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Penetration of Radio Signals Into Buildings in the Cellular Radio Environment

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Penetration of radio signals from Advanced Mobile Phone Service cell site transmitters has been measured in fourteen office and industrial buildings in the Chicago area. Signal levels on the first floor of buildings averaged 14 dB less than reference levels in the adjacent streets. This penetration loss was found to decrease with increasing height. Standard deviations of penetration loss ranging from 5 to 11 dB attest to the diversity of architecture and floor arrangements. Other relationships useful in planning for portable phone terminal applications are derived from the data and are presented in this paper. The data include over 4000 measurements, each being the average of 1024 samples of the local field taken over an eight-second period as the instrumentation traveled about 20 feet over the measurement path. The measurement path in each building was traversed for each of the several cell sites that transmitted signals of adequate strength into the buildings.

I. INTRODUCTION

The use of portable and hand-held terminals in 850-MHz cellular radio systems involves a radio field environment inside buildings that differs from the more familiar highway and street propagation environment of the mobile terminal. The laws that define propagation over open and urban terrain are complicated by a penetration loss in the transmission of the signal into the building's interior. The characterization of this loss, as encountered in large office and commercial

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buildings, was the purpose of an extensive series of measurements made in fourteen buildings served by the Advanced Mobile Phone Service (AMPS) Developmental Cellular System in Chicago. These measurements were then compared with the penetration loss in a single-family residence.

The measurements were made in January 1980 to serve as a basis for evolving system requirements related to the use of portable phone terminals in AMPS systems.

Indoor portable service in cellular systems offers a possible improvement over conventional systems. The multiplicity of serving cell sites should in many cases illuminate all sides of those buildings that enjoy a relatively exposed or unshadowed environment. It was expected that this effect would be somewhat less pronounced in buildings that are more sheltered in the urban core; the data support this conjecture. The data also support expectations that areas with windows would have lower penetration losses than areas without windows; the difference is about 6 dB. First-floor penetration losses averaged 14.2 dB. The loss decreased with height at 1.9 dB per floor, very close to the 2.0- and 2.5-dB rates reported in Refs. 1 and 2. The penetration loss measured in the aluminum-sided ranch house, as a matter of interest, is 7.3 dB, a value close to the findings of Cox et al. in Ref. 3.

Most of the measurements made in the Cellular Test Bed (Ref. 4) and reported in Ref. 5 were of the signal as received by a mobile transceiver. The measurements reported here include the entire distribution of setup channel signal levels throughout the measurement areas for each cell site transmitter that qualified as a server. As such, the data are perfectly applicable to conventional mobile portable and paging applications. The effect is that of taking measurements with the base station in several different locations.

II. ENVIRONMENT AND TEST METHOD

The Chicago AMPS Developmental Cellular System, as described in Ref. 4, uses ten separate setup channels for paging and mobile call origination in the Chicago service area. The channel signals are radiated continuously from omnidirectional antennas. The instrumentation used for the measurements reported in this paper can be tuned manually to any of these frequencies to measure one channel at a time. Figure 1 shows nominal coverage contours for the setup channels of the seven cell sites that served the selected buildings. The related voice-channel coverage is shown in Fig. 2 of the paper by D. L. Huff.[4] The center of each contour represents a cell site location. In general, the cell sites are spaced about 15 miles apart.

A group of buildings in the Chicago area was selected to represent a range of physical characteristics including location, architecture,

