920MHz band propagation characteristics near metal ceiling for secure IoT communication

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Abstract: In this paper, we investigate the path loss characteristics near metal ceiling in 920 MHz band for secure wireless communication of indoor-use equipment such as lighting systems. In order to clarify the propagation mechanism, experiment and electromagnetic simulation are conducted using two models as use cases: a simple model with only a metal ceiling and an office with a metal ceiling.

The results show that the path loss characteristics for vertical polarization near the metal ceiling has a smaller than the free space loss. The path loss characteristic for horizontal polarization, however, changes significantly depending on the floor condition.

Keywords: Metal ceiling, Indoor propagation, Path loss, Ray tracing

Classification: Antennas and propagation

References

[1] W. Honcharenko, H. L. Berton, J. L. Dailing, J. Qian and H. D. Yee, “Mechanisms governing UHF propagation on single floors in modern office buildings,” IEEE Transactions on Vehicular Technology, vol. 41, no. 4, pp. 496-504, Nov. 1992, DOI: 10.1109/25.182602.

[2] Kwok-Wai Cheung, J. H.-M. Sau and R. D. Murch, “A new empirical model for indoor propagation prediction,” IEEE Transactions on Vehicular Technology, vol. 47, no. 3, pp. 996-1001, Aug. 1998, DOI: 10.1109/25.704854.

[3] S. Y. Seidel and T. S. Rappaport, “Site-specific propagation prediction for wireless in-building personal communication system design,” IEEE Transactions on Vehicular Technology, vol. 43, no. 4, pp. 879-891, Nov. 1994, DOI: 0.1109/25.330150.

[4] Rec. ITU-R P.1238-8: “Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks
in the frequency range 300 MHz to 100 GHz”, July, 2015.

[5] H. Shimada, T. Maeyama, N. Yamamoto, T. Hishikawa, “Study of electromagnetic analysis method in large indoor space,” IEICE Technical Report, AP2019-51, Aug. 2019.

[6] N. Yamamoto, T. Hishikawa, K. Saito, J. Takada, T. Maeyama, “Radio wave propagation analysis using FDTD and Ray tracing methods for a simplified model assuming a metal ceiling office in the 920 MHz band,” IEICE Society Conference B-1-12, Sep. 2019.

[7] N. Yamamoto, T. Hishikawa, K. Saito, J. Takada, T. Maeyama, “Studies of Radio Wave Propagation Characteristics near Concrete Ceiling,” IEICE Society Conference B-1-8, Sep. 2020.

[8] J. Takada, “Basic theory of radio wave propagation,” Journal of the Institute of Image Information and Television Engineers, vol.70, No.1, p.143-148, 2016, DOI: https://doi.org/10.3169/itej.70.142.

[9] Constantine A. Balanis, Advanced Engineering Electromagnetics, Chapter5, 2nd edition, Wiley, 2012.

[10] EEM Inc., “EEM-RTM,” http://www.e-em.co.jp/rtm/index.html, accessed April. 15, 2021.

[11] T. Imai, Ray-tracing Method for Radio Propagation Analysis -Fundamentals and Practical Applications-, Chapter6, Corona publishing, 2016 (Japanese edition).

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1 Introduction

In recent years, with the growth of the IoT (Internet of things) market, the wireless systemization of various equipment such as lighting and ventilation system have been accelerating. The applications are, for example, remote control, monitoring, and data collection into the cloud and its analysis. The equipment is often used 920 MHz band in Japan since it has good propagation characteristics and less interference than the 2.4 GHz band which is also used for IoT devices.

In order to realize secure communication, it is important to predict the path loss characteristics in the environment where the equipment is actually used. In particular, the indoor-use equipment is generally installed near the ceiling as well as the access points connected to the equipment. Therefore, it is necessary to clarify the path loss characteristics including the influence of the ceiling material on the equipment.

In this paper, we investigate the path loss characteristics when both antennas are close to near metal ceiling. Metal ceiling is mainly used in non-residential buildings such as offices, hospitals, shopping malls, and airports, for its advantage that it can eliminate the bias of air conditioning with radiation effect generated by cooling or heating the ceiling chamber.

Various studies for the prediction of path loss within the same building floor have been conducted [1, 2, 3]. However, they do not clarify the specific propagation characteristics near metal ceiling. In [4], an empirical indoor propagation
prediction model is standardized. However, it is difficult to predict the propagation characteristics accurately since parameters such as construction materials and structures are not taken into account. Furthermore, the propagation characteristics with respect to the polarization characteristics of the antenna have not been clarified.

