Path Loss Model with Low Antenna Height for Microwave Bands in Residential Areas

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SUMMARY A new path loss model of interference between mobile terminals in a residential area is proposed. The model uses invertible formulas and considers the effects on path loss characteristics produced by paths having many corners or corners with various angles. Angular profile and height pattern measurements clarify three paths that are dominant in terms of their effect on the accurate modeling of path loss characteristics in residential areas: paths along a road, paths between houses, and over-roof propagation paths. Measurements taken in a residential area to verify the model’s validity show that the model is able to predict path loss with greater accuracy than conventional models.

Key words: path loss model, low antenna height, mobile terminal, residential area, microwave band

1. Introduction

Since microwave bands are widely used in wireless communication systems such as cellular systems [1] and wireless LANs [2] and in other non-communication systems such as astronomical systems [3], the availability of frequency resources in microwave bands is extremely tight [3]. To solve the problem of frequency resource shortage, there is a huge demand for spectrum sharing wireless systems [4].

In cases where frequency bands are shared, it is necessary to study interference propagation characteristics to avoid or reduce interference between wireless systems that use the same frequency at the same time. Fundamentally, there are three interference propagation scenarios. The first is between base stations, the second is between a base station and a mobile terminal (MT), and the third is between mobile terminals. So far, studies on interference between MTs have not been particularly important because MTs in conventional wireless systems have been definitely segregated in terms of time or frequency. In case of synchronous wireless systems, interference between MTs does not occur. However, when asynchronous wireless systems sharing the same frequency band are used at the same time, the interference between their MTs is added to that between base stations and between base stations and MTs. In such cases, the interference propagation characteristic between MTs should be considered. It is therefore necessary to construct a path loss model to clarify the propagation characteristics and evaluate interference occurring between MTs in such cases.

Path loss models with low antenna height have been studied for predicting path loss in microwave bands [5]–[7]. The model reported in [5] is constructed on street microcell environments and predicts path loss by using distance attenuation and corner loss. The model reported in [6] expanded the applicability of the street microcell model reported in [5] to a residential area by using loss parameters derived in the area. The model reported in [7] also predicts path loss by using distance attenuation and corner loss, parameters that are derived in residential areas for the 3.4, 5.3, and 6.4 GHz bands.

Although these models can predict path loss with low antenna height where there is a single right angle corner, they do not consider features of residential areas that there are roads with two or more corners and roads with gentle curves less than 90 degrees, and their applicability to such cases has not been clarified. Therefore, to evaluate interference between MTs operating in microwave bands in residential areas, it is necessary to use a path loss model that is applicable to areas where there are many corners and many gently curved corners. In addition, to evaluate propagation characteristics between MTs, the prediction formulas used need to be invertible. This is because if both transmitter (Tx) and receiver (Rx) have the same antenna height, if Tx and Rx are reversed, different calculation results will be obtained under the same conditions despite the reversibility of the propagation path. The models introduced above [5]–[7] cannot satisfy the requirement for invertible prediction formulas. Therefore, it is necessary to construct a path loss model that considers the above area characteristics, is applicable to areas where there are many gently curved corners, and satisfies the requirement for invertible prediction formulas.

Therefore, in this paper, we present a path loss model with low antenna height for application to MTs operating in microwave bands in residential areas. We carried out angular profile measurements with directional antenna to clarify the dominant paths affecting to path loss characteristics in order to analyze the characteristics. To conduct path loss model in microwave bands, we also measure path loss characteristics of these paths by using measurement frequencies of 2.1975, 4.703, and 26.365 GHz and obtain prediction formulas. Finally, we use the measurement results to verify the proposed model’s validity.
2. Conventional Model with Low Antenna Height for Residential Areas

In this section, we discuss a conventional path loss model with low antenna height for application to residential areas [6] since the model can be applied to arbitrary microwave bands. We also note the model’s prediction error and its reversibility.

The model predicts path loss by using distance attenuation and corner loss. The distance attenuation has two inflection points: one is a break point that is based on a two-wave model and the other is a corner. The attenuation coefficient is 20 before the break point and 40 after it. After the corner area, 60 is added to the coefficient. The corner loss is defined as 30 dB.

Measurements were taken in a residential area to confirm the model’s prediction accuracy. Figure 1 shows the measurement environment and measurement routes. Measurement route 1 has two gently curved corners of 3 and 5 degrees at road distance of 80 and 280 m, and after the first corner is NLOS. Measurement route 2 has a right angle corner of 90 degrees at 70 m and is NLOS from Tx. To measure path loss characteristics below house roof height, Tx and Rx antenna height is 2.5 m. Omnidirectional antennas are used at Tx and Rx. Measurement frequencies are 2.1975, 4.703 and 26.365 GHz; however, only measurement and prediction results at 2.1975 GHz are introduced in this section since the comparison results for each frequency tend to be similar.

