Measurement and Modeling of Propagation Losses in a Building at 900 MHz

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Abstract—**A contribution to the modeling of propagation losses in buildings is made by presenting results of measurements at 917 MHz, performed mainly in two large buildings of similar design, and by elaborating an empirical attenuation model based on estimates of "transmission," "reflection," and "diffraction" phenomena occurring in the transmission path. The modeling fits the data within ± 2 dB for 68% of the 729 measurements, the standard deviation between measurements and prediction being slightly less than 3 dB.**

I. Introduction

THE OPTIMAL design of cellular portable communication networks requires, among other things, a knowledge of propagation conditions and losses within buildings. There is a need to establish a prediction model of propagation losses taking into account the variability of architectural configurations, building materials, and the effect of frequency.

The purpose of this paper is to contribute to the modeling of propagation losses within buildings at UHF frequencies. Specifically, it presents results of measurements taken at 917 MHz, mainly in two large buildings of similar design, and it elaborates an empirical attenuation model based on these measurements.

The prediction method proposed requires a fairly detailed knowledge of the building configuration and associates a given communication link to three propagation situations which, in this paper, are denoted by the terms "transmission," "reflection," or "diffraction," respectively. Transmission would refer, for example, to the propagation losses due to obstacles; diffraction would refer to propagation around corners or adjacent corridors; and reflection to the signal gain which can be experienced when transmission and reception are taking place in the same room or corridor, for instance.

A number of studies and results related to signal attenuation at UHF frequencies within buildings can be found in the scientific literature. Among those which have influenced the work reported here, let us note first the papers by Alexander [1], [2] in which the author suggests in particular the use of a logarithmic law of the type $m \log(d)$ (d: distance, m: gradient function of building materials and structure). Also Patsiokas, Johnson, and Dailing [3], [4] have made measurements at 150, 450, and 850 MHz inside a large office building; they have provided results, in particular, for average attenuation versus distance on the same floor and between floors, and a number of indications relative to other factors such as fade depth and the effect of polarization. Kaji [5]–[7] makes the distinction between the attenuated wave component transmitted through walls and floors, the guided wave component transmitted through a corridor, and a penetration wave component reflected or diffracted by surrounding buildings.

This paper is organized as follows. Section II deals with the measuring equipment and the experimental site. Section III defines typical "transmission," "reflection," and "diffraction" phenomena observed in propagation within buildings. Section IV reports the different measurements and associates the measured losses to simple algebraic relationships of the type $y = a + b \log_{10} x$. Section V discusses results of a more qualitative nature, namely the standing wave patterns observed, the effect of antenna orientation or polarization, the effect of antenna height and furniture, the transmitter–receiver reciprocity, and transmission between floors through outside paths. Section VI is devoted to discussions and conclusions, and to an evaluation of how well the modeling fits the data. Finally, the Appendix presents in a short form a synthesis of the proposed model.

II. Experimental Conditions

The experiments have been conducted with a continuous wave emission at 917 MHz. A synthesized signal source was used as transmitter, with a transmit power of 10 dBm for most measurements and 19 dBm for the experiments between two floors and more. Spectrum analyzers were used as receivers, and these permitted measurements down to a threshold of −80 dBm. Quarter-wavelength monopoles with 3 dB gain were used, the ground plane being provided by four wires inclined at 45° to match antenna and coaxial cable impedances.

The transmit antenna was kept fixed for the measurements at a height of 1.7 or 2.5 m. For the signal strength measurements, the receiving antenna was moved, at a height of about 1.7 m, over an area of approximately one square meter and the average attenuation was noted, as visually estimated from the screen of the spectrum analyzer; this manual procedure was judged to carry an uncertainty of ± 1 dB.

