914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings

Scott Y. Seidel, *Student Member, IEEE,* and Theodore S. Rappaport, *Senior Member, IEEE*

Abstract—Quantitative models are presented that predict the effects of walls, office partitions, floors, and building layout on path loss at 914 MHz. The site-specific models have been developed based on the number of floors, partitions and concrete walls between the transmitter and receiver, and provide simple prediction rules which relate signal strength to the log of distance. The standard deviation between measured and predicted path loss is 5.8 dB for the entire data set, and can be as small as 4 dB for specific areas within a building. Average floor attenuation factors (FAF), which describe the additional path loss (in decibels) caused by floors between transmitter and receiver are found for as many as four floors in a typical office building. Average floor attenuation factors are found to be 12.9 and 16.2 dB for one floor between the transmitter and receiver in two different office buildings. For same-floor measurements, attenuation factors (AF) are found to be 1.4 dB for each cloth-covered office partition and 2.4 dB for each concrete wall between transmitter and receiver. Path loss contour plots for measured data are presented. In addition, contour plots for the path loss prediction error indicate that the prediction models presented in this paper are accurate to within 6 dB for a majority of locations in a building.

I. INTRODUCTION

OBJECTS that surround transmitters and receivers severely affect the propagation characteristics of any radio channel. The performance of in-building high capacity wireless communications is limited by the propagation characteristics. Thus, it is important to understand how the physical surroundings impact the propagation environment. Several researchers have measured radio waves in buildings and statistically modeled their results [1]–[9]. A summary of path loss, narrow-band fading statistics, and root mean square (rms) delay spread in many different building types is given in [10].

In this paper, we first present statistical analyses of 914 MHz narrow-band path loss measurements inside four buildings, and then classify the measurements based on the physical surroundings. The measured buildings include a grocery store, a retail department store, and two multistory office buildings. A statistical model of the simple form d^n (see (2)) is used to relate average path loss to the log of distance where

d is the distance between the transmitter and receiver measured in three dimensions, and n is the mean path loss exponent, which indicates how fast path loss increases with distance ($n = 2$ for free space) [1]–[6], [8], [9], [12], [13]. Values of the mean path loss exponent n are found for each building and all four buildings combined. In multifloored buildings, we find that more accurate prediction is possible when the parameter n is viewed as a function of the number of floors between transmitter and receiver. We also develop an alternative path loss model ((5)) for multifloor buildings to quantify the additional path loss caused by multiple floors between transmitter and receiver.

For measurements in the office buildings when the transmitter and receiver are located on the same floor, we quantify average path loss caused by cloth-covered plastic office partitions and concrete walls between the transmitter and receiver. We assume free space propagation with distance and consider additional path loss to be caused by the physical obstructions that lie directly between the transmitter and receiver ((8)). This provides a tractable physical propagation model that is shown to be more accurate than a generic statistical model ((2)) that considers only the distance between the transmitter and receiver terminals, and not site-specific information. Contour plots of locations of equal path loss for a fixed base transmitter are presented for the two office buildings. The models in this paper are used to predict the path loss at the measurement locations. The differences between the measured and predicted path loss are used to develop path loss prediction error contour regions for the office buildings.

Section II describes the measurement procedure and the four measured buildings used to produce the models in this paper. Section III describes the important site-specific building parameters used to develop the models. Section IV presents the measured data and shows the best fit for three different in-building path loss models. Section V shows path loss contour for measured data and error contour regions for the difference between the measured path loss and the path loss predicted from site-specific models given in Section IV. Sections VI and VII conclude with a summary of results and future work.

II. MEASUREMENT PROCEDURE AND LOCATIONS

A. Measurement Procedure

Narrow-band (CW) signal strength measurements were made at 914 MHz with a system nearly identical to the one

The authors are with the Mobile and Portable Radio Research Group, Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

used in [3]. A 1 W CW signal was transmitted by an omnidirectional quarter-wave monopole antenna at a height of either 1.0 or 1.5 m above the floor [11]. The mobile receiver omnidirectional discone antenna was either 1.0 or 1.8 m above the floor. The receiver can instantaneously measure signals between 0 and −91 dBm over a 15 kHz bandwidth. With +29 dBm transmitter power, our maximum system path loss is 120 dB. This is on the order of the maximum dynamic range expected for emerging personal communications networks (PCN) which will be deployed within buildings during the next several years.

The stationary transmitter was placed at several locations within each of the four buildings. Locations which are potential candidates for future microcellular base stations, such as centrally located areas and perimeter areas within a wing of a building were chosen for most transmitter sites. At some other locations, the base antenna was placed within a partitioned office cubicle to determine the effects of office partitions between the transmitter and receiver. For each transmitter location, the mobile receiver thoroughly canvassed the building at transmitter–receiver (T–R) separations that ranged between 1.5 and 90 m. During each measurement, the mobile receiver moved at constant walking velocity along a straight path which varied in length between 2.4 and 60 m, depending on surroundings. The mobile's position was continuously recorded so that site-specific propagation models can be developed from the data.

B. Measurement Locations

1) Grocery Store: The open-plan shopping area of the grocery store has dimensions of 46 m × 67 m, and a ceiling height of 5 m. This area consists of metal shelves that are 22 m long and 2.5 m high. The aisles next to the shelves are each 2.3 m wide. For most measurements, the transmitter was located at the far side of the store while the receiver canvassed the entire shopping area. For several other measurements, the base transmitter was located between two checkout lanes in the front of the store.

2) Retail Store: The single story open-plan retail store has inside dimensions of 61 m × 52 m, and a ceiling height of 4.5 m. The store is divided into several departments. Movable 1.8 m high cloth-covered plastic partitions partially separate some of the departments. We call these soft partitions since they can be relocated easily, and are not a fixed part of the building structure. Other departments are divided by metal shelves ranging from 1.5 to 2 m high. Main aisles are 2 m wide and secondary aisles are 1.2 m wide. The three transmitter locations were near the checkout lanes, in the lawn furniture department, and in the center of the store near small appliances. The receiver moved throughout the shopping area.

3) Office Building 1: Office building 1 has five floors and two wings where office areas are boxed in with soft partitions. These partitions are cloth-covered plastic dividers which divide each large open-plan office area into several smaller individual cubicles. Typical cubicles cover 2.4 m × 2.4 m of floor space and are surrounded by 1.5 m tall soft partitions. Aisles between the cubicles are about 1.2 m wide.

In the center of the West wing of the building are conference rooms with concrete block walls which span from the floor to the ceiling but are typically 5–10 m in width (they do not block off the entire building). On the fifth floor of office building 1, the transmitter was located on the perimeter of the West wing. The direct path between the transmitter and receiver passed outside the building when the receiver was in the Central wing. The schematic drawing for the West wing of the fifth floor can be seen in the contour plots in Figs. 7 and 11. Fig. 1 is a photograph of a typical soft partitioned area in the West wing on the fifth floor.

