A Deterministic Ray Tube Method for an Indoor Propagation Prediction Model

Choon-Gil Suh[1] · Hyung-Wha Koh[1] · Hae-Won Son[2] · Noh-Hoon Myung[2]

Abstract

This paper presents a new 3-D ray tracing technique based on the image theory with newly defined ray tubes. The proposed method can be applied to indoor environments with arbitrary building layouts and has high computational efficiency compared to the precedent methods resorting to the ray launching scheme. Its predictions are in good agreement with the measurements.

Ⅰ. INTRODUCTION

The emergence of a variety of wireless indoor communication systems has created a large interest in characterizing radio propagation inside buildings. Propagation of radio signal inside the buildings is strongly influenced by specific features such as the layout of the building and the construction materials. Due to the site-specific nature of indoor environments, an efficient way to cover a wide variety of indoor environments is required.

Recently, ray tracing propagation models are often used for the prediction of radio propagation in wireless indoor environment. Several propagation models based on the ray tracing techniques have been reported, which employ the image theory or ray launching method[1]~[4].

The ray launching method, where the rays are launched from a transmitter with a constant angle increment, can be successfully used in complex environments but has very bad computational efficiency due to a large number of rays and reception tests. Especially, the generation of so many diffracted rays on the edges makes it impractical. In addition, the ray launching might neglect a wall, which is very small and located between two rays.

The image method guarantees the consideration of each wall with a constant resolution. However, the selection of the walls to generate the images is very difficult for complex environments. Tan et al.[3] attempted to find all possible images in 3-D space using the concept of ?test ray'. However, their test rays are also based on the ray launching scheme and so, the method has no guarantees of including all possible walls and suffers from long computation times.

In this paper, we present a new 3-D ray tracing technique, which is based on image theory, with high computational efficiency and accuracy, compared to the precedent methods resorting to the ray launching scheme. Unlike the conventional image method, our method uses newly defined 'ray tubes', which have information of virtual sources such as image sources on walls and edge sources on corners as well as transmission sources to represent transmitted rays into walls. The three kinds of virtual sources (image, edge and transmission sources) are treated in a simple and unified manner using the concept of 'ray tube'. The proposed method can be applied to various indoor environments with arbitrary building layouts satisfying some reasonable assumptions. The predictions of the proposed method are in good agreement with the published measurements in[5].

Ⅱ. THEORY AND FORMULATION

2-1 Indoor Databases

In this paper, indoor structures are modeled with plain wall segments standing vertically to the bottom or ceiling of the floor (Fig. 1). Each wall extends to finite height from the bottom and has properties such as materials and subdivisions. Subdivisions are typically doors or windows inside a wall and have material properties other than those of the wall. Material properties are taken into account in calculating reflection and transmission coefficients.

For multi-floored buildings (Fig. 1(b)), it is assumed that all floors have the same configuration and so, the same layouts in the plan view. Most of buildings satisfy the assumption except for a specific floor with a large empty space such as a lobby.

2-2 Deterministic Ray Tube Method; Proposed Method

The ray tracing method presented here is able to account for all possible rays undergoing multiple interactions composed of reflections, transmissions and diffractions in indoor environments. Diffractions on horizontal edges and boundaries of

Manuscript received March 26, 2001; revised May 17, 2001.
[1] The authors are with the EE Dept., Kwangwoon Univ.
[2] The authors are with the EE Dept., KAIST.

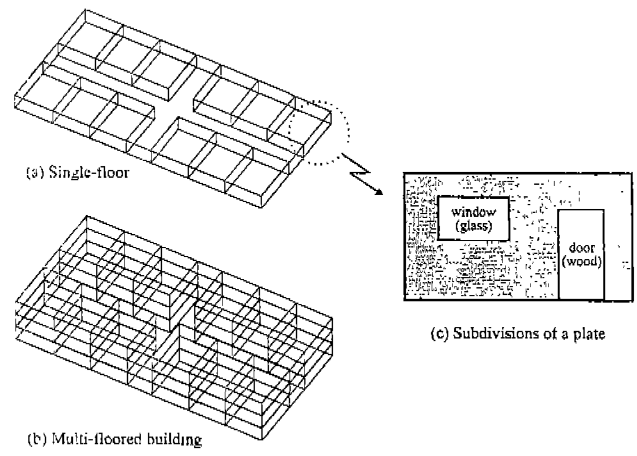


Fig. 1. Indoor databases.

subdivisions are neglected.

