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A STUDY OF INDOOR RADIO PROPAGATION CHANNEL CHARACTERISTICS BY SIMULATION

Submitted by

Ping Wang, B. Eng

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

Master's of Engineering

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

Carleton University
Ottawa, Ontario, Canada K1S 5B6

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A STUDY OF INDOOR RADIO PROPAGATION CHANNEL CHARACTERISTICS BY SIMULATION

Submitted by

Ping Wang, B. Eng

in partial fulfillment of the requirements
for the degree of Master's of Engineering

Thesis Supervisor

Thesis Supervisor

Chair, Department of Systems and Computer Engineering

Carleton University

December 15, 1995

ABSTRACT

The design of Personal Communication Networks(PCNs) within buildings requires a detailed knowledge of propagation properties on indoor radio channel. Indoor radio channels are variable in space and time, and are influenced by multipath signal fading and multipath delay spread. The data rate of indoor wireless network is limited by the multipath characteristics of the indoor radio channel, especially if an indoor radio network is to be incorporated in B-ISDN using the vast information transport capacity offered by the Millimeter Wave frequency band. Multipath delay spread (multipath delay statistics) and multipath signal fading are very important factors to be considered in the design of high speed indoor wireless PCNs.

This thesis looks at the physical indoor environment in which PCNs would operate, and studies the extent and increase of static RMS delay spreads and relative received signal power in several different sizes of empty rooms and rooms with semipermanent partitions. It is shown that the maximum and mean value of static RMS delay spread linearly increase as the diagonal distance between ceiling and floor of a room increase. The RMS delay spread is independent of range between transmitter and receiver antenna. Using directive transmit antenna has shown the effect of reducing multipath signal fading in situations with short antenna separation. The RMS delay has larger variance in the case of using directive base station antenna. Temporal signal variations caused by human traffic moving around network terminal can be eliminated by using spaced antenna diversity, but the location of antennas need to be chosen by aid of using software tools to ensure the accept-

able diversity performance. Received signal variation is a function of transmitted signal bandwidth, this variation is less severe for greater transmitted signal bandwidth.

This thesis provides a developed simulation model and a software tool based on ray tracing techniques. The model can be effectively used to predict static RMS delay spread, relative signal power distributions in empty offices and rooms with dividers for different transmit antenna radiation patterns. The comparison of predicted static RMS delay spread with measurement results is presented to support simulation results. A link budget example based on simulated results is also shown to demonstrate the usefulness of the software.

Dedicated to:

My wife and parents for their love and encouragement

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ACRONYMS

PCN	Personal Communication Networks
PCS	Personal Communication Service
BISDN	Broadband Integrated Service Digital Networks
RMS	Root Mean Square
EM	Electromagnetic Modelling
MM	Millimeter Wave
LOS	Line-of-Sight
NLOS	None-Line-of-Sight
ISI	Intersymbol Interference
CDF	Cumulative Distribution Function
Tx	Transmitter
Rx	Receiver

CHAPTER 1 Introduction

Future developments of indoor radio systems to support B-ISDN services are expected to use the vast information transport capacity offered by the millimeter wave frequency band. This provides the following benefits:

1. It allows more bandwidth and high transmission speed.
2. It has advantages in frequency reuse because of the severe attenuation of signal power on concrete or steel walls of buildings at millimeter-wave frequencies.
3. It avoids the heavily used spectrum in lower frequency bands.

The design of Personal Communication Networks for in buildings uses a detailed study of propagation properties of indoor radio channels. Indoor channels are dynamic channel as a result of changes of multipath signals when human traffic moves inside of the building or near the terminals. Strong multipath signals caused by signals reflected from walls, the floor, the ceiling and human traffic around the terminals will produce a distorted versions of the transmitted signal and resulting in a phenomenon known as multipath fading. The signal components arriving from these different path will cause fluctuations in the received signal envelope and phase and also cause severe intersymbol interference because of delayed and attenuated pulse echoes. If an indoor radio network is to be incorporated in B-ISDN, it must support data rates up to 150Mb/s. The performance of Personal Communication Systems operating inside building will be seriously degraded by multipath fading. Multipath delay spread (multipath delay statistics) and multipath signal

fading are very important factors to be considered in the design of high speed indoor wireless Personal Communication Networks.

Wideband measurements and statistical modelling of indoor radio channels have been performed by many researchers[1]-[7]. The random and complicated indoor radio propagation channels can be characterized using impulse response approach: at each point in a three dimensional environment, the channel is modeled as a linear filter with a complex-valued low pass equivalent impulse response. The statistics of the model parameters such as random amplitude, propagation delay, and phase are determined using the channel impulse response measured for various locations of the transmitter and receiver antennas. Statistical models give performance estimation, and can be used to simulate the indoor channel for the purpose of system performance prediction. However, statistical models of multipath propagation in the indoor environment can not give the particular behavior of given locations within a building. The direct measurements will give accurate channel characteristics and on-site performance, these are very expensive and time consuming. It is thus necessary to consider developing efficient and reliable simulation software to facilitate the study of the effect of putting antennas in specific places. For studying the optimum placement of base and terminal antenna in the building as the fixed point to point application, it will be much easier to do it by using computer models than to make the measurement for every different antenna position.

Electromagnetic modelling is a good approach in developing a reliable on-site propagation modelling tool to predict path loss, impulse response and static RMS delay spread. These predicted parameters give very valuable information when designing a radio system

for a specific indoor environment. This kind modelling can also be used to assess the best location choice of base and a portable antenna to ensure the capability of high speed data transmission.

This thesis presents a study of some factors which influence indoor wireless system performance such as RMS delay spreads, and spatial as well as temporal variations of received signal power. A simulation model based on electromagnetic techniques is implemented to predict the impulse response, received signal power and RMS delay spread in both empty indoor environments and buildings with partitions which are used to create many small office rooms. The relationship between multipath signal fading and transmit signal bandwidth is also investigated.

Results presented in this thesis include: RMS delay spread characteristics for empty office environments and offices with semipermanent partitions, received signal power variations using different base antenna radiation patterns, simulations of multipath received signal fading, received signal power variations when there is human traffic around the radio link terminals and the received signal variations related to transmitted signal bandwidth. A link budget example based on the simulation results is presented to show the usefulness of the work herein.

This thesis is organized as follows:

The first chapter provides a brief introduction to the benefits of using millimeter wave frequencies for indoor wireless networks, and describes the benefit of electromagnetic modelling that was taken. The second chapter presents a literature review of previous work on

statistical modelling of indoor radio channels and current ray electromagnetic techniques used in related fields. The third chapter describes the simulation model and method for using electromagnetic techniques to generate impulse responses and using these impulse response to calculate RMS delay spread and received signal power. The fourth chapter discusses the simulation procedure in detail and gives simulation results for individual indoor environments. The fifth chapter presents an analysis and discussion of the simulation results. Finally Chapter Six presents conclusions on the findings of the thesis and gives recommendations for further study.

CHAPTER 2 Review of Current Research In the Field

This chapter provides background, discusses previous work and outlines the simulation. It contains:

1. A brief description of problems associated with the design of wireless personal communication networks in indoor environments.
2. A concise summary of principle models used in the simulation of indoor radio propagation.
3. An outline of the thesis.

2.1 Problems associated with indoor radio link design

Fig. 1 shows a simple model for radio propagation in indoor environments.

Fig.1. A model for radio propagation in indoor environments.

Typically, in indoor PCN systems, a fixed base station antenna is installed in an elevated position while the portable radio terminal antennas are installed at desk height inside the building. Due to the reflection, diffraction and scattering of radio waves by obstacles inside the building such as walls, furniture etc., the transmitted signal reaches the receiver antenna via more than one path. At any terminal location, the received signal is the vector sum of such signals that vary with time if there is motion in the building. Thus the received signal amplitude and phase also vary in time. Multipath propagation causes fluctuations in space of the received signal envelop and phase. It also produces a series of delayed and attenuated pulses(echoes) for each transmitted symbol. So the received signal is corrupted by unwanted random effects, noise and channel interference. Finally multipath affects the data rate in indoor radio unprotected channels. Multipath fading which causes intersymbol interference can seriously degrade the performance of communication systems.

This thesis examines the problems and limitations of site-specific indoor propagation channels. Simulation software is implemented based on electromagnetic techniques. It can be effectively used to predict the path loss to be caused by radio propagation and physical obstructions that lie between the transmitter and receiver antenna, RMS delay spread throughout buildings and temporal variations of received signal power caused by human traffic around the network terminals. The software and simulation results can be used to study the possibility of facilitating the optimum placement of PCN devices within the building. The comparison of RMS delay spread with actual measurements is also presented.

2.2 Current research in the modelling of indoor radio channels

The mathematical model used for the equivalent impulse response of random, time-varying indoor radio channels was originally suggested by Turin[8] for mobile radio applications. The channel is expressed as a linear time-varying filter with a complex low-pass impulse response given by:

$$C(t, \tau) = \sum_{k=1}^n \beta_k(t) e^{-j2\pi f_c \tau_k(t)} \delta(\tau - \tau_k(t)) \quad (\text{EQ 1})$$

The transmitted impulse $\delta(t)$ is received as the sum of k multipath signals with amplitudes $\{\beta_k\}$, arrival times $\{\tau_k\}$ and phases $\{\theta_k\}$. The statistics of these parameters can be determined using channel impulse response estimates measured in various locations. Early statistical measurements of amplitude fluctuations and power vs. distance for indoor channels were reported by British Telecom[9]. Measurement results give the power law representing signal attenuation as a function of distance. Wideband indoor radio delay spread results reported by BellCore[10]. Multipath time delay spread is the delay between the arrival of the first transmitted signal and the last signal which reflected by the building walls, partitions, ceilings and other fixed or moving objects. This measurement can give the information about the impulse response, the root mean square[RMS] value of time delay spread can be calculated from the measured impulse response.

Hoffman and Cox[11], and Cox, Murray and Norris[12] did some measurement on radio wave propagation and signal level distribution on a moving receiver. They reported that signal envelop variations in a small area closely followed a Rayleigh distribution. Large scale variations of the signal level followed a log-normal distribution.

S. Alexander [13] [14] reported that signal envelope distributions were also close to a Rayleigh distribution. He also characterized distance-power laws for many building plans. The distance-power laws are vary between 1.2 to 6.5 depend on the construction materials used in the building walls and partitions inside of the building.

