A simple model of outdoor to indoor penetration path-loss considering incident angles at 0.9, 2.3 and 5.1 GHz

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Abstract: The fifth generation (5G) of mobile communication systems is actively being investigated worldwide. Various systems exist when considering the microwave bands after the introduction of the 5G systems. Considering microwave propagation characteristics is crucial to minimize possible interferences among systems. This study focused on the fact that wireless communication devices such as smartphones and wireless LANs are primarily used in various indoors environments. Previously, we evaluated the loss due to the difference between the incident angles of the vertical plane with respect to a window through which radio waves enter from outdoor to indoor (O2I). In the present study, we measured the loss when radio waves enter from O2I through a window in the 0.9/2.3/5.1 GHz band, where many IoT devices are expected to be used. From the data analysis of the measured results, we proposed a simple O2I penetration path-loss model using incident angles in the vertical and horizontal planes.

Keywords: radio wave propagation, penetration loss, O2I factor

Classification: Antennas and Propagation

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1 Introduction

The fifth generation (5G) of mobile communication systems is actively being investigated worldwide. Although 5G systems primarily employ millimeter waves, they also make use of frequency bands (< 6 GHz) \[1\]. Various systems have been proposed for the use of microwave bands in 5G systems, especially for frequencies of 900 MHz, 2 GHz, and 5 GHz. We focus on outdoor to indoor (O2I) penetration path-loss because the terminal stations are used at not only outdoor but also indoor scenario while the base station is installed at the outside.

Previously, O2I penetration path-loss models have been proposed \[2\][3]. The fixed value is used in \[2\]. In \[3\], the focus is on the incident angles in the horizontal plane; further, O2I factors, which show the path-loss coefficient, are presented for the 0.8, 2.2, and 4.7 GHz bands. In our previous study, we evaluated the O2I penetration path-loss characteristics at 2 and 5 GHz for different incident angles considering only the vertical plane \[4\].

In the present study, we measured the loss when radio waves enter from O2I through a window in the 0.9/2.3/5.1 GHz band, where many IoT devices are expected to be used. From the data analysis of the measured results, we proposed a simple O2I penetration path-loss model using incident angles in the horizontal and vertical planes. The remainder of the manuscript is structured as follows: The results of the environmental measurements are presented in Sect. 2. Sect. 3 presents a simple model that can be used to calculate the O2I penetration path-loss, based on the incident angle on the vertical and horizontal planes.

2 Measurement of O2I penetration loss

2.1 Measurement environment

We measured the O2I penetration path-loss in the environment shown in Fig. 1(a) at Niigata University. Figure 1(b) shows the top view of the measurement environment. As shown in Fig. 1(a), a receiving antenna was placed on one side of the corridors of the 1st to 8th floors of the building surrounded by the red straight line. As shown in Fig. 1(b), a transmitting antenna was placed at the red dots.

As shown in Fig. 1(b), the incident angle on the horizontal plane, $\phi$, is defined as the angle formed by the straight line perpendicular to the window of the building and that connecting the receiving and transmitting antennas. The incident angles, $\phi$, at each transmitting antenna are 0, 10, 20, 30, 40, 50, and 60° in ascending order. The incident angle, $\theta$, is defined as the angle formed by a straight line parallel to the ground and that connecting the transmitting and receiving antennas. The incident angles, $\theta$, at each...
receiving antenna are 0, 20.2, 38.2, 50.4, 58.4, 64.0, 67.9, and 70.9°, in order from the 1st floor to the 8th floor of the building.

As shown in Fig. 1(b), we set the position of the window of the building to 0[m]. We moved the receiving antenna from the 0[m] position to the 26[m] position located at the end of the passage (21[m] on the 1st floor) at a constant velocity, and we measured the received power with respect to the distance in the indoor section. In this manner, we obtained a total of 56 measurements for the 0.9/2.3/5.1 GHz frequency band on each of the eight floors of the building where the receiving antenna was placed and for the seven points where the transmitting antenna was placed. Vertical polarization sleeve antennas were used as the receiving and transmitting antennas, and the transmission signal was a continuous wave.

2.2 Measurement result
The measured received power was corrected for the loss due to free space ($\alpha = 2$), to ensure that this variable would not affect our results. For each frequency, the normalized received power was standardized so that the maximum received power of the data obtained was 0 dB for the received power. Moreover, the additional loss inside the building was calculated using the normalized received power.

Figure 2.1 shows the additional loss for the distance of the indoor section on the 1st, 3rd, and 5th floors with $\phi = 10, 60^\circ$ at 2.3 GHz. As shown in Figure 2.1, the additional loss increased as the distance in the indoor section increased. It was confirmed that the increase in the additional loss with respect to the distance in the indoor section becomes larger as the incident angle, $\phi$, and $\theta$, increase.

