)$$

As a result of the use of this distance limitation, paths were computed in all cases between every CST and the four nearest BS as illustrated in Figure 91, thereby allowing for the evaluation of macrodiversity.

The associated path loss values were computed for clear-sky conditions only at this point, i.e. rain attenuation loss L_{rain} was set equal to zero.

In those scenarios that included repeaters, two additional sets of predicted paths were determined as illustrated in Figure 92, both under clear-sky conditions as well: i) path sets between pairs of base stations and candidate repeater (CRP) sites, and ii) path sets between pairs of candidate repeater sites and candidate subscriber terminal antenna sites. The path predictions were made in the general manner with the exception of the BS-CRP pairs, in which case only the direct path was computed, i.e. reflection paths were omitted.

A path set was predicted for every BS-CRP pair for which the distance $D_\infty(\cdot)$ between BS and CRP was less than or equal to G . Similarly, the computation of paths

between CRP and CST was limited to those for which the distance $D_{\infty}(\cdot)$ was less than or equal to 800 metres. The value of this last range limit was found by trial and error to result in the exclusion of only a small fraction of all subscribers that are covered by a repeater in the case of unlimited range.

Figure 91: Predicted Path Sets Between CST and Four Nearest BSs

Figure 92: Predicted Path Sets, General Case

6.2.2 Coverage Computation

In all cases, coverage C is computed as a function of MTPL L_{MAX} and specific rain attenuation Γ as follows:

$$C(L_{MAX}, \Gamma) = \frac{N_{cov}(L_{MAX}, \Gamma)}{N_{bldg}} \quad (\text{percentage}) \quad (6.2)$$

where $N_{bldg} = 500$ is the total number of subscriber buildings for which coverage has been evaluated, and N_{cov} is the number of subscriber buildings that are covered, and which is dependent on L_{MAX} and Γ .

A subscriber building is covered if any of the candidate subscriber terminal antenna sites (CST) is covered.

6.2.2.1 Coverage without Repeaters

In those scenarios that do not include repeaters, a CST is covered if Eqn. (5.7) can be satisfied for the effective path loss L associated with any one of four path sets, where each path set is associated with one of the four nearest base stations as illustrated in Figure 91. Prior to evaluating the effective path loss, the rain attenuation L_{rain} is added to the clear-sky path loss of every path in the set to achieve the net path loss as shown in Eqn. (3.2) and (3.7). Note that the value of L varies depending on the assumed mode by which reflections are used.

The method of computing coverage C described above implies that the following procedure be followed in practice during subscriber antenna installation:

- the selection of the rooftop installation site be made after evaluating a number of candidate sites, either in the field or by way of a sufficiently precise planning tool, and
- such site evaluation takes into account a target value for Γ ; for example, a simulated rain attenuation value can be approximated in the field given knowledge of the distances to the base stations in question.

As a consequence of this approach to computing C , it follows that there is no single “best” subscriber antenna rooftop site for all values of L_{MAX} and Γ , nor is there a single “best” base station to which a link should be established. For example, given that a subscriber antenna site has an unobstructed LOS to a distant base station ‘A’ and a partially obstructed LOS to a nearby base station ‘B’, the strongest signal received at the subscriber antenna may originate from ‘A’ under clear skies, but originate from ‘B’ under sufficiently heavy rain.

This approach implies the use of *simple* macrodiversity as described in Section 2.1.4, since link establishment to a subscriber terminal is based solely on the signals that are transmitted by and received from a single base station. The use of more sophisticated forms of macrodiversity are not considered here.

6.2.2.2 Coverage With Repeaters

In those scenarios that include repeaters, a CST is covered if:

- a) Eqn. (5.7) can be satisfied as described in Section 6.2.2.1, in which case the CST is covered directly by a base station, or
- b) both Eqn. (5.9) and (5.10) can be satisfied for any pair of base station and candidate repeater site for which donor and distribution path sets have been computed as illustrated in Figure 92.

The value of coverage C is computed using the following sequence for each value of L_{MAX} and Γ as illustrated in Figure 93:

- 1) the direct coverage of each subscriber building by base stations only is determined,
- 2) the potential coverage of each remaining uncovered subscriber building by any candidate repeater site is determined,
- 3) all candidate repeater sites are evaluated in terms of the additional coverage that they can provide. The CRP that results in the greatest additional increase in coverage, above and beyond that provided by the base stations alone, is selected. The remaining CRPs are then re-evaluated, given the existing coverage provided by the base stations and the previously selected repeater. This selection process is continued until all CRPs have been evaluated, with the first selected being the optimal repeater

site, the second selected being the second best and so on. In the accompanying illustration, base stations, CRPs and subscribers are marked as circles, squares and triangles respectively, the coverage extent of each node is denoted by a dashed line, and the order in which the CRPs are selected, as well as their covered subscribers are marked by 1, 2, 3, etc.

As a result of the coverage computing procedure described above, the coverage that results from the use of N optimally located repeaters within the simulation area is known for a wide range of values of N .

In all other regards, the coverage of a CST is determined in a manner similar to that described in Section 6.2.2.1.

It follows by extension that, for a given repeater, there is no single “best” donor base station for all values of L_{MAX} and Γ , and that there is no single “best” device to which a subscriber should establish a link, whether it be a base station or repeater. Similarly, the choice of optimal repeater locations depends on the values of L_{MAX} and Γ .

The use of simple macrodiversity is assumed here, although in this case the diversity applies to a set consisting of the four base stations that are nearest to the CST in question in addition to any repeaters that are within a range of 800 metres.

Figure 93: Selection of Optimal Candidate Repeater Sites (see text for legend)

6.3 Coverage Prediction: LOS Operation

For each scenario involving LOS operation, coverage was computed in a manner identical to that used in the NLOS operation scenarios (Section 6.2), but for the following exceptions:

- For all links, including base station to subscriber, base station to repeater and repeater to subscriber, only the direct path was evaluated, i.e. all reflection paths were excluded.
- All links were evaluated as being either obstructed or non-obstructed, based on the intersection of the LOS with objects in the terrain database, including buildings, trees, thickets and the ground itself. This is in contrast to the nominal definition of an unobstructed LOS as described in the Glossary; the simplified approach described here has been used for simplicity.
- All obstructed paths were excluded from the simulation, i.e. they were given an effectively infinite excess path loss.
- All non-obstructed paths were given a path loss value based on Eqn. (3.2), with all components of the obstruction loss L_{obstr} being excluded except for the constant offset $\delta = 3.2$ dB, which has been retained to facilitate comparison with the corresponding NLOS operation scenarios. Furthermore, all partial diffraction losses have been excluded for simplicity. The resulting path loss expression is therefore

$$L_{path} = L_{FS} + \delta + L_{rain} \quad (\text{dB}) \quad (6.3)$$

Chapter 7: Coverage Simulation Results

7.1 Interpretation of Results

The results of all simulations described in this chapter are presented as plots that each contain a family of curves, with each curve showing predicted coverage as a function of MTPL L_{MAX} for a fixed value of specific rain attenuation Γ .

These plots can be interpreted in a number of ways, with the most direct interpretation being described below, followed by suggestions for alternative interpretations.

7.1.1 Direct Interpretation

A direct interpretation involves the determination of the predicted coverage for a known system in a known climate region, given a desired (targeted) value for the service availability and a desired (targeted) BER value. In summary:

- 1) the system description and BER target are used to evaluate the MTPL L_{MAX} ,
- 2) the knowledge of climate region together with the availability target are used to estimate a corresponding worst-case value of specific rain attenuation Γ ,
- 3) the predicted coverage is read from the plot by cross-indexing these values of L_{MAX} and Γ .

7.1.1.1 Selection of MTPL Value

The following information can be used to evaluate the MTPL L_{MAX} . All values are required for both uplink and downlink.

- P_T : the average transmitted power in Watts
- G_T : the transmitting antenna gain, relative to an isotropic radiator
- G_R : the receiving antenna gain, relative to an isotropic radiator
- B : the channel bandwidth in Hertz
- F : the receiver noise figure as seen by the demodulator

- $\gamma_{\min}$: the value of SNR that is required to meet the BER target

The MTPL must then be evaluated separately for both the uplink ($L_{MAX}^{(U)}$) and downlink ($L_{MAX}^{(D)}$) using Eqn. (2.7), which is rewritten below with all terms in decibels:

$$L_{MAX}^{(U,D)} = P_T + G_T + G_R + 204 - \gamma_{\min} - F - B \quad (\text{dB}) \quad (7.1)$$

The value of the system's MTPL is then simply the lower of the two.

$$L_{MAX} = \min(L_{MAX}^{(U)}, L_{MAX}^{(D)}) \quad (\text{dB}) \quad (7.2)$$

The selection of values for the SNR threshold $\gamma_{\min}$ depends on aspects of the system's physical layer design, and on the nature of channel impairments that are in addition to shadowing, both of which are outside of the scope of this thesis. For example, the degree to which a system can tolerate fading depends on the diversity that is available to the receiver. In summary, the user must select a suitable channel model to determine the SNR threshold that results in the selected BER value.

This method of evaluating MTPL is intended as a guide, and can be modified as required with additional terms, or replaced in entirety as the user sees fit. Such additional terms could be used, for example, to account for cable losses or transmitter backoff. In summary, the user is free to interpret the relationship between the physical layer system design and the corresponding value of L_{MAX} in all cases. In any case, it should be noted that the coverage predictions given here involve predicted path losses that do not include fading as discussed in Section 5.1.3, so that fading should be taken into account when arriving at a value for L_{MAX} .

7.1.1.2 Selection of Specific Rain Rate Value

The evaluation of F is a four step process, with each step being discussed below. An example of this evaluation is given in Section 7.1.1.3.

- 1) A target value for the system availability is chosen.
- 2) The climate region of interest is chosen.

- 3) Distribution data describing the rain rate for the given region is selected and used to determine the rain rate that corresponds to the availability value.
- 4) A rain attenuation model is selected and used to determine the specific attenuation which corresponds to the rain rate determined in the previous step.

The availability of a service is simply the percentage of time during which it is expected to be operational. In the present context, the availability is the complement of the percentage of time during which outages are expected to occur due to rain attenuation. The following table lists various availability values and the corresponding total outage times in a one year period. For example, a service with 99.99% availability is expected to have rain-induced outages that total 53 minutes over the course of one year.

availability	total rain outage per year
99%	3.7 days
99.9%	8.8 hours
99.99%	53 minutes
99.999%	5.3 minutes

Table 19: Availability and Outage Time

Rain rate distribution data that corresponds to different climate regions is illustrated in Table 8. For example, the upper-left entry of that table indicates that in Region B, the rain rate is expected to exceed a value of 1.8 mm/hr, one percent of the time. Conversely, the rain rate is expected to be less than or equal to 1.8 mm/hr, 99% of the time. Consequently, for a system to have a 99% availability, it must be capable of tolerating the attenuation which arises from a rain rate of 1.8 mm/hr or less.

Finally, a rain attenuation model such as given by Eqn. (2.52) is used to determine the specific rain attenuation in dB/km that arises from the rain rate at the carrier frequency in question. Continuing with the example given above, a rain rate of 1.8 mm/hr results in a specific attenuation of 0.3 dB/km at 30 GHz as illustrated in Table 11 when using the spherical drop rain model. This implies that the system must be capable

of tolerating $\Gamma = 0.3$ dB/km of rain attenuation for it to have an availability of 99% in this case.

This method of evaluating Γ is merely a guide, and can be modified as the user sees fit; in particular, both the distribution of rain rate and the rain attenuation model can be replaced. Nevertheless, the coverage plots have been based on the assumption that rain rate and corresponding attenuation are spatially uniform. The incorporation of a non-uniform rain model would require the generation of a new set of coverage plots, which is a candidate for further study.

7.1.1.3 Nominal Values of L_{MAX} and Γ

The following is a derivation of nominal values for L_{MAX} and Γ that are used throughout the remainder of the thesis for the purpose of making comparisons.

The following parameter values are representative of a conventional LMDS system [19].

Downlink:

• transmit power level	-3 dBW (27 dBm)
• transmit antenna gain	12 dBi
• receive antenna gain	36 dBi
• channel bandwidth	40 MHz
• receiver noise figure	8 dB
• SNR threshold	13 dB (10^{-5} BER in AWGN channel)
• modulation scheme	DQPSK

Uplink:

• transmit power level	-15 dBW (15 dBm)
• transmit antenna gain	36 dBi
• receive antenna gain	12 dBi
• channel bandwidth	2 MHz
• receiver noise figure	8 dB

- SNR threshold 13 dB (10^{-5} BER in AWGN channel)
- modulation scheme DQPSK

Assuming that an additional fade margin of 5 dB is sufficient for both uplink and downlink, we find from Eqn. (7.1) and (7.2) that the MTPL in this case is

$$L_{MAX} = 147 \quad (\text{dB}) \quad (7.3)$$

Assuming a target availability of 99.99%, which corresponds to 53 minutes of rain-induced outage per year, and choosing the Crane model rain region D1, which includes the most populated regions in Eastern Canada, we find from Table 8 that the corresponding worst-case rain rate is 37 mm/hr. The corresponding specific attenuation in dB/km varies depending on the rain attenuation model used; the value chosen here will be based on the spherical drop model that is listed in Table 11:

$$\Gamma = 8.0 \quad (\text{dB/km}) \quad (7.4)$$

7.1.2 Alternative Interpretations

Given that a system has been designed for a certain value of availability with a corresponding specific rain attenuation Γ , the curves can be read to reveal the additional loss in coverage that occurs when and if Γ is exceeded, all else being equal.

