THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 62, No. 9, November 1983
Printed in U.S.A.

Measurements of 800-MHz Radio Transmission Into Buildings With Metallic Walls

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(Manuscript received January 5, 1983)

In this paper we describe an experiment conducted to measure 800-MHz attenuation into buildings. This information is needed for refining the configuration and design of portable radiotelephone systems that will accommodate low-power portable sets. Signal levels have been measured in and around three small buildings and a house, using an instrumentation van with an erectable 27-foot-high antenna. These buildings and the house all have metallic materials in their walls and thus are expected to exhibit high attenuation. The van was parked at one location with respect to the three buildings, and at nine different locations, at distances ranging from 400 feet to 1600 feet, from the house. We found that small-scale signal envelope variations are approximately Rayleigh distributed. For the house, large-scale distributions of the small-scale signal medians are approximately log-normal. Median signal levels outside the house decrease as $d^{-4.5}$, where d is the distance from the van. Inside the house, levels decrease as $d^{-3.9}$ for first-floor locations and as $d^{-3.0}$ for second-floor locations. Average signal levels at 1000 feet, relative to free space, are −12.5 dB outside, −18.5 dB for the first floor, −16.5 dB for the second floor, and −28.9 dB for the basement. Other statistics of the signal levels and of attenuation into the house are also given in the paper. Cross-polarization couplings of −10 dB to 0 dB were measured in and around the three small buildings. The small-scale signal medians inside the three buildings range from 2 dB above to 24 dB below the averages of the signal medians outside buildings.

I. INTRODUCTION

The attenuation of radio signals propagating into buildings has a significant effect on the performance of portable radiotelephone sys-

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tems.[1] Frequencies in the 800-MHz to 900-MHz range are good candidates for such systems. Most earlier propagation measurements at these frequencies in the shadowing and multipath environment around buildings were made for mobile radio systems.[2] Ranges for the mobile radio data are generally greater than one mile. Battery power limitations on portable systems will likely restrict such systems to ranges on the order of 1000 feet. Earlier measurements made in buildings are limited in scope,[3–6] are oriented towards lower frequencies,[7–11] or are directed toward high-power portable sets with ranges greater than one mile.

One important portable radiotelephone environment comprises suburban residential areas characterized by discrete houses and other small buildings with densities ranging from less than one house per acre to a few houses per acre. Houses and small buildings with metallic materials in their walls are expected to exhibit high extreme values of attenuation.

In the residential environment, fixed radio terminals that communicate with portable sets could be placed at convenient locations outside buildings. These fixed terminals will be referred to as Portable Radiotelephone Terminals or PORTs.

We have implemented an experiment to provide 800-MHz attenuation information needed for refining the configuration and design of portable radiotelephone systems that will accommodate low-power portable sets. Measurements were made in and around three small buildings and a house. The buildings and the house all have metallic materials in their walls. An instrumentation van was parked at different locations to simulate different PORTs with distances ranging from 200 to 1600 feet. A 27-foot-high erectable antenna on the van simulated an unobtrusive PORT antenna. A portable signal source was moved in and around a building and signal levels were received and recorded in the van.

Section II of this paper describes the instruments used and how measurements were taken. Section III summarizes building attenuations and cross-polarization couplings measured in the three small buildings. Section IV contains statistical descriptions of the building attenuation for the house.

II. THE MEASUREMENTS

2.1 Instrumentation

2.1.1 Signal source

The portable signal source is a modified 815-MHz* handie-talkie.

* The actual frequency of the measurements is 815 MHz; however, the statistical results are not sensitive to small changes in frequency. Therefore, when frequency is referred to relative to the measurements, it will be rounded to 800 MHz.

The transmitting antenna is a half-wavelength coaxial sleeve dipole attached to the top of the hand-held unit. The dc power is provided by a self-contained nickel cadmium battery through a voltage regulator. The regulator minimizes output power drift due to normal battery discharge. The transmitter output is 0.8 watt. The output varies less than 0.3 dB and 700 Hz over continuous one-hour periods that include ambient temperature changes of 0°C to 25°C.

2.1.2 Instrumentation van

The instrumentation van (movable PORT) is a modified motor home, containing a 5-kw ac generator. An uninterruptable power supply isolates the instrumentation from generator voltage fluctuations that otherwise could affect measurement accuracy. The van is shown in Fig. 1.

Two 27-foot antenna masts are installed in pivoting mounts so they can be stored horizontally for transport and can be erected at the test site. They are 14.2 feet apart and are adjusted to vertical using built-in bubble levels. An 815-MHz collinear receiving antenna is mounted on one mast. A bracket on the other mast holds the 815-MHz signal source to provide a reference signal for calibrating the receiver. The centers of the two antennas are at the same height when erected.

2.1.3 Measuring receiver

The measuring receiver is an 815-MHz frequency-modulated (FM) communications receiver, modified to detect the received signal envelope. The receiving antenna is a collinear array (four dipole elements, 5.8-dB gain over dipole, 18-degree vertical beam width) mounted vertically at the top of the tilt-over mast on the instrumentation van. In the receiver modification, an 11.7-MHz intermediate frequency (IF) output is extracted before the limiter, down-converted to 13 kHz, bandpass-filtered (BW_{3dB} = 8 KHz), and linearly detected. The modified receiver has a −123 dBm sensitivity for 0 dB output s/n from the linear envelope detector and a 45-dB measuring range between levels 6 dB above the noise level and 3 dB below saturation. The measuring range is linear within ±1 dB over a 35-dB range at high signal levels. The entire receiver is enclosed in a sealed brass box to provide radio frequency (RF) isolation. A variable RF attenuator reduces the input signal in 1-dB steps to prevent overloading of the receiver.