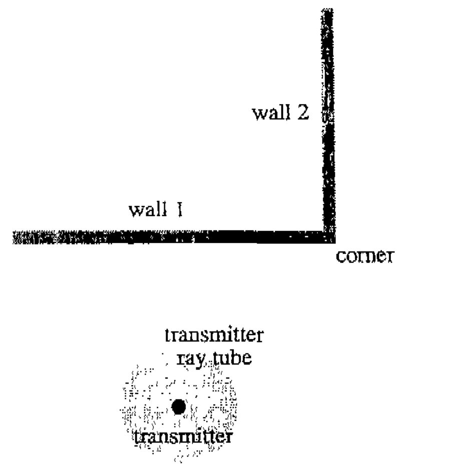
The procedure of the ray tracing in 3-D environments consists of two steps as follows. In the first step, a set of virtual sources (VSs) for a transmitter is constructed in the plan view of a building layout. A set of VSs is composed of image sources for wall reflections, transmission sources for wall transmissions and edge sources for corner diffractions. Unlike a brute force image method, we define, so called, a 'ray tube' for each VS, which has information of virtual source location and its lit region. The lit region represents the area in which a whole family of reflected, transmitted or diffracted rays exists[10]. Fig. 2 shows an example of three types of scattering ray tubes (reflection, transmission and diffraction ray tubes) as well as a transmitter ray tube[9]. A transmitter ray tube represents bundle of rays from a transmitter and its lit region extends to whole direction. Walls or parts of walls in the lit region produce first-order reflection or transmission ray tubes with definite lit regions.

For a reflection ray tube, the lit region is the area bounded by two vectors, $\vec{P}_{r1}$ and $\vec{P}_{r2}$, in counterclockwise direction as well as the corresponding wall. A transmission ray tube has a lit region bounded by two vectors, $\vec{P}_{t1}$ and $\vec{P}_{t2}$, and the transmission source location is the same with the precedent source. Walls or parts of walls in the lit region of the tube also produce next-order reflection or transmission tubes with definite lit regions.

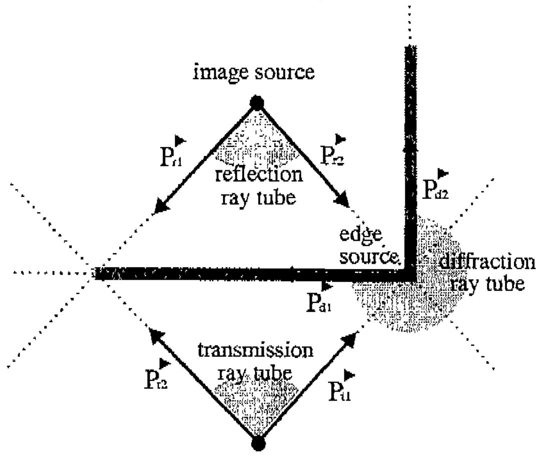
In the same way, corners in the lit region produce next-order diffraction ray tubes with the information of edge sources and specific lit regions bounded by two vectors, $\vec{P}_{d1}$ and $\vec{P}_{d2}$. The two vectors of a diffraction ray tube are determined by two walls adjacent to the corner and bound the lit region in counterclockwise direction.

By this simple and systematic process, a tree structure of ray tubes can be constructed up to a predetermined order which accounts for multiple interactions made of wall reflections, transmissions and corner diffractions as described in [9]. The root of the tree is always a transmitter tube and its depth corresponds to the order of scatterings. In the process of constructing the tree, the number of reflections, transmissions or diffractions can be limited individually by investigating each branch of the tree. Since our method treats reflections, transmissions and diffractions in the same manner using ray tubes, any combinations of reflections, transmissions and diffractions can be taken into account by the simple and unified process as above, without any additional algorithm to account for diffractions.

