

FDTD Analysis of Radio Wave Propagation at Intersection Surrounded by Concrete Block Walls in Residential Area for Inter-Vehicle Communications Using 720 MHz Band

Kenji TAGUCHI^{†a)}, Suguru IMAI[†], Tatsuya KASHIWA[†], Kohzoh OHSHIMA^{††}, *Members,*
and Takeshi KAWAMURA[†], *Nonmember*

SUMMARY An inter-vehicle communication system for the 720 MHz band that is designed to prevent car crashes at intersections has recently been proposed in Japan. This paper presents an analysis of the propagation characteristics of an intersection surrounded by concrete block walls in a residential area. The propagation characteristics were analyzed for the first time using the finite-difference time-domain (FDTD) method. We investigated the influence of wall thickness and source locations on the propagation characteristics. The results of our investigation showed that the most commonly used wall thickness and source locations do not strongly affect propagation loss. Furthermore, we analyzed the power delay profile and delay spread by taking into consideration the structure of the concrete block walls.

key words: inter-vehicle communication, radio wave propagation, intersection, concrete block wall, FDTD method

1. Introduction

In our automotive society, the number of car accidents shows no sign of any significant decline. Many accidents occur at intersections that have poor visibility, and this has posed a significant problem in modern society. An inter-vehicle communication (IVC) system has been proposed to solve this problem [1]–[7]. With the changeover in terrestrial broadcasting from analog to digital broadcasting, part of the 720 MHz band will be newly assigned to the IVC system in Japan. There is a strong possibility that the IVC system will prevent car crashes that occur because vehicles are at the blind spots at intersections where the visibility is poor. Furthermore, the system could potentially be adapted to prevent short-range emergency collisions in the future. In Japan, many residential areas have intersections that are surrounded by concrete block walls [1], [8]–[10]. Because of the presence of these walls, the visibility at these intersections is usually poor. However, the propagation characteristics for 720 MHz at these intersections are not well known.

The radio wave propagation characteristics at an intersection surrounded by buildings have traditionally been ana-

lyzed using the ray-tracing method [3]–[6], [11], [12], which is generally simple and fast. However, the method can not analyze objects smaller than several wavelengths [11]. Moreover, the calculation time increases sharply when the analysis of complex structures in which penetrating waves exist is carried out. In intersections surrounded by concrete block walls, the penetrating waves through the walls may not be ignored because the dielectric constants of the walls are relatively small.

Alternatively, the finite-difference time-domain (FDTD) method is one of the most powerful and versatile methods [7], [13]. Although it is usually inefficient compared with the ray-tracing method, the FDTD method is suitable for heterogeneous and complex structures. The method can be applied to the problems mentioned above, which are not suitable for the ray-tracing method.

This paper presents an analysis of the radio wave propagation characteristics at an intersection surrounded by concrete block walls for the 720 MHz band. The characteristics are analyzed for the first time by using the FDTD method. More specifically, the impact of the thickness of the house compound walls, wave source location, and wall structure on radio wave propagation was investigated from the perspective of clarifying the physical radio wave propagation mechanism. The following tasks are performed: 1) the propagation loss is analyzed; and 2) the quasi-impulse responses are analyzed to obtain the power delay profile and the delay spread. These characteristics are very important when estimating communication quality.

2. Propagation Characteristics of Radio Waves at Intersection Surrounded by Concrete Block Walls in Residential Area

2.1 Intersection Surrounded by Concrete Block Walls

Figure 1 shows an intersection that is surrounded by concrete walls in a residential area. Assuming that the velocity of vehicles driven in residential areas is 40 km/h, the stopping distance would be approximately 20 m. By taking this into account, we set the analysis domain for the intersection as 66 m × 66 m. At that location, there are one-lane roads going in both directions and walls that enclose houses. A commonly accessed road is assumed as the road [14].

Manuscript received March 19, 2011.

Manuscript revised August 5, 2011.

[†]The authors are with the Department of Electrical and Electronic Engineering, Kitami Institute of Technology, Kitami-shi, 090-8507 Japan.

