Outdoor-to-Indoor Path Loss Model
for 8 to 37 GHz Band

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Abstract— **This paper proposed the path loss model which can cover the high frequency bands above the 6 GHz. The path loss characteristics are analyzed on the basis of measurement results obtained using the 8 to 37 GHz band in outdoor-to-indoor environments. It is clarified that the characteristics depend on incident angle of azimuth, incident angle of elevation and frequency. By taking these dependencies into account, the proposed model can decrease the root mean square error of prediction results to about from 2 dB to 6 dB in the 8 to 37 GHz band.**

Index Terms—**Radio propagation, path loss model, millimeter wave, small cell.**

I. INTRODUCTION

The traffic in wireless communication systems has been rapidly increasing in recent years and is assumed to reach 1000 times higher than the current traffic amount in the next 10 years [1]. Moreover, microwave bands below 6 GHz are used extensively in wireless communication systems such as the wireless LAN, mobile system and so on. Therefore, their frequency resource is very tight. To solve these problems, the application of the frequency bands above 6 GHz such as the millimeter-wave bands for the next generation mobile systems is being examined, because millimeter-wave bands can use wider frequency bandwidth that can provide attractive higher throughput. When a new frequency band is used, an understanding the path loss characteristics in a new frequency band is required in order to evaluate the transmission characteristics and cell design. Besides, it is assumed that one of the possible service areas of mobile systems using millimeter-wave bands is urban downtown areas, well known as street microcell environments [2]. Therefore, we have proposed the path loss model for the high frequency bands above the 6 GHz in street micro cell environment [3]. The proposed path loss model is constructed on the assumption that the propagation scenario which the base station (BS) in outdoor is communicated to the user terminal (UT) in outdoor. However, in mobile systems, the coverage area must fully extend inside in building. In order to cell design, the outdoor-to-indoor path loss model is needed on the assumption that the BS in outdoor is communicated to the UT inside building for high frequency band. A lot of outdoor-to-indoor path loss models have been proposed, however no models covering high frequency bands have yet been reported [4]-[6].

To address this deficiency, this paper proposes an outdoor-to-indoor path loss model that can cover the high frequency bands above the 6 GHz. First, the measurement parameters taken by using the high frequency bands from 8 to 37 GHz is described. Second, the measurement and analysis results for the outdoor-to-indoor path loss characteristics is reported. The measurement results are compared with the representative model of Rep. ITU-R M.2135 [4]. It is shown that the Rep. ITU-R M.2135 is not proper for high frequency bands above 6 GHz. Last, the validation of propose model is shown by evaluating the root mean square error (RMSE) between predicted results and measurement results.

## II. MEASUREMENT PARAMETERS AND ENVIRONMENTS

The path loss measurements are taken in the environment shown in Fig. 1. Fig. 1 (a) shows the outdoor environment and Fig. 1 (b) shows the indoor environment. We assume the propagation scenario where the signal is transmitted from BS in outdoor to UT. The measurements are taken in three frequency bands for 8, 26, and 37 GHz in order to ascertain the frequency dependence of the measurements. The transmitter (Tx) antenna is fixed on the roof of a measurement car whose height is 2.5 m. The measurement car is parked on the roadside at A-1, A-2 and A-3 in Fig.1 (a). The incident angle of azimuth is 25 degree at A-1, 52 degree at A-2 and 69 degree at A-3. A-1 to A-3 from Tx antenna is regard as line-of-sight (LOS) environment. A receiver (Rx) antenna is fixed on the Rx vehicle which is located at the 1, 4, 6, 8 floor of building in Fig. 1 (a). Rx antenna height is 1.5m above the floor and the floor height is 3m. The antenna directivity of both Tx antenna and Rx antenna is omni-directional. In order to obtain the path loss in indoor versus the distance from the external wall, the received power level was measured while the Rx vehicle is running along the measurement route as shown in Fig. 1 (b).

Table 1. Measurement parameters.

Frequency, f (GHz)	8, 26, 37
Tx antenna height, h_{BS} (m)	2.5
Rx antenna height, h_{UT} (m)	1.5, 10.5, 16.5, 22.5
Tx/Rx antennas	Omni-directional
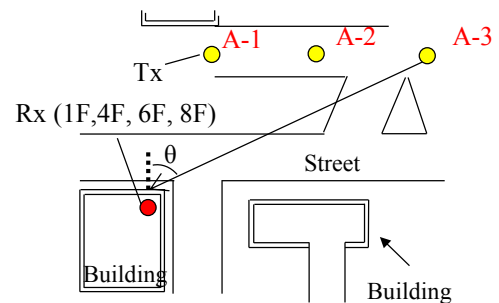
(a) Outdoor environment.
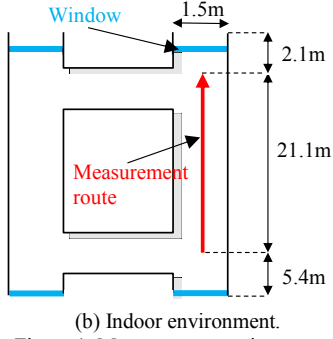
(b) Indoor environment.
Figure 1. Measurement environments.

