Experimental Study of Radio Propagation Characteristics in an Underground Street and Corridors

YOSHIO YAMAGUCHI, MEMBER, IEEE, TAKEO ABE, MEMBER, IEEE, AND TOSHIO SEKIGUCHI, SENIOR MEMBER, IEEE

Abstract—**This paper reports experimental results of radio propagation characteristics both in an underground street and in corridors in a large building. Measurements were carried out on horizontal and vertical polarization characteristics on the propagation loss in a frequency range from 200 MHz to 12.4 GHz. The influence of pedestrians on the attenuation constant is also measured in the underground street. It is shown from experiments that there are optimum frequency bands for the minimum attenuation constant in these structures.**

Key Words—**Propagation, UHF, microwave, underground street, building corridors, optimum frequency, minimum attenuation constant.**
Index Code—**J8b/f, J4b/f.**

I. Introduction

CONSIDERABLE attention has been given to the subject of radio propagation in tunnels, coal mines, corridors in buildings, and underground streets from the viewpoint of wireless communication systems such as cordless telephones and portable phones for emergency, disaster, and so on [1]–[4]. On the other hand, propagation characteristics of radio frequency (RF) signals in buildings or indoors will become an important factor for EMC problems. For example, high-frequency noise may cause trouble with the receiving equipment. It seems worthwhile to investigate the propagation characteristics in these structures at various frequencies.

Underground streets and corridors in buildings, in general, may be regarded as rectangular waveguides similar to tunnels. However, the environment for radio propagation is somewhat different from that of tunnels, because there are many obstacles or scatterers along these structures. These scatterers are pedestrians and irregularly sized projections, such as pillars, signboards, metallic plates, etc. The environment also depends on the traffic density of pedestrians.

Many theoretical analyses have been presented [1]–[8] on the propagation characteristics in tunnels; however, the frequency range under consideration is limited up to the UHF band. According to the theoretical results on the propagation characteristics, the attenuation constant decreases monotonically as frequency increases, i.e., the attenuation constant is inversely proportional to the frequency squared in the UHF band. Therefore it will be expected that in the higher frequencies above the UHF band, there is an optimum frequency for minimum attenuation, because the scattering loss and/or the absorption loss by rough surfaces will become the dominant factor for attenuation. On the other hand, experimental measurements, which have been carried out mainly on VHF and UHF bands [1]–[4], [8], [9], are still needed in higher frequencies above the UHF band.

We measured attenuation constants in a frequency range from 200 MHz to 12.4 GHz in an underground street and in corridors in a building to provide fundamental data for radio communications and for EMC problems. Experiments were performed for horizontally and vertically polarized waves in empty guides, and then in an underground street crowded with pedestrians.

This paper reports the experimental results on the field strengths along these structures and in the transverse cross sections. Attenuation constants are derived by the field strengths along the guide based on the least-squares method. Then the attenuation constants are compared with theoretical ones based on waveguide theory. It is shown from the experimental results that there are optimum frequency bands for minimum attenuation, and that the influence of pedestrians on the propagation characteristics extends over a wide frequency range from UHF to X band, causing additional fluctuation and attention.

II. Experiment

A. Underground Street

The underground street under test was Nishibori ROSA, located in Niigata-shi, Japan. Fig. 1 shows the view and dimensions. The floor, ceiling, and side walls of the underground street are covered with tiles and plastic boards on a ferro-concrete surface as are those walls of ordinary underground streets. Irregularly sized projections, such as signboards, lighting fixtures, and pillars, are placed over the entire surface of the side walls and ceiling. Local variations in the level of surface or projection height relative to the mean surface level are 10–80 cm. Outside the side walls there are many stores which are open during the day and closed, using metallic shutters (about 5 m in width, 2.5 m in height), at night. Also, in the daytime there are many people walking over all regions with an average traffic density of about 2–3 persons/10 m; however, there is no one and no traffic at night. The