^{††}The author is with the Department of Electrical and Computer Engineering, Asahikawa National College of Technology, Asahikawa-shi, 071-8142 Japan.

a) E-mail: ktaguchi@mail.kitami-it.ac.jp

DOI: 10.1587/transele.E95.C.79

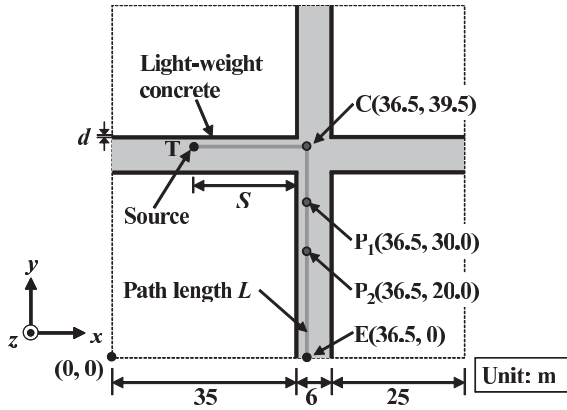
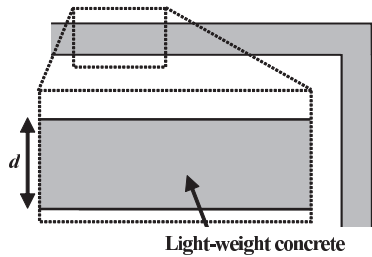
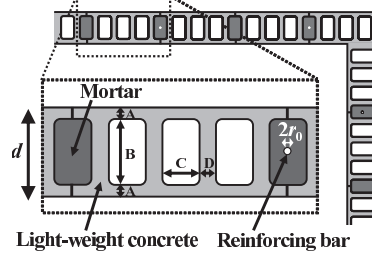


Fig. 1 Intersection surrounded by concrete block walls in residential area.



(a) Uniform concrete walls



(b) Concrete block walls

Fig. 2 Structure of concrete walls.

Point T corresponds to a source location. Parameter S corresponds to a distance from the intersection to point T. Points P_1 and P_2 correspond to the observation locations at the non-line-of-sight (NLOS) region for the quasi-impulse response analyses.

Figure 2 shows the structure of the concrete walls used in the analyses. Figures 2(a) and 2(b) show the uniform concrete walls and the concrete block walls [15], respectively. In this study, we also investigated radio wave propagation characteristics for uniform light-weight concrete walls for the purpose of comparison. The concrete block walls are constructed with light-weight concrete [16], mortar [17], and reinforcing bars. Table 1 displays the sizes of the concrete blocks. These sizes are based on the Japanese Industrial Standards [18]. Here, $d = 0.12$ m and 0.10 m denote the most common thicknesses of concrete block walls in Japan [19].

Table 1 Sizes of concrete blocks.

Thickness d [cm]	Size of concrete blocks [cm]			
	A	B	C	D
12.0	2.4	7.2	8.0	2.4
10.0	2.4	5.2	8.0	2.4

Table 2 Parameters used in this simulation.

Wave source	Frequency f [MHz]	720	
	Distance S [m]	20, 15, 10, 5	
Uniform concrete wall	Thickness d [m]	$\infty, 0.12, 0.10$	
	Light-weight concrete	ϵ_r	2.0
Concrete block wall	Thickness d [m]	σ [S/m]	0.0278
		ϵ_r	2.0
	Mortar	σ [S/m]	0.0278
		ϵ_r	5.6
	Reinforcing bar	σ [S/m]	0.0117
		r_0 [mm]	4.0
Spatial increment	Δ [mm]	8.0	
Time increment	Δt [ps]	17.80	