2.1.4 Data acquisition

The analog receiver output drives a 12-bit-resolution digital storage oscilloscope and an integral 5-1/4-inch flexible disc drive for data storage. The oscilloscope is set to record 2048 samples in a 20-second measurement period. Up to 16 tracks of 2048 samples each can be

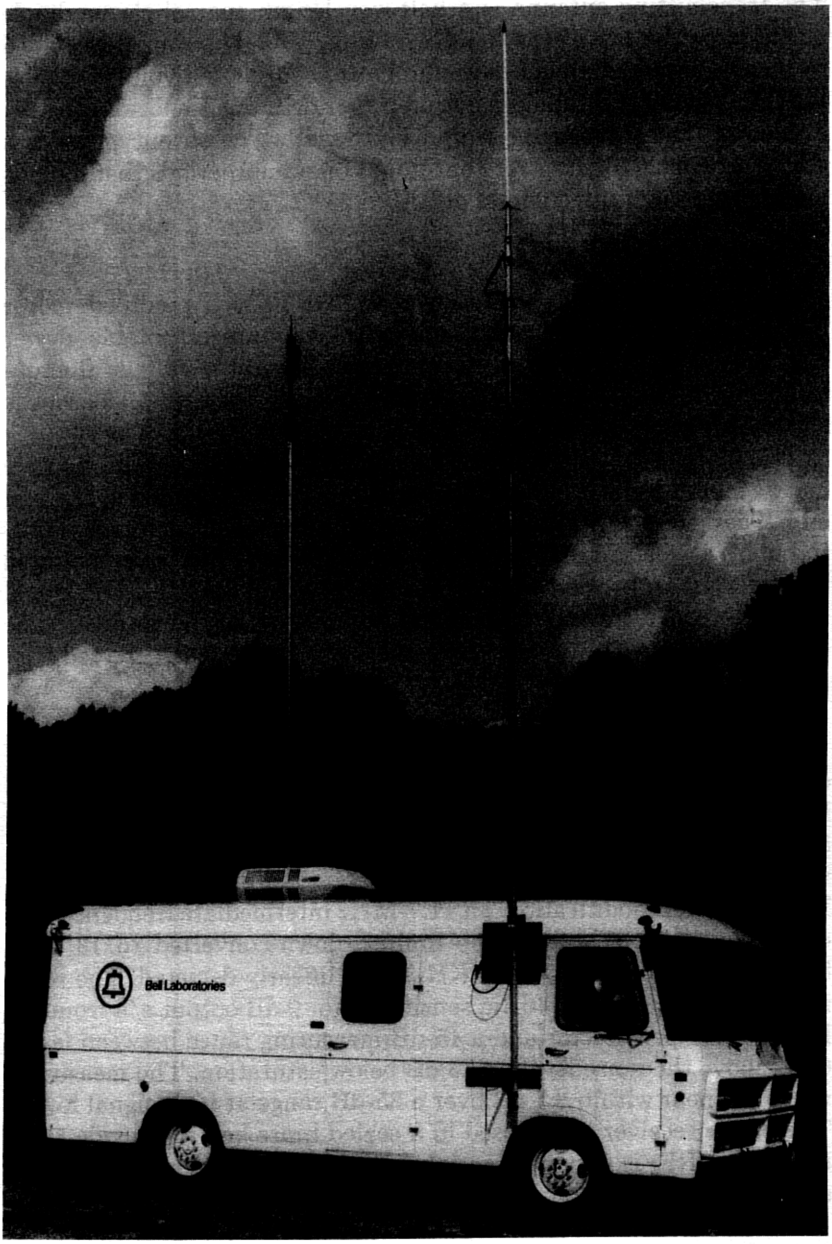

Fig. 1—The instrumentation van with the receiving antenna mast and the reference signal mast erected. The center of the four-element collinear receiving antenna is 27 feet above ground at the top of the mast mounted on the right side of the van near the front. The signal source is at the top of its mast mounted on the left side near the rear. The center of the signal-source dipole is also 27 feet above ground.

recorded on each disc. Data for each parked position of the van, i.e., one PORT location, are stored on a separate disc.

The recorded data are transferred to a desktop computer. At the time of transfer the following steps are performed:

1. Hand-recorded log information is appended to the signal strength data. The log information includes such items as the address of the house, the position of the van, the path azimuth, the path length, and the receiver input attenuator setting.

2. The data are scaled to convert the recorded signal voltages to dB relative to 0 dB at the reference location 14.2 feet from the receiving antenna. The scaling takes into account recorded dc offsets, recorded reference levels, and the receiver input attenuator settings.

3. Medians and cumulative distributions of signal level are calculated from the scaled data.

4. The scaled data are stored on flexible discs within the computer for further analysis.

2.2 Procedure

Van locations were selected using tax maps covering the immediate vicinity of the house. Points were chosen equally spaced in azimuth around the house for each of three radii at about 400, 800, and 1600 feet. Road layout and terrain irregularities influenced the final choices of vehicle placement. A single van location was used for the measurements in the other three small buildings.

Measurements were coordinated between the van and the measurement location over a 450-MHz voice link. The link comprises a 25-watt FM transceiver in the van and a 2-watt handie-talkie carried by the person making the measurements.

A typical procedure for measuring a building starts with the van parked at an appropriate position. The van location must be fairly level. If necessary, wooden ramps are put under wheels to aid in leveling. The portable transmitter is installed on its mast as a local reference source. The mast is erected and is plumbed to vertical. Similarly, the receiving antenna on the opposite side of the vehicle is erected and plumbed. Keeping both masts plumbed on the level van assures a fixed distance between the reference and receiving antennas for calibration purposes. The linear detector IF input is grounded, and the dc level is adjusted and recorded on a disc track. Next, the detector input is ungrounded and the receiver RF attenuator is adjusted so the RF reference level is within the receiver operating range. This level, which serves as a calibration reference at the fixed 14.2 foot distance, is then recorded.

The signal source is removed from the mast and taken to the building for signal level measurements. The unit is hand-held at arm's length, for a scan height of 4.5 feet.[6] At a selected location within the building, a 20-second raster scan is made by moving the transmitter in a horizontal plane at 2.5 ft/s.[6] The 4-foot square scanned area consists of 12 parallel linear scans separated by 4-inch increments. During the scan period 2048 data points are taken at 100 samples/s.

During the scanning period, the oscilloscope is monitored to see that signal amplitudes are within the receiver operating range. If not, the RF input attenuation is adjusted and the scan is repeated. The remaining locations within the building and immediately outside are similarly scanned and recorded. After the measurements are made, the transmitter is reinstalled on the reference mast, erected and plumbed, and the dc level and RF signal reference level are again recorded. The closure error between beginning and ending reference-level recordings is usually <0.5 dB. If the closure is >1 dB, the measurements are repeated. Such high closure error occasionally occurs when the transmitter battery has discharged below the regulation limit of the voltage regulator.

