Measurements and Models for Radio Path Loss and Penetration Loss In and Around Homes and Trees at 5.85 GHz

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***Abstract*— This paper contains measured data and empirical models for 5.85-GHz radio propagation path loss in and around residential areas for the newly allocated U.S. National Information Infrastructure (NII) band. Three homes and two stands of trees were studied for outdoor path loss, tree loss, and house penetration loss in a narrow-band measurement campaign that included 270 local area path loss measurements and over 276 000 instantaneous power measurements. Outdoor transmitters at a height of 5.5 m were placed at distances between 30 and 210 m from the homes, to simulate typical neighborhood base stations mounted atop utility poles. All path loss data are presented graphically and coupled with site-specific information. We develop measurement-based path loss models for propagation prediction. The measurements and models may aid the development of futuristic outdoor-to-indoor residential communication systems for wireless internet access, wireless cable distribution, and wireless local loops.**

***Index Terms*— Residential wireless communications, in-building propagation, building penetration, path loss.**

I. Introduction

On January 9, 1997, the U.S. Federal Communications Commission allocated a large portion of spectrum in the 5.150–5.350-GHz and 5.725–5.825-GHz bands. This spectrum, spanning 300 MHz, is dedicated to Unlicensed National Information Infrastructure (U-NII) devices and is commonly called the NII band [1]. It will support wireless services such as wireless public and private switched telecommunications, wide bandwidth wireless local loops, internet access, and many future information networks for home, school, and campus use. Similar frequency bands already support HIPERLAN networks in Europe [2].

Delivering wireless information into homes may be an important application of the new NII band, particularly for video, internet, or computer communications. Properly designed wireless communication systems for the NII band will require an intimate knowledge of radio wave propagation at this frequency. Numerous propagation studies have already been performed at cellular (900 MHz) and PCS (1900 MHz) frequencies (for example, [3]–[7]), but little is known about frequencies in the NII band (5–6 GHz). Furthermore, most of the literature has been concerned with penetration into urban office buildings, not residential homes.

Several residential radio penetration studies show that path loss and penetration loss increase as the frequency increases. Devasirvatham *et al.* showed how path loss for outdoor-to-indoor propagation in a residential environment increases over the frequency range 455 MHz–4.2 GHz [3]. Additionally, Aguirre *et al.* performed penetration loss experiments for seven homes in the suburbs of Chicago and reported median aggregate penetration loss values of 7.7, 11.6, and 16.1 dB at frequencies of 912, 1920, and 5990 MHz, respectively [8]. The data compare favorably to the averaged aggregate penetration loss of 16.3 dB into homes reported in Section IV of this paper. Siwiak reports that penetration loss into a residential building decreases with increasing frequency up to the 1–3-GHz range, where the loss is about 7–8 dB [9]. Based on the larger 5.85-GHz penetration loss values reported by our propagation study, it appears that residential penetration loss as a function of frequency is at a minimum between 1 and 3 GHz.

Path loss also increases for higher frequency radio waves once they enter the indoor environment. Nobles *et al.* showed a general increase in indoor path loss in the 2–17-GHz frequency range, although the path loss between 1.7 and 4.0 GHz is roughly constant [10], [11]. At higher frequencies, a line-of-sight to the transmitter becomes more important since less power transmits through walls and diffracts around corners. Consequently, indoor path loss generally increases as frequency increases.

This paper presents results on one of the most critical aspects of propagation for emerging consumer wireless systems: signal penetration around and into residential homes. The measurement campaign involved continuous wave (CW) path loss and penetration loss measurements at 5.85 GHz in typical residential environments during May 1997 [12]. Measurements were taken at 270 locations, requiring over 276 000 power measurement samples. A total of 5 typical suburban and rural locations were studied, including 3 houses (inside and outside) and 2 stands of trees.

The work presented here determines three essential propagation parameters: 1) path loss from outdoor base stations to external receivers placed at various locations around homes

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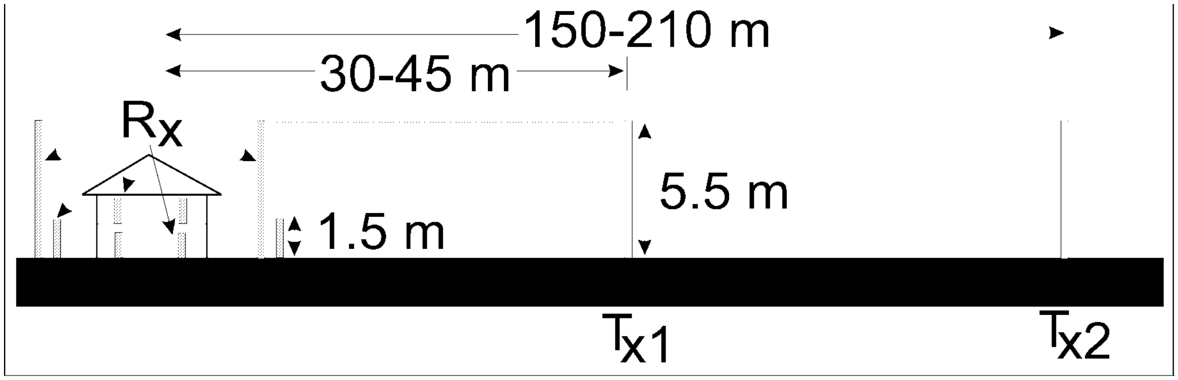


Fig. 1. Transmitters (TX) and receivers (RX) at different heights and separation distances.

in residential neighborhoods, 2) typical penetration loss from outdoor base stations into residential homes, and 3) path loss due to areas of deciduous and coniferous trees. From measurements, we develop empirical path loss models and penetration loss models for 5.5 m tall outdoor transmitter antenna heights, several different transmitter–receiver (TR) separation distances, different external home siding materials, and a variety of foliage.

Section II discusses the experimental hardware, setup, and methodology for path loss and penetration loss measurements. Section III details the measurement campaign and the resulting propagation data. Sections IV–VII summarize the results, present models for residential path loss and penetration loss, and draw conclusions.

II. Experimental Setup

The following section describes the methodology for measuring path loss and penetration loss. Definitions of path loss and penetration loss as well as descriptions of measurement procedures, sites, and hardware are included.

A. Description of Measurement Procedure

Each house is measured using a standard procedure (for reference see Fig. 1). Before any data are collected at a site, the measurement system is calibrated. Then, an omnidirectional CW transmitter is placed at a distance of 30–50 m from the house. The transmitter antenna, located in the clear to simulate a lamp post or utility pole, has a height of 5.5 m.

Outdoor path loss measurements are then made around the front and back sides of the house, first using a receiver antenna height of 1.5 m above ground and then using a receiver antenna height of 5.5 m. Twelve local area measurements were recorded along the front and back of each house. Each CW local area path loss measurement is calculated from a narrow-band power signal averaged over a 20 wavelength (1 m) track during a 5-s period using 1024 power samples.

After the first round of outdoor measurements, indoor path loss measurements are made in each room using a receiver with a 1.5 m antenna height (average head level). Each path loss measurement is a narrow-band power signal averaged over a random track in a room. A local average is recorded for every room of the house.

Then the transmitter is moved to a distance of 150–210 m from the house, and the sequence of outdoor and indoor measurements is repeated. Therefore, both TR separations produce the following data: a) outdoor path loss along the front and back of the house at a receiver height of 1.5 m, b) outdoor path loss along the front and back of the house at a receiver height of 5.5 m, and c) indoor path loss in every room of the home. When the data collection at a site is finished, another hardware calibration is performed to verify system stability.