The fourth floor of the West wing of office building 1 is similar in layout to the fifth floor. The transmitter location on the fourth floor of office building 1 was near the center of a partitioned office cubicle. The transmitter was at least 0.5 m from each of the surrounding partitions. A schematic drawing for the fourth floor in the West wing can be seen in the contour plots in Figs. 8 and 12. For the transmitter locations on the fourth and fifth floors, the mobile receiver moved throughout the West wing on the fourth and fifth floors, and also in the Central wing on the fifth floor. Additional multifloor measurements were made with the transmitter on the first floor near the edge of the building while the mobile receiver traversed a straight path along the edge of the building on the second through fifth floors. Both the length and width are greater than the height of office building 1.

4) Office Building 2: Office building 2 has four stories and office area layouts that are similar to those in office building 1. At one location, the transmitter was placed directly behind a soft partition in an office cubicle on the second floor of office building 2. Several multifloor measurements were made with the transmitter next to an elevator in the basement. The mobile receiver traversed aisles on the second and third floors. A schematic drawing of the second floor of office building 2 can be seen in the contour plots in Figs. 9, 10, and 13. Office building 2 is longer and wider than it is high.

III. DATA PROCESSING

Fig. 2 shows a typical measurement run where the receiver was moved along a 12 m track in an aisle of the retail store. The abscissa represents the T–R separation, which only changes by 10 m along the 12 m measurement run since the receiver was not moved radially away from the transmitter. The median signal strength over a distance of 20 λ (6.56 m) was computed at 20 λ intervals for each measurement run and is considered a discrete measurement location for the development of path loss models and contour plots. A 20 λ distance was chosen so that the fast-fading of the envelope caused by multipath would not influence the large-scale path loss for a given measurement track [13]. Preliminary work at MPRG shows that in buildings, large-scale path loss is uncorrelated at 20 λ spacings. Thus, each path loss measurement represents the median path loss measured over a 6.56 m section of a straight path. Median signal strengths were converted to absolute path loss by subtracting the median received signal strengths from the +29.0 dBm transmitter power. Building blueprints and path loss measurements were imported to a computer-aided design program (AutoCAD).
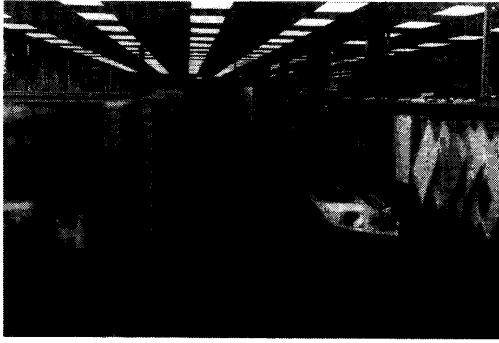
Fig. 1. Picture of a soft partitioned environment in office building 1. Notice the 1.5 m high cloth covered plastic dividers (soft partitions) that separate office cubicles.
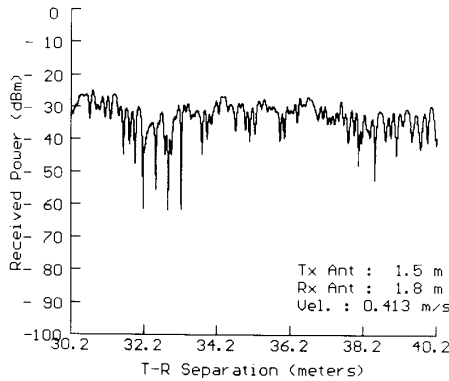

Fig. 2. An example of typical 914 MHz CW signal fading as the receiver is moved in a retail department store. Fade depths which dip 30 dB below the median can occur.

For each path loss measurement, we have the following information:

 median path loss (over 6.56 m track segment)
 blueprints for the measured building
 exact transmitter location
 exact receiver location
 transmitter–receiver separation (measured as a straight line in three dimensions)
 number of floors between transmitter and receiver
 number of soft partitions between transmitter and receiver
 number of concrete walls between transmitter and receiver.

With the above information, we have developed models for path loss as a function of distance, number of floors, soft partitions, and concrete walls between the transmitter and receiver, and wing of the building that the terminals are in. In addition, we have produced contour plots of locations with equal path loss in buildings.

IV. PATH LOSS PREDICTION MODELS

Although the path loss models presented here are for CW measurements, [2] showed that when individual multipath

component amplitudes are uncorrelated, or phases of individual multipath components are independent and identically distributed over $[0, 2\pi)$, CW and wide-band (250 MHz RF bandwidth) path loss measurements are equivalent when averaged over distances of a few wavelengths. Thus, since our modeling uses local spatial path loss values averaged over 20 λ our models may be used to describe average wide band path loss for these environments, as well. Such models are appropriate for emerging systems that use wide bandwidth (i.e., spread spectrum) to mitigate small-scale fades. Furthermore, work in [5], [8], [9] showed virtually no statistical difference in path loss from 900 MHz to 4.0 GHz for same floor measurements in several buildings. From [2], [5], [8], [9], one could logically infer that the same floor path loss models described in this paper could be applied throughout the low microwave bands (1–5 GHz). In [14], it is shown that the attenuation caused per floor was 6 dB higher at 1700 MHz than at 900 MHz. As a first approximation, this result could be used to scale floor loss for different frequencies. However, more work is required to explicitly determine the effect of multiple floors on path loss for different frequencies.

A. Distance-Dependent Path Loss Model

A model used in [1]–[6], [8], [9], [12] indicates that mean path loss increases exponentially with distance. That is, the mean path loss is a function of distance to the n power

$$\overline{PL}(d) \propto \left(\frac{d}{d_0} \right)^n \tag{1}$$

where $\overline{PL}$ is mean path loss, n is the mean path loss exponent which indicates how fast path loss increases with distance, d_0 is a reference distance, and d is the transmitter–receiver separation distance. When plotted on a log–log scale, this power-distance relationship is a straight line. Absolute mean path loss, in decibels, is defined as the path loss from the transmitter to the reference distance d_0, plus the additional path loss described by (1) in decibels

$$\overline{PL}(d)[\text{dB}] = PL(d_0)[\text{dB}] + 10 \times n \times \log_{10}\left(\frac{d}{d_0} \right). \tag{2}$$

For these data, a 1 m reference distance was chosen and we assume $PL(d_0)$ is due to free space propagation from the transmitter to a 1 m reference distance. Assuming antenna gains equal system cable losses, which is valid for our system, this leads to 31.7 dB path loss at 914 MHz over a 1 m free space path. Measurements show this is accurate to within a decibel nominally [3].

