Estimation of Microwave Path Loss and Cross-Polarization Coupling in a Simple Urban Area

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Abstract

Whereas it is well known that microwave propagation around corners of urban area is estimated well by the uniform geometrical theory of diffraction (UTD), it is not clear how much depolarization occurs at a given receiver position and how much transmission through walls affects to total path loss. This paper presents the results of the ray tracing simulation to answer these questions. Simulations of microwave propagation around corners were performed for various line-of-sight (LOS) and out-of-sight (OOS) positions of a receiver, by summing the electrical fields of reflected, diffracted and transmitted rays coherently. Since height difference between transmitter and receiver, as well as ground plane, causes depolarization, the ray tracing simulation estimates the cross-polarization coupling. It was found that the cross-polarization coupling decreases as receiver moves away from transmitter. Another part of the study focused on the signal transmitted through building walls of the corner. It was found that the transmitted field is dominant at OOS region when the conductivity of the walls is low (for example, lower than 0.01 S/m). The simulation results of the ray tracing technique in this study agreed well with an experimental measurement around corners.

I. INTRODUCTION

The characteristics of microwave propagation in urban area should be analyzed accurately, to design appropriate cell structures and proper antenna positions in urban area for mobile communication system. For this purpose, a ray tracing technique with the uniform geometrical theory of diffraction (UTD) has been usually employed to compute the path loss of microwave propagation in urban area in earlier papers[1]~[4], and the simulation results of the ray tracing techniques have been compared with experimental data measured in cities, such as Kyoto, New York, Boston and Tokyo. Because of the complex wall structures, however, the values for the dielectric constant and conductivity of wall surfaces were chosen arbitrary for best data-fit with measurements.

In this work, a down-scaled simple urban structure (crossroads) was constructed using concrete bricks, and the path losses between a transmitter and a receiver at various LOS and OOS positions were measured. We measured the complex permittivities of concrete walls and ground accurately by a ring-resonator-type dielectric probe[5]. The measured path losses agreed very well with the simulated results of the ray tracing technique. The good agreement, especially in OOS region, is partially due to inclusion of rays transmitted through building walls for the estimation of the path loss.

The scatterers and reflectors in urban environment can produce cross-polarized fields, and the cross-polarization coupling improves the signal quality of randomly oriented portable telephone· for radio links[6]. Depolarization can also occur by height difference between transmitter and receiver, as well as ground plane. The path loss of cross-polarization is computed and compared with co-polarization in the following sections.

II. FORMULATION

The total electric field strength received by a receiver can be computed by coherent summation of the electric fields of multi-paths. Because reflections from walls and diffractions from edges are functions of the total path length as well as many other parameters, the total path length should be determined for each path prior to the computation of path loss. In order to determine all possible propagation paths efficiently up to a given number of reflections, the multiple image theory[2],[4] has been used as shown in Fig. 1. When a receiver R_{LOS} is located in the LOS region, the ray paths can be traced by connecting transmitter images to the receiver images. When a receiver R_{OOS} is located in the OOS region, the ray paths can be traced by connecting transmitter images to the receiver images. Some rays,

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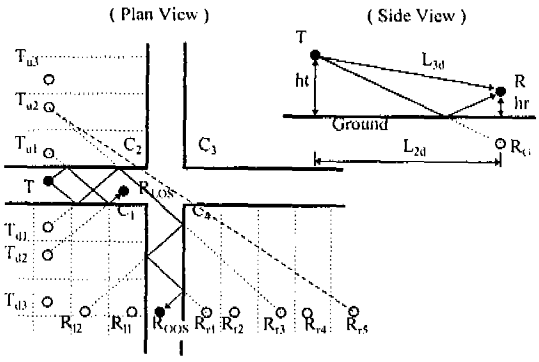


Fig. 1. Street geometry with typical ray paths.

however, cannot reach the receiver as illustrated by the connection between T_{u2} and R_{r5} in Fig. 1. Since the ray tracing simulation is performed for three-dimensional geometry, all reflected rays consist pairs with ground-reflected rays as shown in a side view in Fig. 1.

For the wave diffraction from the corners, C_1, C_2, C_3 and C_4, the corner lines are considered as the receivers and again the rays emanates from the corners. The paths for the diffracted rays can be found similarly as described above.

