Outdoor-to-Indoor Propagation Loss Prediction in 800-MHz to 8-GHz Band for an Urban Area

Hideaki Okamoto, Koshiro Kitao, *Member, IEEE*, and Shinichi Ichitsubo, *Member, IEEE*

Abstract—**In mobile communication systems, it is important to clarify the outdoor-to-indoor propagation loss (building penetration loss) characteristics to improve the quality of communication within buildings. This paper proposes a penetration loss prediction formula that is derived based on measurement results. We measured and analyzed the building penetration loss at higher frequencies that are appropriate for the next-generation system. We measured the propagation loss on 71 floors in 17 buildings in an urban area using four frequencies in the 800-MHz to 8-GHz band. The measurement results showed that the attenuation based on the penetration distance is 0.6 dB/m, the floor height gain is 0.6 dB/m, the constant value for the penetration loss is 10 dB, and there is no frequency dependence of the penetration loss in the frequency range from 0.8 to 8 GHz.**

Index Terms—**Buildings, mobile communication, modeling, propagation measurements, radio propagation.**

I. INTRODUCTION

IN MOBILE communication systems, the coverage area must fully extend inside the buildings. To design an indoor radio link, a formula that predicts the building penetration loss is needed. In future systems, higher frequencies, for example, 5 GHz, will be used, and the prediction formulas must be able to handle these higher frequencies.

Environment: The building penetration loss has been investigated in the following two propagation environments. 1) A street microcell environment: The path between a base station (BS) and an outdoor location in front of the building is line-of-sight (LOS). 2) A macrocell/microcell environment: The path between the BS and an outdoor location in front of the building is non-LOS (NLOS). In 1), the penetration losses for the street microcell [1]–[5] and satellite communications [6]–[8] were investigated. Because the propagation mechanisms for 1) and 2) are different, these environments should be investigated separately. Indoor locations, such as inside residences [9], [10] and office buildings [11]–[20], were investigated. The target of this paper is an office building in a microcell environment.

Frequency characteristics: Up to the present, there have been many reports investigating building penetration loss. However, there are few investigations on the characteristics over a wide frequency range. Thus, it is not clear whether the building penetration loss increases, decreases, or does not change as the frequency increases.

Berg proposed two prediction formulas for a street microcell and a macrocell/microcell in COST 231 [11]. These prediction formulas that target practical use are derived based on a great deal of measurement data and are expressed as detailed characteristics. The applicable frequency range of these prediction formulas is 900–1800 MHz. In Berg's report, the angle-dependent penetration loss is described to increase to 2 dB at 1800 MHz, compared with 900 MHz in a macrocell/microcell environment.

Davidson *et al.* proposed a method for determining the frequency characteristics in the 35-MHz to 3-GHz band based on former measurement data [8], [13]–[15] and their measurement data at 900 and 1500 MHz [12]. In their study, the frequency characteristics showed that the penetration loss decreases at the rate of 7.9 dB/dec as the frequency increases. However, the presented frequency characteristics exhibited a deviation, and so the frequency characteristics are still open to interpretation. To clarify the frequency characteristics, multiple frequencies over a wide range should be measured at the same time using the same measurement method, and the measured data should be analyzed statistically.

Floor height gain: References [16]–[19] reported that the measured floor height gain was approximately 2 dB/floor, and the overall frequency range is 150 MHz to 1.4 GHz. References [13] and [14] reported that the floor height gain was 1.4 dB/floor in the 900- to 2300-MHz band. The preceding floor height gains are converted to 0.7 and 0.5 dB/m when the story height is 3 m. The floor height gain of COST 231 [11] is 0.6 dB/m, as described in Section IV. The previous reports indicate that the floor height gain is approximately 0.6 dB/m in the frequency range of up to 2 GHz. However, the floor height gain in the frequency range above 2 GHz is not clear.

Distance attenuation: COST 231 proposes that the distance attenuation value of 0.6 dB/m be used, which is given by measurements for a street microcell [11]. However, the recommended value for distance attenuation has not yet been verified by measurements for a macrocell/microcell. Verification based on the measurement results in a wide frequency range is still required.

In this paper, the investigation criteria for the building penetration loss are given below. The environment type is a microcell in an urban area, the building type is an office building, the

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H. Okamoto is with the Network Planning Department, NTT DoCoMo, Inc., Tokyo 100-6140, Japan (e-mail: okamotoh@nttdocomo.co.jp).

K. Kitao is with the Radio Access Development Department, NTT DoCoMo, Inc., Kanagawa 239-0847, Japan (e-mail: kitaok@nttdocomo.co.jp).

S. Ichitsubo is with the Radio Access Development Department, NTT DoCoMo, Inc., Kanagawa 239-0847, Japan, and also with the Department of Electrical Engineering, Kyushu Institute of Technology, Fukuoka 804-8550, Japan (e-mail: ichitsubo@ecs.kyutech.ac.jp).