Figure 2 shows measurement results and prediction results obtained by using this conventional model at 2.1975 GHz. The circles and squares represent measurement results at routes 1 and 2, respectively. To eliminate the fast fading effect, we derived the median value of path loss at 10-meter intervals. The measurement results of multiple running at the same route are plotted. The sampling rate is 1.5 kHz and the median value is derived by using about 3000 samples. The solid and dashed lines are prediction results obtained by using the model at routes 1 and 2, respectively. The model predictions are calculated by using road width of 20 m. As the figure shows, at route 1 prediction error increases with increasing distance in the NLOS area and becomes up to 15 dB at around 500 m distance. The model considers that NLOS occurs at right angle corners, but there are many gently curved corners in residential areas. Path loss increases very gradually on roads with such corners, and in such cases this model’s prediction error becomes high. At route 2, prediction error also increases with increasing distance and becomes more than 20 dB at 200 m distance. These results show that this model overestimates the path loss and cannot predict actual path loss after the corner area. This model has a further problem in that the prediction results are not invertible because of the inflection point at the corner. Figure 3 shows the predicted path loss as the road distance from Tx to a corner changes. The total road distance is set to 200 m. The solid line shows the predicted results at normal position, which is from Tx to Rx. The predicted path loss decreases as the road distance increases. The dashed line shows the predicted results in case that the positions of Tx and Rx are reversed. The predicted results are different for the normal and reversed positions except when the corner is set 100 m from Tx, i.e., at the halfway point of the total road distance. In Fig. 2, for example, the predicted path loss is 135.2 dB at a distance of 200 m from Tx of route 2. On the other hand, if the positions of Tx and Rx are reversed, it becomes 127.7 dB. This 7.5 dB difference becomes higher as the difference in the distance...
from Tx or Rx to the corner becomes greater.

As mentioned earlier, when using conventional models prediction error increases where there are gently curved corners or right angle corners in the area. In addition, conventional models cannot be applied to cases where there are two or more corners. However, there are many such cases in residential areas. Therefore, to evaluate path loss characteristics in residential areas, a model that can predict path loss in the above-described types of areas is needed. Furthermore, conventional models cannot satisfy the requirement for invertible formulas and therefore cannot correctly evaluate interference between MTs. In this paper, to conduct path loss modeling with low antenna height in residential areas, we clarify dominant paths for path loss modeling and focus on these paths to analyze path loss characteristics.

3. Proposed Path Loss Model with Low Antenna Height for Residential Areas

This section describes how we identified dominant paths that highly affect path loss characteristics by carrying out a measurement campaign. We use the results obtained to propose a path loss model with low antenna height for use in residential areas.

3.1 Propagation Paths with Low Antenna Height for Residential Areas

To clarify and analyze all the propagation paths in residential areas, we carried out measurements by separating the horizontal plane and the vertical plane.

3.1.1 Arrival Angle Characteristics of Horizontal Plane

We measured angular profiles to analyze the propagation paths in the horizontal plane. Figure 4 shows the measurement environments (the cities of Musashino and Tsukuba) and Table 1 shows the measurement parameters.

In Musashino the average building height is 8.4 m and the building density is 3171.7 buildings per square km. These parameters are higher than those for Tsukuba, where the average building height is 6.6 m and the building density is 461.2 buildings per square km. Assuming a path between mobile terminals, we measured the Tx and Rx antenna heights at 1.2 m. The Tx antenna is omnidirectional. The Rx antenna is a directional antenna with 4 degree half-power beamwidth. We obtained the angular profile of arrival paths by rotating the Rx antenna. To eliminate the beamwidth effect, we processed the obtained profiles by extracting maximum values every 4 degrees. To obtain as high a resolution for the angular profile as possible, we used a 5.2 GHz antenna, which is the narrowest beam antenna we have.

Figures 5(a) and (b) respectively show the measurement results we obtained for measurement points A and B in Fig. 4(a). The received power is normalized to a highest power of 0 dB. In Fig. 5(a), 0 degrees is the road direction and in Fig. 5(b), 0 degrees is the Tx direction. As the figure shows, the received power at measurement points A and B becomes highest in the road direction and the Tx direction, respectively. The paths dramatically rise in each direction and become more than 7 dB higher than the paths in the
other directions.

To analyze dominant paths in the environment, in Fig. 6 we plotted the arrival angle of the highest received power path at all measurement points. Figure 6(a) shows the case where the arrival path of the highest received power is in the road direction, where the road is the shortest path from Tx. Figure 6(b) shows the case where the arrival path of the highest received power is in the Tx direction. Circles and squares represent the measurement results obtained in Musashino and Tsukuba, respectively.

In Figs. 6(a) and (b), the arrival angle is normalized as the road direction and the Tx direction become 0 degrees. As the figure shows, the arrival angle of the highest received power paths at all measurement points lies between −30 and 30 degrees regardless of the Tx-Rx distance and is concentrated in the road direction and the Tx direction. In a residential area where the antenna heights are low, the dominant paths are the propagation paths that lie along a road and arrive in the road direction, and those that lie between houses and arrive in the Tx direction.

### 3.1.2 Path Loss Characteristics of Vertical Plane

In this subsection, we use the height pattern to analyze the propagation paths in the vertical plane.

Measurements were taken in the environments shown in Fig. 4. Table 2 summarizes the measurement parameters.

The measurement frequencies were 2.1975, 4.703, and 26.365 GHz. Omnidirectional antennas were used in both the Tx and Rx. The Tx antenna height was respectively 5 m in Musashino above the ground and 2.5 m in Tsukuba. To enable the path loss characteristics to be measured in the vertical plane, we continuously varied the Rx antenna height between 3.5 and 10 m, and in so doing obtained the height pattern of the path loss. To eliminate the fast fading effect, we calculated the median at 1-meter intervals.