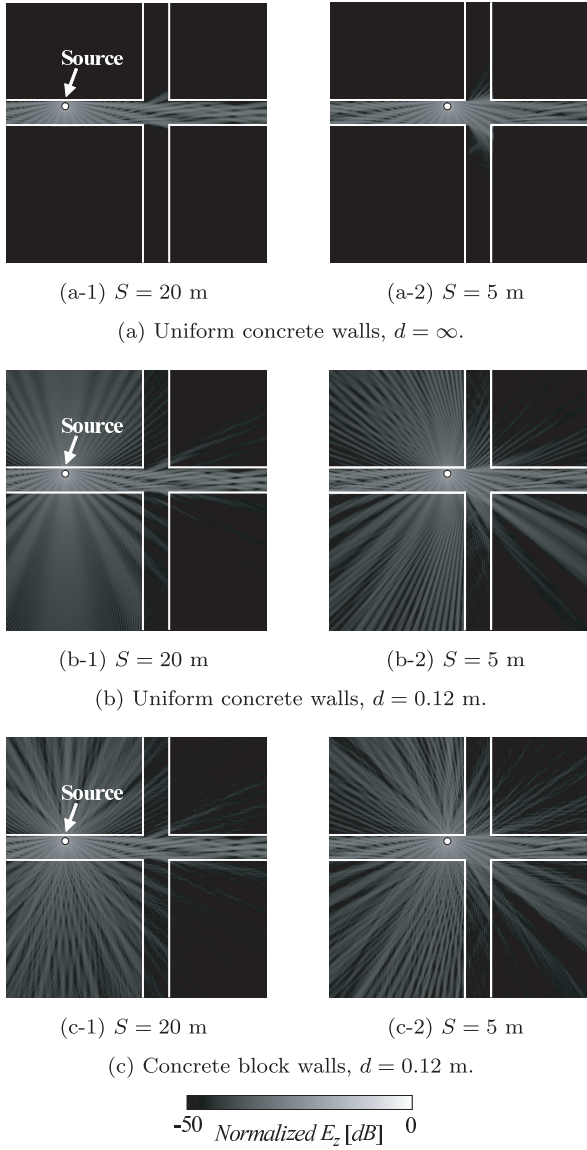
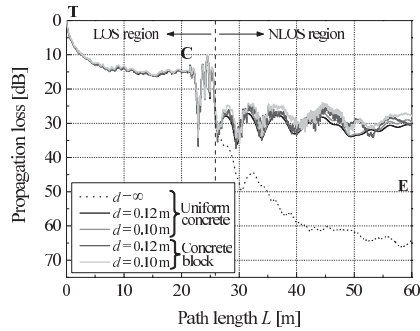
Table 2 displays the parameters used in this simulation. Three types of wall thickness and four types of source locations were considered here. Here, $S = 20$ m corresponds to the stopping distance for a vehicle traveling at a speed of 40 km/h. The wall thickness $d = \infty$ corresponds to the case in which the entire area inside the walls is filled with a uniform light-weight concrete. The light-weight concrete was assumed to have the electric constants of 1 GHz recommended by ITU-R. The generalized perfectly matched layer (GPML) was used as an absorbing boundary condition [20].

The propagation characteristics at an intersection should generally be analyzed in three-dimensional space. In these analyses, many conditions influence the propagation characteristics, including the ground, the shape of the vehicle, and the positions and types of antennas. Therefore, the basic influence of the walls, which is very important, may not be clear in the three-dimensional analyses. Because of these reasons, two-dimensional analyses were carried out in this study as a first step. Here, the FDTD method (E_z , H_x , H_y) was used because vertical polarization will be used in the IVC.

2.2 Propagation Loss Analysis

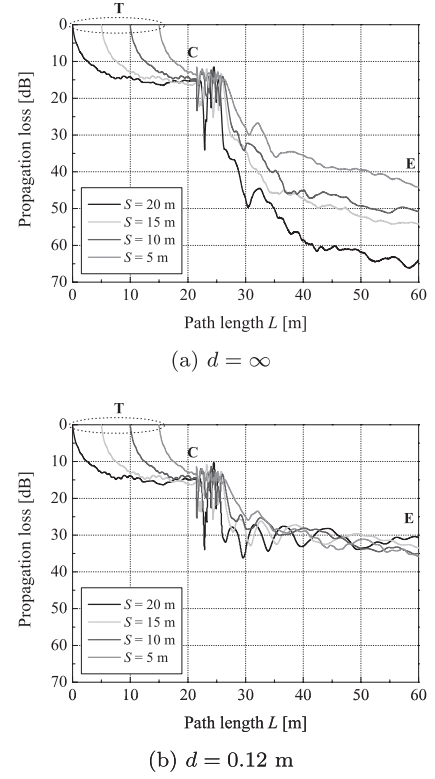
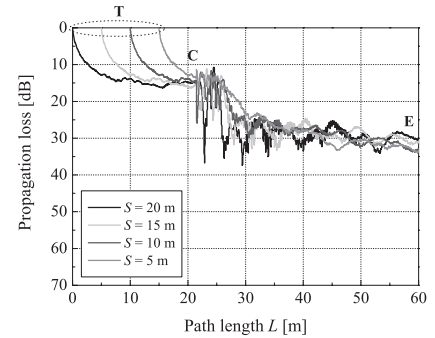
In this section, the propagation loss analyses are discussed. Figure 3 shows the electric field distribution for 720 MHz at an intersection. Here, the white lines represent the concrete walls. In the case of $d = \infty$, the white lines represent the surface of the wall. The electric field distribution is normalized by value on point T.