2.3 Received signal characteristics and attenuation definitions

Motion of the signal source through the 4-foot-square areas inside and outside of buildings results in small-scale signal variations. The variations are caused by multipath propagation.[2,6] Inside houses and in areas shadowed from the van, where propagation is dominated by reflection and scattering, the variations in the received signal envelope are approximately Rayleigh distributed (see Ref. 6 and Section IV of this paper). Received signal minima are separated on the order of one half wavelength.[6] The medians (or means) of these small-scale variations are approximately stationary over the small areas but the medians for areas in different rooms in a building can be significantly different. Thus, the signal statistics can be modeled as a combination of a small-scale, quasi-stationary process (multipath) superimposed on a large-scale process (shadowing). This model is like the models used for mobile radio propagation.[2,12]

Only a single parameter is needed to describe the small-scale Rayleigh-distributed signal variation. The median can be determined if somewhat over half of the samples are above the measurement threshold. The mean, however, will be biased by the receiver noise level unless significantly more than half the samples are above the threshold. Therefore, medians of received signal variations for the 4-ft-square areas are used to characterize the small-scale signal variations at different measurement locations. The lowest median signal measured was 44 dB above the receiver noise level for the data presented in Sections III and IV. The lowest median cross-polarized signal measured was 38 dB above the noise level.

Building attenuation for a location inside a building can be defined as the difference between the signal level at the location and a "representative" signal level outside the building. Both levels are taken to be small-scale medians, measured in decibels, relative to a common reference level.

There are at least two possibilities that could be used for the representative level outside. The first choice is to use the average level of the signal in which the building is immersed. This level can be approximated by taking the average of several median levels, in decibels, measured at different locations surrounding the building. This decibel averaging is appropriate for large-scale variations of the median that are log-normally distributed. Large-scale variations are shown in Section IV to be approximately log-normally distributed. This definition of representative level seems appropriate for system considerations because service would have to be provided all around the exterior of a building.

The second possible choice for a representative level is to use the level of the signal incident on the building from the PORT (or received at the PORT from the incident region, since reciprocity holds). The incident level can be determined readily when the PORT is in line-of-sight of the building and there is little multipath from surrounding buildings. This was the case for the measurements in Ref. 6. However, when there are many intervening buildings between the PORT and the subject building and there is considerable multipath from surrounding buildings, the signal level incident on the building is not easily defined. This second choice of representative level appears least appropriate at the longest distances where the shadowing and multipath are most significant. These are also the distances of most concern in system considerations.

In Section III, comparisons are made of attenuations determined using both choices for representative levels. However, the more appropriate average outside level is used for the statistics in Section IV.

III. ATTENUATIONS AND CROSS-POLARIZATION COUPLINGS FOR THREE BUILDINGS

3.1 Building descriptions

The first building, shown in Fig. 2, is 20 feet by 38 feet, of corrugated steel construction and mounted on a concrete platform. There are metal screened doors inside the main metal doors, and all of the nine windows are metal screened, with the exception of three in the rear. The building inside is a single large area and is about one-third filled with equipment.

The second building is shown in Fig. 3. It is 21.5 feet by 28 feet, is covered with aluminum siding and has one solid door and nine win-

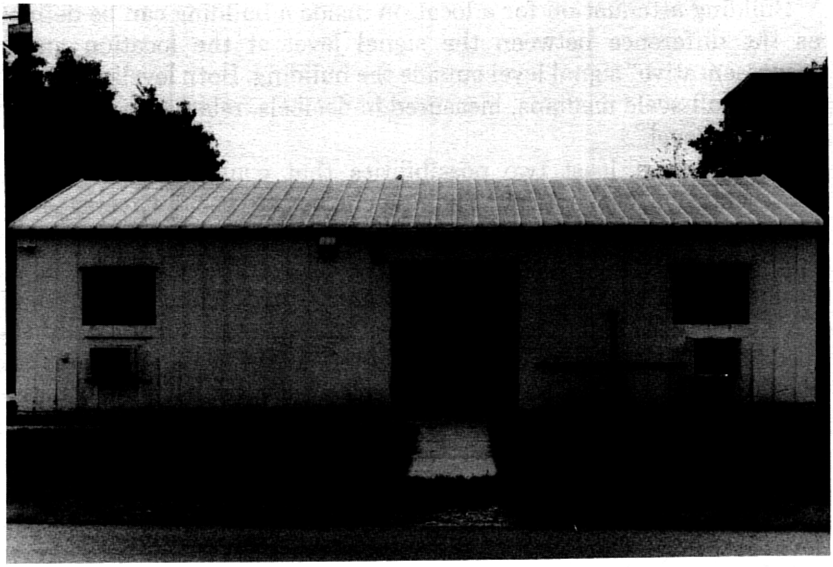

Fig. 2—Corrugated steel building on Crawford Hill as seen from the instrumentation van position.

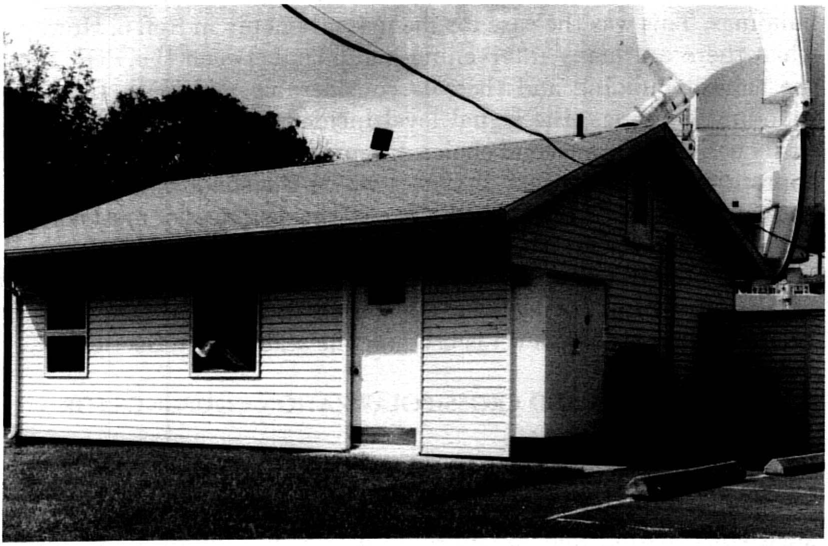

Fig. 3—Antenna Control building on Crawford Hill. The photograph was taken looking toward the building along the path from the van.

dows. All except the three largest windows are metal screened. The building interior is divided roughly in half on the long dimension and is about half filled with equipment.