Similarly, the worst-case effect of additional fading above and beyond the level that was considered when establishing the SNR threshold γ_{min} can be revealed by decreasing the MTPL by a corresponding amount, all else being equal.

More generally, the effect of a change to any of the following factors can be interpreted as corresponding to a change in any one other, with all other factors being held constant:

- climate zone
- availability
- MTPL
- coverage

For example, given a system that is designed for a given climate region, the installation of such a system in a different, rainier climate can be viewed as reducing the system performance in terms of either the availability or the coverage, or requiring an increase in MTPL to retain the performance at the current levels. Furthermore, this approach can be extended to involve the effect of design changes that correspond to the difference between any two plots.

In conclusion, any value of (L_{MAX}, Γ) can be seen as a point in a system design space, where each dimension corresponds to a variable of the system design such as base station antenna height for example, and with each plot presenting a different cross-section through the space.

7.2 Simulation Results

The following applies to all simulations without exception:

carrier frequency	28.7 GHz
cell arrangement	square grid
no. of simulated subscribers	500

Table 20: Common Simulation Parameters

All simulations are identical to the baseline simulation (Section 7.2.1) other than for any noted exceptions.

All references to the cell radius refer to one half of the cell grid spacing, which is equivalent to one half of the base station spacing as illustrated in Figure 88.

All simulation results are presented as plots in Appendix 3. All plots have a circle marking the point corresponding to the nominal values of L_{MAX} (147 dB) and Γ (8 dB/km) that are derived in Section 7.1.1.3. In addition, certain plots have a triangle marking a point for which the MTPL L_{MAX} has been reduced by 20 dB, i.e. $(L_{MAX}, \Gamma) = (127, 8)$; this lower value of MTPL can be interpreted as representing “difficult” propagation conditions. For example, this lower value may be more appropriate if extreme fading is present and not counteracted by way of diversity.

7.2.1 Baseline System (Figure 100)

A system has been simulated for the purpose of acting as a baseline against which all other simulated systems can be compared. It is described by the following:

cell radius	1.5 km
base station antenna height above ground	40 m
subscriber antenna height above rooftop	0.5 m

Table 21: Baseline System Parameters

The simulation area in this case is a 6 km x 6 km square that includes 4 (disjoint) cells as illustrated in Figure 88.

In addition:

- 1) multiple rooftop sites were evaluated for each subscriber building as described in Sections 6.1 and 6.2,
- 2) simple macrodiversity was implemented as described in Sections 2.1.4 and 6.2,
- 3) the choice of base station and subscriber rooftop antenna site for link establishment to the subscriber was re-evaluated for every value of (L_{MAX}, Γ) ,
- 4) link establishment was based on the single least-loss path from the predicted path set (direct and first order reflections), corresponding to Case (B) as described in Section 4.7.

These last four features have been included in the baseline simulation because of the relatively low implementation cost associated with each; in particular, the cost of simple macrodiversity is discussed in Section 2.1.4. In contrast, the exclusion of some or all of these features is evaluated in following simulations.

7.2.2 Worst Case System (Figure 101)

The purpose of this simulation is to evaluate the effect of excluding all of the optional features that are included in the baseline simulation, resulting in a type of a worst case scenario (the unobstructed LOS requirement being another example of worst case scenario). Specifically, the following changes are made relative to the baseline scenario:

- 1) rooftop site selection is excluded, so that the rooftop center point only is evaluated as a subscriber antenna site,
- 2) simple macrodiversity is excluded, so that link establishment is allowed between a ST and the nearest BS only,
- 3) reflections are excluded, so that link establishment is based on the direct path only between the BS and ST in question.

The exclusion of rooftop site selection may be interpreted as corresponding to a situation where the choice of antenna site is limited in practice, such as by the availability of proper anchor points, or for aesthetic reasons.

The exclusion of simple macrodiversity may be interpreted as corresponding to the edge of a service region as shown in Figure 11.

The exclusion of reflections may be interpreted as corresponding to a situation where reflected signals are unsuitable for link establishment due to channel impairments that are outside the scope of this thesis, such as due to additional delay spread, or the potentially ephemeral nature of reflections.

7.2.3 Exclusion of Rooftop Site Selection (Figure 102)

The relative importance of sampling multiple rooftop sites prior to subscriber antenna installation has been evaluated by way of the exclusion of the sampling process relative to the baseline scenario. Refer to Section 7.2.2 for details and interpretation.

7.2.4 Exclusion of Macrodiversity (Figure 103)

The relative importance of simple macrodiversity has been evaluated by way of its exclusion relative to the baseline scenario. Refer to Section 7.2.2 for details and interpretation.

7.2.5 Exclusion of Reflections (Figure 104)

The increase in coverage that is associated with the use of single, naturally occurring reflections has been evaluated by way of the exclusion of reflections relative to the baseline scenario. Refer to Section 7.2.2 for details and interpretation. Consequently, effective path loss (and hence coverage) are computed using Case (A) as described in Section 4.7.

The difference in coverage between Figure 104 and Figure 100 represents the number of subscriber buildings that depend on reflections for link establishment, which is less than the number of subscribers that could in principle establish a link via a reflection.

7.2.6 Maximal Ratio Combining of Reflections (Figure 105)

The greatest possible increase in coverage that results from the optimal combining of all (predicted) received signals, disregarding macrodiversity, has been evaluated by assuming maximal ratio combining at both ends of the link. Consequently, effective path loss (and hence coverage) are computed using Case (C) as described in Section 4.7.

The difference in coverage between Figure 105 and Figure 104 represents the maximum increase in coverage that can be attributed to the use of naturally occurring reflections.

7.2.7 Base Station Antenna Height Above Ground (Figure 106 to Figure 111)

The relative importance of base station antenna height above ground (i.e. mast height) in determining coverage has been evaluated by repeated simulations with the BS antenna HAG ranging from 10 metres to 100 metres, with all else being identical to the

baseline simulation. In all cases, the height increase is applied uniformly to all simulated base stations. Note that while the HAG of each base station antenna is identical, the elevation is not, due to differences in the ground elevation between base station sites.

Mast heights that are less than the baseline value (40 metres) have been included to evaluate the effect of such a cost-saving measure; mast heights greater than the baseline value have been included to evaluate the degree to which coverage can be increased by this method.

7.2.8 Subscriber Antenna Height Above Rooftop (Figure 112 to Figure 123)

The relative importance of subscriber antenna height above rooftop (i.e. mast height) in determining coverage has been evaluated by repeated simulations with the subscriber antenna height above roof ranging from 0.1 metres to 10 metres, with all else being identical to the baseline simulation. In all cases, the height increase is applied uniformly to all simulated subscribers. Note that while the height above roof of each subscriber antenna is identical, the elevation is not, due to differences in the rooftop elevation between subscriber sites.

The resulting set of plots can be read in sequence for any value of (L_{MAX}, I) , thereby illustrating the dependence of coverage on subscriber antenna mast height. This is illustrated in Figure 94 for the nominal values of $(L_{MAX}, I) = (127, 8)$, with the addition of a fourth order polynomial regression curve. This plot can be interpreted to determine the relative proportion of different mast heights that are required to achieve a certain coverage target; for example, referring to Figure 94, 60% of subscribers require a mast height of 1 metre or less, 5% require a mast height of 2 metres, 5% require a mast height of 3 metres, etc. In this manner, coverage can be increased by individually tailoring the subscriber mast heights as required.

Figure 94: Coverage versus Subscriber Antenna Mast Height for Nominal Values of (L_{MAX} , Γ)

7.2.9 Cell Radius (Figure 124 to Figure 130)

The relative importance of cell radius in determining coverage has been evaluated by repeated simulations with the cell radius ranging from 0.5 km to 4.0 km (or equivalently, with the cell diameter ranging from 1.0 km to 8.0 km), with all else being identical to the baseline simulation. The cell radius is defined as being half the spacing between base stations as discussed in Section 7.2.

Three different simulation areas were used in this case to ensure that an integral number of quarter cells were included in each case as outlined below:

cell radius	SA dimensions	no. of cells in SA
0.5 km	4 km x 4 km	16
0.75 km	6 km x 6 km	16
1.0 km	4 km x 4 km	4
1.25 km	5 km x 5 km	4
2.0 km	4 km x 4 km	1
3.0 km	6 km x 6 km	1
4.0 km	4 km x 4 km	0.25

Table 22: Cell Radius Simulation Parameters

The term “cell radius” as used here differs from the notion of a nominal distance to which a base station can provide coverage, which will be termed the “coverage radius”. For example, the degree of cell overlap (Section 2.1.4) depends on the ratio of coverage radius to cell radius. As opposed to cell radius, coverage radius is not an independently controllable parameter, instead being dependent on MTPL. Furthermore, coverage radius has not been included as a metric derived from simulation results for a number of reasons:

- coverage radius can be defined in many ways,
- simulations indicate that the coverage boundary is generally not well-defined; instead, coverage varies gradually as a function of distance, with uncovered subscribers occurring throughout the cell, and
- knowledge of coverage radius is not required to satisfy the thesis objectives.

Cell radii that are greater than the baseline value (1.5 km) have been included to evaluate the effect of such a cost-saving measure; radii that are less than the baseline value have been included to evaluate the degree to which coverage can be increased by this method.

7.2.10 Microcell (Figure 131 to Figure 134)

The installation of base station antennas at the height used in the baseline simulation (40 metres) generally involves great expense and inconvenience for the

purchase or leasing of property, possibly including access rights to multi-story building rooftops, as well as the costs involved in the erection of tall masts.

An alternative would involve the deployment of relatively small, low power base stations on existing lamp posts, utility poles, building exteriors or other man-made structures, with a spacing between base stations on the order of a few hundreds of metres at most.

A number of simulations have been conducted to evaluate the usefulness of this coverage enhancing method. The simulations are identical to the baseline, with the exception of the following:

- the BS height above ground is fixed at 10 metres,
- the cell radius varies from 100 metres to 500 metres.

The simulation area in this case is a 1 km x 1 km square. The equivalent area in terms of cells is given below for each cell radius:

cell radius	no. of cells in SA
100 m	25
200 m	6.25
333 m	2.25
500 m	1

Table 23: Microcell Simulation Parameters

In principle, the cost of deploying such a large number of micro-base stations could be partially offset by providing wireless backbone links to some or all of the micro-base stations, as is suggested by the repeater simulations described in 7.2.11; such a possibility would be the subject of future studies.

7.2.11 Repeaters (Figure 135 to Figure 145)

The increase in coverage that results from the use of non-regenerative repeaters (Sections 2.1.2 and 5.3) has been evaluated by way of a single simulation involving the

evaluation of a number of candidate repeater sites as described in Sections 6.1 and 6.2.2.2. The coverage that results from the installation of various numbers of repeaters at optimal sites is given in the accompanying plots.

Apart from the inclusion of repeaters, the simulation was identical to the baseline in all ways, except for the following:

- The simulation area was a 1.5 km x 1.5 km square, representing a quarter cell. This reduction in SA has been used to reduce the number of candidate repeater sites that must be evaluated.
- Supplementary high gain antennas (36 dBi) were assumed to be installed at the base stations for the purpose of providing additional gain to the donor links, i.e. each base station was assumed to have a high gain antenna pointed at each repeater for which it supported a donor link. This change was added after noting that repeaters otherwise provided little improvement in coverage, due primarily to the dominance of rain-induced outages. In principle, these supplementary antennas could be operated in parallel with the existing base station antennas through the use of simple RF splitters and combiners, with attention being paid to phasing.

As mentioned in Section 6.1, candidate repeater sites were evaluated at all points on a 100 metre grid, and the height above ground of both repeater antennas was set to 10 metres.

Unlike all other simulations that did not involve repeaters, a number of system parameters related to the link budget were specified as shown below. An examination of Equations (5.7) and (5.8) reveals that such parameters are completely determined (abstracted) by the single MTPL parameter when repeaters are not involved; in contrast, an examination of the equivalent equations for the repeater case ((5.9), (5.10), (5.14), (5.15)) reveal that this degree of simplification is not readily achievable.

base station (supplementary) antenna gain G_{BS}	36 dBi
subscriber antenna gain G_{ST}	36 dBi
base station noise figure F_{BS}	8 dB
subscriber noise figure F_{ST}	8 dB

Table 24: Base Station and Subscriber Parameters Used in Repeater Simulation

repeater donor antenna gain G_D	36 dBi
repeater distribution antenna gain G_I	12 dBi
repeater amplifier gain A (bi-directional)	70 dB
repeater noise figure F_R (bi-directional)	8 dB

Table 25: Repeater Simulation Parameters

The values given in Table 24 were selected in accordance with the nominal values given in Section 7.1.1.3, with the supplementary antennas at the base station modelled as being identical to subscriber antennas. Similarly, the values given in Table 25 were largely chosen to represent the same RF technology. The value of repeater amplifier gain $A = 70$ dB has been selected to represent a conservative value in light of the need to avoid potentially destructive positive feedback as discussed in Section 2.1.2.3; in contrast, the effective gain of the nominal BS and ST, not including the antenna gains, would be 117 dB and 92 dB respectively if these were to perform loopback of a signal received at the SNR threshold.

At first glance, the simulation of repeaters as done here appears to be similar to the microcell simulations described in Section 7.2.10, considering the similarity of antenna height and spacing, and assuming ideal donor links. Nevertheless, there are significant differences between the two scenarios:

- the installation of (generally many) micro-base stations on all points on a grid, as opposed to the installation of (generally few) repeaters at selected locations only, and
- the non-ideal nature of the donor link in the case of repeaters, particularly in terms of its susceptibility to rain-induced outages, as opposed to the ideal backbone links that are assumed in the microcell simulations.