After completing the ray tube tree, backward ray tracing is employed to find all the rays in the plan view. Since the construction of the ray tube tree is independent of a receiver location, the tree can be used for any receiver location without



(a) An example of an indoor structure and a transmitter ray tube



(b) Generation of three types of ray tubes

Fig. 2. Generation of ray tubes.

reconstructing it. The procedure to find all the rays is as follows. For a given receiver location, we may search the ray tubes enclosing the receiver by traversing the tree. For each tube enclosing the receiver in its lit region, the sequence of the tubes from it to the transmitter ray tube can be found in the tree. There may be a number of sequences and each of them gives one ray in the plan view. For each sequence of the tubes, reflection, transmission or diffraction points are calculated by backward ray tracing. Since each sequence of the tubes provides one ray exactly, we don't have to check its physical reality unlike the conventional image method. This advantage makes the computational efficiency of our method much higher.

In the second step, each ray found in the plan view is converted to multiple 3-D rays including reflections and transmissions on the bottoms or ceilings of the floors. Each ray in the plan view represents multiple 3-D rays undergoing various combinations of reflections and transmissions on the bottoms or ceilings with the same scattering process around the vertical walls. In our method, we decompose the real scattering process in 3-D space into two independent processes. One is a horizontal scattering process around the vertical walls, and the other is a vertical scattering process on bottoms and ceilings. Each ray found in the plan view corresponds to an individual horizontal scattering process, which has information of (x, y)-coordinates of horizontal scattering points (Q_h) and horizontal propagation distances from a transmitter to the points. The vertical scattering process can be found by multiple image theory in consideration of heights of bottoms and ceilings as well as two antenna heights. Several vertical scattering processes, undergoing multiple interactions composed of reflections and transmissions on bottoms and ceilings, can be found. Each of them has information of z-coordinates of vertical scattering points (Q_v) and vertical propagation distances from a transmitter to the points. Fig. 3(a) and 3(b) show examples of horizontal and vertical scattering processes. A pair of horizontal and vertical scattering processes gives rise to a real 3-D scatteing process, i.e. a real 3-D ray as shown in Fig. 3(c). The 3-D coordinate of each scattering point is determined as follows.

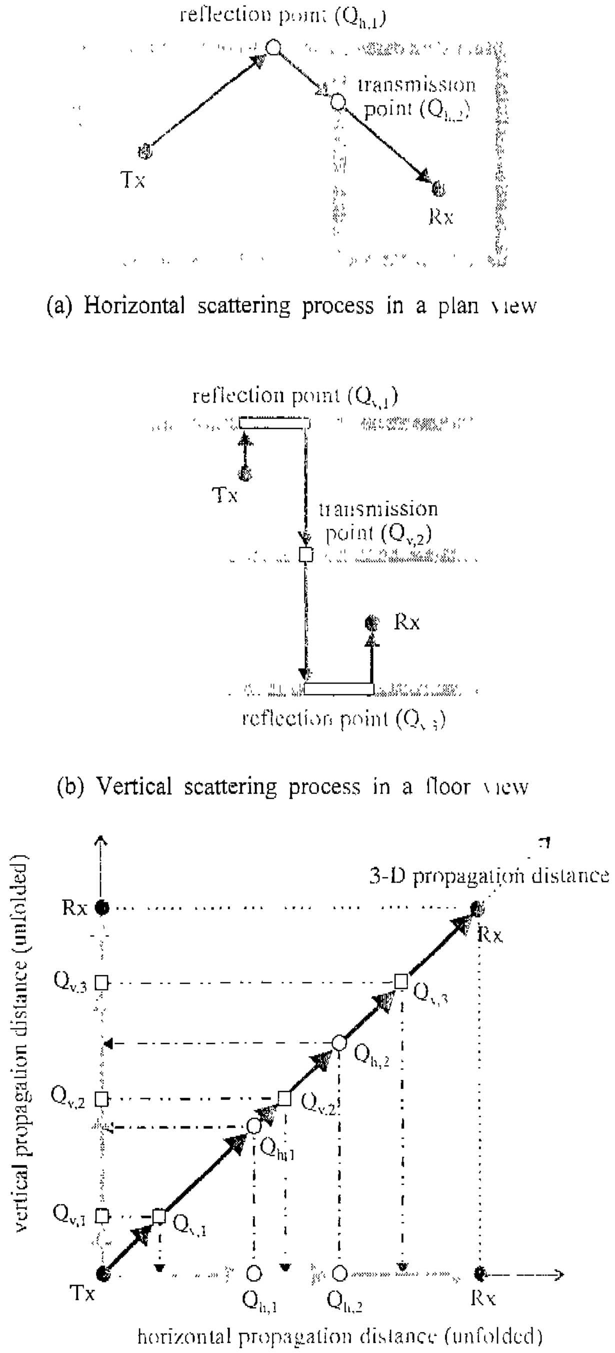
If $Q_{h,i}$ is the i-th horizontal scattering point (i = 0, 1, Λ, I and $Q_{h,0}$ = Tx, $Q_{h,I}$ = Rx) and $Q_{v,j}$ is the j-th vertical scattering point (j = 0, 1, Λ, J and $Q_{v,0}$ = Tx, $Q_{v,J}$ = Rx), the z-coorinate of $Q_{h,i}$ and (x, y)-coordinate of $Q_{v,j}$ are given by equation (1) and (2) respectively.