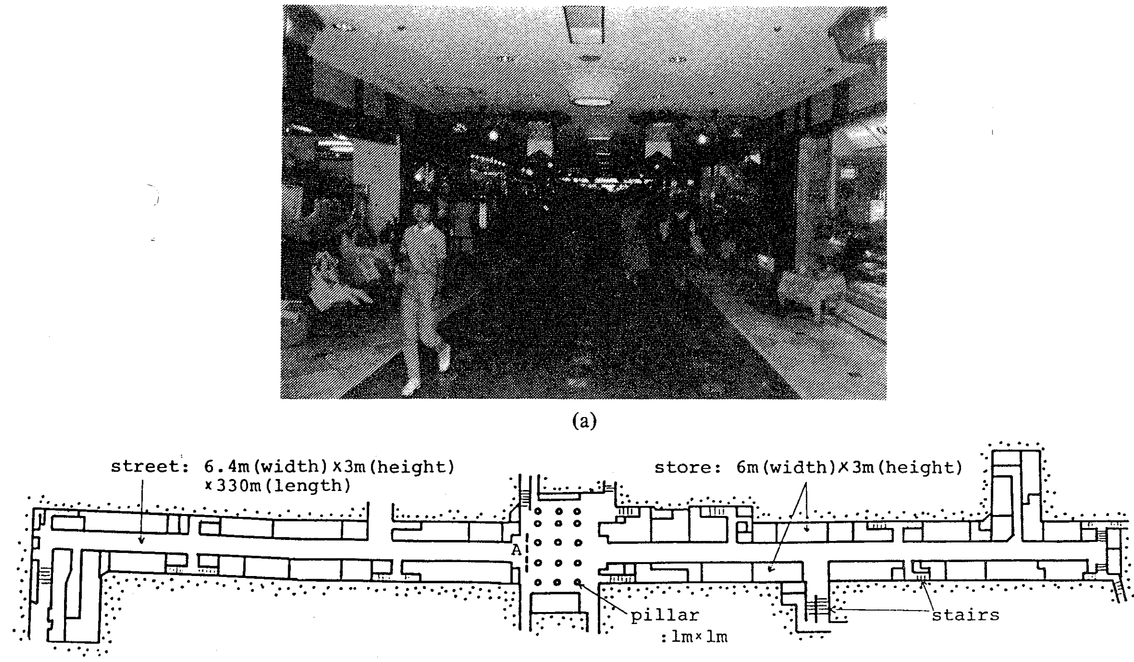
Manuscript received October 22, 1985; revised February 10, 1986. This work was supported in part by the Grant in Aid of the Education Ministry of Japan: Encouragement of Young Scientists under Grant (A) 59750254.

Y. Yamaguchi and T. Abe are with the Department of Information Engineering, Faculty of Engineering, Niigata University, Ikarashi, 2-no-cho, 8050, Niigata 950-21, Japan. 0252-62-6751.

T. Sekiguchi is with Tokyo National Technical College, 1220-2, Hachiouji, Tokyo 193, Japan. 0426-61-3066.

IEEE Log Number 8608937.

0018-9375/86/0800-0148$01.00



(a)

(b)

Fig. 1. Underground street under experiment. (a) Photograph in the daytime. (b) Plane view.

underground street becomes an empty waveguide at night.

A block diagram for the measuring apparatus is shown in Fig. 2. Transmitting and receiving antennas used were five handmade pairs of rectangular horns (above 1 GHz) and two pairs of Yagi dipole arrays with 5–8 elements (below 1 GHz). A transmitting antenna was fixed at the center of the cross section and almost at one end of the underground street. We used a sweep oscillator as a signal source (maximum output power 50 mW) and a spectrum analyzer as a receiver in order to obtain continuous frequency characteristics. The spectrum analyzer was connected to a personal computer, where the output field strength (continuous spectrum) was recorded into a minifloppy disk. In the measurement, we moved the receiving instrument along the underground street at intervals of 1.1 m, corresponding to the interval of tiles on the floor.

Preceding the propagation test, we measured the RF environment by the spectrum analyzer and confirmed that there was no ambient noise in the measurement frequency range. Hence, the received field strength was all due to the transmitter.

We have not measured the propagation characteristics on the orthogonal polarization (horizontal to vertical or vice versa). Also, calibration on the measuremental setup was not done because we could not measure the absolute field strength by our instruments. On the other hand, the relative field strengths in the region far from the transmitter are sufficient to determine the propagation characteristics; hence, we limit our analysis or discussion in the far region only.

B. Corridors

The employed corridors in the measurement were straight ones located between lecture rooms in a building of the Faculty of Engineering, Niigata University, Niigata, Japan.

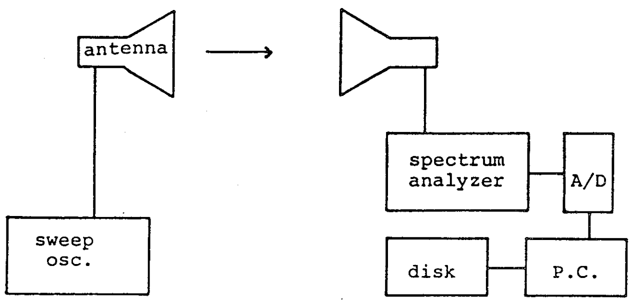


Fig. 2. Block diagram for the measuring apparatus.