Most of the measurements have been taken in two 50 000 square meter buildings, four to five stories high and some 200 m long, namely the Science and Engineering buildings at Laval University. Each building has a number of wings, distant by about 14 m, and offers a mixture of offices, laboratories, and classrooms; these buildings date back to the early 1960's. The floors are in reinforced concrete. They are some 18–25 m wide, supported by concrete beams (spaced 16 ft center

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to center), and held by concrete pillars (generally one pillar at each extremity and one in the middle). Internal walls are made of lightweight concrete and material about 15 cm thick, as are also the external walls, except that approximately half the external wall surface is covered by windows. Each floor is 4.5 m high, with a drop metallic tile ceiling at 3.5 m. Some measurements were also taken in a rectangular-shaped (some 30–40 m in length), relatively open industrial assembly room with metallic walls and high ceilings.

Propagation losses in free space are a function of transmit power, antenna gain, frequency or wavelength, and distance. Two parameters L_{OB} and G_{RM} are introduced to represent the losses due to obstacles or the gain caused by multiple reflections, respectively.

The received signal power P_R will then be given by

$$P_R = P_T + G_T + G_R + L_F + L_{OB} + G_{RM} \qquad (1)$$

where

P_R, P_T the received and transmitted powers,
G_R, G_T the receiver and transmitter antenna gains,
L_{OB} the loss due to obstacles,
G_{RM} the gain due to reflections,

and where the free space loss L_F is given by

$$L_F = 20 \log_{10} (\lambda/4\pi d) \qquad (2)$$

(λ: wavelength, d: distance).

The objective of this paper is to estimate or model the values of L_{OB} and G_{RM} in a variety of conditions within buildings.

III. Classification of Typical Propagation Cases

In our experiments and in the results reported in this paper, the measured signal levels are given relative to free space. Taking as an example the experiment illustrated in Fig. 1, three types of phenomena can be observed. First of all, it is noticeable that the measurements taken in direct line-of-sight in the main corridor are the only ones to show signal strength readings higher than in free space. This is the reflection condition, which is considered present when the geometry of locations associated to a line-of-sight propagation favors a wave canalization effect. The reflection represents a gain relative to free space attenuation.

The transmission phenomenon is well illustrated in rooms 1 and 2 and in corridors A, B, and C. The negative levels indicate losses higher than in free space. The level of these losses is smaller in room 1 and in corridors A and B, and one notes that, in these cases, the $T_x - R_x$ distance is shorter and the line joining the two antennas crosses fewer obstacles. Transmission is then considered here as the phenomenon by which the waves cross the different obstacles between transmit and receive antennas. The relative importance of each factor will be analyzed in the next parts of this paper.

The losses expected in corridors D and F and in room 4 should then be higher than those in room 2, because the number of obstacles along the line joining transmitter and receiver is more important. This is not the case, since the signal transmitted along the main corridor is diffracted toward these locations; hence we have what is called the "diffraction" phenomenon. For the resulting signal to be significant relative to the "transmission" signal crossing the different obstacles, the building configuration must provide ways to bring a strong signal near the receiving site: this can be the case, for example, in a room adjacent to a corridor, along which a signal is transmitted.

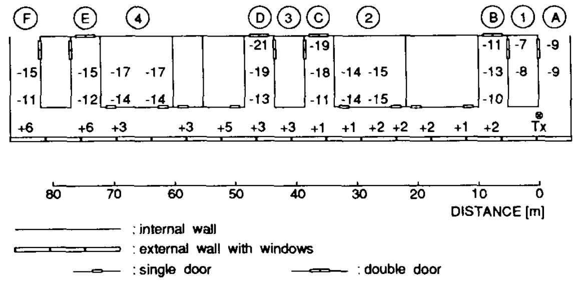

Fig. 1. Signal attenuation experiment (figures are in dB relative to free space loss).

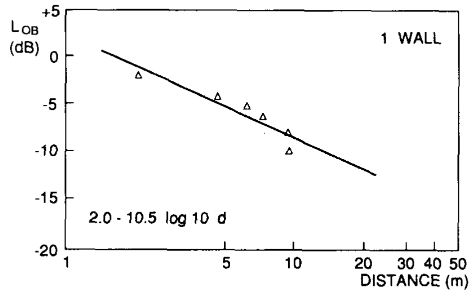

Fig. 2. Losses in function of distance (one wall).