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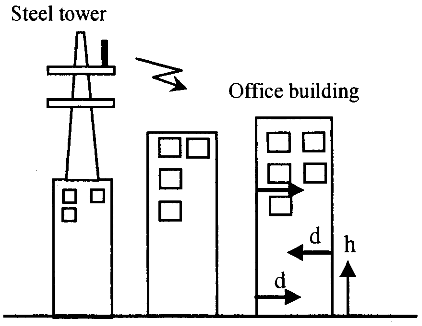


Fig. 1. Investigation environment.

target location is a room with windows, and the frequency range is 800 MHz to 8 GHz.

The second-generation mobile communication system mainly uses the 800-MHz band, and the third-generation system uses the 2-GHz band in Japan. Moreover, future systems may use the 5-GHz band. Therefore, these frequencies were used in the measurement. A frequency higher than 8 GHz was also measured to improve the reliability of the frequency characteristics. The reason for the improvement in the reliability is given hereafter. If it is assumed that the penetration loss monotonously changes due to the frequency, the difference in the penetration losses will be large when the difference in the frequencies is large. When the measurement error of the penetration loss is a constant value, the measurement error of the gradient of the frequency characteristics can be improved by using a higher frequency.

Fig. 1 shows the investigation environment. This paper explains the measurement results in buildings and proposes a prediction formula for the building penetration loss from 800 MHz to 8 GHz.

II. CONSTRUCTION OF PREDICTION FORMULA

A. Prediction Formula of Cost 231

For reference, the prediction formula for the penetration loss proposed in COST 231 is expressed in the following. The applicable condition for this prediction formula is NLOS [environment 2)], and the applicable frequency range is 0.9–1.8 GHz. That is

$$\begin{aligned}\Delta\text{Loss} &= \text{Loss(in)} - \text{Loss(out)}\\ &= \text{We} + \text{Wge} + \max(\Gamma_1, \Gamma_3) - G_{FH}\\ \Gamma_1 &= W_i \cdot p\\ \Gamma_3 &= \alpha \cdot d\\ G_{FH} &= n \cdot G_n \text{ or } h \cdot G_h \end{aligned} \tag{1}$$

where Loss(in) is the propagation loss between the BS and the receiver inside the building, and Loss(out) is the propagation loss between the BS and the receiver outside the building. The term "We" is the loss due to the perpendicular penetration at an external wall, and the value of "We" is 4–10 dB (concrete with a normal-sized window: 7 dB; wood: 4 dB). The term "Wge" is the loss at the external wall (angle-dependent loss). The value of "Wge" is 3–5 dB at 900 MHz and 5–7 dB at 1800 MHz. The term "Wi" is the loss in the internal walls, and the value of "Wi" is 4–10 dB (concrete walls: 7 dB; wood and plaster: 4 dB). The term "p" is the number of penetrated internal walls. "α" is the penetration distance coefficient, and the value of "α" is 0.6 dB/m. The term d is the penetration distance, and "G_n" is the floor height gain. The value of "G_n" is 1.5–2 dB/floor when the story height is less than 4 m, and 4–7 dB/floor when the story height is 4–5 m. The term "G_h" is the floor height gain, and the value of "G_h" is 1.1–1.6 dB/m when the story height is 4–5 m. The term "n" is the floor number, and the ground floor is expressed as $n = 0$. The term "h" is the height above the ground.

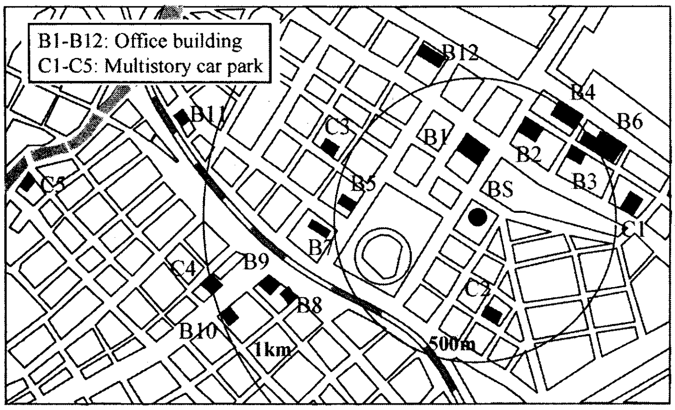


Fig. 2. Location of measured buildings and BS.

B. Construction of Prediction Formula

The propagation parameters and those functions to predict the building penetration loss are as follows:

$$\begin{aligned}\Delta\text{Loss} &= \text{Loss(in)} - \text{Loss(out)}\\ &= \alpha \cdot d - G_h \cdot h + \alpha_f \cdot \log(f) + \alpha_{\text{LOS}} \cdot \text{LOS} + W \end{aligned} \tag{2}$$

where ΔLoss is the building penetration loss, Loss(in) is the propagation loss between the BS and the receiver inside the building, and Loss(out) is the propagation loss between the BS and the receiver, which is on a road that runs around the building. All the losses are in decibels. The distance d is the perpendicular distance to the inside from the nearest window, h is the height of the receiver from ground level, f is the frequency, LOS is the condition of the LOS between the BS and the place at the window on the measured floor (LOS: LOS $= 1$, NLOS: LOS $= 0$), and W is the difference between Loss(out) and Loss(in) at the window and is a constant value. α, G_h, α_f, and α_{LOS} are the penetration distance coefficient (distance attenuation), floor height gain, frequency coefficient, and LOS coefficient, respectively. In this paper, the loss of the inside wall W_i is not examined.