B. Definition of Path Loss and Penetration Loss

To measure path loss, the experiment relies on the narrow-band measurement of a continuous wave (CW) signal at 5.85 GHz. Narrow-band received power fluctuates over a small area due to multipath-induced fading. However, averaging power along a 20λ circular or linear track (about 1 m for 5.850 GHz) yields a reliable estimate of the local average power independent of signal bandwidth [13]. The average power P_i at the ith location is given by

$$P_i = \frac{1}{20\lambda}\int_0^{20\lambda} P(x)\,dx \tag{1}$$

where $P(x)$ is the absolute CW power (in watts) received along the local area track as a function of position. A summation replaces the integral in (1) if discrete power data points are taken. We define path loss (PL) as the *ratio of the effective transmitted power to the received power, calibrating out system losses, amplifier gains, and antenna gains*. All path loss values reported in this paper are relative to free space path loss at 1 m TR separation. Path loss with respect to 1 m free space provides an easy reference for general link budget computations, as given by (2):

$$\begin{aligned} P_R = P_T + G_T + G_R - [\text{Path Loss w.r.t. 1 m FS}] \\ + 20\log_{10}\left(\frac{\lambda}{4\pi}\right) \end{aligned} \tag{2}$$

where λ is wavelength (0.05 m at 5.85 GHz), G_T and G_R are transmitter and receiver antenna gains in dB, and P_T and P_R are transmitter and receiver powers in dBm [13].

We define *aggregate penetration loss* (APL) as *the ratio between the average power measured immediately outside the house and the average power measured inside the house for a*

TABLE I
BUILDING INFORMATION FOR THE THREE HOMES MEASURED

House Name	Rappaport	Woerner	Tranter
Construction Date	1994	1978	1990
Dimensions	19m × 15m	11.5m × 18m	14.5m × 17m
# of Floors	2	2	2
Basement	No	Yes	Yes
Exterior	brick	wood	brick
Insulation Lining	paper	paper	foil
Tree density	light	light	heavy

constant transmitter location [8]. Equation (3), which parallels the definition in [8], expresses this relationship:

$$\text{Aggregate Penetration Loss [dB]} = 10\log_{10}\left[\frac{\frac{1}{N}\sum_{i=1}^{N} P_i^{(\text{outside})}}{\frac{1}{M}\sum_{j=1}^{M} P_j^{(\text{inside})}}\right]. \quad (3)$$

The summation in the denominator of (3) is over the M interior local area power measurements taken in individual rooms, each denoted as P_j. The summation in the numerator is over the N exterior local area power measurements taken immediately outside the house, each denoted as P_i. All powers are in absolute power scale (not dB values). The measurement locations of each local area are given in Section III.

C. Description of Measurement Sites

The three homes measured were located in the town of Blacksburg, VA, and represented typical middle to upper class suburban or rural residences. For each house, we recorded a variety of construction and site information that could affect the propagation of radio waves. The following sections list the houses studied and contain brief descriptions of their construction, location, and layout. Detailed home information is summarized in Table I. A site description of the coniferous and deciduous tree lines is also included.

The two-story Rappaport home sits atop a large hill in a valley surrounded by mountains. Most of the houses in this neighborhood sit on lots of approximately one acre and an empty lot sits immediately to the south of the house. The area is lightly wooded and the house itself has several small-sized trees around the perimeter. The entire exterior of the home is brick. Paper-backed insulation lies within the exterior walls and interior walls use plaster on wood. Many spacious windows open up the walls of the house on every side and the majority have metal screens. The home was built in 1994.

The Woerner home was built in 1978. It is a two-story dwelling with wood siding. The bottom level consists of a garage and a large, unfinished basement. In addition to wood siding, cinderblocks cover the interior completely around the house at the basement level. Paper-lined insulation was used throughout the exterior walls of the house and the interior walls are constructed with plaster wallboard. The Woerner home is in the same neighborhood as the Rappaport home and experiences similar terrain and surroundings. Large trees have grown up very close to the house on the back side and in neighboring yards.

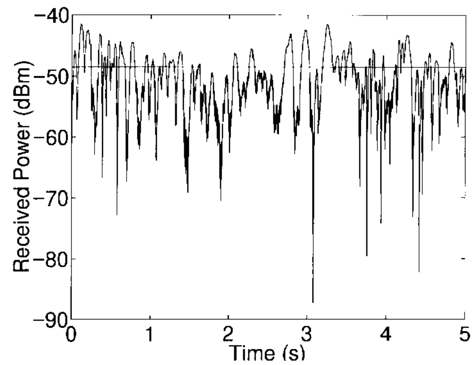


Fig. 2. Typical measurement record of 5 s of 5.85-GHz CW power data captured by the receiver.

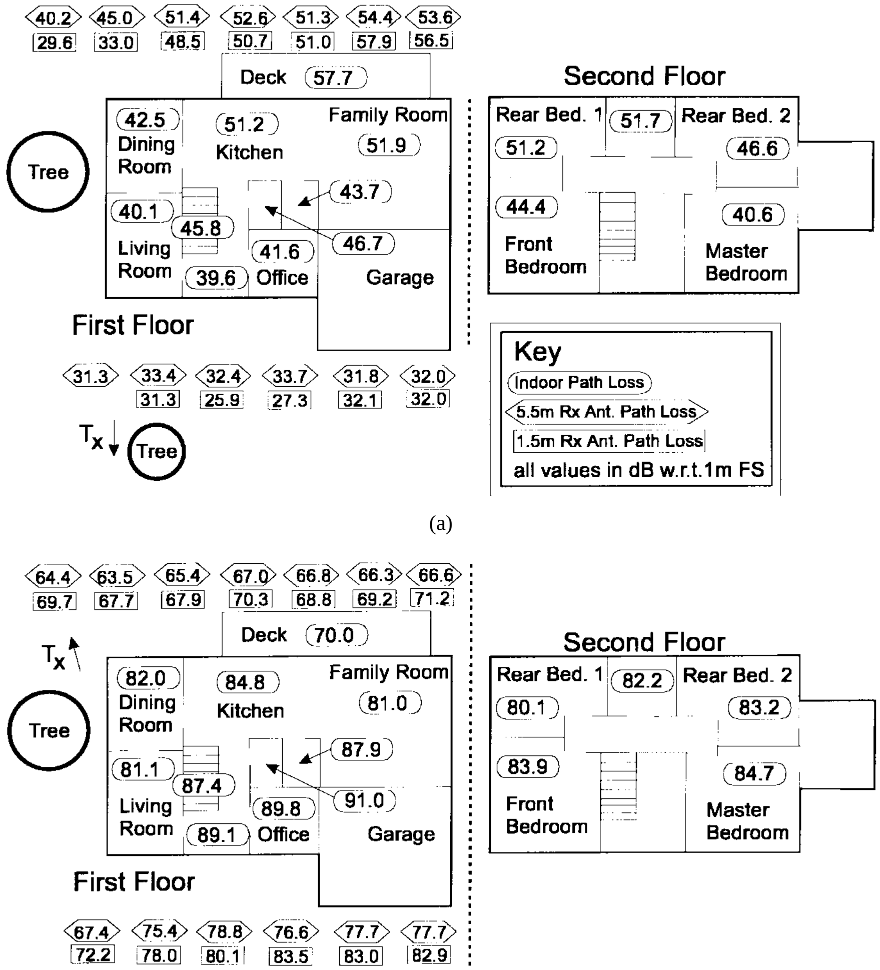
The Tranter home differs from the previous two homes studied because it lies on a heavily wooded lot. The foliage that surrounds the Tranter house is much more dense than the manicured trees of the previous suburban homes. Low level brush coexists with the dense canopies of tall trees. Hilly terrain surrounds the home and the lawn slopes downward toward the back of the yard. The homes in this neighborhood sit on heavily wooded lots of several acres, so trees will be the principle shadowing obstructions for propagation. The brick Tranter home, constructed in 1991, has two stories and an unfinished walkout basement. There are many windows in the home which—with the exception of three sliding glass doors—are covered with metal screens. The inside walls of the house use plaster wallboard construction and the insulation in the exterior walls is aluminum foil-backed.