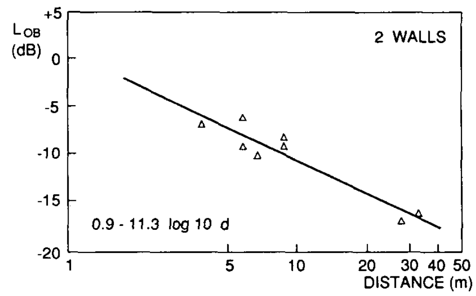

Fig. 3. Losses in function of distance (two walls).

IV. Measurements and Results

A. Transmission

Losses Through Walls: To isolate the transmission phenomenon, measuring sites have been chosen where the reflection and diffraction phenomena were considered negligible; that is, sites where there was no corridor parallel to the line joining transmitter and receiver. Figs. 2–5 give attenuation in excess of free space measured when the transmission path crosses one to four walls of the same type of construction, and when the first wall is at a distance of 3 m or less.

The observation of the regression lines (of the type $a - b \log(d)$, d: distance) in these figures indicates that the coefficients b of the logarithm keep about the same value, while

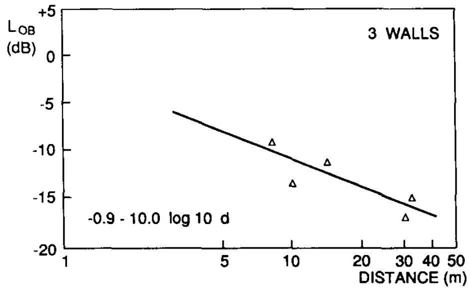

Fig. 4. Losses in function of distance (three walls).

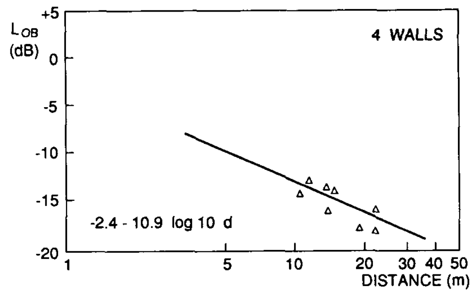

Fig. 5. Losses in function of distance (four walls).

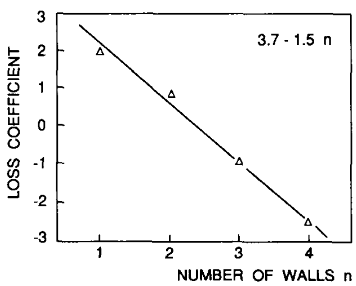

Fig. 6. Coefficient of loss in function of number of walls n.

the constant a decreases as the number of walls increases (Fig. 6). The resulting equation for the losses in excess of free space is

$$L_{OB} = 3.7 - 1.5n - 10.7 \log_{10}(d) \tag{3}$$

where

d the distance between transmitter and receiver (m),
n the number of walls in the transmission path.

Fig. 7 shows the difference between actual measurements and the value predicted by (3) in function of the distance d' between the transmitter and the first wall. When this distance becomes larger than 4 m, there is a change of slope, which leads to a modification of (3):

$$+\begin{cases} 0 & \text{if } d' < 4m \\ -7.8 + 15.3 \log_{10}(d') & \text{if } d' \geq 4m. \end{cases} \tag{4}$$

Losses Through Floors: As mentioned earlier, the floors in the buildings where the measurements were taken were of reinforced concrete and each floor was 4.5 m high with a suspended metallic tile ceiling at 3.5 m.

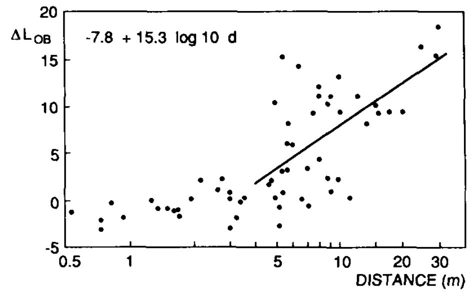

Fig. 7. Difference between measured losses and (3) in function of distance between transmitter and first wall.