For a dipole antenna, the electric field vector is θ^3-direction for vertical antenna orientation in the far-zone and Φ^3- direction for horizontal orientation, when z-axis is vertical to the ground. The electrical field radiated from the transmitting antenna $\overline{E}^i$ can be decomposed by $\overline{E}^i_\perp$ and $\overline{E}^i$, which are perpendicular and parallel polarizations, respectively, as shown in Fig. 2. Then, the electric fields of reflected rays $\overline{E}^r_\perp$ and $\overline{E}^r_{//}$ can be computed using the Fresnel reflection coefficients $R_\perp$ and $R_{//}$ for perpendicular and parallel polarizations, respectively. The electric fields of the transmitted rays through walls $(\overline{E}^{tr}_\perp, \overline{E}^{tr}_{//})$ the diffracted rays from edges $(\overline{E}^{tr}_\perp, \overline{E}^{tr}_{//})$ can also computed from $\overline{E}^i_\perp$, $\overline{E}^i_{//}$ and the structures of the corners. Consequently, co- and cross-polarized reflected electric fields received by receiver antenna are computed as follows;

$$E^r_{co} = (\overline{E}^r_\perp + \overline{E}^r_{//})_V \cdot \theta \text{ and } E^r_{cross} = (\overline{E}^r_\perp + \overline{E}^r_{//})_V \cdot \phi \quad (1)$$

for vertically oriented transmit antenna, and

$$E^r_{co} = (\overline{E}^r_\perp + \overline{E}^r_{//})_H \cdot \phi^3 \text{ and } E^r_{cross} = (\overline{E}^r_\perp + \overline{E}^r_{//})_H \cdot \theta \quad (2)$$

for horizontally oriented transmit antenna. The co- and cross-polarized transmitted and diffracted electric fields can also be computed from $\overline{E}^{tr}_\perp$, $\overline{E}^{tr}_{//}$, $\overline{E}^d_\perp$, $\overline{E}^d_{//}$.

Since building walls have finite thickness, microwave can be transmitted through the walls with attenuation unless those have infinite conductivity. The ray incident on the first wall will have

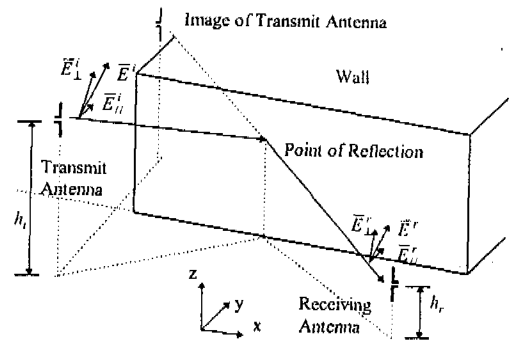


Fig. 2. Geometry for description of a reflected path and field depolarization.

the same direction when it arrives at the receiver as shown in Fig. 3. The transmitted field may be evaluated as follows using the GO method;

$$\overline{E}^{tr}_{\perp,//} = \overline{E}^{i}_{\perp,//}\,\overline{T}^{0}_{\perp,//}\,\overline{T}^{1}_{\perp,//}\,\frac{\exp[-jk_0(s_1+s_3+s_5)-jk_0\sqrt{\varepsilon_r}(s_2+s_4)]}{s_1+s_2+s_3+s_4+s_5} \quad (3)$$

where $\overline{E}^i_{\perp,//}$ is the electric field of the transmitter, ε_r is the complex dielectric constant of the walls and $s_1 \sim s_5$ are distances (Fig. 3). $\overline{T}^0_{\perp,//}$ and $\overline{T}^1_{\perp,//}$ are transmission coefficients for a two-layer medium, which are given in[7] as follows;

$$T^i_{\perp,//} = \frac{4k^i_{0z}\,k^i_{1z}\exp[j(k^i_{0z}-k^i_{1z})d_i]}{(k^i_{0z}+k^i_{1z})^2(1-R^{i\,2}_{\perp,//}\exp[-j2k^i_{1z}d_i])}, \quad i=0,1 \quad (4)$$

where $k^i_{0z}=k_0$, $\cos\theta_i$, $k^i_{1z}=k_0\sqrt{\varepsilon_r-\sin^2\theta_i}$, d_i is the thickness of the walls and $\overline{R}^i_{\perp,//}$ is the Fresnel reflection coefficient. It is worth to note that a ray not passing air after transmitting the first wall is totally reflected inside the second