In [1], [2] path loss was shown to be log-normally distributed about (2). Assuming the distribution of large-scale path loss about (2) is log-normal for our data, we determine the mean path loss exponent n and standard deviation σ (in decibels), which are viewed as parameters that are a function of building type, building wing, and number of floors between transmitter and receiver. Even though our measured data show the distribution is not always strictly log-normal,

the standard deviation provides a quantitative measure of the accuracy of the model used to predict the path loss for a given environment. Further, when a measurement database is large, the distribution of path loss values over a wide range of distances tends to a log-normal distribution. The path loss at a T–R separation of d meters is then given by

$$PL(d)[\text{dB}] = \overline{PL}(d)[\text{dB}] + X_\sigma[\text{dB}] \qquad (3)$$

where X_σ is a zero mean log-normally distributed random variable with standard deviation σ in decibels. Linear regression was used to compute values of the parameters n and σ in a minimum mean square error (MMSE) sense for the measured data. The data have been grouped by building type, building wing, and the number of floors between the transmitter and receiver to provide smaller standard deviations. As is shown subsequently, this model more accurately predicts path loss as a function of distance when the model parameters n and σ are determined as a function of the general surroundings.

Table I summarizes the mean path loss exponents, standard deviations about the mean for different environments, and the number of measurement locations (20 λ track segments) used to compute the statistics for each category. From Table I, it can be seen that the parameters for path loss prediction for the entire data set are $n = 3.14$ and a large standard deviation of 16.3 dB. This large value of σ is typical for data collected from different building types, and indicates that only 68% of actual measurements will be within ±16.3 dB of the predicted mean path loss. These parameters may be used in the model for a first-order prediction of mean signal strength when only T–R separation but no specific building information is known, but is clearly unsatisfactory for site layout or capacity prediction. For measurements where the transmitter and receiver are on the same floor, the path loss is less severe, and the standard deviation is reduced only slightly. We found $n = 2.76$ and $\sigma = 12.9$ dB using data from four buildings.

The best fit exponent value for all measurement runs in the grocery store is less than two ($n = 1.81$) with a standard deviation of 5.2 dB. In the retail department store, mean path loss increases with distance slightly greater than free space ($n = 2.18$) and there is a spread of 8.7 dB about the mean value. The path loss results for the grocery and retail stores closely agree with those found in open-plan factory buildings [2], [3], [5].

Scatter plots of path loss versus T–R separation for office building measurements are given in Figs. 3 and 4. The dotted lines indicate the distance-dependent mean path loss model ((2)) for $n = 1$ through $n = 6$ and a 1 m reference distance. The dashed line indicates the best mean path loss model in a MMSE sense for the data presented in the scatter plot. Different symbols are used to indicate data from different environments, and overall n and σ are given on the left side of each graph. Multifloor measurements were possible in the two office buildings, and nearly all measurements had multiple obstructions such as concrete walls, windows, and soft partitions between the transmitter and receiver. From Fig. 3,

TABLE I
THE PARAMETERS MEAN PATH LOSS EXPONENT n AND STANDARD DEVIATION σ FOR USE IN THE DISTANCE-DEPENDENT PATH LOSS MODEL IN (2) BASED ON MEASUREMENTS AT A CARRIER FREQUENCY OF 914 MHz

|	n	σ(dB)	Number of Locations
All Buildings:			
All Locations	3.14	16.3	634
Same Floor	2.76	12.9	501
Through 1 Floor	4.19	5.1	73
Through 2 Floors	5.04	6.5	30
Through 3 Floors	5.22	6.7	30
Grocery Store	1.81	5.2	89
Retail Store	2.18	8.7	137
Office Building 1:			
Entire Building	3.54	12.8	320
Same Floor	3.27	11.2	238
West Wing 5th Floor	2.68	8.1	104
Central Wing 5th	4.01	4.3	118
West Wing 4th Floor	3.18	4.4	120
Office Building 2:			
Entire Building	4.33	13.3	100
Same Floor	3.25	5.2	37
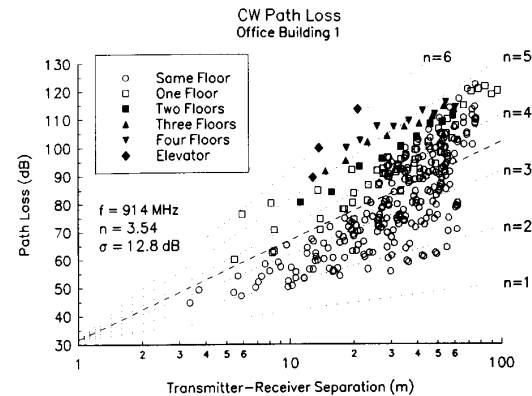
Fig. 3. Scatter plot of CW path loss as a function of distance in office building 1. The symbols represent the number of floors between the transmitter and receiver. Notice the large spread of data about the mean path loss predicted by the simple distance-dependent statistical model with $n = 3.54$.
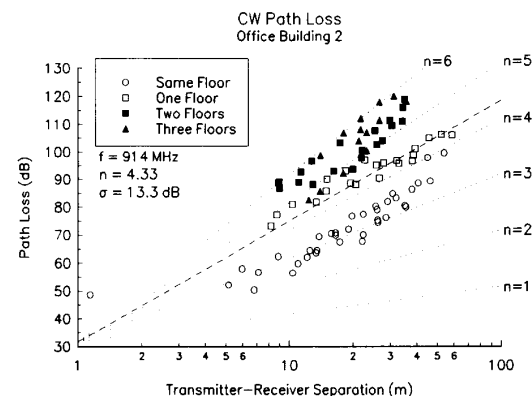

Fig. 4. Scatter plot of CW path loss as a function of distance in office building 2. The symbols represent the number of floors between the transmitter and receiver. Notice the clustering of data as a function of the number of floors between transmitter and receiver.

mean path loss increases with distance to the 3.54 power with a large standard deviation of 12.8 dB in office building 1. The simple d^n path loss model in Fig. 3 does not use knowledge of office partitions or the number of floors between the transmitter and receiver. Transmission between more obstructions leads to higher path loss.

In office building 2, mean path loss increases with distance to the 4.33 power as shown in Fig. 4. The number of floors between the transmitter and receiver can be seen to severely influence the path loss for a given T–R separation. Thus, the number of floors has an impact on the parameter n in the path loss model, and should be quantified for accurate path loss prediction.

