Path Loss Model as a Function of Antenna Height for 300 GHz Chip-to-Chip Communications

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***Abstract*—This paper presents the path loss model of Terahertz (THz) wireless channel inside a desktop size metal enclosure as a function of antenna hight. Measurements for line-of-sight (LoS) propagation inside the metal box show that path loss varies with respect to the transceiver's height from the bottom wall, and for some heights, the path loss is lower than the free space value. Analysis based on the cavity modes shows that the first eight TE modes dominate the resonating modes inside the box. Also, the path loss analysis indicates that the resonating modes combined with the reflections inside the box are responsible for the strong ripples in the path loss curve.**

I. INTRODUCTION

Wireless communication has been proposed as a future solution for chip-to-chip communication inside a desktop for its advantage of reducing the assembly cost of chips and the complexity of system design and maintenance. One limitation of wireless communication is its transmitting data rates. Compared with hundreds of gigabits per second for wired system, wireless communication can hardly achieve ten gigabits per second [1], [2]. To solve this problem, Terahertz (THz) wireless communication has been proposed for its advantage of providing larger bandwidth and requiring smaller antennas [3].

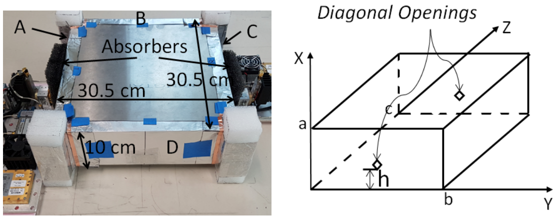
To achieve THz chip-to-chip wireless communication inside a desktop, channel characterization is necessary. In the microwave frequency range, 3.1-10 GHz, measurements for board-to-board communication have been done inside two desktops, one with crowded interior and the other one with relative empty interior [4]. Also, the chip-to-chip communication has been characterized in both closed and open computer cases in the similar frequency band [5]. At THz frequencies, indoor communication has been conducted for line-of-sight (LoS) propagation by varying distance between transmitter (Tx) and receiver (Rx), and for non-line-of-sight (NLoS) propagation with different transmitting and receiving angles, shadowing effect, and reflection and diffraction from various material [6]. Additionally, on-board 300 GHz wireless communication measurements have been performed by considering different possible scenarios like LoS, RNLoS, obstructed-line-of-sight (OLoS), and NLoS [2].

In contrast, this paper presents the LoS path loss model of 300 GHz wireless channel inside a desktop size metal box as a function of antenna height. Here, we have focused on the scenarios of LoS propagation with the variation of transceiver's height, h. Path loss analysis indicates that both traveling wave and the resonating modes contribute to the received power. By analyzing the relationship between the path loss and the antenna's height, the results show that the first eight TE modes dominates the resonance inside the box. Also, the path loss analysis indicates that the resonating modes combined with the reflections inside the box are responsible for the strong ripples on the path loss curve. An initial investigation on the LoS propagation characterization has been reported in [7] shows the variation in the received power with transceivers' height. This was explained with the contribution of first six resonant TE modes. Here, in continuation, we propose mean path loss model in the metal enclosure as the superposition of traveling wave and resonant modes. Also, for more accuracy, we model the received power variation with first eight resonant TE modes.

The remainder of the paper is organized as follows. Section II describes measurement scenario used to derive path loss model. Section III presents measured results, path loss model, and discusses the findings. Section IV provides concluding remarks.

II. A MEASUREMENT SCENARIO

The measurement scenario is similar to the one described in [7], it involves an aluminum box was built with the size of 30.5 cm× 30.5 cm× 9.6 cm, which approximates computer desktop casing. As shown in Fig. 1a, two square aluminum plates with the length of 30.5 cm were fixed by foams at four corners to form the ceil and floor of the metal box. The other four sides of the metal box were covered by aluminum foils. These side walls are labeled as A, B, C, and D as shown in Fig. 1a. Box was sandwiched in the middle of the transmitter (Tx) and the receiver (Rx) with antennas aligned horizontally. Based on the antenna's height, h, two diagonal openings with the horn antenna's size were drilled on the transceiver sides



(a) (b)

Fig. 1: (a) LoS measurement set up and (b) the rectangular metal cavity with diagonal openings

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(side A and side C) of the metal box as shown in Fig. 1b. The distance from the center of antennas to side B of the metal box is equal to half of its width. To characterize the resonant modes inside the metal box, measurements have been performed with h varied from 0 cm to 6.6 cm with the step size of 0.6 cm. The parameter h here refers to the distance between the bottom edge of the horn to the ground of the metal box. The distance between phase center and bottom edge of the horn antenna is 4.575 mm. Absorbers were used to eliminate reflections from the backsides of antennas as shown in Fig. 1a.