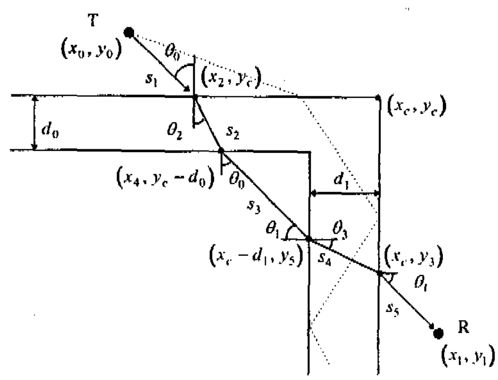


Fig. 3. Geometry with a ray transmitted through walls.

wall and cannot reach the receiver as shown in Fig. 3(dotted line), because corners usually have right angles while dielectric constants of building walls are usually higher than two $(n>\sqrt{2})$.

Total electric field E^{tot} received by the receiver is computed by the coherent summation of reflected field E^r, diffracted field E^d and transmitted field E^{tr}, which are propagated along reflected, diffracted and transmitted rays, respectively. E^r includes directly incident field here. Each ray makes a pair with a ray reflected once at the ground as shown in Fig. 1 (side view). Path loss L in dB scale is defined as follows[2],[4];

$$L = 20 \log_{10}\left|\frac{\lambda}{4\pi}\ \frac{E^{tot}}{E_0}\right| \ \text{(dB)} \tag{5}$$

For estimating path loss around corners, a crossroad as shown in Fig. 4 is considered at first. A transmitter is located in front of wall at a height of 15 m, while a receiver at a height of 1.5 m moves away from the transmitter as shown in Fig. 4.

The received total field can be computed by (1) and (2) for co- and cross-polarizations depending on the antenna orientation, where the electric fields of reflected, diffracted and transmitted rays can be obtained as follows;

$$E^r_{\perp,//} = \begin{cases} \sum_{g=0}^{1} E^i R_G^g \frac{e^{-jkS_{Ig}}}{S_{Ig}} + \sum_{g=0}^{1}\sum_{u=1}^{2}\sum_{l=1}^{ML} E_0 R_G^g R_U^u R_L^l \frac{e^{-jkS_{Rulg}}}{S_{Rulg}}, & \text{(LOS)} \\ \sum_{g=0}^{1}\sum_{l=1}^{ML}\sum_{n=1}^{MN} E^i R_G^g R_L^l R_N^n \frac{e^{-jkS_{Rnvg}}}{S_{Rnvg}}, & \text{(OOS)} \end{cases} \tag{6}$$

$$E^d_{\perp,//} = \sum_{g=0}^{1}\sum_{e=1}^{4}\sum_{l=0}^{ML}\sum_{n=0}^{MN} E^i R_L^l R_N^n R_G^g D_{emkg} \frac{e^{-jkS_{Demkg}}}{\sqrt{S_{IDemkg} S_{DDemkg} S_{Demkg}}} \tag{7}$$

$$E^{tr}_{\perp,//} = \sum_{g=0}^{1}\sum_{l=0}^{ML}\sum_{n=0}^{MN} E^i R_G^g R_L^l R_N^n T_0\, T_l \frac{e^{-j(kS)_{Tlng}}}{S_{Tlng}} \tag{8}$$

where E^i is $E^i_\perp$ or $E^i_{//}$ for perpendicular or parallel-polarization, respectively. R is the Fresnel reflection coefficient depending on polarization of the electric fields. The subscripts G, L and N denote reflections from ground, LOS walls and OOS walls, respectively. The subscript U is for multiple reflections by down-images (u=1) and up-images(u=2). The superscripts denote number of reflections; l is for LOS reflection, n is for OOS reflection, g is 1 with ground reflection and 0 without it, and e denotes number of edges. The diffraction coefficient D can be computed as follows;

$$D_{\perp,//} = D_1 + D_2 + R^n_{\perp,//} D_3 + R^o_{\perp,//} D_4 \tag{9}$$

where D_1, D_2, D_3, D_4 and other relative parameters are given in[4],[8].

