Building Entry Loss (BEL) Characteristics for Incident Angles and Measurement Locations from 3.5 to 24 GHz

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Abstract. An effect of a building entry loss (BEL) on incident angles has been investigated in a traditional office building from 3.5 to 24 GHz band. The BEL was measured at three different positions in the window, the office center, and the corridor, moving a receiver (Rx) from 1 m away from the window (W) to the inside on the 6th (6F) and 9th (9F) floor of the building. As the Rx location moves from the window (W) to O and C inside of the building, the BEL increases and its slope for the azimuth angle decrease on the 6F, where the signal is directly incident. This tendency was not observed in 9F with an elevation angle of 12.8°. These results reveal that there is a breakpoint and propagation mechanism is different at each Rx location. For cumulative distribution function (CDF) of the BEL, as the frequency increases to 3.5, 6, and 10 GHz, the BEL increases. However, it decreases at 24 GHz at all Rx locations and all elevation angles because of frequency dependency of the input impedance of the air dielectric interface in the double layered-glass window. As the elevation angle increases from 0 to 12.8° in the window, the BEL increases from 4.2 to 11.7 dB at 50 percentile level of the CDF.

Keywords: Building entry loss (BEL) · Penetration loss · Outdoor-to-indoor propagation

1 Introduction

Emergence of various wireless communication services such as mobile, WiFi, ZigBee, and internet of thing (IoT) leads to expand available frequencies. Because radio networks have to be carefully planned and optimized, more precise and more diversified radio propagation models are needed over many bands or at high frequencies. Recently, outdoor-to-indoor (O2I) path loss and building entry loss (BEL) are emerging as important issues, because of the large loss contribution, which must be considered when designing radio link networks [1].

S. O. Hwang et al. (Eds.): ICGHIT 2018, LNEE 502, pp. 51–56, 2019.
https://doi.org/10.1007/978-981-13-0311-1_10

Several empirical models and measurement analysis have been investigated under the names of O2I path loss, O2I penetration loss, and O2I propagation loss with different definitions [2–4]. Therefore, these research results are not easy to be applied. In addition, since there are many variables to be considered, such as the environment, the location of a transmitter (Tx) and receiver (Rx), building materials, and its structure, many difficulties are encountered in implementing accurate and standardized models. Moreover, some of the measurement results show clearly contradictory observations [5–8]. Obstruction inside the Fresnel zone or frequency dependency due to a layered glass in a window is one of the main causes [5]. Some study demonstrated that the frequency dependence can be improved by considering multiple reflected and diffracted waves [8]. However, the difference is not clear at millimeter wave. In general, although the BEL increases with increasing incident angle [7, 8] or receiving distance [9], frequency dependency was still unclear. That means that propagation mechanism is different near the window and inside the building. Therefore, various variables and complex propagation mechanisms make it difficult to analyze the measurement results.

In this paper, the characteristics of the BEL have been measured with varying elevation and azimuth angle while changing the position of the Rx inside the building from 3.5 to 24 GHz.

2 Measurement Environment and Scenario

The definitions of BEL and their measurement methods are well documented in the ITU-R document [10–12]. In this work, the O2I BEL measurement was performed in an environment shown in Fig. 1. This traditional office building is with reinforced concrete shear wall and double glazing window without a metal coating. Its 6 mm thick two glasses are separated by the air gap of 12 mm. A thickness of a bearing wall is 35–38 cm. The interior wall is being equipped with a plaster board and foam polyethylene sheet and its thickness is around 25 cm. An outdoor Tx antenna in the front of the building is fixed on a road. In order to investigate the effect of the BEL on an incident angle of azimuth and elevation, an indoor Rx is located in 6F and a received power was measured while moving the Rx as shown in Fig. 1(a). The height of the Rx antenna in the 6F is the same as the Tx antenna. Measurements were repeated at the 9th floor (9F) with different elevation angle. The height difference between 6F and 9F is 10.5 m and the corresponding elevation angle is 12.8°. There is a six-floor deep valley between the building and road as shown in Fig. 1(c).

Figure 2 shows details of the BEL measurement scenario. One fixed outdoor Tx and 28 different Rx points on each floor of the building were selected as shown in Fig. 2(a). Seven reference locations were selected with different incidence angles of azimuth (α), which are from 19.0 to 60.1°. Reference power was measured at a distance of 1.6 m from the exterior wall of the building. By using one reference, the BEL was characterized at three different locations inside the building with the distance of 1 and 5 m from the window in the exterior wall and in the middle of the corridor and their locations are named window (W), office (O), and corridor (C), respectively, as shown in Fig. 2(b). This measurement was repeated in the same manner in the 9F with the incident angle of elevation of 12.8° as shown in Fig. 2(c).