The standard deviations about the mean path loss model for individual buildings and for site-specific classifications of measurements in Table I are smaller than those for data from all four buildings. For example, the standard deviation for data from all four buildings is 16.3 dB. If we consider only office building 1, σ drops to 12.8 dB. For same floor measurements only, $\sigma = 11.2$ dB. Further classification of same floor transmitter and receiver measurements into West wing fifth floor, Central wing fifth floor, and West wing fourth floor reduces the standard deviations to 8.1, 4.3, and 4.4 dB for each of the areas, respectively. Thus, more accurate signal strength prediction must be based on building information.

In multifloor environments, (4) is used to describe the mean path loss as a function of distance. Equation (4) is identical to (2) and emphasizes that the mean path loss exponent is a function of the number of floors between transmitter and receiver. The values of n(multifloor) are given in Table I for use in (4).

$$\overline{PL}(d)[\text{dB}] = PL(d_0)[\text{dB}]$$

$$+ 10.0 \times n(\text{multifloor}) \times \log_{10}\left(\frac{d}{d_0}\right). \quad (4)$$

B. Floor Attenuation Factor (FAF) Path Loss Model

In Section IV-A, the path loss in multifloored environments was predicted by a mean path loss exponent that was a function of the number of floors between transmitter and receiver. Alternatively, a constant floor attenuation factor (in decibels), which is a function of the number of floors and building type, may be added to the mean path loss predicted by a path loss model which uses the *same floor* path loss exponent for the particular building type ((5)).

$$\overline{PL}(d)[\text{dB}] = PL(d_0)[\text{dB}] + 10.0 \times n(\text{same floor})$$

$$\times \log_{10}\left(\frac{d}{d_0}\right) + \text{FAF}[\text{dB}] \quad (5)$$

where d is in meters and $PL(d_0)[\text{dB}] = 31.7$ dB at 914 MHz.

Table II gives the floor attenuation factors, the standard deviations (in decibels) of the difference between the mea-

TABLE II
AVERAGE FLOOR ATTENUATION FACTOR IN DECIBELS FOR ONE, TWO, THREE, AND FOUR FLOORS BETWEEN THE TRANSMITTER AND RECEIVER IN THE TWO OFFICE BUILDINGS; ALSO PRESENTED ARE THE STANDARD DEVIATION IN DECIBELS AND THE NUMBER OF LOCATIONS USED TO COMPUTE THE STATISTICS

	FAF (dB)	σ(dB)	Number of Locations
Office Building 1:			
Through 1 floor	12.9	7.0	52
Through 2 floors	18.7	2.8	9
Through 3 floors	24.4	1.7	9
Through 4 floors	27.0	1.5	9
Office Building 2:			
Through 1 floor	16.2	2.9	21
Through 2 floors	27.5	5.4	21
Through 3 floors	31.6	7.2	21

sured and predicted path loss, and the number of discrete measurement locations used to compute the statistics. Values for the floor attenuation factor in Table II are an average (in decibels) of the difference between the path loss observed at multifloor locations and the mean path loss predicted by the simple d^n model ((2)) where n is the *same floor* exponent given in Table I for the particular building structure and d is the shortest distance measured in three dimensions, between the transmitter and receiver. This is similar to the procedure used in [9], [14] to determine the attenuation caused by floors between transmitter and receiver.

The average floor attenuation factors for an identical number of floors between the transmitter and receiver for the two buildings differ by 3–8 dB. All floors in the two office buildings were made of reinforced concrete. Office building 1 was built within the past ten years, and office building 2 is 20 to 30 years old. Both buildings are longer and wider than they are high. Presently, it is unclear what causes the difference between the two buildings. It is interesting to note that in these buildings the average FAF is not a linear function of the number of floors between the transmitter and receiver as was found in [9], [14]. It is possible different floors cause different amounts of path loss, and there may be other factors such as multipath reflections from surrounding buildings that affect the path loss. More measurements are underway in many multifloored buildings to quantify the floor attenuation factors as a function of frequency and building materials, with the goal that eventually, the loss between different floors in buildings may be predicted without measurements.

As an example of how to use the two different models to predict the mean path loss through three floors of office building 1, assume the mean path loss exponent for *same floor* measurements in a building is $n = 3.27$, the mean path loss exponent for three-floor measurements is $n = 5.22$, and the average floor attenuation factor is FAF = 24.4 dB for three floors between transmitter and receiver. These parameters are found from Tables I and II for office building 1. Then, at a T–R separation of $d = 30.0$ m, the predicted mean path loss using (4) is

$$\overline{PL}(30\text{ m})[\text{dB}] = PL(1\text{ m})[\text{dB}] + 10.0$$

$$\times 5.22 \times \log_{10}(30) = 108.8\text{ dB} \quad (6)$$

or, using (5),

$$\overline{PL}(30 \text{ m})[\text{dB}] = PL(1 \text{ m})[\text{dB}] + 10.0$$
$$\times 3.27 \times \log_{10}(30) + 24.4 = 104.4 \text{ dB}. \quad (7)$$

C. Soft Partition and Concrete Wall Attenuation Factor Model

The previous models include the effects of T–R separation, building type, and the number of floors between the transmitter and receiver, and are a first step for including site information to improve propagation prediction. Although Table I shows standard deviations can be reduced by accounting for the number of floors between the transmitter and receiver, the standard deviations given in Table I for all *same floor* measurements in the two office buildings are still as large as 11.2 and 13.3 dB. This indicates that building features around transmitter and receiver locations must be considered for a more accurate propagation model. This was done in [7] for hallways and rooms adjacent to a main corridor and in [9] for floors and plasterboard partitioned walls.

There are often obstructions between the transmitter and receiver even when the terminals are on the same floor. We consider the path loss effects of soft partitions and concrete walls between the transmitter and receiver for same floor measurements on the fourth and fifth floor of the West wing of office building 1 and the second floor of office building 2. These areas are classified as soft partitioned environments and are all the measured locations where soft partitions and concrete walls were the only obstructions between the transmitter and receiver. For a physical model that will apply in general, we assume path loss increases with distance as in free space ($n = 2$), so long as there are no obstructions between the transmitter and receiver. Then, we include attenuation factors for each soft partition and concrete wall that lie directly between the transmitter and receiver. For simplicity, any kind of concrete support column that wholly or partially blocks the direct path between the transmitter and receiver is labeled a concrete wall. Let p be the number of soft partitions and q be the number of concrete walls between the transmitter and receiver. The mean path loss predicted by the attenuation factor path loss model is then given by

$$\overline{PL}(d)[\text{dB}] = 20.0 \times \log_{10}\left(\frac{4\pi d}{\lambda}\right)$$
$$+ p \times \text{AF(soft partition)}[\text{dB}]$$
$$+ q \times \text{AF(concrete wall)}[\text{dB}]. \quad (8)$$

Notice that no reference distance is used since free space propagation is assumed for all distances. This model is similar in form to one proposed in [9] for floors and walls.