Two lines of trees were also studied to determine the effective propagation loss of trees in a neighborhood environment. One stand of trees was a large row of coniferous pine trees. Coniferous trees are cone-bearing evergreens with needles or scales that remain on the tree year-round. The pine tree line measured in this paper consisted of a single row of tall, bushy trees in a semi-residential area, near a single-story office building. Each tree is approximately 10 m tall and 6 m wide at its base.

Deciduous trees, such as oaks, maples, and beeches, bear leaves during summer months and lose them in the winter. All measurements were recorded during summertime, when deciduous trees have their fullest foliage. The row of deciduous trees consisted of three large beech trees on the campus of Virginia Tech. Each tree is approximately 8 m tall and has a broad 5 m canopy.

D. Measurement Equipment and Setup

The transmitter consists of a signal generator, an amplifier, and a discone antenna [14]. The receiver uses an omnidirectional quarter-wave monopole antenna mounted on a copper ground plane. The received signal passes through two stages of filtering and amplification, then into a spectrum analyzer operating in zero-span mode. A laptop computer records the narrow-band power samples. Fig. 2 shows 5 s of CW power data taken as the receiver is moved around in a 20λ local area. The linear average of received power values is used for all path loss calculations.



(a)

(b)

Fig. 3. Summary of 5.85-GHz path loss measurements at the Rappaport home.

Before initiating measurements at each of the five sites, two sets of calibrations were performed. First, the transmitter and receiver systems were connected back to back with a short, calibrated cable and a step attenuator, bypassing the antennas and the transmitter amplifier. Next, the transmitter and receiver antennas are reconnected to the system and a free space calibration was performed in an open area with the antennas extended 5.5 m above ground and separated by exactly 1 m. Overall system gain and reference path loss with respect to 1 m free space are calculated from these calibrations, which were repeatable to ±1 dB throughout the campaign.

III. Measurement Results

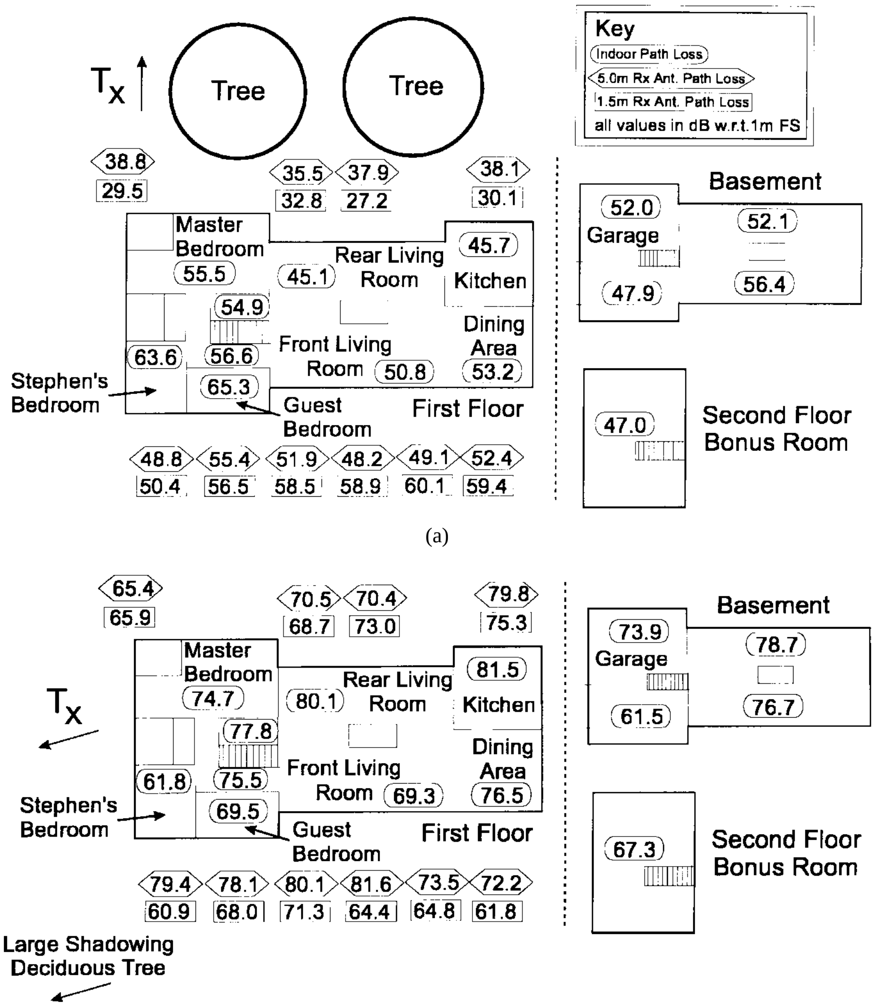
This section reports path loss data recorded from measurements at the five sites described in Section II. All path loss values are recorded relative to 1 m free space, as described by (2).

A. Rappaport Home Results

Fig. 3 illustrates the receiver locations, the layout, and the measured path loss data for the Rappaport home. A total of 81 local area measurements were taken outside and inside the Rappaport home with the transmitter antenna at a height of 5.5 m. Dimensions and receiver locations were carefully measured at this and other sites using a tape measure.

For the near TR separation, a transmitter was placed across the street at a distance of nearly 30 m from the front of the house. Outdoor measurements with the receiver antenna on a 5.5 m mast were made close in to the house, around the front and back sides at locations marked in Fig. 3. Outdoor receiver measurements at these locations were repeated using a receiver height of 1.5 m—typical for a hand-held phone. Using Fig. 3, one may observe the difference in measured path loss induced by a shadowing deciduous tree for 5.5 m and 1.5 m receiver heights at the back corner of the house.

The same receiver locations were measured again using a TR separation of 150 m. This time the transmitter illuminated the back side of the Rappaport home. A house and a patch of trees shadowed the transmitter from all of the measured points at the Rappaport home and there was a modest downward ground slope in the direction of the transmitter. A total of 30 indoor local areas were also measured using the two transmitter locations. One local area path loss measurement was made in every room of the house, on the



(b)

Fig. 4. Summary of 5.85-GHz path loss measurements at the Woerner home.

first and second levels, with receiver antenna heights at a constant 1.5 m.

B. Woerner Home Results

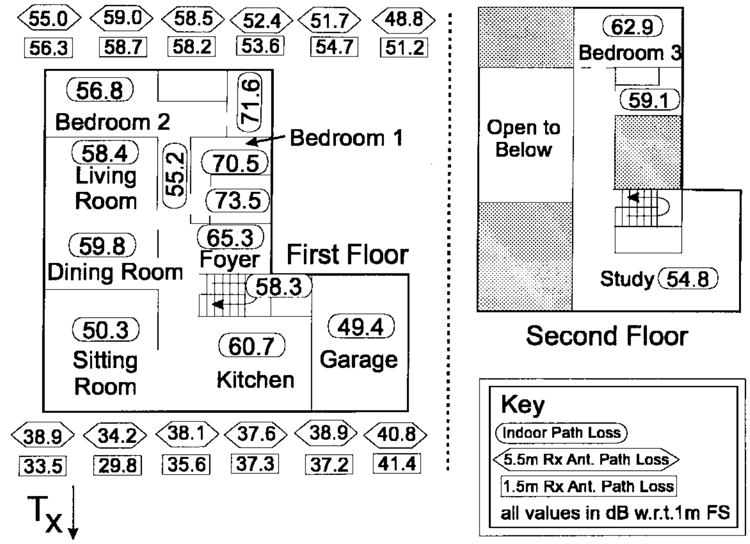
Fig. 4 shows the receiver locations, the layout, and the measured path loss data for the Woerner home. A total of 68 local area measurements were made at this home. The near CW transmitter was placed at a distance of 30 m behind the house. Two large trees in the backyard lay between the 30 m transmitter and the side of the house. The line of receiver locations on the back side of the house were parallel with the rear wall of the house and were sandwiched between the large deciduous trees and the home. Fig. 4 shows a surprising amount of attenuation for the 5-m-high receiver due to the tree canopy. The 1.5-m-high receiver locations have a line-of-sight to the transmitter *underneath* the bushy tree canopy. Consequently, path loss is almost identical to free space values at these head-level locations.