The observed difference between the baseline plot (Figure 100) and the repeater plot having zero repeaters (Figure 135) is due to the fact that the SA used for the baseline simulation is 16 times larger than the SA used for the repeater simulations; as a result, a greater degree of spatial averaging is involved in the baseline simulation, which is evident due to the relative smoothness of the curves. Nevertheless, the difference in predicted coverage between both plots is generally on the order of 3% or less.

7.2.12 Repeaters and Reduced Cell Radius (Figure 146)

The simulation described in Section 7.2.11 was repeated with the cell radius being reduced to 1.25 km from its original value of 1.5 km, the SA being consequently reduced in size to maintain a quarter cell area, and all else being equal.

This simulation evaluates the use of this strategy to provide high coverage under difficult propagation conditions, i.e. with the nominal value of MTPL being reduced by 20 dB as discussed in Section 7.2.

7.2.13 Exclusion of Trees (Figure 147)

The purpose of this simulation is twofold:

- to illustrate the degree to which trees influence coverage in the present context, and
- to illustrate, by an extreme example, the degree to which coverage can vary depending on local terrain characteristics. In particular, newly developed residential areas are generally planted with saplings which fall far short of the average rooftop height, and for this reason the current simulation can represent such a scenario.

The baseline simulation was repeated with all trees and thickets removed from the terrain database, and all else being equal.

7.2.14 LOS Operation (Figure 148 to Figure 174)

The purpose of these simulations is twofold:

- to evaluate the effectiveness of applicable coverage enhancement methods when LOS operation is required, i.e. when there is a requirement for an unobstructed LOS between transmitting and receiving antennas on all links, whether between base station and subscriber, base station and repeater or repeater and subscriber, and
- to determine the degree of coverage enhancement which can result from the use of NLOS operation, by way of comparison with the results of equivalent simulations involving NLOS operation.

The following table lists the simulations involving LOS operation, as well as the corresponding NLOS simulations. For brevity, only those simulations which result in an increase in coverage relative to the baseline have been repeated here.

CEM	LOS operation	NLOS operation
baseline	Figure 148	Figure 100
BS ant. HAG, 50 - 100 m	Figure 149 to Figure 151	Figure 109 to Figure 111
ST ant. HAR, 1 - 10 m	Figure 152 to Figure 161	Figure 114 to Figure 123
cell radius, 0.5 - 1.25 km	Figure 162 to Figure 165	Figure 124 to Figure 127
μ cell, 100 - 500 m radius	Figure 166 to Figure 169	Figure 131 to Figure 134
repeaters, 0 per km ²	Figure 170	Figure 135
repeaters, 1.3 per km ²	Figure 171	Figure 138
repeaters, 4.4 per km ²	Figure 172	Figure 141
repeaters, 8.9 per km ²	Figure 173	Figure 143
repeaters, 26.7 per km ²	Figure 174	Figure 145

Table 26: Comparison of LOS Operation and NLOS Operation

In addition, those trials which involve a change in subscriber antenna height above roof have been summarized in Figure 95; refer to Section 7.2.8 for interpretation.

Figure 95: Coverage versus Subscriber Antenna Mast Height for Nominal Values of (L_{MAX}, I) – NLOS Operation (grey dashed) & LOS Operation (black solid)

7.3 Comparison of Coverage Enhancement Methods

7.3.1 NLOS Operation

The coverage predictions given in Appendix 3 can be used to compare the effectiveness of several methods for increasing coverage to high levels. In each case examined here, the method will involve a change relative to the baseline system design, its implementation or usage, i.e. the change will be relative to the baseline scenario as given in Section 7.2.1.

The degree to which each change must be applied, if possible, to reach a coverage of 90% or more, given the nominal values for MTPL and specific rain attenuation (Section 7.1.1.3), is listed below.

CEM	amount	notes
increase MTPL L_{MAX}	+ 17 dB	(1)
use maximal ratio combining of all received reflected signals	NA	(2)
increase base station antenna height above ground	NA	(3)
increase subscriber antenna height H above rooftop	$0 \text{ m} < H < 9 \text{ m}$	(4)
decrease cell radius R	$R \approx 1 \text{ km}$	(5)
use microcell architecture (cell radius R)	$R \approx 400 \text{ m}$	(6)
add repeaters	1.3 repeaters per km^2	(7)

Table 27: Methods for Increasing Coverage to 90 % Given Nominal (L_{MAX} , I) – NLOS Operation

- 1) An increase in MTPL can be accomplished using one or more methods as discussed in Section 2.1.1.
- 2) The total power received from all reflections is insufficient to have a significant effect on coverage.
- 3) A base station antenna height above ground of greater than 100 metres would be required to reach 90% coverage.
- 4) The relative proportion of required subscriber antenna heights can be derived from Figure 94.
- 5) The number of base stations required to cover a given area must be roughly doubled as a result of the decrease in cell radius from 1.5 km to 1.0 km.
- 6) The resulting micro-base station spacing is roughly 800 metres.
- 7) In this case, the density is equivalent to 12 repeaters per cell.

Similarly, the degree to which each change must be applied, if possible, to reach a coverage of 90% or more, given the difficult values for MTPL and specific rain attenuation (Section 7.2), is listed below.

CEM	amount	notes
increase MTPL L_{MAX}	+37 dB	
increase subscriber antenna height H above rooftop	NA	(1)
decrease cell radius	$R \approx 0.5$ km	(2)
use microcell architecture (cell radius R)	$R \approx 150$ m	(3)
add repeaters	8.9 repeaters per km ²	(4)
add repeaters and decrease cell radius R	5.8 repeaters per km ² & $R = 1.25$ km	(5)

Table 28: Methods for Increasing Coverage to 90% Given Difficult (L_{MAX} , I) – NLOS Operation

- 1) An increase in subscriber antenna height alone is not sufficient in this case because the combined FSPL and rain attenuation to the furthest point on the cell boundary (145 dB) is greater than the difficult value of MTPL (127 dB).
- 2) A decrease in cell radius from 1.5 km to 0.5 km results in a ninefold increase in the number of base stations required to cover a given area.
- 3) The resulting micro-base station spacing is roughly 300 metres.
- 4) In this case, the density is equivalent to 80 repeaters per cell.
- 5) In this case, the density is equivalent to 36 repeaters per cell, and the number of base stations required to cover a given area must be increased by roughly 50% as a result of the decrease in cell radius from 1.5 km to 1.25 km.

7.3.2 LOS Operation

The analysis given in the previous section is repeated here in the case of LOS operation, namely with the additional requirement that links be established on unobstructed direct paths only.

The degree to which each change must be applied, if possible, to reach a coverage of 90% or more, given the nominal values for MTPL and specific rain attenuation (Section 7.1.1.3), is listed below.

CEM	amount	notes
increase MTPL L_{MAX}	NA	(1)
increase subscriber antenna height H above rooftop	$0 \text{ m} < H < 13 \text{ m}$	(2)
decrease cell radius R	$R \approx 0.5 \text{ km}$	
use microcell architecture (cell radius R)	$R \approx 200 \text{ m}$	
add repeaters	NA	(3)

Table 29: Methods for Increasing Coverage to 90% Given Nominal (L_{MAX} , I) – LOS Operation

- 1) An increase in MTPL past the nominal value is generally of use only in the case of NLOS operation, where it will counter additional attenuation due to obstructions.
- 2) The relative proportion of required subscriber antenna heights can be derived from Figure 95.
- 3) For repeater densities of 26.7 per km² or greater, the resulting coverage value is constant at 85%, which is close to but not matching the coverage target used here.

Similarly, the degree to which each change must be applied, if possible, to reach a coverage of 90% or more, given the difficult values for MTPL and specific rain attenuation (Section 7.2), is listed below.

CEM	amount	notes
decrease cell radius	$R < 0.5 \text{ km}$	(1)
use microcell architecture (cell radius R)	$R \approx 150 \text{ m}$	
add repeaters	NA	(2)

Table 30: Methods for Increasing Coverage to 90% Given Difficult (L_{MAX} , I) – LOS Operation

- 1) At a radius of 0.5 km, the coverage is 80%, and is expected to further increase with decreasing radius.
- 2) For repeater densities of 26.7 per km² or greater, the resulting coverage value is constant at 85%, which is close to but not matching the coverage target used here.

Chapter 8: Discussion

8.1 Propagation Model

8.1.1 Degree of Specialization

The propagation model presented here has been developed for a specific task, and consequently the model is specialized relative to that which would result from a literal implementation of ray tracing principles. The most important intentional specializations involve:

- the lack of predicted multipath fading, and
- the high degree to which possible propagation paths are omitted from the output set of predicted paths.

In contrast, there are a number of additional factors that limit the scope of the model, being due more to necessity than intent; these factors are discussed in Sections 8.1.2 and 8.1.5.

The output of predicted reflections is not to be confused with the prediction of multipath (and subsequent delay spread and fading) as is commonly done with ray tracing based propagation simulators. The predicted reflections are not combined in the model; instead they can be viewed as separate signal sources, thereby providing a form of diversity given appropriate receiver antennas. In principle, the propagation model could be easily extended to include the vectorial summation of multipath components, although this approach is not recommended due to a) the high degree of error associated with the predicted reflections that has been demonstrated during the validation process, b) the intentional omission of many possible paths from the predicted set, and c) the sensitivity of derived quantities, such as delay spread, to errors in predicted multipath, as demonstrated for example in [85]. Furthermore, the summation of multipath components requires a description of the antenna beam patterns and pointing angles if one or more of

the antennas is highly directional; in contrast, this step can be omitted in ray tracing simulators that assume the use of omnidirectional user terminal antennas.

The presented propagation model is also specialized due to the small number of predicted paths in the output path set. This form has been chosen based on field observations, where it was noted that, in general, the vast majority of the total received energy is accounted for by a small number of discrete sources being separated in azimuth and each having a relatively narrow angular spread. Consequently, the model presented here involves the intentional omission of a large number of relatively weak propagation paths.

8.1.2 Conditions for Usage and Related Confidence

The propagation model has been developed specifically to match measurements that have been made under the following conditions:

- a carrier frequency of 28 GHz,
- one antenna height being 40 metres above ground,
- the other antenna height being 5 metres above ground,
- the antenna separation ranging from 250 metres to 2.5 kilometers,
- the geographical area corresponding to a “typical” suburban residential area, characterized by:
 - flat terrain,
 - the existence of predominantly one and two story buildings with a density on the order of 750 buildings per square kilometer,
 - mature trees covering roughly 20% of the ground area.

Furthermore, the development and matching procedure has involved the use of a terrain database that is roughly characterized by the following degree of accuracy:

- ground elevation accuracy on the order of one metre,
- most individual trees and groups of trees being included and correctly represented, with outlines and elevations accurate to a metre or two,

- most buildings being included and correctly represented, with roofs approximated by flat horizontal surfaces, walls approximated by flat vertical surfaces, and building outlines including details with dimensions on the order of two metres or greater.

Subsequently, the model can be used with a degree of confidence under similar conditions and with a similarly detailed terrain database, and with a reduced degree of confidence under significantly different conditions as discussed in Section 8.1.4.

More specifically, a comparison with field measurements reveal that, under the conditions noted above:

- the standard deviation of the predicted loss for the direct path is on the order of 9 dB,
- only the very strongest predicted reflections have a degree of reliability, while all weaker predicted reflections are largely unreliable, both individually and statistically, yet
- coverage values that are derived from the predicted path set have an accuracy that depends on the manner in which reflections are used. Coverage errors are on the order of 2% when reflections are not involved, and 5% when reflections are optimally combined at the receiver.

8.1.3 Interpretation of Predicted Path Loss

The nature of the predicted path loss (shadowing) values can be interpreted by considering the measured power values that were used for model development. These measured values consist of the maximum CW power observed over a period of a few seconds, during the summer months and under clear-sky conditions.

In spite of the fact that the measurements were made at CW, the resulting predicted path loss values can be applied to broadband channels as well (on the order of a few tens of MHz) if the fading in practice is generally flat and not frequency selective. There are a number of indications that support this notion:

- Fading would be essentially flat if it were caused by wind-induced changes in the degree to which foliage blocks the transmitted signal. The possibility of this mechanism is supported by findings reported in [59].

- A field trial conducted by CRC [7] found that the 90th percentile of the RMS delay spread was 9 nsec, which corresponds to a coherence bandwidth of roughly 100 MHz. This trial was conducted with a horn receiver antenna having a beamwidth of 12° in both planes.
- Both a theoretical and experimental study of the fading due to motion by trees [37] indicate that such fading is flat across a bandwidth of roughly 40 MHz. The theoretical model involves multipath fading caused by scattering from all points on a tree. It was found that the path length differences through the tree were not sufficient to cause frequency selectivity. The experimental study involved the use of a filter bank to simultaneously characterize narrowband and wideband fading on a path that was obstructed by a single tree, with the effect of wind being simulated using ropes tied to the tree.

Consequently, the power received over a broadband channel is expected to generally undergo significant temporal variations (i.e. flat fading) due to corresponding variations in CW power that have been observed in practice as discussed in Section 8.1.4.