The dimensions of these corridors are shown in Figs. 3 and 4. The side walls of both corridors are made mainly of concrete surfaces, partially of wooden doors with glass windows, and metallic plates about 1 by 0.7 m on concrete walls. The thickness of the concrete side wall is 15 cm. Ceilings are made of wood combined with plaster board with a thickness of about 1 cm, and latticed metal pipes are placed behind the ceiling board at intervals of 30 cm. One of them in Fig. 3 (hereafter abbreviated as Corridor D) has rough-surface side walls, i.e., metallic lockers (1.8 m in height, 2.5 m in width, and 0.5 m in depth) that are placed in contact with concrete side surfaces, and are situated at random along the corridor length. The area of metallic wall is about 1/3 of the total side-wall area. Another corridor in Fig. 4 (abbreviated Corridor A) has side walls with small roughness, i.e., projections are door knobs, lights, and metallic plates on concrete walls, of which projection height into the corridor is less than 10 cm.

We measured the relative field strength in these corridors in a way similar to that for the underground street. The interval of receiving points was 60 cm for both corridors.

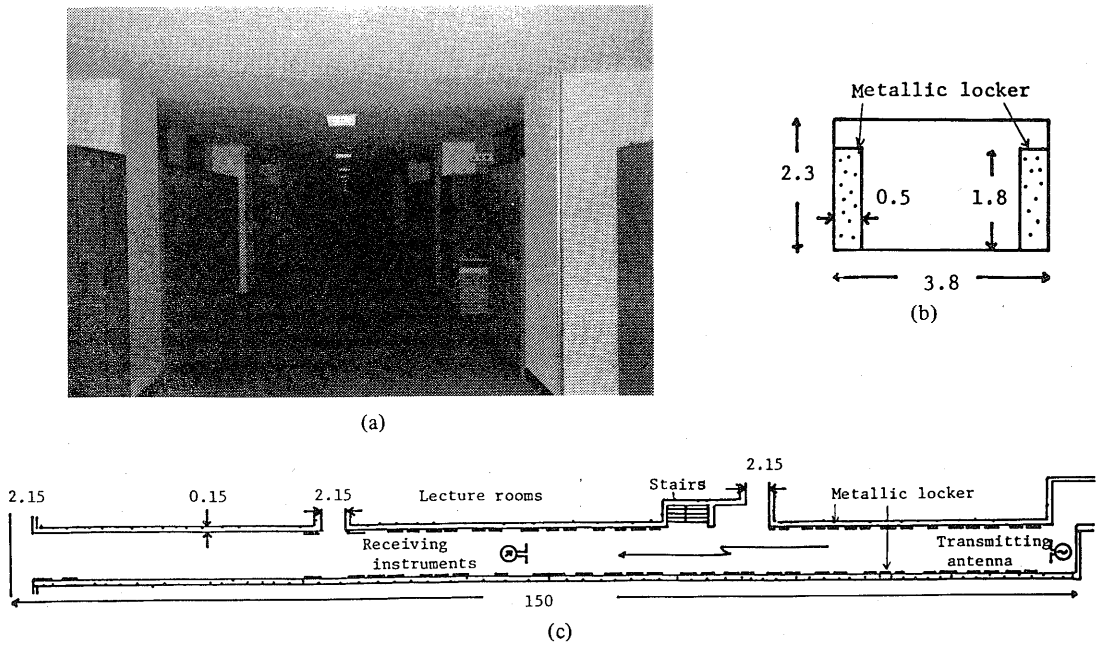


Fig. 3. Corridor *D*: (a) photograph; (b) cross section; (c) plane view. All dimensions are in meters.