For each of the discrete path loss measurements in the soft partitioned environments, we computed the difference between the measured path loss and the path loss that would occur due to free space propagation for a transmitter and receiver at the same separation distance. We also recorded the number of soft partitions and the number of concrete

walls (or concrete building support columns) between the transmitter and receiver. Linear regression was used to find the best fit, in a minimum mean square error sense, for the attenuation factors of each soft partition and each concrete wall between the transmitter and receiver, where we assume all soft partitions induce identical path loss, and all concrete walls induce identical path loss. We also found the standard deviation in decibels of the difference between the measured path loss and the path loss predicted by (8).

When all path loss measurements in soft partitioned environments are considered, the AF is 1.39 dB for each soft partition and 2.38 dB for each concrete wall between the transmitter and receiver. When each soft partitioned environment is considered separately, the attenuation factors range from 0.92 to 1.57 dB for each soft partition and from 1.99 to 2.45 dB for each concrete wall. Fig. 5 shows a scatter plot of the actual measured path loss versus the path loss predicted by (8) with AF (soft partition) = 1.39 dB and AF (concrete wall) = 2.38 dB for the three soft partitioned environments. The diagonal straight line in Fig. 5 shows where measured and predicted path loss are identical. The standard deviation of the difference between measured and predicted path loss is 4.1 dB. Compare the 4.1 dB standard deviation of the attenuation factor model for the data from three Soft Partitioned environments to the standard deviations for the distance-dependent path loss model in (2) for each area considered separately. In office building 1, the standard deviations are 4.4 and 8.1 dB for same floor measurements in the West wing on the fourth and fifth floor, respectively, and 5.2 dB for the second floor of office building 2. The soft partition and concrete wall attenuation factor model in (8) explains the deviation of the mean path loss exponent from free space ($n = 2$) based on a physical model that assumes free space propagation with distance and attributes additional path loss to identifiable physical obstructions between the transmitter and receiver. The first such attenuation factors were presented in [2] for open-plan factory buildings.

Although the 4.1 dB standard deviation of the attenuation factor model is greater than the 2.94 dB for in-building path loss models reported in [7], the building areas modeled here are much different propagation environments than those in [7]. For our data, multiple obstructing objects are present between the transmitter and receiver whereas in [7], measurements were made in open hallways and rooms adjacent to hallways. In [7], the effects of obstructions between the transmitter and receiver used a received power model of the form $a - b \log$ (distance) where the a and b are found by a minimum mean square error fit similar to the method used here. The parameter a has no physical significance and is essentially an offset used to fit the data. It would be possible to model our data with an offset to reduce the standard deviation. However, an offset which varies from building to building that cannot be associated with the physical surroundings is not useful for a propagation prediction tool that could be used to predict path loss contours in a particular building *a priori*. In [9], standard deviations were 3–4 dB after correcting for floors and walls. However, no values for the attenuation these obstructions caused are given.
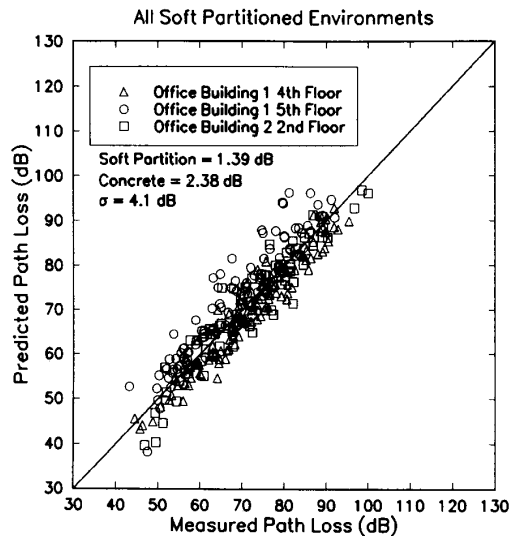
All Soft Partitioned Environments

Fig. 5. Scatter plot of measured versus predicted path loss for soft partitioned environments. The standard deviation of the prediction error is 4.1 dB.
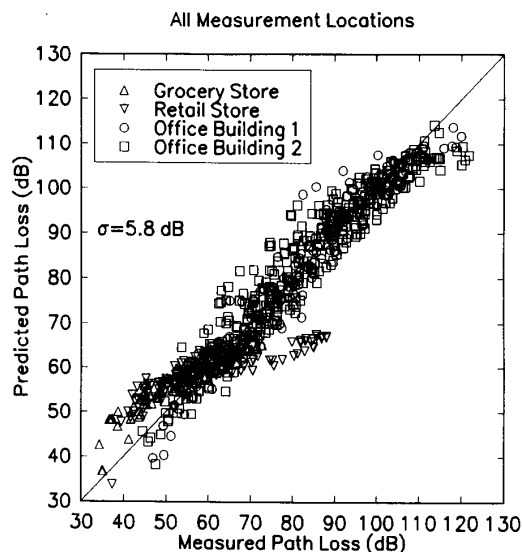
All Measurement Locations

Fig. 6. Scatter plot of measured versus predicted path loss for all measurement locations. The prediction error is log-normally distributed with a standard deviation of 5.8 dB.

Fig. 6 shows a scatter plot of measured and predicted path loss for all measured locations in the four buildings. The predicted values were found using the distance-dependent path loss model ((2)) for all locations in the grocery and retail stores, and all co-floor transmitter and receiver combinations in the office building areas that cannot be classified as soft partitioned environments. The floor attenuation factor model ((5)) was used for multifloor locations in the two office buildings. In the soft partitioned environments in the office buildings, the soft partition and concrete wall attenuation
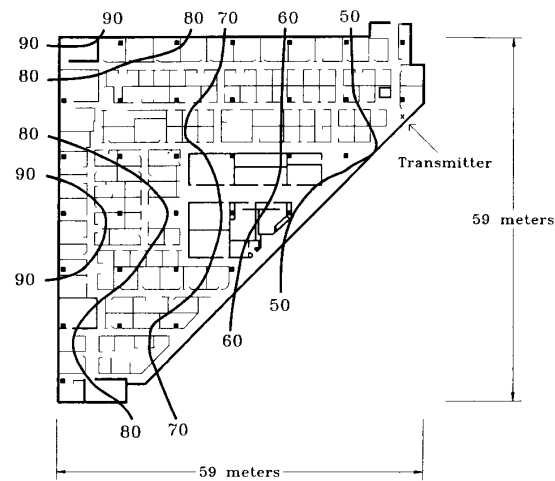

Fig. 7. Contour plot of locations with equal path loss in 10 dB steps for the fifth floor of the West wing of office building 1. The transmitter was located in the upper right corner of the figure.

factor model ((8)) was used to predict path loss. We have found that the distribution of errors between measured and predicted path loss is log-normal with a standard deviation of 5.8 dB. Path loss was also shown to be log-normally distributed after the attenuation caused by floors and walls was corrected for in [9]. By including the effects of floors, soft partitions, and concrete walls between the transmitter and receiver, we have reduced the standard deviation of our path loss prediction error from 16.3 to 5.8 dB.