Figure 7 shows the height pattern measurement results obtained at 2.1975 GHz measurement frequency. We show these results since this frequency enables us to obtain as wide a dynamic range as possible. In this figure the Tx-Rx distance is 927 m in Tsukuba. The dashed lines represent the measured path loss and the circles are the median values obtained at 1-meter intervals. We plot the measurement results obtained for Rx antenna heights below 8 m because these heights are below the buildings’ roof-top level. As the figure shows, the median value increases by more than 10 dB as the antenna height becomes lower. This means that the path loss characteristics have height gain and are affected by the propagation paths in the vertical plane.

When the direct distance from Tx to Rx is relatively long, the propagation paths in the horizontal plane encounter multiple turns as a result of corners and multiple shielding by houses. Therefore, the horizontal plane propagation loss is increased. In addition, since the width of the houses in these residential areas is almost uniform regardless of height, the height gain of the horizontal plane paths becomes low. On the other hand, propagation paths above houses are seldom shielded by houses since house height in a residential area tends to be uniform. For this reason, we consider that the over-roof propagation path is a dominant
path with respect to path loss characteristics in the vertical plane.

As referred to above and in Sect. 3.1.1, the dominant paths with respect to path loss characteristics for a low antenna height in a residential area are the propagation paths along a road, paths between houses, and the over-roof path above houses.

3.2 Proposed Path Loss Model Using Three Propagation Paths

In Sect. 3.1, it is shown that the dominant paths for a low antenna height in a residential area are the horizontal plane paths arriving in the road direction and the Tx direction, and the vertical plane path arriving in the Tx direction. Therefore, we used these three dominant paths in constructing the path loss model shown in Fig. 8. The model was constructed by using three paths: a path that lies along a road and arrives in the road direction, a path that lies between houses and arrives in the Tx direction, and an over-roof propagation path that lies above houses and arrives in the Tx direction. In the case of a low antenna height in a residential area, these paths significantly affect the path loss characteristics obtained. In the following Eq. (1), whole path loss $L$ is calculated by using path loss along a road $L_r$, path loss between houses $L_b$, and over-roof propagation path loss $L_v$.

$$L = -10\log\left(1/10^{L_r/10} + 1/10^{L_b/10} + 1/10^{L_v/10}\right)$$  \hspace{1cm} (1)

where $L$, $L_r$, $L_b$, and $L_v$ are in dB.

The next section describes the measurement methods and parameters we used to analyze these path loss characteristics and to construct prediction formulas.

4. Measurement Methods and Parameters

We used different methods and parameters to carry out measurements so as to obtain the different characteristics of each path. In the next two subsections, we first describe our measurements for path loss along a road and between houses, and then our measurements for over-roof propagation path loss.

4.1 Measurement of Path Loss along a Road and between Houses

Measurements were taken in a residential area equivalent to that shown in Fig. 4. Table 3 summarizes the measurement parameters; we used these to measure both the path loss along a road and that between houses. The measurement frequencies were 2.1975, 4.703, and 26.365 GHz. The radiation pattern of the Tx antenna was omnidirectional in the horizontal plane. The Tx was set up on the road and the Tx antenna height was 2.5 m above the ground. To receive the dominant paths arriving between $-30$ and $30$ degrees (Sect. 3.1.1), an antenna with 70 degree half-power beamwidth was used for the Rx antenna; it was set on the rooftop of a measurement vehicle. We chose this antenna height (i.e., 2.5 m) because the antennas are set on the vehicle and the measurements carried out with the vehicle running to obtain the measurement data over a wide area. We had previously taken measurements at antenna heights of 1.2 m and 2.5 m to confirm the height gain characteristics. Figure 9 shows the comparison results obtained at 2.1975 GHz where the antenna height is set at 1.2 m and 2.5 m. We carried out the measurements at the same route in Tsukuba (shown in Fig. 4) and confirmed that the over-roof propagation path loss was higher than that for the other 2 paths. To eliminate the effect of fast fading, we obtained median values at 3-meter intervals. As the figure shows, the measurement results show a similar tendency as the running distance increases. The median value of the differences is $-1.07$ dB, meaning the differences are very small. For this reason, we used the antenna height of 2.5 m. For measuring path loss along a road, the antenna’s main lobe was faced in the running direction. For measuring path loss between houses, it was faced vertical to the running direction. When measuring in the Tx direction, to remove path loss in the other directions, we exclude the data obtained from outside the Rx antenna’s beam. To attenuate the over-roof propagation path, we excluded the measurement points where the angle of the top of the Rx antenna’s vertical half-

<table>
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<th>TABLE 3 Measurement parameters.</th>
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<td>Frequency</td>
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<td>Antenna height</td>
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<td>Tx antenna</td>
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<td>Rx antenna</td>
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![Fig. 9 Path loss comparison between antenna heights of 1.2 m and 2.5 m.](image)
power beamwidth exceeded the angle of the top of the nearest building in the Tx direction. Since the Rx antenna’s vertical half-power beamwidth is 70 degrees, we excluded the measurement points where the angle of the top of the nearest building was less than 35 degrees. To eliminate the fast fading effect, we derived the median value of path loss at 10-meter intervals.