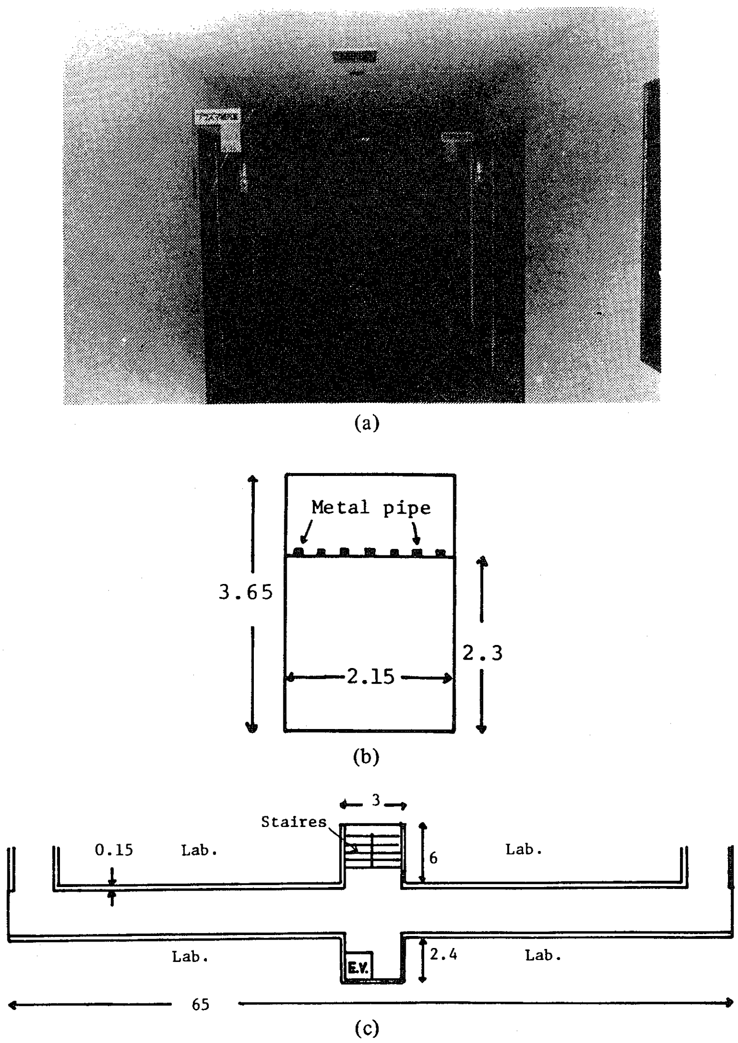


Fig. 4. Corridor *A*: (a) photograph; (b) cross section; (c) plane view. All dimensions are in meters.

III. Measurement Results

A. Underground Street

Fig. 5 shows some examples of received field strength along the underground street during the day and at night. These values are relative ones; however, the relative values against distance from a transmitting antenna are sufficient to determine the propagation constant. Thus the vertical axis in Fig. 5 is measured by 10 dB per division to show both horizontal and vertical polarization characteristics.

As seen from Fig. 5, fluctuations are observed in almost all regions. They do not depend on polarization characteristics. For frequencies of 210 MHz and 10 GHz, there is no significant difference in the fluctuation between daytime and nighttime circumstances. However, the difference is obvious for frequencies of 800 MHz and 5.5 GHz. The maximum value of the fluctuation or deviation is up to 20 dB for 5.5 GHz in the nighttime. The influence of pedestrians on the propagation characteristics is the most significant near 5 GHz.

The attenuation constant can be calculated from the received field strength by the least-squares method. To derive the attenuation constant, first we looked carefully at the total field pattern along the street; then we selected an interval which was almost inversely proportional to distance in the far region. For example, for the case of Fig. 5(a) in the daytime, 289 data were recorded in the floppy disk in order of distance from the transmitter. We omitted the first 15 data in the near region (of which distances are within 20 m of the transmitting antenna) and employed the remaining 274 data for calculating the attenuation constant. The resultant attenuation constant is 8.2 dB/10 m. However, this specific value is not unique because the value depends on the selected interval. Hence, we examined the tolerance on the value by selecting different intervals, e.g., by a method of omitting the first 30 or 50 data, at least three trials. As a result, the deviation from the specific value of the attenuation slope was within 3 percent in this case.

This procedure has been repeated for all frequencies; the deviation from the specific attenuation constant has been within 10 percent at most. Though the numbers of omitted data depend on the total pattern along the street for each frequency, at least the first 15 data in the near-zero region (the data within 20 m of the transmitting antenna) are omitted in the calculation of the attenuation constant.

The calculated attenuation constants are shown in Fig. 6 as a function of frequency with theoretical values to be discussed in the next section. As seen in this figure, the attenuation constant at night decreases somewhat oscillatorily with increasing frequency below 2–5 GHz, then increases at the higher frequencies. The optimum frequency for minimum attenuation is in the range of 2–5 GHz. The attenuation constant in the daytime, on the other hand, seems to decrease with increasing frequency as a whole, and the value approaches the daytime one at higher frequencies above 10 GHz. The difference between the daytime and nighttime attenuation constants is due to the absorption loss and/or the scattering loss by pedestrians in addition to the scattering loss by open side-wall boundaries. There are so many stores open in the daytime that the side-wall boundary and guide width cannot be determined. The influence of pedestrians on the attenuation constant extends over a wide frequency range from UHF to X band.

Field distributions are shown in Fig. 7 for frequencies 11, 5, 1.5, and 0.8 GHz measured along the broken line depicted in Fig. 1, almost at the center of the underground street. The receiving antenna was moved at intervals of 55 cm and kept at a constant height of 1.5 m from the floor. It is seen that the patterns are close to cosine distributions. Hence, the propagating wave is similar to the dominant mode, as in rectangular tunnels.

B. Corridors

The received field strengths along the corridors were similar to those of the underground street. The maximum range of fluctuations was about 15–20 dB at a frequency of 5 GHz. These experimental data are omitted here because there is no significant difference from the result of the underground street.

Frequency characteristics of the attenuation constants are shown in Fig. 8 for corridor D and Fig. 9 for corridor A, both for horizontally and vertically polarized waves. The frequency characteristics are similar to those of Fig. 6. The minimum attenuated frequency is about 2 GHz in both corridors and for both polarizations although dimension sizes are different. Hence, waves in the frequency range 2–5 GHz seem to be the least attenuated ones in these structures.