The far transmitter was placed 210 m from the Woerner home in an open field. The principle shadowing elements for the receiver locations are houses and trees. In particular, there is a large deciduous tree in the next-door neighbor's yard that blocks the entire front of the Woerner home from the transmitter. Notice the large difference in path loss along the front of the house between the 1.5 m and 5 m receiver heights. All of the high receivers are blocked by the large deciduous tree in the neighboring yard. Once again, the 1.5 m receivers experience less path loss because of the line-of-sight path underneath the tree.

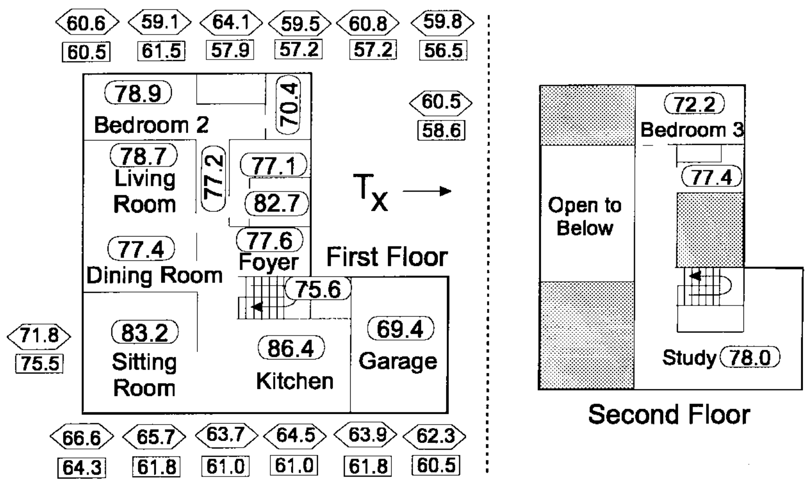
Fig. 4 also illustrates the indoor path loss relative to 1 m free space for both transmitter configurations. Note that the path loss in the cinderblock wall basement is comparable to the path loss on the first floor of the home for the 30 m transmitter. However, the walkout basement is directly illuminated on the outside by propagation underneath the trees. The first floor, which actually corresponds to the 5 m outdoor receiver height, is shielded by the tree canopy.

C. Tranter Home Results

The receiver and transmitter configurations for the 84 local area measurements taken at the Tranter home are shown in Fig. 5. The near transmitter was placed 48 m in front of the house on the other side of a heavily wooded area. The trees in front of the Tranter home are forest-like. Unlike the typical



(a)



(b)

Fig. 5. Summary of 5.85-GHz path loss measurements at the Tranter home.

neighborhood trees at the Woerner home, foliage in this area is dense at all heights. The smaller difference in path loss for 1.5- and 5.5-m-high receivers along the front side of the home demonstrates how trees attenuate uniformly as a function of receiver antenna height for this home. The transmitter was moved down the street to a distance of 160 m from the Tranter home and measurements were repeated. The 5.5-m-high receivers experience marginally more path loss than the 1.5 m receivers, most likely due to higher concentrations of the tree canopy at the higher level.

Fig. 5 also illustrates indoor path loss for both transmitter configurations. For the near transmitter, path loss decreases in rooms that are farther from the transmitter. This trend is interrupted by the relatively low path loss measurement of 56.8 dB in Bedroom 2. Bedroom 2 is furthest from the transmitter, but additional tree-scattered power enters into the room through a large sliding glass door on the left side of Fig. 5.

When compared to outdoor path loss values, penetration through the brick exterior into the Tranter home incurs about 3 dB more loss than the brick Rappaport home. Unlike the previous houses studied, the Tranter home has aluminum foil-backed insulation around the entire house. This thin conductive shield likely accounts for the additional loss.

D. Coniferous and Deciduous Trees

Fig. 6 shows the site sketch of the pine tree row with measured path loss values. Measurements were made at receiver antenna heights of 1.5 and 5.5 m. The back-side path loss exhibits a received power drop in excess of 10 dB when compared to the front side. Unlike many deciduous trees in the residential neighborhoods, there is still significant loss at the 1.5-m-high receiver; there is no line-of-sight opening underneath the pine tree canopy.

The row of deciduous trees comprised of three large beech trees. The canopies of the beech trees cleared the ground by 1–1.5 m. The transmitter was placed in a parking lot across the street and had a line-of-sight to the front side receiver locations. For measurements at a height of 5.5 m, Fig. 6 shows significant attenuation in the range of 12–16 dB for

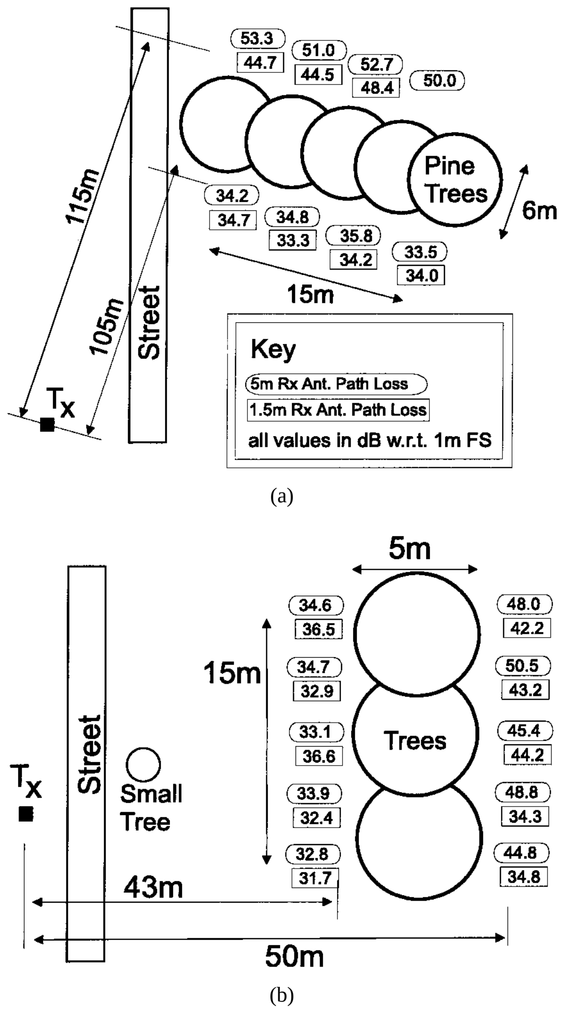


Fig. 6. Summary of 5.85-GHz path loss measurements for stands of deciduous and coniferous trees.

locations behind the trees. This large attenuation is absent at a receiver height of 1.5 m, even though the rim of the broad canopy blocked the optical line-of-sight for some locations. The clearing underneath the tree provided a strong propagation path with line-of-sight characteristics.

E. A Summary of Measured Data Trends

Before providing detailed analysis in Section IV, we associate path loss data with site-specific information, revealing trends that would otherwise lie hidden in the raw data. Below are several general measurement-based observations that summarize residential propagation at 5.85 GHz.