III. MEASUREMENT FOR OFFICE BUILDINGS

A. Measurement

The propagation losses were measured in 12 office buildings in an urban area in Yokohama, Japan. The BS is established

TABLE I
DETAILS OF THE MEASURED BUILDINGS

Symbol in Fig. 2	Kind of building or building's owner	Distance from BS (m)	Number of floors (F)	Story height (m)	Building interval (m)
B1	Public facilities (Media, Communications)	180	12	3.5	31
B2	Hotel	240	9	3.0	15
B3	Public facilities (Meeting, Seminar)	310	3	3.0	13
B4	Public facilities (Industry, Trade)	350	9	3.1	23
B5	Non Profit Organization	380	8	3.1	16
B6	Concert hall	410	6	3.2	20
B7	City Office	480	2	3.5	42
B8	Hotel	580	11	3.0	15
B9	Public facilities (Education)	635	10	3.0	30
B10	Public facilities (Culture)	790	8	3.0	10
B11	Foundation	900	13	3.1	16
B12	Prefectural office	465	13	3.0	26
C1	Multistory car park	421	10	3.0	24
C2	Multistory car park	286	8	3.0	15
C3	Multistory car park	464	7	2.8	13
C4	Multistory car park	807	9	3.0	23
C5	Multistory car park	1300	7	3.0	24

on a steel tower affixed to the NTT Yamashita building, and the height of the BS is 80 m. All the buildings used in the measurements are within approximately 1 km from the BS. Fig. 2 shows the location of the BS and the measured buildings (indicated as B1–B12). Table I shows details pertaining to the measured buildings. Table I shows the building type or building purpose, the distance from the BS, the number of floors, the height of the story, and the building interval. The building interval is the space between buildings that contains a roadway and a sidewalk. The building interval shown in Table I is the average of the building intervals on all sides of the target building. In the distribution of the building height in the measurement area, the 10%, 50%, and 90% cumulative values are 3F, 6F, and 10F, respectively.

Four continuous-wave (CW) radio signals for the narrowbands of 0.81, 2.2, 4.7, and 8.45 GHz are used in the measurement, and the radio signals are simultaneously measured. Since the propagation loss does not depend on the frequency band, a narrowband was used to simplify the measurement.

Four transmitters and four sleeve antennas are installed in the BS. All the transmission outputs are 20 W. The mobile site is a utility cart equipped with four receivers and four sleeve antennas. The output signals of the four receivers and the distance pulse generator are recorded by a digital audio recorder. The height of the receiver antennas is 1.5 m from the floor. The 136 measurement courses are measured on 50 floors within 12 buildings.

Fig. 3 shows the number of measurement courses for each floor. The number of LOS courses is also shown in Fig. 3. All the measurement rooms face the windows and are offices, meeting rooms, lobbies, or classrooms. Table II shows the number of courses for each measurement location. The measurement courses are straight and perpendicular to the window. The average length of the measurement courses is 8 m, and the standard deviation is 4 m. The received level is sampled in 1-cm intervals, and the median values of each 1-m section are calculated. The average height of a story for the 12 buildings is 3.1 m, and the standard deviation is 0.2 m. Table III gives the measurement features.

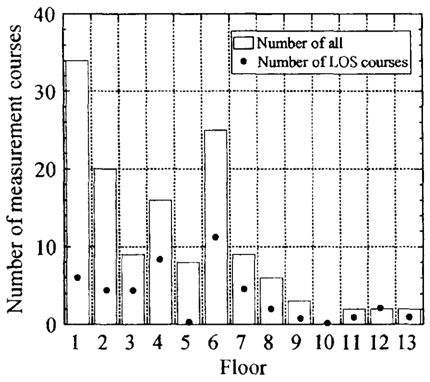


Fig. 3. Number of measurement courses for each floor.

TABLE II
MEASUREMENT PLACES

Measurement places	Number of courses
Meeting room	42
Passageway	36
Classroom	22
Lobby	16
Exhibition room	9
Banquet hall	3
Rest room	3
Entrance hall	3
Office	2
Total	136

The construction material for the measured buildings is reinforced concrete and not brick or wood boards. All the windowpanes in the measured room are general glass and not shielded glass, such as metal glazed windows or wire glass. The average number of windows per room is approximately 1.

TABLE III
MEASUREMENT FEATURES (OFFICE BUILDINGS)

Frequency	0.81, 2.2, 4.7, 8.45 GHz
Base station	Steel tower (height: 80 m)
BS antenna	Sleeve antenna (for all frequencies)
MS antenna	Sleeve antenna (for all frequencies)
Measurement location	12 buildings, 50 floors, 136 courses
Course length	Average: 8 m, Standard deviation: 4 m
Floor	1-13F

TABLE IV
SIZE OF WINDOW

	Window		Windowpan	
	Height (m)	Width (m)	Height (m)	Width (m)
Average	2.0	3.8	1.7	1.3
Standard deviation	0.8	1.5	0.6	0.5

In the measurement, the 136 courses included office buildings, and there were 53 courses (39%) in which an entire wall consisted of windows. In the remaining 83 courses, the greater part of the wall is covered with windows, the window height is 1.5–2 m, and the width of the window is about equal to the width of the wall with the window. Table IV shows the size of the windows. The "Window" in Table IV represents the entire window, and the "Windowpane" only represents the window glass. The "Window" consists of multiple windowpanes. In all of the window sizes in the 136 measurement courses, the average height of the window is 2.0 m with the standard deviation of 0.8 m, and the average width of the window is 3.8 m with the standard deviation of 1.5 m. The statistical values of the size of the windowpanes are also shown in Table IV. In all the measurement courses, the thickness of the windowpane is 3–10 mm based on visual observation.