The significance of the duration of time over which the maximum power value was observed is a further element that requires interpretation. The maximum value observed over several seconds may or may not correspond to (for example) the 99th percentile that would be observed over a much longer period of time, such as several hours. For a significant discrepancy to occur in this case, it would be necessary that the measurement be taken during a fading event that is roughly as long as or longer than the several-second observation window, as may be caused by the chaotic nature of wind gusts for example. Such long fade events have not been ruled out, nevertheless the measured coherence time of envelope fading [56] has been found to be on the order of 1 second, which suggests that very long fading events do not occur. If long fade events do occur, the propagation model would have an associated error when used to predict long-term coverage. This error would result in pessimistic coverage predictions, assuming that mitigation techniques are available that can deal with the long fades (via macrodiversity in particular), or optimistic coverage predictions, assuming that the long fades are insurmountable.

The significance of the use of the maximum observed power value (as opposed to the average) also requires explanation. To some degree, the choice of a metric to represent the long-term tendency of a time-varying quantity is arbitrary, so long as the definition of the metric is kept in mind when applying the results. Consequently, the choice of the maximum value requires, when considering the effect of fading as discussed in Section 8.1.4, that the estimated fading be measured relative to the maximum. Furthermore, the mean and maximum values that are observed in practice over several minutes differ by only 5 decibels or less as is shown in the envelope fading distributions presented in [56], so that fading statistics measured relative to the signal mean are applicable in this case.

Nevertheless, the possibility exists for very long term changes in shadowing, and these changes should be considered when evaluating coverage. Two sources of long term change in shadowing by trees are discussed below: seasonal variations and tree growth.

The model output corresponds to the shadowing that occurs during the summer months, since the model has been adjusted to agree with measurements that were taken during that time. Field trials by various parties indicate a trend towards reduced attenuation when the trees are bare, so that the resulting coverage results are correct w.r.t. seasonal variation from the point of view of the need for establishing reliable service over a period of one year or more, i.e. the predicted shadowing values are the seasonal worst case.

Tree growth, on the other hand, is likely to result in a steady reduction in coverage if the system is not changed in accordance. The effect of tree growth could in principle be investigated by artificially increasing the size of all trees represented in the terrain database.

8.1.4 Unmodelled Temporal Variations in Path Loss

The path loss values resulting from the propagation model represent the expected long term minimum path loss values (i.e. shadowing), from which temporal variations are measured as an additional time-varying positive path loss (i.e. fading).

These temporal variations are not included in the model presented here. Nevertheless, they potentially have a considerable effect on successful link establishment due to their severity as illustrated in Section 2.5.4.5. In principle, the effect of these variations can be accounted for in the thesis results by way of a fade margin in the MTPL estimate, with the value of the margin depending on the effectiveness of any mitigation techniques, such as error correction coding or the use of diversity. In contrast, the use of power control cannot be assumed to globally mitigate fading in the present context, given that the MTPL value is based on the maximum transmit power level (as may be capped by safety regulations for example). Consequently, power control could be used to mitigate fading only at those sites where the path loss is significantly less than the MTPL.

8.1.5 Generality

In principle, propagation models that are based solely on ray tracing have a high degree of generality, being applicable to a wide range of frequencies, antenna positions and environments, given that the environment is described by a sufficiently detailed database. In contrast, purely empirical propagation models have a degree of generality that is limited to the range of conditions that apply to the measured data upon which the model was based. The model presented here is quasi-empirical, which suggests that its generality is somewhere between the two extremes.

Assuming that nothing is known of a model other than it being quasi-empirical, one would be forced to assume that its generality is no better than that of an equivalent purely empirical model that had been derived using the same set of measured data. Nevertheless, the model presented here is known to be largely based on ray tracing, with the empirical parameters playing a relatively minor role, which suggests that the propagation model can be extended with some degree of confidence to conditions outside of those that apply to the measured data set.

Nevertheless, there are many aspects of the presented model that cast doubt on any such extension, in particular there are several components of the model that have not been verified in isolation or otherwise supported by theory or experiment, such as:

- the manner in which multiple diffraction is computed,
- the heuristics involved in the construction of the predicted path set,

- the application the knife-edge model to predict diffraction by trees.

In conclusion, the propagation model presented here results in a reduced degree of confidence when applied to areas that are significantly different from the model area, such as newly constructed residential areas in which the tree canopy does not extend past the average roofline, industrial parks, or urban core areas. Furthermore, it is reasonable to expect some degree of variation in the coverage values that would result in practice from one location to the next, even if these locations are similar in terms of broad characteristics; it is then reasonable to expect some degree of error when applying the model to other (albeit similar) regions.

The model also results in a reduced degree of confidence when used in situations that are significantly different from the model conditions, i.e.

- carrier frequencies that are much above or below 28 GHz,
- base station antenna heights that are much above or below 40 metres,
- subscriber antenna heights that are much above or below 5 metres,
- antenna separations much greater than 2.5 kilometers.

Similarly, the use of the model with a terrain database that is significantly less accurate than the one described in Section 8.1.1 involves a reduction in confidence.

Nevertheless, the application of the model in any of the situations described above is not entirely without value, due to the systematic manner in which each of these factors is represented in the model. For example, a change in carrier frequency will result in a corresponding change in the predicted FSPL and the loss associated with individual diffractions, with the confidence inherent in such a change in frequency being related to the generality of the component models, namely the free space propagation model and the knife-edge diffraction model. However, the final predicted path loss involves heuristic and empirical elements that are not frequency dependent, with associated frequency-dependent errors being likely to result.

8.1.6 Interpretation of Empirical Parameters

The role played by each of the four empirical parameters (α , β , γ , δ) (Section 3.2) is discussed below.

Together, the parameters $\gamma = 0.8$ and $\delta = 3.2$ result in a linear transformation of the initial clear-sky excess path loss estimate L_{EP} , i.e.

$$L'_{EP} = 0.8L_{EP} + 3.2 \quad (\text{dB}) \quad (8.1)$$

The addition of such a transformation was motivated by the observation that a systematic error in the predicted EPL value remained following the parameter optimization procedure. The final value of predicted EPL remains nonetheless close to its initial value, so that this transformation does not represent a radical departure. The value of the offset δ is small in comparison with the average value of predicted EPL that occurs in practice. The fact that $\gamma < 1$ may represent the effect of a compensation for unmodelled paths, i.e. the heuristic nature of the path selection algorithms implies that paths exist that are erroneously overlooked, and that may have path loss values that are less than the chosen ones.

The parameter $\alpha = 0.8$ results in a reduction in the predicted path loss due to diffraction by trees, relative to the initial value that is based purely on the knife edge model, i.e.

$$L_{TD} = 0.8L_{KE} \quad (\text{dB}) \quad (8.2)$$

The addition of this parameter was motivated by an observed offset between errors in predicted tree and building diffraction losses. The fact that $\alpha < 1$ may represent a compensation for unmodelled paths, such as may be due to diffraction at points that are closer to the centre of the tree than the points on the modelled tree edge. In addition, the value of α may be associated with the roughness of the tree surface, with reduced diffraction losses due to surface roughness being discussed in [42, p.112] for example.

The parameter $\beta = 0.6$ is involved in the manner selected for predicting multiple diffraction loss, which is illustrated below:

$$L_{MD} = L_D^{(0)} + 0.6L_D^{(1)} + (0.6)^2 L_D^{(2)} + (0.6)^3 L_D^{(3)} + \dots \quad (\text{dB}) \quad (8.3)$$

where $L_D^{(0)} > L_D^{(1)} > L_D^{(2)} > \dots$ represent the individual diffraction losses on the path in question, sorted in order of descending value. The selection of this method for computing multiple diffraction loss was motivated by the computational complexity of existing methods, as well as by an observed trend in the predicted multiple diffraction loss error that existed when this was computed using simple unweighted addition of all component losses, namely the multiple diffraction error was observed to correlated strongly with the number of diffractions involved.

There is strong agreement between the multiple diffraction loss predicted by the method presented here (Equations (8.3) or (3.17)), which is essentially an empirical model, with a corresponding theoretical model [74] for the special case of a small number of equally spaced knife edges that are coplanar with both the transmitter and receiver as illustrated in Figure 96. The theoretical model is given by

$$L_T = 20 \log(1 + N) \quad (\text{dB}) \quad (8.4)$$

where N is the number of edges and L is the multiple diffraction loss in decibels. This form is also given in [83] and illustrated in [84]. In this case, the diffraction loss due to a single knife edge is 6 dB, so that the empirical formula (3.17) reduces to

$$L_E = 6.0 \sum_{i=0}^{N-1} (0.6)^i \quad (\text{dB}) \quad (8.5)$$

The loss predicted by both methods is illustrated in Figure 97.

Figure 96: Equally Spaced Coplanar Knife Edges

Figure 97: Comparison of Multiple Knife-Edge Diffraction Models

8.2 Interpretation of Coverage Predictions

The coverage that occurs in practice at any particular site can be loosely defined as the ability to establish a bi-directional link of sufficient quality, particularly in terms of BER and other error statistics characterizing short-term drop-outs due to fading, and long-term availability due to rain-induced outages. At any particular instant in time, the occurrence of a bit error will depend on all possible distortions of the received signal, including signal attenuation (due to both shadowing and fading), interference, ISI, depolarization, etc, so that a realistic coverage prediction must in principle involve the prediction of each of these distortions, or at least the effect of each. Alternatively, a simpler coverage prediction can be based on the effect of shadowing only, which is the approach taken here. This approach results in an upper bound (i.e. optimistic) prediction, since the reception of sufficient signal power over the long term is necessary but not sufficient for the coverage of a site.

Nevertheless, the use of the shadowing-based coverage predictions is justified for a number of reasons. Existing field studies indicate coverage values on the order of 50% for conventional systems, where the coverage values in this case are based on the effect of shadowing only. The solution to the shadowing problem can be viewed as a necessary

first step towards achieving high coverage (by any definition) in practice. To this end, the results given here can be interpreted as presenting solutions to the shadowing problem only. Furthermore, there exists in principle the possibility of approaching the presented upper-bound coverage values in practice by way of additional mitigation techniques, although at some cost both in terms of complexity and system capacity, for example through the use of diversity, coding, etc.

The predicted coverage values presented here can be applied with some confidence to other residential suburban areas that have similar characteristics, due in part to:

- the degree of homogeneity within typical suburban areas, and
- the degree of spatial averaging that has taken place during the derivation of the results.

A lower degree of confidence is associated with the application of the predicted coverage values to areas with significantly different terrain, due to the high degree to which coverage depends on the ground clutter. In these situations, it is recommended that new coverage values be derived by repeating the simulations after replacing the original terrain database with one more representative of the given environment.

On the other hand, the predictions of the relative merit of the coverage enhancing methods can be applied with a greater degree of confidence to different suburban areas, since these predictions are based on changes in coverage as opposed to the coverage values themselves.

Chapter 9: Conclusions

9.1 : Effectiveness of Coverage Enhancing Methods

An examination of the coverage simulation results reveals the following. Unless stated otherwise, all statements apply to changes in coverage relative to a scenario that involves:

- a baseline system (Section 7.2.1) having a MTPL = 147 dB which corresponds to a conventional deployment,
- a specific rain attenuation = 8 dB/km,
- a suburban residential area with characteristics similar to those described in Section 4.1.1.

Furthermore, a target value of 90% coverage is assumed when discussing the effectiveness of coverage enhancing methods.

9.1.1 Influence of Rain Attenuation on Effectiveness

Throughout the results, it is evident that all coverage enhancing methods become progressively less effective as specific rain attenuation increases. Consequently, the predicted increase in coverage associated with a method can generally be further increased by decreasing the availability requirement.

9.1.2 Use of NLOS Operation

A significant increase in coverage can be achieved using NLOS operation, relative to the coverage resulting from LOS operation, given sufficient MTPL. The simulation results indicate that, in the case of NLOS operation, coverage increases gradually with MTPL over a wide range of values, and can be made to approach 100% in this manner in all cases. In contrast, coverage values are typically limited to a value which is well below 100% in the case of LOS operation, which merely indicates the percentage of subscribers which do not have an available unobstructed path to any base

station or repeater. In particular, coverage is limited to roughly 50% in the baseline scenario when LOS operation is in effect, regardless of the MTPL value, but can be increased to 90% or more using NLOS operation.

The gain in coverage which results from the use of NLOS operation depends on type of CEM which is applied as well as the degree to which it is applied. Comparison of the results of LOS and NLOS operation are given in the following sections:

- (Section 9.1.6) increasing base station antenna height,
- (Section 9.1.7) increasing subscriber antenna height,
- (Section 9.1.8) decreasing cell radius,
- (Section 9.1.9) using a microcell architecture,
- (Section 9.1.10) the addition of repeaters.

This list includes only those CEMs which can be used to increase coverage beyond the baseline value given LOS operation. As such, macrodiversity and rooftop antenna site selection are notable omissions.

Nevertheless, the use of NLOS paths for link establishment entails additional costs associated with increases in channel impairments other than shadowing. Most significantly, paths that are obstructed by trees are subject to severe fading [56]; in contrast, unobstructed LOS paths undergo little or no shadowing or fading [56], unless a strong multipath reflection is present [81]. In addition, it has been observed that several such impairments increase with increasing path loss as discussed in Section 2.5.1.2.

9.1.3 Increasing MTPL

Given LOS operation, an increase in MTPL generally has little effect on coverage, due to the fact that lack of coverage is predominantly due to a lack of available unobstructed paths, and not predominantly due to rain attenuation. For example, the coverage resulting in the baseline scenario varies from roughly 45% to roughly 50% as the MTPL is increased from its nominal value towards infinity.