V. PATH LOSS CONTOUR PLOTS

Building blueprints and both measured and predicted path loss data were imported to a computer-aided design program (AutoCAD). The data have been used to form contour plots of locations of equal path loss for a given transmitter location. In each figure, the transmitter location is indicated by an arrow pointing to an "X" at the transmitter location. Curved solid lines indicate locations of equal path loss from the transmitter in 10 dB steps. The amount of path loss is indicated at the end of the lines on the perimeter of the blueprints.

A. Measured Path Loss Contours

The contour plot of locations with equal measured path loss for the West wing on the fifth floor of office building 1 is given in Fig. 7. The transmitter was located in the upper right-hand corner of the figure as indicated. Curved solid lines represent contours of equal path loss from the transmitter in 10 dB steps. The thin lines on the drawing indicate 1.5 m high soft partition cubicle dividers. In the center of the wing are conference rooms with concrete block walls which span from the floor to the ceiling. These walls are indicated by thick lines on the drawing. In Fig. 7, notice that when the thick conference room walls are between the receiver and the transmitter, the signal is attenuated much more rapidly than at other locations. Along the diagonal hallway along the edge
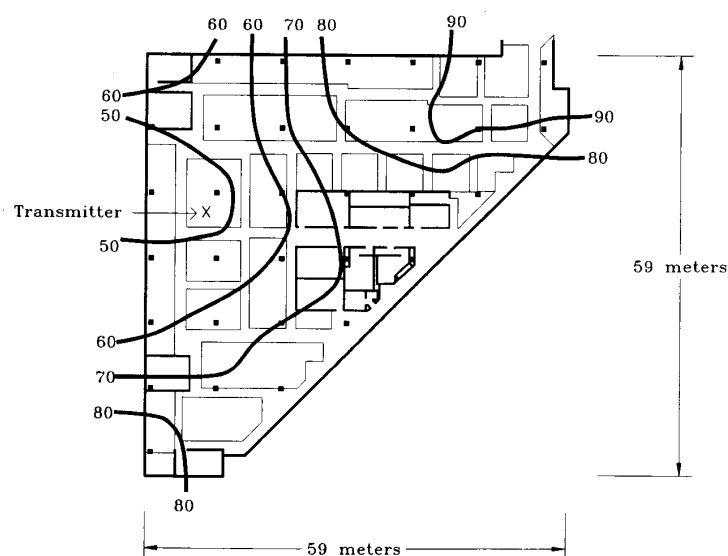
Fig. 8. Contour plot of locations with equal path loss in 10 dB steps for the fourth floor of the West wing of office building 1. The transmitter was located on the left side of the figure.

of the building, the radio coverage is quite good, and obeys better than free space propagation. Propagation better than in free space was also observed in [2], [3], [7] for open hallways that can guide signal energy.

The contour plot for the fourth floor West wing of office building 1 is shown in Fig. 8. The transmitter was located inside an office cubicle on the left side of the figure. Thick lines indicate concrete block walls that span from floor to ceiling. The thin lines which surround rectangular areas represent the perimeters of soft-partitioned office cubicles. Both the transmitter and the receiver antenna were 1.0 m above the floor. The path loss seems to be consistent with T–R separation and is not greatly affected by the direction of propagation.

Fig. 9 shows the contour plot for the second floor of office building 2. Notice that the contour lines for equal path loss extend farther from the transmitter toward the top of the figure. This is because the geometry in the favorable direction is similar to a line-of-sight aisle where path loss generally falls off slower than free space due to guiding of signal energy. The 80–100 dB path loss lines near the top of the figure indicate that path loss increases much more rapidly through the concrete walls than through the soft partitions.

Fig. 10 gives the contour plot in 5 dB steps for identical receiver locations on the second floor of office building 2 with the transmitter located in the basement of the building directly below the location indicated by an ''X'' in the figure. The path loss is primarily due to the concrete floors between the transmitter and receiver. These floors cause the mean path loss exponent to be 5.31 for measurements on the second floor with the transmitter in the basement when (4) is used to predict path loss. The nearly circular contours indicate that a simple d^n model can be used to accurately predict site-specific path loss in multifloored environments. A d^n

path loss model predicts circular contours since the path loss depends only on the distance from the transmitter.

B. Predicted Path Loss for Soft Partitioned Environments Using (8)

The soft partition and concrete wall attenuation factor model in (8) was used to predict path loss in soft partitioned environments. The attenuation factors for soft partitions and concrete walls used to predict the path loss were determined from measurements in three soft partitioned environments. AF (soft partition) = 1.39 dB and AF(concrete wall) = 2.38 dB.

The differences between measured and predicted path loss have been used to generate error contours. The absolute value of the error has been plotted to show regions where the model in (8) accurately predicts the path loss and regions where the model is less accurate. The path loss prediction error is proportional to the darkness of the shaded region. It is important to note that the error can be positive or negative within a single shaded region. This is done to indicate regions where the models have difficulty predicting the path loss. Thus, the use of a correction factor for the shaded regions is not appropriate.