Figures 4, 5, and 6 illustrate the propagation loss on the path TCE for 720 MHz. The path length L is measured from point T for the case of $S = 20$ m. The propagation loss is obtained by taking the average of E_z over the vehicular width $w_v = 1.8$ m in transverse direction to the path. More-

**Fig. 3** Electric field distribution.**Fig. 4** Propagation loss on the path TCE for wall thickness d , where source location $S = 20$ m.

over, the propagation loss on the path is normalized by the value on point T.

Hereafter, we will investigate the influence of wall

**Fig. 5** Propagation loss on the path TCE for source location S in the uniform concrete walls.**Fig. 6** Propagation loss on the path TCE for source location S in the concrete block walls, where the wall thickness $d = 0.12$ m.

thickness, source location, and wall structure.

2.2.1 Characteristics of Uniform Concrete Walls

First, the influence of wall thickness d is described. In the case of $d = \infty$, most propagation waves can not arrive at the NLOS region; therefore, the propagation loss become very large, as shown in Figs. 3 and 4. In contrast, in the case of $d = 0.12$ m, the relatively strong waves penetrating through the walls are observed at the NLOS region; as a result, the propagation loss becomes small. Furthermore, walls with thicknesses $d = 0.12$ m and 0.10 m, which are most commonly used, have almost the same propagation loss characteristics as those shown in Fig. 4.

Next, the influence of source location S is described. In the case of $d = \infty$, the propagation loss depends strongly on the source location S , as shown in Fig. 5. In contrast, in the case of $d = 0.12$ m, the propagation loss does not depend strongly on the source location S .

2.2.2 Characteristics of Concrete Block Walls

First, the influence of wall thickness d is described. As shown in Fig. 4, the propagation loss does not depend on the most commonly used wall thickness; this characteristic is similar to that observed in the case of the uniform concrete wall.

Next, the influence of source location S is described. As shown in Fig. 6, the dependence on the source location S is small, similar to the uniform concrete wall case.

Finally, the influence of wall structures is described. The propagation loss for concrete block walls is slightly different from that for uniform concrete walls on the whole.

2.3 Quasi-impulse Response Analysis

Although a strict impulse response analysis should be carried out, the FDTD method can not treat pure impulse waves. For that reason, quasi-impulse waves are used. The modulated Gaussian pulse wave was input in the quasi-impulse response analyses. The center frequency and the half-power bandwidth of the modulated Gaussian pulse wave were $f_c = 720$ MHz and $f_0 = 60$ MHz, respectively.

In the quasi-impulse response analyses, the power delay profile, the azimuthal power delay profile, and the delay spread were observed at points P_1 and P_2 . The azimuthal power delay profiles were obtained by the method in which the direction of arrival is estimated using the multiple signal classification (MUSIC) algorithm [21]. It becomes possible to estimate the propagation path of radio waves based on the observation results for the arrival time and the arrival direction of the azimuthal power delay profile. The elements of the array antenna were lined up in the x direction at the observation points. The number of elements was five. Each distance between array antennas was set to 64.0 mm.

2.3.1 Power Delay Profile

Figures 7, 8, and 9 display the power delay profile and the azimuthal power delay profile. The values are normalized by the maximum value on point T. The arrival angle θ is measured from the x axis.

First, the characteristics for uniform concrete walls are described. In the case of $d = \infty$, the received power for the source location $S = 20$ m at the NLOS region is very small because there are no penetrating waves through the wall, as shown in Fig. 7. Furthermore, the diffraction waves that reach the NLOS region are extremely small. In addition, at the point P_1 , relatively strong penetrating waves passing through the vicinity of the wall edges are observed only in the case of $S = 5$ m. In contrast, in the case of $d = 0.12$ m,