Given NLOS operation, the target coverage value can be reached with a global increase of 17 dB in the MTPL. Such a change entails certain difficulties:

- Maximum transmit power levels are restricted by safety considerations amongst other factors. For example, recently suggested EIRP spectral density limits [69] of 14 dBW/MHz and 30 dBW/MHz for the base station and subscriber terminal respectively result in corresponding maximum transmit power limits of 27 dBm and 48 dBm given the nominal bandwidths and antenna gains used here. These power limits are nevertheless at least 12 dB greater than the nominal values used here.
- An increase in antenna gains is also capped by the same limits on EIRP spectral density. Furthermore, an increase in subscriber antenna gain above the nominal value of 36 dBi requires a corresponding decrease in beamwidth below the nominal value of 2° , resulting in pointing error problems due to wind-induced antenna motion. An increase in base station antenna gain above the nominal value of 12 dBi requires an increase in the number of sectors beyond $N = 8$, such that the base station complexity increases, and the total power transmitted by the base station remains constant.
- A decrease in noise figure below the nominal value of 8 dB is possible but at increased receiver cost.

For example, the MTPL can be increased by 17 dB while remaining under the quoted EIRP limits by applying the following changes to the nominal system:

- decrease the noise figure of both BS and ST receivers from 8 dB to 5 dB,
- increase the BS antenna gain from 12 dBi to 18 dBi by increasing the number of sectors from 8 to 36,
- increase the ST transmit power from 15 dBm to 23 dBm,
- increase the BS transmit power (per sector) from 27 dBm to 35 dBm.

In contrast, the use of adaptive modulation and coding remains as a possible manner of selectively increasing the MTPL of certain subscribers as required while decreasing the MTPL of others. The effectiveness of such an approach has not been investigated here.

9.1.4 Usage of Naturally Occurring Reflections

By definition, naturally occurring reflections cannot be used with LOS operation.

Given NLOS operation, the optimal combining of naturally occurring reflections is by itself far from being sufficient to meet the coverage target, as can be seen by comparing the measurement based coverage prediction curve in Figure 83 with that in Figure 81. Furthermore, the benefit of optimal combining, relative to the possible use of a single reflection for link establishment, is negligible. This is in contrast to the potential benefit of using such a method to mitigate fading, which is a possible topic for future study.

Furthermore, even the use of single reflections for link establishment results in a small increase in coverage, on the order of 2% at most.

9.1.5 Usage of Relatively Inexpensive CEMs

Given NLOS operation, the baseline simulation includes the use of three coverage enhancing methods that are either low cost or virtually free of additional cost: a) the use of single reflections for link establishment, as may be achieved by simply re-pointing the subscriber antenna, b) the use of simple macrodiversity, which similarly results from antenna re-pointing, and c) the sampling of multiple candidate rooftop subscriber antenna sites during installation.

Individually, the removal of any one of these CEMs results in a relatively small decrease in coverage, nevertheless the combined effect is significant as shown in the below:

use of single reflections	2%
simple macrodiversity	4%
rooftop site selection	12%
combined effect	18%

Table 31: Coverage Enhancement Associated With Inexpensive Methods

Given LOS operation, the baseline simulation includes the use of all methods mentioned above except for the use of single reflections. The relative importance of the remaining methods in this case has not been investigated.

9.1.6 Increasing Base Station Antenna Height

Given either NLOS or LOS operation, a base station antenna HAG value greater than 100 metres is required to reach the target coverage value; nevertheless coverage is strongly dependent on BS antenna height.

The effectiveness of this method can be explained in either of two ways; an increase in BS antenna height will result in a) an increase in the percentage of unobstructed paths, and b) a decrease in the shadowing on those paths which remain obstructed, due to a decrease in diffraction angles as well as a decrease in the number of obstructions.

9.1.7 Selectively Increasing Subscriber Antenna Height

Given either NLOS or LOS operation, the target coverage value can be reached by individually increasing the ST antenna heights as required, using a rooftop mounted mast with a height ranging anywhere from 0 to roughly 9 metres (NLOS operation) or 13 metres (LOS operation). The percentage of subscribers which require antenna mast heights within any given range of values can be read from Figure 94 (NLOS operation) and Figure 95 (LOS operation).

The effectiveness of this method can be explained in the same manner as that of increasing base station antenna heights (Section 9.1.6).

9.1.8 Decreasing Cell Radius

Given NLOS operation, the target coverage value can be reached by decreasing the cell radius from 1.5 km to 1.0 km, which implies a doubling of the number of cells and subsequently a doubling in the number of base stations.

Given LOS operation, the target coverage value can be reached by decreasing the cell radius from 1.5 km to 0.5 km, which implies a ninefold increase in the number of cells and subsequently a ninefold increase in the number of base stations.

The use of NLOS operation instead of LOS operation results in little potential gain when very small cells (with radius of 500 metres or less) are used with conventional base station antenna heights (40 metres HAG), but can result in significant gains when the cell radius is greater than 500 metres.

9.1.9 Microcell Architecture

Given NLOS operation, the target coverage value can be reached by using base stations that are placed roughly 10 metres above ground and at a spacing of roughly 800 metres, i.e. with a cell radius of roughly 400 metres.

Given LOS operation, a base station spacing of roughly 400 metres is required to reach the target coverage value, i.e. with a cell radius of roughly 200 metres; this represents a fourfold increase in the number of base stations relative to the NLOS case.

In practice, such a system could be deployed by mounting low-power base stations on existing fixtures such as light posts or utility poles. The cost of such an approach could be further reduced by providing wireless backbone links to the base stations.

An additional and important benefit that results from the use of microcells is the greatly reduced sensitivity to rain attenuation, which comes as a result of the reduced path lengths.

The effect of using NLOS operation instead of LOS operation is very pronounced when a microcell architecture is in place; there is a negligible difference between the two cases when the cell radius is 200 metres or less, but LOS operation becomes completely infeasible for cell radii greater than 200 metres, resulting in coverage values of 30% or less, while coverage values of 90% or more are easily achieved with NLOS operation for cell radii up to 500 metres.

9.1.10 Usage of Repeaters

Given NLOS operation, the target coverage value can be reached by using bidirectional, non-regenerative repeaters that are placed roughly 10 metres above ground

and with a spatial density of roughly 1.3 repeaters per square kilometre, which is equivalent to 12 repeaters per cell in the present context. In addition, the use of repeaters was found to be ineffective without the installation on base station towers of a supplementary high gain antenna for each repeater that the base station supports via a donor link.

Given LOS operation, the target coverage value cannot be reached regardless of the number of repeaters, but can be approached when a very large number of repeaters are used, for example, 75% coverage results from 8.9 repeaters per square kilometre, and 85% coverage results from 26.7 repeaters per square kilometre. Increases in coverage beyond 85% were not achieved in simulation, in spite of having repeaters placed at every point on a 100 metre grid in the most extreme case, equivalent to 100 repeaters per square kilometre. Any further increases would be difficult in practice due to necessary limitations on the number of repeater sites which would be available.

The use of supplementary high gain antennas as simulated here results in a maximum EIRP that is in excess of recommended limits [69] by 3 dB/MHz. Similarly, repeater emissions may also exceed limits in certain cases, although this has not been verified. The possibility of reducing the required supplementary antenna gain by decreasing the repeater and/or subscriber noise figure, and/or increasing the repeater amplifier gain is a possible topic for future study.

The usage of repeaters as investigated here differs from the microcell simulations in certain significant ways that are listed below, nevertheless the two options are closely related and can be merged given appropriate changes:

- The repeaters are non-regenerative, while the micro-base stations are assumed to perform demodulation/modulation and error correction on the backbone link. Subsequently, repeaters do not result in greatly reduced sensitivity to rain, since the effect of rain accumulates over the total length of both the donor and distribution links.
- The micro-base stations are placed on a regular grid, while the repeaters are optimally located.

9.1.11 Combined Reduction in Cell Radius and Use of Repeaters

Given NLOS operation, the net effect of both a reduction in cell radius (from 1.5 km to 1.25 km) and the use of repeaters (at a spatial density of 5.8 repeaters per km²) has been investigated as a possible solution to the coverage problem that results when an additional 20 dB of fade margin is required. In contrast, solutions involving single CEMs generally result in extreme requirements. The use of the additional fade margin is intended to represent the effect of extreme fading as has been observed in the field [56] without mitigation. In practice, such fading could be mitigated by error control coding and diversity.

The use of this combined method in the case of LOS operation has not been investigated.

9.2 Recommendations for Achieving High Coverage

Considering the demonstrated difficulty involved in achieving high coverage with LOS operation, as well as the predicted increases in coverage which can be achieved when NLOS operation is used in addition to one or more coverage enhancement methods, the use of NLOS operation is recommended as being the subject of future consideration.

Given NLOS operation, several of the coverage enhancing methods that have been studied here can be used to achieve a high degree of coverage. Of all, there is no single method that stands out as being the best solution in all cases, due to the cost, difficulty or remaining uncertainty associated with each. The choice of a best implementation depends in large part on economic issues that are outside the scope of this thesis, such as implementation costs and anticipated demand, as well as the nature of the terrain and the climate that exists in the intended coverage regions. In particular, it may be desirable to use different CEMs in different regions.

Furthermore, a combined approach to increasing coverage may prove to be the best option in many cases, due to the relatively small change associated with each method. For example, it may be relatively easy to reach a coverage target by simultaneously applying modest changes to receiver noise figure, the number of base station sectors, the cell radius, the transmit power, the number of repeaters, etc. The

effectiveness of such combinations cannot generally be derived directly from the existing results due to the interactions between methods. A single combination has been studied as described in Section 9.1.11, with the study of all other combined methods being a potential topic for further study.

Given LOS operation, it would be necessary to use either a) a microcell architecture with base station spacing on the order of 400 metres, or b) a combination of several coverage enhancing methods, including global increases to base station antenna heights, selective increases to subscriber antenna heights, a global reduction in cell radius, and the addition of repeaters. In this case, the use of any single CEM other than microcells leads to the need for system parameter values which are extreme in terms of cost and feasibility.

9.3 : Recommendations for Further Study

9.3.1 Additional Coverage Simulations

The propagation and coverage models that have been presented here can be used in an iterative manner and without modification to evaluate the effectiveness of various combinations of CEMs in various scenarios. This approach is recommended over an attempt at a full characterization of all possibilities.

One such class of scenarios involves modifications to the repeater parameters, such as noise figure or amplifier gain, with the intent of controlling EIRP.

The associated simulation software could be readily modified to allow for the investigation of alternative architectures, such as a two-tier architecture as described in [10], in which case the millimetre-wave bands are used for links that feed micro-base stations or repeaters, and lower frequency bands are used for links from these to the subscribers.

An additional architecture that could be readily simulated involves the creation a wireless mesh network or “multipoint-to-multipoint” system, involving either dedicated

local transponders or having subscriber terminals take on the role of transponder as described for example in [16].

Nevertheless, all such simulations would suffer from the incomplete validation of the propagation model, so that further testing and refinement of the propagation model is recommended as a prior step.

9.3.2 Repeaters

Limitations on the performance of wideband bidirectional nonregenerative repeaters exist due to implementation issues such as the linearity of broadband amplifiers and the occurrence of unwanted positive feedback. These issues have only been lightly touched upon here. More thorough knowledge of the limitations on repeater performance is required to better evaluate their effectiveness for coverage enhancement.

9.3.3 Propagation Model

9.3.3.1 Improvements

The validation of the propagation model could be completed by way of a second, independent set of field measurements that is nonetheless similar in all other ways to the measurement set used during the model development process. Furthermore, the generality of the model could be tested through the use of additional measurements that are taken under different conditions, such as different antenna heights, carrier frequencies, or in areas with notably different ground clutter characteristics for example. Further comparisons of this sort would naturally lead to refinements of the model, such as might involve the empirical parameters.

The simulations that have been completed to date have generally resulted in the prediction of paths that are characterized by multiple diffraction over trees. Because of the importance of this propagation mode, it is recommended that the multiple diffraction model be improved. Such improvement could result from a stronger basis in theory as in done in [74] for example, as well as through the study of special field measurements that would be tailored to isolate this propagation mode. Similarly, specialized field

measurements could be used to characterize the transmission of RF energy through several trees with arbitrary spacings.

The second most important component of path loss has been found to be rain attenuation, which could similarly benefit from improved modelling. At present, there is no universally accepted rain attenuation model as is indicated in [55] for example. The suitability of currently popular models for rain attenuation (such as the Crane [12] and ITU-R [40] models) to the problem at hand is brought into doubt due in part to the relatively long path lengths that were involved in the derivation of these models [8]; less spatial averaging occurs on shorter paths, hence these are likely to experience more variability in specific attenuation as a result of the motion of rain cells. An effort to develop a rain model that accounts for this effect, as well as predicting the gain resulting from spatial diversity is current under way [32].

An improvement to the modelling of relatively weak specular reflections would be justified if the model were to be used to investigate broader issues of interference, spatial diversity to mitigate fading, and delay spread. Such an improvement would be justified in light of the poor performance of the model in this area. Due to the computational expense involved in the use of ray tracing to predict these weak reflections, a statistical approach may prove more fruitful.

9.3.3.2 Extensions

The propagation model can evidently be extended in principle to predict all quantities associated with broadband signals, such as fading, polarization and impulse response for a wide range of carrier frequencies. Nevertheless, due to the large number of obstructing objects that typically occur, as well as due to the current infeasibility involved in the modelling of trees and buildings at the scale of the carrier wavelengths involved, it is not recommended that such extensions be made by way of purely deterministic modelling. Alternatively, the model could be augmented with separate statistical models for the quantities in question, with the models being nevertheless dependent to some degree on such parameters as antenna height and being at least somewhat site specific.