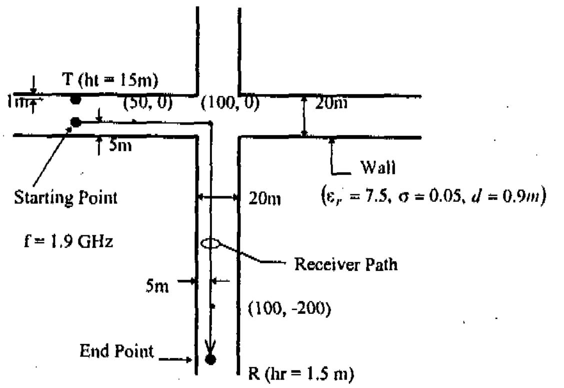


Fig. 4. Geometry for estimation of the path loss.

Ⅲ. SIMULATION RESULTS

The formulation described in the preceding section was used to simulate microwave propagation around corners at 1.9 GHz as shown in Fig. 4. The transmitter is located 1 m apart from the wall at a height of 15 m, and the receiver at a height of 1.5 m moves away from the transmitter passing LOS and OOS regions in the street of 20 m width. The dielectric constant ε_r, relative permeability μ_r and the conductivity σ of the walls in this simulation are selected arbitrary as 7.5, 1 and 0.05 S/m, respectively, because the values of ε_r, μ_r and σ for limestone wall reported in [9] were about 7.51, 0.95 and 0.03 S/m at 4 GHz. Then, propagation path losses were computed to examine the cross-polarization coupling and the effect of transmission-through-walls.

At first, the convergence tests were performed to determine minimum number of reflections in order to compute the path loss precisely. A direct ray and a couple of reflected rays are enough for precise estimation of path loss when the receiver is near the transmitter in LOS region, while more than ten images of transmitter and receiver should be considered for the receiver at the position of (100, −200) in OOS region.

The simulations show that the diffracted field is dominant at OOS region beyond 106 m (Fig. 4), while the reflected field is dominant at LOS region. The simulations also show that the vertically oriented antennas give slightly higher received signal than the horizontal antennas at OOS region, because of characteristics of reflection and diffraction coefficients.

Fig. 5 shows the cross-polarization coupling generated by the height differences of transmitter and receiver images and the ground. There is no depolarization when the receiver is lined up with the transmitter perpendicularly to the wall (distance of 0 m in Figs. 4 and 5), and when the distance is infinity. According

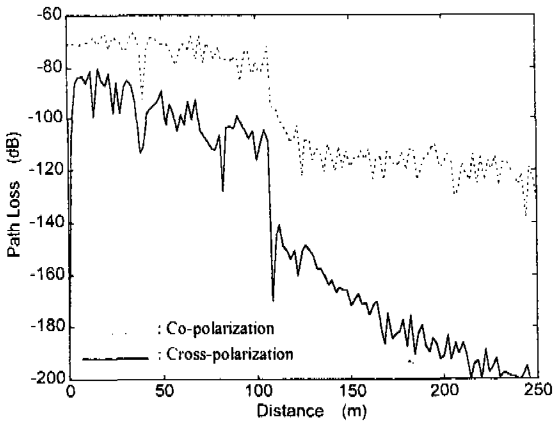


Fig. 5. Cross-polarization coupling compared with co-polarization.

to Fig. 5, maximum cross-polarization coupling occurs at the distance of 10~30 m in this case, and the cross-polarization coupling decreases as the distance between the transmitter and the receiver increases.

Fig. 6 shows the contribution of ray transmission to total received signal at OOS region when the position of the receiver is in the OOS region. The signal transmitted through a wall of conductivity σ = 0.01 S/m is higher than diffracted signal, whereas the transmitted signal is negligible for a wall of conductivity σ = 0.05 S/m. The thickness of the wall was chosen to 0.9 m in this computation. If the loss of wall is low (σ<0.03 S/m in this case), the transmission may dominate the received signal at OOS region. We note that while the transmission through the wall decreases as the conductivity increases, the reflection and diffraction from the wall increases and the amount of the increase might depend on the structure of the street. The effects of the dielectric constant and the permeability might be similar to the conductivity, considering the Fresnel reflection, transmission and diffraction coefficients.

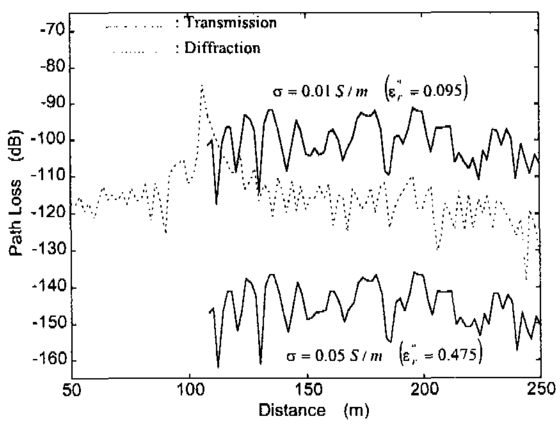


Fig. 6. Transmission through walls dependent on conductivity of walls.