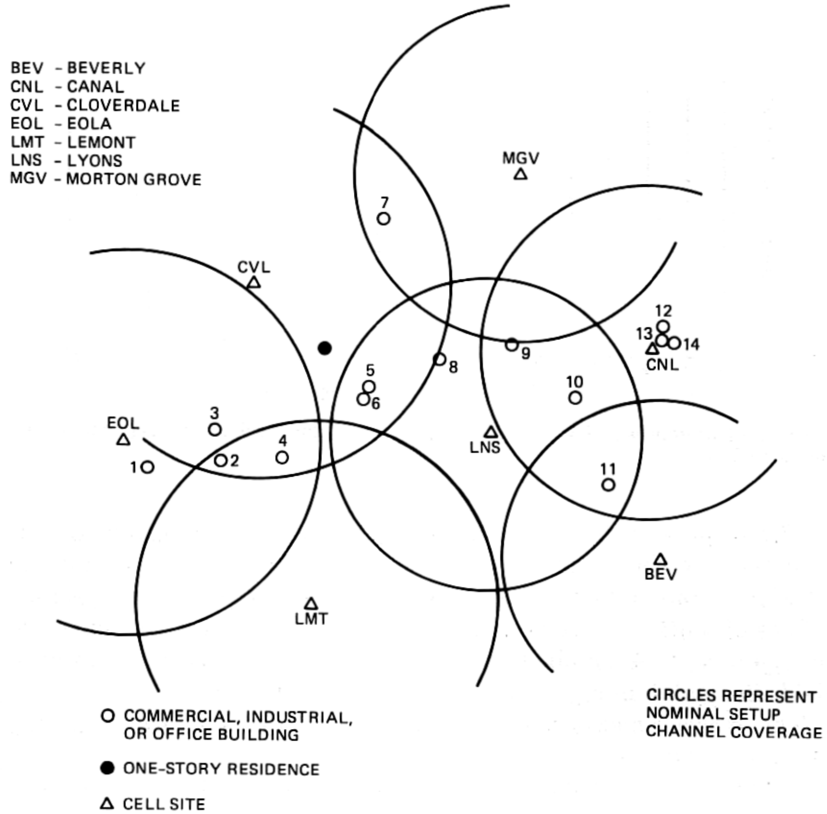

Fig. 1—AMPS Developmental Cellular System locations of 15 buildings and seven serving cell sites.

and local environment. Signal strength measurements were made along planned routes on selected floors of these buildings. A Propagation Measuring Set (PMS) was used to measure the strength of signals transmitted from cell sites.

Building penetration loss for a given floor area is defined to be the difference between the average of these measurements and an average of measurements made on the outside at street level.

Outside signal strength was measured at street level around the perimeter of the building, along the closest available path to the building's outside walls. These paths included driveways, streets, or parking lots, as required to achieve proximity to the building under test.

The PMS data output was transcribed for subsequent analysis by a computer program. The analysis was performed in the AMPS cellular test bed data processing facility described by DiPiazza, Plitkins and Zysman in Ref. 4.

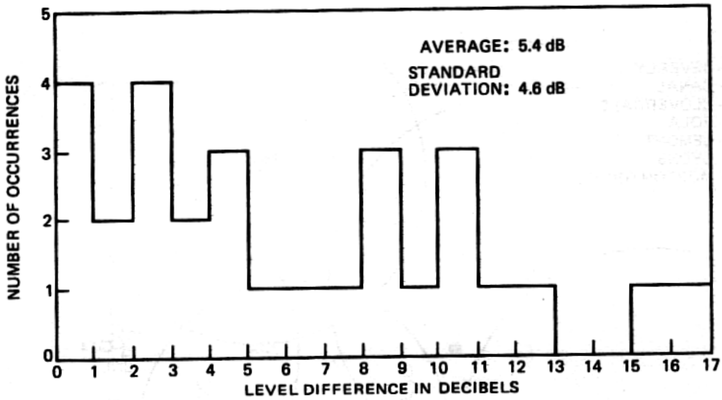

Fig. 2—Differences in level between the strongest and weakest serving channels on the same floor.

The purpose of the measurement program, as stated previously, was to determine the extent to which signals available from AMPS cell sites penetrate buildings. A first-order determination was desired; effects of 5 dB or more on the loss measurements were considered to be significant. A detailed investigation of the structure of interior fields in small buildings is reported by Cox in Ref. 3.

The measurements were subject to the effects of the following different conditions:

1. Different types of outside wall construction, such as steel-framed glass, brick, block masonry, etc.
2. Urban vs. suburban areas to identify difference between buildings in exposed locations and buildings sheltered in the dense urban core.
3. Changes in floor elevation.
4. Different building orientations with respect to serving cell sites.
5. Different percentages of window areas in the outside walls.
6. Different types of window treatment currently used to reflect sunlight and heat.

Time was an important factor in selecting the coverage objective for each building. Test runs were chosen to require about three hours of operations in any given building. The total time of recorded data is a small percentage of that.

Six significant categories of interior areas were identified. These were defined as open, enclosed, and hallways—each with and without windows. Typical of the areas that were considered to be "open" were cafeterias, lobbies, and large office spaces or conference rooms. Typical of "enclosed" areas were small, walled areas with space for only a few occupants, such as small office areas or workrooms.