The outdoor propagation loss is measured in the same way as that for the inside. The outdoor measurement course follows a path around the building and comprises four roadways. The measurement vehicle is used for the mobile site. Loss(out) is the average of all 1-m median values over the measurement course.

B. Measurement Results and Analysis

1) Penetration Distance Characteristics: Fig. 4(a) shows an example of the dependency of the propagation loss Loss(in) on the penetration distance. The measurement results shown in Fig. 4(a) are the average of 43 courses, the lengths of which are greater than 10 m. The propagation loss increases according to the increase in the penetration distance.

Fig. 5 shows the penetration distance coefficient α versus frequency. The penetration distance coefficient in each building is calculated for each frequency, and the average value of all the office buildings or all the multistory car park is calculated for each frequency. Eight average values are shown in Fig. 5. The standard deviation that each average value has is approximately 0.6. Fig. 5 shows a tendency in which the penetration distance coefficient increases with an increase in frequency. However, the rate of the increment is small in comparison with the standard deviation that each average value has.

To show the deviation in the penetration distance coefficient for each building, the average of the penetration distance coefficient is calculated using all the frequencies in each building. Fig. 6 shows the penetration distance coefficient for each building. The horizontal axis indicates the distance between the BS and the building. The penetration distance coefficient does not depend on the distance between the BS and building. The average value for the penetration distance coefficient is $\alpha = 0.67$ dB/m for office buildings.

2) Floor Height Characteristics: The penetration loss decreases in proportion to the floor height. Fig. 7 shows the floor height gain G_h for each frequency. The floor height gain in each building is calculated, and the average value for all the buildings is calculated. Based on Fig. 7, we did not observe the distinct frequency characteristic of the floor height gain.

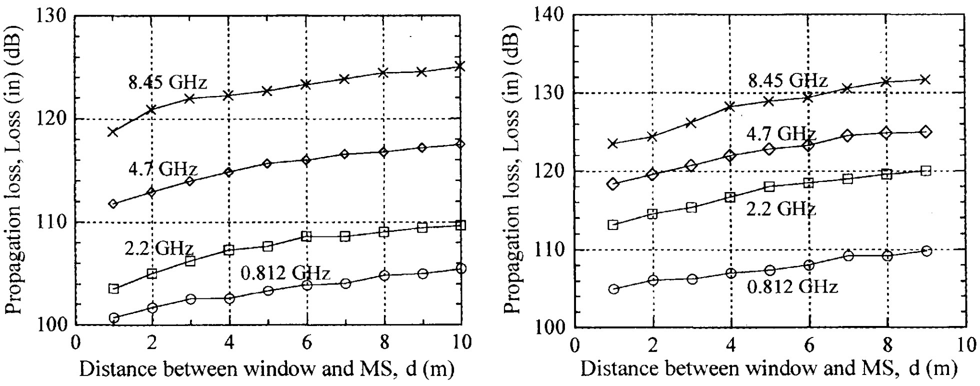
The average of the floor height gain is calculated using all the frequencies in each building. Fig. 8 shows the floor height gain for each building. The horizontal axis indicates the distance between the BS and the building. The floor height gain does not depend on the distance between the BS and the building. The average value of G_h is 0.58 dB/m for office buildings.

3) Frequency Characteristics: The average values of the propagation losses Loss(in) between the BS and the receiver are calculated for each frequency. Fig. 9 shows the frequency characteristics for the propagation loss. The frequency coefficient of Loss(in) in Fig. 9 is close to 20, which is the same as that for free space loss. The distance between the BS and the building or the measured floor height is different for each building. The average of the propagation losses in the office buildings or multistory car parks includes these differences. Therefore, the difference in the loss between the office buildings and the multistory car parks in Fig. 9 is relative.

Fig. 10 shows the frequency characteristics for the building penetration loss ΔLoss. The difference in the loss between the office buildings and the multistory car parks is also relative because the measured floor height is different for each building. The vertical axis indicates the relative value. Since the frequency coefficient for the outdoor propagation loss Loss(out) is also close to 20 (more precisely 19.8), the building penetration loss is independent of the frequency. It was reported that the frequency coefficient of Loss(out) for an outdoor cellular environment is close to 20 [21], [22].

Fig. 11 shows the frequency coefficient for each building. The average value for the frequency coefficient is $\alpha_f = -0.6$ for office buildings.