The third building is of wooden construction, is 16 feet by 54 feet

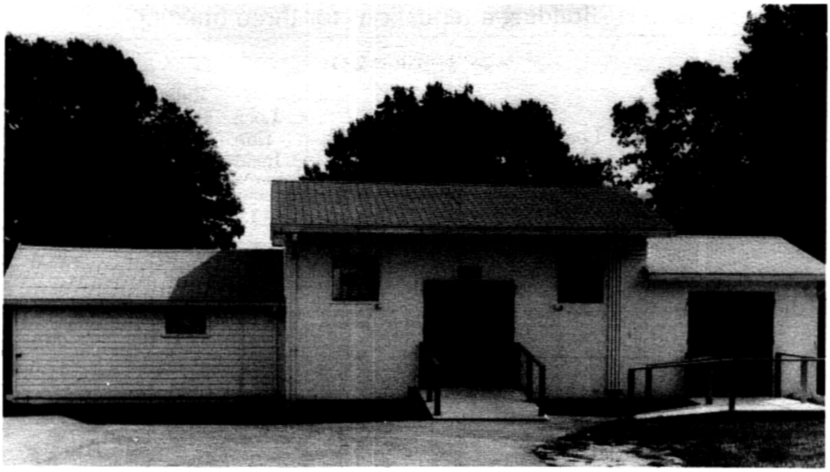

Fig. 4—Wooden building on Crawford Hill. The propagation path from the van was into the corner to the left in the photograph.

and contains vapor barrier foil insulation in the walls. This building, shown in Fig. 4, was empty. In front it has two doors with unscreened windows and three other unscreened windows. The room with double doors to the right in Fig. 4 is attached to an exterior wall. Measurements were not made in the attached room.

3.2 Attenuations for the three buildings

Signal levels were measured at four locations outside and two or three locations inside of the three buildings from a single van (PORT) location. These levels are summarized in Table I. The distances indicated in the table (i.e., 225 feet, 330 feet, and 845 feet) are the path length from the van antenna to the fronts of the buildings. The centers of the four outside locations for each building were about 5 to 10 feet away from the midpoints of the four sides of the building. The outside locations are numbered clockwise looking down on the building from above, starting with the side closest to the van. The small-scale median signal levels in decibels and the decibel average for the four outside locations are tabulated in the column labeled "Level/dB". These levels are relative to 0 dB at the signal level reference 14.2 feet from the van receiving antenna. The column labeled $1/r^2$/dB contains the signal levels that would occur in free space ($1/r^2$) at the distance of the measurement location. These levels are also relative to 0 dB at the 14.2 foot reference location. The $1/r^2$ level in the row labeled Avg. is the free space value at the building midpoint.

For the wooden building positioned at 330 feet from the van and for the building with metal siding positioned at 845 feet, the signal medians measured in front of the buildings are 1 to 2 dB greater than

Table I—Building attenuations for three buildings

Building Material	Location Outside	Level (dB)	$1/r^2$ (dB)	Location Inside	Relative to Average Attenuation (dB)	Relative to Incident Attenuation (dB)
All metal (225 ft)	Avg.	−29.0	−24.3			
	1	−24.9	−23.7	1	22.3	26.0
	2	−27.8	−24.1	2	18.7	22.3
	3	−36.2	−25.0	3	24.0	27.3
	4	−27.1	−24.1			
Metal siding (845 ft)	Avg.	−45.8	−35.7			
	1	−34.3	−35.6			
	2	−43.2	−35.5	1	9.0	20.4
	3	−49.5	−35.8	2	0.3	11.8
	4	−56.2	−35.8			
Wood (330 ft)	Avg.	−31.3	−27.5			
	1	−24.8	−26.8			
	2	−40.6	−27.7	1	−1.8	3.9
	3	−34.5	−27.8	2	2.6	9.0
	4	−25.4	−27.2			

the free-space values. The signal median in front of the all-metal building positioned at 225 feet is about 1 dB below the free-space value. These values are all consistent with the effects of a single reflection from the relatively flat dry ground between the van and the buildings.[13] The 27-foot van antenna height and a reflection coefficient phase angle of nearly 180 degrees, appropriate for small angles between the incident wave and smooth dry ground, yield signal maxima at distances above the ground of about 3 feet for 330 feet from the van and of about 8 feet for 845 feet from the van. For the same conditions, a minimum occurs about 4 feet above the ground at 225 feet from the van. Recall, the signal source is scanned about 4.5 feet above the ground. Therefore, at 330 feet, the scan is near a broad maximum that could be as much as 6 dB above free space if the ground were perfectly reflecting. The measured level at 330 feet is 2 dB above free space. At 845 feet, the scan should be down on the side of an 8-foot-high maximum. The measured level at 845 feet is 1.3 dB above free space. At 225 feet, the scan is near the first minimum above the ground. The measured level at 225 feet is 1.2 dB below free space.

The interior locations of the buildings are arbitrarily numbered in the column labeled "Location Inside". The column labeled "Relative to Average Attenuation in decibels" contains the differences between the median signal levels measured at the locations and the average of the four outside median levels for the building. Positive attenuation indicates the signal level inside is smaller than the average level outside.

Within a period of a few minutes, three separate measurements were made at Location 1 inside the metal-sided building. The spread of the resulting three medians was only ±0.5 dB around the average value listed in the table. Two separate measurements were made at Location 2 outside the wooden building. The resulting two medians were within ±0.3 dB of the average value listed. Thus, the measurement repeatability is good and is consistent with the ±0.5 dB standard deviation of the medians expected for the statistical fluctuation resulting from the limited number (≈150) of independent samples in a 4-foot-square area. Measurements were made at the same locations in and around the metal building on three different days that had different ground moisture conditions, etc. The three medians for each location were averaged and the difference was taken between the location average and the individual medians. The standard deviation of the differences was 1 dB.

The column labeled "Relative to Incident Attenuation in decibels" contains the differences between the median levels at the inside locations and the median level for the outside location that is closest to the van. These outside closest locations have the largest signal levels measured for their corresponding buildings. The outside level is corrected for free space ($1/r^2$) for the distance between the outside location and the inside location being considered. This is the second definition of building attenuation described in Section 2.3. This second definition of attenuation is essentially the same definition of building attenuation that was used in Ref. 6 for the same all-metal building listed first in Table I (the values in Ref. 6 were not corrected for $1/r^2$). The second definition attenuation values are within 1 or 2 dB of the values in Ref. 6 for Locations 1 and 3 inside the metal building. At Location 2, however, the attenuation in Table I is 6 dB less than the earlier value. Items inside the building have been rearranged since the earlier measurements, but no reason for such a large change is evident. The second definition attenuation into the all-metal building is greater than attenuation from the front (van side) to the back of that building (10.0 dB front-to-back attenuation including $1/r^2$ correction). The second definition attenuation into the other buildings is less than the front-to-back attenuation (21.7 dB for the metal-sided bulding and 15.0 dB for the wooden one). This suggests that the dominant mechanism for signal propagation behind the metal building is scatter and/or reflection from objects behind and to the side of that building rather than passage through the building itself. The dominant mechanism for propagation behind the other two buildings is not evident from these simple measurements since either passage through multiple walls or scatter and/or reflection is consistent with the result.