Measurements in the first floors and second floors, together, were thought to represent a worst case. Higher floors, thought to represent better penetration, were included with less regularity. Test routes were designed to distribute measurements over the floor areas in a uniform manner.

III. BUILDING SELECTION

The buildings chosen in the Chicago AMPS service area were those where multiple cell sites could provide outside building signal levels of at least −90 dBm.

In the downtown section of Chicago, tests were made in three buildings. These represent the urban group. The downtown buildings in which tests were made can be characterized as "single tenant buildings".

In the suburban area around Chicago, tests were made in eleven commercial buildings and one residential dwelling. Only the data from commercial buildings were included in subsequent analyses.

From the standpoint of architectural variety the program provided measurements in a warehouse, a manufacturing plant, open-space offices, cafeterias, lobbies, small offices, and hallways. Outside wall construction varied from unwindowed concrete slab to steel-framed windows occupying about 90 percent of the outside surface.

The locations of the buildings where tests were conducted are shown on the map of Fig. 1. The circles show the idealized boundaries of regions of cell site control channel coverage. Table I shows the distribution of floor levels in buildings where tests were conducted and the cell sites whose transmissions served the various floor levels. A more detailed description of each of the buildings is given in the appendix.

Several factors were considered when selecting floors and floor areas for measurement. From a test sampling standpoint the first and second floors were chosen when available since building penetration was expected to be poorest at the lower levels. Higher floor levels were included in the tests to provide data on the sensitivity of building penetration to height. On any particular floor, areas were chosen that represent the different types of interiors; test paths were chosen to be uniformly distributed over the floor. In two instances measurements were attempted in basement areas but signal strength levels were below the threshold of the PMS.

IV. MEASUREMENT TECHNIQUE

A portable Propagation Measurement Set (PMS) designed for field strength measurements was adapted for this test program by mounting it in a small "tea" cart equipped with a battery, battery charger, and a mobile antenna mounted on a 2-foot by 2-foot ground plane. The

Table I—Buildings, floors, and serving cell sites contributing to measurements

	Buildings	Floors	Cell Sites*						
			CVL	EOL	LMT	LNS	CNL	MGV	BEV
1	Nabisco	1		X					
	Naperville	2		X	X				
		4	X	X	X				
2	Metropolitan	1	X	X					
	Naperville	2	X	X	X				
		3	X	X	X				
3	Bell Labs	1	X	X					
	Naperville	3	X	X					
		5	X	X	X				
4	BSCTE	1	X	X	X				
	Lisle	3	X	X	X				
		5	X	X	X	X			
		9	X	X	X	X			
5	Illinois Bell	1	X	X	X	X			
	Oakbrook	2	X	X	X	X			
6	McDonalds	1	X		X	X			
	Oakbrook	2				X			
		8	X	X	X	X			
7	Chrysler	1	X					X	
8	Allied Van	1				X			
	Lines	2	X		X	X			
	Hillside	4	X		X	X	X		
9	Illinois Bell	3				X	X	X	
	Oak Park	4				X	X	X	
10	Western Elec-	1				X			
	tric	2				X			
	Cicero	3				X	X	X	
11	Illinois Bell	1				X	X		X
	Kedzie	4				X	X		X
12	American Medi-	1				X	X	X	
	cal Assn	2				X	X	X	
13	Illinois Bell	1					X		
	Headquarters	3					X		
	Randolph	5					X	X	X
14	Illinois Bell	1					X		
	Adams	2					X		
		12					X		
		15					X		
	One-story residence (data not included in analyses)	1	X	X	X	X			

* CVL–Cloverdale; EOL–Eola; LMT–Lemont; LNS–Lyons; CNL–Canal; MGV–Morton Grove; BEV–Beverly.

ground plane was positioned 4-1/2 feet above floor level, at approximately shoulder height.

The design of the PMS is based upon the instrumentation receiver of the mobile communications laboratory described by DiPiazza, Plitkins, and Zysman in Ref. 4.

The PMS has an internal calibration system that calibrates the receiver over an 80-dB range in 1-dB increments. In the measurement mode, the basic unit of measurement is a one-second power average derived from a log-amplifier output sampled at a 128-Hz rate. The data output of the set can be adjusted to provide one average value, also derived as a power average, for a group of 1 to 128 of these one-second averages, selectable in binary increments. The measurement range of the set is −40 dBm to approximately −122 dBm.