4) Multiple Regression Analysis: In Sections I–III, each characteristic is extracted from the measured data and investigated. Multiple regression analysis, which is a synthetic analytical method, is executed to verify the foregoing analysis results. Multiple regression analysis is a kind of multivariate analysis. Multiple coefficients that properly approximate the measurement data can be found using multiple regression analysis. When the found coefficient is 1, using multiple regression analysis is the same as using the least square method. The measured data that are used in multiple regression analysis are the median values of each 1-m section for the building



(a)

(b)

Fig. 4. Propagation loss Loss(in) versus distance d. (a) Office building. (b) Multistory car park.

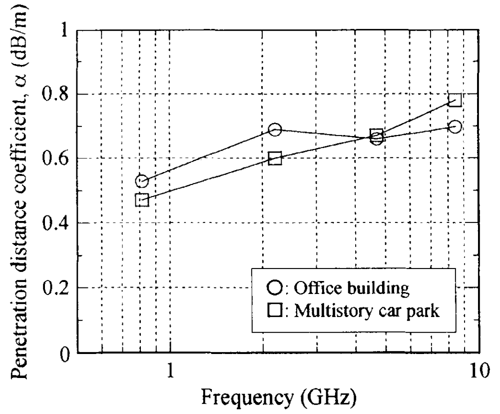


Fig. 5. Penetration distance coefficient versus frequency.

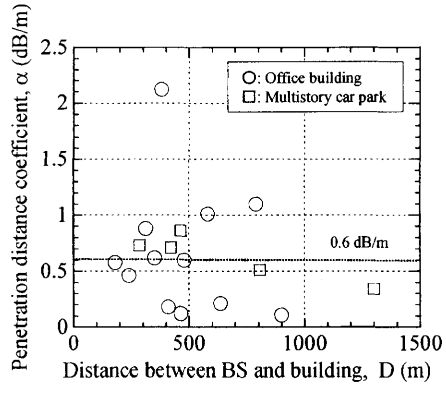


Fig. 6. Penetration distance coefficient.

penetration loss. The coefficients α, α_f, and α_{LOS} that can properly approximate the measurement data are found through multiple regression analysis using the variable and the function shown in (2).

The multiple regression formula based on (2) using all the measured data is expressed as

$$\begin{aligned}\Delta\mathrm{Loss} = {} & 0.41d - 0.50h - 2.1\log f \\ & -0.8\mathrm{LOS} + 11.5 \quad \text{(in decibels)}. \qquad (3)\end{aligned}$$

When the values of the measurement conditions are assigned to the variables d, h, f, and LOS in (3), the prediction value

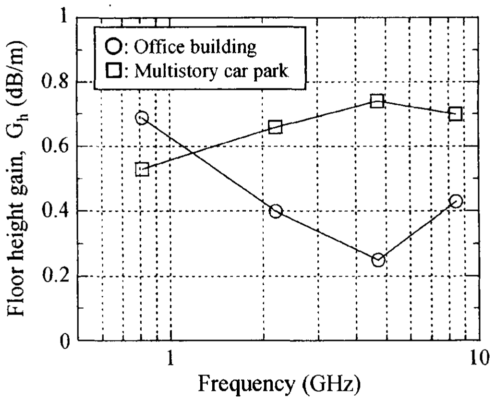


Fig. 7. Floor height gain versus frequency.

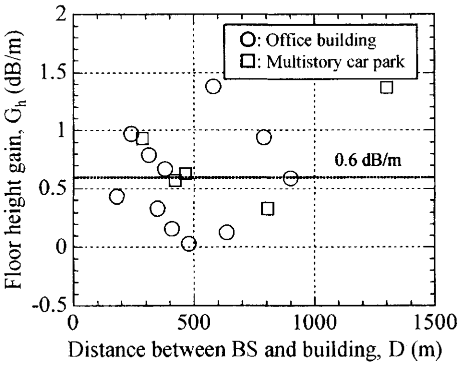


Fig. 8. Floor height gain.

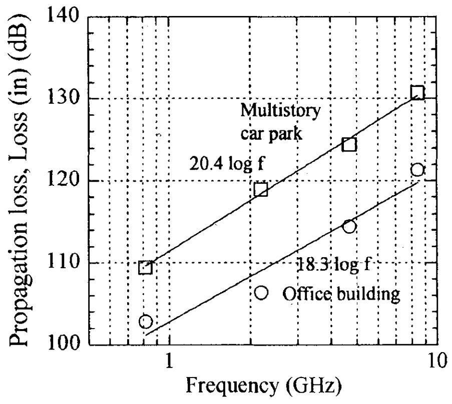


Fig. 9. Frequency characteristic of propagation loss Loss(in).

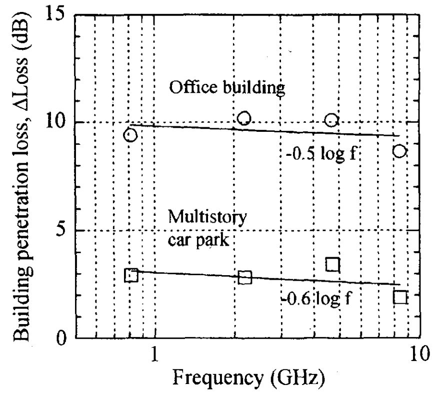


Fig. 10. Frequency characteristic of building penetration loss ΔLoss.