For Location 1 in the wooden building, the first definition attenuation is negative. This indicates that the median level inside at that location is greater than the average of the four outside medians. This is a reasonable situation because the signal levels at one side and at the back of that building are much lower than the signal level inside Location 1. This inside location has unscreened windows between it and the outside in the direction of the van. As mentioned in Section II, this first definition of attenuation seems more appropriate for use in system analysis since a system would have to serve the outside locations at all sides of a building. Of course, the distribution of outside levels relative to the outside average is also needed for a complete assessment of system performance.

The building attenuations by either definition are greatest for the all-metal building with metal screened windows. Since both of the other buildings have metal in their walls, attenuation into them probably depends strongly on coupling through the nonscreened windows.

3.3 Cross-polarization couplings for the three buildings

Cross-polarization coupling in multipath propagation is significant in reducing the effects of the random orientation of portable radiotelephones.[14] Cross-polarization coupling is defined as 20 $\log(E_x/E_t)$, where E_t is the average or median field magnitude of the polarization aligned with the transmitted polarization and E_x is the average (or median) field magnitude of the polarization orthogonal (crossed) to E_t. An indication of the cross-polarization coupling can be obtained by orienting the signal-source dipole antenna horizontally and scanning a measurement location with the dipole pointed towards the van (end-on orientation). The scan can be repeated with the dipole perpendicular to the direction of the van (broadside orientation).

If the multipath propagation were uniformly distributed in azimuth around the measurement location and were confined to a horizontal plane, horizontally polarized multipath would produce a median received signal level in a scanned horizontal dipole that was 3 dB less than the median that would be produced by the same multipath in a scanned loop oriented with its plane horizontal. The 3-dB decrease results from the nonuniform directivity pattern of the dipole in any plane containing the dipole. The median level received by the loop in the horizontally polarized multipath would be the same as the median level received by a scanned vertical dipole in vertically polarized multipath of the same average intensity. The multipath signal variations in all cases would be Rayleigh distributed.

For the measurement situation, equal median signal levels for end-on and broadside horizontal scans would be consistent with multipath having a uniform azimuthal distribution. Then, under the assumption that the propagation directions are confined to a horizontal plane, the cross-polarization coupling would be 3 dB greater than the signal difference $\Delta = L_v - L_h$, where L_v is the median level of the signal from a scan with the source oriented vertically, and L_h is the median level of the signal from a scan with the source oriented horizontally. The medians have a statistical fluctuation with a standard deviation on the order of ±0.5 dB because of the limited number of independent samples. Therefore, for differences between the medians of the two horizontal scans of one or two decibels, they can be taken as equal and their average value can be used to determine Δ.

Table II summarizes the cross-polarization measurements made in and around the three buildings. The medians of the end-on and broadside scans are tabulated in columns labeled End-on and Broadside. The values are in decibels relative to the median of the signal scan at the same location with the source antenna oriented vertically. That is, columns End-on and Broadside indicate Δ for end-on and broadside scans. The column labeled cross-polarization is 3 dB greater than the average Δ for end-on and broadside scans.

The locations inside the metal building would yield a small positive value for cross-polarization coupling. This probably indicates a breakdown of the assumption that the multipath propagation is confined to a horizontal plane, so the coupling is taken as 0 dB. If the multipath propagation were uniformly distributed in all directions in three dimensions, the orientation of the antenna would be irrelevant. Since the data show only a small bias towards stronger median signal for the vertical antenna in the metal building, an alternative assumption for that building would seem to be uniformly distributed multipath propagation in all directions in three dimensions.

The cross-polarization values in Table II are all greater than −10 dB and most are greater than −6 dB. Another point worth noting is that the locations with the lowest signal levels (greatest attenuation) also have the largest cross-polarization coupling with values greater than −6 dB and usually greater than −3 dB. Since cross-polarization

Table II—Cross-polarization coupling for three buildings

Building Material	Location Outside	Location Inside	Broadside Scan (dB)	End-on Scan (dB)	Cross-polarization (dB)
All metal	3	—	−9.3	−6.8	−5.0
	—	1	−1.0	+0.4	0
	—	2	−4.4	−0.9	0
	—	3	−1.0	—	0
Metal siding	2	—	−13.6	−10.6	−9.1
	4	—	−5.0	−6.2	−2.6
	—	1	−4.0	−4.5	−1.3
Wood	2	—	−5.7	—	−2.7
	—	1	−8.4	−10.2	−6.6

coupling increases the effectiveness of diversity in mitigating the effects of random portable set orientation and multipath propagation,[14] this trend could be significant in determining system performance.

IV. ATTENUATION STATISTICS FOR A HOUSE

4.1 House description

The house is a two-story colonial located on a level, one acre lot. It is in a newly developed area with a density of one house per acre and with relatively few trees. The house has an area of 2400 square feet, consisting of living room, dining room, kitchen, and den on the first floor, and four bedrooms on the second floor. It also has a basement and a two-car attached garage. It is constructed with wood, with aluminum siding on three sides and nonmetallic siding on the front. All exterior walls contain insulation faced with a metal foil vapor barrier.

4.2 Small-scale statistics

The cumulative distributions of the envelope variations of multipath propagation for a scan of a 4-foot-square location are expected to be Rayleigh.[2,6] Figure 5 shows the distributions measured at four locations in and around the house. A Rayleigh distribution is a straight line with the particular slope indicated on the figure. The distributions are good approximations to the Rayleigh distribution for many locations inside the house and behind the house from the van. A few locations on the same side of the house as the van and only 400 feet from it experience essentially line-of-sight propagation. At these few locations the signal variation is small and the envelope distribution significantly departs from Rayleigh, as indicated by the example plotted as squares on the figure. The medians of the four distributions on the figure have been normalized to 0 dB. The two distributions that show the greatest departure from Rayleigh were selected as the extremes that have the greatest and least spread in attenuation of any of the distributions in the data set.

4.3. Large-scale statistics of small-scale medians for outside locations

The open data points in Fig. 6 are the medians of the measured signal envelopes for the small-scale locations outside the house. The medians are plotted versus the distance between the van antenna and the location. The median levels are in decibels relative to the signal level at the van reference. The outside locations are in front of the midpoints of the four outside walls of the house. The decibel averages of the four locations for each van position are indicated by the solid data points.