Devasirvatham conducted time delay spread measurements within two dissimilar office buildings [16]. For all locations in a larger building with plane dimension of 315×110 m, the median RMS delay spread was 120 ns and the worst case was 250 ns. Median RMS delay spreads of 60 ns and a worst case of 218 ns was reported for a small building with plane dimension of 118×48 m. These results show large differences in RMS delay spread for different building sizes and geometries.

Wideband measurements taken in factories were reported by Rappaport in [17]. The measured RMS delay spreads were found to be uncorrelated to the transmitter - receiver distance. They seemed to be more depended on wall location and ceiling height. The median RMS delay spread was 95 ns over line-of-sight and 105 ns over obstructed paths.

All above reported wideband measurements for indoor radio channels are concerned with the statistics of the multipath or the power in the received profiles.

Saleh and Valenzuela [1] conducted wideband measurements in a medium sized two-story office building at AT&T Bell laboratories. The measurements were made using low-power 1.5 GHz, 10 ns pulses with 600 ns repetition periods. Using time delay spread and attenuation measurements, a statistical model based on Turin's model[8] for urban radio propagation was proposed. The proposed model assumes that the rays of an impulse response time delay have a Poisson arrivals independent Rayleigh amplitudes and independent uniform phases. Based on the observation of channel profiles collected from research laboratories, Saleh and Valenzuela concluded that multipath signals arrive in clusters. The arrival of the clusters is also assumed to have Poisson distribution. They suggested that the ray powers and the clusters both decay exponentially with certain delay rates. The cluster formation depends on building structures. The rays in a cluster are formed by multiple reflections from objects close to the transmitter and receiver.

Bultitude [18] made CW envelop, phase and attenuation measurements at 910MHz in two types of buildings. In one, the floor space was divided into small separated office rooms. The other was an open office environment. It was found that in line-of-sight configurations, the received power varies as $R^{-1.8}$, where R represents distance from the transmitter. Average diffraction losses of between 10 dB and 15 dB were reported in cases where the line-of-sight is blocked by one or more partitions.

In any fixed receiver location, temporal variations in the received signal envelop are caused by the movement of personal and machinery. Such variations are slow, and have bandwidth of only about 4Hz [2]. When the floor space is divided into separate rooms fading is likely to occur in bursts which are tens of seconds in duration. The dynamic range of

such fading is about 30dB. In open office environments fading is more continuous, with a dynamic range of about 17dB. Temporal envelope fading distributions are Rician, and have K ratios between -6 dB and -12 dB. Fading statistics are statistically nonstationary in the strict sense. Wide sense stationary characteristic are exhibited for periods of time up to 2 seconds.

Modified Poisson delays and log-normal amplitude distributions were reported by Ganesh and Pahlavan. The Modified Poisson (the D-K model), first suggested by Turin et al [8] to describe arrival time sequences on the mobile channels, and was fully developed by Suzuki [20]. This model is based on two sets of measurement data both in manufacturing floors and college offices. On a manufacturing floor there is plenty of open space usually without any presence of walls, most of the received power is therefore concentrated in the first few received rays. College office areas, on the other hand, have a wider spread of power delay, because of less open space and the frequent obstruction of the signal between the transmitter and the receiver by one or more walls. In this model, the arrival of multi-path signals is reported to fit a modified Poisson processes and the power amplitudes follow a log-normal distribution. The mean and standard deviation of the log-normal distribution are shown to decay exponentially with delay.

Temporal variations of received signal power, RMS delay spread caused by human traffic around terminals have been investigated by some researchers. Bultitude's measurement [18] showed the temporal variations in the received signal envelope are caused by the movement of personnel and machinery. The dynamic range of such fading is about 30 dB in divided office rooms and 17 dB in open office environments.

Rappaport [22] measured temporal fading of the received signal envelope over a 100-second period during the normal working hours of the factory. His analysis of the temporal fading data showed that the dynamic range is about 10 dB. Both above researchers compared the temporal fading data to the Rayleigh and Rician distributions, and showed that the Rician distribution fits the data well.

Recently MM-Wave frequency band for indoor radio communication attracts researchers because of the ability to offer vast information transport capacity and short frequency reuse distance due to the fact that millimeter wave are severely attenuated by most inner walls.

Kalivas, El-Tanany, and Mahmoud reported measurements at 21.6 GHz and 37.2 GHz locating a moving receiver antenna in various areas of one floor in the faculty of Engineering at Carleton University[24]. These measurements included mainly obstructed conditions. Cumulative distribution functions of the normalized envelope for both experiments showed that the statistics of the fading envelope of the signal follows a Rayleigh distribution. Estimated power-law exponents were reported to be lower than the free-space exponent($n=2$) which indicates a waveguiding effect. This, together with low plasterboard wall losses indicates a feasibility of indoor radio system in which every one or two rooms, as well as every corridor, can be covered by one antenna.

Smulderas and Wagemans conducted wide-band MM-wave indoor radio channel measurements[26]. The antennas were identical biconical horns which exhibit an omnidirectional radiation pattern in the azimuth plane and a 9 dB gain in the elevation plane. The measurements confirmed the possibility of achieving near uniform coverage by antenna

gain compensation as predicted by [25]. Measured power versus distance delay rate values appeared to be small compared to those commonly found for UHF channels. Typical RMS delay spread values ranged between 15 and 45 ns for small rooms and between 30 to 70 ns for larger ones. Blockage of the direct path caused only slight change in delay spread. Based on this measurement, a statistical model for the MM-wave indoor radio channel was reported. Its major assumption in generating ray amplitude distributions is that the multipath behavior is a stationary process. The second conjecture is that individual rays are uncorrelated. The multipath rays are modeled as a discrete uncorrelated scattering process. Ray statistics appear to be very similar for all environments. The rays arrive with independent uniformly distributed phases. The ray amplitude fits a Rayleigh distribution. The distribution can be modeled as a function of excess delay. It consists of a constant level to 50 ns followed by an exponentially decreasing function with a power decay time constant between 16 and 75 ns. The rays have a mean interarrival time in the range from 0.7 to 1.0 ns. These numerical values are comparable to the measurement resolution. So it appears that the multipath process converges toward a continuous Rayleigh process.

Ray tracing techniques have been proposed to predict path loss and time-invariant impulse response functions and RMS delay spread. This approach provides a challenge to the indoor propagation modelling. It achieves channel modelling without the need for detailed measurements.

The use of a two dimensional ray tracing algorithm to predict the radio propagation in the indoor radio channel from the layout of the plane was presented by Holt, Pahlavan, Lee [27]. The user is able to interactively design any two dimensional floor plan and to place a

transmitter and receiver anywhere in the design. The program determines the received power and RMS delay spread from the calculated response. For the simple environment of the wire cage of 3m×3m, the simulation was shown to be very close to actual measurements. In the case of more complex environments, the simulation was found to be relatively close to measurements.

Valenzuela reported a 3 dimensional ray tracing prediction technique of indoor radio channel[28]. This technique is applied to predict the local mean power and RMS delay spread in AT&T Bell laboratories at Crawford Hill. The predicted powers are compared with measurements and are found to follow the same trend, although the predicted values are somewhat higher than the measured values. In their prediction results, the predicted propagation loss does not change more than 1 dB when including paths with three or more reflections. The predicted RMS delay spread is still affected by weak, highly delayed paths, but does not change by more than 2 ns if paths with three or more reflections are not included. They also discussed using this prediction technique to study a large variety of alternatives such as multicasting, antenna directivity, antenna diversity, polarization diversity and frequency plans etc.

Bultitude et. al used a 25-path ray tracing computer model to aid in deriving conclusions from experiments regarding the variation of RMS delay spread with range [29]. From the reported measurement and equipment adjusted simulation, they concluded that:

- 1). The variation of static RMS delay spread as a function of transmitter- receiver antenna separation (range) in empty indoor environments such as meeting halls and shopping

malls, is a peaked characteristic that has a maximum at a range that is dependent upon building dimensions and the electrical properties of the building walls and windows.

2). In empty buildings with no windows, the static RMS delay spread peak occurs at a minimum range that is approximately equal to half the building width when the transmitter/receiver geometry is symmetrical with respect to the side walls.

3). Furniture and mazes of semipermanent partitions which create many random reflections have the effect of flattening the relationship between RMS delay spread and range, making it reasonably constant for all ranges.

4). Variations of indoor static RMS delay spread, as well as other parameters not discussed, can be studied using simple ray-tracing techniques and a knowledge of only the outside dimensions of buildings and appropriate dielectric constants. However, such studies should, as minimum, simulate double reflections since single-reflection models significantly underestimate static RMS delay spread values.

2.3 Literature review summary

From literature reviewed, it is apparent that as demand for "High speed and high capacity" indoor personal communication is increasing, the site-specific propagation prediction is required to be more accurate. This accurate prediction of power loss, signal fading and RMS delay spread can be applied to the design of indoor communication systems in order to optimized the placement of PCN devices.

This thesis presents an effective site-specific propagation computer prediction model that considers transmitted rays and reflected rays. This electromagnetic model explores:

- 1). RMS delay spread for various building sizes using different transmit antenna radiation patterns.**
- 2). RMS delay spreads behavior in the building with partitions.**
- 3). Multipath signal fading in empty buildings with different base station antenna patterns.**
- 5). Temporal received signal power variations due to human traffic close to the terminal antenna.**
- 6). Received signal variation is related to transmitted signal bandwidth.**
- 7). Based on simulation results, a link budget example for an open space indoor environment is presented to show the usefulness of this prediction tool.**

In chapter 3, the model used in calculating the ray paths, reflectivity of the walls, relative multipath power and RMS delay spread is described. Chapter 4 describes building configuration, antenna radiation patterns and the assumption of the human traffic moving around the receive antenna. Simulation results are also presented in this chapter. Chapter 5 contains an analysis and discussion of the simulation results. In the last chapter we presented conclusions on the findings of this thesis and recommendations for further work.

CHAPTER 3 Description of Simulation Model

3.1 Electromagnetic Modelling

The building geometry, furniture, partitions and human traffic inside a building all influence the average path loss of wideband signals and multipath characteristics of indoor radio channels. Received signal characteristics are also influenced by large scale environmental factors, such as the location of base and portable stations and building geometry.