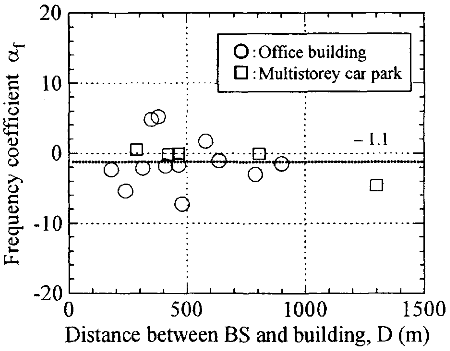


Fig. 11. Frequency coefficient.

of ΔLoss is calculated. The difference between this prediction value of ΔLoss and the measured value is called the residual. The root mean square (RMS) value of the residual for (3) is 7.7 dB from the results of multiple regression analysis. The values of each coefficient for (3) are close to those shown in Figs. 6, 8, and 11, respectively. Therefore, the validity of the analysis results is confirmed.

IV. MEASUREMENT FOR MULTISTORY CAR PARKS

A. Measurement

The propagation losses are measured in five multistory car parks in the same urban area to obtain positive evidence for the penetration loss characteristics. It is easy to establish the measurement courses in a multistory car park in comparison with an office building. For example, in the measurement for the floor height characteristics, it is desirable to vertically measure at the locations in the same building. In a multistory car park, it is easy to keep the locations vertically aligned. Therefore, since the adjustment of the measurement conditions is easy, stable characteristics are observed.

Fig. 12 shows an example of the multistory car park. The other multistory car parks also have a similar structure. The windows of the multistory car park occupy approximately 50% of the wall. The percentage of windows in the multistory car parks is approximately the same as that in the office buildings. All the multistory car parks do not have glass for the windows, and this condition is different from the office building.

The measurement method is the same as that in the office buildings. The BS is the same as well. Twenty-one courses are measured on 21 floors within five buildings. The measurement floors are 1F to 9F. The average length of the measurement courses is 14 m, and the standard deviation is 3 m. The average height of a story for the five buildings is 3.0 m, and the standard deviation is 0.1 m.

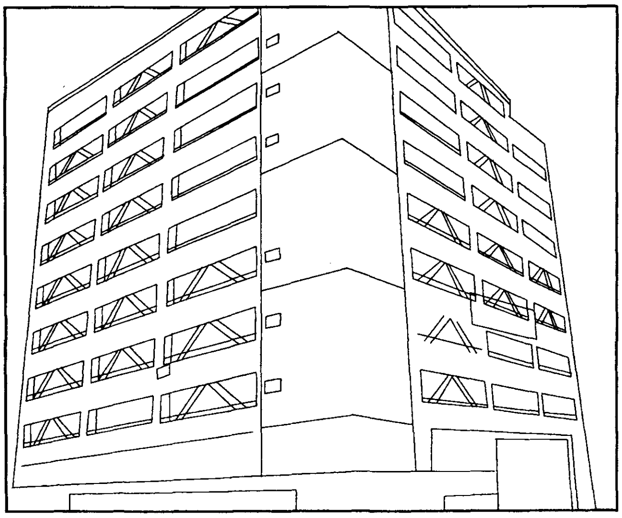


Fig. 12. Example of the measured multistory car park.

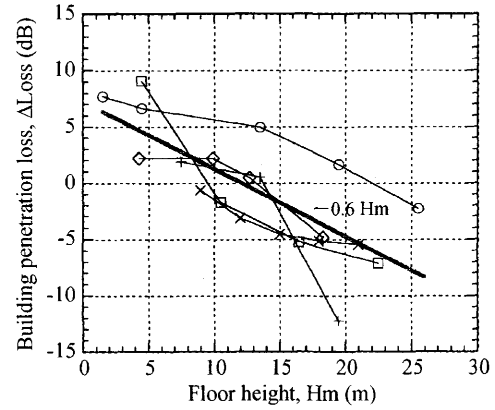


Fig. 13. Floor height gain characteristic (multistory car park).

B. Measurement Results and Analysis

The measurement data for multistory car parks are processed in the same way as those for the office buildings. Fig. 4(b) shows that the propagation loss Loss(in) depends on the penetration distance. These losses are the average of the propagation losses for all the measured courses. Figs. 5–11 show each characteristic for the multistory car parks. The characteristics are plotted using the symbol "□" in the graphs. The characteristics for the multistory car parks are similar to those for office buildings. In Figs. 6 and 11, the dispersion of the coefficients for the multistory car parks is small.

Fig. 13 shows the floor height characteristic for five multistory car parks. The averaged gradient of five curves is $G_h = 0.6$ dB/m. The height of the high floor for measurement is roughly equal to the height of the surrounding buildings. Therefore, the floor height characteristics for when the height of the floor is higher than that of the surrounding buildings are not obtained.