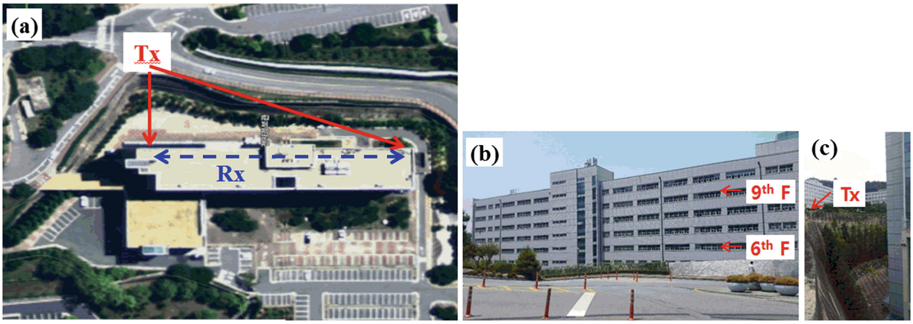


Fig. 1. Photographs of the building for the BEL measurement on Chosun university campus (Gwangju, in Korea). (a) Tx position on the road, and Rx movement route in the building, (b) the external façade of the building, and (c) a valley between the Tx and the building

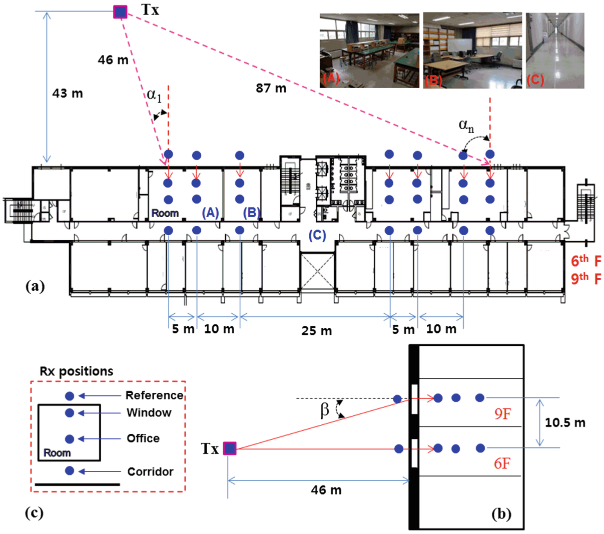


Fig. 2. Details of the BEL measurement scenario. (a) Reference and indoor Rx positions in the 6F and 9F floor in the building, the incident angle of azimuth (α), and photographs of university laboratories (a, and b) and corridor (c), (b) the incident angle of elevation (β) for the floor height, and (c) name for Rx points; window (W), office (O), and corridor (C).

Measurements were taken by using continuous wave (CW) of 3.5, 6, 10, and 24 GHz. The antennas used for both the outdoor Tx and indoor Rx were omnidirectional ones. The Tx antenna was mounted on a pole on the roadside whose height is 2.5 m above the ground. The Rx antenna was fixed on a handcart inside the building and its height was 1.5 m above the floor. The Tx consisted of a signal generator (SG) and a power amplifier connected with the antenna. The Rx was composed of the identical antenna, low-noise amplifier and spectrum analyzer.

3 Measured Results and Analysis

The BEL in this campaign has been calculated by using definition in Recommendation ITU-R P.2040-1 [12] as:

$$BEL = P_{ref} - P_{indoor}[dB]$$

where BEL is the building entry loss, P_{ref} is the spatial median of the power received outside the illuminated face of a building, and P_{indoor} is the received power at the indoor locations.

The median value of the BEL for the incident angle of each frequency is calculated. Figure 3 presents the BEL characteristics for the incident angle at each measurement location. The BEL tends to increase with increasing the incident angle of azimuth at all locations. The BEL in 9F ($\beta = 12.8^{o}$) increases, compared to the BEL in 6F ($\beta = 0^{o}$). As the location moves from window (W) to office (O) to corridor (C), the BEL tends to increase. When the incident angle of azimuth increases beyond 52°, the BEL characteristics change significantly irrespective of the frequency and location. It is obvious that only a small part of the incident wave enters into the building and there is a complicated path of reflection and diffraction. However, the frequency dependence of the incident angle of azimuth is not clear and the BEL at 24 GHz is low. In general, the input impedance of the air dielectric interface in the double layered-glass window depends on frequency [5].