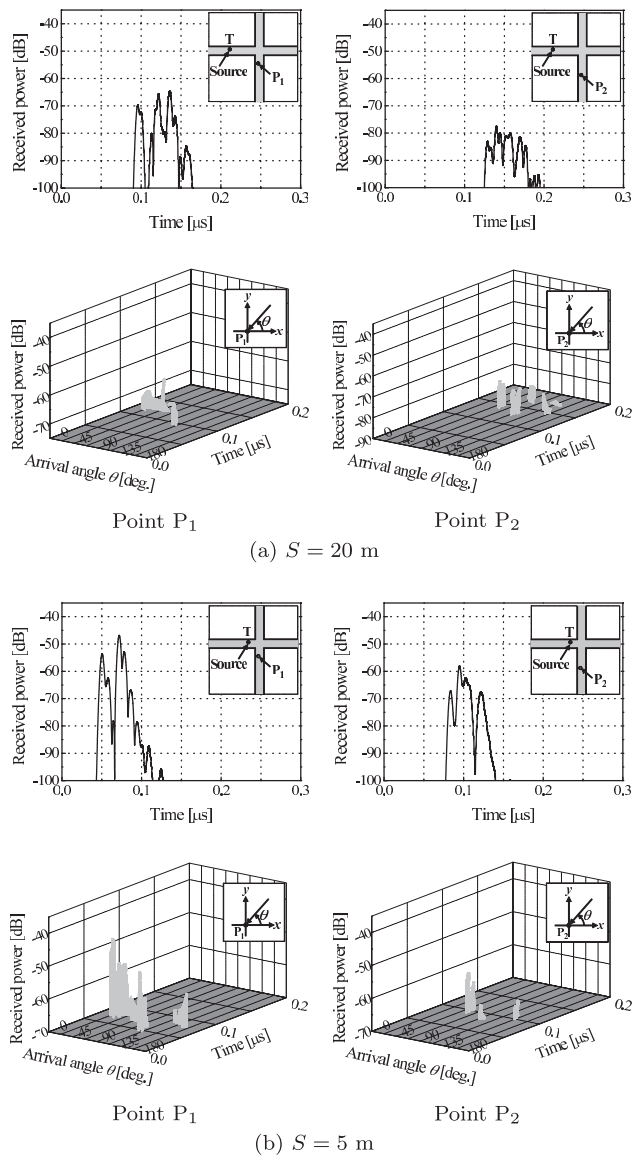


Fig. 7 Power delay profile and azimuthal power delay profile for uniform concrete walls, where wall thickness $d = \infty$.

both the penetrating waves and the reflected waves can be observed at both observation points in the NLOS region, as shown in Fig. 8. The figure shows that the penetrating waves through the wall are stronger than the reflected waves from the opposite side wall when the source location is far from the intersection. On the other hand, the penetrating waves are as strong as the reflected waves when the source location is near the intersection.

Next, the characteristics for concrete block walls are described. As shown in Fig. 9, the penetrating waves through the wall are almost always stronger than the reflected waves from the opposite side wall. Moreover, the penetrating waves remain consistently strong in comparison with those in the case of uniform light-weight concrete walls. This seems to be due to the fact that the reflection coefficient of the walls is reduced by cavities in the con-

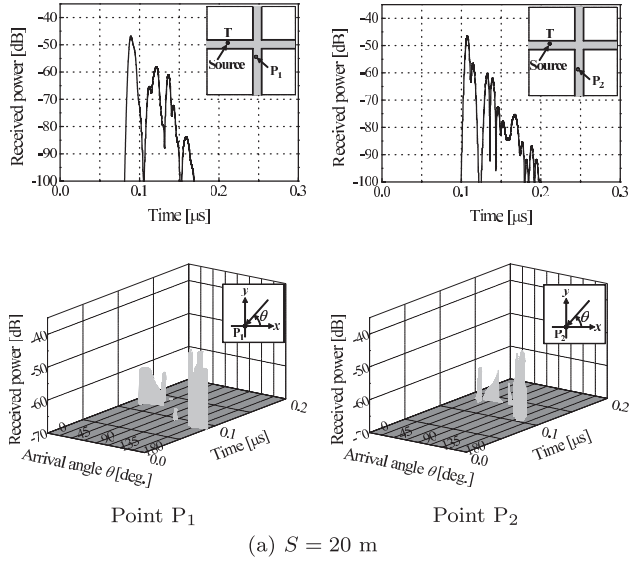
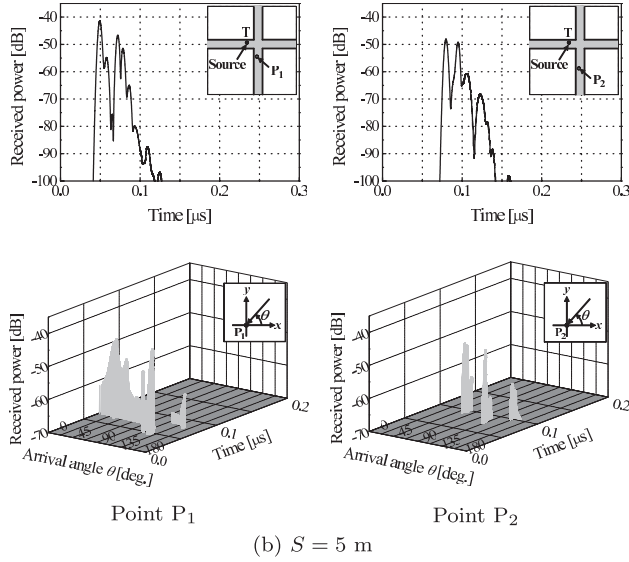
(a) $S = 20$ m(b) $S = 5$ m

Fig. 8 Power delay profile and azimuthal power delay profile for uniform concrete walls, where wall thickness $d = 0.12$ m.

crete blocks. Furthermore, the shapes of power delay profiles spread compared with those for uniform concrete walls regardless of the source location S .