4.2 Measurement of Over-Roof Propagation Path Loss

For these measurements, we used the same methods and parameters as those given in Sect. 3.1.2.

5. Measurement Results and Analysis

This section describes how we used measurement results to analyze the path loss characteristics obtained for each path of the proposed path loss model. It also describes how we developed prediction formulas.

5.1 Characteristics of Path Loss along Road

Since the propagation characteristics are different before and after the corner area, we measured and analyzed the characteristics for both cases.

5.1.1 Before Corner Area

Figure 10 shows the measurement results for path loss before the corner area. Circles, squares, and triangles respectively show the path loss characteristics before the corner area at 2.1975, 4.703, and 26.365 GHz. We obtained measurement results for all the measurement routes before the corner area. Assuming the path was that along the road, we used the road distance $d_r$ as the horizontal axis in the figure. The solid and dashed lines respectively represent the free space loss and the regression lines for each of the frequencies given above. The regression results are calculated from the following equations.

$$L_{rbc} = \begin{cases} 
18.8 \log(d_r) + 43.1 & (2.1975 \text{ GHz}) \\
20.3 \log(d_r) + 48.1 & (4.703 \text{ GHz}) \\
19.9 \log(d_r) + 64.4 & (26.365 \text{ GHz}) 
\end{cases}$$

As Fig. 10 and Eq. (2) indicate, the measurement and regression results tend to be similar to the free space loss at each frequency. This is because the measurement points are basically LOS before the corner area. Therefore, the path loss before corner area $L_{rbc}$ is represented by the free space loss of the following equation.

$$L_{rbc} = 20 \log(4\pi d_r/\lambda)$$

5.1.2 After Corner Area

To construct the prediction formulas for the path loss after the corner area, we analyzed the relation between the path loss characteristics and the road geometry. Here, it should be noted that the prediction formulas should be invertible. If they are, the same prediction results should be obtained when the parameters used in the prediction are interchanged, e.g., Tx and Rx are reversed. In case of the conventional model referred to in Sect. 2, since different attenuation coefficients are used before and after the corner as the inflection point, the reversibility requirement for the prediction formulas cannot be satisfied by reversing Tx and Rx. Therefore, in this paper, instead of using an attenuation coefficient, we construct prediction formulas with symmetry expression, which satisfies the reversibility requirement.

In addition, to construct prediction formulas for the case where there are two or more corners, we first construct formulas for the case where there is only one corner. We then use the results to construct formulas for the case where there are two or more corners.

5.1.2.1 Area after First Corner

Figure 11 shows the road geometry and the parameters considered in this paper. $x_1$ is the road distance from Tx to the first corner. $x_2$ is the road distance from the first corner to Rx. $x_1$ and $x_2$ are expressed in meters. $\theta_1$ is the road angle of the corner based on the straight line before the corner. $\theta_1$ is expressed in degrees. Here, since the road angle $\theta_1$ is the same value when the positions of Tx and Rx are reversed, the reversibility of the prediction formulas is not affected. To construct the prediction formulas, we analyze the relation between the road geometry parameters and the path loss characteristics.

Figure 12 shows the measurements results obtained for the measurement routes whose $x_1$ is 100 m. Circles, squares,
and triangles respectively represent the measurement results obtained for the routes whose road angle $\theta_1$ is 3, 22, and 90 degrees. The solid, dashed, and dotted lines respectively represent the regression results obtained for the same three routes. To analyze the attenuation in the area after the first corner, we use Eq. (3) to derive the path loss in excess of that before the corner area. Assuming that the excess loss occurs after the corner, we use $x_2$ as the horizontal axis in the figure. As the figure shows, the excess loss increases as $x_2$ increases and becomes a constant value when $x_2$ reaches certain values. These values are about 11, 21, and 23 dB for the routes whose road angle $\theta_1$ is respectively 3, 22, and 90 degrees. We consider that the excess loss in the area after the first corner can be calculated from a function that converges the values.

In addition, to analyze the dependence of the excess loss on $x_2$, we measured the path loss by changing the Tx position in the measurement route whose road angle $\theta_1$ is 90 degrees. Figure 13 shows the measurement results. Circles, squares, and triangles respectively represent the measurement results obtained at 2.1975, 4.703, and 26.365 GHz. The solid, dashed, and dotted lines represent the regression results obtained for the same three frequencies. As the figure shows, $K$ increases with increasing $\theta_1$. On the basis of the regression results, this relation is calculated from the equation $K = A_1 \log(\theta_1) + B_1$. As the frequency varies, $A_1$ remains almost constant and $B_1$ varies dynamically. Therefore, we analyzed the frequency characteristics of $B_1$.

