Analysis of Radio Wave Propagation Characteristics in Rectangular Road Tunnel at 800 MHz and 2.4 GHz

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1. Introduction

As of January 2003, there are total 184 tunnels on Korean expressways. Tunnels are expected to grow in number in Korea. The cross sectional shapes of the tunnel in Korea are various, including rectangular, arched, and semicircular ones. However, the number of arched and semicircular exceeds that of rectangular tunnels, due to problems related to tunnel structure and construction. The radio wave environment inside tunnels is very different from that in the open air. The cutoff frequency inside a tunnel is determined by its cross-section[1][2]. The propagation of radio waves inside a tunnel is affected by direct waves, reflective waves, diffracted waves, and scattered waves, and the radio wave characteristics change subject to the degree of internal curvature of the tunnel[3]. The parameters which most affect the radio wave propagation inside a tunnel are its height, width, internal medium characteristics, surface roughness, obstacles inside, and polarization states of transmitter and receiver antennas.

Among the analysis methods for determining radio wave characteristics inside tunnels, there are statistical method, the hybrid wave guide mode method[4], geometrical optics, ray-tracing, and ray-launching method, etc. These methods all come with their own advantages and disadvantages to be considered and applied within the analysis. For the analysis of propagation effects in typical sized tunnels, the ray-tracing method is the most preferred [4]-[9].

This study analyses and compares the simulated and measured receiver powers as a function of distance between transmitter and receiver antennas. The specific tunnel geometry used for this study is the newly built straight three-lane rectangle tunnel on Pyungtaek-Ansung expressway in Korea, which is not in operation at this time.

2. Simulations and Measurements

1) Tunnel geometry and measurement system

The cross sectional view of Pyungtaek tunnel in Korea is shown in Fig. 1. Its width is 14.7 meters; its height 6.15 meters; its length 360 meters. Fig. 2 shows the measurement set-up diagram. The heights of T_x and R_x antennas are both 1-meter and they are located on the centerline in the tunnel.

Simulations and measurements are performed at 884㎒ and 2.45㎓. The T_x and R_x antennas have vertical polarization. The antenna has the gain of 5dB at 884㎒ and 8dB at 2.45㎓. The output of the signal generator is 0 dBm. The receiving components of R_x antenna, measuring receiver, and spectrum analyzer were loaded on the cart.

2) Received power using ray-tracing method

The Pyungtaek tunnel was constructed with concrete of which complex permittivity (ε_r^*) is given by

$$\varepsilon_r^* = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} \tag{1}$$

where ε_r is the real part of the relative permittivity, σ is the conductivity, ε_0 is the free space permittivity, and ω is the angular frequency.

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The distance between T$_x$ antenna and R$_x$ antenna is R_0. The received power P_r can be expressed by the summation of three types of fields, they are, direct waves, waves reflected from side walls, and waves reflected from the top and bottom surfaces as shown in equation (2) [5]-[9].

$$P_r = P_t\left(\frac{\lambda_0}{4\pi}\right)^2 \cdot \left(\left|\frac{G_d e^{-jkR_0}}{R_0} + \sum_{i=1}^{n}\frac{G_{vi}(\Gamma_{vi})^i e^{-jkR_{vi}}}{R_{vi}} + \sum_{i=1}^{n}\frac{G_{hi}(\Gamma_{vi})^i e^{-jkR_{hi}}}{R_{hi}}\right|^2\right)(w) \qquad (2)$$

The parameters used in equation (2) are defined as follows:

P_t : Transmitted power (W)

λ_0 : Wavelength in free space

R_0 : LOS path length between T$_x$ and R$_x$ antenna

k : Wavenumber

$G_t,\ G_r$: Gain of T$_x$ and R$_x$ antennas

$H,\ W$: Height and width of the tunnel

$G_d = \sqrt{G_t \cdot G_r}$: Geometric mean of T$_x$ and R$_x$ antenna gains for direct wave

$R_{vi} = \sqrt{(R_0)^2 + (i \cdot H)^2}$: Path length for i-th wave reflected between the and bottom surfaces

$\theta_{vi} = \tan^{-1}\frac{H(i+1)}{2R_0}$: Grazing angle of i-th wave on top and bottom surfaces

$G_{vi} = \sqrt{G_t(\theta_{vi})\cdot G_r(\theta_{vi})}$: Geometric mean of T$_x$ antenna gain $G_t(\theta_{vi})$ and R$_x$ antenna gain $G_r(\theta_{vi})$