TABLE V
PROPOSED PREDICTION FORMULA

Proposed formula
ΔLoss = 0.6 d – 0.6 h + 10 [dB]

Applicable range
ΔLoss: Penetration loss
d: Distance from window 0-20 m
h: Floor height 1.5-30 m
Frequency 0.8-8 GHz
Area: Room or hallway with window

The multiple-regression formula using all the measured data for multistory car parks is expressed as

$$\Delta\text{Loss} = 0.51d - 0.69h - 0.63\log f - 3.9\text{LOS} + 9.2 \quad \text{(in decibels)}. \quad (4)$$

The residual is 4.4 dB. The penetration distance coefficient, floor height gain, and frequency coefficient in (4) are approximately the same as those for office buildings. The values for the LOS coefficient are slightly different for both, but the reason for the difference is not clear. The constant loss for the office building is greater by 2 dB. The reason for the difference of 2 dB may be the influence of the loss of glass.

V. INVESTIGATION OF PREDICTION FORMULA

A. *Proposed Prediction Formula*

The results in Figs. 6, 8, and 11 and those derived from (3) and (4) show that the penetration loss characteristics for multistory car parks are similar to those for office buildings. The results can be expressed as follows. If limited to the penetration loss, a multistory car park can be included as a kind of office building.

Therefore, the averages of α, G_h, and α_f are calculated using the measurement data for multistory car parks and office buildings shown in Figs. 6, 8, and 11. The calculated average values are $\alpha = 0.6$ dB/m, $G_h = 0.6$ dB/m, and $\alpha_f = -1.1$. These values are shown by dotted lines in Figs. 6, 8, and 11.

Considering the dispersion of the measured values, the constant loss of $W = 10$ dB is used, which is rounded off from the value $W = 11.5$ in (3). The frequency characteristics are removed since the fluctuation in loss is small within the applicable frequency range. The fluctuation in the loss is approximately 1 dB (0.1 to -1.0 dB) in the frequency range from 0.8 to 8 GHz using loss $= -1.1\log f$ for the frequency characteristic.

The prediction formula for the penetration loss is proposed as follows for NLOS conditions (LOS = 0):

$$\Delta\text{Loss} = 0.6d - 0.6h + 10 \quad \text{(in decibels)}. \quad (5)$$

Table V shows the proposed prediction formula and the applicable range. The applicable range for the distance from the nearest window is 0–20 m, the applicable frequency is 0.8–8 GHz, and the applicable area is a room or hallway with a window. The applicable range of the floor height is 1.5–30 m, which is as high as the height of the surrounding buildings. The prediction formula for (5) is evaluated using the prediction error based on the measured data. For office buildings and multistory car parks under NLOS conditions, the average of the prediction error is 0.5 and -3 dB, and the RMS value for the prediction error is 11 and 9 dB, respectively. The average values of the prediction error are low, but the RMS values are large. The reason for this is that the deviation due to each measurement point is large.

TABLE VI
TRANSMISSION LOSS (IN DECIBELS) [23]

Material	Frequency (MHz)			
	457	920	1,450	2,200
Brick (60mm)	3.2	1.3	0.8	1.4
Brick (water content)	6.0	1.9	3.1	5.8
Concrete (100mm)	4.6	4.9	7.6	10.9

TABLE VII
REFLECTION LOSS (IN DECIBELS) [24]

Material	Frequency (GHz)					
	0.5	0.6	0.7	1	6	10
Concrete	4.0	7.5	0.5	7.5	8.0	9.0
Reinforced Concrete	5.5	7.0	9.5	9.5	8.0	9.0

For office buildings and multistory car parks under LOS conditions, the average of the prediction error is -2.3 and -7.5 dB, respectively. The average values for the prediction error increase under LOS conditions. The average values for the prediction error for each frequency were calculated, but the differences in the values are small.

B. *Investigation*

First, the transmission and reflection coefficients of the radio waves for a specific frequency are confirmed [23], [24]. Tables VI [23] and VII [24] show the transmission coefficients of concrete and brick, and the reflection coefficients of concrete, respectively. All the building materials of the measurement building were concrete. The brick in Table VI is shown for reference. In Tables VI and VII, the reflection/transmission coefficients change based on the frequency but do not monotonously change due to the frequency.

The Fresnel diffraction loss for the size of the window is investigated. When even the size of the window is half of the first Fresnel zone, the diffraction loss does not become large based on the theory of the Fresnel zone. When the distance between the window and the transmission point is infinite, the radius of the first Fresnel zone r_1 at the window is expressed as $r_1 = (d\lambda)^{0.5}$, where d is the distance between the window and the received point, and λ is the wavelength. When the frequency is at its lowest (810 MHz), and the distance d is 10 m, r_1 is 1.9 m (the diameter is 3.8 m). If the window is wider than its width, and the height of the window is 2 m, the size of the window is larger than half of the first Fresnel zone. Therefore, a diffraction loss does not occur, and the difference in the diffraction losses for different frequencies does not occur.

The applicable frequency range for the COST [11] prediction formula is 0.9–1.8 GHz, and that for the proposed formula is expanded to 0.8–8 GHz. This means that the applicable range of each coefficient is expanded to 0.8–8 GHz in the proposed formula.

The penetration distance coefficient for the proposed formula is 0.6 dB/m, and this value is the same value previously proposed by COST.