III. Measurement Results and Analysis for 8 to 37 GHz Band

A. Prediction formula of M.2135

The M.2135 is the representative example in outdoor-to-indoor environment [4]. It summarizes the wireless interface evaluation method of the IMT-Advanced system. In order to evaluate the path loss characteristics, we compare the M.2135 for reference and measurement results in this paper. The path loss predicted by the M.2135 is obtained by using the following equations.

$$PL = PL_d + PL_{tw} + PL_{in} \tag{1}$$

$$PL_d = 22\log_{10}(d_{out} + d_{in}) + 28 + 20\log_{10}f \tag{2}$$

$$PL_{tw} = 14 + 15(1 - \cos\varphi)^2 \tag{3}$$

$$PL_{in} = 0.5d_{in} \tag{4}$$

where PL_d, PL_{tw}, PL_{in} are the path loss between Tx antenna and Rx antenna, building penetration loss, and path loss in indoor, respectively. The parameter d_{out} is distance from Tx antenna to the wall next to the Rx antenna and d_{in} is perpendicular distance from wall to Rx antenna. φ is incident angle of azimuth between the wall and a unit vector normal to the wall. The unit of incident angle is radian. The f is frequency whose unit is GHz. The penetration loss predicted by the M.2135 is 14 to 29 depending on incident angle of azimuth. The M.2135 proposes that distance attenuation coefficient 0.5 dB/m be used and the distance attenuation coefficient is linearly increased.

B. Measurement results

In this subsection we discuss the path loss characteristics in indoor in the 8 to 37 GHz band whose Tx antenna position is A-1 and Rx antenna position is 8 floor as shown in Fig. 2. The path loss in indoor $PL_{indoor.meas}$ is obtained by subtracting of free space loss in outdoor from measured path loss in building PL_{meas}.

$$PL_{indoor.meas} = PL_{meas} - 20\log_{10}(4\pi d_{out}/\lambda) \tag{5}$$

In order to compare measurement results and predicted results with M.2135, the predicted results with M.2135 are calculated by subtracting of the path loss in outdoor from the path loss between Tx antenna and Rx antenna with M.2135 by following formula.

$$PL_{indoor.M.2135} =$$
$$PL_d + PL_{tw} + PL_{tw} - (22\log_{10}d_{out} + 28 + 20\log_{10}f) \tag{6}$$

Figure 2 shows that the predicted results with M.2135 is smaller than the measurement results. The RMSE is about 5.3 dB at 8GHz, about 11.9 dB at 26GHz and about 12.7 dB at 37GHz, respectively. It can be seen that the RMSE value increases as the frequency increases. It is

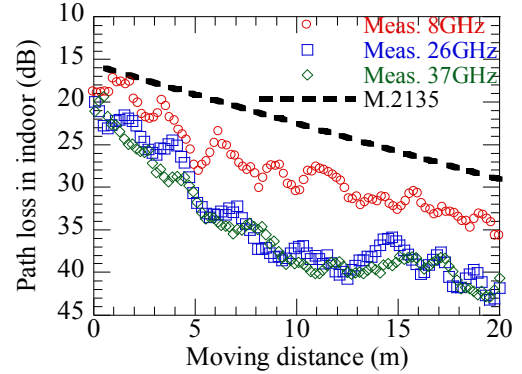therefore seen that M.2135 cannot cover the high frequency band above 6 GHz.