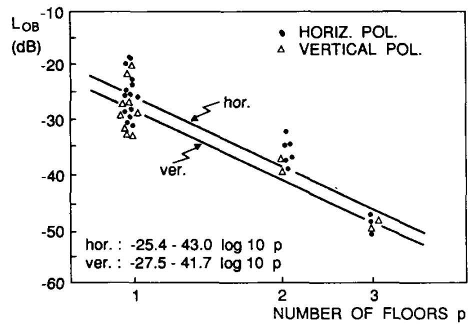

Fig. 8. Attenuation in function of number of floors.

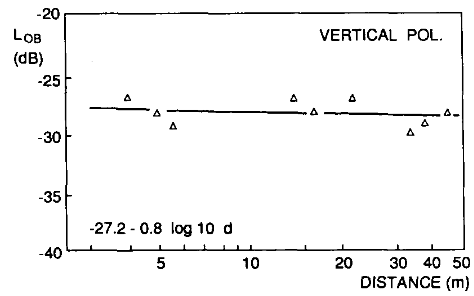

Fig. 9. Attenuation on next floor in function of distance (vertical distance fixed at 4.5 m).

Fig. 8 gives the attenuation observed as a function of the number of floors. Typical attenuation values are 22 dB for one floor, an additional 16 dB (38 dB) for a second floor, and an additional 10 dB (48 dB) for a third floor. These measurements are representative of average signal strength levels over a five square meter area and refer to cases where the transmitting and receiving antennas were aligned in the vertical direction.

Fig. 9, taken for the case of transmission between two adjoining floors, shows that the effect of distance in the horizontal direction is not very significant in itself, once one has taken out the normal increase of attenuation with distance predicted by the free space equation.

Transmission losses between floors can be described then by the following equation:

$$L_{OB\text{ final}} = L_{OB\text{ initial}} - 27.5 - 41.7 \log_{10} p \tag{5}$$

where p is the number of floors.

The effect of stairways has not been found significant except

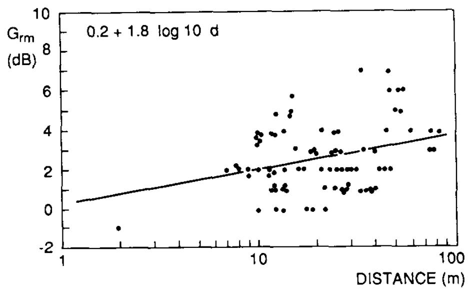

Fig. 10. Attenuation (gain) in corridor (without obstruction).

on the next floor, near the stairway, where additional signal levels on the order of 7 dB have been measured.

Other Cases: Other cases have also been studied; namely the effect of doors (when they are open), of windows, and of window screens. In the case of furniture, it has been found that the effect of low-level office furniture (chairs and desks) was not significant with the antenna heights considered. A synthesis of all results is given in the Appendix.

B. Reflection

When a wave encounters an obstacle, there will be reflections, which can be canalized by certain wall configurations and which bring about significantly higher signal levels than would be the case with free space propagation. This effect has been observed in corridors and in large rooms when there was no obstruction between antennas.

The case of corridors without any obstruction is illustrated in Fig. 10, and the associated gain is described by the following equation:

$$G_{RM} = 0.2 + 1.8 \log_{10}(d). \quad (7)$$

A similar reflection phenomenon is observed in large rooms (Appendix).

Corridors with Transversal Doors: A behavior different from (3), (6), and (7) has been obtained for corridors obstructed with transversal doors, commonly called fire doors, as are normally found in corridors of public buildings, and which were in this case double doors made of wood with a glass window. This behavior was also present when the doors were open, but one must point out that, in a corridor 3.5 m in height and 2.3 m in width, a door opening of 2 by 1.6 m is only a partial opening. This, of course, raises the question of changes in propagation modes caused by obstructions.