IV. Theoretical Considerations

It is difficult to obtain the exact propagation characteristics theoretically considering boundary conditions. To simplify the theoretical considerations, we only examine the propagation characteristics in the underground street at nighttime and corridors by the waveguide method [1], [5], [7]. We assume these structures to be rectangular waveguides surrounded by lossy dielectric materials, of which intrinsic constants are different in side walls and in ceiling and floor (Fig. 10).

Under the condition that the transverse dimensions of a guide are somewhat larger than the free-space wavelength, a rectangular waveguide of width a and height b may be modeled as a combination of two infinite slot guides with widths a and b, perpendicular to each other. This modification enables us to calculate the propagation constant in a rectangular waveguide easily. There are two dominant propagation modes with the lowest attenuation rates according to polarizations, which have the electric field polarized predominantly in the horizontal and vertical directions. By matching the impedance normal to the boundaries [5], the characteristic equations for the horizontally polarized mode are given as follows:

$$k_y \tan (k_y b/2) = j(k_y^2 + k_0^2(\epsilon_{r2}^* - 1))^{1/2} \tag{1}$$

$$\frac{k_x \tan (k_x a/2)}{k_0^2 - k_y^2} = \frac{j(k_x^2 + k_0^2(\epsilon_{r1}^* - 1))^{1/2}}{k_0^2 \epsilon_{r1}^* - k_y^2} \tag{2}$$

$$k_z = \beta - j\alpha = (k_0^2 - k_x^2 - k_y^2)^{1/2} \tag{3}$$

where k_x, k_y are complex transverse wavenumbers, $k_0(=2\pi/\lambda)$ is the free-space wavenumber, λ is the free-space wave-