$$z_{Qh,i} = z_{Qv,j} + (z_{Qv,j+1} - z_{Qv,j}) \frac{d_{v,Qh,i} - d_{v,Qv,j}}{d_{v,Qv,j+1} - d_{v,Qv,j}} \qquad (1)$$

where $d_{v,Qh,i} = d_{h,Qh,i} \dfrac{d_{v,total}}{d_{h,total}}$

$Q_{v,j}$, $Q_{v,j+1}$ = successive vertical scattering points satisfying $d_{v,Qv,j} < d_{v,Qh,i} < d_{v,Qv,j+1}$

$d_{h(v),Q}$ = horizontal(vertical) distance from a transmitter to a scattering point (Q)



(a) Horizontal scattering process in a plan view

(b) Vertical scattering process in a floor view

(c) Conversion to 3-D scattering process

Fig. 3. Generation of a 3-D scattering process, i.e., 3-D ray from a fair of horizontal and vertical scattering processes.

$d_{h(v),total}$ = total horizontal(vertical) distance from a transmitter to a receiver

$$x_{Qv,j} = x_{Qh,i} + (x_{Qh,i+1} - x_{Qh,i}) \frac{d_{h,Qv,j} - d_{h,Qh,i}}{d_{h,Qh,i+1} - d_{h,Qh,i}} \quad (2a)$$

$$y_{Qv,j} = y_{Qh,j} + (y_{Qh,i+1} - y_{Qh,i}) \frac{d_{h,Qv,j} - d_{h,Qh,i}}{d_{h,Qh,i+1} - d_{h,Qh,i}} \quad (2b)$$

where $d_{h,Qv,j} = d_{v,Qv,j} = \frac{d_{h,total}}{d_{v,total}}$

$Q_{h,i}$, $Q_{h,i+1}$ = successive horizontal scattering points satisfying $d_{h,Qh,i} < d_{h,Qv,j} < d_{h,Qh,i+1}$

The sequence of 3-D scattering points is determined by the 3-D propagation distances from a transmitter to them as shown in Fig. 3(c). Fig. 3(c) shows an example of a 3-D scattering process (Tx- $Q_{v,1}$- $Q_{h,1}$- $Q_{v,2}$- $Q_{h,2}$- $Q_{v,3}$-Rx) generated from the combination of a horizontal scatteing process (Tx- $Q_{h,1}$- $Q_{h,2}$ -Rx) and a vertical scattering process (Tx- $Q_{v,1}$- $Q_{v,2}$- $Q_{v,3}$-Rx). If the number of horizontal scattering processes is M and that of vertical ones is N, '$M \times N$' 3-D rays can be found. Fig. 4 shows an example of 3-D rays found by the proposed method. In general, a few hundreds of rays are found by our method and summed to give total signal strength.

2-3 Field Calculation

After finding 3-D rays, the sector average field[1] is calculated by summing the individual ray intensities carried to the receiver site. For calculating the field due to reflections and transmissions, we make use of the local ray-fixed coordinate system or the edge-fixed coordinate system and the appropriate dyadic reflection and transmission coefficients. The transmission coefficients are calculated using $T = \sqrt{\chi(1-|\Gamma|^2)}$[1], where Γ is the dyadic reflection coefficient and χ (between 0 and 1) is a variable denoting the power loss due to diffuse scattering for the walls under consideration. For example, $\chi = 1$ for homogeneous and lossless walls. To calculate the diffracted field, the PAW (perfectly absorbing wedge) diffraction coefficients[8] are used.