Fig.2. A model for the radio propagation in indoor environment.

The three dimensional electromagnetic model used here applies geometrical optics to find different radio paths between a transmitter and receiver as shown in Fig. 2.

Such techniques can be used to model the indoor radio channel. The received signal variations in space caused by multipath propagation can be predicted using ray tracing over the predetermined paths. Although the technique employed is not actually ray tracing, but uses pre-determined images to define radio paths, the term ray tracing will be employed hereinafter for brevity.

A static indoor multipath radio channel can be modeled as linear filter with complex-valued envelope low pass equivalent impulse response given by

$$h(t) = \sum_{k=1}^n \beta_k \delta(t - \tau_k) e^{j\theta_k} \quad (\text{EQ 2})$$

where the β_k are real positive amplitudes, the θ_k are the phases and the τ_k are the propagation delays of all the channel multipath components.

The goal of channel modeling is to determine the set of β_k , θ_k and τ_k for selected terminal location in the floor plane. The rays transmitted from the transmit antenna are traced through the environment. The first part of these rays intersect the receiver antenna without many reflections. The second part of these rays have reflected several times and generally have lower power.

After correctly calculating the magnitude, phase and arrival time of every ray that intersects the receiver antenna, the channel impulse response for a specific receiver location can be formed. From this channel impulse response, the received signal power and static RMS delay spread of the channel can be calculated.

3.2 Reflection From the Building Walls

3.2.1 Finding the Point of Reflection

The ray path is a very important parameter to be used in calculating received signal power, excess time delay and phase shift. When this information is obtained for all rays, the channel impulse response can be estimated.

Currently, there are two publications that address the algorithm of calculating the reflection position. One is reported by Bultitude[29], and the other is reported by Valenzuela[28]. In both report, the arbitrary ray path is defined by the sequence of surfaces (walls, floor or ceiling) of which the signal must reflect to travel from the transmitting to the receiving antenna. The assumption was also made that all reflecting surface are orthogonal and deferring the case of walls set at arbitrary angles, or curved surfaces for further studies. The difference between these two is that 3 dimensional algorithm is used in Valenzuela's report instead of 2 dimensional used in Bultitude's report. Valenzuela's algorithm was used herein. With the assumption that all reflecting surfaces are orthogonal to each other, the coordinates for the image of a point reflection over a surface are found simply by "reflecting" the coordinate corresponding to the axis parallel to the surface normal. Fig. 3 shows a simple example. The point P, with coordinates (a,b,c) and a reflecting surface par-

allel to the YZ plane and located a distance D along the x axis. It can be seen that the image, I , has coordinates $(2D-a, b, c)$.

Fig 3. Image location example.

This simple procedure[28] suggests that the coordinates of the image of the receiver antenna are found by successively reflecting the receive antenna coordinates over the sequence of reflecting surfaces intersected by the path under consideration. Once the coordinates for the images of the receiver antenna are known, path lengths can be computed.

Consider the rectangular office room shown in the Fig. 4, The walls 1 and 4 are parallel to the X- Z plane and are located at $y=0$ and $y= D_2$ along the Y axis. Wall 2 and 3 are parallel to the Y- Z plane, located at $x=0$ and $x= D_1$. Assuming the transmit antenna is located at point T, and the receive antenna is located at point R, with the coordinates of (a,b,c) . By tracing the path from T to R with reflections by walls $x= D_1$, $y= D_2$, two images of the receiver antenna can be found.

Fig.4. Image construction for determining of the reflection position

The first order image of the receiver antenna in wall $y = D_2$ can be found by “reflecting” the receiver coordinate (a, b, c) over wall $y = D_2$. The coordinator of I_1 is $(a, 2D_2 - b, c)$. Then the second order image of the receiver antenna wall $x = D_1$, at point I_2 can be found by reflecting the first order image of receiver antenna I_1 over the wall of $x = D_1$, the coordinate of I_2 will be $(2D_1 - a, 2D_2 - b, c)$.

Once all the image points have been found, the reflection locations in wall 3 and wall 4 can be decided as follows. The first reflection point in the wall 3($x=D_1$), r_1 , is the intersection of line from the transmitter antenna and second order image I_2 . The second reflection position on wall 4($y=D_2$), r_2 is the intersection of line, r_1-I_1 with wall 4. From these transmitter and receiver locations and reflection positions, the ray path can be easily calculated by adding the distance between transmitter antenna and first reflection position, first reflection position and second reflection position, second reflection position and receiver antenna location. From this, the excess delay and phase of each reflected ray can be obtained.

3.2.2 Calculation of Reflection coefficients for Building Walls

Accurate calculation of reflection coefficients for building walls and interior partitions is very important to model the multipath characteristics of indoor environments. The plane waves have different modes of intersection with scatters as shown in Fig. 5. Namely, specular (1) and diffuse (2) reflection, specular (3) and diffuse (4) transmission (or refraction) [30]. The electromagnetic image approach uses pre-determined images to define radio paths and use computer model to study the indoor channel characteristics. The ray tracing approximation approach can effectively estimate the specular reflection and transmission, but can not take consideration for the diffusion phenomena. This is considered acceptable since the diffuse components have powers that are much lower than the specular ones.

Fig.5. Modes of interaction of electromagnetic waves with boundaries between media.

The reflection and transmission paths are defined by the sequence of surfaces such as walls, floors, ceilings and partitions. The transmitted signal must be reflected by these surfaces and then transmitted to the receiving antenna. In this thesis it has been assumed that all reflecting surfaces are orthogonal to each other. This is true for many office buildings.

Specular transmission and reflection can be calculated using Snell's law. Given an incident ray and an infinite plane boundary between two media with dielectric permittivities ϵ_1 and ϵ_2 respectively[31], Snell's law can be express as:

$$\epsilon_1 \cdot \sin(\theta_i) = \epsilon_2 \cdot \sin(\theta_t) \quad (\text{EQ 3})$$

where θ_i , θ_t are incidence and refraction angle.

The reflected and refracted rays are always in the plane formed by the incident ray and the normal line at the point of intersection. In addition, the angle made by the reflected ray with the normal is always equal to the angle between the incident ray and the normal line, and the angle made by the refracted ray can be computed using (EQ3).

Fig.6. Direction of reflected and refracted rays

Polarization also must be considered in the calculation of reflection coefficients and transmissivity. When a signal undergoes consecutive reflections from orthogonal surfaces, the E field of the incident ray is resolved into transverse Electric and transverse Magnetic components, and appropriate reflection and transmission coefficients are determined for each. The vector sum of reflected rays is computed as the total reflected field. [29].

The reflectivity and transmissivity of walls depend on the polarization of the incident waves. It can be expressed in terms of the reflectivity and transmissivity associated with polarizations in the parallel and perpendicular directions respectively [31], as:

$$R_p = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad (\text{EQ 4})$$

$$R_n = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} \quad (\text{EQ 5})$$

If the incident wave is polarized with its **E** vector normal to the plane of incidence, the **E** vector of both the reflected and transmitted waves will also be perpendicular to the plane of incidence[31]. That is, the reflected wave has no component in the plane of incidence. To allow comparisons with the measurement results, the antenna was assumed to be vertically polarized.

The power loss of an EM-wave passing through the dividers that separate small offices is obtained directly from the attenuation versus frequency characteristics [37]. Assuming plywood as the partition material, the attenuation for the frequency band of 20-30 GHz is about 3 dB. This attenuation parameter was used in simulation regardless of the incident angle. The reflectivity is calculated by considering at most two reflections from building walls. Three or more reflections were not included in the calculations because these rays have little influence on the propagation loss and the RMS delay spread [28].

3.3 Received power and root mean square delay spread

3.3.1 Impulse response generation

As discussed earlier, indoor radio channels can be modeled as linear filters with impulse response functions given by EQ 6, repeated here for convenience. Once all of the ray path

length have been calculated, such impulse response can be modelled using the techniques outlined above. Assuming an impulse $\delta(t)$ is transmitted, the equivalent lowpass complex envelope of the received signal, or impulse response of the channel is given by:

$$h(t, \tau) = \sum_{k=1}^n \beta_k(t) e^{-j\theta_k} \delta(t - \tau_k(t)) \quad (\text{EQ 6})$$

where β_k is the amplitude of the k -th ray, the θ_k is the phase shift and the τ_k is the propagation delay.

To calculate the magnitudes of the arrived ray (β_k), two basic facts are used. Firstly the power of each ray drops according to the law of free space transmission, (i.e., in proportion with $1 / r^2$), where r is the distance. Secondly, the power of each ray is reduced by reflections from walls. The reduction depends on the reflection coefficient of the walls. The amplitude of the k -th ray is given by:

$$\beta_k = \frac{A}{r_k} \prod_{kj} R_{kj} \quad (\text{EQ 7})$$

where r_k is the k -th path length, A is a constant and R_{kj} is the reflectivity of wall j for the k -th ray.

The parameter θ_k in EQ. 8 is the phase change of the k -th path, it can be determined by

$$\theta_k = \frac{2\pi f_c r_k}{c} \quad (\text{EQ 8})$$

where f_c is the carrier frequency and c is the speed of light. The delay of each ray τ_k , is calculated by the ray path length and the transmission speed of electromagnetic waves.

3.3.2 Root mean square delay spread

The RMS delay spread is an important parameter for quantitatively assessing the severity of multipath dispersion, and it had been studied by many researchers [1-7]. It has been reported that RMS delay spread values can be used as a measure of temporal extent of the multipath delay profile, which is related to the performance degradation caused by intersymbol interference. Using a symbol period much greater than the average RMS delay spread is commonly applied in the design of communication systems to operate at a certain data rate with negligible performance degradation due to intersymbol interference[22].

As indicated by Cox [32], noise and low-powered multipath components at long delays can greatly influence the computed RMS delay spread. For this reason, measured data were run through a threshold algorithm to eliminate components at large delays, which have powers that are lower than 25 or 30 dB below the peak impulse response power and are therefore considered to be insignificant in the degradation of communication system performance [33]. For RMS delay spread calculation reported here, a -28 dB noise thresholds is employed.