Figs. 11 and 12 illustrate the observed behavior. It appears from the measurements that the distance between the transmitter and the obstructing doors determines the slope of the loss factor behind the doors (i.e., the coefficient of the logarithm of distance). This suggests that segments of corridor be taken, starting from the transmitter, using the end value of a segment as the initial value of the next one. Procedures and relationships are given in the Appendix.

C. Diffraction

This effect, when present in locations adjacent to zones of strong power level—such as corridors, where a transmission antenna is located—will tend to generate in these locations

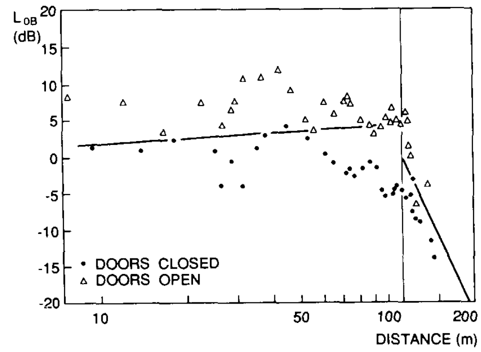

Fig. 11. Attenuation in corridor with transversal door at 112 m.

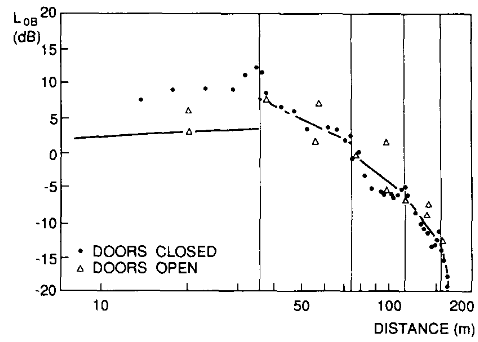

Fig. 12. Attenuation in corridor with transversal doors at 35, 74, 112, and 152 m.

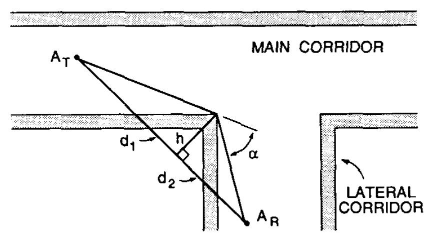

Fig. 13. Geometric diffraction parameter (h) for lateral corridor opening on main corridor.

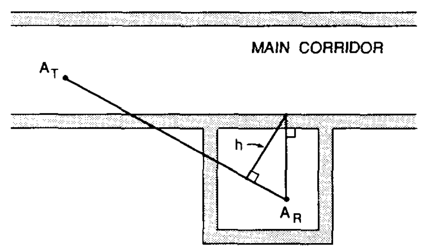

Fig. 14. Geometric diffraction parameter (h) for room adjacent to corridor.

signal levels higher than would be predicted by simple transmission.

In theory, attenuation caused by sharp edge diffraction behaves according to Huygen's principle and can be described using the Fresnel parameter ν. The computation of ν for each location of interest is somewhat tedious. Instead, a "geometric diffraction" parameter h—defined as in Fig. 13 for the case of a lateral corridor, or as in Fig. 14 for the case of a

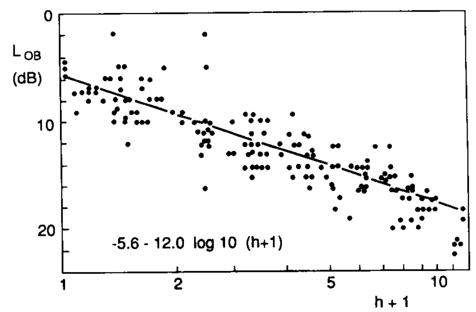

Fig. 15. Attenuation in excess of free space for lateral corridors located at 30 m or more from transmitter.

room adjacent to a main corridor where the signal source is located—has been used here.