The most important of these quantities is the fading that occurs on links that are obstructed by trees, due to the severity of the fading as shown in [56] and [59], and due to the likelihood of it being flat as discussed in Section 8.1.3. A field measurement campaign is recommended for the purpose of developing an empirical model, ideally including spatial correlation information so that the diversity gain resulting from paths that are separated by an arbitrary angle-of-arrival can be estimated. The goal of such a campaign would be to determine whether the fading is predictable to any degree, based on available knowledge such as the geometry of the obstructing trees as represented in the corresponding terrain database, and subsequently to model the predictable elements accordingly.

This leads to the general possibility of extending the model to include a measure of certainty associated with predictions, or more generally, to output distributions for all predicted quantities. In principle, the certainty information could be either empirical or theoretical in nature. Severe difficulties are anticipated in the theoretical case, such as would result by replacing fixed quantities in a ray tracing model with random variables, due to the complex and highly nonlinear way in which the involved terrain objects and their corresponding distributions for position, roughness, electrical properties etc. would be involved in the final expressions. Monte Carlo or numerical techniques would likely suffer from the computational burden. Empirical confidence information, on the other hand, may require an impractical number of measurements to be taken. Nevertheless, it may be possible and useful to provide crude confidence estimates in practice.

Terrain database accuracy plays an important role in determining the confidence associated with predicted quantities. Both empirical and theoretical approaches are possible to investigate associated issues. For example, it may be possible to investigate the degree to which increased accuracy in the representation of tree outlines leads to increased accuracy in predictions.

9.3.4 Coverage Model Extension

Ideally, the coverage model could be expanded into a full system simulation which involves system capacity and interference issues. Such a simulation could in

principle include traffic modelling, dynamic channel allocation, power control, adaptive modulation and adaptive antennas, and would involve fading and the role of diversity.

To achieve a simulation of this complexity, it may be necessary or desirable to abandon the current approach to propagation modelling and replace it with a simpler statistical model that is not dependent on a detailed terrain database. Nevertheless, the additional errors associated with the move to such a simpler model are not known, and a number of predictive abilities would be lost, depending on the sophistication of the replacing model. Given that the current simulator is capable of approximating interference levels in a practical amount of time, it is recommended that development continue to be based on the current simulator.

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Appendix 1

Building Rooftop Diffraction

The energy diffracted over the rooftop of a building may typically be sufficient to provide coverage in a significant portion of the building's shadow zone, as illustrated below. In spite of the high carrier frequency considered here (28 GHz), the diffracted energy is significant due to the very shallow diffraction angles typically involved. In the example shown below, a diffraction angle of only 1° is required for a ray to reach the shadow midpoint.

Given the typical geometry shown in Figure 98, the resulting shadow zone extends 286 metres from the obstruction. The received power level relative to the unobstructed case as predicted by the knife-edge diffraction model is plotted in Figure 99 as a function of the distance X travelled into the shadow zone.

An examination of Figure 99 reveals that coverage may result for a portion of those sites that are within shadow zones, assuming that sufficient power margin exists, and that the diffracted signal is not made unsuitable by other impairments such as depolarization. For example, assuming a power margin of 25 dB, as may be provided to counteract the attenuation due to a single tree, and assuming that the building is the sole source of attenuation, coverage would occur within roughly one third of the shadow zone.

Figure 98: Building Rooftop Diffraction

Figure 99: Diffraction Loss in Shadow Zone

Appendix 2

Ray Tracing Algorithm Specification

The following is a logical description of the ray tracing algorithm that determines a set of paths between points *A* and *B*. The description has been written for clarity, and as such does not represent a practical implementation; in particular, acceleration techniques are not included, and a number of operations are repeated in the description while in practice they would be computed only once.

Refer to Section 3.3 for further explanation of this algorithm.

Notation

Notation of the form

$X, Y = \text{FunctionName}(A, B)$

indicates that a sequence of steps perform a function described by **FunctionName**, which take as inputs the entities **A** and **B**, possibly modifying them, and producing output entities **X** and **Y**. The sequence of steps involved in **FunctionName** is expanded elsewhere in the listing. Notation of the form

$X.y$

refers to an element (component) **y** of a more complex entity **X**. The notation

$X = A$

refers to the assignment operation, in which case **X** is given the value of **A**. The notation

$X += A$

refers to accumulation, i.e. the addition of **A** to the existing value of **X**.

The iterative repetition of a sequence of steps (a “loop”) is denoted by

repeat for index (i) ranging from (i = a) to (i = b) by step (s)

where at each iteration the index (i) is incremented by the value s from an initial value of a to a final value of b. If the step is omitted, the default value is 1.

An explanatory note is denoted with # to differentiate it from a step of the algorithm

this is a comment

When a variable first appears in a function body, it can be assumed to have a value of 0 in the case of a scalar, or to be empty in the case of a set.

Sets

Sets are denoted by variable names that begins with the character **L** (for List) or by curly braces {a,b,c,...} enclosing all members. The ith element of a list is denoted as

$L[i]$

The elements of **L** are indexed from 0 to N-1, where N is the number of elements in the set. The notations

$L \ll X \quad X \gg L$

refer to the inclusion of entity **X** into set **L** and similarly

$L \gg X \quad X \ll L$

refer to the extraction of **X** from **L**.

Data Structures

A *point* **X** is composed of a set of 3D spatial coordinates, as well as supplementary information associated with that location, such as type and path loss. Types of point include diffraction, reflection, and antenna location. A diffraction point includes the following information:

X.keh	(knife-edge model height h)
X.ked1	(knife-edge model distance $d1$)
X.ked2	(knife-edge model distance $d2$)
X.doo	(degree of obstruction)

A *segment S* is composed a straight line segment that extends between two points S.a and S.b, as well as supplementary information associated with the segment, including:

S.Lblock	(set of objects that block S)
S.Latten	(set of attenuators on S)
S.Lfolint	(set of foliage intervals on S)
S.Lpart	(set of objects that partially obstruct S)
S.Lpdiff	(set of partial diffraction points on S)

A *path P* is an ordered set of alternating points X_i and segments S_i , which begins and ends with a point. For example,

$$P = \{X1, S1, X2, S2, X3\}$$

where

$$\begin{array}{ll} S1.a = X1 & S1.b = X2 \\ S2.a = X2 & S2.b = X3 \end{array}$$

Algorithm

The ray tracing algorithm begins with the function **Raytrace()**, from which point all other functions are called. They are listed here in alphabetical order.

(This function finds the knife-edge model parameters h , $d1$ and $d2$ associated with diffraction point D based on the geometry of $S1$ and $S2$, which are adjacent segments joined at point D .)

ComputeKnifeEdgeParameters(S1,D,S2):

construct line $L1$ that passes through $S1.a$ and $S2.b$
construct line $L2$ which:

passes through D
 is perpendicular to L1
 passes through L1 at M
 D.keh = Distance(D,M)
 D.ked1 = Distance(S1.a,M)
 D.ked2 = Distance(M,S2.b)

(This function computes the net path loss associated with path P.)

loss = ComputePathLoss(P):

R = TotalPathLength(P)

loss = FreeSpaceLoss(R) + ObstructionLoss(P) + RainLoss(R)

(This function computes reflection point coordinates.)

R = ComputeReflectionPoint(A,B,W):

Using the method of images, find the coordinates of the reflection point R as defined by points A and B and the infinite plane corresponding to building wall W.

(This function finds a diffraction point D that is on the bottom of polyprism O, relative to segment S, and is otherwise identical to CreateTopPolyPrismDiffractionPoint)

D = CreateBottomPolyPrismDiffractionPoint(S,O):

details omitted

(This function finds a diffraction point D that is on the bottom of tree O, relative to segment S, and that is otherwise identical to CreateTopTreeDiffractionPoint.)

D = CreateBottomTreeDiffractionPoint(S,O):

details omitted

D is the bottommost point of intersection of L with Y

(This function creates, using method M, a set Lc of candidate paths that are based on path P, given that segment S is intersected by object O. The candidate paths fall into two classes: those that involving transmission through object O, and those involving diffraction on the surface of O. In the case of the diffraction class, segment S is replaced by the sequence (S1,D,S2) where D is a diffraction point on the surface of O, and S1 and S2 are adjacent segments joined at point D. In the case of the transmission class,

segment S is retained, and object O, initially classified as a blocker on S, is reclassified as being an attenuator on S.)

Lc = CreateCandidatePathSet(P,S,O,M):

switch on the type of object O

if type Building	Lc = CreateCandPathSet_Building(P,S,O)
if type Tree	Lc = CreateCandPathSet_Tree(P,S,O,M)
if type Thicket	Lc = CreateCandPathSet_Thicket(P,S,O,M)
if type Ground	Lc = CreateCandPathSet_Ground(P,S,O)

(This function creates a set Lc consisting of three candidate paths that are based on path P, given that segment S is intersected by building O. The three candidate paths involve diffraction over the top of, around the left side of, and around the right side of building O.)

Lc = CreateCandPathSet_Building(P,S,O):

repeat for index (i) ranging over all elements in O.Lwa

D = O.Lwa[i]

C = CreateDiffractionCandidatePath(P,S,D)

Lc << C

(This function creates a set Lc consisting of a single candidate path that is based on path P, given that segment S is intersected by ground square O. The candidate path involves diffraction over the top of ground square O.)

Lc = CreateCandPathSet_Ground(P,S,O):

D = O.Lwa

C = CreateDiffractionCandidatePath(P,S,D)

Lc << C

(This function creates a set Lc consisting of five candidate paths that are based on path P, given that segment S is intersected by thicket O. If the parameter M has a value of "general", five candidate paths are created, involving diffraction over the top of, under, around the left side of, and around the right side of the thicket, and transmission through the thicket. If M has a value of "limited", the list of ways around the thicket O.Lwa contains only a single element, and only a single candidate path is created, involving diffraction over the top of the thicket.)

Lc = CreateCandPathSet_Thicket(P,S,O,M):

repeat for index (i) ranging over all elements in O.Lwa

D = O.Lwa[i]

C = CreateDiffractionCandidatePath(P,S,D)

Lc << C

if M is “general”

C = CreateTransmissionCandidatePath(P,S,O)

Lc << C

(This function creates a set Lc consisting of five candidate paths that are based on path P, given that segment S is intersected by tree O. If the parameter M has a value of “general”, five candidate paths are created, involving diffraction over the top of, under, around the left side of, and around the right side of the tree, and transmission through the tree. If M has a value of “limited”, the list of ways around the tree O.Lwa contains only a single element, and only a single candidate path is created, involving diffraction over the top of the tree.)

Lc = CreateCandPathSet_Tree(P,S,O,M):

repeat for index (i) ranging over all elements in O.Lwa

D = O.Lwa[i]

C = CreateDiffractionCandidatePath(P,S,D)

Lc << C

if M is “general”

C = CreateTransmissionCandidatePath(P,S,O)

Lc << C

(This function creates candidate path C, which is identical to path P, except that segment S is replaced with a sequence consisting of diffraction point D and two new adjoining segments S1 and S2.)

C = CreateDiffractionCandidatePath(P,S,D):

C = P

note that C contains { ... ,S, ... }

S1 = CreateSegment(S.a,D)

S2 = CreateSegment(D,S.b)

Replace(C,{S},{S1,D,S2})

mark S1 and S2 as being active segments

(This function creates a foliage interval F based on interspan I.)

F = CreateFoliageIntv(J):

details omitted

(This function creates an *interspan* J that extends from point A to point B. An interspan is a line segment that denotes a non-disjoint intersection interval of a line and solid.)

J = CreateInterSpan(A,B):

details omitted

(This function finds a diffraction point D that is on the left side of polyprism O, relative to segment S.)

D = CreateLeftPolyPrismDiffractionPoint(S,O):

for each tier T in set O.Lipt

for each vertical edge E in T

if E supports diffraction

if E is to left of S

P,Q = NearestApproach_TwoLines(S,E)

if P is on S and Q is on E

X = Q

X.doo = Distance(P,Q)

Ld << X

D = SelectMax(Ld,doo)

(This function finds a diffraction point D that is on the left side of tree O, relative to segment S.)

D = CreateLeftTreeDiffractionPoint(S,O):

the tree O includes ellipsoid E that is defined by centre point C,

vertical semi-axis A and horizontal semi-axis B

J = FindTreeInterSpan(O,S)

find M, the midpoint of line segment J

construct a cylinder Y that encloses E, having height 2A, radius B and centre C

construct a horiz. line L that passes through the vert. axis of E and through M

D is the leftmost point of intersection of L with Y

D.doo = Distance(M,D)

(This function finds a diffraction point D that is on the right side of polyprism O, relative to segment S, and is otherwise identical to CreateLeftPolyPrismDiffractionPoint)

D = CreateRightPolyPrismDiffractionPoint(S,O):

details omitted

(This function finds a diffraction point D that is on the right side of tree O, relative to segment S, and that is otherwise identical to CreateLeftTreeDiffractionPoint.)

D = CreateRightTreeDiffractionPoint(S,O):

details omitted

D is the rightmost point of intersection of L with Y

(this function creates a segment S from a pair of points X1, X2)

S = CreateSegment(X1,X2):

S.a = X1

S.b = X2

(This function finds a diffraction point D that is on the top of the ground square O, relative to segment S.)

D = CreateTopGroundDiffractionPoint(S,O):

a ground square O is defined by a set of four points Lp

Lp forms a square in the XY plane

each element of Lp has a different elevation in general

J = FindGroundInterSpan(O,S)

find M, the midpoint of line segment J

find Z, the point in Lp that has the greatest elevation

construct a horizontal plane W that passes through Z

construct a vertical line L that passes through M

D is the point of intersection of L and W

D.doo = Distance(M,D)

(This function finds a diffraction point D that is on the top of polyprism O, relative to segment S.)