1) Receiver Antenna Heights: Many of the 5.5-m-height receiver antenna measurements showed considerably more path loss than measurements at a height of 1.5 m, largely due to treetop shadowing. However, rooftop receivers appear to be beneficial in areas that are shadowed by houses instead of trees. Under these conditions, measurements with 5.5 m receiver masts showed consistently less path loss when compared to ground-level receivers. The increase in received power most likely comes from decreased rooftop diffraction loss. Section IV shows there is typically 8–12 dB additional path loss when a receiver at a height of 1.5 m is raised to 5.5 m and becomes shadowed by a tree. Close-in shadowing by a house, on the other hand, exhibits anywhere from 2–13 dB additional path loss when the receiver is *lowered* from a height of 5.5–1.5 m.

2) Propagation at Different Floors: All of the homes studied had at least two floors. There was no significant difference in path loss measurements between 2nd and 1st floor measurements. While the second floor may have benefited from less rooftop diffraction loss from neighboring homes, it also *lost* more power from treetop foliage attenuation.

Not surprisingly, the path loss was noticeably greater in basement areas. Typically, each basement showed an additional 6–10 dB of path loss when compared to measurements on the first floor of the home. Both basements measured were unfinished and at least partially underground.

3) Effect of Windows on Penetration: In general, windows provide a low-attenuation path for radio waves to enter a home. However, the majority of all windows in the homes studied were covered by metal screens, which appeared to attenuate propagation. The exceptions were rooms with sliding glass doors. Most sliding glass doors provide a large aperture which is never more than half-covered by a metal screen. Rooms with sliding glass doors showed consistent decreases in path loss throughout the measurement campaign.

4) Effect of Insulation on Penetration: Insulation can play an important part in radio wave penetration since it fills every exterior wall of a home. The highest penetration loss was observed in the Tranter home, the only house with foil-backed insulation. The Rappaport home, a comparable brick house with paper-backed insulation, and the Woerner home, a wood siding house with paper-backed insulation, exhibited less penetration loss. Measurements indicate that foil-backed insulation may add as much as 4 dB to the penetration loss. This dependence on insulation type suggests that the transmission of electromagnetic waves through solid walls is an important mode of home penetration.

5) Tree Effects: Deciduous trees, such as beeches or maples, can be potent shadowers at 5.85 GHz. The wavelength at 5.85 GHz is 5 cm—less than the largest dimension of most leaves. Tree shadowing becomes critical in older neighborhoods, where the canopy is thick and developed and concentrated at rooftop level. In many cases, it is easier to propagate *underneath* the canopy to ground level receivers. This behavior suggests that deciduous trees appear to be "floating masses" and typically introduce 10–13 dB of loss in excess of free space path loss.

Thick stands of coniferous trees, such as pines, attenuate a propagating radio wave at 5.85 GHz every bit as much as their deciduous counterparts. Unless intentionally pruned, pine trees grow much thicker at the base than leaf-bearing trees. The measurement results show comparable loss in excess of free space at all receiver heights with typical values ranging from 11 to 16 dB.

IV. Data Analysis

The following section presents general analysis of the measured path loss data. This includes regression models for

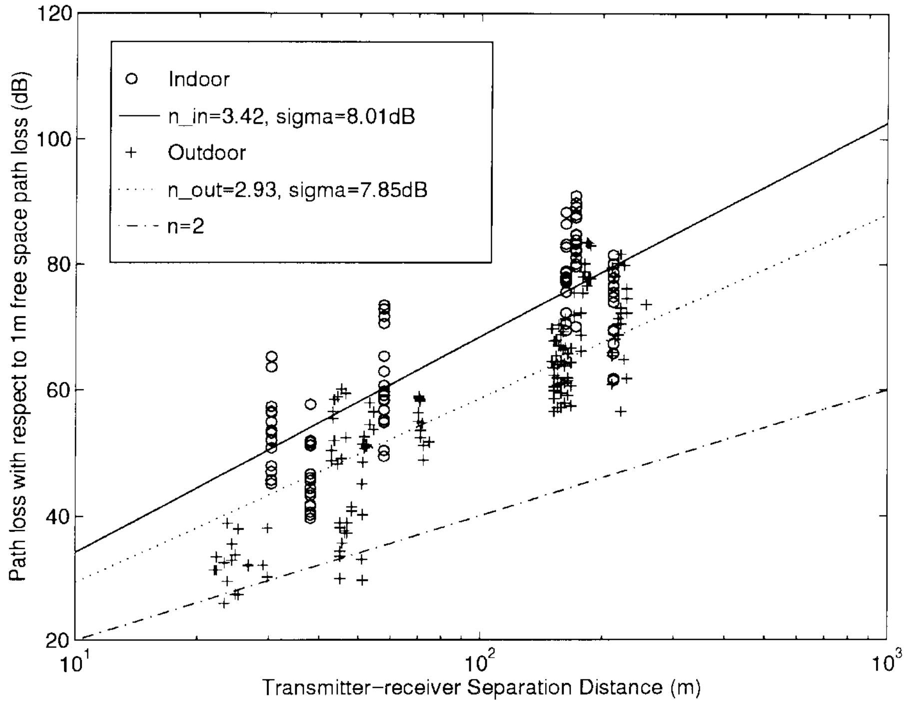


Fig. 7. Path loss scatter plot for all the residential measurement data (not including data from tree lines).

different transmitter and receiver configurations, average shadowing effects by houses and trees, and aggregate penetration loss into homes.

Each path loss value reported in this paper has been calculated from the linear average of hundreds of local area power samples (see Section II). For comparison, several tables that contain *sets* of path loss values provide both a linear average and a dB average of the path loss measurements. A linear average is calculated by first converting the path loss values from the dB scale to an absolute value. The mean of the absolute path loss is computed and converted back to a dB value by taking $10\log_{10}(\,)$, resulting in the linear average. A dB average is computed as the mean of the individual dB measured values without conversion to the absolute scale. The dB average tends to deemphasize the large variations from the mean, whereas a linear average may be heavily skewed by one or two extreme values. Both approaches are comparable when only small variations exist in the averaged data, as is the case for most of our local area path loss values.

A. Path Loss Exponents

Path loss can be described by the distance-dependent path loss model

$$\overline{PL}(d)\ [\text{dB}] = \text{PL}(d_0)\ [\text{dB}] + 10n\log_{10}\left(\frac{d}{d_0}\right) \tag{4}$$

where $\overline{PL}(d)$ is the average path loss value in dB at a TR separation of d, $\text{PL}(d_0)$ is the path loss in dB at a reference distance $d_0 = 1$ m, and n is the path loss exponent that characterizes how fast the path loss increases with increasing TR separation [13]. For free space propagation, n equals 2. Obstructions between the transmitter and receiver as well as multipath propagation change the n value in practice.

Fig. 7 presents a path loss scatter plot for all indoor and outdoor measurement data. In this scatter plot, all house data are processed together. Linear regression using a minimum mean square error (MMSE) criterion is used to estimate n for all the indoor and outdoor measurements at the residential homes. The path loss exponent, n, is found to be 3.4 for measurements inside the home and 2.9 for measurements made just outside the home. The standard deviation is 8.0 and 7.9 dB, respectively, for outdoor and indoor measurement data in Fig. 7. Notice that the value of n increases as the receiver goes from outdoor to indoor environments due to penetration loss.

Table II summarizes the MMSE path loss exponent and standard deviation for the variety of transmitter–receiver configurations measured in the experiment and provides specific models for each of the measured houses. For both indoor and outdoor locations, the level or height of the receiver has *no statistically significant effect on the path loss exponent.*

B. House Shadowing

Some of the houses were measured with receiver locations on both the transmitter and shadowed sides of the house. The effects of close-in house shadowing (excess loss induced by a receiver on the side of the house opposite the transmitter compared to a receiver on the same side of the house as the transmitter) were studied in this configuration by comparing the average path loss on both sides of the home. Table III lists the differences in dB between the linearly averaged path loss on the transmitter and shadowed sides of a house for two different receiver heights. For example, the linear average of path loss w.r.t. 1 m FS on the back side of the Rappaport home with 150 m TR separation is 65.9 dB for the 5.5-m-height receivers. Along the front, with the house

TABLE II
SUMMARY OF PATH LOSS EXPONENTS FOR VARIOUS TRANSMITTER-RECEIVER CONFIGURATIONS AT 5.85 GHz USING 5.5 m TRANSMITTER HEIGHT.