2.3.2 Delay Spread

The delay spread σ_τ for the power delay profile $p(t)$ in the noiseless environment was defined in [22]

$$\sigma_\tau = \sqrt{\frac{\int_{-\infty}^{\infty} (t - \mu)^2 p(t) dt}{\int_{-\infty}^{\infty} p(t) dt}}, \quad (1)$$

where μ is defined by

$$\mu = \frac{\int_{-\infty}^{\infty} t p(t) dt}{\int_{-\infty}^{\infty} p(t) dt}. \quad (2)$$

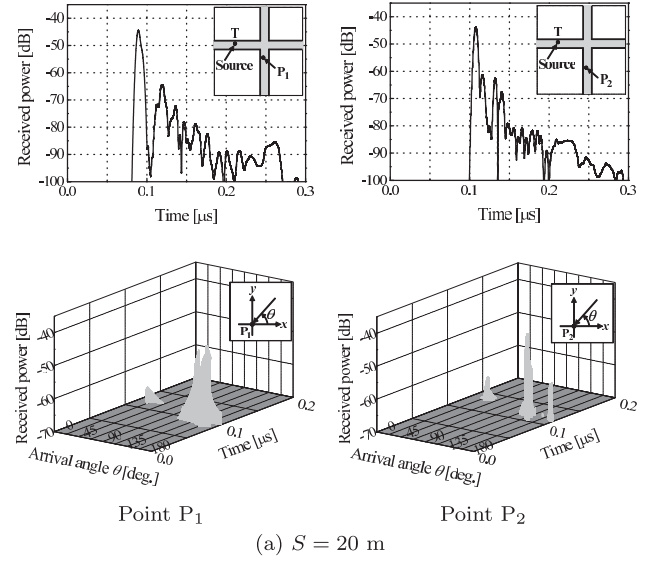
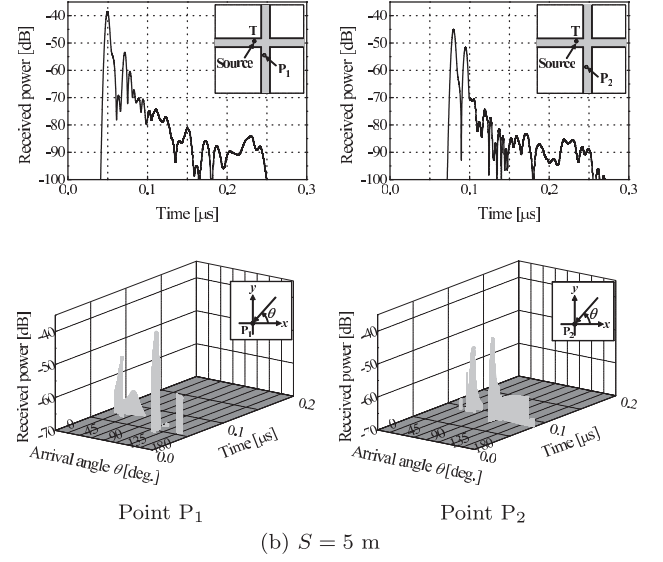
(a) $S = 20$ m(b) $S = 5$ m

Fig. 9 Power delay profile and azimuthal power delay profile for concrete block walls, where wall thickness $d = 0.12$ m.

Table 3 shows the delay spread for the power delay profile. The delay spread σ_τ for uniform concrete walls indicates a nearly constant value at each observation point regardless of the wall thickness d . On the other hand, the delay spread for concrete block walls becomes large compared with that for uniform concrete walls. The reason for this seems to be that the waves scattered by the concrete block walls arrive late from various angles.

The basic model used in this analysis, which does not take into consideration any variation in vehicles and antennas, has resulted in an increase in the delay time and delay spread in comparison with the results obtained for uniformly light-weight concrete walls. These values are lower than the guard interval time indicated by the experimental guidelines [2] for inter-vehicle communication.

Table 3 Delay spread σ_τ for power delay profile.