D = CreateTopPolyPrismDiffractionPoint(S,O):

```

    for each stack K in set O.Lips
        for each roof edge E in K
            if E supports diffraction
                if E is above S
                    P,Q = TwoDIntersection(S,E)
                    if P is on S and Q is on E
                        X = Q
                        X.doo = Distance(P,Q)
                        Ld << X

D = SelectMax(Ld,doo)

```

(This function finds a diffraction point D that is on the top of tree O, relative to segment S.)

D = CreateTopTreeDiffractionPoint(S,O):

```

# the tree O contains includes ellipsoid E that is defined by centre point C,
# vertical semi-axis A and horizontal semi-axis B
find U and V, the points of intersection of segment S with E
find M, the midpoint of line segment UV
construct a cylinder Y that encloses E, having height 2A, radius B and centre C
construct a vertical line L that passes through M
D is the topmost point of intersection of L with Y
D.doo = Distance(M,D)

```

(This function creates candidate path C, which is identical to path P, except that object O (which must be a foliage object) on segment S is marked as non-blocking (attenuating).)

C = CreateTransmissionCandidatePath(P,S,O):

```

C = P
C.S.Lblock >> O
C.S.Latten << O
mark S as being an active segment

```

(This function computes the loss associated with all diffraction points on path P, including partial diffractions.)

loss = DiffractLoss(P):

```
ListFullDiffractionLosses(Ldloss,P)
ListPartialDiffractionLosses(Ldloss,P)
loss = MultipleDiffractionLoss(Ldloss)
```

(This function computes the distance R between two points A and B.)

R = Distance(A,B):

```
# details omitted
```

(This function evaluates a path loss estimate for path P. This estimate is for the purpose of comparing candidate paths only, and as such only certain components that are assumed to differ significantly between candidates are evaluated; free space path loss, rain loss and partial diffractions are omitted.

pl_est = EstimatePathLoss(P):

```
for every segment S in path P
    IdentifyFoliageIntervals(S)
tranloss = TransmisLoss(P)
ListFullDiffractionLosses(Ldloss,P)
ListBlockerLosses(Ldloss,P)
diffloss = MultipleDiffractionLoss(Ldloss)
pl_est = tranloss + diffloss
```

(This function evaluates the degree to which object O obstructs segment S.)

EvaluateDegreeOfObstruction(O,S):

```
D = SelectMin(O.Lwa,doo)
O.doo = D.doo
```

(This function evaluates S.Lpdiff, the set of partial diffraction points that exist on segment S. The partial diffraction points are associated with S.Lpart, the set of objects that partially obstruct segment S.)

EvaluatePartialDiffractions(S):

```
for every object O in set S.Lpart
```

switch on the type of object O

if type Tree	EvaluateTreePartialDiff(O,S)
if type Building or Thicket	EvaluatePolyPrismPartialDiff(O,S)

(This function finds one or more partial diffraction points on segment S that result from the polyprism O.)

EvaluatePolyPrismPartialDiff(O,S):

```

for every edge E in polyprism O
  if edge E supports diffraction
    P,Q = NearestApproach_TwoLines(S,E)
    if P is on S and Q is on E
      d = Distance(P,Q)
      if d < first Fresnel radius
        D = P
        D.keh = -d
        D.ked1 = Distance(S.a,D)
        D.ked2 = Distance(D,S.b)
        S.Lpdiff << D

```

(This function finds the partial diffraction point D on segment S that results from the tree O.)

EvaluateTreePartialDiff(O,S):

```

# the tree O includes ellipsoid E
P,Q = NearestApproach_LineEllipsoid(S,E)
d = Distance(P,Q)
D = P
D.keh = -d
D.ked1 = Distance(S.a,D)
D.ked2 = Distance(D,S.b)
S.Lpdiff << D

```

(This function finds the direct path P between points A and B.)

P = FindDirectPath(A,B):

```

P = InitializePath({A,B})

```

ResolvePath(P)

(This function finds J, the interspan of ground square O on segment S.)

J = FindGroundInterSpan(O,S):

 construct a rectangular prism Y by extending the ground square O vertically
 towards infinity in both directions
 find J.a and J.b, the points of intersection of S with Y

(This function creates Lpp, which is the set of cells in polyprism O that are intersected by segment S.)

Lpb = FindIntersectedCells(S,O):

 for each cell Pb in polyprism O
 if Pb intersects S
 Lpb << Pb

(This function evaluates O.Lips, which is the set of stacks in polyprism O that are intersected by segment S. Segment S is not specified directly; instead Lpb is given, which is the set of cells in O that are intersected by S.)

FindIntersectedStacks(Lpb,O):

 for each polytstack K in O
 if one or more cells in set Lpb is contained in K
 O.Lips << K

(This function evaluates O.Lipt, which is the set of tiers in polyprism O that are intersected by segment S. Segment S is not specified directly; instead Lpb is given, which is the set of cells in O that are intersected by S.)

FindIntersectedTiers(Lpb,O):

 for each tier T in O
 if one or more cells in set Lpb is contained in T
 O.Lipt << T

(This function finds L, the set of interspans of object O on segment S.)

L = FindInterSpans(O,S):

 switch on the type of object O

```

if type Building
    L = FindPolyPrismInterSpans(O,S)
if type Tree
    J = FindTreeInterSpan(O,S)
    L = {J}
if type Thicket
    L = FindPolyPrismInterSpans(O,S)
if type Ground
    J = FindGroundInterSpan(O,S)
    L = {J}

```

(This function finds the set L_p of points of intersection of the segment S with the prism P . Intersection points generally occur in pairs.)

$L_p = \text{FindPrismIntersectionPoints}(P,S):$

```

# a prism P consists of a horizontal "roof" surface, a horizontal "floor"
# surface, and a set of vertical "wall" surfaces
if S intersects the roof at point P
     $L_p \ll P$ 
if S intersects the floor at point P
     $L_p \ll P$ 
for every wall W in P
    if S intersects wall W at P
         $L_p \ll P$ 
sort the member points of  $L_p$  in order of their distance from S.a

```

(This function finds L_j , the set of interspans of prism P on segment S .)

$L_j = \text{FindPrismInterSpans}(P,S):$

```

 $L_p = \text{FindPrismIntersectionPoints}(P,S)$ 
# N is the number of elements in  $L_p$  and is even
repeat for (i) ranging from (i=0) to (i=N-2) by step (2)
     $J = \text{CreateInterSpan}(L_p[i], L_p[i+1])$ 
     $L_j \ll J$ 

```

(This function evaluates $O.Lips$ and $O.Lipt$, which are the sets of stacks and tiers in polyprism O that are intersected by segment S .)

FindPolyPrismIntersections(S,O):

```

    Lpp = FindIntersectedCells( $S,O$ )
    FindIntersectedStacks( $Lpp,O$ )
    FindIntersectedTiers( $Lpp,O$ )

```

(This function finds L_j , the set of interspans of polyprism O on segment S .)

$L_j = \text{FindPolyPrismInterSpans}(O,S)$:

```

    for every stack  $P$  in polyprism  $O$ 
         $L = \text{FindPrismInterSpans}(P,S)$ 
         $L_j \ll L$ 

```

(This function finds a set L_r of zero or more reflection paths between points A and B .)

$L_r = \text{FindReflectionPathSet}(A,B)$:

```

     $L_h = \text{SelectReflectiveBuildingSet}(B)$ 
    for every building  $H$  in  $L_h$ 
        for every wall  $W$  of building  $H$ 
             $R = \text{ComputeReflectionPoint}(A,B,W)$ 
             $P = \text{InitializePath}(\{A,R,B\})$ 
             $\text{TestReflectionPointValidity}(P,R,W)$ 
            if  $R$  is a valid reflection point
                 $\text{ResolvePath}(P)$ 
                 $\text{TestReflectionPointValidity}(P,R,W)$ 
                if  $R$  is a valid reflection point
                     $L_r \ll P$ 

```

(This function finds J , the interspan of tree O on segment S .)

$J = \text{FindTreeInterSpan}(O,S)$:

```

    # the tree  $O$  includes ellipsoid  $E$ 
    # find points  $J.a$  and  $J.b$ , the points of intersection of segment  $S$  with  $E$ 
    #details omitted

```


(This function finds the possible *ways around* each blocker on segment S using method M. The ways around a blocker B are represented by B.Lwa, which is a set of diffraction points on the surface of B. Each way around has an associated *degree of obstruction*. Method M has a value of either “general”, in which case all ways around the blockers are evaluated, or “limited”, in which case only the top way around the blocker is evaluated.)

FindWaysAroundBlockers(S,M):

```

    for every blocker B in S.Lblock
        switch on the type of object B
            if type Building      FindWaysAroundBuilding(B,S,M)
            if type Tree          FindWaysAroundTree(B,S,M)
            if type Thicket       FindWaysAroundThicket(B,S,M)
            if type Ground        FindWaysAroundGround(B,S)

```

(This function evaluates O.Lwa, which is a set of diffraction points that correspond to ways in which the segment S can be brought around the building O. If the parameter M has a value of “limited”, only the top way around is evaluated, otherwise all possible ways around are evaluated.)

FindWaysAroundBuilding(O,S,M):

```

    FindPolyPrismIntersections(S,O)
    if M is “limited”
        D = CreateTopPolyPrismDiffractionPoint(S,O)
        O.Lwa = {D}
    else
        D1 = CreateLeftPolyPrismDiffractionPoint(S,O)
        D2 = CreateRightPolyPrismDiffractionPoint(S,O)
        D3 = CreateTopPolyPrismDiffractionPoint(S,O)
        O.Lwa = {D1,D2,D3}

```

(This function evaluates O.Lwa, which is a set of diffraction points that correspond to ways in which the segment S can be brought around the ground square O. In this case, only the top way around is evaluated.)

FindWaysAroundGround(O,S):

```

    D = CreateTopGroundDiffractionPoint(S,O)
    O.Lwa = {D}

```

(This function evaluates $O.Lwa$, which is a set of diffraction points that correspond to ways in which the segment S can be brought around the thicket O . If the parameter M has a value of “limited”, only the top way around is evaluated, otherwise all possible ways around are evaluated.)

FindWaysAroundThicket(O,S,M):

```

FindPolyPrismIntersections( $S,O$ )
if  $M$  is “limited”
     $D = \text{CreateTopPolyPrismDiffractionPoint}(S,O)$ 
     $O.Lwa = \{D\}$ 
else
     $D1 = \text{CreateLeftPolyPrismDiffractionPoint}(S,O)$ 
     $D2 = \text{CreateRightPolyPrismDiffractionPoint}(S,O)$ 
     $D3 = \text{CreateTopPolyPrismDiffractionPoint}(S,O)$ 
     $D4 = \text{CreateBottomPolyPrismDiffractionPoint}(S,O)$ 
     $O.Lwa = \{D1,D2,D3,D4\}$ 

```

(This function evaluates $O.Lwa$, which is a set of diffraction points that correspond to ways in which the segment S can be brought around the tree O . If the parameter M has a value of “limited”, only the top way around is evaluated, otherwise all possible ways around are evaluated.)

FindWaysAroundTree(O,S,M):

```

if  $M$  is “limited”
     $D = \text{CreateTopTreeDiffractionPoint}(S,O)$ 
     $O.Lwa = \{D\}$ 
else
     $D1 = \text{CreateLeftTreeDiffractionPoint}(S,O)$ 
     $D2 = \text{CreateRightTreeDiffractionPoint}(S,O)$ 
     $D3 = \text{CreateTopTreeDiffractionPoint}(S,O)$ 
     $D4 = \text{CreateBottomTreeDiffractionPoint}(S,O)$ 
     $O.Lwa = \{D1,D2,D3,D4\}$ 

```

(This function computes the free space propagation loss over the distance R .)

loss = FreeSpaceLoss(R):

details omitted

(This function finds S.Lblock, the set all objects that block segment S.)

IdentifyBlockers(S):

```

    for each object O in the world
        test for intersection of S and O
        if intersection occurs
            S.Lblock << O

```

(This function determines the foliage intervals that exist on segment S, based on S.Latten, the set of attenuators on S.)

IdentifyFoliageIntervals(S):

```

    reset S.Lfolint to empty state
    for each element O in S.Latten
        switch on the type of object O
            if type Tree
                J = FindTreeInterSpan(O,S)
                S.Lfolint << CreateFoliageIntv(J)
            if type Thicket
                Lj = FindPolyPrismInterSpans(O,S)
                for every interspan J in set Lj
                    S.Lfolint << CreateFoliageIntv(J)

```

(This function finds S.Lpart, the set all objects that partially block segment S.)

IdentifyPartialBlockers(S):

```

    for each object O of type Tree, Building or Thicket
        test for intersection of O and the first Fresnel zone of segment S
        if intersection occurs
            S.Lpart << O

```

(This function evaluates the degree of obstruction for each object in S.Lblock, the set of blockers on S, and selects the worst blocker O, i.e. the blocker with the greatest degree of obstruction.)

O = IdentifyWorstBlocker(S):

```

for every blocker B in S.Lblock
    EvaluateDegreeOfObstruction(B,S)
O = SelectMax(S.Lblock,doo)

```

(This function creates a path P from an ordered set of points Lx.)