COST describes that the floor height gain can be divided into two groups, i.e., in the range of 1.5–2 dB/floor and 4–7 dB/floor. The latter values were taken from buildings with story heights of approximately 4–5 m. As the story heights for our measured buildings are approximately 3 m, our floor height gain was compared with the former values for COST. When the story height is 3 m, the former values (1.5–2 dB/floor) can be translated to 0.5–0.67 dB/m. This value is the same as our proposed value. Since no clear frequency dependency of the floor height gain appears in Fig. 7, it is assumed that the floor height gain is a constant value.

In terms of the frequency characteristics, COST indicates that the angle-dependent penetration loss increases to 2 dB at 1800 MHz compared with 900 MHz. On the other hand, [12] describes that the penetration loss decreases to −7.9 dB/dec as the frequency increases. In our measurement, however, the frequency coefficient is small, as shown in Figs. 10 and 11. We use the frequency coefficient of zero.

COST proposes a constant loss $W(= \mathrm{We} + \mathrm{Wge})$ in which the perpendicular penetration loss We is 7 dB (concrete with normal window size), and the angle-dependent loss Wge is 3–5 dB (900 MHz) and 5–7 dB (1800 MHz). Therefore, the constant loss W for COST is 10–14 dB. Our constant loss $(W = 10\ \mathrm{dB})$ is almost equal to the COST value.

The outdoor propagation loss-prediction formula is required to predict the propagation loss within a building. For example, the outdoor prediction formula for a microcell in 0.8–8 GHz is proposed [22], [25], and it is expressed as

$$\mathrm{Loss} = 54 + 40 \log d - 30 \log \mathrm{hb} + 21 \log f \quad \text{(in decibels)} \quad (6)$$

where Loss is the propagation loss between a BS and an outdoor receiver, d is the distance between the BS and the outdoor receiver, hb is the height of the BS, and f is the frequency. The applicable ranges of the parameters are $100 \leq d \leq 3000$ m, $10 \leq \mathrm{hb} \leq 100$ m, and $0.8 \leq f \leq 8$ GHz. The propagation loss within a building can be predicted using such a prediction formula.

VI. CONCLUSION

The building penetration loss in an urban area has been investigated for the radio link design of the next-generation mobile communication system. The propagation loss was measured in 12 office buildings and five multistory car parks. The measurement data were statistically analyzed, and the characteristics for building penetration loss were shown. The obtained results are as follows.

1) The characteristics for building penetration loss are as follows in office buildings in an urban area at the frequency range of 0.8–8 GHz. The penetration distance coefficient is 0.6 dB/m, the floor height gain is 0.6 dB/m, the frequency coefficient is 0, and the constant loss is 10 dB.

The noteworthy results are that the frequency coefficient of the penetration loss is small in the frequency range of 0.8–8 GHz, and the measured value is $\alpha_f = -1.1$.

2) The prediction formula for the building penetration loss is proposed based on the preceding results.

This paper has shown the statistical penetration loss characteristics of buildings. However, the outdoor-to-indoor propagation mechanism was not sufficiently clarified. It is important to derive a prediction formula based on the propagation mechanism. These are our future objectives.

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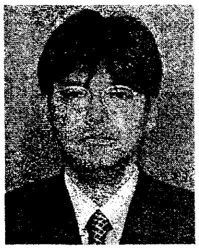
Hideaki Okamoto was born in Kanagawa, Japan, in 1968. He received the B.E. and M.E. degrees in science engineering from Saitama University, Saitama, Japan, in 1992 and 1994, respectively.

In 1994, he joined the Wireless System Communications Laboratories, Nippon Telegraph and Telephone (NTT) Corporation, Kanagawa, Japan. Since 1994, he has been engaged in the research and development of access systems and radio propagation for mobile communication systems. He is currently the Manager of the Network Planning Department, NTT DoCoMo, Inc., Tokyo, Japan. His current interests include watching the bioelectromagnetics trend and confirming the safety of the operation for wireless communications.

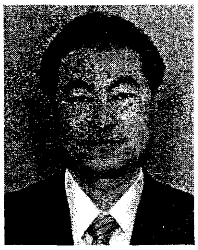
Mr. Okamoto is a member of the Institute of Electrical, Information, and Communication Engineers (IEICE) of Japan.



Koshiro Kitao (M'04) was born in Tottori, Japan, in 1971. He received the B.S. and M.S. degrees from Tottori University in 1994 and 1996, respectively.

Since 1996, he has been with the Wireless Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan, where he has been engaged in the research and development of radio propagation for mobile communications. He is currently an Assistant Manager with the Radio Access Network Development Department, NTT DoCoMo, Inc., Kanagawa.

Mr. Kitao is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan.



Shinichi Ichitsubo (M'94) was born in Kagoshima, Japan, in 1963. He received the M.S. and Ph.D. degrees in electrical engineering from Kyushu University, Fukuoka, Japan, in 1988 and 2001, respectively.

Since 1988, he has been with the Wireless System Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan, where he has been engaged in the research and development of radio propagation for mobile communication systems. Since 1999, he has been a Senior Engineer with NTT DoCoMo, Inc., Kanagawa. He is also currently an Associate Professor with the Department of Electrical Engineering, Kyushu Institute of Technology, Fukuoka.

Dr. Ichitsubo is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan. He received the IEEE AP-S Japan Chapter Young Engineer Award in 1993.