Measurements in lateral corridors located more than 30 m from the transmit antenna are reported in Fig. 15. The straight line in the figure is the predicted attenuation value in excess of free space and is given by

$$L_{OB} = -5.6 - 12 \log_{10}(h + 1) \quad d > 30m. \tag{8}$$

V. Other Factors

This section is devoted to more qualitative discussions and observations on the measurement results. The topics treated include the standing wave pattern, the statistics of the received signal envelope in function of distance, the effect of polarization, the lack of transmitter-receiver reciprocity in some cases, and propagation through outside paths.

A. Standing Wave Pattern and Probability Density of the Envelope

A number of standing wave patterns in function of distance have been measured with a spatial resolution on the order of 5 cm. As expected for this wavelength, distances of about 15 cm between fades have been observed.

When moving from or toward the transmitting antenna in a corridor or a room, large fades on the order of 10–20 dB are generally noticeable. The envelope probability density $f_R(r)$, normalized to a standard deviation of unity, appears slightly Rician but comes close to a Rayleigh law, with its peak located near $r = 1$ at a probability level of 0.5.

In locations where the signal is especially strong, such as in corridors and rooms where both transmit and receive antennas are located, some samples taken show much more shallow fades, typically less than 10 dB, and the probability density of the envelope $f_R(r)$ shows a broad peak extending from $r = 1$ to $r = 3$ at a probability level of 0.3, as is typical of a Rician law normalized to a standard deviation of unity.

When the receiving antenna displacement is transversal relative to the transmitting antenna, the fades are more spaced. In corridors at a large distance from the transmitter (35 m), the number of lobes in the standing wave pattern diminishes significantly: situations with only one to three lobes in a 2.3-m-width corridor have been observed.

B. Polarization–Antenna Orientation

The relationships given in this paper are valid for the vertical polarization of a monopole antenna. A number of experiments have been conducted, however, with horizontal polarization, and these can provide some insight into the effect of polarization and antenna orientation.

Horizontal polarization has been observed to have an advantage of about 2 dB relative to vertical polarization for transmission between different floors. This advantage is not significant in practice, considering the high attenuation experienced from floor to floor. Experiments have shown that, on the same floor, vertical polarization has an advantage of at least 4 dB, which is compatible with the characteristics of the antenna pattern.

C. Antenna Height-Effect of Furniture

As mentioned earlier, these experiments were conducted with the receive antenna at a height of about 1.7 m and the transmit antenna at a height of 1.7 or 2.5 m. At those heights, it has been found that small or medium size low-height office furniture had little effect on attenuation. As will be noted in the Appendix, high nonmetallic furniture (including office separators) attenuation has been estimated at 1 dB, with 2–4 dB in the case of high metallic furniture.

D. Lack of Transmitter–Receiver Reciprocity

In free space, propagation losses are identical if one interchanges receiver and transmitter locations. Within buildings, this reciprocity is not always observed. This observation stems, in particular, from (4)—where the distance between the transmitter and the first wall is taken into account—and from the situation in corridors obstructed by transversal doors.

Equations (6) and (7), relative to signal strength in a corridor and toward the end of a corridor, are also representative of nonreciprocal relationships. If an antenna at the center is transmitting to an antenna at the corridor end, (7) is applicable; and (6) in the reverse situation.

E. Propagation Through Outside Paths

To identify the possibility of significant outside transmission paths near windows, experiments have been made with the transmission antenna located near a window and the reception antenna in the room below. Comparable levels of losses in the lower room have been measured wherever the transmit antenna was located in the upper room, even with a parallel building wing outside at a distance of some 14 m. This result applies, of course, to monopole antennas and a moderate height building.

VI. Conclusion

It is clear that the influence of different building materials and the great variability in architectural configurations limit the accuracy of any model and its applicability to a prediction method for signal attenuation within buildings. There will be a spread between the predicted and the real (measured) signal strength values.