P = InitializePath(Lx):

```

# N is the number of elements in Lx
repeat for index (i) ranging from (i = 0) to (i = N-2)
    X1 = Lx[i]
    X2 = Lx[i+1]
    S = CreateSegment(X1,X2)
    P << X1
    P << S
P << X2

```

(This function computes the diffraction loss for diffraction point D based on the parameters D.keh, D.ked1 and D.ked2.)

loss = KnifeEdgeLoss(D):

```

# details omitted

```

(This function determines the individual losses associated with each interspan of each blocker on path P, and appends the loss values to list Ld. Each interspan is modelled as resulting in a diffraction loss that is proportional to the length of the interspan.)

ListBlockerLosses(Ld,P):

```

for every segment S in path P
    for every blocker B in S.Lblock
        L = FindInterSpans(B,S)
        Lj << L
for every interspan J in Lj
    loss = 1.0 * Distance(J.a,J.b)
    Ld << loss

```

(This function determines the individual losses associated with each full diffraction point in path P, and appends the loss values to list Ld.)

ListFullDiffractionLosses(Ld,P):

```

for every diffraction point D in path P
    # note that P contains { ... ,S1,D,S2, ... }
    ComputeKnifeEdgeParameters(S1,D,S2)
    switch on the type of object on which diffraction point D exists
        if type Building      dloss = KnifeEdgeLoss(D)
        if type Tree           dloss = alpha * KnifeEdgeLoss(D)
        if type Thicket        dloss = alpha * KnifeEdgeLoss(D)
        if type Ground          dloss = alpha * KnifeEdgeLoss(D)
    Ld << dloss

```

(This function finds the net loss resulting from the multiple diffraction losses found in Ld.)

loss = MultipleDiffractionLoss(Ld):

```

SortDescending(Ld)
# N is the number of elements in Ld
repeat for index (i) ranging from (i = 0) to (i = N-1)
    loss += beta^i * Ld[i]

```

(This function finds point P, which is the point on line L that is the closest to ellipsoid E, and similarly Q which is the point on E that is the closest to L. The line segment defined by points P and Q is the shortest line segment that joins line L to ellipsoid E. Line L is found by extending segment S to infinity in both directions.)

P,Q = NearestApproach_LineEllipsoid(S,E):

```

# details omitted

```

(This function finds point P, which is the point on line L1 that is the closest to line L2, and similarly Q which is the point on L2 that is the closest to L1. The line segment defined by points P and Q is the shortest line segment that joins lines L1 and L2. Lines L1 and L2 are found by extending segments S1 and S2 respectively to infinity in both directions. The line segment PQ is perpendicular to both L1 and L2.)

P,Q = NearestApproach_TwoLines(S1,S2):

```

# details omitted

```

(This function determines the individual losses associated with each partial diffraction point in path P, and appends the loss values to list Ld.)

ListPartialDiffractionLosses(Ld,P):

```

    for every segment S in P
        for every partial diffraction point C in S
            # knife-edge parameters have been previously computed
            dloss = KnifeEdgeLoss(C)
            Ld << dloss

```

(This function computes the loss associated with all obstructions on path P.)

loss = ObstructionLoss(P):

```

    loss = gamma * (DiffractLoss(P) + ReflectLoss(P) + TransmisLoss(P)) + delta

```

(This function computes the loss due to rain attenuation over the distance R.)

loss = RainLoss(R):

```

    #details omitted

```

(This function finds all paths between points A and B, namely the direct path P and a set Lr of zero or more reflection paths.)

P,Lr = RayTrace(A,B):

```

    P = FindDirectPath(A,B)
    Lr = FindReflectionPathSet(A,B)

```

(This function computes the loss associated with all reflections in path P.)

loss = ReflectLoss(P):

```

    # details omitted

```

(This function replaces each negative diffraction point and adjoining segments with a single segment. The new segment is resolved using method M.)

RemoveNegativeDiffractions(P,M):

```

    for each diffraction point D in path P
        if D is a negative diffraction point
            # note that P contains { ... ,S1,D,S2, ... }
            S3 = CreateSegment(S1.a,S2.b)

```

```

        Replace(P,{S1,D,S2},{S3})
        IdentifyBlockers(S3)
        ResolveSegment(P,S3,M)
    if path P has changed
        RemoveNegativeDiffractions(P,M)

```

(this function replaces the subset of elements L1 in set L with the subset L2

Replace(L,L1,L2):

details omitted

(This function resolves path P into two intermediate versions of the path, each time using a different search method, and selects the version with the lower path loss.)

ResolvePath(P):

```

    P1 = P
    P2 = P
    ResolvePathByMethod(P1,"general")
    ResolvePathByMethod(P2,"limited")
    P = SelectMin({P1,P2},loss)

```

(This function resolves path P using method M. The path is resolved by resolving each segment in turn, removing superfluous diffraction points from P, and computing the net path loss.)

ResolvePathByMethod(P,M):

```

    for each segment S in path P
        IdentifyBlockers(S)
        ResolveSegment(P,S,M)
    RemoveNegativeDiffractions(P,M)
    P.loss = ComputePathLoss(P)

```

(This function resolves segment S of path P using method M, given that S is blocked by the objects listed in set S.Lblock.)

ResolveSegment(P,S,M):

```

    if S.Lblock is empty
        IdentifyFoliageIntervals(S)

```

```

        IdentifyPartialBlockers(S)
        EvaluatePartialDiffractions(S)
    else
        FindWaysAroundBlockers(S,M)
        O = IdentifyWorstBlocker(S)
        Lc = CreateCandidatePathSet(P,S,O,M)
        for each candidate path C in set Lc
            for each active segment T of candidate path C
                IdentifyBlockers(T)
                C.pl_est = EstimatePathLoss(C)
        P = SelectMin(Lc,pl_est)
        for each active segment T of path P
            mark segment T as inactive
            ResolveSegment(P,T,M)

```

(This function selects the entity X that has the least value of X.a of all entities in set L)

X = SelectMin(L,A):

details omitted

(This function selects the entity X that has the greatest value of X.a of all entities in set L)

X = SelectMax(L,A):

details omitted

(This function selects a set of buildings that will be tested for reflections.)

Lh = SelectReflectiveBuildingSet(B):

Create a set of buildings Lh that are either

- a) taller than H_tall, or
- b) closer to point B than D_near.

(This function sorts the elements of L in descending order, such that L[0] has the greatest value and L[N-1] has the smallest value.)

SortDescending(L):

details omitted

(This function tests the validity of a predicted reflection, i.e. the fulfilment of conditions that must be met for a reflection to exist.)

TestReflectionPointValidity(P,R,W):

note that path P includes { ...,S1,R,S2, ...}

Test whether the point R, the segments S1 and S2, and the building wall W satisfies the following two conditions:

- a) The segments S1 and S2 are both outside of the wall W as defined by an outward-pointing normal vector associated with W.
- b) The reflection point R falls onto the surface of wall W.

(This function computes the total length R of all segments in path P.)

R = TotalPathLength(P):

for each segment S in path P

R += Distance(S.a,S.b)

(This function computes the loss associated with transmission through foliage intervals.)

loss = TransmisLoss(P):

loss based on S.Lfolint for all S in P

details omitted

(This function finds points P on line L1 and point Q on line L2. Lines L1 and L2 are found by extending segments S1 and S2 respectively to infinity in both directions. Points P and Q have the same XY coordinates.)

P,Q = TwoDIntersection(S1,S2):

construct infinite line L1 by extending S1 to infinity in both directions

construct infinite line L2 by extending S2 to infinity in both directions

construct horizontal line H1 by projecting L1 onto XY plane

construct horizontal line H2 by projecting L2 onto XY plane

X = intersection of H1 and H2

construct vertical line L3 which passes through X

P = intersection of L3 and S1

Q = intersection of L3 and S2

Appendix 3

Predicted Coverage Plots

Figure 100: Baseline System

Figure 101: Worst Case System (Multiple Exclusions)

Figure 102: Exclusion of Rooftop Site Selection

Figure 103: Exclusion of Macrodiversity

Figure 104: Exclusion of Reflections

Figure 105: Maximal Ratio Combining of Reflections

Figure 106: Base Station Antenna Height Above Ground: 10 Metres

Figure 107: Base Station Antenna Height Above Ground: 20 Metres

Figure 108: Base Station Antenna Height Above Ground: 30 Metres

Figure 109: Base Station Antenna Height Above Ground: 50 Metres

Figure 110: Base Station Antenna Height Above Ground: 60 Metres

Figure 111: Base Station Antenna Height Above Ground: 100 Metres

Figure 112: Subscriber Antenna Height Above Rooftop: 0.25 Metres

Figure 113: Subscriber Antenna Height Above Rooftop: 0.25 Metres

Figure 114: Subscriber Antenna Height Above Rooftop: 1.0 Metre

Figure 115: Subscriber Antenna Height Above Rooftop: 2.0 Metres

Figure 116: Subscriber Antenna Height Above Rooftop: 3.0 Metres

Figure 117: Subscriber Antenna Height Above Rooftop: 4.0 Metres

Figure 118: Subscriber Antenna Height Above Rooftop: 5.0 Metres

Figure 119: Subscriber Antenna Height Above Rooftop: 6.0 Metres

Figure 120: Subscriber Antenna Height Above Rooftop: 7.0 Metres

Figure 121: Subscriber Antenna Height Above Rooftop: 8.0 Metres

Figure 122: Subscriber Antenna Height Above Rooftop: 9.0 Metres

Figure 123: Subscriber Antenna Height Above Rooftop: 10.0 Metres

Figure 124: Cell Radius: 0.5 Kilometres

Figure 125: Cell Radius: 0.75 Kilometres

Figure 126: Cell Radius: 1.0 Kilometre

Figure 127: Cell Radius: 1.25 Kilometres

Figure 128: Cell Radius: 2.0 Kilometres

Figure 129: Cell Radius: 3.0 Kilometres

Figure 130: Cell Radius: 4.0 Kilometres

Figure 131: Microcell (10 Metre BS Antenna HAG) and Cell Radius: 100 Metres

Figure 132: Microcell (10 Metre BS Antenna HAG) and Cell Radius: 200 Metres

Figure 133: Microcell (10 Metre BS Antenna HAG) and Cell Radius: 333 Metres

Figure 134: Microcell (10 Metre BS Antenna HAG) and Cell Radius: 500 Metres

Figure 135: Repeaters: 0 per Square Kilometre

Figure 136: Repeaters: 0.4 per Square Kilometre (4 per Cell)

Figure 137: Repeaters: 0.9 per Square Kilometre (8 per Cell)

Figure 138: Repeaters: 1.3 per Square Kilometre (12 per Cell)

Figure 139: Repeaters: 1.8 per Square Kilometre (16 per Cell)

Figure 140: Repeaters: 2.2 per Square Kilometre (20 per Cell)

Figure 141: Repeaters: 4.4 per Square Kilometre (40 per Cell)

Figure 142: Repeaters: 6.7 per Square Kilometre (60 per Cell)

Figure 143: Repeaters: 8.9 per Square Kilometre (80 per Cell)

Figure 144: Repeaters: 13.3 per Square Kilometre (120 per Cell)

Figure 145: Repeaters: 26.7 per Square Kilometre (240 per Cell)

Figure 146: Repeaters: 5.8 per Sqr. Km (36 per Cell) and Reduced Cell Radius: 1.25 Km

Figure 147: Exclusion of Trees

Figure 148: Baseline System & LOS Operation

Figure 149: Base Station Antenna HAG: 50 Metres & LOS Operation

Figure 150: Base Station Antenna HAG: 60 Metres & LOS Operation

Figure 151: Base Station Antenna HAG: 100 Metres & LOS Operation

Figure 152: Subscriber Antenna HAR: 1.0 Metre & LOS Operation

Figure 153: Subscriber Antenna HAR: 2.0 Metres & LOS Operation

Figure 154: Subscriber Antenna HAR: 3.0 Metres & LOS Operation

Figure 155: Subscriber Antenna HAR: 4.0 Metres & LOS Operation

Figure 156: Subscriber Antenna HAR: 5.0 Metres & LOS Operation

Figure 157: Subscriber Antenna HAR: 6.0 Metres & LOS Operation

Figure 158: Subscriber Antenna HAR: 7.0 Metres & LOS Operation

Figure 159: Subscriber Antenna HAR: 8.0 Metres & LOS Operation

Figure 160: Subscriber Antenna HAR: 9.0 Metres & LOS Operation

Figure 161: Subscriber Antenna HAR: 10.0 Metres & LOS Operation

Figure 162: Cell Radius: 0.5 Kilometres & LOS Operation

Figure 163: Cell Radius: 0.75 Kilometres & LOS Operation

Figure 164: Cell Radius: 1.0 Kilometres & LOS Operation

Figure 165: Cell Radius: 1.25 Kilometres & LOS Operation

Figure 166: Microcell Architecture & Cell Radius: 100 Metres & LOS Operation

Figure 167: Microcell Architecture & Cell Radius: 200 Metres & LOS Operation

Figure 168: Microcell Architecture & Cell Radius: 333 Metres & LOS Operation

Figure 169: Microcell Architecture & Cell Radius: 500 Metres & LOS Operation

Figure 170: Repeaters: 0 per Square Kilometre & LOS Operation

Figure 171: Repeaters: 1.3 per Square Kilometre (12 per Cell) & LOS Operation

Figure 172: Repeaters: 4.4 per Square Kilometre (40 per Cell) & LOS Operation

Figure 173: Repeaters: 8.9 per Square Kilometre (80 per Cell) & LOS Operation

Figure 174: Repeaters: 26.7 per Square Kilometre (240 per Cell) & LOS Operation