In this study, the following two models are considered in order to clarify the propagation mechanism near metal ceiling in the 920 MHz band. Model 1 denotes the case only with a metal ceiling. This model assumes that the reflection from the metal ceiling is predominant propagation mechanism and the reflection from the floor can be negligibly small. The propagation characteristics of both vertical and horizontal polarizations (denoted as V-pol. and H-pol. respectively) for Model 1 are obtained by experiment and theoretical analysis based on image method. Model 2 denotes the case with an actual metal ceiling office with a floor. To clarify the propagation characteristics, an experiment was conducted in an actual office and numerical simulation using an equivalent simplified model. The simulation method used in the propagation prediction is the ray-tracing method, which is commonly used in site-specific propagation prediction [3], [5], [6].

2 Experimental site and simulation model

Figs. 1(a) and 1(b) show the experimental site and corresponding simplified simulation model for Model 1.

(a) Model 1: Anechoic chamber with metal floor modeling a metal ceiling of upside-down office

(b) Simulation model for Model 1

(c) Model 2: Metal ceiling office

(d) Simulation model for Model 2

Fig. 1. Experimental sites and corresponding simulation models.
We use a five-sided anechoic chamber for EMC (Electromagnetic Compatibility) test site showed Fig. 1(a) as an experimental site to eliminate the influence from other components of the metal ceiling. The metal floor of the anechoic chamber models a metal ceiling of the upside-down office. For the simulation model shown in Fig. 1(b), the ceiling is simply assumed to be a plane PEC (Perfect Electrical Conductor). The antennas at the Tx and Rx are half-wavelength dipole antennas, respectively. The distance from the ceiling to the antenna feed point is set to \( h = 0.1 \text{ m} (\approx 0.3\lambda) \), which is the same for Tx and Rx, where \( \lambda \) is the wavelength.

Figs. 1(c) and 1(d) show the actual metal ceiling office and the corresponding simulation model for Model 2. In Fig. 1(d), the materials of the ceiling and the floor are assumed to be PEC, the distance between the ceiling and the floor is 2.5 m in order to match the conditions with the experimental site shown in Fig. 1(c). In the simulation model, concrete walls of the non-residential buildings are not considered because the experiment was conducted in the large room with low ceiling, 20 m (W) \( \times \) 100 m (D) \( \times \) 2.5 m (H). The conditions of Tx and Rx antennas are the same as in the case of Model 1. In both Model 1 and Model 2, the path loss characteristics are obtained by experiments and simulations with the Tx and Rx antennas placed in parallel to each other in both cases of V-pol. and H-pol. and \( d \) is the distance between Tx and Rx. \( d \) is set within the range 1 m to 20 m, which represents the typical communication range of IoT devices.

3 Experimental and simulation results

3.1 Model 1 : Metal ceiling only

Fig. 2(a) shows the path loss characteristics of experiments and geometrical optics theory for Model 1. The experimental plot is the power average of 461 points measured within a radius of about 2 wavelengths at each \( d \). The theoretical values are calculated using Eqs. (2), (3), and (4) described below. As shown in Fig. 2(a), the experimental and theoretical results are almost same. It is also found that the results of the V-pol. and H-pol. are quite different. The interpretation of the results is explained as follows. The model of Fig. 1(b) is the well-known two-path model. In this case, the path gain \( G \) defined as the ratio of the transmitted power \( P_T \) to the received power \( P_R \) is given by the following equation [8]:

\[
G = \frac{P_R}{P_T} = \left( \frac{\lambda}{4\pi d} \right)^2 G_T \cdot G_R \left| 1 + R \cdot \exp(jk\Delta l) \right|^2, \tag{1}
\]

where \( G_T \) is Tx antenna gain, \( G_R \) is Rx antenna gain, \( R \) is the reflection coefficient of the ceiling, \( k = 2\pi/\lambda \) is the wave number, \( \Delta l \) is the path difference of direct wave and reflection wave. \( \Delta l \) can be expressed as the following equation:

\[
\Delta l = \sqrt{(h_T + h_R)^2 + d^2} - \sqrt{(h_T - h_R)^2 + d^2} \approx \frac{2h_T h_R}{d}, \tag{2}
\]

