Simulations and Measurements of Wave Propagations in Curved Road Tunnels for Signals from GSM Base Stations[1]

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Introduction

Simulations and measurements of wave propagations in tunnels have been performed by many investigators; e.g., [1]-[10]. In [5]-[7], measurements were presented for propagation characteristics in straight tunnels having rectangular cross-sections, and the ray-optical method was applied to simulate the field distributions. A ray launching approach with the Monte Carlo method has been proposed to determine the propagation properties in curved tunnels [2][3], and wave propagations in tunnels with and without traffic were modeled with a shooting and bouncing ray (SBR) image method [1]. In [4] and [8], some statistical characteristics of the propagation channel in tunnels were described. As for [9] and [10], the ray-optical method with ray density normalization was developed to determine wave propagations for GSM bands in underground railroad tunnels.

This paper presents a ray-tube tracing method for wave propagations in curved tunnels. The waves from a transmitting antenna are modeled with many ray tubes [11], and those ray tubes are traced by including multiple reflections and diffractions from curved structures. Measurements for signals in curved road tunnels from GSM900/1800 base stations have been performed and are compared with those obtained from the ray-tube tracing method.

Ray tracing method for curved tunnels

As presented in [11], the waves from a transmitting antenna are simulated by shooting many ray tubes, each composed of four rays, in all directions based on the far field pattern of the antenna, and the spreading factors of the waves are evaluated from the cross-sectional area of the ray tubes. A ray-tracing approach improved from that developed in [11] is applied in this paper. For determining the fields inside curved road tunnels, reflections from curved surfaces and diffractions from curved edges are added in the ray-tracing program. Only the approach for evaluating those two ray contributions is described below:

Curved surfaces of the tunnels are approximated with sections of cylindrical and spherical surfaces. When a ray tube is intersected with a curved surface, reflections from the curved surface for the four rays of the ray tube are determined from the Snell's law with the incident angles evaluated from the norms of the surface at the intersection points, respectively. Those four reflected rays become a ray tube and are then traced further. The spreading factor of the fields can be obtained from the cross-section of the reflected tube. However, for reflections from curved tunnels, crossover

[1] This work was supported in parts by the National Science Council of ROC under Grants NSC-89-2213-E-011-162 and NSC-90-2213-E-011-031.

of the rays in a ray tube may occur; i.e., the rays pass through a caustic, and then a $90°$ phase jump should be included [12]. To check whether the rays passing through a caustic or not, angles between adjacent rays are evaluated and the location most close to the caustic is determined. Thus, the focusing of the ray tube reflected from the concaved interior surface of the curved tunnel may be properly simulated both in amplitude and phase.

When a ray tube illuminates the edges of the curved tunnel, diffracted waves are excited and can be determined by applying the UTD method [12]. Those edges include the tunnel entrances and the interior wedges inside the tunnel, as shown in Figs. 1 and 2. Since a diffracted cone should be generated according to the UTD, many astigmatic tubes of rays forming the cone are produced. The caustics of the astigmatic tubes, as shown in Fig. 1, are evaluated by first finding the two intersection points of the incident tube on the diffracting edge. Then, based on the Fermat's principle, diffracted rays from the intersection points are obtained. Also, the diffracted rays from the two intersection points with the same angle from the wedge surface are used to find the caustic of the diffracted rays away from the edge. Other parameters of the UTD formula for evaluating the diffracted ray tube can be obtained from the incident ray tube and the curved wedge. For example, radii of curvature of the incident and reflected wave fronts at the point of diffraction may be evaluated by finding the rays on the tube surfaces lying in the planes for determining the radii of curvature. Thus, with this ray tube approach, diffracted ray tubes from a curved wedge can be determined. Those ray tubes are then traced further to obtain the contributions to a receiving antenna. Multiple reflections and diffractions are included to evaluate the received power of an antenna located inside or near a curved road tunnel.

Simulations and Measurements

The ray-tracing simulations and field measurements in two road tunnels are compared in this section. As shown in Fig. 3, one tunnel, called the Xin-hai tunnel, has an arched cross-section and a straight longitudinal part through a mountain. The other tunnel is an underground passage, called the Lin-sen subway, which has rectangular cross-section but curved longitudinal sections, as shown in Fig. 4. Two Yagi-Uda antennas are mounted on the ceiling of the Xin-hai tunnel. One antenna (Tx1) is for GSM900 and the other is for GSM1800 base stations to provide good coverage inside the tunnel. In the Lin-sen subway, two antennas for the GSM900 and GSM1800 are located at about the same location (Tx).