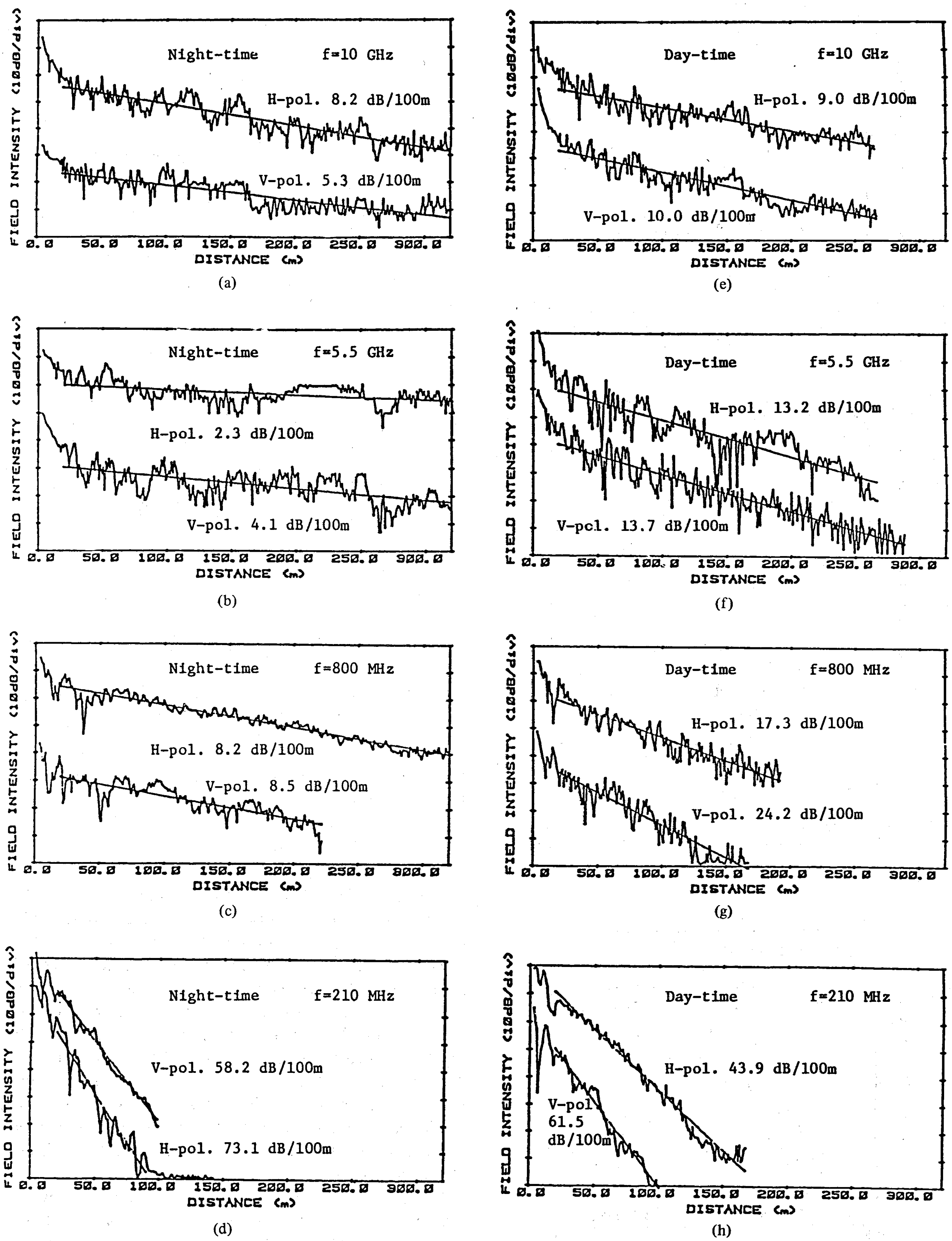


Fig. 5. (a)–(h) Examples of received field strength along the underground street.

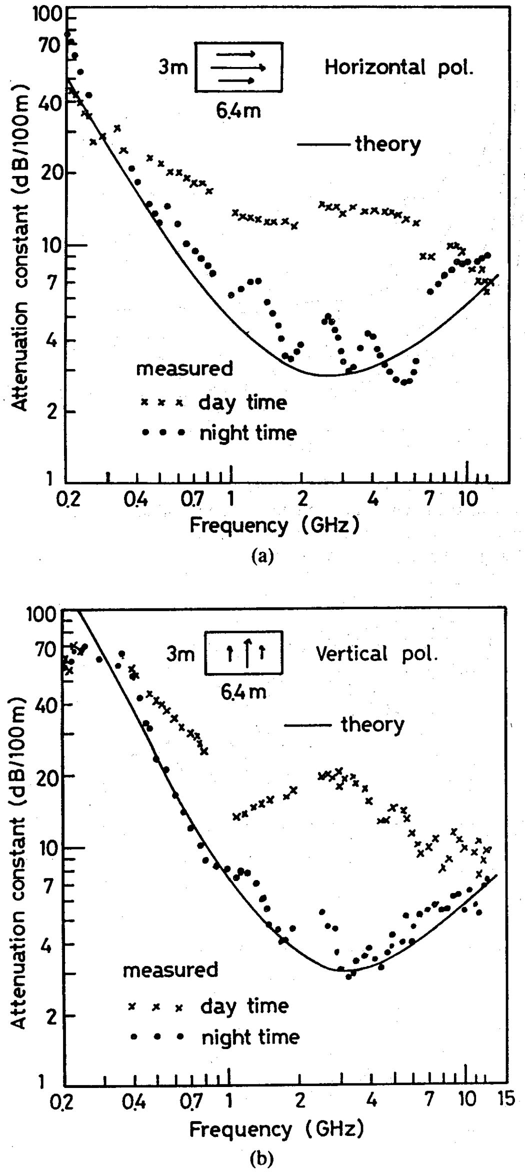


Fig. 6. Frequency characteristics of the attenuation constant in the underground street. (a) Horizontal polarization. (b) Vertical polarization.

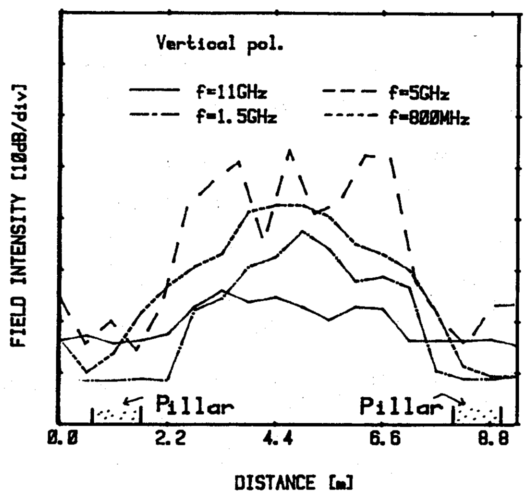


Fig. 7. Field distribution in the cross section of the underground street.