The error contours for the West wing of the fifth floor of office building 1 and the contours of measured path loss for the same transmitter location and building wing are given in Fig. 11. The prediction error is less than 3 dB for about half the area in this location. There are several places where the prediction error is greater than 9 dB. This may be partly explained in that the Attenuation Factors for the fifth floor in the West wing of office building 1 were the lowest measured and differ by about 0.4 dB from the attenuation factors used to predict path loss. Thus, on average, we predict 0.4 dB more path loss than was actually observed for each partition
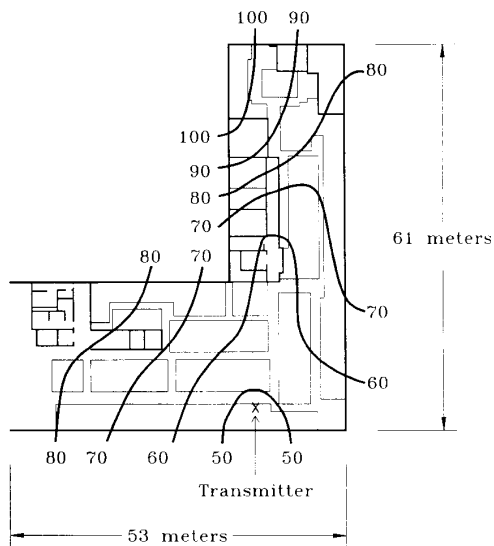
Fig. 9. Contour plot of locations with equal path loss in 10 dB steps for the second floor of office building 2 with the transmitter on the same floor. The transmitter was in the lower right corner of the figure.
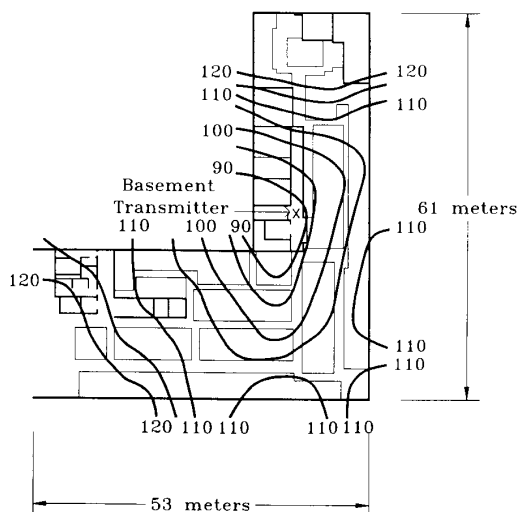

Fig. 10. Contour plot of locations with equal path loss in 5 dB steps for the second floor of office building 2 with the transmitter in the basement.

and concrete wall in this wing. When many partitions and concrete walls are between the transmitter and receiver, the error can be 4–5 dB.

Fig. 12 shows the measured and error contours for the fourth floor West wing of office building 1. The prediction error is less than 3 dB for over half the locations and less than 6 dB for nearly all of this wing. The error contours for this portion of the building show that (8) can be used to accurately predict path loss based on site-specific information.
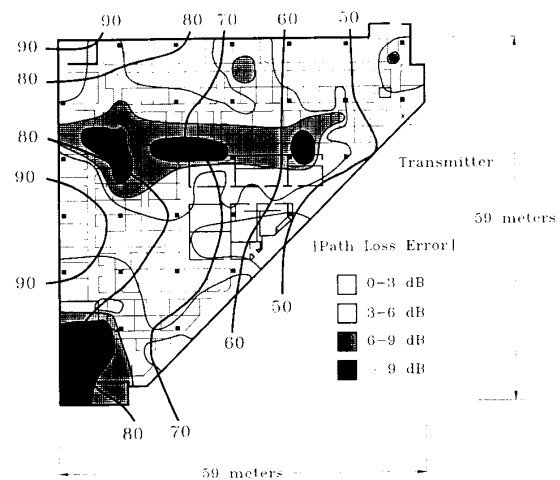

Fig. 11. Error contour plot for the fifth floor of office building 1. Path Loss error is proportional to the darkness of the shaded region. The path loss was predicted using (8) with AF(soft partition) = 1.39 dB and AF(concrete wall) = 2.38 dB.

Fig. 13 shows the error contour plot for the second floor of office building 2. The contours of measured path loss are given in Fig. 13. As in the case of the fourth floor West wing of office building 1, the path loss error is less than 3 dB in over half of the area and less than 6 dB for nearly all of the floor. Once again, error contours indicate that (8) can be used to accurately predict path loss in soft partitioned environments.

VI. CONCLUSION

Path loss models based on measured data at 914 MHz have been presented for four different buildings. The models are based on a simple d^n exponential path loss vs. distance relationship. In open-plan buildings such as the grocery store and the retail store, the path loss exponent n is close to 2. For environments with many more obstructions between the transmitter and receiver, the path loss exponent can be much higher. The models have been shown to be more accurate when different buildings and dissimilar areas within the same building are considered separately.

A floor-dependent path loss exponent (Table I) may be used to model the effects of the number of floors between the transmitter and receiver in conjunction with (4). Alternatively, the path loss exponent for co-floor propagation, along with a floor attenuation factor (Table II) to account for the additional path loss due to floors, may be used to predict path loss in conjunction with (5).

Attenuation factors for plastic covered office partitions and concrete walls that are located between the transmitter and receiver have been found. These factors are useful since they allow us to predict path loss in terms of free space path loss and physically identifiable objects that are part of the propagation environment. With the model in (8), it is possible to predict path loss contours for a transmitter and receiver located in the same wing of an office building where individ-
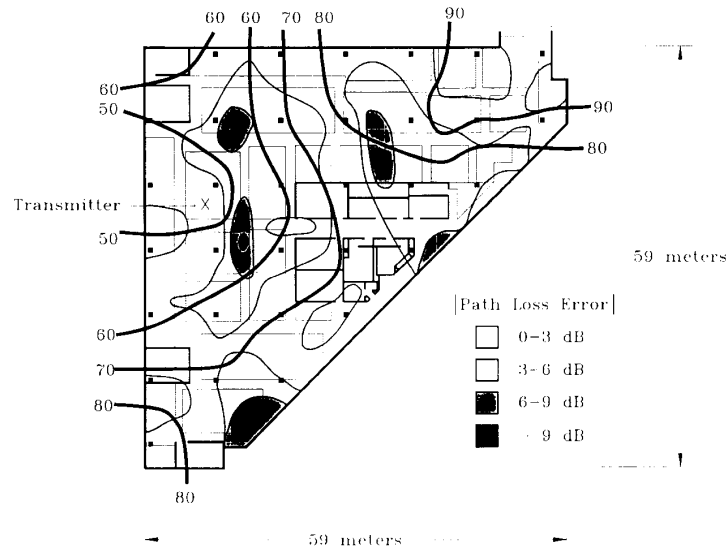
Fig. 12.　Error contour plot for the fourth floor of office building 1. The large unshaded region indicates where the path loss prediction error is less than 3 dB.
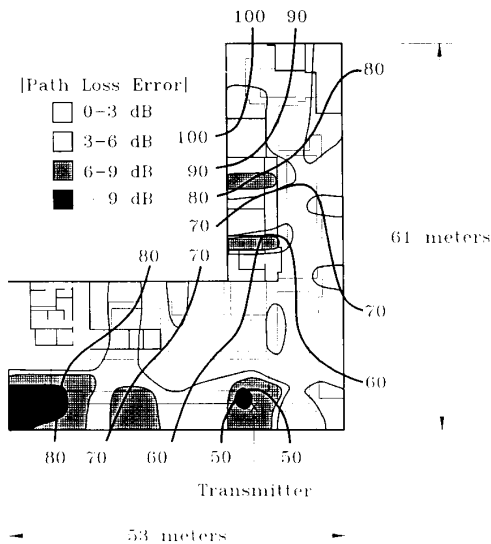
Fig. 13.　Error contour plot for the second floor of office building 2 with the transmitter on the same floor. The prediction error is less than 6 dB for nearly the entire floor.

ual office cubicles are separated by cloth-covered plastic dividers. For all of our measured data, AF(soft partitions) = 1.39 dB/partition and AF (concrete walls) = 2.38 dB/wall.