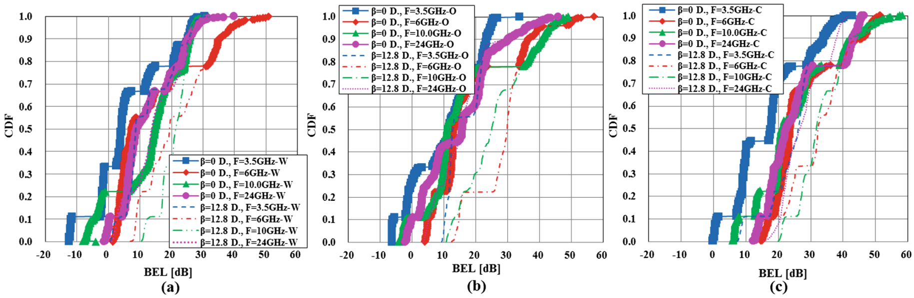


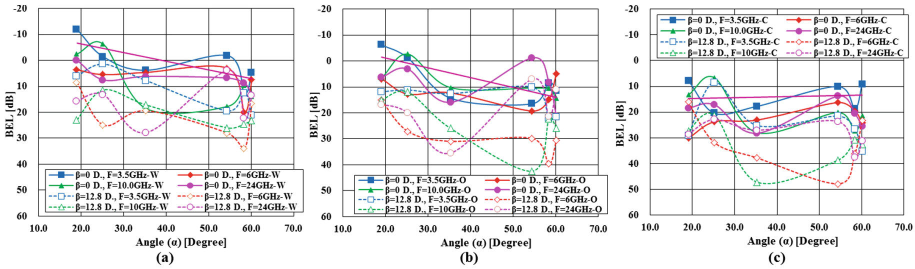
Fig. 3. Incident angle dependency of the BEL for each Rx location (a) window (W), (b) office (O), and (c) corridor (C) [D: degree].

By using a linear regression analysis, the linear regression lines at 3.5 GHz in each location are shown in Fig. 3. The BEL slope for the incident angle of azimuth in each location is extracted. The results are summarized in Table 1. As the measuring position moves from the window to the inside of the building, the BEL increases and its slope decrease on the 6F ($\beta = 0^{o}$). This tendency was not observed in 9F ($\beta = 12.8^{o}$). A consistent change in the BEL slope means that a breakpoint is present and propagation mechanism is different for each location. In the case of the 9F with a large elevation angle, a part of the radio wave illuminated on the exterior wall enters into the building and it seems to be influenced by the complex clutters inside. For the window location, the BEL per an incident azimuth angle is 0.335 dB/degree at 3.5 GHz and the highest value of 0.413 dB/degree is observed at 10 GHz. For other frequencies, the trends are similar. However, there was no frequency dependence of the slope.

Table 1. BEL slope for the incident angle of azimuth [dB/degree]

Location	Window (W)		Office (O)		Corridor (C)	
β [degree]	0	12.8	0	12.8	0	12.8
3.5 GHz	0.335	0.380	0.382	0.202	−0.032	0.218
6.0 GHz	0.180	0.281	0.069	0.344	−0.184	0.271
10 GHz	0.413	0.188	0.241	0.392	0.295	0.159
24 GHz	0.186	−0.075	0.135	−0.207	0.039	0.148

Figure 4 shows the cumulative distribution function (CDF) of the measured BEL for each Rx location. On the 6F, the minimum point of the BEL increases by 11.2 dB when the Rx location moves from the W to O and the C. The CDF distribution on 6F is wide, compared to that on 9F. At 50 percentile level of CDF, as the frequency increases to 3.5, 6, 10 GHz, the BEL increases, but it decreases at 24 GHz at environments (W, O, and C) and β. In the W and C, as the elevation angle increased from 0 to 12.8°, the BEL increase range is from 4.2 to 11.7 dB and also its fluctuations is not very large. However, in the office, as the elevation angle increases, the BEL fluctuates significantly. In the case of W and C, the structure is simple and obstacles in the propagation path are a few, compared to the O.



(a) (b) (c)

Fig. 4. CDF of the BEL for each Rx position. (a) window (W), (b) office (O), and (c) corridor (C).

4 Conclusion

In this work, the BEL of the traditional office building has been measured and analyzed from 3.5 to 24 GHz bands. Its characteristics for the incident angles were analyzed at three different locations in the 6F and 9F with elevation angles of 0 and 12.8°, respectively. The BEL tends to increase with increasing the azimuth and elevation angle at all locations. As the Rx location moves from the window (W) to office (O) and corridor (C), the BEL increases, but its BEL slope for the azimuth angle decreases. These results reveal that a breakpoint is present and the propagation mechanism is different for each location. Especially, the BEL slope for the azimuth angle at 24 GHz is 0.186, 0.135, and 0.039 dB/degrees for W, O and C, respectively. At 50 percentile level of CDF, as the frequency increases from 3.5 GHz to 6 and 10 GHz, the BEL increases, but it also decreases at 24 GHz at all measurement locations and β.

Acknowledgment. This research was supported by a grant of the research and development fund from the National Radio Research Agency (RRA) in Korea, 2017 and supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2017R1D1A3B03036543).

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