The PMS uses a paper tape printer for hard copy output. The output data include frequency, a sequential "major marker," the power average, and the one-second sample variance for the group of one-second samples contributing to each longer-term mean. In this application, a mean value was generated each eight seconds. The "major marker" is used to key measurements to the time of day and to logged operator observations.

Prior to a series of measurements, the PMS is calibrated and the calibration results are printed on paper tape. A received signal strength meter in the PMS provides a visual indication of the receiver output without operating the paper tape recorder. The measurement team uses it to verify test set operation and to choose the group of control channels for measurement. The set also contains start, stop, and pause controls to limit data output to areas of interest.

To increase the confidence level of outside measurements, two methods were used where possible to determine outside signal strength. One method used the Mobile Telephone Laboratory (MTL) vehicle, which has the capability of power averaging instantaneous signal strength samples. This facility is described by Huff in Ref. 4. The MTL receivers were sampled at a rate of 32 samples per second. The short-term (1/2-second) MTL power averages were grouped in segments representing building faces and then further power averaged to provide a single mean value for each face segment. The segment means were then decibel averaged over all faces to develop the outside reference.

The second method used the PMS at the time of the in-building measurements to spot check MTL data as a guard against system variations.

MTL measurements were not available for the buildings in the Chicago downtown area, the AMA building, the IBT Headquarters building at Randolph, and the Bell Training Center at West Adams. The PMS was used to collect both inside and outside measurements.

V. TEST PROCEDURES

The PMS was transported to the building locations in a step van. While the PMS was in the van, the van rooftop antenna was connected to it, and street-level data were recorded along the building perimeter.

The measurements collected along the entire perimeter were decibel averaged to provide the outside reference.

The largest possible variety of areas was included in the routing chosen for the PMS measurements in each particular building. In measuring areas within a building the data were marked so that the different interior types could be distinguished. The PMS has a provision for including a marker number in the data output. As the PMS measurements were made along each route, an accompanying commentary was made on a cassette recorder. This commentary provided information about the type of building interior area being measured and the associated major marker number. The major marker information and the interior type were used subsequently in coding the data for computer program input.

Also, this commentary was useful in flagging data that should be discarded and in coordinating the data with the floor area to which it applied.

As we noted earlier, the PMS has the capability to generate average values that can be selected to represent from 1 to 128 seconds of real time. The 8-second average was chosen for output data in these measurements. That value represents a compromise between the volume of data points and the number of feet of travel per data point. With the operational procedures used in these tests, the 8-second averages result in one data point for about each 20 feet of travel. A total data volume of approximately 4000 data points was accumulated for the entire series of in-building measurements.

During the initial planning phase, the expected setup channel signal strength in the vicinity of each building was predicted from propagation contours of the cell sites in the Chicago AMPS System (see Fig. 1). Before measuring each building floor, the operator of the PMS noted the received signal strength indicator (RSSI) value at several locations on the floor. If it was determined that a high percentage of the area was served at signal strengths above the PMS receiver threshold, the operator proceeded to collect data at each setup channel frequency over the entire prescribed route for the selected building floor.

In the measurements made in the first building in the measurements program (Bell Laboratories, Naperville), a high degree of repeatability was noted when the measurements from PMS output tapes were compared for repeated runs. Based on these visual observations it was decided that a single pass at each frequency of interest would provide sufficient accuracy for measurements in the remaining areas.

A comparison of repeated measurements over a common route is shown in Table II. The results indicate run averages are repeatable within approximately 1 dB.

Table II—Repeatability of measurements*

Floor	Channel	First Run Avg. Level (dBm)	First Run Std. Dev. (dB)	Second Run Avg. Level (dBm)	Second Run Std. Dev. (dB)	Level Diff. (dB)
3	780	−93.7	7.2	−94.6	7.4	0.9
3	798	−109.3	6.5	−108.6	8.0	−0.7
5	780	−77.4	10.4	−78.0	11.2	0.6
5	788	−94.3	9.0	−94.7	9.6	0.4
5	798	−85.5	9.5	−85.0	9.0	−0.5

* Measurements made at Bell Laboratories, Naperville, IL.