TR Configuration	n	σ (dB)	# of Meas. Locations	# of Homes
Indoor				
Overall	3.4	8.0	96	3
First Floor	3.5	8.3	58	3
Second Floor	3.3	7.3	38	3
Outdoor				
Overall	2.9	7.9	147	3
1.5m	2.9	9.0	73	3
5.5m	3.0	6.4	74	3
Rappaport				
First Floor	3.5	9.7	23	1
Second Floor	3.5	7.4	10	1
1.5m	3.1	10.2	26	1
5.5m	3.0	6.5	27	1
Woerner				
First Floor	3.2	6.2	8	1
Second Floor	3.3	7.7	22	1
1.5m	2.9	8.2	22	1
5.5m	3.1	6.2	20	1
Tranter				
First Floor	3.6	6.9	8	1
Second Floor	3.4	3.1	27	1
1.5m	2.7	6.4	26	1
5.5m	2.8	5.3	26	1

TABLE III
ATTENUATION (IN dB) FOR CLOSE-IN SHADOWING OF A SINGLE HOUSE AND AGGREGATE PENETRATION LOSS (APL) VALUES FOR ALL HOMES AT 5.85 GHz USING 5.5 m TRANSMITTER HEIGHT. N/A DENOTES LOCATIONS THAT WERE NOT MEASURED FOR SHADOWING LOSS WITH EXTERNAL RECEIVERS.

		Shadowing Loss		
Home	TR sep	5.5m RX (dB)	1.5m RX (dB)	APL (dB)
Rappaport	30m	19.1	23.2	13.3
	150m	10.8	11.9	16.4
Woerner	30m	14.1	27.8	13.1
	210m	N/A	N/A	7.2
Tranter	48m	17.2	19.0	21.1
	160m	N/A	N/A	15.3
Linear Average		16.3	23.6	16.3
dB Average		15.3	20.5	14.4

shadowing the receivers, the linear average is 76.7 dB. The difference between the two path loss values, 10.8 dB, estimates the effective loss of close-in shadowing by the Rappaport house. The measurement locations for the far transmitters at the Tranter and Woerner homes did not permit house shadowing calculations.

The linear and dB average of all close-in, single-house shadowing loss are shown at the bottom of Table III for each receiver height. Clearly there is a 5–6 dB advantage to using a tall receiver at a location shadowed by a house. Rooftop diffraction gives every shadowed 5.5 m receiver additional power over its 1.5 m counterpart in Table III.

C. Tree Line Shadowing

The coniferous stand of trees exhibited an attenuation of 16.5 dB at a height of 5.5 m and an attenuation of 11.5 dB at a height of 1.5 m. The deciduous stand of trees showed an attenuation of 12.8 dB at a height of 5.5 m and an attenuation of 4.4 dB at 1.5 m. Each attenuation is calculated as the loss in received signal power when moving from the front to the back of the tree line, in addition to the free space path loss. It is computed from the linearly averaged path loss values on each side of the tree line. The stands of trees can be treated as partitions of attenuation which can be applied to many of the partition-based models outlined in later sections.

D. Aggregate Penetration Loss (APL)

Aggregate penetration loss (APL) is defined by (3) as the ratio of the linear averages of outdoor power to indoor power for a given transmitter location. The averaged indoor power is taken over all of the indoor measured points. The averaged outdoor power is taken over measured locations on the side of the house *closest* to the transmitter to *avoid house shadowing effects* [8]. Received data for both 1.5- and 5.5-m high antennas are used.

Table III shows all of the aggregate penetration loss values for the homes studied. The average value of 16.3 dB compares favorably to the median value of 16.1 dB obtained by Aguirre *et al.* at the same frequency [8]. Note that APL represents a gross average outdoor-to-indoor loss for all rooms inside the home. It is important to note that APL is different than the loss in excess of free space due only to the exterior wall, which is explored in Section V.

V. PARTITION-DEPENDENT PROPAGATION ANALYSIS

In propagation analysis, the path loss exponent n that minimizes the standard deviation is useful for gaining quick insight into the general propagation at 5.85 GHz. These methods often lead to large, unacceptable standard deviations for prediction at specific locations. To decrease the standard deviation for a prediction and extract useful propagation information about the site, a more comprehensive propagation model is needed [15], [16].

A. Least-Squares Formulation

Finer propagation models use *partition-dependent attenuation factors,* which assume $n = 2$ free space path loss with additional path loss based on the objects that lie between the transmitter and the receiver [17], [18]. For the outdoor-to-indoor propagation environment, these objects may be trees, wooded patches, house exteriors, or series of plasterboard walls. The path loss with respect to 1 m free space at any given point is described by the equation

$$\mathrm{PL}(d) = 20\log_{10}(d) + a \times X_a + b \times X_b \cdots \tag{5}$$

where a, b, etc., are the quantities of each partition type between the receiver and transmitter and X_a, X_b, etc., are their respective attenuation values in dB [18].

For measured data at a known site, the unknowns in (5) are the individual attenuation factors X_a, X_b, etc.. One method to calculate the attenuation factors is to minimize the mean-square error of measured versus predicted data. If P_i represents the path loss w.r.t. 1 m FS measured at the ith location, then N measurements will result in this system of equations:

$$P_1 = 20\log_{10}(d_1) + a_1 \times X_a + b_1 \times X_b \cdots \tag{6}$$

$$P_2 = 20\log_{10}(d_2) + a_2 \times X_a + b_2 \times X_b \cdots$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$P_N = 20\log_{10}(d_N) + a_N \times X_a + b_N \times X_b \cdots \qquad (7)$$

This system can be written more elegantly in matrix notation:

$$A\vec{x} = \vec{p} - 20\log_{10}(\vec{d}) \qquad (8)$$

where

$$\vec{p} = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix}, \quad \vec{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix}, \quad \vec{x} = \begin{bmatrix} X_a \\ X_b \\ \vdots \\ X_z \end{bmatrix},$$

and

$$A = \begin{bmatrix} a_1 & b_1 & \cdots & z_1 \\ a_2 & b_2 & \cdots & z_2 \\ \vdots & \vdots & \ddots & \vdots \\ a_N & b_N & \cdots & z_N \end{bmatrix}. \qquad (9)$$

The vector $\vec{x}$ is the unknown quantity in (8) but cannot be solved immediately because there are more measured points in $\vec{p}$ than unknowns in $\vec{x}$. Multiplying both sides by the transpose of A yields a tractable linear matrix equation:

$$A^T A\vec{x} = A^T[\vec{p} - 20\log_{10}(\vec{d})]. \qquad (10)$$

Equation (10) represents a system called the *normal equations* [19]. Solving the normal equations—taking the proper precautions against ill-conditioned matrices—simultaneously minimizes the mean-squared error with respect to all values in $\vec{x}$. Since these data represent large-scale path loss, which tends to a log-normal distribution, the mean-squared error criterion, as well as mean and standard deviation comparisons, are based on the dB values of path loss. The resulting attenuation values produce predictions that match measurements with a near-zero mean and a small standard deviation error.