Figure 2. Comparison of measurement and prediction results with M.2135 model (Tx: A-1, Rx: 8F).
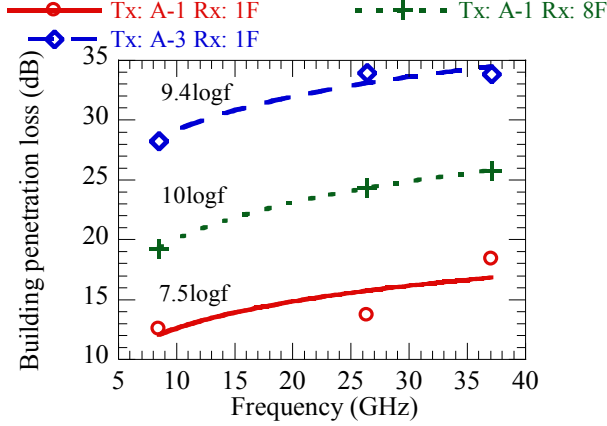
C. Analysis of the building penetration loss and the distance attenuation coefficient in indoor

We mainly analyzed the building penetration loss PL_{tw} and the distance attenuation coefficient in equation (3), (4), in terms of its dependence on frequency. M.2135 reported that the building penetration loss depends on incident angle. However, the each coefficients in the high frequency bands above the 6 GHz is not clear. Furthermore, the incident angle dependency of the distance attenuation coefficient in equation (4) is not clarified. Therefore we also analyzed the building penetration loss PL_{tw} and the distance attenuation coefficient, in terms of its dependence on incident angle. The building penetration loss and the distance attenuation coefficient are carrying out least square method by using the measured path loss in indoor $PL_{indoor.meas}$. In order to compare measurement results and the predicted results with M.2135, those functions are used with $\alpha d_{in}+\beta$. The building penetration loss is obtained from the fitting results β and the distance attenuation coefficient is obtained from the fitting results α with least square method.

Frequency dependency: Figure 3 (a) shows that the frequency characteristics for the building penetration loss PL_{tw}. The red line shows that Tx position is A-1 and Rx position is 1 floor in building. The blue line shows that Tx position is A-3 and Rx position is 1 floor in building. The green line shows that Tx position is A-1 and Rx position is 8 floor in building. From the Fig. 3 (a), the building penetration loss increases as the frequency increases. The rate of the increment is obtained by logarithmic approximation of the results of building penetration loss. The value of slope is 7.5logf ~ 10logf. The results mean that the frequency dependency is larger about 7.5logf ~ 10logf than free space loss. Accordingly, it can be seen that the building penetration loss depends on the frequency. Figure 3 (b) shows that the frequency characteristics for the distance attenuation coefficient. It shows that a tendency in which the distance attenuation coefficient increases with an increase in frequency. However, the rate of the increment is small about 0.02logf ~ 0.16logf, the distance attenuation coefficient is independent of frequency.

Incident angle dependency: Figure 4 (a) shows that the incident angles characteristics of azimuth for the distance attenuation coefficient and the building penetration loss PL_{tw}. The azimuth angle of measurement results in Fig. 4 (a) is 25 degree at A-1, 52 degree at A-2 and 69 degree at A-3. It can be seen that the building penetration loss increases as the azimuth angle increases. It is also found that the distance attenuation coefficient decreases as the azimuth angle increases. Figure. 4 (b) shows that the incident angle of elevation. The elevation angle of measurement results in Fig. 4 (b) is 13 degree at A-

1 at 4 floor, 21 degree at A-1 at 6 floor and 29 degree at A-1 at 8 floor. From fig. 4 (b), it shows that the building penetration loss and the distance attenuation coefficient increases according to the increase in the elevation angle. We assume that the distance attenuation coefficient of Fig. 4 (b) increases because the diffracted wave from the nearest window to the Rx antenna is dominant. Therefore, the building penetration loss and the distance attenuation coefficient is relative to the elevation and azimuth angle. These dependencies on both frequency and incident angle of azimuth and elevation need to be taken into account.
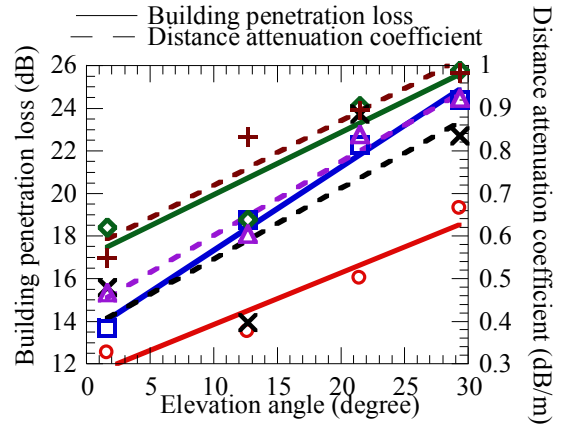