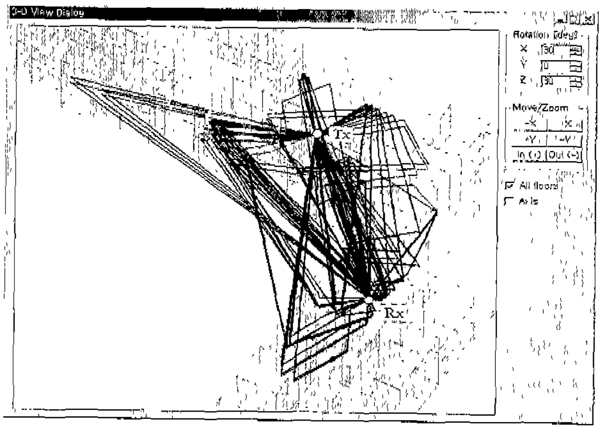


Fig. 4. An example of ray tracing by the proposed method. The transmitter and receiver are located on the 1st and 3rd floors respectively.

Ⅲ. PREDICTION RESULTS AND COMPARISON WITH MEASUREMENTS

To check the accuracy of the proposed ray tracing method, prediction results are compared with the published measurements in [5]. Fig. 5 shows the building layout as well as three transmitter locations and three measurement routes. The measurements were done at 1.8 GHz using quarter-wavelength monopole antennas. The distance between the measurement points was 0.8 λ and the median value of the path loss was computed with an interval of 15 instantaneous values, corresponding to a distance of 2 m. To predict the signal path loss. 4 reflections and 1 diffraction around vertical walls and 4 reflections on bottoms and ceilings were allowed. The number of transmissions was not limited and we discarded the ray tubes to give rise to path loss more than 140 dB by estimating the approximate signal strength from ray tubes in the plan view. The electrical properties used for the building materials are given in Table 1, which are estimated from results in references[6],[7].

Figs. 6~8 show the detailed comparisons of the predicted results with the measurements in the three routes - route 1 for Tx 1, route 2 for Tx 2 and route 3 for Tx3. The means and

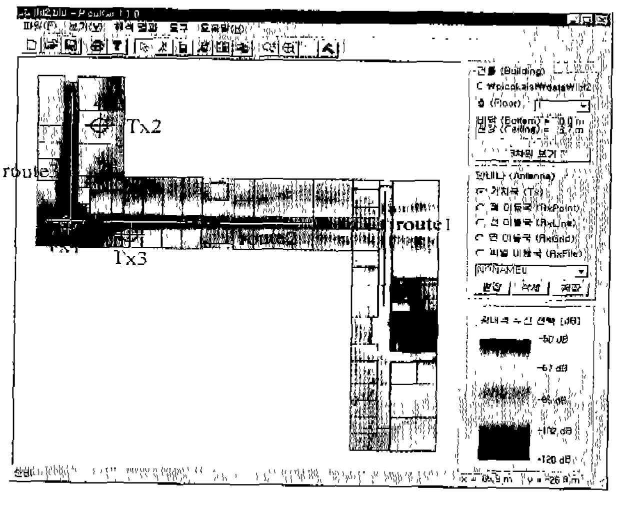


Fig. 5. Building layouts where the measurements were made in [5]. Three transmitter locations and three measurement routes are shown as well as the path loss map for Tx 1 in the whole area of the building.