To form an opinion about the accuracy of the model and its eventual applicability for prediction, Fig. 16 presents the probability density of the estimation error e obtained for a large number of measurements. One notes that 68 percent of these measurements fall within ± 2 dB of the estimated level

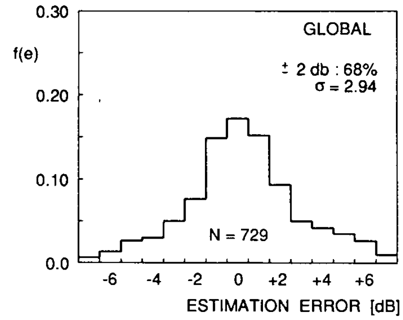

Fig. 16. Probability density of estimation error. *All measurements at all distances.*

TABLE I
PERCENTAGE OF ESTIMATES WITH ERROR SMALLER THAN ±2 dB AND STANDARD DEVIATION OF ESTIMATION ERROR, IN FUNCTION OF DISTANCE

Distance (m)	% (±2 dB)	σ
0–10	79	2.32
10–20	76	2.43
20–30	68	2.88
30–40	63	3.27
≥40	59	3.34

and that the standard deviation of e is slightly lower than 3 dB. It is clear, however, from Fig. 16 that there always remains a certain number of cases where the estimation error is important (i.e., 6 dB, 1–2% of the cases).

Probability densities of the estimation error for different ranges of distance have been obtained with shapes similar to Fig. 16, and with the characteristics of Table I. The accuracy decreases with the increase in distance, which of course corresponds to increasing uncertainty and diversity in architectural configuration, geometry, furniture, building materials, etc.

The experimental study described in this paper has permitted the construction of a model of propagation losses in a building. The method used requires a fairly detailed knowledge of the building architectural configuration and consists of identifying the prevailing propagation phenomena—called in this paper transmission, reflection, or diffraction—and of describing the propagation losses due to these phenomena by relationships of the type $y = a + b \log_{10} x$.

The study reported here is limited to one frequency and one type of building construction. In addition, a number of points have not been or have been only partially studied, such as the effect of antenna height and exact location (i.e., near a ceiling or a wall), the distance between floors and the effect of stairways, and the propagation conditions in large rooms. Also, the propagation within buildings of radio waves emitted from outside locations has not been touched. As it stands, then, this study is a contribution to a field of growing interest but is by no means the final word.

It is considered, however, that the approach itself, which consists in modeling the losses in excess of free space, is of general value and that it is worth being extended to cover a variety of cases to obtain more than a modeling—perhaps as a technique of prediction for propagation losses within buildings.

APPENDIX

SUMMARY OF THE MODEL

A. General

The results apply to a vertical quarter-length monopole antenna. Power levels and losses are in decibels. Distances are in meters:

$$P_R = P_T + G_T + G_R + L_F + L_{OB} + G_{RM} \quad (9)$$

$$L_F = 20 \log(\lambda/4\pi d). \quad (10)$$

B. Specific Cases

Emission in a room: see G.

Emission in a corridor: reception in same corridor; see D
reception in lateral corridor; see E
reception in room adjacent to corridor; see F

C. Obstacles, General Case ($G_{RM} = 0$ if not Otherwise Indicated)

1) n Walls Between Antennas:

$$L_{OB} = 3.7 = 1.5n - 10.7 \log_{10} d + \begin{cases} 0, & \text{if } d' < 4m \\ -7.8 + 15.3 \log_{10} d', & \text{if } d' \geq 7m \end{cases} \quad (11)$$

where d' is the distance transmitter to first wall. (*Note*: 1 corner = 1 wall; 1 thin wall = 1/2 wall; 1 thick wall = 2 walls.)

2) Door Between Antennas:

y: distance behind door (m),
θ: angle between $T_x - R_x$ line and door wall or window.