Measurements of the control channels of the GSM signals from the base stations were performed by using a spectrum analyzer, a preamplifier, and an omni-directional antenna. For the Xin-hai tunnel, a dipole antenna was used for receiving, which was mounted on top of a car and located 1.8m above the road. As for the Lin-sen subway, a biconical antenna was employed, which was also mounted on top of the car but at 1.85m above ground.

Simulations of the received signals in those two tunnels were performed by applying the ray tracing program we have developed for the curved tunnels. The radiation patterns of Yagi-Uda antennas were used for the transmitting sources. To compare the results of the simulations and measurements, the differences of the mean values for the line-of-sight (LOS) signals near the transmitting antennas are used to shift the simulated results to the similar levels of the measured signals for matching with the actual system power outputs. As given in Figs. 5-10, good agreements between the measured and simulated results are obtained for GSM900/1800 signals and vertical/horizontal polarizations. The wave-guiding properties of the tunnels can be seen from the comparisons with the free-space case. Also, more attenuation of the signals occurs in the Lin-sen subway, which has curved longitudinal sections.

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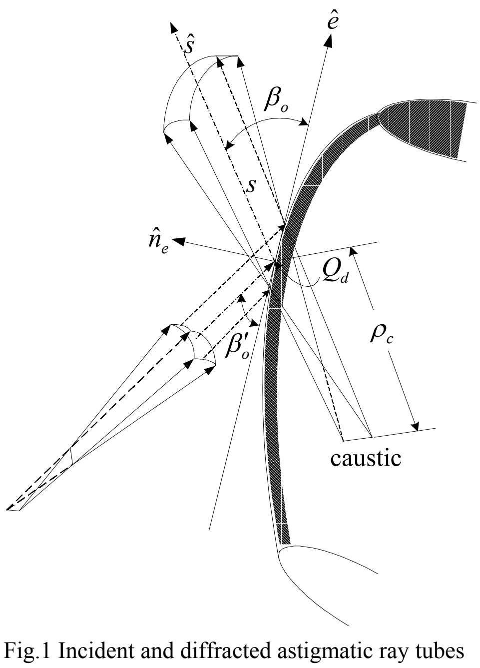