The RMS delay spread is given by [1]:

$$\sigma = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} \quad (\text{EQ 9})$$

where

$$\overline{\tau^n} = \left(\sum_k \tau_k^n \beta_k^2 \right) / \left(\sum_k \beta_k^2 \right) \quad \begin{matrix} n = 1, 2. \\ k=1,2,3,4.... \end{matrix}$$

σ can be computed from parameters for static (non-fading) channels, and is referred to as static RMS delay spread [29].

3.3.3 Received signal power

The received signal level is the vector sum of that in all the received rays. These received signals are close to one another in time and will be enforced or cancelled out depending on their phases. The direct (line-of-sight) and reflected or transmitted rays exhibit a $1/r^2$ power dependence according to the free space transmission formula, where r represents the total path length travelled by each ray.

An approximation for the received power in the Line-of-sight microwave mobile systems is given by [34],

$$P_r = K \cdot \left| \frac{G_d}{r} + \sum_{k=1}^{N-1} \frac{G_{dk} \cdot R_k \cdot \exp(j\Delta\theta_k)}{r_k} \right|^2 \quad (\text{EQ 10})$$

where K is a proportionality constant, G_d is the product of T_x and R_x antenna amplitude gains in the direction of the main ray, G_{dk} is the antenna amplitude gain product in the direction of k -th ray component, R_k is the reflection coefficient of wall from which the k -th ray is reflected, r and r_k are the path lengths of the direct and each of the k -th reflected rays, $\Delta\theta_k$ is the k -th phase difference between the direct and k -th reflected ray.

The received signal power in this thesis was computed by considering equal antenna gains for each transmitted ray. The constant K in EQ(10) was set to 1 in the simulations. This factor can be easily changed to be consistent with actual system parameters.

CHAPTER 4 Simulation Procedure

4.1 Static RMS delay spread in an empty room

Indoor radio channels varying in time and space, and are characterized by high path losses and sharp changes in the signal level. It was also reported that [29] static RMS delay spread is fairly independent of the separation distance within each environment where there is furniture inside of the building. The simulation in this thesis shows that in the empty and partitioned office building, the RMS delay spread is also relatively independent of the antenna separation distance for a larger separation distance in two office room and building with dimension of 22 (ft)×16.5 (ft)×10 (ft) and 125 (ft)×75 (ft)×9 (ft).

For static RMS delay spread calculations, a threshold (cut-off level) of -28 dB was employed. This particular - 28 dB value is chosen to obtain results similar to the available measured data.

4.1.1 Description of measurements and simulations

In order to verify the simulation model, the simulation of RMS delay spread as a function of range in an empty room were compared to the measurement results in [29]. The measurement were made previously by Bultitude et. al in two empty office buildings having the dimensions of 22 (ft)×16.5 (ft)×10 (ft) (40 GHz) and 125 (ft)×75 (ft)×9 (ft) (950 MHz). Static RMS delay spreads were calculated based on measured impulse response at every location of transmitter and receiver. The transmit antenna was moved in steps along the center line of buildings and, additionally, along concentric arcs centered on the

receiver location for 125 (ft)×75 (ft)×9 (ft) building, while the receive antenna remained fixed at locations specified in [29].

For the measurements at 40 GHz, a BPSK modulated pseudo-random sequence having a chip rate of 40 Mb/s and a sequence length of 63 bits was used as the sounding signal. A 40 GHz up/down converter having an intermediate frequency of 5.2 GHz was employed. All oscillators in the system were slaved to a single rubidium frequency standard to provide phase stability. The transmitter and receiver antenna were vertically polarized and had nearly the same gains and radiation patterns, being omnidirectional in the H plane and having E plane beamwidths of between ± 35 and ± 45 degrees with respect to the horizon[35].

The room had an wall that consisted of plasterboard on steel studs affixed to concrete blocks. The southernmost wall was a steel studded partition, with plasterboard on both sides of the studs. The wall separating the room from the corridor was made of concrete blocks, with steel studs and plasterboard on both sides. The north-most wall was of the same construction as the corridor wall. This is normal office construction layout in Fig 7.

During the measurements, the receive antenna was placed at 5 ft from the north wall and at 40 in above the floor level. The transmit antenna was moved in steps of 1 ft along the centerline of the room at the same height. For each transmitter location, the receive antenna was moved in a small circle of 1 in diameter to simulate slight hand motions. Three impulse responses were recorded for each transmitter/receiver range. Each set of three impulse responses were averaged for noise reduction. The local area circle diameters were chosen to be large enough to provide averaging over at least 1 wavelength, but

small enough so that range did not vary appreciably within each local area[35]. Static RMS delay spreads were calculated by thresholding the impulse response power function at - 28 dB. Only the components of larger than the threshold were used to calculate the static RMS delay.

Fig. 7. Floor plan showing transmit and receive antennas locations

Fig.8. Floor plan showing transmit and receive antenna locations in a large office room.

Correlation measurements were also made in a larger but more modern three-story building (Fig.8) having dimensions of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft) at 950 MHz. The measurement system used an analog sliding correlator at a center frequency of 950 MHz. Transmit and receive antennas were laboratory-constructed monopoles comprised of thin vertical radiators with four evenly spaced copper radials, which simulated ground planes. Their E and H plane radiation patterns were measured in an anechoic chamber, and were reported to be almost identical to those of a vertical half-wavelength dipole.

The building, where the measurements were made, was constructed of concrete blocks with reinforcing steel bars. It has windows on three sides. The floor is of reinforced concrete with closely spaced steel rods at regular intervals. The ceilings are hung at a height of 9 ft on a metallic grid about 3 ft below the floor of the next level.

During the measurements, the receive antenna remained in a local area at a distance of 10 ft from the north end of the building(Fig.8), while the transmit antenna was manually moved away from the transmit antenna along the building centerline. At each range, the receive antenna was located at three different points. These points were, respectively, 2 ft to the west side of the building centerline, on the center line, and 3 ft to the east side of the building centerline. While the receive antenna was at each of these 3 points, the transmit antenna was moved sequentially to each of five locations on a local circle. The static RMS delay spread for each transmit and receive antenna range was calculated by thresholding the impulse response power at -28 dB, and the median of 15 RMS delay spread values in five local areas for each of the 3 receive antenna points was calculated as the RMS delay

spread for this transmit and receive range. This statistical computation was made to mitigate the influence of measurement system bandwidth[29].

Another set of measurements was made in this large building. The receive antenna was located at 10 ft from the north wall as in the previous case, while the transmit antenna was moved along concentric arcs centered on the receive location. The range was increased in 10 ft increments. At each range the static RMS delay spread was represented by the median value of static RMS delay spreads along this curve.

In this thesis, a 37-ray computer model for empty rooms was implemented based on the ray tracing techniques discussed earlier. The user can input the building data, including the dimensions of the office environment, the permittivity of construction material used for each wall, floor, or ceiling as well as transmit antenna and receive antenna locations. The program uses the input data and image algorithm to generate an impulse response for the specified transmit and receive antenna locations. The static RMS delay spread can be calculated by using this generated impulse response.

There are some parameters that need to be considered in the simulations. Firstly, in implemented ray tracing model, only single and double reflections from building wall, floor and ceiling were considered. Those rays that undergo reflection more than two times were considered to be of very low power and their influence in the calculation of RMS delay spread was neglected. Secondly, the calculation of reflectivity was implemented by assuming the transmitter antenna is vertically polarized, as used in previous measurements by Bultitude. Polarization change occurs in double reflection cases, when a ray undergoes consecutive reflection from orthogonal surfaces[29]. To compare with measurement con-

ditions the equal transmit and receive antenna height was assumed in simulations. Thirdly, the permittivity of $\epsilon_r=6.25$ for concrete wall[29] was used for all reflecting surfaces.

First the simulation of RMS delay spread behavior was studied while the transmit antenna moved along the centerline of the office room with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). The receive antenna was assumed to be located at centerline, 10 ft from north end of the building. Two hundred transmit antenna locations were generated along the center line from initial range of 5 ft between transmit and receive antenna. For each transmit antenna location, an impulse response was generated, and static RMS delay spread was calculated from this generated impulse response. The static RMS delay spread of both simulation and experiment are shown in Fig.9, which shows good agreement.

Fig.9. Static RMS delay spread as a function of distance between transmit and receive antenna at 950 MHz.

Secondly, the static RMS delay behavior was computed as the transmit antenna moved along arcs with same transmit and receive antenna range as shown in Fig.8. For each transmit antenna range, 20 transmit antenna locations were used to calculate static RMS delay spreads. The median of these values was calculated as representative Static RMS delay spread for each range. Fig.10 shows the result of simulations and measurements.

Fig.10. Static RMS delay spread as a function of distance between transmit and receive antenna when transmit antenna moves along arcs of concentric circles at 950 MHz.

For the small office room with dimension of 22 (ft) $\times$ 16.5 (ft) $\times$ 10 (ft), the simulation procedure is identical to the first case. The center operating frequency was changed to 40 GHz in order to compare with the available measurement data, the permittivity of 6.25

was still used in simulation. The RMS delay spread may be influenced by rough surface scattering at high frequencies such as MM-wave frequency band, but this is not being considered in the simulation program, and thus, no change is expected when the centre frequency is changed in simulation. Actually the permittivity of construction material for MM-Wave frequency signal should be less than the permittivity used at 950 MHz[36]. Unfortunately ϵ_r for MM-waves is not available at this time. The comparison of simulation with measurement is shown in Fig. 11, where it can be seen that the simulation results are consistently lower at longer ranges, the reasons for this are not yet clear.

Fig.11. Static RMS delay spread as a function of distance between transmit and receive antenna when transmit antenna moves along the centerline in a small room at 40 GHz.

4.1.2 Spatial variations of static RMS delay spread

It has mentioned by previous researchers that the RMS delay spread is dependent on antenna separations [10]. The RMS delay spread was also reported within individual rooms and was not found to be correlated with the distance between transmit and receive antenna [1]. Bultitude's work shows that the static RMS delay spread in an empty room is a peaked characteristic that has a maximum at a range is dependent upon building dimensions and the electrical properties of the building walls and windows[29].