- Door open ($\theta > 30°$), no other wall:

$$\begin{array}{lll} \text{if } y \leq 2, & L_{OB} = 0, & G_{RM} = 2 \\ \text{if } 2 < y < 10, & L_{OB} = 0, & G_{RM} = 0 \\ \text{if } y \geq 10, & L_{OB} = -2, & G_{RM} = 0. \end{array} \quad (12)$$

- Door closed (or open with $\theta < 30°$), no other wall:

$$\begin{array}{lll} \text{if } y \leq 2, & L_{OB} = -2, & G_{RM} = 0 \\ \text{if } y > 2, & \text{eq. (11) with } n = 1 & \end{array} \quad (13)$$

- Walls and doors:

$$\begin{array}{l} x_1 \text{ doors and } x_2 \text{ walls } (x_2 > 0) \\ \text{eq. (11) with } n = x_1 + x_2. \end{array} \quad (14)$$

3) Windows Between Antennas:

$$\begin{array}{lll} \text{1 window,} & \theta > 45° & L_{OB} = 0 \\ \text{1 window,} & \theta < 45° & \text{eq. (11) with } n = 1 \\ \text{1 window,} & x \text{ walls} & \text{eq. (11) with } n = x \\ \text{2 windows} & & \text{eq. (11) with } n = 1 \\ \text{2 windows,} & x \text{ walls} & \text{eq. (11) with } n = x \\ \text{3 windows,} & x \text{ walls} & \text{eq. (11) with } n = x + 1. \end{array} \quad (15)$$

4) Furniture Between Antennas:

- Nonmetallic furniture

$$L_{OB} = \text{eq. (11)} - 1. \quad (16)$$

- High, metallic furniture

$$\begin{array}{ll} \text{with wall} & L_{OB} = \text{eq. (11)} - 2 \\ \text{without wall} & L_{OB} = -4. \end{array} \quad (17)$$

5) Propagation Between Buildings (Exterior Distance <80 m)

Equation (11) :(1 window + 1 screen = 1 wall).

6) Propagation Between Floors:

$$\begin{array}{l} L_{OB\ \text{final}} = L_{OB\ \text{initial}} - 27.5 - 41.5 \log_{10} p \\ p\text{: number of walls.} \end{array} \quad (18)$$

Note: The attenuation on the next floor, in front of the stairway, will be some 7 dB less, if the stairway is open.

D. Emission in a Corridor

1) Main Corridor, No Transversal Doors:

$$G_{RM} = 0.2 + 1.8 \log_{10} d. \quad (19)$$

2) End of Corridor (last 8 m), No Obstacle:

$$G_{RM} = 1.6 + 3.9 \log_{10} d. \quad (20)$$

3) Main Corridor with Transversal Doors (Doors Closed or Open, with Significant Frame):

- In front of doors: see D-1.
- Behind doors: solve following equations sequentially for each corridor segment between doors, as if one gradually moved the receiver away from the transmitter.

$$L_{OB} \text{ or } G_{RM} = b_k + m \log_{10}(d) \quad (21)$$

where

$$m = -0.0067k^2 + 2.35,$$

$$b_k = P_k - m \log_{10}(k)$$

and where

k distance between transmitter and the last obstructing door (nearest the receiver),
P_k signal level estimated at k m (i.e., at the end of preceding corridor segment).

E. Lateral Corridor Opening on Main Corridor (d > 30 m)

1) No Door at Junction:

$$L_{OB} = -5.6 - 12 \log_{10}(h + 1). \quad (22)$$

2) Door at Junction:

Door open: see (22)
Door closed: see (23)

F. Room Adjacent to Corridor (d > 30 m)

$$L_{OB} = -7.6 - 11.5 \log_{10}(h + 1). \quad (23)$$

G. Emission in a Room

1) Within the Same Room:

$$G_{RM} = 0.2 + 1.8 \log_{10}(d) \quad (24)$$

if furniture, see subsection C-4.

2) In Adjacent Room:
See general case, subsection C-1.

3) In a Corridor in Line of Sight:

$$L_{OB} = -3 \log_{10}(d). \quad (25)$$

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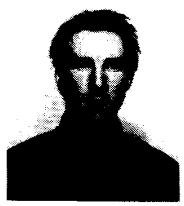

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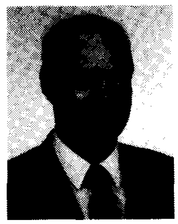

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