A strong dependence of signal level on distance is evident in Fig. 6.

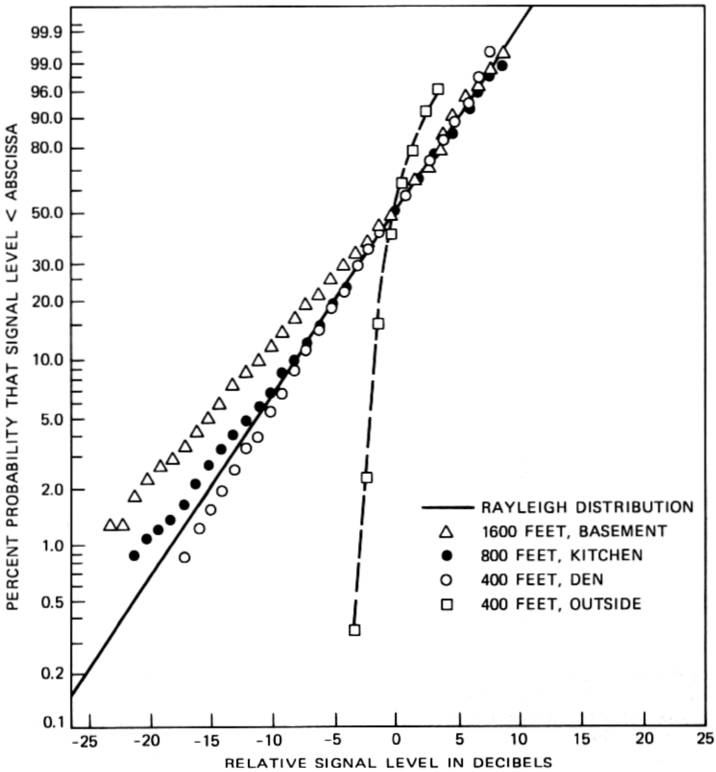

Fig. 5—Measured signal envelope distributions from four small (4-ft square) areas. On these coordinates, Rayleigh distributions are straight lines with the slope indicated. Distances between the van and the measurement location are indicated in the key.

The solid line is the linear-least-squares regression fit to the 36 medians from the four locations for each of the nine van positions. The least-squares regression fit to the averages of the four locations for each van position yields the same solid line. Signal level varies with distance as $d^{-4.5}$ for the solid line. The dotted line represents free-space propagation (d^{-2}) relative to 0 dB at the van reference. At 1000 feet from the van, the signal level represented by the solid line is 12.5 dB lower than the level would be in free space, i.e., the average excess attenuation over free space is 12.5 dB at 1000 feet. The distance dependence exponent is probably reliable only to several tenths because of the large spread in the data and the relatively small number of data points. The signal level outside was correlated to distance with a coefficient of 0.8.

The lower dashed line is the linear regression line for the data near 400 feet and 800 feet only. The upper dashed line is for the data near 800 feet and 1600 feet. The distance dependence for the 400-foot to

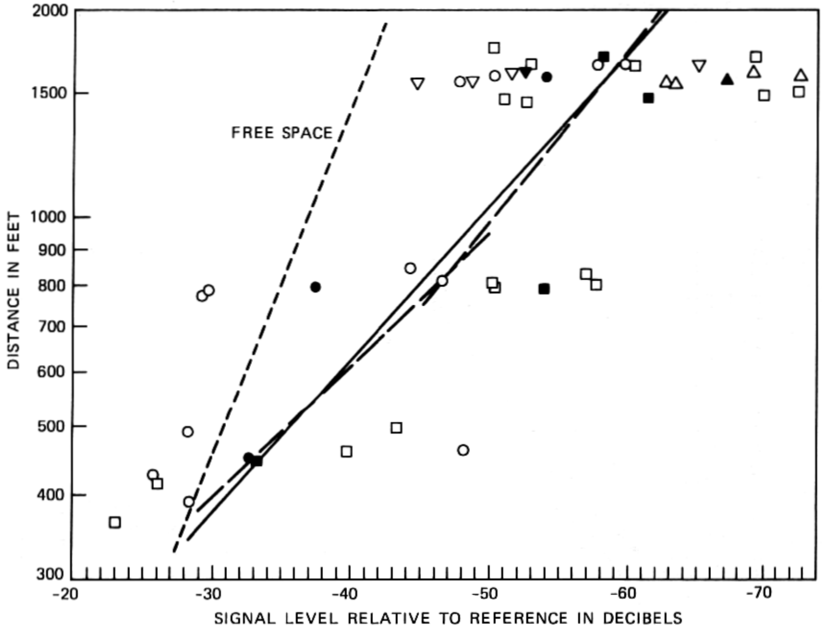

Fig. 6—Medians of the small-scale envelope variations for different outside measurement locations plotted versus distances between the locations and the van antenna. Open data points are medians for individual outside locations. Solid points are averages of the medians for the four measurement locations for each of the van locations. Points represented by the same symbols at nearly the same distance designate the four measurements associated with a particular van position. Signal levels are with respect to 0 dB at the signal reference located 14.2 feet from the van receiving antenna. The dotted line represents free-space propagation ($1/r^2$) relative to 0 dB at the signal reference. The solid line and the dashed lines are linear-least-squares regression lines, as discussed in the text.

800-foot distances is $d^{-5.1}$; the dependence for the 800-foot to 1600-foot distances is $d^{-4.1}$. Thus, the signal decreases faster with distance in the first several hundred feet than it does farther from the house. This is reasonable because, for the first few hundred feet, there are few obstructions along the path and propagation approaches line-of-sight. After several hundred feet, the number of intervening houses increases. Reflection from the ground also causes the signal to decrease more rapidly with distance than it does in free space.

The data points at 400 feet that are greater than free space values deserve comment. These points are from locations that are not shadowed from the van, i.e., they are within line-of-sight. A single ground reflection from a 27-foot-high antenna 400 feet away would produce a signal maximum about 4 feet above the ground. The signal maximum would be greater than the single-path free-space value. (It would be 6 dB greater for a reflection coefficient of unity.) The signal levels a few dB above free space are not unexpected 4.5 feet above the ground in locations that have large reflecting surfaces (walls of houses) nearby in addition to the ground.

Figure 7 is the cumulative distribution of the data from Fig. 6 after the distance dependence, $d^{-4.5}$, is removed. The calculated standard deviation for the data points is 9.0 dB. A straight line on the coordinates in Fig. 7 represents a log-normal distribution of signal level. The measured distribution is a reasonable approximation to a log-normal distribution.