To investigate the variations of static RMS delay spread in an empty office building, it is computed by generating an impulse response at randomly generated receive antenna locations for a fixed transmit antenna in indoor environments with different diagonal dimensions (D). D is the length of the diagonal from the lower left to the upper right corners of the room as shown in Fig.12. The transmit antenna located at 5 ft from one side of the wall on the centerline, 1000 receive antenna locations at desk height were randomly generated within the shaded area of Fig.12. The RMS delay spread are shown in Figs 13 and 14.

Fi.g.12. Layout showing receive and transmit antenna locations.

Fig. 13. Static RMS delay spread as a function of distance between transmit and receive antenna in an empty building of dimension of 125ft $\times$ 75ft $\times$ 9ft at 950 MHz.

Fig.14. Static RMS delay spread as a function of distance between transmit and receive antenna in an empty room of dimension 22ft $\times$ 16.5ft $\times$ 10ft.

Fig. 15 and Fig. 16 show the cumulative distribution of RMS delay spread based on one thousand impulse response estimates in the small room and large rooms, respectively. The RMS delay spread can be seen to be dependent on room and building size. It is also a function of the wall and building construction.

Fig. 15 Cumulative distribution of RMS delay spread in large size building of dimension 125ft $\times$ 75ft $\times$ 9ft at 950 MHz.

Simulation results show that the static RMS delay spread has a peaked characteristic in empty buildings. This peak is not simply correlated with the distance between transmit and receive antenna range. It is depended on building dimensions and electrical properties of building walls. For the larger room, there is another positive change in slop after about 100 ft as shown in Fig.13. Although using different ray tracing models, different algo-

rithms in finding the reflecting point and different number of rays, the results are very close to the measured value reported in [28].

Fig.16 Cumulative distribution of RMS delay spread in a small size office of dimension 22ft × 16.5ft × 10ft at 950 MHz

The mean and maximum value of RMS delay spread for each empty room studied was obtained by averaging 1000 individual RMS delay spreads. These RMS delay spread is calculated from generated impulse response of randomly generated 1000 terminal locations for a fixed base station antenna. Fig.17 shows the maximum and mean value of static RMS delay spread in these empty rooms with different diagonal dimensions. It is interesting to note that, even though there is no clear dependence between static RMS delay spread and antenna separation, the maximum and mean value of RMS delay in each empty room shows a linear dependence with the diagonal dimension.

Fig.17. Mean and Maximum value of RMS delay spread versus 3 dimensional diagonal distance(D) between ceiling and floor in 20 empty room with concrete walls with permittivity of 6.25.

4.1.3 RMS delay spread with directive transmit antennas

Intuitively, one would expect that multipath signal fading and RMS delay spread should be reduced by using directive transmit antennas. This is because directive antennas should eliminate rays that are reflected from the back wall and ceiling. A fictitious directional transmit antenna was assumed in the simulation to study the effect of the directivity. The radiation intensity was assumed constant within the beam solid angle. The program was implemented to collect the rays emitted from the transmit antenna within the beamwidth.

For simplicity we also assume the centroid of the transmit antenna beam is aligned with the receive antenna as shown in Fig. 18.

Fig.18. Layout showing receive and transmit antenna locations

The simulation was performed with two different room sizes. One was a small room with dimensions of 22 (ft) $\times$ 16.5 (ft) $\times$ 10 (ft), the other was a modern office building with dimensions of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). In the small office room case (Fig. 7), the RMS delay spread is reduced by using directive transmit antenna compared with that using omnidirectional transmit antenna for short antenna separations as shown in Fig.19. In the case of large size office buildings, Fig. 20a, RMS delay spread is also reduced to certain extent at shorter antenna separations. This might be because, at short antenna separation distance, the RMS delay spreads are dominated by paths which directly reflected from the

walls, floor and ceiling of the building under one reflection. With the directive base station antenna, some of these rays are not inside of the beam width and there is no influence on the RMS delay spread calculation under consideration. As the increase of transmit-receive antenna separation, more transmitted rays from inside the beamwidth will arrive at the receive antenna after consecutive reflections. This will make no significant differences in the RMS delay spreads. Fig 20b shows the cumulative distribution of RMS delay spread using directive and omnidirectional in this large building. The dotted curve shows the RMS delay spread distribution for a directive base station antenna with 60 degree beamwidth for base station antenna. The worst - case RMS delay spread is 58.4 (ns). The solid curve shows the RMS delay spread distribution for a omnidirectional base station antenna, the worst RMS delay spread is 51.62 (ns). At shorter RMS delay spread, with the directional antenna is showing a smaller RMS delay spread value. At longer RMS delay spread, on the other hand, is showing a larger RMS delay spread with directional antenna. The reason for this is not clear yet. As shown in Fig. 50, some rays component were eliminated by using directive antenna, but the rays which have the dominant effect on static RMS delay spread were kept. Base on above simulation, It appears that using directive base station antenna are not necessary imply the decrease of RMS delay spread.

Fig. 19. Comparison of RMS delay spread in a room with dimensions of 22ft×16.5ft×10ft when using omnidirectional and directional antenna.

Fig. 20a Comparison of RMS delay spread in a building with dimensions of 125ft×75ft×9ft when using omnidirectional and directional antennas.

Fig 20b. The Cumulative distributions of static RMS delay Spread using dielectric and omnidirectional base station antenna.

4.2 RMS delay spread in divided small office areas

In most modern office buildings, partitions are used to divide large areas into many small offices. Determination of the RMS delay spread in such office can be used to evaluate the severity of multipath induced ISI in common office buildings. In the following simulation, a modern office building with dimensions of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft) was divided into 4 small areas as shown in Fig. 21. The transmit antenna was located at Tx, while two hundred receive antenna locations are randomly generated along the centerline at desk height. One thousand receive antenna locations were also randomly generated in each of the two smaller rooms at desk height.

Fig.21. Floor plan showing transmit and receive antenna locations.

LOS between Tx and Rx was assumed in the case of terminal displacement along the centerline, the LOS was blocked by the partitions in the cases when the terminal locations

were inside the small rooms. The material which used to divide the small areas was assumed to be plywood with relative permittivity of 2.1 [36]. An attenuation of 3 dB was used as the penetration loss each time as the millimeter wave passed through a plywood partition based on previous measurement result [37].

Fig. 22 shows the simulated results of terminal antenna displacements along the centerline for empty and partitioned conditions. Fig. 23 and 24 show that the RMS delay spread corresponds to receive antennas inside the smaller rooms. A comparison is also made with values for the same locations but under empty conditions.

In all three cases, the RMS delay spread was found to be smaller in partitioned smaller areas, and along the centerline compared to the empty building situation.

Fig. 22. Comparison of RMS delay spread corresponding to terminal antenna displacement along centerline under empty and partitioned conditions.

Room 1.

Fig.23. Comparisons of RMS delay spread corresponding to terminal antenna displacement inside the smaller rooms and in the same location but under empty condi-

Room 2.

Fig.24. Comparison of RMS delay spread corresponding to terminal antenna displacement inside of the smaller rooms and in the same location but under empty conditions

4.3 Received signal power

Indoor wireless links between base stations and portables will support high speed and high quality digital communications services. The quality is affected by indoor channel multipath characteristics like multipath fading, delay spread and co-channel interference. To keep the system quality of a satisfactory level, the system may use diversity, equalization, and channel coding etc. However, if the channel can be correctly predicted, one can facilitate the prudent placement of portable antennas to maximize the performance and capacity of indoor wireless networks. To investigate the indoor multipath fading characteristics and the effect of using directive transmit antenna, several simulations of relative received signal power in indoor environments were performed. The following section describes the detailed simulation procedure and results.

4.3.1 Received signal power using omnidirectional antennas

The simulation of received signal power was performed in a small room and in a modern open office building with dimension of 22 (ft) $\times$ 16.5 (ft) $\times$ 10 (ft) and 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). The receiver antenna was located near the north side wall as shown in Fig.7 and 8. Transmit antenna locations were generated along the centerline of the office and larger building at desk height. The received signal power presented here is the relative received signal power with the constant K of equation (10) set to 1. The power in each portable location is calculated by using equation (10). The parameter in this equation is derived from the generated impulse response for that location by using the ray tracing algorithm to find the ray path and reflection coefficient as described earlier. The direct and reflected ray

signals are close to one another in time and either cancel out or add together depending on their phases. Rays which are reflected three or more times have been neglected in the calculation of received signal power.

The result of received power when the portables are displacement along the centerline are shown in Fig. 25 and 26. It can be seen that indoor radio channels are highly varies in space. The strength of the received signal at each portable location depends on the attenuations caused by the passage and reflections of the signal from building walls, ceiling or floor and on how the multipath signals are being vector added. Multipath variations cause deep nulls in some locations. The system performance of a PCN will be degraded if a portable were placed in one of these positions.

Next, results of received signal power from the simulation of small spatial variations of portable antenna locations were studied. For a fixed base station antenna, the portable antenna was moved along a small circle with diameter of 0.5 m to simulate a slight hand motion. The separation distance between base station and portable antenna are 7 ft for small office room with dimension of 22 (ft) $\times$ 16.5 (ft) $\times$ 10 (ft) and 76.32 ft for a large building with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). It can be seen from Fig.27, 28 that even the portable antennas were moved in a small area, the multipath fading causes changes in the received signal level. This received signal variation in a small area could affect the quality of indoor radio system. Later we will show that the use of directive antennas can minimize these fadings to some extent.

Fig.25. Relative received signal power for portable antenna displacements along the center-line in a small office of dimension 22 ft. $\times$ 16.5 ft. $\times$ 10 ft.

Fig. 26. Relative received signal power for portable antenna displacements along the center-line in a large office building of dimensions 125 ft. $\times$ 75 ft. $\times$ 9 ft.

Fig.27. Relative received signal power when the portable antenna is moved along a small circle with antenna separation of 7 (ft) at an empty office room with dimension of 22 ft. $\times$ 16.5 ft. $\times$ 10 ft.

Fig.28. Relative received signal power when the portable antenna moved along a small circle with antenna separation distance of 76.32 (ft) in an empty office building with dimension of 125 ft $\times$ 75 ft $\times$ 9 ft.

4.3.2 Received signal power when directive base station antenna are used

To investigate the effect of using directive base station antennas minimizing the multipath fading, the simulation of received signal power using directive antenna in base station were performed. Two assumptions were made in the simulations. First, the radiation intensity was assumed to be constant for all angles within the beam solid angle for base station antenna. The omnidirectional antenna was assumed for terminal antenna. Secondly, the radiation center of the major lobe is in the direction of the direct trajectory to each terminal location. The biconical antenna was also assumed in the simulation.