(a) Building penetration loss.
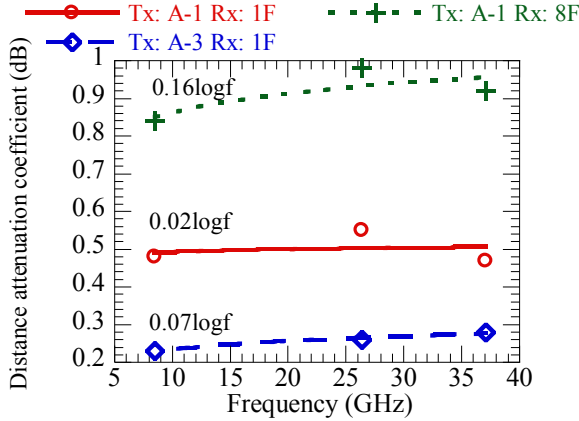
(b) Distance attenuation coefficient.
Figure 3. Dependency on frequency.
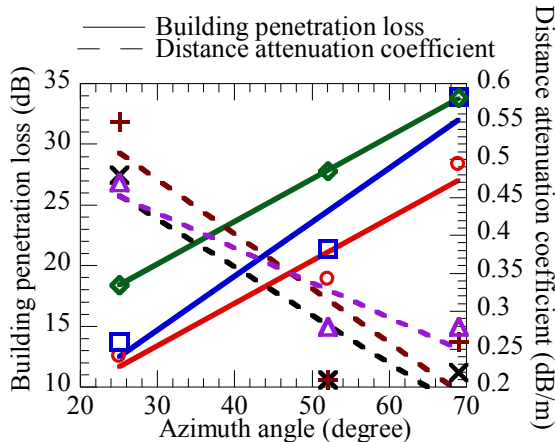
(a) Azimuth angle.

(b) Elevation angle.
Figure 4. Dependency on Incident angle.

IV. PROPOSED PATH LOSS MODEL

A. Model description

As the analysis results in Fig. 3 and 4 indicate, in order to predict the path loss in indoor at the high frequency band it is important to take into account the dependency on frequency and incident angle of azimuth and elevation. We therefore propose a path loss model in indoor that takes these dependencies into account for extending the applicable frequency band. The proposed model is shown below in (7), (8). Here, the fitting parameters for the proposed model are carrying out multiple regression analysis of the measurement results for each floor and Tx antenna position.

$$PL_{tw.prop} = 35.9(1 - \cos\varphi)^2 + 236.6(1 - \cos\theta)^2 + 7.5\log_{10} f + 7.5 \qquad (7)$$

$$PL_{in.prop} = (-0.6\sin\varphi + 0.7\sin\theta + 0.8)d_{in} \qquad (8)$$

where $PL_{tw.prop}$, $PL_{in.prop}$ are the building penetration loss and path loss in indoor, respectively. θ is incident angle of elevation, φ is incident angle of azimuth, f is frequency. The building penetration loss obtained by equation (3) is substituted into equation (7) and the the path loss in indoor obtained by (4) is substituted into equation (8). The applicable range for the frequency f is 8 to 37 GHz band, the applicable distance from wall d_{in} is the 2.1 ~ 23.2 m.

B. Verifying validity of proposed path loss model

Figure 5 shows path loss measurement results, prediction results obtained with the M.2135, and prediction results obtained with the proposed model for the A-1 at 8 floor, A-3 at 1 floor. From Fig. 5 (a) whose azimuth angle is 69 degree, it can be seen that better fitting between predicted and measured values is obtained with the proposed model than with the M.2135 model, with the former reducing the RMSE value to about 2.5 dB at 8 GHz, 7.7 dB at 26 GH and 9 dB at 37GHz. From Fig. 5 (b) whose elevation angle is 29 degree, it shows that with the proposed model the RMSE values decrease about 3.1 dB at 8 GHz, 9.2 dB at 26 GHz, 10.1 dB at 37 GHz than with M.2135 model. It is found that the propose model can accurately predict the incident angle in three dimension. Figure 6 shows that the RMSE values for 8 to 37 GHz. The RMSE values with the M.2135 increases as the frequency increases and the median values are about 7.3 dB for 8 to 37 GHz. On the other hand, the median values of RMSE with the proposed model are 3.5 dB for 8 to 37 GHz. Particularly the amount of decreasing the RMSE is 5.4dB at 37 GHz. This shows that the proposed model can cover the high frequency bands from 8 to 37 GHz.
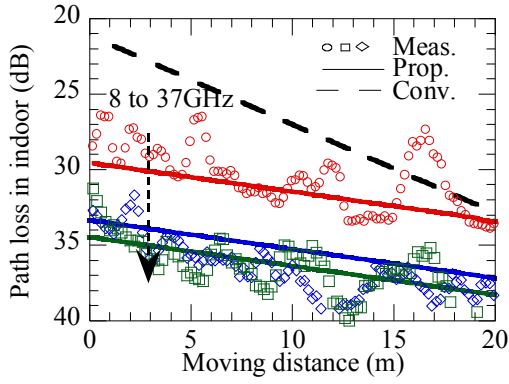
(a) Tx: A-3 Rx: 1F.
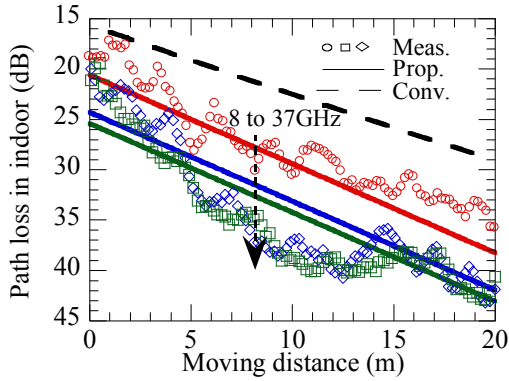
(b) Tx: A-1 Rx: 8F.