Next, we analyzed the relation between the coefficient $S$ and the road geometry parameters. Figure 16 shows the relation between the coefficient $S$ and the road distance from Tx to the first corner $x_1$ derived by the regression of measurement results. The measurements were carried out by changing the Tx position at the route where the road angle $\theta_1$ is 3 degrees and 90 degrees. Circles, squares, and triangles respectively represent the results obtained for the routes whose road angle $\theta_1$ is 3, 22, and 90 degrees. The solid, dashed, and dotted lines respectively represent the regression results obtained for the same three routes. To analyze the attenuation in the area after the first corner, we use Eq. (3) to derive the path loss in excess of that before the corner area. Assuming that the excess loss occurs after the corner, we use $x_2$ as the horizontal axis in the figure. As the figure shows, the excess loss increases as $x_2$ increases and becomes a constant value when $x_2$ reaches certain values. These values are about 11, 21, and 23 dB for the routes whose road angle $\theta_1$ is respectively 3, 22, and 90 degrees. We consider that the excess loss in the area after the first corner can be calculated from a function that converges the values.

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On the basis of the above measurement results, the excess loss after the first corner $L_{ex}$ is calculated from the following function:

$$L_{ex} = K(1 - \exp(-Sx_2))$$  \(\text{Eq. (4)}\)

where $K$ is the converged value. When $x_2$ becomes an infinite value, $L_{ex}$ becomes $K$. $S$ is the converging speed and $L_{ex}$ rapidly becomes the converged value $K$ as $S$ increases.

The coefficient of the above equation is calculated from the road geometry parameters. We derive the relation between the coefficient and the parameters by using the measurement results regressed by (4).

Figure 14 shows the relation between the coefficient $K$ and the road angle $\theta_1$ derived by regression of the measurement results.

The measurement results were obtained at the three routes whose $\theta_1$ was 3, 22, and 90 degrees. $x_1$ is 100 m for each route. Circles, squares, and triangles respectively represent the measurement results obtained at 2.1975, 4.703, and 26.365 GHz. The solid, dashed, and dotted lines represent the regression results obtained for the same three respective frequencies. As the figure shows, $K$ increases with increasing $\theta_1$. On the basis of the regression results, this relation is calculated from the equation $K = A_1 \log(\theta_1) + B_1$. As the frequency varies, $A_1$ remains almost constant and $B_1$ varies dynamically. Therefore, we analyzed the frequency characteristics of $B_1$.

Figure 15 shows the frequency characteristics of $B_1$ derived in Fig. 14. The solid line represents regression results. As the figure shows, $B_1$ increases with increasing frequency. On the basis of the regression results, the relation between $B_1$ and the frequency is calculated from the equation $B_1 = A_2 \log(f) + B_2$.

Since no clear dependence of $K$ on $x_1$ can be confirmed, $K$ is calculated from $K = A_1 \log(\theta_1) + A_2 \log(f) + B_2$.
gles respectively represent the regression results at 2.1975, 4.703, and 26.365 GHz. As the figure shows, \( S \) tends to increase with increasing \( x_1 \) in almost every case and the weakest tendency is for 26.365 GHz at 3 degrees. However, even if the measurement results are regressed by using only 26.365 GHz, the maximum difference between the regression results is 5.9 dB at \( x_2 = 119 \) m in the case of \( \theta_1 = 3 \) degrees. In the case of \( \theta_1 = 90 \) degrees at 26.365 GHz, the maximum difference between the regression results is 2.6 dB at \( x_2 = 19 \) m. In addition, even if the regression results obtained by using all 3 frequencies are used, the median value differences of the prediction errors are less than 4 dB and the prediction error values are less than the prediction error of the path loss model given in Sect. 7. This means that the difference of \( S \) between each frequency has little effect on the prediction results. To simplify the prediction formulas, \( S \) is regressed by using all 3 frequencies. Therefore, the relation between \( S \) and the \( x_1 \) is represented by the dashed line of the regression results, calculated from the equation \( S = A_3 x_1 \).

We also analyzed the relation between coefficient \( A_3 \) and the road angle \( \theta_1 \). Figure 17 shows this relation as derived by regression of the measurement results. The results were obtained for the three routes whose \( \theta_1 \) is 3, 22, and 90 degrees. \( x_1 \) is 100 m for each route. Circles, squares, and triangles respectively represent the measurement results at 2.1975, 4.703, and 26.365 GHz. As the figure shows, \( A_3 \) tends to increase with increasing \( \theta_1 \). Therefore, the relation between \( A_3 \) and \( \theta_1 \) is represented by the dashed line of the regression results, calculated from the equation \( A_3 = A_4 \theta_1 \).

In accordance with the above, the coefficient \( S \) is calculated from the equation \( S = A_5 \theta_1 x_1 \).

From the above regression results, the excess loss after the first corner \( L_{ex} \) is calculated from the following function.

\[
L_{ex} = (A_1 \log(\theta_1) + A_2 \log(f) + B_3) \cdot (1 - \exp(-A_5 \theta_1 x_1 x_2)) \quad (5)
\]

Each coefficient of this equation is derived by regression of the measurement results at the routes having one corner. The regression is carried out by varying the coefficients \( A_1, A_2, B_3, \) and \( A_5 \) continuously and minimizing the error between the regression results and measurement results by using the dataset of \( L_{ex}, x_1, x_2, \theta_1, \) and \( f \). As a result, the equation becomes the following equation.

\[
L_{ex_{\text{NLOS}}} = (0.78 \log(\theta_1) + 4.1 \log(f) + 15.2) \cdot (1 - \exp(-2.24 \cdot 10^{-5} \theta_1 x_1 x_2)) \quad (6)
\]