where \( h_T \) and \( h_R \) are the distances between the ceiling and Tx antenna, and between the ceiling and Rx antenna, respectively. In this case, \( h_T = h_R = h \). According to the image theory [9], reflection coefficient \( R \) of V-pol. of the plane
PEC is 1, and that of H-pol. is -1. This is the reason of the difference for both polarizations. By considering $R$ for V and H-pol. and taking the reciprocal of Eq. (1) and substituting Eq. (2) into Eq. (1), the path losses for V-pol. and H-pol. in the condition of near metal ceiling can be approximated by the following equation:

$$L_V = \left(\frac{2\pi d}{\lambda}\right)^2 \cdot \frac{1}{\left|\cos\left(\frac{kA}{2}\right)\right|^2} \approx \left(\frac{2\pi d}{\lambda}\right)^2,$$

$$L_H = \left(\frac{2\pi d}{\lambda}\right)^2 \cdot \frac{1}{\left|\sin\left(\frac{kA}{2}\right)\right|^2} \approx \left(\frac{d}{h}\right)^4.$$  

In the applicable range of Eq. (3) and Eq. (4), the breakpoint of the two-path model is defined by following equation [8]:

$$d_{bp} = \sqrt{2kh_T h_R}.$$  

Only range beyond breakpoint is discussed in this study because $h$ is sufficiently small. The breakpoint is 0.27 m when it is calculated by Eq. (5) in case of $h = 0.1$ m. Therefore, in the range of Fig. 2 (a), the path loss exponent is $\alpha = 2$ for V-pol and $\alpha = 4$ for H-pol, respectively. Note that the path loss component is $\alpha = 2$ in the free space.

3.2 Model 2: Metal ceiling office

Fig. 2 (b) shows the path loss characteristics of the experimental and the simulation results of Model 2 for V-pol. and H-pol., respectively.

The experimental plot is the power average of 461 points measured within a radius of about 2 wavelengths at each $d$. The measurement in the office of Model 2 was performed in the distance range $d$ of up to 10 m due to the constraints of the experimental site. The simulation result is obtained by using the ray tracing [10]. The simulation model and conditions are shown in Fig. 1(d) and Table 1, respectively. In order to investigate the effect of the metal floor, the ray tracing simulation is conducted with considering only the metal ceiling and floor. To be consistent with the measurement data, the simulation plots are the moving averages within the range of $\pm 2$ wavelengths along the observation line.

As shown in Fig. 2 (b), the path loss for V-pol. is less than the free space loss as in the case of Model 1. It can be also seen that the experimental and simulation results are in good agreement. That is, the path loss is more dominated by the metal ceiling rather than the floor.

In contrast, the path loss for H-pol. is very different from that of Model 1 and is also smaller than the free space loss as in case of V-pol.. It is considered that the wave reflected from the metal floor in Model 2 results in the small path loss of H-pol., as the guiding effect in the parallel flat plate consisting of the metal ceiling and floor. In case of H-pol. path loss measurement, the dipole antennas were horizontally set, as shown in Fig. 1(d). From this, radio waves with the same power were radiated to the floor and ceiling, due to omni-directional radiation pattern of the dipole antenna. Consequently, the guiding effect can be observed.
On the other hand, it was found from Fig. 2(b) that the waveguide effect of V-pol. is smaller than that of H-pol., since the wave reflected from the floor was small because of the radiation pattern of the vertically set dipole antenna.

In order to properly calculate the guiding effect in ray tracing simulation, the maximum number of reflections was set to be 100 shown in Table 1 [11].

![Path loss characteristics](image_url)

**Fig. 2.** Path loss characteristics.

**Table 1.** Simulation parameters.

| Parameter                                           | Value                     |
|-----------------------------------------------------|---------------------------|
| Frequency                                           | 928MHz                    |
| Method                                              | Ray launching             |
| Tx and Rx Antenna                                   | Half wavelength dipole    |
| Antenna polarization                                | Vertical, Horizontal      |
| Ray discrete angle                                  | 1 degree                  |
| Number of reflections                               | 100                       |
| Number of divisions of observation line             | 2000 (100 samples/m)      |
| Moving average range                                | 4λ (±2λ)                  |

**4 Conclusion**

This paper presented the path loss characteristics near metal ceiling in 920 MHz band. It was found from the experimental and theoretical results of the geometric optics for Model 1 that the path loss for V-pol. has different behavior from two-path model, and it is smaller than the free space loss.

It was also found from the experimental and simulation results for Model 2 that the path loss for V-pol. is the same as in Model 1. On the other hand, the path loss for H-pol. is very different from that of Model 1 and is also smaller than the free space loss as the guiding effect in the parallel flat plate consisting of the metal ceiling and floor. As a result, the path losses of both V and H-pol. are smaller than the free space loss.