Table 1. Electrical properties for the building materials

Material	εr	σ [S/m]	χ
Glass window	5.0	1.0	1.0
Wooden door	3.0	0.0	0.7
Thin brick wall	4.0	0.01	0.45
Thick brick wall	4.0	0.01	0.25
Concrete wall	6.0	0.01	0.05
Ceiling	2.0	0.1	0.35
Bottom of floor	8.0	0.1	0.05

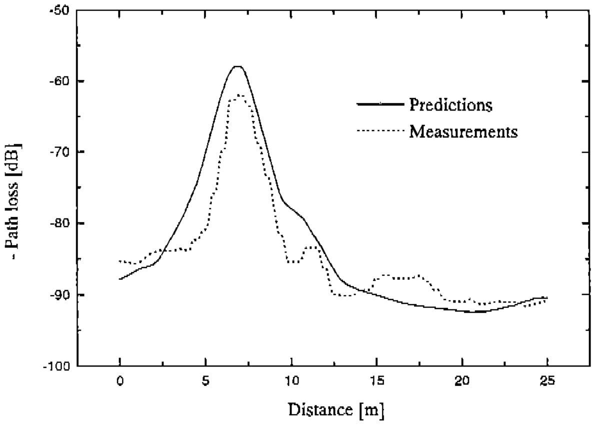


Fig. 6. Comparison of predictions versus measurements along route 1 for Tx 1.

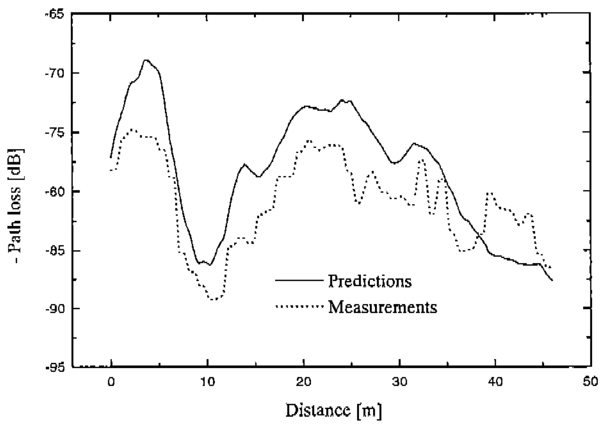


Fig. 7. Comparison of predictions versus measurements along route 2 for Tx 2.

standard deviations of the predicted errors as well as RMS errors are listed in Table 2. The RMS errors are around 4 dB and so, the predictions of the proposed method are in good agreement with the measurements. Fig. 5 also shows the path loss map for Tx 1 in the whole area of the building. To obtain

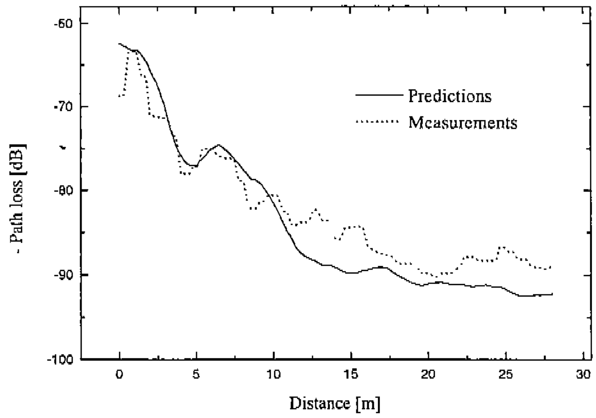


Fig. 8. Comparison of predictions versus measurements along route 3 for Tx 3.

Table 2. Statistics of the errors between predictions and measurements

Transmitter	Route	Prediction errors [dB] (Predictions - Measurements)		
		Mean	Std-dev	RMS error
Tx 1	Route 1	1.32	3.75	3.97
Tx 2	Route 2	2.61	2.93	3.92
Tx 3	Route 3	−1.42	2.73	3.07

the result, it took 27 seconds to construct the ray tube tree and 164 seconds to compute signal path loss for about 2,300 individual receiver locations on a pentium PC-600 MHz.

Ⅳ. CONCLUSION

The proposed method in this paper is a versatile 3-D ray tracing technique that can provide accurate site-specific propagation predictions in indoor environments. The method is based on the image theory with newly defined ray tubes, and has high computational efficiency compared to the precedent methods resorting to the ray launching scheme. The model surpasses empirical channel models and provides a bounty of additional information including RMS delay spread, angle of arrival, and overall wideband channel impulse response. The model was validated with measurements in an indoor environment where a transmitter and a receiver were on the same floor. Further validations in cross-floor propagation environments will be done in the near future.

This work was supported by KOSEF (Korea Science and Engineering Foundation).