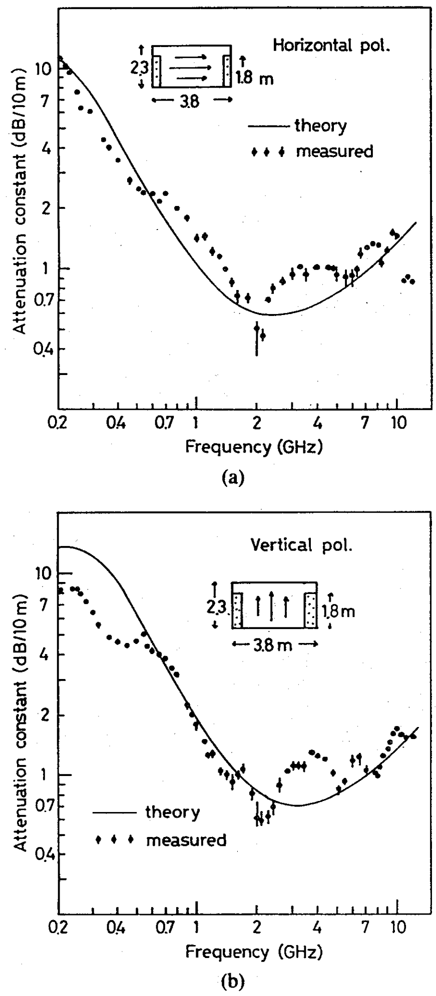


Fig. 8. Frequency characteristics of the attenuation constant in Corridor *D*. (a) Horizontal polarization. (b) Vertical polarization.

length, α is the attenuation constant, β is the phase constant, both to be computed:

$$\epsilon_{ri}^* = \epsilon_{ri} - j(\epsilon_{ri}'' + \sigma_i/(\omega\epsilon_0)), \qquad i = 1,\ 2 \tag{4}$$

where ϵ_{ri} is the relative dielectric constant and σ_i is the conductivity. The quantity ϵ_{ri}'' is the loss tangent of the materials, and ϵ_0 is the permittivity of free space.

The characteristic equations for the vertically polarized mode can be obtained by rotating the coordinate axis by 90°.

The above equations include a relation between the transverse wavenumbers, which are different from those of [1] and [7]. In the calculation, once the root in a transverse direction is determined from the first characteristic equation, then the second characteristic equation is solved by using the first root. We refer to the attenuation constant for the dominant mode calculated from the characteristic equation as the fundamental attenuation constant.

Next, the attenuation constant due to roughness, which is regarded as local variations in the level of surface relative to the mean level of the surface of a wall, is given in [1] by

$$\alpha_{\text{roughness}} = 4.343\pi^2\lambda((h_1/a^2)^2 + (h_2/b^2)^2) \quad \text{(dB/m)} \tag{5}$$

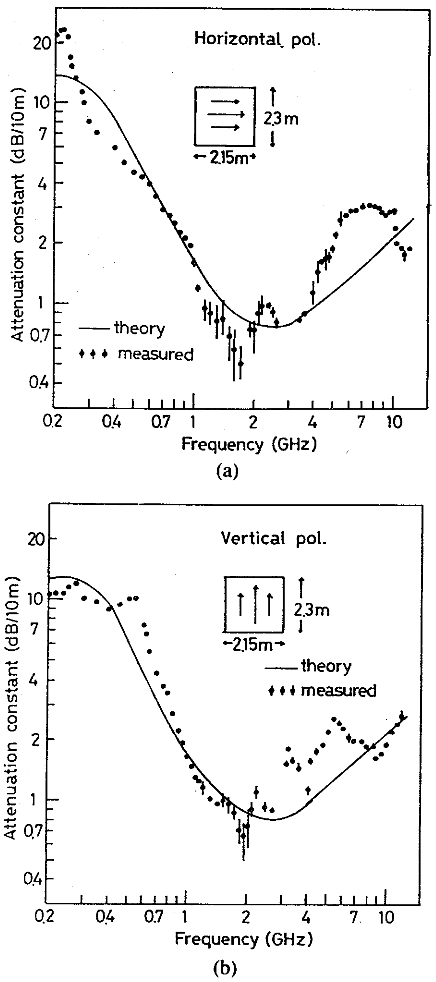


Fig. 9. Frequency characteristics of the attenuation constant in Corridor *A*. (a) Horizontal polarization. (b) Vertical polarization.

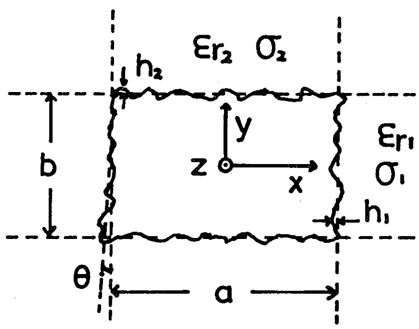


Fig. 10. Cross section of a rectangular waveguide and material constants.

where h_1, h_2 are root-mean-square roughnesses for the case of a Gaussian distribution of the surface level.

Also, the attenuation constant due to wall tilt [1] is

$$\alpha_{\text{tilt}} = 4.343\pi^2\theta^2/\lambda \qquad (\text{dB/m}) \tag{6}$$

where θ is the root-mean-square tilt.