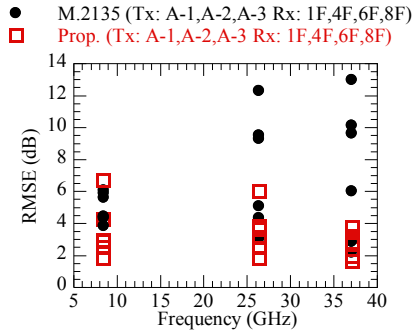Figure 5. Comparison of proposed and conventional model results.

Figure 6. RMSE in 8 to 37 GHz.

V. THE PROPAGATION PATH OF BUILDING PENETRATION

In this subsection, it is clarified that the dominant path of building penetration by simulating it. From the measurement results and analysis, it is shown that the building penetration loss has the frequency dependency and the incident angle dependency. The diffracted wave which is varied by the frequency and incident angle is assumed to be affected. Therefore, the two building penetration paths are considered. The one of propagation path is that the radiated radio from Tx antenna is diffracted at the external wall, then arrived at Rx antenna. The other path is that the radiated radio from Tx antenna is diffracted at the external wall, then arrived at Rx antenna while being multiple reflected at the wall in indoor. Figure 7 shows the simulation model of the building penetration path. The path loss of the building penetration path is calculated by ray-tracing. The diffractions at the external wall of one times and the multiple wall reflections of five times are accounted in each simulations.

The material of the wall is assumed to be concrete with the dielectric constant of 7 and conductivity of 0.0023 S/m. Table 2 shows the RMSE values between the penetration loss of the measurement results and the penetration loss of the calculated results in each Tx position. The RMSE values with diffracted wave and multiple reflected wave is about 3 dB and the RMSE values with diffracted wave and multiple reflected wave tends to decrease about 2.6 ~ 4 dB for 8 to 37 GHz than with only diffracted wave. The building penetration loss with only diffracted wave is larger because the angle of diffraction is smaller than with diffracted wave and multiple reflected wave. These results shows that the diffracted and multiple reflected path is dominant. It is found that the path in considering diffracted and multiple reflected wave is affected to the frequency dependency because the RMSE values is small in high frequency bands from 8 to 37 GHz.
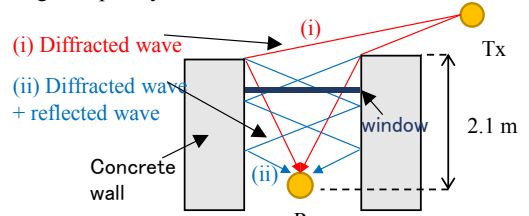

Figure 6. Simulation model.

Table 2. The difference between measured and calculated The building penetration loss.

Frequency (GHz)	RMSE (dB)	
	Diffracted wave	Diffracted wave + Reflected wave
8	6.78	2.16
26	6.97	3.01
37	6.10	3.53

VI. CONCLUSION

We proposed an applicable high frequency model above 6 GHz that takes account of frequency and incident angle dependencies. The outdoor-to-indoor path loss characteristics are measured and analyzed for the 8 to 37 GHz band with aim of developing a path loss model. The measurement results clarified that path loss in indoor depends on frequency, incident angle of azimuth and incident angle of elevation. Its validity is confirmed by evaluating the RMSE values of prediction results obtained with it. The evaluations confirmed it can predict path loss with RMSE of 2 to 6 dB for the 8 to 37 GHz band. Moreover, the building penetration path is simulated and it is clarified that the path in considering the diffracted wave and the multiple reflected wave is affected to the frequency dependency.

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