VI. DATA PROCESSING

As the first step in data processing, all measurements are coded to associate them with major marker numbers. The coding identifies the:

1. Building
2. Floor number (or outside street-level data)
3. Serving frequency
4. Time of day
5. Number of 1-second samples included in each average
6. Type of interior area (six possible types)
7. Flags indicating:
   (a) repeated measurements
   (b) data to be rejected because of operational trouble
   (c) omission of N data points (beginning or end) for reasons of ambiguity.

The time-of-day information permits verification of the major marker sequence and data group duration.

Data become ambiguous when the transition from one major marker to the next is accomplished without halting the measurements system. The ambiguous data point (8-second sample) contains portions of data from two major markers; it is deleted from the database.

The outside street-level data are used for developing a reference for building penetration loss calculations. After the data are encoded, the processing is performed in four steps (or passes) as described below:

1. Initial processing of the data (Pass I) develops statistics for all data for each separate category (building, floor, area type, and channel frequency). Invalid data points are eliminated. A summary listing is provided that includes the number of entries, the number of entries below PMS threshold, the average power level, and the standard deviation for each group of data from categories of areas. In addition to this summary, histograms for each group are developed.

2. The second pass introduces the outside street-level reference information and combines it with the Pass I data. This produces a display of the data for each frequency with its differential level relative to the outside reference (penetration loss).

3. The third pass combines the penetration loss for all the measurement frequencies on common floors, as generated in Pass II. This allows penetration loss to be used as a base for further combining to classify losses by area type, floor level, etc.

4. The fourth pass combines the penetration loss data from Pass III across different buildings. In the combining process similar data from different buildings are weighted to compensate for differences in the data volume collected in each specific building. The weighted average loss for a class of data from several buildings represents equal contribution from each building. Pass IV generates information about the effects of classes of building locations (suburban vs. urban) and penetration loss by floor and area type, for all buildings.

VII. SIGNIFICANT CONCLUSIONS

The conclusions made as a result of our extensive measurements are as follows:

1. Urban vs. suburban—First-floor penetration loss measurements were processed for three different groupings of buildings. The urban (downtown Chicago) building penetration for three buildings shows an average value of 18.0 dB. The penetration loss distribution for suburban buildings has an average value of 13.1 dB. These statistics are listed in Table III. The comparison indicates a loss for the urban group that is approximately 5 dB greater.

2. Penetration loss sensitivity to transmitter location—Different penetration losses are measured on common floors of common buildings as a function of the specific serving-site identity. These differences arise when a building is served by multiple cell sites. The distribution of the "max-min" decibel values for such multisite penetration loss differences is plotted in Fig. 2. The average max-min penetration loss difference for all the data is 5.4 dB with a sigma of 4.6 dB. This

Table III—Penetration loss

Buildings	Floor	Loss (dB)	St. Dev. (dB)	No. of Bldgs.
Urban	1	18.0	7.7	3
Suburban	1	13.1	9.5	10
All	1	14.2	9.3	13
	2	10.6	8.5	8
	3	6.8	9.8	6
	4	−0.8	10.7	4
	5	2.9	9.2	3
	8	−4.3	9.0	1
	9	−1.4	8.8	1
	12	15.3	4.9	1
	15	10.9	5.0	1

suggests that building penetration is a relatively strong function of the direction of illumination.

3. Penetration loss sensitivity to interior type—Table IV compares all interiors with and without windows for all buildings and all floors. The presence of windows is shown to reduce the average penetration loss by 6 dB, with a sigma of 5.2 dB. Not included in the data is the office area of the Chrysler building in Elk Grove where the copper-sputtered glass windows blocked out all measurable signal levels. For the windowed data category, Table IV lists penetration loss for three combinations of interior types. Open interior areas are shown to have 3 dB less penetration loss than hallways.

4. Floor height effect—A list of building penetration loss values ranked by floor height is shown in Table II. The high values of loss for the twelfth and fifteenth floors of a single building are the result of the shadowing effect of adjacent buildings. While these buildings effectively sandwiched the subject building, the adjacent street areas were relatively open. This may be a relatively common occurrence in the urban core and would appear to substantiate the observations of Durante.[1] Figure 3 is a scatter diagram with a straight line fit for penetration loss vs. floor level. The dots indicate data points that represent decibel averages of penetration losses. For each floor, there is a data point for each channel that served that floor. Only floor levels having three or more data points are included in the diagram and the building described above was omitted. The mean values for all data on each floor are indicated by "X's." The "least-squares" straight line fit to these means is also shown. The slope of the line is −1.9 dB per floor. The first floor intercept is 10.4 dB. While this loss rate agrees closely with the findings in Refs. 1 and 2, the first-floor penetration loss is about 10 dB lower. Subsequent measurements by Bell Laboratories in the Newark, N.J., Cellular Test Bed have confirmed the ranges of loss values and loss rates presented in this paper. It is assumed that differences in penetration loss with respect to values reported previously are probably due to differences in the methods of establishing the outside street-level reference.