Wall type	Thickness d [m]	Delay spread σ_τ [ns]			
		$S = 20$ m		$S = 5$ m	
		P_1	P_2	P_1	P_2
Uniform concrete	∞	18.03	17.89	12.62	13.71
	0.12	18.82	18.50	13.87	14.15
Concrete block	0.12	36.51	33.58	32.73	34.72

3. Conclusion

This paper describes the analysis of the propagation characteristics at an intersection surrounded by concrete block walls in a residential area. These characteristics were analyzed for the first time using the FDTD method. We investigated these characteristics taking into account wall thickness, source location, and wall structure. As a result, the following new information was obtained:

- 1) Penetrating waves through concrete block walls can not be ignored.
- 2) Concrete block walls have propagation loss characteristics that are similar to those for uniform concrete walls when the thickness is the same.
- 3) Propagation loss is almost independent of common wall thickness and source location.
- 4) The amount of delay time and delay spread are increased in comparison with the results obtained for uniformly light-weight concrete walls.

In the near future, we plan to investigate the propagation characteristics taking into consideration the ground, antennas, vehicles, and the Doppler effect in three-dimensional space.

Acknowledgment

This work was supported by MEXT, KAKENHI (23560433, 21510174, 22560400, and 22760260). The authors would like to thank Mr. D. Matsuda for his helpful discussion in our laboratory.

References

- [1] Ministry of Internal Affairs and Communications Website: http://www.soumu.go.jp/main_content/000025421.pdf
- [2] "Experimental guideline for vehicle communications system using 700 MHz band ITS Forum RC-006 Version 1.0," ITS Information Communications Forum of Japan, Feb. 2009.
- [3] I. Sugae, H. Iwai, H. Sasaoka, S. Cai, K. Sasaki, and T. Horimatsu, "Experimental results and evaluation by ray-tracing on received signal level in V2V environments," IEICE Technical Report, AP2008-38, July 2008.
- [4] S. Sai, E. Niwa, K. Mase, M. Nishibori, J. Inoue, M. Obuchi, T. Harada, M. Sawada, H. Ito, K. Mizutani, and M. Kizu, "UHF band propagation loss characteristics for roadside-to-vehicle and vehicle-vehicle communications in urban area," IEICE Technical Report, AP2009-111, Oct. 2009.
- [5] K. Ieda, Y. Murakami, H. Unada, S. Fujimoto, and T. Oshida, "A

- study on UHF band propagation loss characteristics for inter-vehicle communication at road faces variation," IEICE Technical Report, AP2010-7, April 2010.
- [6] H. Iwai and I. Sugae, "Path loss and delay profile models for its in 700 MHz band," IEICE Technical Report, AP2010-8, April 2010.
- [7] K. Taguchi, T. Kashiwa, K. Ohshima, and T. Kawamura, "Propagation analysis of electromagnetic waves in 700 MHz band at intersection for inter-vehicle communications using the FDTD method," IEICE Trans. Electron., vol.E94-C, no.1, pp.18–23, Jan. 2011.
- [8] T. Kamura, "Investigation on concrete masonry garden walls: Part 15 summary," Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, Structures II 1993, pp.1035–1036, July 1993.
- [9] Y. Hirayama, K. Kikuchi, M. Kuroki, H. Nonaka, and M. Ito, "Study on seismic safety of existing concrete masonry garden walls and regional earthquake disaster prevention: Part 5. field investigation on actual condition of existing garden walls in Takio, Oita city," AIJ Kyushu Chapter Architectural Technical Report (Structure), vol.48, pp.685–688, March 2009.
- [10] K. Kawakami and M. Amano, "Actual condition of a concrete masonry garden walls and fences in Yuki-city," The Research Reports of Oyama Technical College 36, pp.171–176, March 2004.
- [11] Y. Kishiki and J. Takada, "Introduction technique and application result of complex radar cross section for ray tracing simulation of microcell propagation channels," URSI-F Japanese Committee Meeting, no.522, March 2008.
- [12] T. Imai, "Mobile radio propagation simulation based on ray-tracing method," IEICE Trans. Commun. (Japanese Edition), vol.J92-B, no.9, pp.1333–1347, Sept. 2009.
- [13] A. Taflov and S.C. Hagness, Computational Electrodynamics: The Finite-Difference Time-Domain Method, 3rd ed., Artech House, 2005.
- [14] Ministry of Land, Infrastructure, Transport and Tourism, "Guidebook on special permissions in the zoning code under building standard law to promote rebuilding in densely built-up areas," Technical Note of NILIM, no.368, Jan. 2007.
- [15] Japan Architectural Concrete Block Industry Association Website: <http://www.jcba-jp.com/daijiten/c02/02.html>
- [16] Rec. ITU-R P. 1238-5, "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz," ITU-R Recommendations, Feb. 2007.
- [17] K. Akita, "Dielectric constants and radio wave reflection characteristics of concretes," IEICE Technical Report, EMC78-38, Nov. 1978.
- [18] JIS A5406: 2010, JIS A5406: 2005
- [19] Y. Hirakawa, K. Kikuchi, M. Kuroki, H. Nonaka, and M. Ito, "Study on seismic safety of existing concrete masonry garden walls and regional earthquake disaster prevention: Part 5. field investigation on actual condition of existing garden walls in takio, oita city," AIJ Kyushu Chapter Architectural Technical Report (Structure), vol.48, pp.685–688, March 2009.
- [20] J. Fang and Z. Wu, "Generalized perfectly matched layer for the absorption of propagating and evanescent waves in lossless and lossy media," IEEE Trans. Microw. Theory Tech., vol.44, no.12, pp.2216–2222, Dec. 1996.
- [21] Y. Ogawa, N. Hamaguchi, K. Ohshima, and K. Itoh, "High resolution analysis of indoor multipath propagation structure," IEICE Trans. Commun., vol.E78-B, no.11, pp.1450–1457, Nov. 1995.
- [22] M.R. Pakravan, M. Kavehrad, and H. Hashemi, "Indoor wireless infrared channel characterization by measurement," IEEE Trans. Veh. Technol., vol.50, no.4, pp.1053–1073, July 2001.