The overall attenuation constant is the sum of the above losses. The resultant attenuation constants are shown in Figs. 6, 8, and 9 as a function of frequency with appropriate parameters so that they may agree with the experimental results. The parameters chosen in the calculation are listed in

TABLE I
PARAMETERS USED IN THE CALCULATION

	Width (m)	Height (m)	Tilt (degree)	Roughness h_1	h_2	Material constants ε_{r1}	ε_{r2}	σ_1	σ_2
Underground street	6.4	3.0	0.35	0.4	0.2	15	10	0.5	0.1
Corridor A	2.15	2.3	0.7	0.1	0.05	10	5	0.3	0.2
Corridor D	3.8	2.3	0.55	0.5	0.1	10	10	0.2	0.1

$\varepsilon''_{r1} = \varepsilon''_{r2} = 1 \sim 3$ for all structures.

Table I. The effects of material constants are not unique, e.g., conductivities from 0 to 0.2 (S/m) give the same result.

It is seen in Figs. 6, 8, and 9 that the waveguide theory seems applicable to the propagation in the underground street in the nighttime and corridors. It should be noted that the attenuation constant for the wall tilt is the dominant factor in the higher frequency regions above 5 GHz, and that the fundamental attenuation constant becomes dominant in the lower frequencies. The attenuation constant by roughness has less contribution to the total attenuation constant in this calculation. This means that the attenuation constant in the higher frequencies in these structures can be decided only by the wall tilt. The values of wall tilt in the calculations are obtained deductively from the comparison with the experimental results. However, the tilt θ seems to be relatively large in the corridors or the underground street because the maximum height difference at each side wall, according to the tilt, becomes about 8 cm for the underground street, and this height difference is too large for the construction. Hence, the other factor must be taken into account for the attenuation constant at the higher frequencies, which has a form similar to (6) with a typical factor $1/\lambda$. This argument and the propagation characteristics in a street crowded with pedestrians will be treated in a future investigation.

V. CONCLUSION

We measured the propagation characteristics of radio waves in an underground street and two corridors in a building, and derived the attenuation constant from 200 MHz to 12 GHz. From the experimental results, the field strength varies with distance quite rapidly, the range of fluctuation becomes up to 20 dB or more. The attenuation constant decreases with increasing frequency below 2–5 GHz, and then increases with frequency. This frequency characteristic was common to three guide structures. The value of the attenuation constant depends on the dimensions of the guide; however, it becomes a minimum in the frequency range of 2–5 GHz.

ACKNOWLEDGMENT

The authors wish to thank Mr. Watanabe, the Chief Director of the Checking Center Against Disaster of Niigata Chikakaihatsu Company, Ltd., for his kind cooperation, and also the people working at his company.

REFERENCES

[1] A. G. Emslie, R. L. Lagace, and P. F. Strong, "Theory of the propagation of UHF radio waves in coal mine tunnels," *IEEE Trans. Antennas Propagat.*, vol. AP-23, no. 2, pp. 192–205, Mar. 1975.

[2] J. Chiba, T. Inaba, Y. Kuwamoto, O. Banno, and R. Sato, "Radio communication in tunnels," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, no. 6, pp. 439–443, June 1978.

[3] S. Kozono, T. Suzuki, and T. Hanazawa, "Experimental study of mobile radio propagation characteristics in rectangular tunnels," *Trans. Inst. Electron. Commun. Eng. Japan,* vol. J62-B, no. 6, June 1979.

[4] H. Kishimoto, "Indoor radio propagation analysis by ray method," IECE of Japan, Tech. Rep. Antennas Propagat., A.P76-62, 1976.

[5] Y. Yamaguchi, T. Abe, and T. Sekiguchi, "Improvement of attenuation characteristics in tunnels (I)," IECE of Japan, Tech. Rep. Antennas Propagat., A.P83-11, May 1983.

[6] S. F. Mahmoud and J. R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels," *Radio Sci.,* vol. 9, no. 12, pp. 1147–1158, Dec. 1974.

[7] B. Jacard and O. Maldonado, "Microwave modeling of rectangular tunnels," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-32, pp. 576–581, June 1984.

[8] D. B. Large, L. Ball, and A. J. Farstad, "Radio transmission to and from underground and coal mines—Theory and measurement," *IEEE Trans. Commun. Technol.,* vol. COM-21, pp. 194–202, 1973.

[9] A. E. Goddard, "Radio propagation measurements in coal mines at UHF and VHF," in *Proc. Through-the-Earth Electromagnetics Workshop* (Colorado School of Mines, Golden, CO), Aug. 15–17, 1973.

[10] J. R. Wait, "Propagation under the earth surface (a review)," presented at Symp. Electromagnetic Wave Theory, Int. Union of Radio Science, London, England, 1974.

[11] Y. Yamaguchi, O. Majima, M. Sakuma, and T. Abe, "Radio wave propagation in the underground street," presented at Int. Symp. EMC '84, Tokyo, Japan, Oct. 1984, pp. 491–494.