Table IV—Penetration loss comparisons

Windowed/nonwindowed areas = 6.0 dB	(Standard Deviation = 5.2 dB)
For windowed areas:	
where enclosed areas are in conjunction with hallways	
Enclosed/Hallways = 0 dB	(Standard Deviation = 6.0 dB)
where open areas are in conjunction with enclosed areas	
Open/Enclosed = 1.0 dB	(Standard Deviation = 4.8 dB)
where open areas are in conjunction with hallways	
Open/Hallways = 3.1 dB	(Standard Deviation = 5.2 dB)

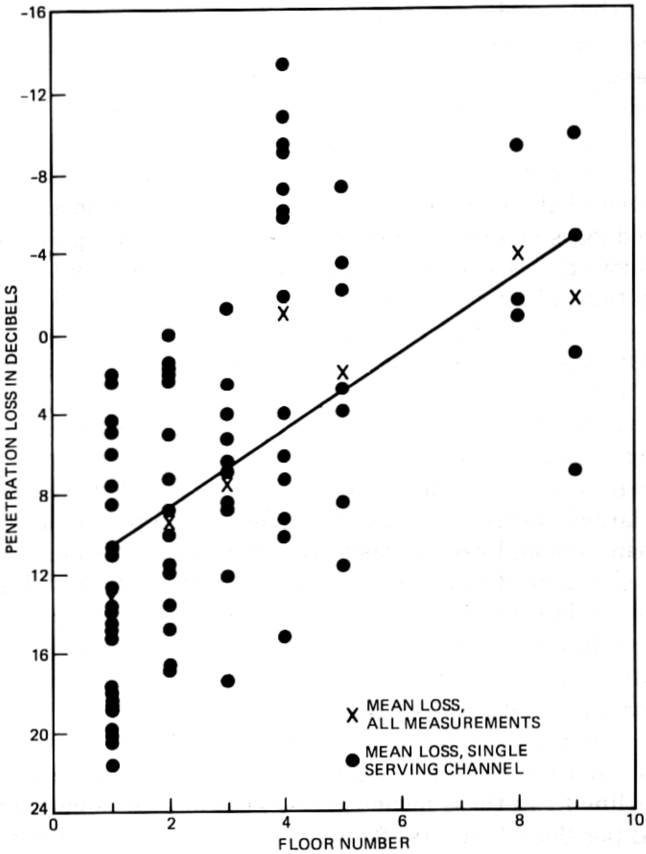

Fig. 3—Penetration loss measurements.

VIII. ACKNOWLEDGMENTS

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APPENDIX

Building Descriptions

A.1 *Nabisco, Naperville*

Surroundings: Open area, without nearby multistory buildings.

Construction: Masonry with some corrugated siding. The interior has some windowed office space but a large portion is devoted to cereal processing equipment.

Cell site signals: 1st floor—Eola
2nd floor—Eola, Lemont
4th floor—Cloverdale, Eola, Lemont.

A.2 *Metropolitan Life Insurance Co., Naperville*

Surroundings: Open area without nearby structures.

Construction: Large glass sections alternated with large concrete slab sections.

Cell site signals: 1st floor—Cloverdale, Eola
2nd floor—Cloverdale, Eola, Lemont
3rd floor—Cloverdale, Eola, Lemont.

A.3 *Bell Laboratories, Naperville*

Surroundings: Open area without nearby structures.

Construction: Low light transmission glass in metal framework. Mostly windowed halls with interior office space.

Cell site signals: 1st floor—Cloverdale, Eola
3rd floor—Cloverdale, Eola
5th floor—Coverdale, Eola, Lemont.

A.4 *Bell System Center for Technical Education, Lisle*

Surroundings: Open area without nearby structures. Located at the bottom of a hill to the East.

Construction: Brick and glass with high-rise dormitory area. Windowed office space.