4.4 Large-scale statistics of small-scale medians for inside locations

The distance dependences for the linear-least-square fits to the medians for measurement locations inside the house were somewhat different for the different floors of the house. The variation with distance was $d^{-3.9}$ for the first floor, $d^{-3.0}$ for the second floor, and $d^{-3.2}$ for the basement. Since only one location was measured in the basement, this value for the basement may contain considerable statistical

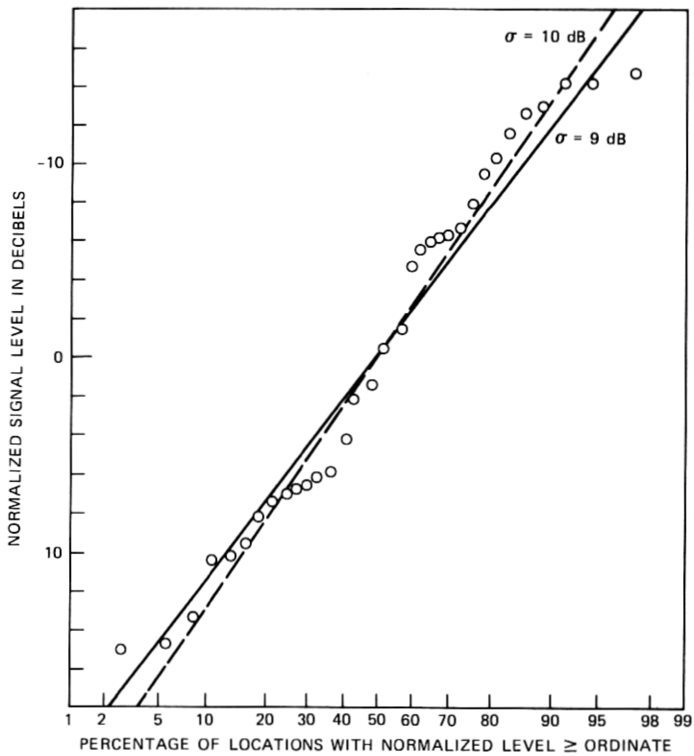

Fig. 7—Cumulative distribution of the medians of the small-scale envelope variations for outside locations after the values for the solid regression line in Fig. 6 are subtracted out. The solid line and the dashed line in this figure represent log-normal distributions with standard deviations of 9 dB and 10 dB, respectively.

error. The variation with distance for the composite set of data from the entire house (eight measurement locations inside the house and nine van positions) was $d^{-3.5}$. The less rapid decrease in signal level with distance for the second floor compared with the first floor is reasonable because the height of the second floor results in less attenuation from intervening houses. Since the decrease in signal level with distance is less rapid for the locations inside the house than outside, the apparent building attenuation will decrease somewhat with distance.

At 1000 feet, the excess attenuation over the free space values are 18.5 dB for the first floor, 16.5 dB for the second floor, 29.9 dB for the basement, and 19 dB for the composite data set for the entire house. The average building attenuation at 1000 feet, which is the difference between the linear regression values outside and inside, is then 6.0 dB for the first floor, 4.0 dB for the second floor, 16.4 dB for the basement, and 6.5 dB for the entire house.

4.5 Large-scale statistics of the building attenuation

The building attenuation considered in this section uses the first definition in Section 2.3, i.e., attenuation is with respect to the average of the four outside median levels. Building attenuations for the house are plotted versus distance in Fig. 8. The open data points represent data from the first floor; the solid data points and the points marked B represent data from the second floor and the basement, respectively. As noted in the previous section, the attenuation is weakly dependent on distance. Also, the attenuation into the basement is significantly greater than the attenuation into the other two floors. The linear regression lines are labeled on the figure for several combinations of the data. The variation of attenuation with distance is $d^{-0.6}$ for the first floor, $d^{-1.5}$ for the second floor, $d^{-1.4}$ for the basement, and $d^{-1.0}$ for the first and second floor together and for the entire house. The attenuation at 1000 feet taken from the regression lines is 6.0 dB for the first floor, 4.0 dB for the second floor, and 16.4 dB for the basement. These 1000-ft attenuation values are the same as those obtained in the previous section from the separate linear regression lines to the signal levels inside and outside.

Means (m) and standard deviations (σ) for several different groupings of the attenuation data are tabulated in Table III. It appears that most of the difference in the distance dependence for the first and second floors results from the different attenuation averages at 1600 feet.

The different distance dependences and different average attenuation for the different floors present a dilemma if they are real effects not confined to this data set. For radio system analysis, a single

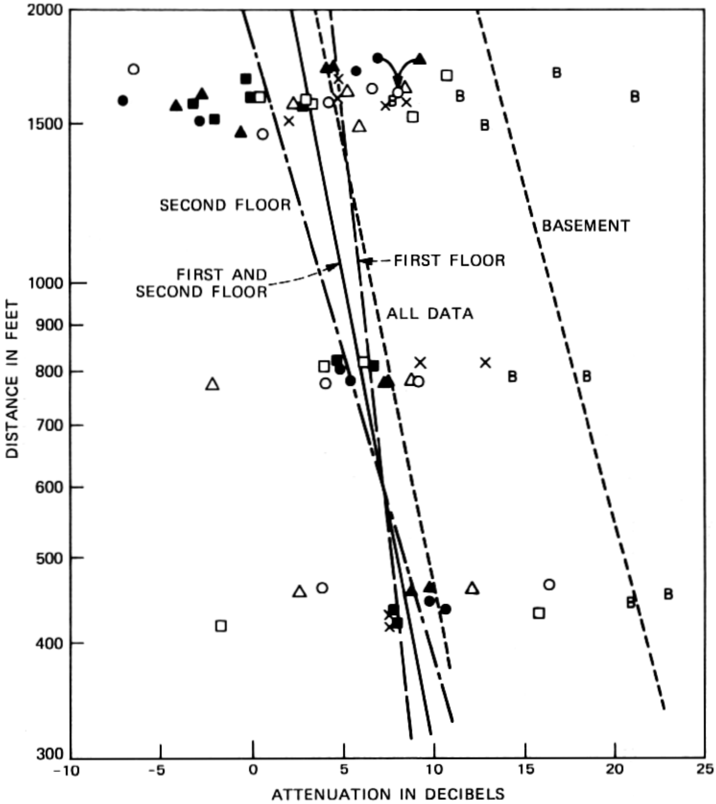

Fig. 8—Building attenuation by the first definition, i.e., relative to the average of the median levels for the four outside locations, plotted versus distance. Open data points and X points are from the first floor, solid data points are from the second floor, and points marked B are from the basement. All points marked with a particular symbol are from the same measurement location in the house but are for different van positions. The lines are linear-least-squares regression lines through different groupings of points.