Kenji Taguchi was born in Hokkaido, Japan, on July 2, 1978. He graduated from the Dept. of Electrical and Electronic Eng. of Kitami Inst. of Tech., in 2001, completed the M.S. and doctoral programs in 2003 and 2006, respectively. He became a research associate in the Dept. of Info. and Comm. Eng. of Kumamoto National College of Tech. in 2006. He has been an associate professor in the Dept. of Electrical and Electronic Eng. of Kitami Inst. of Tech. since 2009. He has been engaged in the

analysis of electromagnetic fields.



Takeshi Kawamura was born in Hokkaido, Japan, in 1962. He received a Bachelor's degree, a Master's degree, and a Ph.D. in precision engineering from Hokkaido university in 1987, 1989, and 2003, respectively. From 1991 to 2003, he worked as a lecturer at the department of Electrical and Electronic Engineering in Kitami Institute of Technology. From 2003, he served as an associate professor. He is a member of SICE, ISCIE, IEEJ, JSIAM, and RSJ.



Suguru Imai was born in Hokkaido, Japan, on June 23, 1981. He graduated from the Dept. of Computer Science of Kitami Institute of Technology, Japan, in 2005, completed the M.S. and the doctoral programs in 2007 and 2010, respectively. He became a research associate in the Dept. of Electrical and Electronic Eng. the same university in 2010.



Tatsuya Kashiwa was born in Hokkaido, Japan, on June 3, 1961. He graduated from the Department of Electrical Engineering of Hokkaido University in 1984 and completed the M.S. program in 1986. Before completing the doctoral program, he became a research associate in Department of Electrical Engineering in 1988. He became an associate professor in the Department of Electrical and Electronic Engineering of Kitami Institute of Technology in 1996. He has been a professor since 2008 in the

same university. His research interests include the analysis of electromagnetic fields, acoustic fields, and optimization of microwave circuits. He received an IEEE AP-S Tokyo Chapter Young Engineer Award in 1992. He is a coauthor of Handbook of Microwave Technology (Academic Press) and Antenna and Associated System for Mobile Satellite Communications (Research Signpost). He is a member of technical committee on microwave engineering (MW), and was a member of applications of body area radiowaves (ABR) of IEICE, and secretary of committee of computational electromagnetics of IEEJ. He holds a D.Eng. degree, and is a member of IEEJ and IEEE.



Kohzoh Ohshima was born in Hokkaido, Japan, on December 4, 1969. He was graduated from the Dept. of Electronic Eng. of Hokkaido University in 1992, completed the M.S. and doctoral programs in 1994 and 1997, respectively. He became a research associate in the Dept. of Electrical and Computer Eng. of Asahikawa National College of Tech. in 1998. He has been an associate professor since 2000 in the same college. He has been engaged in research on DOA estimation.