$R_{hi} = \sqrt{(R_0)^2 + (i \cdot W)^2}$: Path length for i-th wave reflected between walls

$\theta_{hi} = \tan^{-1}\frac{W(i+1)}{2R_0}$: Grazing angle of i-th wave on wall surface

$G_{hi} = \sqrt{G_t(\theta_{hi})\cdot G_r(\theta_{hi})}$: Geometric mean of T$_x$ antenna gain $G_t(\theta_{hi})$ and R$_x$ antenna gain $G_r(\theta_{hi})$

The Pyungtaek tunnel has been constructed using concrete material. The reflection coefficient for the vertically polarized waves reflected from top and bottom surfaces is expressed in equation (3) and for the horizontally polarized waves reflected from the walls, in equation (4).

$$\Gamma_{vi} = \frac{\varepsilon_r^* \sin(\theta_{vi}) - \sqrt{\varepsilon_r^* - \cos^2(\theta_{vi})}}{\varepsilon_r^* \sin(\theta_{vi}) + \sqrt{\varepsilon_r^* - \cos^2(\theta_{vi})}} \quad (3), \qquad \Gamma_{hi} = \frac{\sin(\theta_{hi}) - \sqrt{\varepsilon_r^* - \cos^2(\theta_{hi})}}{\sin(\theta_{hi}) + \sqrt{\varepsilon_r^* - \cos^2(\theta_{hi})}} \quad (4)$$

The complex permittivity of concrete material is assumed to be $\varepsilon_r^* = 7 - j0.8$. Fig. 3 shows the magnitude of reflection coefficient as a function of grazing angle for the frequency range of 2 ㎒ ~5.8 ㎓. As the grazing angle increases from 0° to 90°, the magnitude of reflection coefficient $|\Gamma_{hi}|$ gradually decreases from 1 to 0.45, but $|\Gamma_{vi}|$ becomes very small at the Brewster angle 20°.

3) Simulations

The simulation parameters are summarized in Table 1. Using equation (2) and parameters in Table 1, the simulated receiver power is plotted as a function of distance in Fig. 4.

The received power decreases as R_0 increases with a feature of fast fading due to multipath effects. When the receiver is moved farther away from the transmitter, the path difference between the direct wave and reflected wave decreases, and the fading phenomena occur less. The received power at the frequency 884 ㎒ is approximately 10 ㏈ higher than that at 2.45 ㎓ in this simulation. In most of the simulations, the received power has converged at about 10th wave reflected.

4) Measurements and comparisons

The measurement of received power was conducted in the tunnel seen in Fig. 1. When the measurement was performed, the newly built tunnel was not in operation. The circumstances in the tunnel were quite similar to those of the simulation because there were not any obstacles inside. Under such condition of no obstacles, the propagation loss has been reported to be lower[5]. No obstacles also mean that there does not exist larger roughness than the wavelength [8][9].

The measurement using vertically polarized T_x and R_x antennas has been performed along a central line following the tunnel axis by 1 meter. The measured receiver power is compared with the simulated ones in Fig. 5(at 884 ㎒) and Fig. 6(at 2.45 ㎓), respectively. The measured result is very similar to the simulated ones, which has been performed in Pyungtaek tunnel.

The received powers are shown to decrease as the distance increases up to about 90 meters. Beyond 90 meters, the average propagation loss is almost constant(55dBm) at 884 ㎒, and (65dBm)at 2.45 ㎓ throughout the tunnel. The depth of fading is in the range of 10 ~ 20dB for both frequencies.

3. Conclusion

We analyze radio wave propagation characteristics in tunnel using simulations by ray-tracing method and measurements for a newly constructed tunnel in Korea.

As the simulation results using direct wave and 25 reflected waves and the measurement ones against the 14.7 meters wide, and 6.15 meters high, and 365 meters long tunnel is similar to each other, the radio wave propagation model for predicting received power in the tunnel can be applied to the other tunnels.