5.1.2.2 After Area with Two or more Corners

In cases where there are two or more corners, since the view from the first corner is shielded at the second corner, thus changing the propagation conditions, path loss in excess of that before the first corner occurs. This is the same as for
the earlier-described case, i.e., before and after the first corner. Therefore, the excess loss after the second corner is derived by using (6). Figure 18 shows the path loss along a road having three corners. Circles represent the path loss occurring after the first corner, where $x_1$ is 100 m and $\theta_1$ is 3 degrees. Squares represent that occurring after the second corner, whose $x_1$ is 150 m and whose $\theta_2$ is 90 degrees. Triangles represent that occurring after the third corner, whose $x_1$ is 280 m and whose $\theta_3$ is 90 degrees. The solid, dashed, and dotted lines respectively represent the prediction results obtained by using (6). After the second and third corners, the prediction results are calculated by adding the calculation results obtained before the corners. As the figure shows, the prediction results tend to be similar to the actual path loss for each route. This confirms that the path loss occurring after two or more corners can be predicted by adopting (6) where there are two or more corners. Therefore, to increase the prediction accuracy, the coefficients of Eq. (5) are obtained by regression of all dataset included in more than 2 corners. In accordance with the above, by using the regression results, the path loss occurring after a corner is calculated from the following equation.

$$L_r = L_{rbc} + \sum_i (7.18 \log(\theta_i) + 0.97 \log(f) + 6.1) \cdot \left[1 - \exp\left(-3.72 \cdot 10^{-5}\theta_i x_1 x_2\right)\right]$$

(7)

where $\theta_i$ is the road angle at the $i$th corner, $x_{1i}$ is the road distance from Tx to the $i$th corner, and $x_{2i}$ is the road distance from the $i$th corner to Rx. In Fig. 11, therefore, $x_{11}$ is $x_1$, $x_{21}$ is $x_2$, and $d_r$ is $x_1 + x_2$ after the first corner, and $x_{12}$ is $x_1 + x_2$, $x_{22}$ is $x_3$, and $d_r$ is $x_1 + x_2 + x_3$ after the second corner.

5.2 Characteristics of Path Loss between Houses

In this subsection, we analyze the path loss characteristics of paths between houses.

5.2.1 Measurement Results

Figure 19 shows the measurement results for path loss between houses at 2.1975 GHz. Circles and squares respectively represent measurement results obtained in Musashino and Tsukuba. In this figure, path loss increases with Tx-Rx distance. In comparing the measurement results for the two environments, we found that the path loss in Musashino tended to be higher than that in Tsukuba, where building density is lower. For example, the path loss became more than 160 dB at a distance of 900 m only in Musashino.

We assume that in cases of high building density, path loss caused by shielding and scattering from houses increases. However, the degree of shielding and scattering from houses increases as not only building density but also building size increase. Therefore, to predict path loss between houses, it is necessary to use parameters that consider factors such as building density and building size. Visibility is known to be one such parameter.

5.2.2 Path Loss Prediction using Visibility

It is known that visibility represents the degree of shielding by houses at arbitrary Tx-Rx distance [8]. Visibility $v$ is calculated from the following equations.

$$v = \exp(-d/R)$$

(8)

where $d$ is Tx-Rx distance and $R$ is mean visible distance. The latter is calculated by using the building condition parameters $n_4$, which represents the density of buildings having four or more stories, and $m_4$, which represents the average height of buildings having four or more stories [8]. These parameters can be obtained from officially published building data or from a 3D map database. The overall building density and average building height included buildings of less than four stories. Building widths are calculated by using these parameters, and from these calculated results the mean visible distance $R$ can be obtained [8]. The visibility $v$ becomes 1 at a distance of 0 m and approaches 0 with increasing distance.

Figures 20(a) and (b) respectively show the relation between excess loss and visibility in Musashino and Tsukuba. Circles, squares, and triangles respectively represent measurement results obtained at 2.1975, 4.703, and 26.365 GHz. In this figure, to analyze the path loss caused by building shielding and scattering, we use the loss in excess of free space loss as the path loss characteristic. The solid line rep-
Fig. 20 Relation between excess loss and visibility.

represents the visibility. The mean visible distance $R$ is 16.95 in Musashino and 28.88 in Tsukuba. The parameters $n_4$ and $m_4$ are 88.86 buildings per square km and 22.51 m in Musashino, and 29.41 buildings per square km and 13.18 m in Tsukuba. We use $v' = -\log(v)$ in the figure since it tends to be similar to the excess loss characteristics. $v' = -\log(v)$ represents $d/R\log(e)$ where the parameter decreases with increasing distance. The degree of decrease corresponds to the mean visible distance $R$ derived from the building parameters. As the figure shows, both the visibility and the excess loss tend to be similar and increase corresponding to the Tx-Rx distance. This tendency is seen in both Musashino and Tsukuba even though they have different building parameters.