Examination of error contours which show the difference between measured and predicted path loss for the buildings given here show how simple path loss models that use site-specific information, such as the locations of soft partitions and concrete walls, can be used to predict path loss in buildings. Although there are some locations where the path

loss error is greater than 9 dB, the majority of locations are predicted to within 6 dB. Thus, it seems the method could offer an improvement in indoor communication system design and installation.

This work shows that site-specific information can be used to predict path loss in buildings with many different obstructions between the transmitter and receiver with a standard deviation of 5.8 dB. With more measurements, it is likely that the models can be refined and expanded to reduce the standard deviation and predict path loss in many more diverse environments.

VII. FUTURE WORK

A statistical distance-dependent path loss model is useful for understanding the propagation of radio waves in buildings. However, exhaustive measurements were required to obtain the data to determine the appropriate parameters for the models for these particular buildings. Models that allow a system designer to predict path loss contours for all types of buildings without measurements would be extremely cost-effective and time-efficient. In order to develop these models, attenuation factors for many different types of common objects in buildings must be determined for different frequency ranges. More measurements in similar and different building types at different frequencies are required to determine the effects of multipath propagation must be considered for extremely accurate propagation prediction.

comments of the reviewers that helped improve the quality of this paper are gratefully appreciated.

REFERENCES

[1] D. C. Cox, R. R. Murray, and A. W. Norris, "800 MHz attenuation measured in and around suburban houses," *AT&T Bell Lab. Tech. J.*, vol. 63, pp. 921–954, July/Aug. 1984.

[2] T. S. Rappaport, "Characterization of UHF multipath radio channels in factory buildings," *IEEE Trans. Antennas Propagat.*, vol. 37, pp. 1058–1069, Aug. 1989.

[3] T. S. Rappaport and C. D. McGillem, "UHF fading in factories," *IEEE J. Select. Areas Commun.*, vol. 7, pp. 40–48, Jan. 1989.

[4] F. C. Owen and C. D. Pudney, "Radio propagation for digital cordless telephone at 1700 MHz and 900 MHz," *Electron. Lett.*, vol. 25, no. 1, pp. 52–53, 1989.

[5] D. A. Hawbaker and T. S. Rappaport, "Indoor wideband radiowave propagation measurements at 1.3 GHz and 4.0 GHz," *Electron. Lett.*, vol. 26, no. 21, pp. 1800–1802, 1990.

[6] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 128–137, Feb. 1987.

[7] J-F. Lafortune and M. Lecours, "Measurement and modeling of propagation losses in a building at 900 MHz," *IEEE Trans. Veh. Technol.*, vol. 39, pp. 101–108, May 1990.

[8] D. M. J. Devasirvatham, M. J. Krain, and D. A. Rappaport, "Radio propagation measurements at 850 MHz, 1.7 GHz, and 4.0 GHz inside two dissimilar office buildings," *Electron. Lett.*, vol. 26, no. 7, pp. 445–447, 1990.

[9] A. J. Motley and J. M. Keenan, "Radio coverage in buildings," *British Telecom Tech. J.*, Special Issue on Mobile Communications, vol. 8, no. 1, pp. 19–24, Jan. 1990.

[10] D. Molkdar, "Review on radio propagation into and within buildings," *Inst. Elec. Eng. Proc.*, pt. H, vol. 138, no. 1, pp. 61–73, Feb. 1991.

[11] S. Y. Seidel and T. S. Rappaport, "900 MHz path loss measurements and prediction techniques for in-building communication system design," presented at *41st IEEE Veh. Technol. Conf.*, St. Louis, MO, May 21, 1991, pp. 613–618.

[12] T. S. Rappaport, S. Y. Seidel, and K. Takamizawa, "Statistical channel impulse response models for factory and open plan building radio communication system design," *IEEE Trans. Commun.*, vol. 39, pp. 794–807, May 1991.

[13] W. C. Y. Lee, *Mobile Communications Engineering*. New York: McGraw-Hill, 1982.

[14] A. J. Motley and J. M. P. Keenan, "Personal communication radio coverage in buildings at 900 MHz and 1700 MHz," *Inst. Elec. Eng. Electron. Lett.*, vol. 24, no. 12, pp. 763–764, 1989.
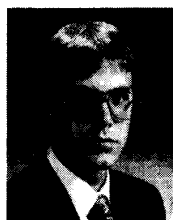
Scott Y. Seidel (S'89) was born in Falls Church, VA, in 1966. He received the B.S. and the M.S. degrees in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, in 1988 and 1989, respectively. He is pursuing the Ph.D. degree in electrical engineering at Virginia Polytechnic Institute and State University under the support of an NSF Graduate Research Fellowship.

Since 1989, he has been a member of the Mobile and Portable Radio Research Group at Virginia Tech. He has been involved in the development of both urban microcellular and indoor radio channel models and is interested in site-specific propagation prediction and system design. He is co-inventor of SIRCIM, an indoor radio channel simulator that has been adopted by over 40 companies and universities.

Mr. Seidel is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi.

Theodore S. Rappaport (S'83–M'84–S'85–M'87–SM'90) was born in Brooklyn, NY, on November 26, 1960. He received the B.S.E.E, M.S.E.E, and Ph.D. degrees from Purdue University, West Lafayette, IN, in 1982, 1984, and 1987, respectively.

From 1984 to 1988 he was with the NSF Engineering Research Center for Intelligent Manufacturing Systems at Purdue University. In 1988, he joined the Electrical Engineering faculty of Virginia Tech where he is an Assistant Professor and Director of the Mobile and Portable Radio Research Group. He conducts research in mobile radio communication system design and RF propagation prediction through measurements and modeling, and consults often in these areas. He guides a number of graduate and undergraduate students in mobile radio communications, and has authored or coauthored more than 50 technical papers in the areas of mobile radio communications and propagation, vehicular navigation, ionospheric propagation, and wide-band communications. He holds a U.S. patent for a wide-band antenna, and is co-inventor of SIRCIM, an indoor radio channel simulator that has been adopted by over 40 companies and universities.

Dr. Rappaport received the Marconi Young Scientist Award in 1990 for his contributions in indoor radio communications. He serves as senior editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. He is a member of IEEE COMSOC Radio Committee, and is a Fellow of the Radio Club of America. He is a member of ASEE, Eta Kappa Nu, Tau Beta Pi, Sigma Xi, and is a life member of the ARRL.