B. Example of Attenuation Factor Calculation at Rappaport Home

This subsection presents a sample attenuation factor calculation using data for the 30 m transmitter at the Rappaport home. Attenuation in addition to ideal free space path loss for this environment is attributed to three types of objects: the small tree in the front yard, the exterior brick wall, and the interior plaster walls. By looking at the house site and floor plan (Fig. 3), the TR separation and quantity of each partition between the transmitter and receiver were recorded in Table IV.

Consider the receiver location in Rear Bedroom 1. The front yard tree, the exterior brick wall, and one plaster wall lie between the indoor receiver and the outdoor transmitter. At the row corresponding to this measurement, a 1 is placed in each column in Table IV, since one of each obstruction type lies between the transmitter and receiver. This procedure repeats for all of the measured locations. Notice that the back side outdoor receiver locations were omitted from the calculation; the preliminary data in Section III showed that transmission *through* the house was not as important as outdoor multipath scattering. Including these house-shadowed locations in the calculation would distort the physical meaning of the attenuation values.

TABLE IV
PARTITION FREQUENCY, DISTANCE, AND 5.85 GHz PATH LOSS .W.R.T. 1 m FREE SPACE FOR THE 30 m TRANSMITTER AT THE RAPPAPORT HOME USING AN OUTDOOR 5.5 m TRANSMITTER HEIGHT.

Location	Small Tree	Brick Ext.	Int. Wall	TR Sep. (m)	PL (dB)
1	1	0	0	22	31.3
Outdoors 2	1	0	0	22	33.4
Front Side 3	0	0	0	23	32.4
5.5m height 4	0	0	0	25	33.7
5	0	0	0	27	31.8
6	0	0	0	29	32.0
1	1	0	0	22	31.3
Outdoors 2	0	0	0	23	25.9
Front Side 3	0	0	0	25	27.3
1.5m height 4	0	0	0	27	32.1
5	0	0	0	29	32.0
1st Floor					
Living Room	1	1	0	32	40.1
Front Hall	0	1	0	30	39.6
Office	0	1	0	32	41.6
Stairs	0	1	0	31	45.8
Bathroom	0	1	1	35	46.7
Laundry	0	1	1	35	43.7
Kitchen	0	1	2	38	51.2
Dining Room	1	1	0	38	42.5
Family Room	0	1	2	41	51.9
2nd Floor					
Front Bed	1	1	0	32	44.4
Rear Bed 1	1	1	1	38	51.2
Bathroom	0	1	2	38	51.7
Rear Bed 2	0	1	1	42	46.6
Master Bed	0	1	0	34	40.6
	A			$\vec{d}$	$\vec{p}$

The calculation results in attenuation values of 3.5 dB for the small deciduous tree outside, 4.7 dB for the interior plaster walls, and 10.2 dB for the brick exterior. Once all of the $\vec{x}$ values are solved, the mean square error (or variance) of the system can be calculated by

$$\sigma^2 = \frac{1}{N}|A\vec{x} + 20\log_{10}(\vec{d}) - \vec{p}|^2 \qquad (11)$$

A comparison of the optimized predictions to measurements results in a mean error of 0 and a standard deviation of 2.6 dB. The low standard deviation is intuitive since the procedure minimizes mean-square error between measured and predicted data.

C. Summary of Partition Values

A summary of all partition-based model results is shown in Table V. The values can be used by any of the partition-based models described in the next section. The attenuation values in Table V represent loss in excess of free space, which is the loss induced by the obstruction in addition to the ideal free space path loss ($n = 2$). Each overall attenuation value is a dB average of previously calculated partition-based attenuations.

TABLE V
SUMMARY OF ALL ATTENUATION VALUES (LOSS IN EXCESS OF FREE SPACE) AT 5.85 GHz WITH OUTDOOR TRANSMITTERS AT 5.5 m HEIGHT ABOVE GROUND.

Partition	Loss (dB)	σ (dB)	$\Delta\sigma$ (dB)
Home exteriors			
Brick†	12.5		
Rappaport Home, 30m TX	10.2	2.6	3.1
Rappaport Home, 150m TX	14.8	2.1	4.5
Brick*	16.4		
Tranter Home, 48m TX	16.1	3.4	3.9
Tranter Home, 160m TX	16.6	3.2	4.5
Wood Siding†	8.8	3.5	0.9
Cinderblock wall	22	3.5	6.4
Subterranean basement	31		
Tranter Home, 48m TX	34	3.4	3.7
Tranter Home, 160m TX	29	3.2	2.7
Home Interior			
Plaster walls	4.7		
Rappaport Home, 30m TX	4.7	2.6	1.1
Rappaport Home, 150m TX	4.6	2.1	0.8
Plasterboard walls	4.6		
Tranter Home, 48m TX	3.6	3.4	1.9
Woerner Home, 30m TX	5.6	3.5	1.2
Foliage Shadow			
Small deciduous tree	3.5	2.6	0.5
Large deciduous tree	10.7		
Woerner Home, 30m TX	9.0	3.5	1.7
Woerner Home, 210m TX	12.3	3.3	2.4
tree line, 5.5m RX	12.4	–	–
Large coniferous tree	13.7		
tree line, 5.5m RX	16.4	–	–
tree line, 1.5m RX	11.0	–	–

† paper-backed insulation
* foil-backed insulation

For example, the attenuation of 4.7 dB listed under *Plaster walls* is an average of the attenuations calculated for the two different TR separations used at the Rappaport home. Note, however, the consistency of results for all plasterboard or plaster walls calculated from measurements. All attenuation values lie between 3.6 and 5.6 dB, implying that the typical value of 4.7 dB may be a near-optimal value for interior walls in *any* home.

The right-hand column of Table V, labeled $\Delta\sigma$, represents the change in optimal standard deviation between measured versus predicted values for a model *with* and *without* the specified partition. For example, the model in the previous section included a partition for the brick wall of the Rappaport home and resulted in a measured versus predicted standard deviation error of 2.6 dB. If the partition for the brick wall was removed from the model and new optimal partition values were calculated, then the standard deviation error would increase by 3.1 dB, according to Table V. The value $\Delta\sigma$ roughly gauges the importance of the specific partition to the model.

VI. SUMMARY OF MODELS FOR PROPAGATION PREDICTION

The data extracted from the previous two sections are useful for residential outdoor-to-indoor link design and interference prediction. Several models are presented in this section which explain how to use the information gathered in this paper. Different models emphasize different aspects of propagation. For maximum utility, it is important to know the tradeoffs of each model.

A. Path Loss Exponent Models

The simplest method of propagation prediction is the path loss exponent model, given in (4). This method may use different path loss exponents for outdoor or outdoor-to-indoor propagation to predict the mean received signal strengths. Actual path loss tends to be log-normally distributed around the predicted path loss [17]. Values for the path loss exponent and standard deviation are given in Table II. This method only requires knowledge of TR separation and is meant for rough estimates of signal strength.

B. Path Loss Exponent Models With Aggregate Penetration Loss

Adding penetration loss into the path loss exponent model increases its accuracy for outdoor-to-indoor propagation. In this model, the outdoor n value is used to estimate received signal strength outside the home. An *aggregate penetration loss* is added to the outdoor result to obtain the indoor received power:

$$P_R = P_T + G_T + G_R + 20\log_{10}\left[\frac{1}{4\pi}\left(\frac{\lambda}{1\text{ m}}\right)\right] - 10n_{\text{out}}\log_{10}\left(\frac{d}{1\text{ m}}\right) - \text{APL} \quad (12)$$

The aggregate penetration loss, APL, is chosen from Table III based on the house exterior.

Aggregate penetration loss differs from the penetration loss defined by the partition-based model. APL represents an average difference between the indoor and outdoor path loss, regardless of the location inside the house, and does not take into account the specific number of walls or height above ground. The partition-based penetration loss is defined as the path loss differences between two locations that lie on the immediate inside and outside of the exterior wall.