Ⅳ. MEASUREMENTS

Recently, many simulation results using the ray tracing technique are compared with experimental data measured in Manhattan-type streets[1]~[4]. However, the structures of buildings and streets are very complicate and the complex dielectric constants of the building surfaces are usually not predictable. Therefore, comparisons between simulation results and measurements were very difficult.

To verify the simulation program of this paper, a down-scaled crossroad was constructed with bricks on a concrete ground plane as in Fig. 4, where width of the street is 80cm. The path losses between two vertically oriented dipole antennas were measured at 10 GHz. The transmitter consists of a dipole antenna and a signal generator(Advantest TR4515), and the receiver consists of a dipole antenna, a spectrum analyzer (HP8693A), and an X-band amplifier(Avantek AMT-12444). Since the gains of the amplifier, connection cables, and each antenna were 27 dB, −10 dB, and 1.34dB, respectively, total system gain was 19.68 dB. Therefore, the system gain of 19.68 dB and the transmitted power of 14 dBm were subtracted from the received power, to compute the ratio (in dB) of the received and the transmitted electric fields.

The complex dielectric constants of the wall and ground have been measured using a ring resonator and a network analyzer at 1.15 GHz[5]. The measured complex dielectric constants were ε_r = 3.5 − j 0.31 and ε_r = 3.5 − j 0.46 for walls and ground, respectively, and these values were used in the simulation assuming the measured permittivity doesn' t vary drastically up to 10 GHz. The surface roughness of the walls was also measured, and the standard deviation of the surface height was σ_h = 1.5

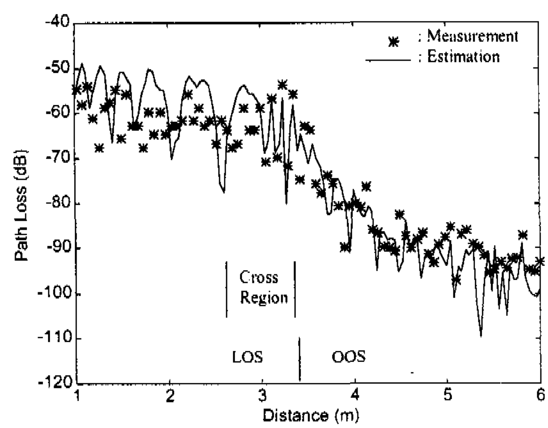


Fig. 7. Comparison of measurement and estimation.

mm. The scattering loss factor ρ_s given in [9] was multiplied to Fresnel reflection coefficients for the simulation, and theoretical pattern of $\lambda/2$ dipole antenna was also included in the simulation.

Fig. 7 shows comparison of simulation results and measurements of propagation path loss in the crossroads. The path loss computed using the ray tracing technique around corners at the down-scaled crossroad agrees well with the experimental measurements. Fig. 8 shows contributions of ray reflection, diffraction and transmission on total received signal. It was found that the reflection dominates at LOS region and the first part of OOS region (D<4.3 m), and the diffraction dominates the second part (D>4.3 m), while the transmission is comparable with the diffraction at last part of OOS region of this simulation.

The path loss in a city street in Seoul as shown in Fig. 9 has been measured using a receiving system, two dipole antennas and a transmitter. The transmitter sent a continuous wave at 1.1 GHz with a dipole antenna, which was fixed at 2.5 m height from ground. The receiver with a dipole antenna was moved while receiving the signal, following the path-1 and path-2 as shown in Fig. 9. The system gain was 19.5 dB including the antenna gain of 1.5dBi (x 2 for both), the amplifier gain of 19.2 dB and the cable loss of 2.7 dB.