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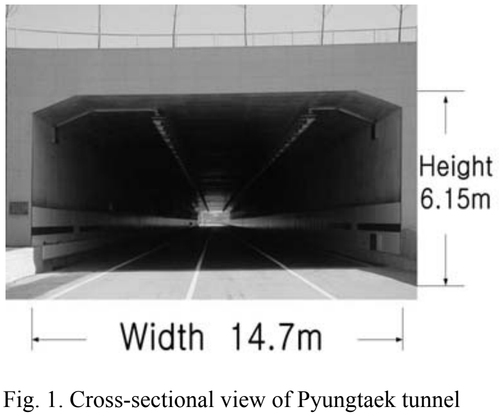

Fig. 1. Cross-sectional view of Pyungtaek tunnel

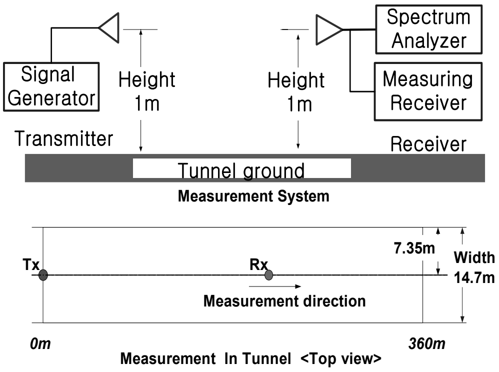

Fig. 2. Measurement set-up diagram

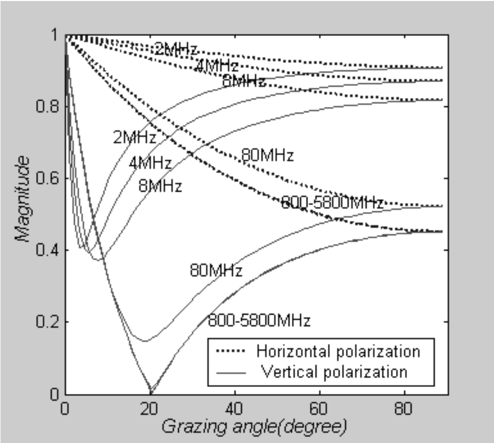

Fig. 3 Reflection coefficient as a function of grazing angle

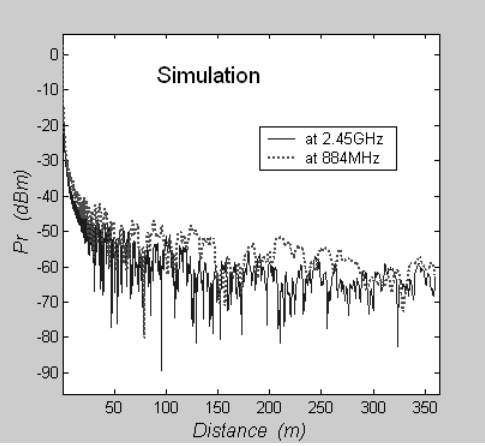

Fig. 4 Simulated receiver power in tunnel

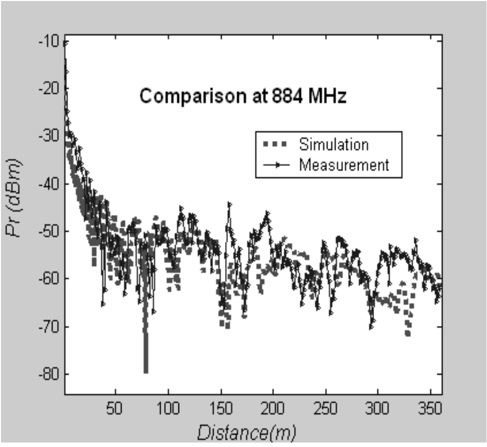

Fig. 5 Comparison between simulated and measured receiver powers at 884 MHz

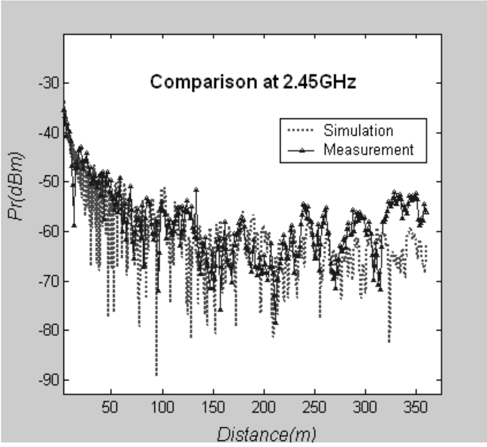

Fig. 6 Comparison between simulated and measured receiver powers at 2.45 GHz

Table 1. Parameter value for simulation

Items	Value
Patch antenna gain of transmitter	5dBi(884 ㎒), 8dBi(2.45 ㎓)
Patch antenna gain of receiver	5dBi(884 ㎒), 8dBi(2.45 ㎓)
Transmitting power	0dBm
Complex permittivity of tunnel wall	7.0 – j0.85
Conductivity of wall	0.0239 S/m
Tunnel cross section	14.7m × 6.15m
Number of reflections	25 times