III. PATH LOSS MODEL AS A FUNCTION OF ANTENNA HEIGHT

Figure 2a presents the measured path loss for in the box measurements and compares them with the Friis formula. For the measurements with $h < 1.8$ cm, path loss is lower than Friis formula prediction, while for $h > 1.8$ cm, path loss is aligned with the Friis formula prediction. This variation of path loss can be explained by observing that different resonating modes contribute to the received power. We note here that since transmit power is kept constant, the variation in the path loss is equal to the variation of the received power. Therefore, the path loss of LoS propagation inside the metal box can be considered as the combination of the path loss of traveling wave and the received power variation due to the resonating modes. Fig. 2b compares the measured and calculated mean path loss with respect to height, h. The mean of measured path loss at certain height, h, is calculated by averaging the continuous wave, as shown in Fig. 2a, over all recorded frequencies. The measured path loss curve shown in Fig. 2b is the interpolation of these averaged points which are also marked on the curve.

The theoretical path loss $(PL^T)_{\mathrm{dB}}$ in Fig. 2b is calculated as

$$(PL^T)_{\mathrm{dB}} = (\overline{\tilde{PL}})_{\mathrm{dB}} + 10\log_{10}(|E|^2)^{-1} \tag{1}$$

where $\overline{\tilde{PL}}$ represents the mean path loss of traveling wave and can be calculated by averaging Friis formula over the frequency band as

$$\overline{\tilde{PL}} = \frac{1}{\Delta f}\int_{\Delta f}\left(\frac{4\pi df}{c}\right)^2 df, \tag{2}$$

where d represents the distance between Tx and Rx, and c is the speed of light. Here, $d = D = 30.5$ cm, which is the length of the box. $10\log_{10}(|E|^2)^{-1}$ represents the received power variation contributed by resonating modes. $|E|^2$ can be written as

$$|E|^2 = |E_x|^2 + |E_y|^2 = |\sum_{m=1}^{M} E_{ym}|^2 + |\sum_{m=1}^{N} E_{xm}|^2, \tag{3}$$

where E_{ym} and E_{xm} are given as [8]

$$E_{ym} = \frac{j\omega_{mnp}\mu k_x H_0}{k_{mnp}^2 - k_z^2}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}\sin\frac{p\pi z}{z}, \tag{4}$$

$$E_{xm} = -\frac{j\omega_{mnp}\mu k_y H_0}{k_{mnp}^2 - k_z^2}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\sin\frac{p\pi z}{z}, \tag{5}$$

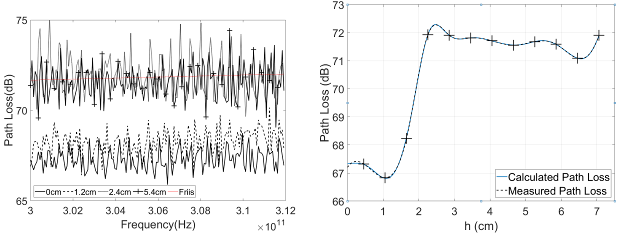
where H_0 is an arbitrary constant with units of A/m and m, n, and p are integers. The eigenvalues k_{mnp} satisfy:

$$k_{mnp}^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{c}\right)^2 = k_x^2 + k_y^2 + k_z^2, \tag{6}$$

where k_x=$m\pi\ a$, k_y=$n\pi\ b$, k_z=$p\pi\ c$, and a, b, and c represent the height, length, and width of the cavity as shown in Fig. 1b. For h variation in the x direction, (4) and (5) can be simplified as follows

$$E_{ym} = A_m \sin(m\pi x\ a), E_{xm} = B_m \cos(m\pi x\ a). \tag{7}$$

Using curve-fitting, we have found that the first 8 modes of the TE mode dominate the resonant cavity in the box and the coefficients of these modes are empirically found to be $A_1 = 0.441, B_1 = -0.173, A_2 = -0.583, B_2 = 0.060, A_3 = 0.757, B_3 = -0.056, A_4 = -0.254, B_4 = 0.352, A_5 = 0.274, B_5 = -0.113, A_6 = 0.128, B_6 = 0.394, A_7 = 0.968, B_7 = 0.892, A_8 = 0.269, B_8 = 0.323$.



(a) (b)

Fig. 2: Measured and calculated (a) path loss variation in frequency and (b) mean path loss for LoS in a metal box as function of the antenna's height, h.

IV. CONCLUSIONS

This paper presents the path loss model of THz wireless channel inside a metal box as a function of antenna height. It is found that both traveling wave and resonant modes exist inside the box. The analysis of LoS propagation inside the metal box shows that the received power variation with respect to the antenna's height is due to the resonant modes dominated by the first eight TE modes inside the metal box.

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