Fig. 10 (a) shows the measurement of the path loss for the receiver path of 'Path-1' (refer to Fig. 9) compared with the

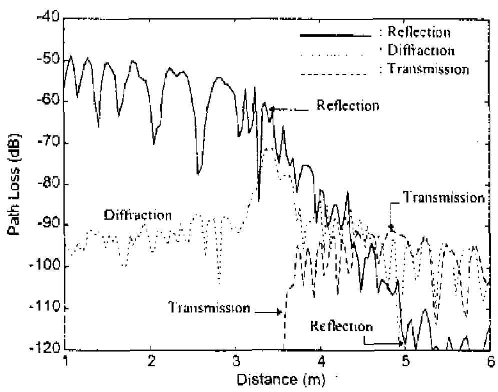


Fig. 8. Contribution of reflected, diffracted and transmitted rays on total path loss.

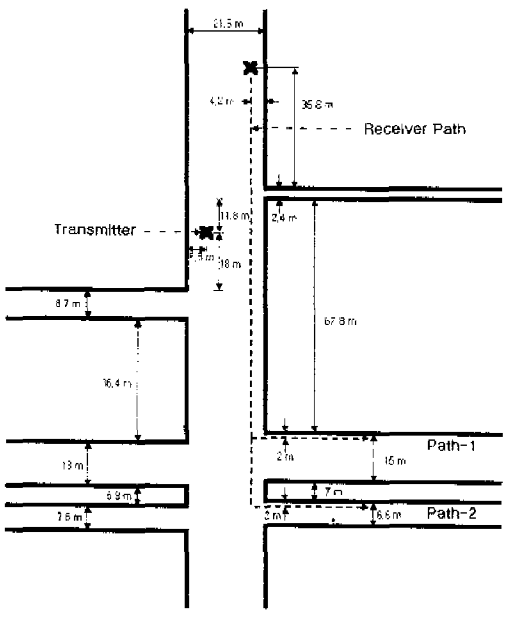
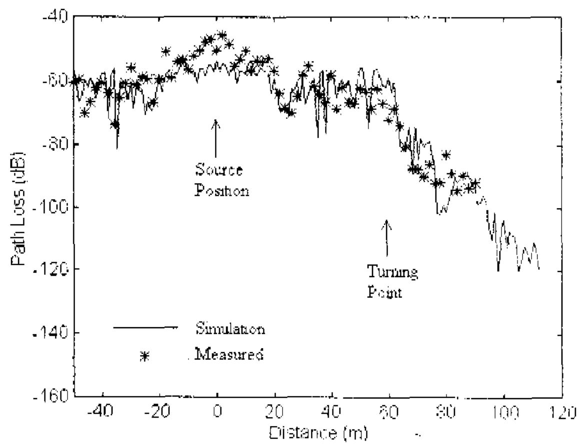
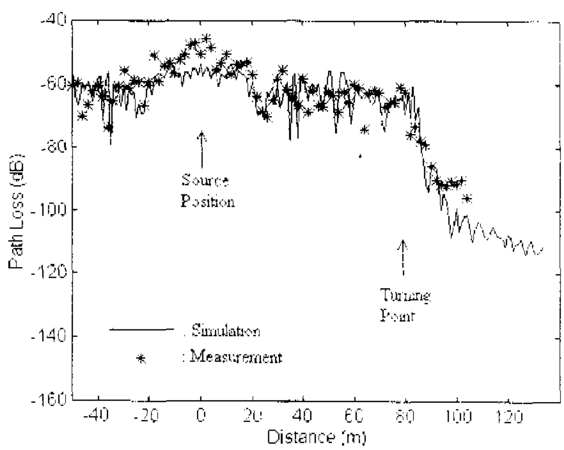


Fig. 9. Street structure for measurement.



(a)



(b)

Fig. 10. Comparison between computational results and experimental measurements for a co-polarized wave for (a) path-1 and (b) path-2.

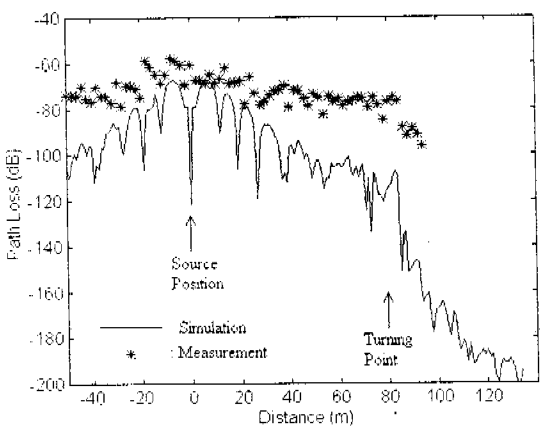


Fig. 11. Comparison between computational results and experimental measurements for a cross-polarized wave.