Fig.1 Incident and diffracted astigmatic ray tubes

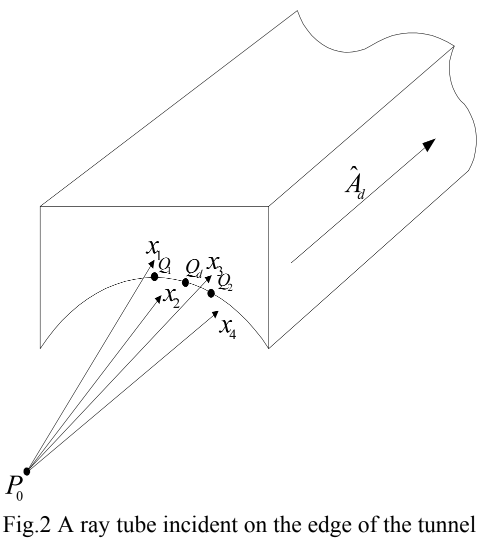

Fig.2 A ray tube incident on the edge of the tunnel

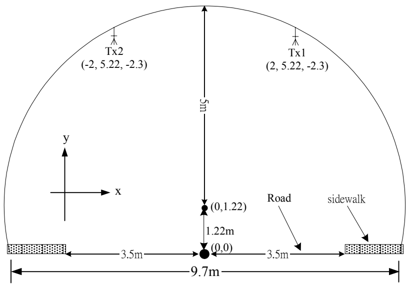

Fig. 3 The Xin-hai tunnel

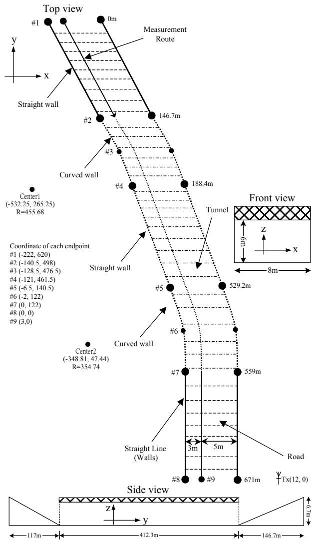

Fig. 4 The Lin-sen subway

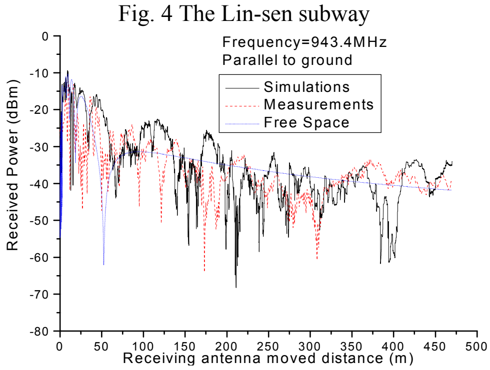

Fig. 5 Results at 943.4MHz for a receiving antenna parallel to ground in the Xin-hai tunnel.

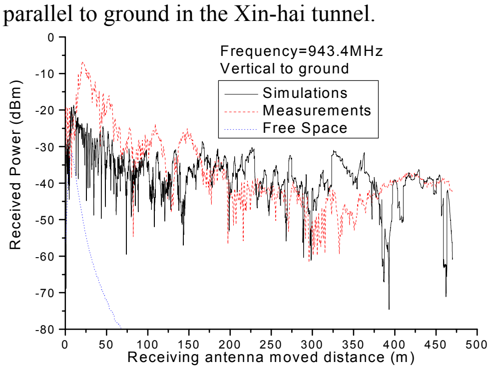

Fig. 6 Results at 943.4MHz for a receiving antenna vertical to ground in the Xin-hai tunnel.

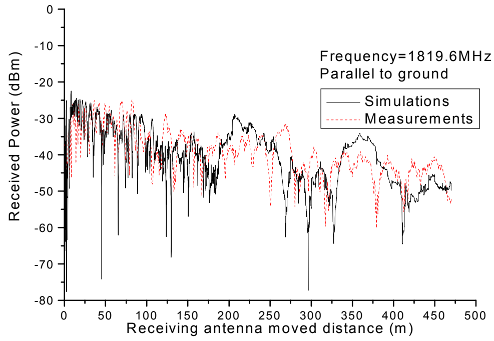

Fig. 7 Results at 1819.6MHz for a receiving antenna parallel to ground in the Xin-hai tunnel.

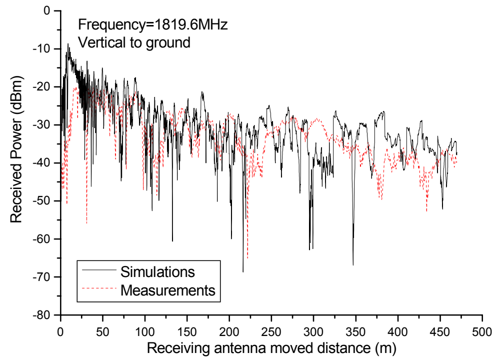

Fig. 8 Results at 1819.6MHz for a receiving antenna vertical to ground in the Xin-hai tunnel.

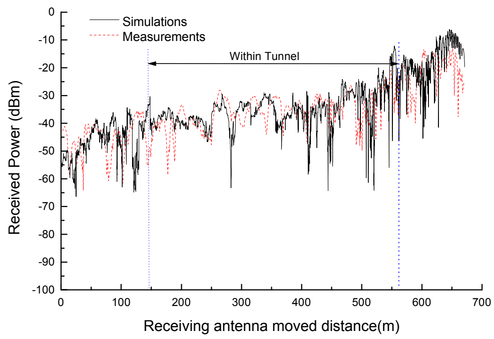

Fig. 9 Results at 942MHz for a receiving antenna vertical to ground in the Lin-sen subway.

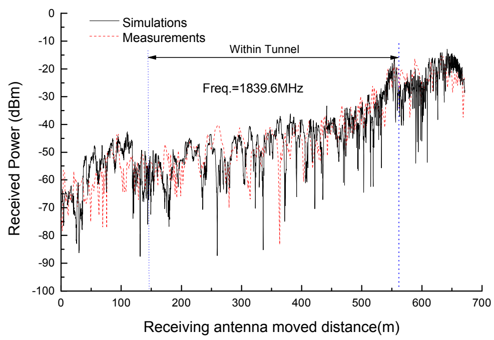

Fig. 10 Results at 1839.6MHz for a receiving antenna vertical to ground in the Lin-sen subway.