Table III—Attenuation and standard deviations for the house (table values are in dB)

Floor	m σ	400 ft	800 ft	1600 ft
First	m	8.1	6.5	4.8
	σ	6.4	4.5	3.9
Second	m	9.1	6.1	0.7
	σ	1.1	1.3	4.6
Basement	m	22.1	16.4	13.8
	σ	1.7	2.8	5.1
First and second	m	8.5	6.3	3.1
	σ	4.8	3.4	4.7
First, second and basement	m	10.2	7.6	4.4
	σ	6.4	4.7	5.9

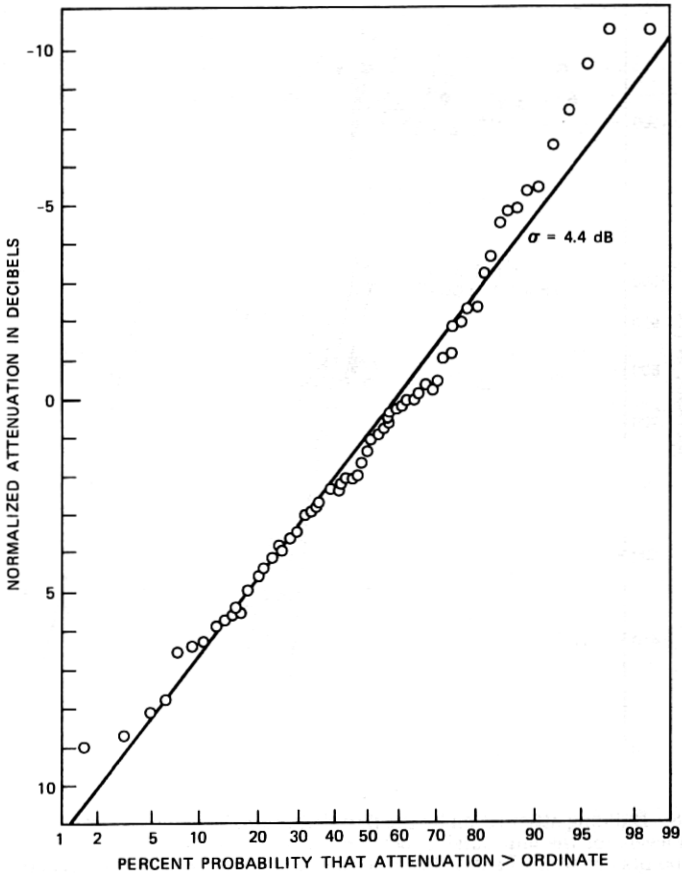

Fig. 9—Cumulative distribution of the building attenuations from Fig. 8 for the first and second floors after the values for the first- and second-floor regression line (solid line in Fig. 8) are subtracted out. The straight line represents a log-normal distribution with a standard deviation of 4.4 dB.

distance dependence and average attenuation are desirable; however, if only the composite regression line for the whole house were removed from the data, the variation remaining in the residual attenuation data would have a significantly larger standard deviation ($\sigma = 6.2$ dB) than if the individual regression lines for each floor were removed separately ($\sigma = 4.1$ dB). Also, the composite line for the entire house depends on the number of measurements made on each floor. For systems analysis, these numbers of measurements should be related to the probability of calls being made on those floors (or at those locations); but these probabilities are unknown.

The separation in decibels between the regression lines on Fig. 8 for the first and second floors is not extreme over the 4 to 1 distance covered. Also, the attenuation averages for these floors for the three distances are not grossly different (all within ±2 dB). Therefore, it seems reasonable to simplify the description of the attenuation by combining the first and second floor data. The composite regression line for this combination is also shown on the figure. When this composite regression line is removed from the first and second floor data, the resulting cumulative distribution of attenuation is as shown in Fig. 9. The standard deviation of the attenuation data plotted in Fig. 9 is 4.4 dB, not significantly different from the 4.1-dB standard deviation for all the data with the regression line for each floor removed separately. The distribution in Fig. 9 is a reasonable fit to a log-normal distribution, especially considering the limited size of the data set. Combining the basement data with the data from the other floors is not reasonable because of the large difference in average attenuations. Since this difference can be expected to exist for all houses, the attenuation into basements will probably have to be described separately from the attenuation for the rooms on other floors.

V. CONCLUSIONS

Signal levels were measured in and around three small buildings from a single position of an instrumentation van. Measurements were also made in and around a house from nine different van positions ranging from 400 feet to 1600 feet away. The received signal envelope is approximately Rayleigh distributed over most small-scale areas about 4 feet square. For the three buildings, building attenuation of the small-scale signal medians ranged from −2 to 24 dB relative to the average signal level outside each building.

For the house, some of the parameters of the medians of the small-scale envelope variations and of the building attenuation defined in this paper are summarized in Table IV. After the distance dependence is removed from the median signal levels outside of the house, the distribution of the residual large-scale signal-level variations is ap-

Table IV—Summary of signal-level and attenuation parameters for the house

Parameter	Outside	First Floor	Second Floor	Basement	First & Second Floors	Units
Signal-level distance dependence exponent	−4.5	−3.9	−3.0	−3.2	—	—
Signal-level relative to free space at 1000 ft.	−12.5	−18.5	−16.5	−28.9	—	dB
Building attenuation exponent	—	−0.6	−1.5	−1.4	−1.0	—
Average building attenuation at 1000 ft.	—	+6.0	+4.0	+16.4	+5.1	dB

proximately log-normal with a standard deviation of 9 dB. The standard deviation of the building attenuation for the first and second floors is 4.4 dB after distance dependence is removed. Because of the large average attenuation into the basement of the house, it does not appear reasonable to combine the basement attenuation statistics with the statistics for the rooms above ground level.

Cross-polarization coupling is strong inside and outside of the three buildings. For all locations measured, the coupling is greater than −10 dB and for most locations it is −6 dB or greater.

VI. ACKNOWLEDGMENTS

Initial design of the van masts and mounts was done by W. I. Tohlman and H. H. Hoffman. We wish to thank H. W. Arnold for permitting the measurements reported in this paper to be made in his house. The continued support of L. J. Greenstein and D. O. Reudink is greatly appreciated.

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