C. Partition-Based Outdoor-to-Indoor Model

The error (i.e., standard deviation) of path loss using exponent models for outdoor-to-indoor propagation may be too great for widespread neighborhood deployment of a wireless network. A pseudodeterministic method uses the partition-based path loss model given by

$$P_R = P_T + G_T + G_R + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) - \sum_{i=1}^{N} X_i \quad (13)$$

where X_i is the attenuation value (chosen from Table V) of the ith obstruction intersected by a line drawn from the transmitter to the receiver point. An outdoor obstruction may be a deciduous or coniferous tree, a section of terrain, or a house. An indoor obstruction is usually a wall. This model can easily extend to three dimensions by taking into account the high and low blocking of trees.

Based on this work, the partition-based outdoor-to-indoor model works well for TR separations less than 50 m and for more distant transmitters, provided there are few scatterers in the nearby area. If the number of nearby scatterers is high, however, multipath penetration begins to dominate and the partition-based model loses its physical significance. This also happens when the model attempts to predict propagation *through* a house. While one drawback to the partition-based model is the need for a site-specific database with outdoor site features and indoor floor plans, it is possible that some applications might warrant such detail and additional accuracy [20].

D. Partition-Based Outdoor Model

The partition-based outdoor model is identical to the indoor-to-outdoor model, but ignores the internal layout of the individual houses. Instead, all of the partition losses used in Eq. (13) correspond to outdoor elements. A shadowing house can be assigned an attenuation from Table III based on the receiver height. If indoor path loss is desired, aggregate penetration loss values from Table III may be added to the outdoor predictions. The partition-based outdoor model only requires knowledge of the outdoor environment and can estimate signal levels in the shadow of buildings. Otherwise, it faces some of the same difficulties as the outdoor-to-indoor partition-based model.

VII. CONCLUSION

This paper has presented the results of path loss and building penetration loss measurements in residential areas and homes. Detailed measurements were performed in the 5.85 GHz NII band for three typical middle- to upper-middle-class houses and for deciduous and coniferous stands of trees. Specific effects of foliage, house shadowing, TR separation, and receiver height were quantified for outdoor path loss in residential areas. This work also determined how exterior shadowing, house construction, and floor plan influence the penetration of radio waves into homes. Results show that, at 5.85 GHz, home penetration attenuates signals at an average of 14 dB, tree shadowing attenuates signals between 11 and 16 dB, and close-in house shadowing attenuates signals between 15 and 21 dB, depending on the height of the receive antenna.

Propagation models developed in Sections IV–VI may aid in the site planning and deployment of outdoor-to-indoor residential wireless NII systems. In particular, the partition-dependent models developed in Section V produce precise predictions with minimal calculation time—two excellent characteristics for incorporation into software-based site modeling tools. These models will be useful for the rapid deployment and link design for wireless local loops and internet access systems in residential neighborhoods.

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REFERENCES

[1] FCC, "Report and order for NII band allocation," *Tech. Rep. RM-8648 and RM-8653, Federal Communications Commission*, Jan. 9, 1997.
[2] R. O. LaMaire, A. Krishna, P. Bhagwat, and J. Panian, "Wireless LAN's and mobile networking: Standards and future directions," *IEEE Commun. Mag.*, vol. 34, pp. 86–94, Aug. 1996.
[3] D. M. J. Devasirvatham, R. R. Murray, H. W. Arnold, and D. C. Cox, "Four-frequency CW measurements in residential environments for personal communications," in *Proc. 3rd IEEE ICUPC*, Oct. 1994, pp. 140–144.
[4] R. Gahleitner and E. Bonek, "Radio wave penetration into urban buildings in small cells and microcells," in *Proc. IEEE 44th Veh. Technol. Conf.*, Stockholm, July 1994, pp. 887–891.
[5] W. J. Tanis, II, and G. J. Pilato, "Building penetration characteristics of 880 MHz and 1922 MHz radio waves," in *Proc. IEEE 43rd Veh. Technol. Conf.*, Secaucus, NJ, May 1993, pp. 206–209.
[6] A. F. de Toledo and A. M. D. Turkmani, "Propagation into and within buildings at 900, 1800, and 2300 MHz," in *Proc. IEEE 42nd Veh. Tech. Conf.*, Denver, CO, May 1992, vol. 2, pp. 633–635.
[7] E. H. Walker, "Penetration of radio signals into buildings in the cellular radio environment," *Bell Syst. Tech. J.*, vol. 62, no. 9, pp. 2719–2734, Nov. 1983.
[8] S. Aguirre, L. H. Loew, and L. Yeh, "Radio propagation into buildings at 912, 1920, and 5990 MHz using microcells," in *Proc. 3rd IEEE ICUPC*, Oct. 1994, pp. 129–134.
[9] K. Siwiak, *Radio Wave Propagation and Antennas for Personal Communications*. New York: Artech House, 1995.
[10] P. Nobles, D. Ashworth, and F. Halsall, "Propagation measurements in an indoor radio environment at 2, 5, and 17 GHz," in *Proc. IEE Colloq. 'High Bit Rate UHF/SHF Channel Sounders—Technol. Meas.'*, London, U.K., pp. 4/1–4/6, 1993.
[11] D. M. J. Devasirvatham, M. J. Krain, D. A. Rappaport, and C. Banerjee, "Radio propagation measurements at 850 MHz, 1.7 GHz and 4 GHz inside two dissimilar office buildings," *IEE Electron. Lett.*, vol. 26, no. 7, pp. 445–447, Mar. 1990.
[12] G. D. Durgin, H. Xu, and T. S. Rappaport, "Path loss and penetration loss measurements in and around homes and trees at 5.85 GHz," *Tech. Rep. MPRG TR-97-10*, Virginia Tech, June 1997.
[13] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice-Hall Inc., New Jersey, 1996.
[14] ——, "Tunable discone antenna," *U.S. Patent 4851859*, July 25, 1989.
[15] M. A. Panjwani, A. L. Abbot, and T. S. Rappaport, "Interactive computation of coverage regions for wireless communication in multifloored indoor environments," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 420–430, Apr. 1996.
[16] R. D. Murch, J. H. M. Sau, and K. W. Cheung, "Improved empirical modeling for indoor propagation prediction," in *Proc. IEEE 45th Veh. Technol. Conf.*, Chicago, IL, July 1995, pp. 439–443.
[17] S. Y. Seidel and T. S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multi-floored buildings," *IEEE Trans. Antennas Propagat.*, vol. 40, pp. 207–217, Feb. 1992.
[18] R. R. Skidmore, T. S. Rappaport, and A. L. Abbot, "Interactive coverage region and system design simulation for wireless communication systems in multifloored indoor environments: SMT plus," in *ICUPC'96 Conf. Rec.*, Cambridge, MA, Sept. 1996, vol. 2, pp. 646–650.
[19] D. S. Watkins, *Fundamentals of Matrix Computations*. New York: Wiley, 1991.
[20] T. S. Rappaport and S. Sandhu, "Radio-wave propagation for emerging wireless personal-communications systems," *IEEE Antennas Propagat. Mag.*, vol. 36, pp. 14–24, Oct. 1994.
[21] C. A. Balanis, *Advanced Engineering Electromagnetics*. New York: Wiley, 1989.
[22] R. Kattenbach and H. Fruchting, "Wideband measurements of channel characteristics in deterministic indoor environment at 1.8 and 5.2 GHz," in *Proc. IEEE PIMRC*, vol. 3, pp. 1166–1170, 1995.
[23] A. Louzir, A. Aemamra, D. Harrison, and C. Howson, "Spatial characterization of single room indoor propagation at 5.8 GHz," in *IEEE Antennas Propagat. Soc. Int. Symp.—Dig.*, June 1995, vol. 1, pp. 518–521.
[24] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*. New York: Wiley, 1981.