Therefore, in Fig. 21 we use the visibility to represent the excess loss for both cities. Circles and squares respectively represent excess loss in Musashino and Tsukuba. The path loss, corresponding to the visibility derived from the building parameters in each city, showed a similar tendency in both cities. To increase regression accuracy, we constructed prediction formulas by using the measurement results obtained for both cities. Here, $\log(e)$ is calculated as a constant term. The dashed line in Fig. 21 is the regression results, which are calculated from the following equation.

$$L_{\text{ex}_{2.1975\text{GHz}}} = 30.6 \log(d/R) + 7.36 \quad (9)$$

Next, we analyze the frequency characteristics. Figures 22(a) and (b) show the path loss difference between each of the three frequencies in Musashino and Tsukuba, respectively.

In the figure, circles, squares, and triangles respectively represent path loss differences between 2.1975 and 4.703 GHz, and between 2.1975 and 26.365 GHz. The solid and dashed lines are the regression lines for each plot. The slopes of each regression line are between 0.07 and 0.08. This means that variation of path loss difference is less than 2 dB at visibility of 25. Therefore, assuming that the frequency characteristics of path loss between houses stay constant corresponding to distance, we constructed a prediction formula by using the measurement results obtained at 2.1975 GHz. The formula will be expanded to other
frequencies since the largest number of samples was obtained at 2.1975 GHz. Figure 23 shows frequency characteristics derived from the median of the path loss difference shown in Fig. 22. The median is normalized to the value of 2.1975 GHz for 0 dB. Circles and squares respectively represent the medians obtained for Musashino and Tsukuba. As the figure shows, path loss increased with higher frequency since the largest number of samples was obtained at 2.1975 GHz. From the reversibility of the propagation bands is calculated from the following equation.

Therefore, the excess loss between houses of microwave bands is calculated from the following equation.

where \( f \) is frequency in GHz.

In accordance with the above, by adding the free space loss to the excess loss of (11), the path loss between houses is calculated from the following equation.

In this subsection, we analyze the path loss characteristics of an over-roof propagation path in the vertical plane.

### 5.3 Characteristics of Over-Roof Propagation Path Loss

In this subsection, we use measurement results to verify the validity of the double knife-edge diffraction model described in Sect. 5.4.1. However, at 26.365 GHz, over-roof propagation path loss cannot be measured because the path loss becomes higher than the dynamic range of the measurement sets. Therefore, in this paper, having verified that the double knife-edge diffraction model can predict the over-roof path loss at 2.1975 and 4.703 GHz, we consider that the over-roof propagation path is modeled as shown in Fig. 24. The main feature of this over-roof propagation path model is that the number of diffraction edges is always set up as two. These edges are defined as the nearest building walls from Tx and Rx in the building profile between Tx and Rx. Buildings except for the nearest building from Tx and Rx are ignored. Accordingly, over-roof propagation path loss is calculated from the following equations by using double knife-edge diffraction loss [9].

where \( b_{Tx} \) and \( b_{Rx} \) are the nearest building walls from Tx and Rx. The top values of \( b_{Tx} \) and \( b_{Rx} \) are the line-of-sight ones from Tx and Rx. \( a, b, \) and \( c \) are the distances between Tx and \( b_{Tx} \), between \( b_{Tx} \) and \( b_{Rx} \), and between Rx and \( b_{Rx} \). \( h_{b_{Tx}} \) and \( h_{b_{Rx}} \) are the heights of the nearest building from Tx and Rx. The heights of \( b_{Tx} \) and \( b_{Rx} \) are defined as \( h_{b_{Tx}} \) and \( h_{b_{Rx}} \). \( h_{Tx} \) and \( h_{Rx} \) are the antenna heights of Tx and Rx. These parameters correspond to those in Fig. 24.
model can be applied to 26.365 GHz and to other microwave bands.

Figure 25 shows example measurement results and calculation results obtained by using the double knife-edge diffraction model. The dashed and solid lines respectively represent measurement and calculation results. To eliminate fast fading effects, we calculated median values at 1-meter intervals of the measurement results and plotted them as circles in the figure. The measurement method and parameters are given in Sect. 4.2. Figures 25(a) and (b) are for the case of 2.1975 and 4.703 GHz, respectively. The geometric parameters of double knife-edge diffraction calculation are as follows: \(a = 175.3\), \(b = 150.0\), and \(c = 4.2\) m, and \(h_{b,Tx}\) and \(h_{b,Rx}\) are 7.7 and 12.2 m. As the figures show, the measured and calculated path loss results increase with lower antenna height and tend to be similar at each frequency.

To compare the measured and calculated results, in Fig. 26 we show the prediction error between measurement and prediction results obtained by using double knife-edge diffraction loss at all measurement points. To focus on low antenna height conditions, we used an antenna height of 4 m to calculate the prediction error. As the figure shows, the prediction error values are between \(-2.8\) and 8.3 dB for each frequency and location. These values are less than those of between \(-5\) and 10 dB obtained with a path loss model that can accurately predict the actual path loss [10]. This means that the double knife-edge diffraction model can predict the over-roof propagation path loss varied by shielding houses.

### 6. Proposed Model Summary and Applicable Range

This section summarizes the proposed model’s formulas and its applicable range.