Cell site signals: 1st floor—Cloverdale, Eola, Lemont
3rd floor—Cloverdale, Eola, Lemont
5th floor—Cloverdale, Eola, Lemont, Lyons
9th floor—Cloverdale, Eola, Lemont, Lyons

A.5 *Illinois Bell, Oak Brook*

Surroundings:	Stand-alone with other multistory buildings spaced several hundred yards distant.
Construction:	Brick and glass windowed office space and work space.
Cell site signals:	1st floor—Cloverdale, Eola, Lemont, Lyons 2nd floor—Cloverdale, Eola, Lemont, Lyons.

A.6 *McDonalds, Oak Brook*

Surroundings:	Stand-alone with other multistory buildings spaced several hundred yards distant.
Construction:	Narrow windows with concrete in a ratio of approximately 50 percent. Interior office space uses half-height dividers. First floor is a lobby area.
Cell site signals:	1st floor—Cloverdale, Lemont, Lyons 2nd floor—Lyons 8th floor—Cloverdale, Eola, Lemont, Lyons.

A.7 *Chrysler, Elk Grove*

Surroundings:	Open area without nearby multistory buildings.
Construction:	Concrete slabs, only one floor. The interior is a large warehouse with metal storage bins for automobile parts. An attached office building had no measurable signal because copper-sputtered windows constituted 100 percent of outside surface.
Cell site signals:	Cloverdale and Morton Grove.

A.8 *Allied Van Lines, Hillside*

Surroundings:	Residential area without nearby multistory structures.
Construction:	Concrete and glass with windowed office and work space.
Cell site signals:	1st floor—Lyons, Canal 2nd floor—Cloverdale, Lemont, Lyons 4th floor—Cloverdale, Lemont, Lyons, Canal, Morton Grove.

A.9 *Illinois Bell, Oak Park*

Surroundings:	Corner buildings in area with other multistory buildings of about same height.
Construction:	Brick and glass. Windowed office space and work space.
Cell site signals:	3rd floor—Lyons, Canal, Morton Grove 4th floor—Lyons, Canal, Morton Grove.

A.10 *Western Electric, Hawthorne*

Surroundings: Corner building without nearby structures.

Construction: Brick and smaller glass windows typical of factory construction. First floor is open area with heavy machinery; second floor is open area with assembly lines; third floor is office space with windowed space.

Cell site signals: 1st floor—Lyons
2nd floor—Lyons
3rd floor—Lyons, Canal, Morton Grove.

A.11 *Illinois Bell, Kedzie and 61st Street*

Surroundings: Corner building in area with other multistory buildings of similar height.

Construction: Brick and glass. Windowed office space and work space.

Cell site signals: 1st floor—Lyons, Canal, Beverly
4th floor—Lyons, Canal, Beverly.

A.12 *American Medical Association, State Street (Downtown)*

Surroundings: Bounded on all sides by streets or parking area.

Construction: Reflective glass windows and concrete. The interior office area is open with three-quarter partitions.

Cell site signals: 1st floor—Lyons, Canal, Morton Grove
2nd floor—Lyons, Canal, Morton Grove.

A.13 *Illinois Bell, Randolph (Downtown)*

Surroundings: Bounded on four sides by city streets. Neighboring buildings are multistory.

Construction: Concrete and glass with lobby on first floor and windowed work and office spaces on upper floors. Office partitions are three-quarter-high dividers.

Cell site signals: 1st floor—Canal
3rd floor—Canal
5th floor—Canal, Morton Grove, Beverly.

A.14 *Bell Training Center, West Adams (Downtown)*

Surroundings: Neighboring multistory buildings in a business district. The building front is open to the street and both sides abut neighboring buildings. The rear of the building opens into a service courtyard.

Construction: Concrete and glass. Interior upper floors have windowed office space.

Cell site signals: 1st floor—Canal
2nd floor—Canal
12th floor—Canal
15th floor—Canal.

A.15 *Private Home, Lombard*

Surroundings: Residential neighborhood.
Construction: Aluminum siding.
Cell site signals: Cloverdale, Eola, Lemont, Lyons.

The outside reference measurements for this building were incomplete because a complete perimeter path was not available. The measurements for this building are not combined with the results from other buildings.

The penetration loss for this building based on the available street-level reference measurements is 7.3 dB with a sigma of 6.7 dB.

AUTHOR

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