The program was implemented to consider the antenna beamwidth of base station antenna. The beamwidth of the main beam in the desired direction can be adjusted in each simulation run. The emitted signal outside the beamwidth of main lobe was neglected, because these signals only have small contributions to the received power after being attenuated by consecutive reflections from walls, ceiling or floor.

In the simulation, the base antenna was located near the north side wall as previously stated. The separation distance of base and portable antennas was increased from an initial value of 5 ft. to 15 ft. in the small empty room and 10 ft. to 100 ft. in the large empty building.

Fig. 29 and Fig. 30 illustrate the received signal using a directive antenna with 60 degrees beamwidth. Compared with the signal in Fig. 25 and Fig. 26, the received signal variations caused by multiple reflections seem to be less in the case of using directive antennas at short separation distance between transmit and receive antenna. In the small office room

this is more pronounced. As the separation distance between the two antennas increases, the effect of using a directive antenna is not as great as that for short ranges. This is because, as the range increases in an empty building, except for the signal first reflected from the back wall, there will be more rays within the transmit antenna beamwidth arrive at the portable antenna after one or more reflections than that in short separating distance.

Fig. 31 and Fig.32 give a comparison of received signal power using directive and omnidirectional antenna at base station in both small office room and a open space building, while terminal antenna was moved along a small circle with diameter of 0.5 m. The range between two antenna are 7 ft in small office room and 76 ft in larger building. These two figures show that the small spatial signal variations have also been much reduced using directive antenna. When directive antenna being operated inside of the building as base station antenna, the number of emitted rays that reach to the portable antenna under go one or two reflections will be less than that when using omnidirectional base station antenna. Basically there will be no rays reach to the terminal antenna under go one reflections from back wall, Because of high reflection coefficient on the ceiling (large incident angle), the ray reflected from ceiling normally produce important fading in received signal. The directional base station antenna will basically limit the number of rays reflect from ceiling and also eliminate the rays reflected from back wall.

Fig. 29 Relative received signal power for portable antenna displacements along the center-line of a small office with dimension of 22 ft. $\times$ 16.5 ft. $\times$ 10 ft.

Fig.30. Relative received signal power for portable antenna displacements along the center-line of a large office building with dimension of 125 ft. $\times$ 75 ft. $\times$ 9 ft.

Fig.31. Relative received signal power for portable antenna displacements along a small circle in an empty room with dimension of 22 ft $\times$ 16.5 ft $\times$ 10 ft.

Fig.32. Relative received signal power for portable antenna displacements along a small circle in an empty building with dimension of 125 ft $\times$ 75 ft $\times$ 9 ft.

4.4 Path loss and local area signal variations

The objective of propagation modelling is to obtain a model that can be used in the prediction of coverage in a variable indoor environment. A good prediction model can be used in designing and planning of indoor wireless network systems.

The path loss can be used as a parameter to determine the received power dependence on the distance between the transmitter and receiver antennas. This parameter is useful in determining the necessary transmitted power to cover the defined areas and used for link budget calculations. In the simulations, the power decay index is calculated by considering an open office environment, in which the distance between antennas is increased gradually along the center line of a building. The received power is calculated by a model previously described in equation(10). The distance power decay formula can be expressed as[1]

$$L_i = L_0 + 10 \cdot n \cdot \log(d) \quad (\text{EQ 11})$$

where n is the power decay index, d is the distance between the receiver and the transmitter, L_0 is the loss at 1 meter.

Each individual n related to a separation distance between the receive and transmit antenna was calculated by the above equation using the received power L_i calculated by the simulation model. The median value of all calculated index n was obtained as a best estimate for power decay index n . The received power was found in simulation for open

space empty building to decrease with distance as $1/d^{1.75}$. Fig. 33 gives the received power versus distance and best fit line in simulation.

Fig. 33 Received signal power as a function of distance along a center line in a open space building at 950 MHz.

Comparison with Bultitude's measurement result of $R^{-1.8}$ for the power law in a hallway of a large building[18], simulation gives a very good comparison. The predicted value of n is smaller than free space propagation power loss index ($n= 2$). This means that the open space office room with concrete walls and floor has a waveguide effect.

Local area signal variations were predicted by considering 200 portable antenna locations inside an open concrete wall building. For each of these 200 locations, 200 antenna positions along a small circle with diameter of 0.5 m at desk height were considered. In each of these local area, the received power is normalized by the median value of the received power. The cumulative distribution functions for local signal variation was calculated by

considering all these 200 areas. Fig. 34 shows the CDF for the power variation within local areas.

Fig.34 Cumulative distribution function for local power fading in an open space building.

4.5 Signal power coverage

Coverage was also calculated by the simulation model. For one fixed base station, 1000 terminal locations were generated in an open office building with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft) as distributed in Fig 35. The maximum distance between base station antenna and terminals is 35 meters. The received power at each terminal location was calculated by simulation. The received power was adjusted by a factor of 64.48 dB as a free space loss reference point of 1 meter at 40 GHz. The relative received signal power for Line-of-sight is shown in Fig. 35 and for non-Line-of-sight is in Fig. 37. In Fig 37, the base station was located in a small plywood partitioned office. Line-of-sight was assumed

to be blocked by these partitions. The 3 ranges of path loss were plotted in these two figures as indicated by *, •, o. In this open space office environment the maximum relative path loss is 54 dB for line-of-sight and 60 dB for non-Line-of-sight with the same antenna separation distance in these two case. The power attenuations caused by 40GHz millimeter wave penetrated the plywood partitions is 3 dB used in here according the previous measurements [37]. Fig. 36 and 38 also show the contour plot of locations of equal path loss for a given transmitter location. The plotted data is based on 400 receiver locations inside the building. The transmitter location is indicated by Tx in Fig.36 and Fig.38. The curved solid line in this two figures show the locations of equal path loss from transmitter in 10 dB steps. This prediction will give the power coverage estimate. It is usable for indoor wireless network planing work and link budget calculations. However, more accurate prediction will rely on the availability of better information about the construction materials. An example of a link budget prediction for this office will be presented in a later chapter.

Fig35. Power loss distribution in an open space building with Line-of-sight

fig.36 Contour plot of locations with equal path loss in 10 dB steps for an empty office room with

Fig.37 Power loss distribution in a open office building with none-Line-of-Sight.

Fig.38. Contour plot of locations with equal path loss in 10 dB steps for a empty office building with none-Line-of-Sight.

4.6 Temporal received signal variation due to shadowings

PCNs operating at MM-wave frequencies in the indoor environment will suffer from the signal level variations due to human traffic close to the network terminal[24]. Indoor radio channel characteristics can change dramatically, if the line-of-sight is blocked by humans or other objects.

The following simulation concerns the situation where the line-of-sight is blocked by human traffic. Energy in the rays which are blocked is assumed to be completely absorbed, and no further reflected rays is generated. The simulations were performed for a small empty office room and a modern open office building. A fixed portable terminal R inside an empty room or building was simulated as in Fig. 39. The purpose of this simulation is to investigate the signal variation due to human traffic close to the fixed terminal antenna in Line-of-sight environment. The distance between two antenna is 10(ft) for small office room and 95(ft) for large open building. The omnidirectional antenna was assumed for both base station and network terminal in the simulation. Two cases of simulations were performed in a small office rooms and a large open space building. A human traffic was assumed moving around the fixed terminal antenna in position R as in Fig.39. The base station antenna was assumed to be located near one side wall at T. The program was implemented to monitor if the direct ray emitted from the base station was blocked, in which case it's contribution to the received signal power will be neglected.

Fig.39. Floor layout for shadowing simulation.

Fig. 40 Floor layout of the base antenna and terminal antenna loca-

Fig.41 Floor layout of the base antenna and terminal antenna

Figs. 42 and 43, show the simulation results of received signal power variations when direct ray path is blocked in these two empty indoor environment. In empty building, the power contained in the direct ray path dominates the received signal level. When this direct ray is obstructed by human traffic, the received signal power decreases significantly. The dynamic range of this variation is different for each portable location. In these simulation cases, the fading due to blocking of the direct ray reaches 12 dB or more.

The signal fading caused by human traffic around a portable will degrade PCN system performance. One mitigation method is to use antenna diversity. Assume two antennas, T1 and T2 are installed in an empty room as in Fig. 40. For the fixed terminal R, when the line-of-sight between T1 and R is blocked and the received signal level decreases to a specified level, the system should switch to the other antenna. Fig. 44 shows the received signal power from the two antennas. The deep signal fading in these two channels is at separate times. If a good switching system were employed, the deep signal fading caused by human traffic might be effectively avoided. In the other case, when T₁ and T₂ are located as in Fig.41, the received signal power will change as in Fig. 45. Here the received signal level with line-of-sight between T₁ and R has almost the same level as the channel between T₂ and R in block line-of-sight situation. The cumulative distribution function of signal variation caused by blocking line-of-sight over 1000 terminal locations was also calculated for an open space. Fig.46 shows this distribution. At 95th percentile terminal locations the received signal fading caused by human body blocking the line of sight is less than 10 dB, and less than 17 dB for 99th percentile terminal locations.

Fig.42 Variation of received signal power caused by human traffic near a portable block line-of-sight in a small office with dimension of 22 ft $\times$ 16.5 ft $\times$ 10 ft.

Fig. 43 Variation of received signal power caused by human traffic near terminal block-line of-sight in modern office building with dimension of 125 ft $\times$ 75 ft $\times$ 9 ft.

Fig. 44 Variation of received signal power from two channels caused by human traffic block the line-of-sight in modern office building with dimension of 125 ft $\times$ 75 ft $\times$ 9 ft.

Fig.45 Variation of received signal power from two channels caused by human traffic block line-of-sight in modern office building with dimension of 125 ft $\times$ 75 ft. $\times$ 9 ft.

Fig. 46 Cumulative distributions of temporal signal fading caused by human traffic blocking line-of-sight.

4.7 Relationship between spatial signal power variation and bandwidth

Fading as a function of signal bandwidth was discussed in [38]. Both Line-of-sight and non-line-of-sight configurations were considered. The results show that fading margins to be allocated for fixed indoor EHF links depend on the signal bandwidth, and can be smaller for greater bandwidth.