computation. The buildings of the street had the irregular shapes of walls, windows, attachments and other belongings. The ground of the street has also irregular roughness. Many different-shaped trees were at the side of the street. A lot of cars and pedestrians were moving. Therefore, the precise modeling of the street (Fig. 9) for the UTD computation was impossible, even though the scaled crossroad of Fig. 4 was modeled precisely. In the UTD computation for the street structure of Fig. 9, the parameters were chosen approximately (or arbitrary) by the rule of thumb, *i.e.*, the dielectric constant of 3.5 and the conductivity of 0.08 S/m are assumed, the walls are assumed to be flat concrete, a flat ground is assumed, no trees are included, the cars and pedestrians are excluded in this model. Even though the path loss was estimated approximately based on a very simple model, Figs. 10 (a) and (b) show relatively good agreements between the measurements and the estimation of the path loss.

Fig. 11 shows the comparison of the cross-polarized path losses between the measurement and the estimation. The measurement is much higher than the estimation because the estimation was based on a simplified model, ignoring the presence of cars, pedestrian, trees, irregularities of building walls and ground, other structures in the street, which can produce the cross-polarized waves.

V. CONCLUSIONS

Simulations of microwave propagation around corners were performed using a ray tracing technique with the UTD at various situations in this paper. Contributions of reflection, diffraction and transmission-through-walls have been examined. It was found that the rays transmitted through brick walls had better to be included for precise estimation of path loss. Cross-polarization coupling has been computed and compared with co-polarized received signal. The simulation of microwave propagation around corners is verified by comparison with the experimental data obtained from a scaled crossroad.

It was also found that the measured path loss from a city street in Seoul agreed quite well with the UTD computation for co-polarized wave even though the computation was based on a simplified model, while the measurements for cross-polarized wave show higher path loss than the estimation.

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REFERENCES

[1] F. Ikegami, T. Takeuchi and S. Yoshida, "Theoretical prediction of mean field strength for urban mobile radio", *IEEE Trans. Antennas Propag.,* vol. 39, pp. 299-302, March, 1991.

[2] S. Y. Tan and H. S. Tan, "UTD propagation model in an urban street scene for microcellular communications", *IEEE Trans. EM Compatib.,* vol. 35, pp. 423-428, November, 1993.

[3] V. Erceg, A. J. Rustako, and R. S. Roman, "Diffraction around corners and its effects on the microcell coverage area in urban and suburban environments at 900 MHz, 2 GHz, and 6 GHz", *IEEE Trans. Vehic. Technology,* vol. 43, pp. 762-766, August, 1994.

[4] S. Y. Tan and H. S. Tan, "A microcellular communications propagation model based on the uniform theory of diffraction and multiple image theory", *IEEE Trans. Antennas Propag.,* vol. 44, pp. 1317-1326, October, 1996.

[5] K. Sarabandi and E. S. Li, "Microstrip ring resonator for soil moisture measurements", *IEEE Trans. Geosci Remote Sensing,* vol. 35, pp. 1223-1231, September, 1997.

[6] D. C. Cox, R. R. Murray, H. W. Arnold, A. W. Norris and M. F. Wazowicz, "Cross-polarization coupling measured for 800 MHz radio transmission in and around houses and large buildings", *IEEE Trans. Antennas Propag.,* vol. 34, pp. 83-87, January, 1986.

[7] J. A. Kong, *Electromagnetic Wave Theory,* John Wiley and Sons, New York, 1990.

[8] D. A. McNamara, C. W. I. Pistorius and J. A. G. Malherbe, *Introduction To The Uniform Geometrical Theory of Diffraction,* Artech House, 1990.

[9] 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 Propag.,* vol. 44, pp. 341-351, March, 1996.

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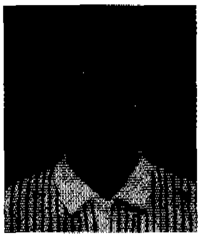

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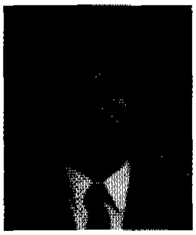

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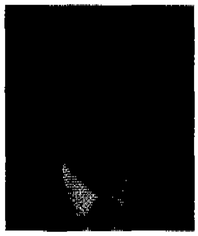

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