REFERENCES

[1] W. Honcharenko, H. L. Bertoni, J. L. Dailing, J. Qian and H. D. Yee, "Mechanisms Governing UHF Propagation on Single Floors in Modern Office Buildings", *IEEE Trans. Veh. Technol.,* vol. 41, no. 4, pp. 496-504, May, 1990.

[2] S. Y. Seidel and T. S. Rappaport, "Site-Specific Propagation Prediction for Wireless In-Building Personal Communication System Design", *IEEE Trans. Veh. Technol.,* vol. 43, no. 4, pp. 879-891, Nov., 1994.

[3] S. Y. Tan and H. S. Tan, "Improved Three-Dimensional Ray Tracing Technique for Microcellular Propagation Models", *Electron. Lett.,* vol. 31, no. 17, pp. 1503-1505, Aug., 1995.

[4] U. Dersch and E. Zollinger, "Propagation Mechanisms in Microcell and Indoor Environments", *IEEE Trans. Veh. Technol.,* vol. 43, no. 4, pp. 1058-1066, Nov., 1994.

[5] G. Wolfle and F. M. Landstorfer, "Prediction of the Field Strength inside Buildings with Empirical, Neural, and Ray-Optical Prediction Models", *7th COST 259 MCM-Meeting in Thessaloniki,* Greece, COST 259, TD (99) 008.

[6] C. F. Yang, C. J. Ko and B. C. Wu, "A Free Space Approach for Extracting the Equivalent Dielectric Constants of the Walls in Buildings", in *IEEE AP-S Int. Symp. URSI Radio Sci. Meet.,* Baltimore, MD, July, 1996, pp. 1036-1039.

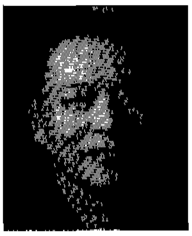
[7] O. Landron, M. J. Feuerstein and T. S. Rappaport, "A Comparison of Theoretical and Empirical Reflection Coefficients for Typical Exterior Wall Surfaces in a Mobile Radio Environment", *IEEE Trans. Antennas Propagat.,* vol. 44, no. 3, pp. 341-351, Mar., 1996.

[8] L. B. Felsen and N. Marcuvitz, *Radiation and Scattering of Waves,* Englewood Cliffs, NJ: Prentice-Hall, 1973.

[9] H. W. Son and N. H. Myung, "A Deterministic Ray Tube Method for Microcellular Wave Propagation Prediction Model", *IEEE Trans. Antennas Propagat.,* vol. 47, no. 8, pp. 1344-1350, Aug., 1999.

[10] H. W. Son and N. H. Myung, "3-D Ray Tracing Technique for Wave Propagation in Urban Environments", *Electron. Lett.,* vol. 35, no. 11, pp. 932-933, May, 1999.

Choon-Gil Suh



1989. 3.~1996. 10.: Korea Radio Station Management Agency
1996. 2. : EE Dept., Kwangwoon Univ. (MSc.)
1997. 4.~present: President of Intelinx Inc.
(Development of location finding algorithm, Prediction of electromagnetic environment)

Hae-Won Son

1994. 2.: EE Dept., Kyungpook National Univ. (BSc.)
1996. 2.: EE Dept., KAIST (MSc.)
2001. 2.: EE Dept., KAIST (Ph.D.)
2001. 3.~present: Samsung Electronics Co.
(Ant. & microwave engineering, Design & measurement of PCS phone)

Hyung-Wha Koh

1979. 2.: EE Dept., Seoul National Univ. (BSc.)
1982. 2.: EE Dept., Seoul National Univ. (MSc.)
1989. 2.: EE Dept., Seoul National Univ. (Ph.D.)
1985~present: Prof. at Kwangwoon Univ., EE Dept.
(Compression & transmission of images, Wavelet-based image processing, Digital communications)

Noh-Hoon Myung

1976. 2.: EE Dept., Seoul National Univ. (BSc.)
1982. 12.: EE Dept., The Ohio State Univ. (MSc.)
1989. 2.: EE Dept., The Ohio State Univ. (Ph.D.)
1986~present: Prof. at KAIST, EE Dept.
(Wave propagation & scattering, Ant. & Radar system design, EMI/EMC, Satellite & Mobile communications)