3 Analysis of measurement results
The O2I factor $\gamma$ is a variable representing the magnitude of the increase in additional loss that occurs owing to the increase in the distance of the indoor section [4]. Assuming an additional loss of $L$ dB, the O2I factor and transmit distance should be equal to $\gamma$ and $d$ m, respectively. The common logarithm
Fig. 2. Analysis result

regression curve in Eq. (1) was approximated using the least squares method.

\[ L = \gamma \log_{10}(d + 1) + \beta \quad [\text{dB}] \quad (1) \]

\[ \gamma = \frac{\sum_{i=1}^{N} L_i}{\sum_{i=1}^{N} (\log_{10}(d_i + 1))} \quad (2) \]

\[ \gamma = a\theta + b \quad (3) \]

The constant value of \( \beta \) in Eq. (1) is determined based on frequency. In this analysis, the maximum received power (0 dB) was considered as the value of \( \beta \). The value of \( \gamma \) in Eq. (1) was calculated using Eq. (2). In Eq. (2), \( N \), \( L_i \), and \( d_i \) denote the number of data samples, \( i \)-th additional loss, and \( i \)-th distance for \( L_i \), respectively. The regression line was approximated based on Eq. (3), using the least squares method on the incident angle \( \theta \) along the X-axis and the O2I factor \( (\gamma) \) along the Y-axis. The results of this analysis are shown in Fig. 2.2. As shown in Fig. 2.2, \( \gamma \) tends to increase linearly with the increase in \( \theta \) irrespective of \( \phi \) at any frequency.

When \( \phi \) is small, the increase in \( \theta \) has a large effect on the additional loss; further, when \( \phi \) is large, the increase in \( \theta \) has a small effect on the additional loss. When both \( \phi \) and \( \theta \) are small, the direct wave reaches the devices even if the distance of the indoor section is long; thus, the additional loss is small. As \( \theta \) increases, it becomes difficult for direct waves to reach as the distance in the indoor section increases, and the received radio waves include reflected waves.
and diffracted waves. In addition, the loss in the reflected and diffracted waves increases with $\theta$ due to the increase in the number of reflections; in addition, the loss that occurs owing to diffracting increases. As $\theta$ increases, the reflected and diffracted waves are also significantly attenuated, increasing the additional loss with respect to the distance of the indoor section.

When $\phi$ is large, the viewing angle to the window is large, even if $\theta$ is small; thus, the direct wave is weak and the received reflected and the diffracted waves are relatively strong, even when the distance of the indoor section is short. Therefore, the additional loss is large irrespective of $\theta$.

Because the viewing angle to the window hardly changes even if $\theta$ increases, the effect of the increase in $\theta$ on the additional loss is smaller than when $\phi$ is small.

We approximated $a$ and $b$ in Eq. (3) using the least squares method for linear functions with $\phi$ as the x-axis. Fig. 2.3 shows the results of the linear approximation of $a$ and $b$ in Eq. (3) with $\phi$ using the least squares method. Eqs. (4), (5), and (6) are approximate equations expressing $\gamma$ at 0.9, 2.3, and 5.1 GHz using $\phi$ and $\theta$.

$$
\gamma_{0.9\text{GHz}} = (-0.00392\phi + 0.406)\theta + 0.248\phi + 4.76 \quad (4)
$$
$$
\gamma_{2.3\text{GHz}} = (-0.00344\phi + 0.299)\theta + 0.267\phi + 4.72 \quad (5)
$$
$$
\gamma_{5.1\text{GHz}} = (-0.00428\phi + 0.306)\theta + 0.283\phi + 4.67 \quad (6)
$$

We calculated the root mean square error (RMSE) between the additional loss observed during the measurement and the estimation equations, Eqs. (4), (5), and (6), using Eq. (7). In Eq. (7), $N$ is the number of data points at a certain measurement point, $L_i$ is the $i$-th additional loss obtained from the measurement results, and $x_i$ is the estimated value of the $i$-th additional loss.

$$
RMSE = \sqrt{\frac{\sum_{i=1}^{N}(L_i - x_i)^2}{N}} \quad [\text{dB}] \quad (7)
$$

$$
L = 0.5d + 14 + 15(1 - \cos(\theta))^2 \quad [\text{dB}] \quad (8)
$$

Fig. 3.1 shows the calculated RMSE at each measurement point. As shown in the figure, the RMSE is approximately 10[dB] at the measurement points where $\phi$ and $\theta$ are large; however, at many measurement points, the RMSE is within 8[dB]. When both $\phi$ and $\theta$ were small, the RMSE value was within 5[dB]. The RMSE between the ITU-R. M2135 UMi O-to-I model in Eq. (8) [5] and the additional loss observed during the measurement was calculated.

Figure 3.2 shows the RMSE estimated using ITU-R. M2135 UMi O-to-I model and Eq. (4). As shown in Fig. 3.1, when both $\phi$ and $\theta$ are larger than 50$^\circ$, the ITU-R M2135 UMi O-to-I model may be more accurate than the derived estimating equation. However, when either $\phi$ or $\theta$ is smaller than 50$^\circ$, the estimating equation is equivalent to or more accurate than the conventional model; further, when both $\phi$ and $\theta$ are smaller than 20$^\circ$, the estimation error is considerably smaller than that of the conventional model.
4 Conclusion

In this study, we evaluated the loss when radio waves enter from O2I through a window. We considered the O2I penetration path-loss characteristics due to the difference in the horizontal and vertical incident angles at 0.92/2.29/5.12 GHz, and we created a simple O2I penetration path-loss model using the horizontal and vertical incident angles.

We have demonstrated that the RMSE between the additional loss observed during the measurement and the O2I penetration path-loss model was smaller than that of the ITU-R. M2135 UMi O-to-I model when the incident angle on the horizontal and vertical planes is small.

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