The detailed study of the relationship between the transmitted signal loss and bandwidth is useful in predicting the system performance for different bandwidths. The following is the simulation result of relative signal loss for different signal bandwidths. For each base and portable location configuration, the normalized received signal power is calculated by integrate the received signal power in a bandwidth and then normalized by that bandwidth (10 MHz, 20 MHz, 40 MHz and 80 MHz). The simulation was performed with a fixed base station and 1000 randomly generated portable station positions building with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). At a fixed center frequency 40 GHz, the impulse response was generated for the different transmitted signal frequencies in the selected bandwidth. The frequencies were selected with fixed spacing of 20 KHz in those 4 different bands. The normalized received signal power of a given bandwidth was calculated by summing all the received powers in this bandwidth, then divided by that bandwidth. The ratio of these normalized received signal power with that of a bandwidth of 10 MHz was calculated to measure the relative signal loss based on different bandwidth during the signal transmission inside of the building. The cumulative distribution of these ratio is based on the calculation of 1000 randomly generated portable locations for a fixed base station. Fig. 47 shows the distribution of this ratio for different bandwidths.

The results show that, at the 80th percentile, the ratio K_1 is fit for bandwidth of 2 MHz, K_2 and K_3 are fit for bandwidth of 40 MHz and 80 MHz. The relation between them is $K_1 > K_2 > K_3$. This indicates that the average received signal power is larger for greater bandwidth in the same indoor environment.

All above simulation results related to signal spatial fading and temporal signal variation caused by human traffic blocking the line of sight and path loss will be used in link budget calculation. A detailed example of radio link calculation will be presented in the next chapter. This example is also used to show the usefulness of this simulation model.

Fig. 47 Cumulative distribution of the ratio which is the normalized received signal power related to that with 10 MHz bandwidth transmitted signal.

CHAPTER 5 Discussion

The objective of the research in this thesis is to investigate the characteristics of MM-wave radio channels inside buildings. Results from simulations are presented regarding the multipath characteristics and received signal power characteristics.

Static RMS delay spread and multipath fading as well as other radio parameters, can be studied by site-specific electromagnetic modelling techniques. In general, indoor radio channels vary both in space and time. The variations are caused by signal reflections from building walls or by the movement of personnel and machinery in the building. The software tools that were developed in the course of this thesis work can be used to predict signal variations of the indoor channels caused by these influences.

Static RMS delay spreads and relative received signal power for different antenna patterns were derived from simulations for different indoor environments and used to draw conclusions about the characteristics of indoor radio channels. The dynamic range of the signal fading caused by human traffic blocking line of sight was also predicted by the simulation. The results show that deep signal fading nulls caused by human traffic block line-of-sight may be avoided using space diversity. The relationship of transmitted signal loss with signal bandwidth and several link budget parameters were also studied.

5.1 RMS Delay Spread

Using the discrete-time impulse response model EQ(1), the RMS delay spreads for static channels were calculated after thresholding the impulse response power functions at a re-

cific levels and using the power of received rays and excess time delay to calculate RMS delay spread by equation (9). The simulation was performed in an office building. Following the measurement procedure conducted at CRC by Bultitude, the receiver antenna was located near a wall, while the portable antenna was displacement along the centerline of the area under study. For each portable location, the RMS delay spread was calculated from the generated impulse response. Other simulations were performed by locating the portable station along concentric arcs centered on the base location, with radius increments of 10 ft. It was shown that the predicted and measured values are in very good agreement. However, the predicted values are slightly larger than the actual measurement value. This could be because, in the simulation model, the reflection surfaces are assumed to be perfectly smooth, the roughness of reflecting surface and scattering loss were not accounted for.

To investigate the RMS delay spread behavior inside of the empty building, 1000 terminal locations were randomly generated inside the empty building, with antennas at desk height, and the RMS delay spread was calculated for each. Static RMS delay spread values versus distance between the base station and portable locations were shown in Fig.13 and 14. The value of RMS delay spread was found to initially increase with increases of separation distance between the two antennas in a limited range, then reach the peak and remain constant for longer separation distances. The value of static RMS delay spread is dependent on the dimensions of building and the electromagnetic properties of materials used in the walls, ceiling and floor. This result shows that the portables with larger separation from the base station do not always have larger RMS delay spread. The peak of the RMS delay spread in all these simulations with different dimension of the empty room

occurs at a range that is less than half of the diagonal length between ceiling and floor in three dimensional cubic empty office room or building (see Fig.13, 14). It can also be concluded that the RMS delay spread is much larger in large office buildings. This is believed to be the result of larger transmission distances for each reflected ray that causes much larger excess delay than in small office.

Simulations of RMS delay spread behavior inside office buildings with semipermanent partitions such as, plasterboard, plywood, etc., were also made to study the multipath characteristics in most modern office buildings. For a fixed base station, static RMS delay spread was calculated for each of 1000 randomly generated portable locations. Non-line-of-sight conditions were assumed in all simulations. A penetration loss of 3 dB passing through plywood partitions was assumed.

Fig. 23 and 24, show the comparison of RMS delay spread versus distance between base and portable antennas in both empty building and building with plywood partitions. It is shown that the RMS delay spread in the partitioned case is less than that without partitions. It can be concluded therefore that the presence of partitions will have the effect of decreasing the RMS delay spread in indoor environments. This result will be useful in the prediction of bit rate which a PCN can support in a modern office environment with semipermanent partitions. If the signal bit rate requirement can be supported by a PCN in an empty environment, it can also support this required bit rate if the environment is furnished. Static RMS delay spreads in empty buildings or office environments are easy to predict using the prediction software tools discussed herein.

Series of simulations were performed to calculate the maximum and mean value of RMS delay spread in different size empty rooms of the same construction material. For each room, the base station antenna was fixed at one end of the building. The maximum and mean values of RMS delay spread were calculated by considering the value of RMS delay spread of 1000 randomly generated portable locations in each case. A total of 20 different sizes of rooms were used in the simulation. The 3 dimensional diagonal distance (D) was used to quantify the size of each. Fig. 17 shows the relation of maximum and mean value of RMS delay spread versus diagonal distance(D) in these 20 empty rooms. It is interesting to find that the maximum and mean value of RMS delay spread is linearly increased as the increase of the room size quantified by diagonal distance.

Normally, PCNs operating inside buildings use a certain number of base stations to cover each small area in order to affect channel reuse patterns. The materials which are used to divide these small areas are identical in most cases. This simulation package would provide very useful information for system designers to evaluate the maximum unprotected transmission rate achievable with different cell sizes, avoiding the need for expensive and time consuming measurements in each area.

In the case of using directive base station antennas, the mean and median value of static RMS delay spread is smaller than the results where omnidirectional antenna are used. However, as the increase of antenna separation, there is no significant differences in RMS delay spread. As shown the channel impulse response in Fig.49 and 50, even using directive base station antennas, the rays which have the larger excess delays still have considerable power. These components affected the value of RMS delay spread. Fig. 19 shows that

using directive base station antenna has the effect to decrease RMS delay spread, but the change is too small to be considered as a practical way to permit high unprotected data rates.

Fig.49 Impulse response profile for a separation distance of 90 ft between the base station and portable antennas using an omnidirectional base station antenna.

Fig. 50 Impulse response profile for a separation distance of 90 ft between base station and portable antennas using a directional base station antenna.

The above results showing RMS delay simulations in indoor environment based on ray tracing techniques have given an easy way to predict the channel multipath characteristics inside buildings. The simulation results of RMS delay spread behavior can be used for PCN system designs for empty office buildings and buildings which are partitioned in different areas. In addition, simulation of channel characteristics using different antenna patterns is possible using the simulation tool presented in this thesis. More extensive channel characteristic simulation of indoor radio channel can be done by just modifying appropriate parameters in the program.

5.2 Received Signal Power

PCN portables must receive a certain amount of power from the base station to facilitate information transmission. However, the indoor radio channel is highly variable in time and space. This makes indoor PCN system more difficult to design in order to cover all the expected portable stations. If the power loss at each portable location can be accurately predicted, a maximum range can be specified, making it possible to provide relatively little power as well as minimizing co-channel interference. Simulations such as those discussed herein can be used as a good way to effectively predict the power loss in the indoor environment.

The received signal power at each portable station is the vector sum of the direct ray and reflected rays from building walls, ceiling, floor and other objects inside the building. Figs. 25 and 26 show the relative received signal power with portable displacements along

the centerline of empty rooms or building to increased ranges. The received signal power is highly variable among different portable locations. In some locations, a very severe signal attenuation occurs. Clearly if a PCN terminal is located in the position which has a deep signal null, the system performance will be greatly degraded. Using directive base station antennas has shown the effect of reducing these multipath signal variations (Fig. 29). The directive base station antenna basically eliminates the multipath signals first reflected from the back wall or ceiling if the base stations are located in an elevated position. Because of a larger incident angle for the ray reflected from ceiling, the reflection coefficient is higher than that for the ray reflected from other walls or floor. So the signal power reflected from ceiling has significant influence on multipath signal fading even if the dielectric constant of materials used in the ceiling is lower than that of materials used in the walls and floor. As the increase in separation distance between two antenna, the effect of using directive base station antenna is not significant. This is because for short separation distances the number of transmitted rays within the beamwidth which under go one reflection and intersect the portable antenna is less than for longer antenna separations. The power in each reflected ray decrease as for free space transmission, which is proportion to $1 / r^2$. The ray with one reflection normally has a short path to reach the portable antenna and has a larger influence on signal fading. Temporal signal fading caused by traffic near the portable was also investigated. In simulations, it was found that signal fading caused by human traffic blocking line-of-sight can reach to 12 dB. For different locations of base station antennas in the empty building, received signal fading caused by such blocking of line-of-sight between base and portable antennas is separated in time. This makes it possible to use space antenna diversity to eliminate deep fading (Fig. 44). However, the base station antennas need to be displacement in selected locations to ensure

gains from space antenna diversity. Fig. 45 shows a case in the simulation, in which the received signal power between channel T_1 and R is higher than the normally received signal power between channel T_2 and R, even when line-of-sight is blocked by human traffic. If the channel between T_1 and R was blocked and the received signal level dropped to a specific level, the system should switch to the other channel between T_2 and R. Unfortunately at this base station antenna location the received signal power between T_2 and R is even less than the level in deep fading between T_1 and R. In this case space antenna diversity may not be used to improve the system performance. From previous simulation, we found that the indoor channel is time and space varying and is characterized by high path loss and sharp changes in the received signal power because of multipath effect. If the antenna was located in the positions which has the deep null in the received signal power, the space diversity may not be effectively used to eliminate signal fading. Thus, the base station and fixed terminal antenna needs to be put in the location selected to ensure the better operation performance.