As represented by Eq. (19), the model predicts whole path loss \(L\) by using path loss along a road \(L_r\), path loss between houses \(L_b\), and over-roof propagation path loss \(L_v\).

\[
L = -10\log(10^{L_r/10} + 10^{L_b/10} + 10^{L_v/10})
\]  
(19)

\[
L_r = \begin{cases} 
L_{rbc} & \text{(before corner)} \\
L_{rac} & \text{(after corner)}
\end{cases}
\]  
(20)

\[
L_{rbc} = 20\log(4\pi d/\lambda)
\]  
(21)

\[
L_{rac} = L_{rbc} + \sum_i (7.18\log(\theta_i) + 0.97\log(f) + 6.1) \cdot \{1 - \exp(-3.72 \cdot 10^{-5} \theta_i x_{1i} x_{2i})\}
\]  
(22)

\[
L_b = 20\log(4\pi d/\lambda) + 30.6\log(d/R) + 6.88\log(f) + 5.76
\]  
(23)

\[
L_v = 20\log(4\pi d/\lambda) + L_1 + L_2 + L_c
\]  
(24)

| \(d\) : Tx-Rx distance | 10 – 1000 (m) |
| \(f\) : Frequency | 2.1975 – 26.365 (GHz) |
| Tx and Rx antenna height | \(1.2 - h_{b,\text{min}}\) (m) \(\{h_{b,\text{min}}: \text{Height of the lowest building in the area}\}\) |
| \(\theta_i\) : Road angle at \(i\)th corner | 0 – 90 (degrees) |

| Area | Residential |

---

**Fig. 25** Example measured and calculated results.

**Fig. 26** Prediction error of over-roof propagation path.
\[
L_1 = 6.9 + 20 \log \left( \sqrt{(v_1 - 0.1)^2 + 1} + v_1 - 0.1 \right) \\
L_2 = 6.9 + 20 \log \left( \sqrt{(v_2 - 0.1)^2 + 1} + v_2 - 0.1 \right) \\
v_1 = \left( h_{RT} - h_{T} \right) \sqrt{\frac{2}{A} \left( \frac{1}{a} + \frac{1}{b} \right)} \\
v_2 = \left( h_{RS} - h_{R} \right) \sqrt{\frac{2}{A} \left( \frac{1}{b} + \frac{1}{c} \right)} \\
L_c = 10 \log \left[ \frac{(a + b)(b + c)}{b(a + b + c)} \right]
\]

7. Verification of Path Loss Model Validity

In this section, to verify the proposed model’s validity, we compare the prediction results obtained with the proposed model and those obtained with the conventional model described in Sect. 2. The measurement routes and measurement method were the same as those described in Sect. 2.

Figure 27 shows the comparison results. We plotted the prediction results obtained by using the proposed model on the graph shown in Fig. 2. The dotted lines show the prediction results obtained by using the proposed model at routes 1 and 2, respectively. As the figure shows, for both routes the prediction error of the proposed model was less than that of the conventional model.

In addition, to evaluate the proposed model itself, we obtained prediction and measurement results for an area that had two or more corners and corners of less than 90 degrees. Figure 28 shows the measurement route, in which the areas from A to F had respectively 2, 1, 0, 1, 2 and 3 corners and corner road angles of 5, 3, 90, 90 and 90 degrees. Figure 29(a) shows the measured and predicted results, respectively represented by circles and a solid line. To analyze the prediction accuracy in wide area, we show these results of 2.1795 GHz since this frequency enables us to obtain as wide a dynamic range as possible. Figure 29(b) shows the prediction results for each path. As the figure shows, there are areas in which path loss of each type is dominant. Path loss along a road \( L_r \) is mainly dominant from 0 to 430 m and from 550 to 950 m of running distance, path loss between houses \( L_b \) is mainly dominant from 430 to 550 m, and over-roof propagation path loss is mainly dominant from 950 to 1300 m. The proposed model can predict path loss that varies around corners by using 3 path losses. For example, from area B to A, and from D to E, the prediction results tend to be similar although the measured path loss decreases substantially.

Figure 30 plots prediction error versus running distance; triangles represent prediction errors that reflect the
difference between the measurement results and the prediction results. In the figure, the median, standard deviation, and root mean square prediction error values are respectively 4.1 dB, 3.7 dB, and 4.9 dB. The prediction error values lie between −5 dB and 10 dB for the areas where each type of path loss is dominant. This range of values is identical to that obtained with a path loss model that can accurately predict the actual path loss [10]. These results show that the proposed path loss model can accurately predict the measured path loss along the whole route. This means that the model is able to take into account the effects produced by the existence of many corners and corners of various angles.

8. Conclusion

In this paper, we proposed a path loss model with low antenna height for use in microwave bands in residential areas. The model uses invertible formulas and considers the effects on path loss characteristics produced by paths having many corners or corners with various angles. To develop the proposed path loss model, we carried out measurements with a directional antenna and clarified that three types of propagation paths were dominant with respect to their effect on the accurate modeling of path loss characteristics. These paths are paths along a road, paths between houses, and over-roof propagation paths. We used these paths to develop our new path loss model. We also measured path loss in each of these paths and constructed prediction formulas. As a result, we ascertained that the model is able to consider road geometry and building parameters in residential areas in predicting path loss. We took measurements to verify the model’s validity and the results showed that it can predict path loss with greater accuracy than conventional models. The model was also found to enable accurate predictions of path loss characteristics in areas where there are roads with gentle curves and roads with two or more corners.

References


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