Spatial received signal fading with different bandwidths in MM-wave links was also studied in this thesis. The empirical distribution based on measurement data analysis in [38] shows that the change in fade depth with bandwidth is not linear. In data analysis, Parseval's Theorem was used to compute the power that would be received following the transmission of white signals of different bandwidths through indoor channels. The simulated impulse response function were analyzed by using FFTs to get corresponding transfer functions. Herein, a simulation of normalized received signal power which is the total received signal power in bandwidth divided by that signal bandwidth was performed and the ratio of this normalized power related to that in a 10 MHz bandwidth was used to com-

pare the signal loss for different transmit bandwidths in empty indoor environments. For a fixed base station and each of 1000 portable locations in an empty room with concrete walls (permittivity of 6.25), the total received power across a selected bandwidth was calculated by simulation. The frequency components were equally spaced of 20 KHz within the bandwidths of 10 MHz, 20 MHz, 40 MHz and 80 MHz at a center frequency of 40 GHz. Results show (Fig. 47) the distribution of the ratio of the normalized received power in 20 MHz, 40 MHz and 80 MHz bandwidths relative to that in a 10 MHz bandwidth. The distribution is based on the simulation result of 1000 portable station location for a fixed base station antenna. It is clear that the transmitted signal power loss for fixed indoor MM-wave links is related to signal bandwidth. At 90 percent of portable locations, this ratio is less than 3 for 80 MHz bandwidth signal, 2.5 for 40 MHz and 1.8 for 20 MHz signal. On the basis of this result, one can conclude that signal loss in the empty rooms or building differs for different transmission signal bandwidth. This losses are small for larger bandwidths.

5.3 Link Budget Example

The radio link between a base station and a fixed portable should provide high quality communications. This quality is affected by fading and other indoor propagation phenomena. To implement high quality indoor wireless systems, one must consider the quality of service and locations of portables which meet customer requirements as well as those dictated by building architectures.

The simulation of signal path loss, local signal variation and signal attenuation caused by human traffic blocking line-of-sight is useful for planning link budget calculations for specific building. Such simulations should also consider blocking of all rays which intersect the portable antenna. This topic is being recommended for further study of indoor channel simulation. Considering the link availabilities, simulation results based on software support can also help decide on the necessity of using base station diversity to cover the radio link in a specific indoor environment.

The following example shows a radio link budget which operates at 40 GHz in an open concrete building with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). The statistics of spatial power variation are shown in Fig. 34. The CDF values based on 4000 terminal locations in simulation gives a probability of 10^{-2} that fade depth is less than or equal to 13 dB for omnidirectional base station antenna. This means that a margin at 13 dB is required for 99% link reliability. Temporal fading caused by human traffic inside of the building in this case was also calculated by software. The CDF of signal variation caused by blocked line-of-sight over 1000 portable locations using omnidirectional antennas for this building was shown in Fig. 46. At 95th percent of portable locations, the received signal fading caused by blocking line-of-sight is less than 10 dB.

Contour plots of relative received signal power in this open space building were shown in Fig.36, and 38. Base station was placed inside of the building with line-of-sight and non-line-of-sight. In non-line-of-sight situations, the line-of-sight was assumed to be blocked by plywood partitions. The maximum path loss was calculated by simulated result of power law. For maximum base and terminal separation, the path loss was calculated by

EQ(11) with power decay index of 1.75. The maximum path loss was 81.32 dB for MM-wave at 40 GHz with the portable antenna located near one other end wall opposite base station antenna for a range of 121 ft. This path loss was used in budget calculation to ensure the link availability. The omnidirectional antenna and a 5 dB antenna gain were used for both base and portable antenna in this links budget prediction. The system requirement KTB was calculated by considering antenna noise temperature and equivalent temperature of receiver with 7 dB noise figure($T=290 \times (F-1)$), Boltzmann's constant and transmitted signal bandwidth. The transmitted signal bandwidth (4 MHz) is calculated by considering maximum RMS delay spread (50 ns) in this building and 5 times of this maximum RMS delay was used as the signal symbol in case no special measures against multipath effect are taken [26]. Table 1. shows the link budget result. It can be seen that required transmit power will be 16 mW.

TABLE 1. Indoor Radio Link Example

KTB ($F_{\text{sys}} = 7 \text{ dB}$) System Requirement	-99 dBm
Required Static SNR ($P_e=10^{-4}$), DBPSK modulation scheme	9 dB
Temporal Fading Margin (Predict at 99th percentile) (Fig. 44)	17 dB
Required Average Power at Receiver Input	-73 dBm
Maximum Propagation Loss (Line-of-sight)	-82 dB
$P_t G_t G_r$	9 dB_m
Base Antenna Gain	5 dB
Terminal Antenna Gain	5 dB
Required Transmitter Power (Single Location)	-1 dB_m
Spacial Fading to 1st Percentile (Fig. 32)	13 dB
Required Transmitter Power 16 mW	12 dB_m

CHAPTER 6 Conclusions and Recommendations

6.1 Conclusions

A software tool based on ray tracing and image theory was developed to compute indoor radio channel impulse response functions. Static RMS delay spread and multipath signal power variations in indoor environment were studied.

The comparison of RMS delay spreads calculated from simulation with actual measurements was used to examine the accuracy of this software. For a modern empty modern office building with concrete walls, simulation results for a range of displacements of a portable along the building center line and along different arcs centered on the base station location gave a good comparison with measurements.

The values of RMS delay spread in an empty indoor environment are initially increased as the separation distance between antennas increases, then reaches a maximum value and remains at this value for larger separations. The minimum range at the maximum value was found to be less than half of diagonal distance in 3 dimensional cubic empty building.

The maximum and mean value of RMS delay spread for a large number of randomly generated portable locations in an empty room linearly increases with increases of the diagonal distance between ceiling and floor.

It appears that RMS delay spread do not depend on the type of antennas applied for base station, on the other hand, the RMS delay spread values depended on the antenna locations. Using directive base station antennas has the effect of reducing the mean and

median values of RMS delay spread for short antenna separations, but this change is too small to be considered as a potential way to increase the maximum data rates achievable. The RMS delay has larger variance in the case of using directive base station antenna.

The value of RMS delay spread in small areas divided by semipermanent partitions is less than that of an empty building. Thus, the transmission bit rates can be increased in partitioned building.

Multipath signal power variations are severe in both large and small empty buildings. These variations are caused by signals reflected from walls, the ceiling, the floor and other obstacles, and can be reduced by using a directive base station antenna. The directive antenna eliminates the multipath signal reflected from the back wall and ceiling which causes a significant signal fading. However, as the separation distance between base and portable antenna increases, the reductions in spatial variations are not significant.

Temporal variations of the received signal power caused by human traffic close to a portable were also predicted using simulation software. The deep signal fading caused by blocking the line-of-sight can be as high as 12 dB. For separated base station antennas in an empty room, the fading caused by line-of-sight obstruction occur at different times. Therefore, it is possible to avoid this deep signal fading by using space diversity. However, the location of diversity antennas must be selected to ensure diversity improvement.

Transmitted signal power loss on MM-wave links operating inside empty buildings are related to transmitted signal bandwidth. The simulation of such power loss at bandwidths

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of 80 MHz, 40 MHz and 20 MHz relative to those at a bandwidth of 10 MHz shows that the loss are lower for greater bandwidths.

A link budget example was presented to show the usefulness of the simulation tool developed herein. The information used to predict the minimum necessary transmit power to cover an indoor environment includes propagation loss, a fading margin, and the extent of spatial power variations. According to the simulation results, a spatial margin of 13 dB is required for 99 percent reliability, and a 10 dB margin is required to compensate for fading caused by human traffic blocking the line of sight for 95 percent of portable locations. Based on the above simulated results, 16 mW transmitted power from base station is required to cover an open space office environment with dimension of 125 (ft) $\times$ 75 (ft) $\times$ 9 (ft). The relation between fading and signal bandwidth were not considered in this link budget calculations. The software tool developed here can be used for indoor wireless network planning. Further work is necessary to develop a graphical user interface. System designers could use it to input structure of indoor environment with small divided office rooms and also to set particular base station and terminal locations. The software tool will give the system design parameters and optimize the selection of base station locations.

6.2 Recommendations

Improvement of the software used in this thesis is necessary to provide a graphic user interface. Simulation results should be displayed with detailed information on power loss, RMS delay spread and other parameters related to indoor radio channel for any specific area. The results should also automatically produce a link budget, recommend antenna

type and give estimates of the maximum (empty room) amount of dispersion that can be expected.

Electromagnetic modelling techniques need a knowledge of dielectric constant of construction materials in different frequency bands, especially at MM-wave lengths. The scattering, shadowing and roughness of surfaces should also be considered in the simulation to give more accurate predictions. For a specific coverage area, the direction of trajectory and beamwidth of directive base station antenna also need to be studied in PCN designs.

The CDF of local area signal variation caused by the movement of people or machinery inside buildings is focused on the influence of blocking the line-of-sight. The fading will also occur when other important rays are blocked and also due to multipath component phases. Further simulations should consider different ray components which influence the receiver signal power. The effect of using directive antenna, spatial antenna diversity, two directional antenna of the base and portable and different directional antenna polarization also need to be studied.

From the simulation, the cumulative distribution function of local area signal variation could be compared with Rayleigh, Rice and other distribution. This might provide useful information regarding the fading statistics.

The spatial fading relationship with signal bandwidths studied in this thesis concludes that increasing the bandwidth results in a higher average received signal and proves that signal variations are lower for larger bandwidths. Further simulations are necessary to provide

the relative fade depths for the different bandwidths and using it as the parameter in the link budget calculation.

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